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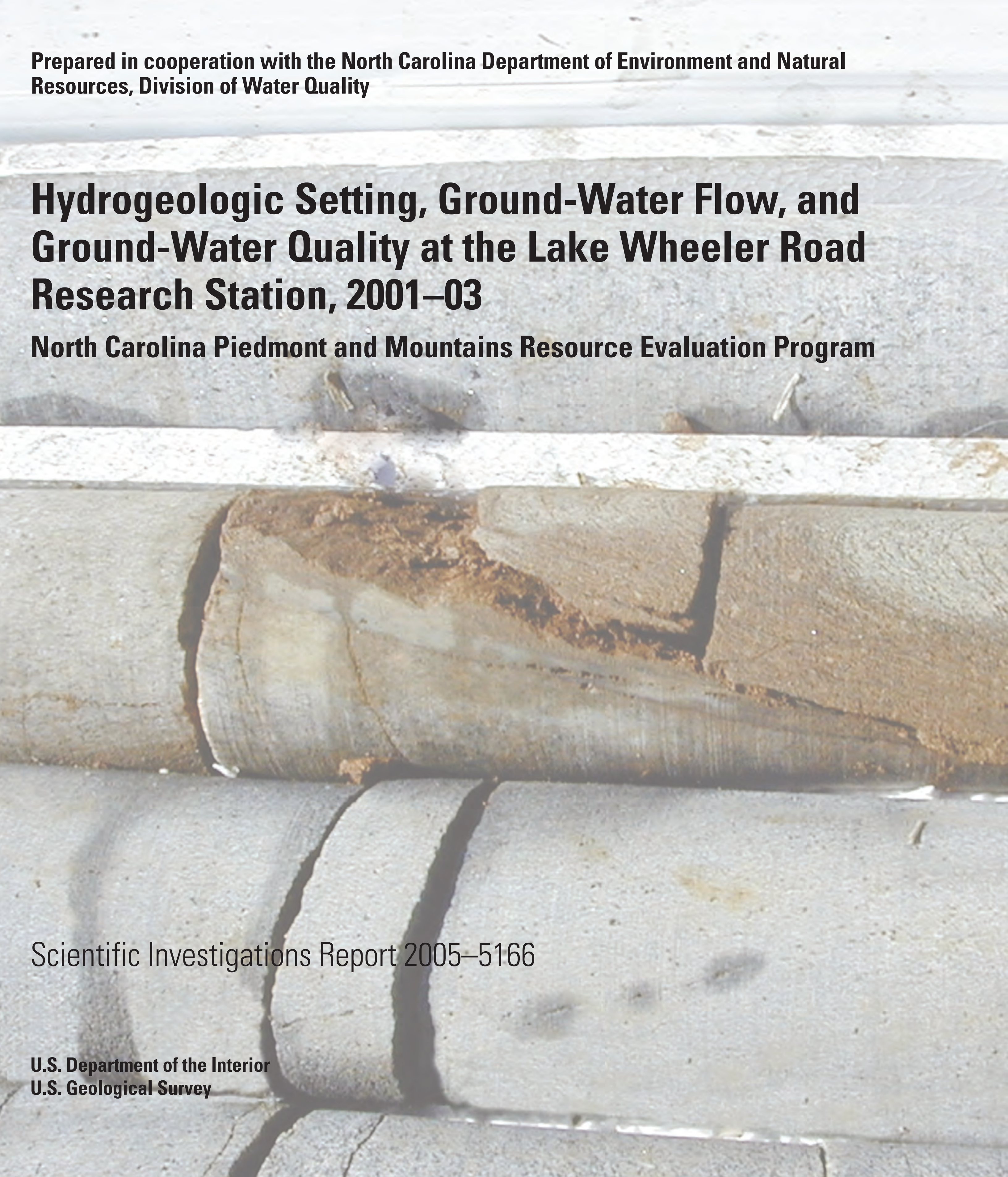
Hydrogeologic Setting, Ground-Water Flow, and Ground-Water Quality at the Lake Wheeler Road Research Station, 2001–03

North Carolina Piedmont and Mountains Resource Evaluation Program



Scientific Investigations Report 2005–5166

U.S. Department of the Interior
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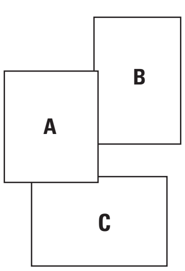
Front cover. **Bedrock core sample from the Lake Wheeler Road research station, North Carolina** *(photograph by Richard E. Bolich, North Carolina Department of Environment and Natural Resources, Division of Water Quality, Aquifer Protection Section)***.**

Back cover.



A. Sampling activities, B. drilling *(photographs by Charles C. Daniel III, U.S. Geological Survey, retired),* and **C. monitoring-well cluster 1 and data-collection platform** *(photograph by Brad A. Huffman, U.S. Geological Survey)* **at the Lake Wheeler Road research station, North Carolina.**

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North Carolina Piedmont and Mountains Resource Evaluation Program

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Gale A. Norton, Secretary

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Conversion Factors

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	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.784	liter (L)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Specific capacity	
gallon per minute per foot ([gal/min]/ft)	0.207	liter per second per meter ([L/s]/m)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature may be converted as follows:

$$°F = (1.8 \times °C) + 32$$

$$°C = (°F - 32) / 1.8$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

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 height above the vertical datum.

Water year is defined as the period from October 1 through September 30 and is identified by the year in which the period ends.

Acronyms and Abbreviations:

APRASA	Appalachian Valleys-Piedmont Regional Aquifer System
DGPS	Differential Global Positioning System
DO	dissolved oxygen
DWQ	Division of Water Quality
ET	evapotranspiration
GWSI	Ground-Water Site Inventory
hr	hour
LWRRS	Lake Wheeler Road research station
mg/L	milligram per liter
MP	measuring point
NCDENR	North Carolina Department of Environment and Natural Resources
NCGS	North Carolina Geological Survey
NCSU	North Carolina State University
NURE	National Uranium Resource Evaluation
NWIS	National Water Information System
OTV	optical televiewer
PMREP	Piedmont and Mountains Resource Evaluation Program
PVC	polyvinyl chloride
SC	specific conductance
SOP	standard operating procedure
USGS	U.S. Geological Survey
µg/L	microgram per liter

Hydrogeologic Setting, Ground-Water Flow, and Ground-Water Quality at the Lake Wheeler Road Research Station, 2001–03

North Carolina Piedmont and Mountains Resource Evaluation Program

By Melinda J. Chapman[1], Richard E. Bolich[2], and Brad A. Huffman[1]

Abstract

Results of a 2-year field study of the regolith-fractured bedrock ground-water system at the Lake Wheeler Road research station in Wake County, North Carolina, indicate both disconnection and interaction among components of the ground-water system. The three components of the ground-water system include (1) shallow, porous regolith; (2) a transition zone, including partially weathered rock, having both secondary (fractures) and primary porosity; and (3) deeper, fractured bedrock that has little, if any, primary porosity and is dominated by secondary fractures. The research station includes 15 wells (including a well transect from topographic high to low settings) completed in the three major components of the ground-water-flow system and a surface-water gaging station on an unnamed tributary.

The Lake Wheeler Road research station is considered representative of a felsic gneiss hydrogeologic unit having steeply dipping foliation and a relatively thick overlying regolith. Bedrock foliation generally strikes N. 10° E. to N. 30° E. and N. 20° W. to N. 40° W. to a depth of about 400 feet and dips between 70° and 80° SE. and NE., respectively. From 400 to 600 feet, the foliation generally strikes N. 70° E. to N. 80° E., dipping 70° to 80° SE. Depth to bedrock locally ranges from about 67 to 77 feet below land surface. Fractures in the bedrock generally occur in two primary sets: low dip angle, stress relief fractures that cross cut foliation, and steeply dipping fractures parallel to foliation.

Findings of this study generally support the conceptual models of ground-water flow from high to low topographic settings developed for the Piedmont and Blue Ridge Provinces in previous investigations, but are considered a refinement of the generalized conceptual model based on a detailed local-scale investigation. Ground water flows toward a surface-water boundary, and hydraulic gradients generally are downward in recharge areas and upward in discharge areas; however, local variations in vertical gradients are apparent.

Water-quality sampling and monitoring efforts were conducted to characterize the interaction of components of the ground-water system. Elevated nitrate concentrations as high as 22 milligrams per liter were detected in shallow ground water from the regolith at the study site. These elevated nitrate concentrations likely are related to land use, which includes agricultural practices that involve animal feeding operations and crop fertilization. Continuous ground-water-quality data indicate seasonal fluctuations in field water-quality properties, differences with respect to depth, and fluctuations during recharge events. Water-quality properties recorded in the regolith well following rainfall indicate the upwelling of deeper ground water in the discharge area, likely from ground water in the transition-zone fractures. Additionally, interaction with a surface-water boundary appears likely in the ground-water discharge area, as water levels in all three ground-water zones, including the deep bedrock, mimic the surface-water rise during rainfall.

Introduction

In 1999, the U.S. Geological Survey (USGS), North Carolina Water Science Center, and the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality (DWQ), began a multiyear cooperative study to measure ambient ground-water quality and describe the ground-water-flow system in the Piedmont and Blue Ridge (Mountains) Physiographic Provinces in North Carolina (Daniel and Dahlen, 2002). This study is supported by the Piedmont and Mountains Resource Evaluation Program (PMREP), which was created by the North Carolina Legislature to ensure the long-term availability,

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[2]North Carolina Department of Environment and Natural Resources, Division of Water Quality, Raleigh Regional Office, Aquifer Protection Section, Raleigh, N.C.

sustainability, and quality of ground water in the State. The study was designed to be a 10-year intensive field investigative effort through the establishment of hydrogeologic research stations within representative hydrogeologic settings. To date (2005), seven research stations (fig. 1) have been selected for study across the Piedmont and Mountains region, and wells have been installed at five of the research stations. Data from these research stations will provide information to refine the historical conceptual ground-water-flow models for the Piedmont and Blue Ridge Physiographic Provinces in North Carolina and the Southeastern United States.

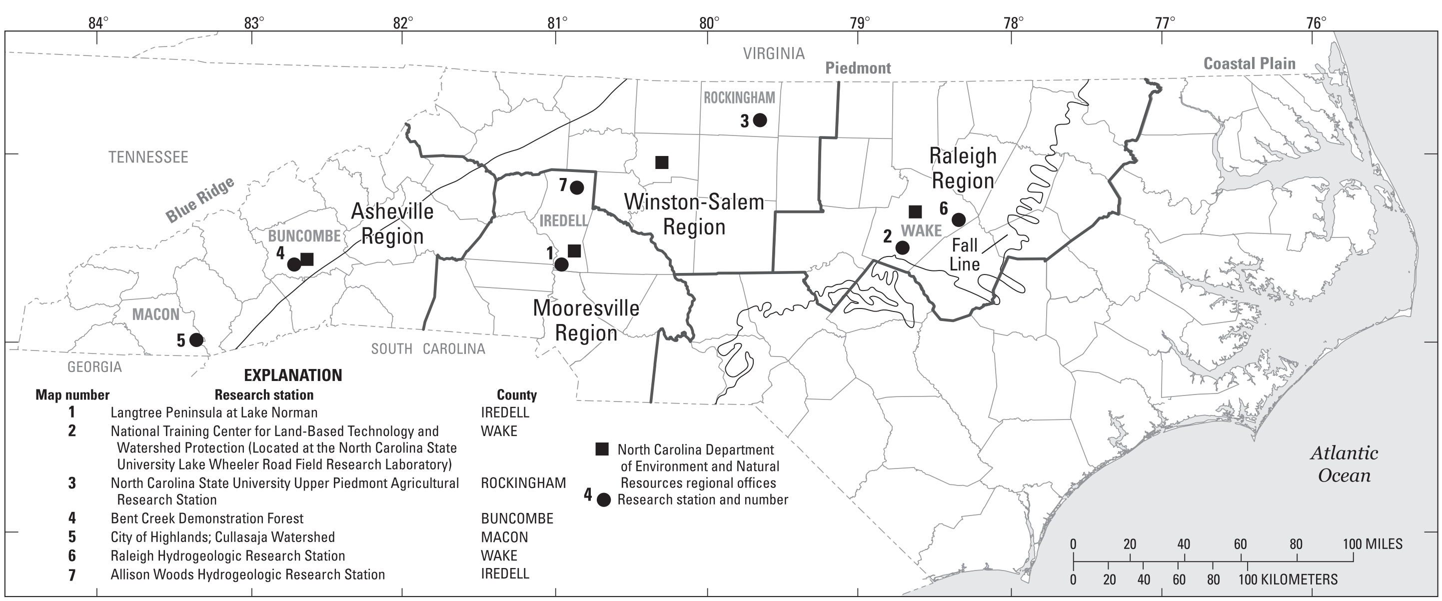
The Lake Wheeler Road research station (LWRRS) in Wake County lies within the Raleigh litho-tectonic belt (fig. 2) and is underlain by a metamorphosed felsic gneiss that is part of the Raleigh Formation (Parker, 1979; Heller, 1996). Felsic gneisses compose the geologic setting of about 20 to 30 percent of the Piedmont and Blue Ridge Provinces in North Carolina. The LWRRS was selected for study (Daniel and Dahlen, 2002) to evaluate the effects of felsic gneiss rock type and steeply dipping foliation on ground-water quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. The LWRRS also represents a hydrogeologic setting where ground-water quality has been affected by agricultural activities. In addition, the close proximity of the research station to the USGS and the NCDENR DWQ offices facilitates training opportunities in methods of hydrogeologic characterization in piedmont settings for agency staff members.

Background

The Piedmont and Blue Ridge Physiographic Provinces in North Carolina extend over about 30,544 square miles (mi^2) and 54 counties. In 2000, the population of this area was about 6.11 million. Total ground-water use for the Piedmont and Mountains region in 2000 was estimated to be about 244 million gallons per day (U.S. Geological Survey, 2004a). Ground water is the primary source of drinking water for most rural and some suburban households in the Piedmont and Blue Ridge Provinces, whereas surface water is the primary drinking-water source in metropolitan areas (Daniel and Dahlen, 2002). Most of the population lives in or near the metropolitan areas of Raleigh/Durham/Chapel Hill, Greensboro/Winston-Salem, and Charlotte—all of which are located in the Piedmont region.

Although a major metropolitan area (Raleigh) lies within Wake County, about 90,000 county residents use wells as their primary source of drinking water. About 275 community wells and 600 private domestic wells were inventoried in the county's database in 2003 (Camp, Dresser, and McKee, 2003). Most of the land use in Wake County is urban and suburban; as a result, many contaminant-release incidents are reported. By March 2004, more than 1,000 contaminant-release incidents had been reported, of which 380 incidents affected ground water (Mr. Rick Bolich, North Carolina Department of Environment and Natural Resources, written commun., 2003).

Ground water in the Piedmont and Blue Ridge Provinces flows through geologic settings composed of metamorphic,



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 1. Research stations selected for investigations as part of the cooperative U.S. Geological Survey-North Carolina Division of Water Quality Piedmont-Mountains Ground-Water Study in North Carolina.

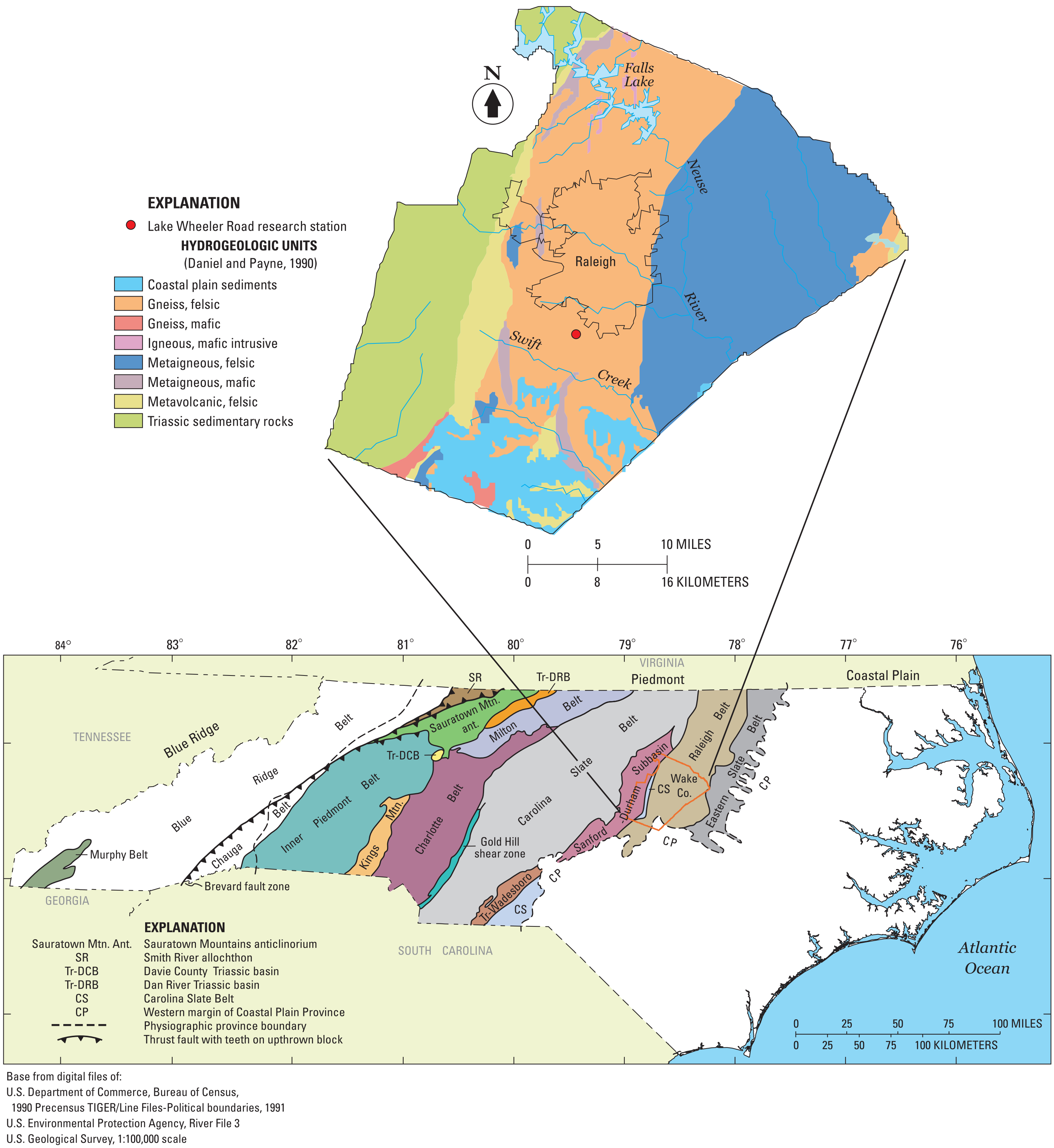


Figure 2. Hydrogeologic units underlying the Lake Wheeler Road research station in Wake County, and geologic belts delineated in the Piedmont Physiographic Province of North Carolina (modified from North Carolina Geological Survey, 1985; Daniel and Payne, 1990).

igneous, and sedimentary (Triassic basins) rocks. Weathered regolith, composed of soil, residuum, saprolite, alluvium, and colluvium, overlies the fractured bedrock (Heath, 1980). Ground-water flow is complex, consisting of an interconnected but distinct two-component ground-water system, with the regolith providing storage to the underlying fractures in the bedrock (Heath, 1980). A third component, the transition zone, commonly occurs between the regolith and bedrock (fig. 3; Harned and Daniel, 1992). The role of the transition zone in the ground-water-flow system is being investigated as part of the PMREP. The transition zone generally is considered to be the most transmissive part of the ground-water-flow system and likely susceptible to contamination. Common descriptions of the transition zone include partially weathered, highly fractured rock that has dominant anisotropy from fractures and also retains some primary porosity.

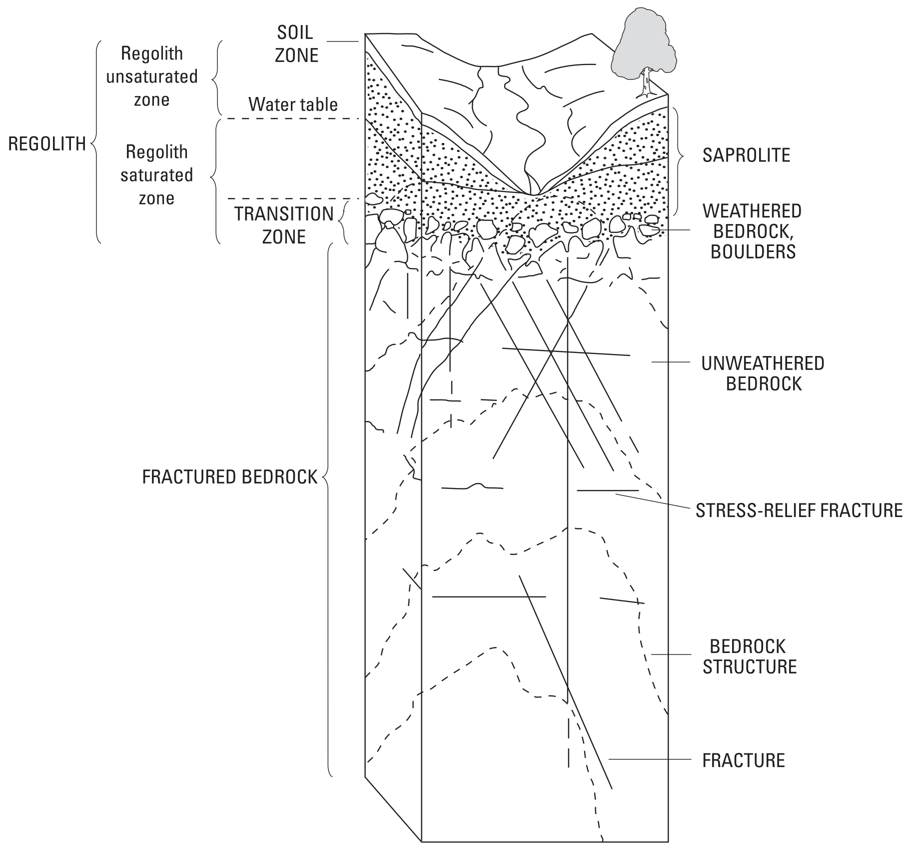


Figure 3. Conceptual components of the ground-water system in the North Carolina Piedmont and Mountains (from Harned and Daniel, 1992).

Because the shallow regolith and underlying bedrock fractures are connected, the aquifer systems of the Piedmont and Blue Ridge Physiographic Provinces are considered to be unconfined, although local confinement may occur in discontinuous water-bearing fracture zones. Additionally, because the aquifers in these provinces are shallow, they are susceptible to contamination from activities on the land surface (Daniel and Dahlen, 2002). A primary goal of the DWQ for the PMREP is to investigate the vulnerability of the ground-water system to contamination in order to better protect and manage the resource. The work conducted as part of this study supports the USGS mission of understanding processes in complex ground-water systems to aid water-resource managers in the protection and management of the resource.

Program Objectives

The principal objectives for the regional PMREP are to

(1) define the hydrogeologic framework of the Piedmont and Blue Ridge Provinces;

(2) identify and characterize the hydrologic processes active in each province;

(3) investigate the functioning of representative ground-water-flow systems in the regolith-fractured-rock aquifer systems by means of applied research, analytical methods, and computer simulation;

(4) refine the understanding of recharge and discharge processes and their effects on ground- and surface-water quality;

(5) estimate regional water budgets, including rates of natural discharge and recharge, changes in aquifer storage, and withdrawals;

(6) determine the importance and interrelation of surface- and ground-water-flow systems, the relation to water quality, and potential for resource development; and

(7) develop a comprehensive ground-water database for the region.

These objectives are addressed by the interpretation of data collected at research stations constructed in representative hydrogeologic settings as part of this study. Results of this study in combination with other studies in the Blue Ridge and Piedmont Provinces of North Carolina and the Eastern United States will provide information needed for management of the Nation's water resources by defining water quality and quantity (Daniel and Dahlen, 2002).

Purpose and Scope

This report presents the results of a study at the LWRRS from May 2001 through September 2003 to describe the hydrogeologic framework, ground-water quality, and ground-water flow beneath the study area. The report includes ground-water-quality and ground-water-level data and descriptions of the regional surficial geology and ground-water and surface-water interactions.

The LWRRS was designed to distinguish and evaluate the three primary zones of the Piedmont ground-water system: (1) the shallow regolith, (2) the transition zone, and (3) the deeper fractured, crystalline bedrock (fig. 3). Water quality, hydraulic properties, and flow patterns were evaluated in each of the components of the ground-water system at the study site. The quality of water in each of the three zones was characterized by collecting periodic samples for laboratory analysis, and recording pH, specific conductance (SC), temperature, and dissolved oxygen (DO) at hourly intervals at one well cluster during July 2001 through September 2003. Slug tests were performed on all wells to compare hydraulic conductivity estimates. The fracture system in the bedrock was further characterized from borehole geophysical logs and optical televiewer images. Interaction of ground water and surface water was evaluated by using data from continuously recorded (15-minute intervals) tributary gage height and water-quality properties.

Description of the Study Area

The LWRRS is located about 5 miles (mi) southwest of the city of Raleigh, North Carolina, and encompasses about 7 acres on the North Carolina State University (NCSU) Lake Wheeler Road Field Laboratory farm campus. The NCSU Lake Wheeler Road farm campus is used for various agricultural research projects. Hog barns and waste-disposal lagoons are located about 1,000 feet (ft) south of the LWRRS well clusters (fig. 4). Row crops, such as corn, also are planted on the farm. The entire area was agricultural before NCSU established the Field Laboratory campus approximately 40 years ago (Mr. Ken Snyder, Manager, North Carolina State University Lake Wheeler Road Field Laboratory, oral commun., 2004).

The climate at the study area is typical of the Piedmont region of the Southeastern United States—warm, humid summers and generally mild winters. The State Climate Office of North Carolina maintains a meteorological data station (Raleigh 4 SW; State Climate Office of North Carolina, 2002) located about 0.25 mi south of the LWRRS (fig. 4).

The NCSU Lake Wheeler Road Field Laboratory also is used for educational and training purposes. Demonstration and training models of various wastewater-disposal systems are located throughout the site, but no actual wastewater is discharged from these systems. At the NCSU On-Site Wastewater Training Center (fig. 4), many of the decentralized wastewater-treatment technologies used throughout the country are demonstrated, using above-ground, hands-on demonstrations and educational displays. The technologies that are demonstrated range from the traditional septic system to the latest, most advanced types of on-site technologies that can be used to protect the environment and public health while facilitating cost-effective development. The Soil and Water Environmental Technology Center also is located on the NCSU's Lake Wheeler Road Field Laboratory campus, and the surrounding agricultural area is used for various repetitive research projects.

Previous Studies

Several studies of ground water and geologic mapping have been conducted in the Wake County area and the Piedmont region of North Carolina since the late 1960s. One of the first detailed hydrogeologic studies was by May and Thomas (1968), who analyzed the yields of 268 wells in Wake County with respect to topography. Their study also included results of analyses for major ions and nutrients in samples from 17 wells in Wake County. May and Thomas (1968) described the mica gneiss unit as a biotite-feldspar gneiss, quartzitic gneiss, garnetiferous biotite gneiss, and interbedded gneiss and schist. This unit is similar to the felsic gneiss at the LWRRS. Foliation and gneiss structures were described as being well developed. Metamorphic structures generally strike northeast, having variable dip directions and angles. A second unit described by May and Thomas (1968) was a light- to pinkish-gray medium- to coarse-grained biotite granite.

May and Thomas (1968) reported that well yields (total of 80 wells) for the mica gneiss unit in Wake County averaged 19 gallons per minute (gal/min), ranging from about 0.5 to 295 gal/min; about 6 percent of these wells yielded 1 gal/min or less. Higher yields for industrial or municipal supplies may be obtained from large quartz veins or highly fractured rocks in this geologic unit. The ground water in this unit generally was described as soft; it can, however, contain high concentrations of iron. The granite unit in Wake County had an average yield of about 20 gal/min (total of 77 wells), ranging from 0 to 82 gal/min; about 2 percent of these wells yielded less than 1 gal/min.

Parker (1979) conducted geologic mapping of the Raleigh area and provided the first detailed summary of the geology of Wake County. In Parker's 1979 geologic map, the LWRRS is located near a contact between a felsic gneiss and schist unit, and an injected gneiss and schist unit. Structural measurements from the 1979 report show foliation striking about N. 12° to 13° E. and a vertical dip angle.

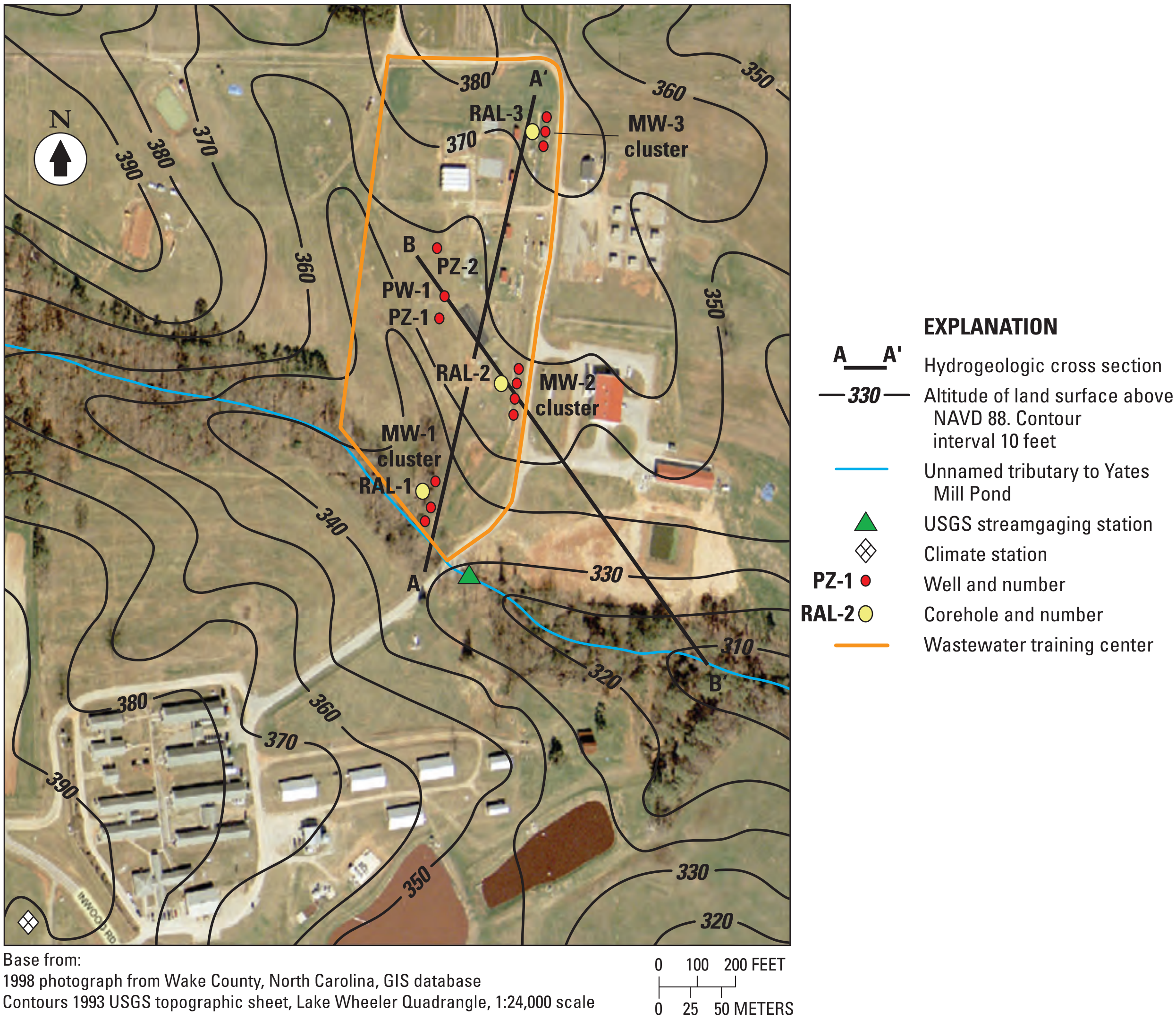


Figure 4. Aerial photograph of the Lake Wheeler Road research station, North Carolina, overlaid with topographic features showing locations of well clusters, streamgage, climate station, and lines of section.

Farrar (1985) published a regional-scale geologic map of the eastern North Carolina Piedmont, including the Raleigh “block.” Summaries of the tectonic relations between rocks of the Raleigh metamorphic belt can be found in Blake and others (2001) and Stoddard and Blake (1994). The most detailed geologic mapping of the study area was conducted by Heller (1996) as part of the North Carolina STATEMAP component and the educational component (EDMAP) of the National Cooperative Geologic Mapping Program (U.S. Geological Survey, 2005).

According to a generalized hydrogeologic unit map of the Piedmont and Mountains region of North Carolina by Daniel and Payne (1990), the LWRRS is located in the “GNF” hydrogeologic unit. The GNF unit is described as “mainly granitic gneiss, light-colored to gray, fine- to coarse-grained rocks, usually with distinct layering and foliation, often interlayered with mafic gneisses and schists.”

Carpenter and Reid (1993) presented the results of the National Uranium Resource Evaluation (NURE) program in which ground-water samples from 5,778 wells in North Carolina were analyzed for uranium, vanadium, dysprosium, sodium, aluminum, manganese, bromine, chlorine, and fluorine. Briel (1997) summarized ground-water quality in North Carolina wells as part of the Appalachian Valleys-Piedmont Regional Aquifer System (APRASA) study.

Most recently, Camp, Dresser, and McKee (2003) performed an analysis of ground-water quality and quantity data for Wake County using existing ground-water-quality data, primarily from the NCDENR Public Water Supply Section. The ground-water-quality data were analyzed in relation to drainage basins and hydrogeologic units in the county. Well yields for the felsic gneiss unit were reported to range from about 5 to 20 gal/min.

Acknowledgments

The authors graciously thank the following individuals for their help and guidance: Ken Snyder, Manager, NCSU Lake Wheeler Road Field Laboratory; Mike Hoover, NCSU Soil Science Extension Service; Tyler Clark, NCDENR Geological Survey; David Blake, The University of North Carolina, Wilmington Geology Department; and Edward F. (Skip) Stoddard, NCSU Department of Marine, Earth, and Atmospheric Science. The authors also thank members of the NCDENR/USGS Piedmont and Mountains Resource Evaluation Program who continually contributed to data collection and interpretation during this project. These members include Chuck Pippin of the Mooresville DWQ Regional Office, Don Geddes of the Winston-Salem DWQ Regional Office, Ted Campbell and Landon Davis of the Asheville DWQ Regional Office, and Carl Bailey and Walt Haven of the Raleigh DWQ Central Office. In addition, the authors thank the NCDENR-DWQ drillers for the hard work, perseverance, and patience they displayed in dealing with conditions in the field and their willingness to do whatever was necessary to complete their work. The authors would like to thank Lester Williams and Gloria Ferrell, USGS, for their contributions to this report as colleague reviewers. The foundation was laid for this study by contributions to the science of piedmont and mountains ground-water hydrology by retired USGS ground-water hydrologists Charles Daniel, Ralph Heath, and Harry LeGrand. The authors appreciate ongoing technical discussions with these scientists.

Methods of Investigation

The methods described in this report were used during an investigation of the hydrogeology and ground water at the LWRRS between May 2001 and September 2003. The methods also are summarized in standard operating procedures (SOP) for the PMREP (North Carolina Department of Environment and Natural Resources, Division of Water Quality, Groundwater Section, and U.S. Geological Survey, Water Resources Division, written commun., 2002).

Research Station Design and Monitoring

The LWRRS is located in the Piedmont Physiographic Province, which is characterized by gently rolling hills and moderately well-developed drainage features. The topography in the vicinity of the well transect slopes gently toward the draw to the west (intermittent stream) and the surface-water site to the south (fig. 4). The altitude along the transect ranges from approximately 376 ft to approximately 327 ft. The unnamed tributary empties into other unnamed perennial streams, eventually joining the Swift Creek drainage area of the Neuse River basin.

The LWRRS consists of three monitoring-well clusters constructed along a topographic transect, an outlying bedrock well and two shallow piezometers, and a surface-water gage. Each well cluster at the LWRRS consists of three to four wells to monitor ground-water conditions—(1) a shallow well completed in the upper part of the regolith, (2) an intermediate well completed in saprolite in the lower part of the regolith, (3) a transition zone completed in the open fractures near the top of bedrock, and (4) a bedrock well completed in the deeper fractured bedrock (fig. 3).

The transect is oriented along a conceptual high to low topographic profile, described by LeGrand (2004) as a "slope-aquifer" system, from recharge to discharge areas (figs. 4, 5). Wells in each cluster were installed to monitor the regolith, transition, and bedrock zones in the ground-water system.

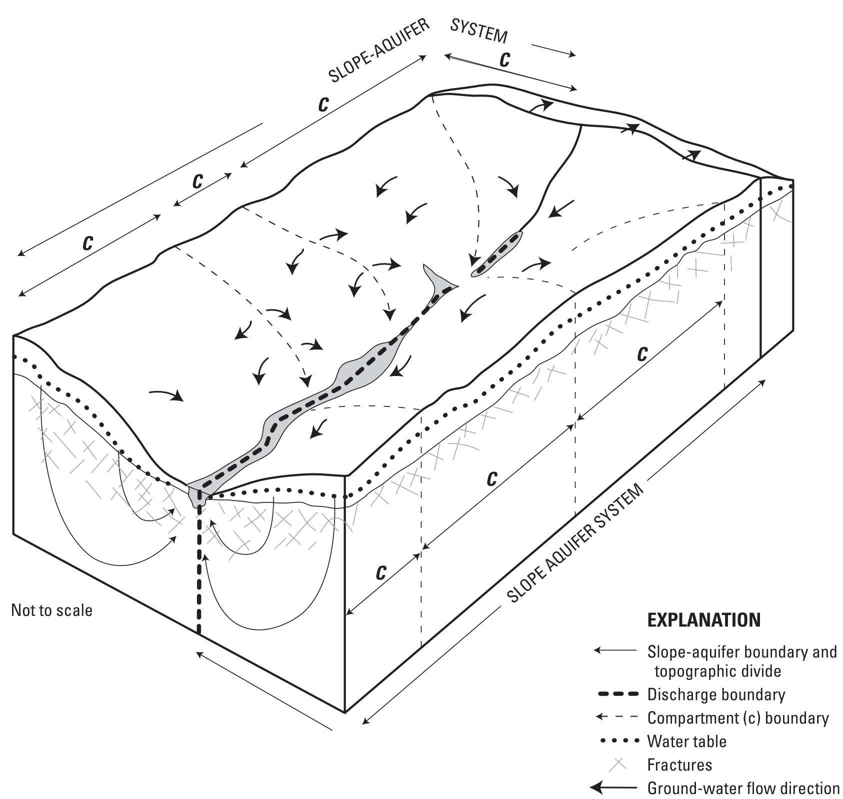


Figure 5. Conceptual view of the slope-aquifer system and related compartments (modified from LeGrand, 2004).

Geologic Coring

A continuous soil and bedrock core was collected at each of the monitoring-well cluster locations—MW-1, MW-2, and MW-3 (fig. 4). The coreholes at these three locations were designated RAL-1, RAL-2, and RAL-3, respectively (fig. 4). The coreholes provided continuous samples of the soil-to-bedrock profile at each well cluster, which were used to determine construction requirements for the monitoring wells. Detailed descriptions of the soil and rock cores from each well-cluster location are included in the appendixes.

The coreholes were drilled by using a wire-line coring rig owned by the NCDENR-DWQ. A 5-ft-long, 2.5-inch inside diameter core barrel sampler was used with a wire-line retrieval system. A carbide-tipped soil-sampling core barrel bit was used to penetrate the unconsolidated material, and a diamond-tipped bit was used to penetrate the competent bedrock. The site hydrogeologist logged the core retrieved from the sample barrel, noting rock type, fracture type and orientation, weathering, and geologic features. The cores were then marked for section correlation and placed in cardboard boxes for on-site storage. The cores currently (2005) are used to demonstrate subsurface conditions during training classes at the NCSU On-Site Wastewater Training Center.

Well-Cluster Transects and Aquifer-Test Wells

Well-cluster locations were selected to provide water-quality and water-level data along a topographic transect spanning areas of recharge and discharge based on conceptual models developed for the slope-aquifer system (LeGrand, 2004). Criteria for determining well-cluster locations included topographic position, accessibility, and site boundaries. Fifteen wells were installed at the LWRRS during this investigation (table 1). A conceptual hydrogeologic cross section was constructed along the well transect from cluster MW-3 (presumed recharge area) to cluster MW-1 (presumed discharge area; fig. 6). Three other wells (PW-1, PZ-1, and PZ-2; fig. 4) were installed to collect aquifer-test data and hydrogeologic data for site characterization.

Well Construction

Monitoring wells at the LWRRS were constructed by using air-rotary, mud-rotary, and hollow-stem auger drilling methods. Mud-rotary drilling techniques were used to construct the shallow and intermediate-depth wells in the MW-1 cluster and to bore the casing for MW-1D because of the less-competent, unconsolidated material at that location. Hollow-stem auger drilling techniques were used to construct the shallow and intermediate-depth wells in the MW-2 and MW-3 well clusters and the aquifer-test piezometers. All bedrock “D” wells were drilled by using both mud-rotary (surface-casing installation) and air-rotary methods (open-borehole drilling). Construction techniques used to install the monitoring wells are described in the following sections. Specific well-construction information is listed in table 1. All wells were developed following completion to remove drilling fluids and improve hydraulic connection between the wells and the aquifer. Bladder pumps were used to develop the regolith (shallow and intermediate depth) and transition-zone wells, and the bedrock wells were developed by using air-lift drilling methods. All of the wells were completed with a locking steel protective casing.

Shallow and Intermediate-Zone Regolith Wells

Both mud-rotary and hollow-stem auger methods were used to construct the regolith wells at the LWRRS. Mud-rotary methods were used to drill and install the shallow and intermediate-depth regolith wells in the MW-1 well cluster. Hollow-stem auger methods were used to drill and install all other shallow and intermediate-depth regolith wells in well clusters MW-2 and MW-3 (figs. 4, 6). After the boring reached the prescribed depth, the mud-rotary roller bit or augers were withdrawn from the borehole, and a 4-inch-diameter schedule 40 polyvinyl chloride (PVC) well casing was placed in the boring. All of the shallow monitoring wells were constructed with a 0.01-inch machine-slotted well screen. Screen lengths ranged from 10 to 20 ft (table 1). Stainless steel centralizers were placed on the outside of the PVC casing at 20-ft intervals to center the well screen and riser casing within the borehole. Clean sand filter material gradually was poured into the annular space between the PVC casing and the boring to a level 2 ft above the top of the well screen. A 2-ft-thick dry bentonite chip seal was placed on top of the sand filter pack and hydrated with water obtained from a supply well. Dry bentonite chips then were placed above the hydrated seal to just below the land surface.

Transition-Zone Well

One well, MW-2T, was installed to monitor water levels and quality in the shallow fractures of the transition zone (fig. 6). Mud-rotary drilling was used to install a 10-inch-diameter casing boring. The boring was terminated at the top of competent rock, as determined by the depth at which penetration of the roller cone mud-rotary drill bit slowed. Six-inch-diameter PVC casing was placed in the boring, and cement grout was pumped into the bottom of the annular space. PVC casing material was assembled without solvent-based glues to minimize the potential for metals and volatile organic compound contamination. After the grout hardened, a 6-inch-diameter air hammer was used to drill out a grout plug and into the partially weathered rock and competent bedrock. Transition-zone well MW-2T was completed as an open borehole (fig. 6).

Table 1. Characteristics of the monitoring wells and the surface-water gage at the Lake Wheeler Road research station, North Carolina.

[NAVD 88, North American Vertical Datum of 1988; MW, monitoring well; S, shallow regolith; I, intermediate zone regolith; D, deep; PW, designated pumping well; PZ, piezometer; PVC, polyvinyl chloride casing; Galv. Steel, galvanized steel; R, regolith; B, bedrock; T, transition zone; SW, surface-water site; na, not applicable]

Site identification	Station name (fig. 4)	Construction date	Land-surface altitude (feet above NAVD 88)	Casing material (inches)	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
						from	to		
354356078403501	MW-1S	5/24/2001	334.38	PVC	4.0	5	20	0.01 slotted PVC	R
354356078403502	MW-1I	5/29/2001	335.36	PVC	4.0	31.5	41.5	0.01 slotted PVC	I
354356078403503	MW-1D	6/5/2001	338.62	PVC	6.0	47	302	Open hole	B
354356078403504	MW-1DUZ[a]	7/16/2002	338.62	PVC	6.0	47	75[b]	Open hole	T
354356078403505	MW-1DLZ[a]	7/16/2002	338.62	PVC	6.0	75[b]	302	Open hole	B
354359078403101	MW-2S	5/9/2001	362.00	PVC	4.0	20	40	0.01 slotted PVC	R
354359078403102	MW-2I	5/9/2001	361.19	PVC	4.0	40	50	0.01 slotted PVC	I
354359078403103	MW-2T	5/9/2001	360.44	PVC	6.0	50	80	Open hole	T
354359078403104	MW-2D	4/19/2001	359.77	PVC	6.0	81	601	Open hole	B
354404078403101	MW-3S	5/10/2001	375.02	PVC	4.0	20	35	0.01 slotted PVC	R
354404078403102	MW-3I	5/14/2001	375.49	PVC	4.0	45	60	0.01 slotted PVC	I
354404078403103	MW-3D	5/16/2001	376.35	PVC	6.0	66	301	Open hole	B
354401078403401	PW-1	6/14/2001	358.07	Galv. Steel	6.0	62.5	302	Open hole	B
354400078403401	PZ-1	6/20/2001	354.87	PVC	2.0	30	50	0.01 slotted PVC	R
354402078403401	PZ-2	6/20/2001	359.09	PVC	2.0	17	37	0.01 slotted PVC	R
0208762750	Unnamed tributary	4/1/2002	326.87	na	na	na	na	na	SW

[a]Zone isolated from the open borehole using a single packer (UZ, upper zone; LZ, lower zone).

[b]Depth of packer.

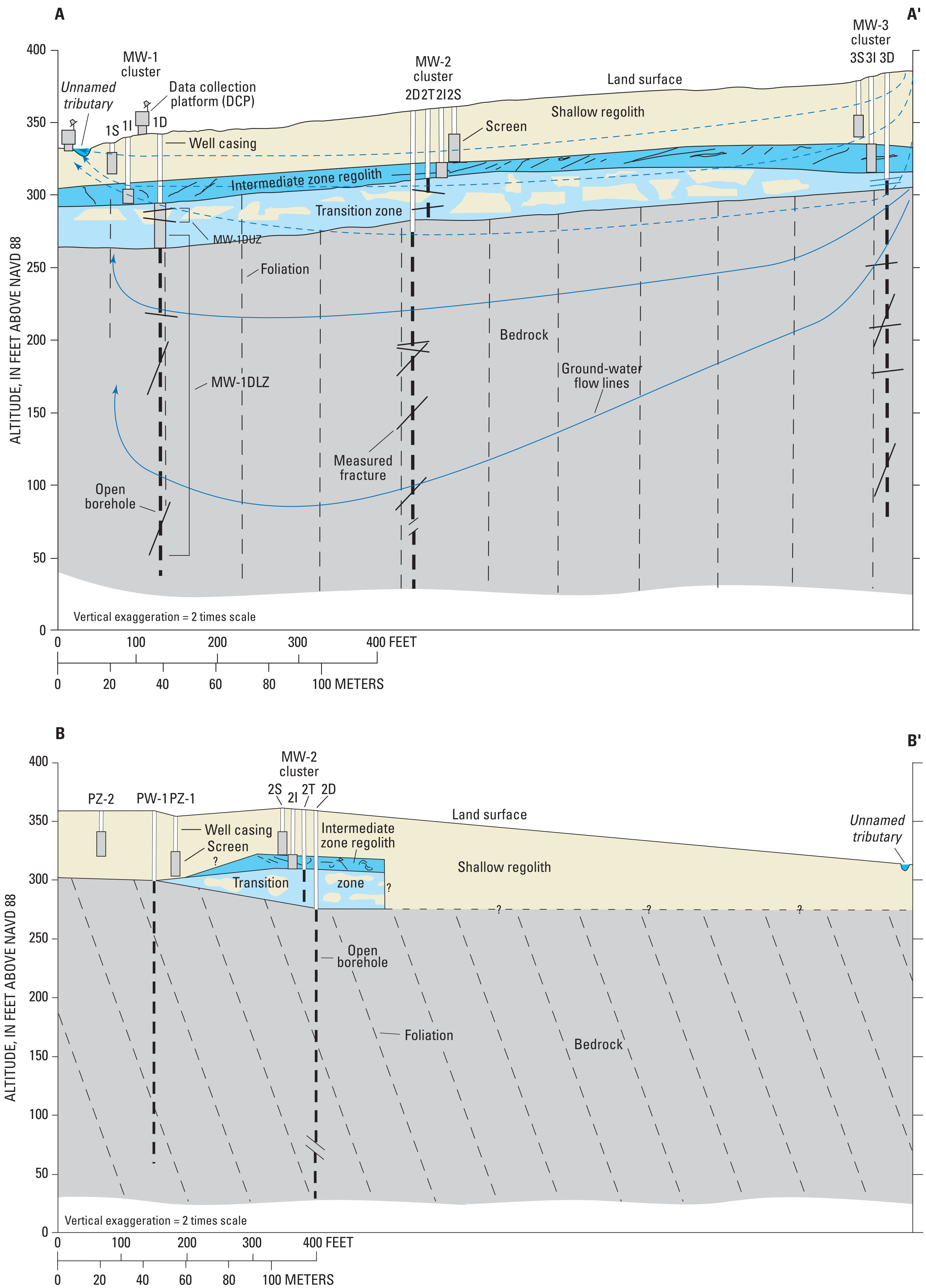


Figure 6. Generalized hydrogeologic cross sections A-A′ and B-B′ along the well transect at the Lake Wheeler Road research station, North Carolina. (Locations of sections A-A′ and B-B′ are shown in figure 4.)

Bedrock Wells

A 12-inch-diameter air hammer was used to set the surface casings for all of the bedrock monitoring wells. Mud-rotary drilling was used to install the casing boring in all bedrock wells. Bedrock casing borings were terminated after about 5 ft of competent bedrock was penetrated. The depth to competent bedrock was determined based on previous coreholes and observations of the rate of penetration during drilling. After the casing boring was completed, a 6-inch-diameter PVC casing was lowered into the boring. PVC casing was used in the bedrock monitoring wells at each of the three well clusters. Cement grout was then pumped into the bottom of the casing boring annular space using a metal tremie pipe. This procedure was used in all of the bedrock monitoring wells and initially in well MW-2D. The open-borehole sections of the bedrock wells were drilled using air-rotary methods. Total depths for the bedrock wells were about 300 ft for wells MW-1D and MW-3D, and 601 ft for well MW-2D (table 1).

After the initial grouting of the surface casing in bedrock well MW-2D, a hole in the casing was discovered. This hole allowed much of the bentonite grout to flow into and partially fill the well. Borehole geophysical logs run in July 2001 indicated that bentonite was present in MW-2D from about 450 to 600 ft. A 4-inch-diameter PVC liner pipe was then installed in well MW-2D that extended 1 ft below the bottom of the surface casing. The liner pipe was grouted in place using cement and sealed at the bottom with a butyl rubber boot. Most of the bentonite and sediment were removed from the well; however, visible bentonite remained on the borehole wall from a depth of about 442 to 461 ft, as noted from the optical televiewer image.

Aquifer-Test Wells

To evaluate the potential effects of galvanized casing on ground-water quality, a bedrock well was installed using galvanized steel surface casing and only 20 ft of cement grout in the uppermost part of the annular space. Total depth for bedrock well PW-1 was 302 ft (table 1). The lowermost part of the annular space was backfilled with native material. This construction is similar to that used for many public and private water-supply wells in the Piedmont and Mountains region of North Carolina. This well, designated as PW-1 (fig. 4), was used as the pumping well for aquifer testing. PW-1 was equipped with a dedicated 0.5-horsepower electric submersible pump.

Two piezometers (wells PZ-1 and PZ-2, fig. 4) were installed in the regolith near PW-1 to provide water-level data for the aquifer test. Each piezometer was constructed of 2-inch-diameter schedule 40 PVC with a 0.01-inch slotted screen. The piezometers were drilled with 4.25-inch inside diameter hollow-stem augers to the top of the transition zone and completed similar to the regolith wells. A sand filter pack was placed up to 2 ft above the screen and topped with bentonite to land surface. The aquifer test well and piezometers were drilled in a triangular configuration between well clusters to evaluate potential anisotropy. The distance between bedrock well PW-1 and well MW-2D is about 350 ft (fig. 4).

Borehole Geophysical Logging

Borehole geophysical logging data were collected in three phases in the bedrock wells to characterize fractures and lithologies at depth. During the first phase of borehole geophysical logging, caliper, natural gamma, electrical (resistance, short-normal, long-normal, and lateral resistivity), and fluid (temperature, fluid resistivity) logs were run. During the second phase of borehole geophysical logging, vertical flow near fracture zones was measured by using a heat-pulse flowmeter. Measurement range for the heat-pulse flowmeter is reported to be about 0.01 to 1.5 gal/min (U.S. Geological Survey, 2004b). During the third phase of borehole geophysical logging, an optical televiewer (OTV) was used to obtain an oriented, digital image of the borehole. The OTV image and associated interpretation software permits direct observation of lithology, such as felsic or mafic. During this investigation, orientation of fractures and foliation, as well as lithology, were interpreted from the OTV images. The OTV data were corrected for borehole deviation (azimuth and inclination angle) and magnetic declination.

Continuous Monitoring

Continuous monitoring at selected sites at the LWRRS included the collection of ground-water levels, surface-water stage, and water-quality measurements, including temperature, pH, specific conductance (SC), and dissolved oxygen (DO). Continuous data were collected at 1-hour intervals at selected periods in the wells and at 15-minute intervals at the surface-water site. Data collection and periods of record for each station at the LWRRS are listed in table 2.

Monitoring of water levels, water temperature, pH, SC, and DO began in the three wells in cluster MW-1 (MW-1S, MW-1I, and MW-1D) in December 2001 and at the nearby surface-water site (unnamed tributary to Swift Creek near Yates Mill Pond, N.C.) in April 2002 (fig. 4; table 2). Continuous-monitoring data are transmitted by satellite every 4 hours to the USGS National Water Information System (NWIS) database for near real-time public access (U.S. Geological Survey, 2002b). Data collected through September 30, 2003, are presented in this report.

Ground-Water Levels

Continuous ground-water levels were measured in three wells in cluster MW-1 from December 2001 through September 2003 and for a shorter time in two bedrock wells—May through September 2003 in MW-2D and intermittently between February 6 and September 26, 2003, in MW-3D (figs. 4, 6; table 2). Continuous water levels were recorded in wells MW-2D and MW-3D to evaluate the response of

Table 2. Period of data collection for ground-water levels, surface-water stage, and water-quality measurements in wells and the unnamed tributary at the Lake Wheeler Road research station, North Carolina.

[na, not applicable]

Station name	Water level/stage		Water quality (temperature, pH, specific conductance, and dissolved oxygen)
	Periodic data (monthly)	Continuous data (1 hour for wells and 15 minutes for surface water)	Continuous data (1 hour for wells and 15 minutes for surface water)
MW-1S	7/03/01–9/17/03	12/01–9/03	12/01–9/03
MW-1I	7/03/01–9/17/03	12/01–9/03	12/01–9/03
MW-1D	6/20/01–7/12/02	12/01–9/03	12/01–7/02
MW-1DUZ	7/16/02–9/11/03	7/02–9/03	7/02–9/03
MW-1DLZ	7/22/02–9/17/03	7/02–9/03	7/02–9/03
MW-2S	5/29/01–9/17/03	na	na
MW-2I	5/29/01–9/17/03	na	na
MW-2T	5/29/01–9/17/03	na	na
MW-2D	7/03/01–9/26/03	5/03–9/03	na
MW-3S	5/29/01–9/17/03	na	na
MW-3I	5/29/01–9/17/03	na	na
MW-3D	5/29/01–9/17/03	2/6/03–4/5/03; 4/30/03–8/13/03; 9/11/03–9/26/03	na
PW-1	7/03/01–9/17/03	na	na
PZ-1	7/03/01–9/17/03	na	na
PZ-2	7/03/01–9/17/03	na	na
Unnamed tributary	na	4/02–9/03	4/02–9/03

bedrock wells located in the recharge areas to rainfall and barometric-pressure fluctuations. The zones monitored in well cluster MW-1 include the shallow zone in the regolith (MW-1S), the intermediate zone in the regolith (MW-1I), and the bedrock (MW-1D). An inflatable packer was installed in well MW-1D on July 16, 2002, to isolate zones MW-1DUZ and MW-1DLZ, which facilitated monitoring open fractures in the transition zone (MW-1DUZ) from 47 to 70 ft and in the bedrock lower fracture zones (MW-1DLZ) from 70 to 300 ft. Water-level data, relative to feet below land surface, were collected by using submersible pressure transducers in the wells.

Surface-Water Stage and Discharge

Water-level (stage) data were collected from April 2002 through September 2003 at the unnamed tributary to Swift Creek near Yates Mill Pond, N.C. (fig. 4; table 2), by using a gas-purge system equipped with a built-in compressor and nonsubmersible pressure transducer. An orifice mounted in the tributary was connected by an air line to the gas-purge system housed in an instrument shelter on the bank. Every 15 minutes, the compressor purged air from the line, and the pressure transducer recorded a pressure reading. This reading was referenced periodically to stage height from the staff gage during field visits. The stage in the tributary allowed the orifice to be submerged at all times during the year.

Periodic discharge measurements were made by using a pygmy current meter or by making a volumetric measurement at the downstream side of a culvert. Rating curves were established by plotting discharge against stage. Control alterations, from erosion or debris buildup, resulted in a stage shift and re-calculation of the discharge rating curve.

Water Quality

Water-quality probes were used to collect water temperature, DO, pH, and SC from the three MW-1 cluster wells and the tributary. The water-quality probes were inspected and cleaned at least once a month following USGS guidelines (Wagner and others, 2000). For the tributary probe, inspections occurred more often (twice monthly) because of algal growth on the probe sensors, particularly during the summer months. If the cleaning process failed to bring a sensor within the calibration criteria, the sensor was re-calibrated according to USGS guidelines (Wagner and others, 2000).

The depth of each water-quality probe was chosen to best represent the conditions of each zone being monitored and to ensure submergence throughout the year. The probes in the shallow wells (MW-1S and MW-1I) were set in the middle of the screened interval; in the open-borehole bedrock well (MW-1D), the probes were set in the middle of a major fracture zone at a depth of about 48 to 65 ft. In the tributary, the water-quality probe was housed in a protective steel pipe and set at mid-depth in a pool just downstream from a culvert about 150 ft southeast of the MW-1 well cluster (fig. 4).

Periodic Water-Level Measurements

Ground-water levels were measured monthly or every 2 months at all of the wells at the LWRRS to identify seasonal water-level trends in each of the three zones (regolith, transition, and fractured bedrock) and to determine vertical hydraulic gradients between wells in each cluster. Measurements were made from a specified measuring point (MP) on the top of the well casing using an electric water-level tape. Altitudes of the MPs were determined by surveying to a common datum established at the site prior to this study. Typically, water levels are recorded in feet below land surface. Water-level data were entered into the USGS Ground-Water Site Inventory (GWSI) database and are available online (U.S. Geological Survey, 2002a).

Slug Tests

Rising and falling head slug tests were conducted in all of the wells to assess horizontal hydraulic conductivity. A 5-ft-long, 2.5-inch (solid slug and(or) a 3-inch-diameter bailer) PVC slug were used to displace water inside each well. The PVC slug was rinsed with distilled water before use in each well. A pressure (15 pounds per square inch (lb/in^2)) transducer was used to measure water-level fluctuations during each test. The transducer data were verified with manual water-level measurements.

When the solid slug was used, both falling (slug-in) and rising (slug-out) head data were analyzed. The falling head test measured the rate at which water levels returned to static conditions following the introduction of the solid PVC slug; the rising head test measured the recovery of water levels to static conditions following the removal of the slug. Efforts were made to avoid splashing effects during the introduction of the slug below the water level. The tests were terminated when water levels recovered to within 95 percent of the pre-test static level.

The slug-test data were analyzed by using the Bouwer and Rice (1976) analytical method. The Bouwer and Rice (1976) analytical method accounts for the effects of partial penetration and changing aquifer thickness of unconfined aquifers. A basic assumption of this method is that the aquifer is representative of a porous medium and is considered isotropic, with no directional variation in hydraulic properties in the zone being tested. Additional assumptions of the method are that the effects of elastic storage can be neglected, and the position of the water table (saturated thickness of the aquifer) outside of the area around the well does not change during the slug test (Butler, 1998). The Bouwer and Rice (1976) analytical method is widely used for slug-test analyses. Spreadsheets developed by Halford and Kuniansky (2002) were used for analytical interpretations of slug-test data.

Aquifer Tests

An aquifer test was conducted to estimate the transmissivity and storage coefficients for the bedrock and regolith components of the ground-water system. A 0.5-horsepower electric submersible pump was installed in PW-1 at a depth of 280 ft below land surface. A plastic gate valve was installed at the wellhead to regulate the pump discharge rate. A flowmeter, calibrated by a graduated bucket and stopwatch, was used to measure the pumping rate. The pump discharge was directed to an intermittent stream about 300 ft from the pumping well. A step-drawdown test for PW-1 indicated an optimum pumping rate of about 3 gal/min for a constant-discharge aquifer test.

Pressure transducers were placed in wells PZ-1, PZ-2, MW-2D, and MW-2S several days before the aquifer test to allow time for the transducers to stabilize and to monitor trends in background water levels. The pressure transducers were attached to an electronic data logger. During the aquifer test, the data logger was programmed initially to record water levels at sub-second logarithmic time intervals, and subsequently at 2-minute intervals for the duration of the test. Water-level measurements were made at the remaining wells in clusters MW-2 and MW-3 during the aquifer test using hand-held water-level indicators. Water levels in the MW-1 well cluster were recorded hourly using the satellite telemetry data-collection and transmitting equipment.

Pumping in bedrock well PW-1 began at a rate of 3.1 gal/min at 1043 on April 2, 2002. This pumping rate was maintained by adjusting the discharge valve as necessary until the pump was shut off on April 4, 2002, at 1709, at which time the recovery was recorded on the data-logging equipment. A total volume of about 10,040 gallons of water was pumped from PW-1 during this test.

Water-Quality Sampling

Water-quality samples were collected semiannually from 11 of the wells at the LWRRS (excluding the piezometers, PZ-1 and PZ-2). Water-quality properties (pH, SC, DO, and temperature) were measured during purging. Sampling methods include the use of submersible (2-inch-diameter) and peristaltic pumps. Prior to sample collection, the 4-inch-diameter shallow, screened wells tapping the regolith (shallow and intermediate zones) were purged until at least three well volumes of ground water were removed. For the deeper, 6-inch-diameter open-borehole transition-zone and bedrock wells, use of the low-volume submersible sampling pumps to extract three volumes of ground water prior to sample collection was impractical. For these wells, a minimum of one volume of casing water was removed, and water property stabilization was obtained prior to sample collection. In addition, the sampling pump was placed near the more dominant fracture zones at depth. Water property stabilization was a required prerequisite to sampling all wells.

Well and Surface-Water Station Numbering System

USGS well and surface-water stations are given a unique identification number based on geographic location. A "latitude-longitude" system is used for wells and a "downstream order" system is used for surface-water stations. The latitude and longitude of each well cluster and the streamgage at the LWRRS were determined by using a differential global positioning system (DGPS) and are considered accurate to within a few feet.

Wells were assigned a 15-digit site number based on the latitude and longitude of each well or, in the case of this study, well cluster. The first 13 digits (latitude and longitude, respectively) are followed by two sequence numbers used to distinguish between wells at the same location. Each well in a cluster has the same site-identification number except for the last two digits. Typically, the assigned sequence numbers begin with 01 for the shallowest well and progress with well depth. Thus, the deeper the well, the higher the sequence number.

In addition, the wells in this study were assigned a local identifier, which consists of a two-letter county code followed by a three-digit sequence number. For example, wells in Wake County have a "WK" prefix followed by three numbers assigned sequentially. The station name includes the site identifier (Lake Wheeler Road research station), well descriptor, and number. The well descriptors used in this study are as follows: MW for monitoring well, PW for pumping well, and PZ for piezometer. Following the well descriptor is a cluster number and a letter, which indicates the aquifer section or "zone" that is being monitored: S for shallow zone in the regolith, I for intermediate zone in the regolith, T for transition zone, and D for deeper zone in the bedrock. For example, well MW-1S is a monitoring well in cluster 1 and is completed in the shallow regolith zone.

The downstream order number or station number assigned to a surface-water station is based on the location of the station in the downstream direction along the main stem. The first two digits of the 8- to 10-digit station number identify the hydrologic unit (U.S. Geological Survey, 1974, 1975) used by the USGS to designate the major drainage system. The next six digits indicate the downstream order within the major drainage system. An additional two digits are added at the end of the station number in areas of high station density.

Geologic Setting

The geology of most of the Piedmont and Mountains region is complex. Rocks in this region have undergone intense metamorphism, folding, faulting, and igneous intrusion. In North Carolina, the regional sequences of rocks are grouped into belts. Although rocks within the belts generally are similar with respect to lithology, more details on variation and complexity can be observed on a local scale. Daniel and Dahlen (2002) provided an overview of the major hydrogeologic units of the Piedmont and Mountains region as referenced to the geologic belts of the State.

The Piedmont region of North Carolina is primarily underlain by metamorphic and igneous rocks; metamorphic rocks are the most common. Sedimentary rocks are present in Mesozoic basins. The metamorphic-grade facies in the Piedmont typically range from greenschist to amphibolite. Unmetamorphosed igneous intrusive rocks are present as diabase dikes and granitic veins or as batholith-scale igneous or felsic intrusions.

The study area is within the Raleigh litho-tectonic belt or felsic gneiss hydrogeologic unit (Daniel and Payne, 1990; fig. 2). The Raleigh Belt is a north-northeast trending belt that extends through Wake, Vance, Warren, and Franklin Counties in the eastern Piedmont. The rocks in the Raleigh Belt are characterized by amphibolite facies metamorphic rocks, in contrast to the greenschist facies rocks that surround them. A right lateral shear zone, known as the Nutbush Creek fault zone (Farrar, 1985), forms the western boundary of the Raleigh Belt. A large granite intrusion, the Rolesville batholith, is roughly in the center of the Raleigh Belt. The Rolesville batholith is composed of a series of granite intrusions having similar gross mineralogy (Schneider and Samson, 2001) to the surrounding rocks of the Raleigh Belt. These intrusions, however, are massive and generally weakly foliated in sharp contrast to the Raleigh Belt metamorphic rocks, which have well-developed foliation. The intrusions of the Rolesville batholith were formed during or after metamorphism.

The intensive chemical weathering of crystalline metamorphic and igneous rocks in the Piedmont region produces saprolite and soil residuum. Saprolite retains much of the fabric of the underlying parent rock. Weathering of feldspars and micas produces clay as residuum. As a result, saprolite and soil residuum typically have high porosity values but low to moderate hydraulic conductivity. Ground water flows through intragranular pore spaces or through relict fractures in soil and saprolite. In contrast, ground water in the underlying bedrock flows through secondary fractures and discontinuities because the unweathered bedrock has very low porosity and permeability.

Local Geologic Setting

Based on the bedrock-core samples from the LWRRS, the study site is underlain by rocks of the Raleigh Gneiss Formation. The Raleigh Gneiss has been described as "injected gneiss" (North Carolina Geological Survey, 1985), hornblende-biotite gneiss (Horton and others, 1992), and biotite-hornblende gneiss (Heller, 1996). The Raleigh Gneiss is characterized by migmatitic compositional banding producing black, gray, and white intervals within the rock. Foliation is pronounced and consistent, although local variations in direction may be present, presumably a result of fluid intrusions and ductile flow conditions; some changes in direction of foliation also could be the result of localized folding.

Structurally, the LWRRS lies on the eastern flank of the Raleigh Antiform (Parker, 1979; Stoddard and Blake, 1994; Heller, 1996; and Blake and others, 2001). The Raleigh Antiform strikes in a northeast-southwest direction, with an axis west of the study area. The predominant structural fabric in the rocks at the study area strikes northeast-southwest, and dips toward the east-southeast (Heller, 1996). From data reported by Heller (1996), foliation near the LWRRS trends N. 5° E. and has a subvertical dip. Dip reversals are possible from upright folding (Heller, 1996). Rocks in the vicinity of the study area show evidence of ductile deformation, presumably as a result of regional shear stresses. The regional Nutbush Creek Fault (Wylie, 1984) strikes north-northeast, dips subvertically, and is associated with a stretching lineation that declines very gently (less then 10° in this area) toward the southwest. Heller and others (1998) noted brittle fault zones in the vicinity of the study area. These brittle fault zones likely represent the youngest geologic structures in the area, although their age has not been determined. The brittle faults trend N. 70° W. to N. 80° E. and have a subvertical to moderate dip angle. Microscopic examination of a core sample (RAL-1, appendix 1) showed a transition from ductile to brittle deformation along a small shear zone.

Heller (1996) identified a granitic gneiss member within the Raleigh Gneiss. The granitic gneiss is a light gray to pinkish-gray orthogneiss with a distinctly uniform granitic composition. The alignment of micas in the granitic gneiss in the study area indicates a weak but consistent foliation that strikes about N. 10° E. with dips about 80° W-NW. The granitic gneiss appears to be more prevalent along the western boundary of the Raleigh Gneiss (Mr. M.J. Heller, North Carolina Department of Environment and Natural Resources, oral commun., 2002).

Ground-Water System Characteristics

The ground-water system of the Piedmont and Mountains region has two primary components: the shallow, weathered regolith and the deeper, unweathered bedrock. Ground water occupies pore spaces in the shallow, weathered regolith. Directional hydrogeologic properties (anisotropy) are possible where strong saprolitic features are present. Because the bedrock has little primary porosity or permeability, ground water occupies secondary fractures and discontinuities. The regolith is the primary storage reservoir and is the source of recharge to the bedrock fractures (Heath, 1983, 1984, 1994; Heath and Jennings, 1995). In some areas, a transition zone between the regolith and bedrock may be present (Harned and Daniel, 1992).

Three coreholes were drilled at the LWRRS near each of the well clusters MW-1, MW-2, and MW-3 (fig. 4). Detailed core descriptions are provided in appendixes 1–3. Descriptions of the cores and interpretations of geophysical logs are summarized in the following sections. The Munsell Soil Color Chart (2000) was used for all regolith color descriptions.

Regolith

The regolith is the shallow component of the Piedmont ground-water system. The term "regolith," as used in this report, includes all unconsolidated or poorly consolidated materials overlying crystalline bedrock. The regolith at the LWRRS includes soil, residuum, alluvium, and saprolite. Eight shallow wells were completed in the regolith—two at each of the three clusters (MW-1S, MW-2S, MW-3S, MW-1I, MW-2I, and MW-3I), and two near bedrock well PW-1 (PZ-1 and PZ-2, fig. 4, table 1). The "S" wells were completed in the shallow part of the regolith, such as the residuum or alluvium. The "I" wells were completed in the intermediate part of the regolith in the saprolite.

Residuum/Alluvium

The thickness of the residuum/alluvium was fairly consistent along the well transect at the LWRRS. Approximately 42 to 50 ft of regolith was encountered in borings RAL-2 and RAL-3 (appendixes 2, 3). About 42 ft of regolith was encountered at RAL-1 in the lowest topographic area, of which 17 ft was described as alluvium (appendix 1).

The residuum generally is described as in-place weathered material lacking geologic structure. At the LWRRS, the residuum is reddish-brown silt with some clay containing little mica and a trace amount of fine sand. The residuum typically is moist, soft, and massive with no apparent relict rock texture. Two wells, MW-2S and MW-3S, tap the residuum at the LWRRS (fig. 6).

The 17-ft thick alluvium encountered in corehole RAL-1 is adjacent to a perennial tributary. Scouring and deposition of alluvial material during floods likely have occurred along the flood plain of this tributary. Well MW-1S is completed in the alluvium (figs. 4, 6).

Saprolite

Saprolite was encountered in the coreholes at the LWRRS in thicknesses ranging from about 33 ft in RAL-2 to about 42 ft in RAL-3. Saprolite thickness was estimated to be about 25 ft for RAL-1, but this estimate is problematic because of poor core recovery between 17 and 41 ft (appendixes 1–3). The saprolite, formed by the weathering of the underlying biotite gneiss, displayed relict foliation expressed by color banding and mineralogic composition. The relict foliation dip angle was high, typically 70° to 80°.

The saprolite was characterized typically as dark yellowish-brown vermiculitic silt, fine sand, with trace amounts of fine to coarse quartz. Grain size generally increased with depth, whereas silt and vermiculite content generally decreased with depth. The coarsening downward trend was especially evident in RAL-3, where a 3-ft thick layer of fine to medium quartz and weathered gneiss was encountered at the bottom of the saprolite layer.

The intermediate zone (lower part of the regolith) was characterized as a fairly consistent interval at the lowermost section of the saprolite containing coarser material (higher sand content) than the overlying “typical” reddish-brown saprolite. The intermediate zone was monitored at the three LWRRS well-cluster locations as wells MW-1I, MW-2I, and MW-3I (fig. 6). The intermediate zone was characterized by fine- to medium-grained quartz and feldspar with very minor amounts of silt and clay particles. The intermediate zone was delineated at the LWRRS to evaluate its hydraulic properties and the zone’s effect on ground-water quality. The depth and thickness of the intermediate zone is shown in figure 6.

The intermediate zone in RAL-2 and RAL-3 was characterized by a high percentage of sand-sized quartz grains with some gravel-sized particles; some feldspar grains and mica flakes also were observed (appendixes 2, 3). The relict gneiss texture is moderately well preserved in this zone. Feldspar and micas have not completely weathered to clay minerals. A thin (approximately 3-ft thick) layer of subrounded quartz was encountered at a depth of 50 ft in RAL-3. The coarser textural characteristics of the intermediate zone (lower part of the regolith) indicate a potentially higher hydraulic conductivity in this zone.

Transition Zone

Shallow fractures near the top of bedrock at the LWRRS were delineated as part of the transition zone between the regolith and bedrock. Two wells, MW-2T and MW-1DUZ (fig. 6; table 1), were used to monitor ground-water conditions in this zone. Both transition-zone wells were completed in fractures in partially weathered bedrock as open boreholes. Well MW-1DUZ was isolated within bedrock well MW-1D using a single packer. The shallow fractures near the top of the bedrock in well MW-3D most likely represent the transition zone.

Partially weathered gneissic bedrock and numerous open, low-angle fractures characterize the transition zone. Vertical fractures may be more common than observed in the cores at this site because of the steep foliation angle of the bedrock, which makes it less likely to encounter such fractures in near-vertical boreholes. The bedrock in this zone is weathered and altered, but not to the degree necessary to create sand- and gravel-sized particles and(or) substantial clay minerals. The cores from the partially weathered, fractured bedrock of the transition zone remained damp for several days after extraction, indicating that there is some degree of porosity in this zone. The transition zone near well cluster MW-1 (RAL-1, fig. 4) was characterized by a higher percentage of water-bearing fractures in RAL-1 than noted in the other two coreholes. The depth and thickness of the transition zone along the well transect is depicted in figure 6.

Packer Zone MW-1DUZ

Well MW-1D (fig. 6) had the highest estimated yield (about 40 gal/min) of all the wells installed at the LWRRS. The high yield indicates that this well taps an area of interconnected fractures. Well MW-1D is completed in both the transition zone and the consolidated bedrock. The open-hole interval is from the bottom of the casing at about 47 ft, to a total depth of about 339 ft (table 1). The major water-bearing fractures are in the lower part of the transition zone, from the bottom of the casing depth at about 47 ft to about 67 ft below land surface (fig. 6). The transition zone initially was described from the core samples (RAL-1, appendix 1) as consisting of saprolite and partially weathered rock from about 42 to 72 ft. In July 2002, the transition zone was isolated from the lower part of the borehole by placing a single packer at a depth of about 70 ft. These two zones were designated MW-1DUZ and MW-1DLZ for the upper and lower zones, respectively (fig. 6).

Based on geophysical logging interpretations, six fracture zones were delineated in MW-1DUZ—three fractures are open, and three are partially open. In figure 7, images of the fracture zones can be seen at depths of 48–48.5 ft (open), 51.5–51.6 ft (partially open), 53.5–53.6 (partially open), 55.3–55.5 ft (partially open), 57.5–58.2 ft (open), and 64.8–65.3 ft (open). The length of open borehole tapping the three open fractures ranges from about 0.5 to 0.7 ft, and borehole diameter enlargements are as much as about 10.8 inches (fig. 7). Vertical borehole flow measured near these fractures using the heat-pulse flowmeter under both ambient (natural) and stressed (pumping) conditions indicates upflow near all but the lowermost fracture in the transition zone. Most of the water-bearing fractures in the transition zone are low angle, having a dip of less than 20° (fig. 7), and likely are stress-relief fractures that formed as the rock weathered. The average strike

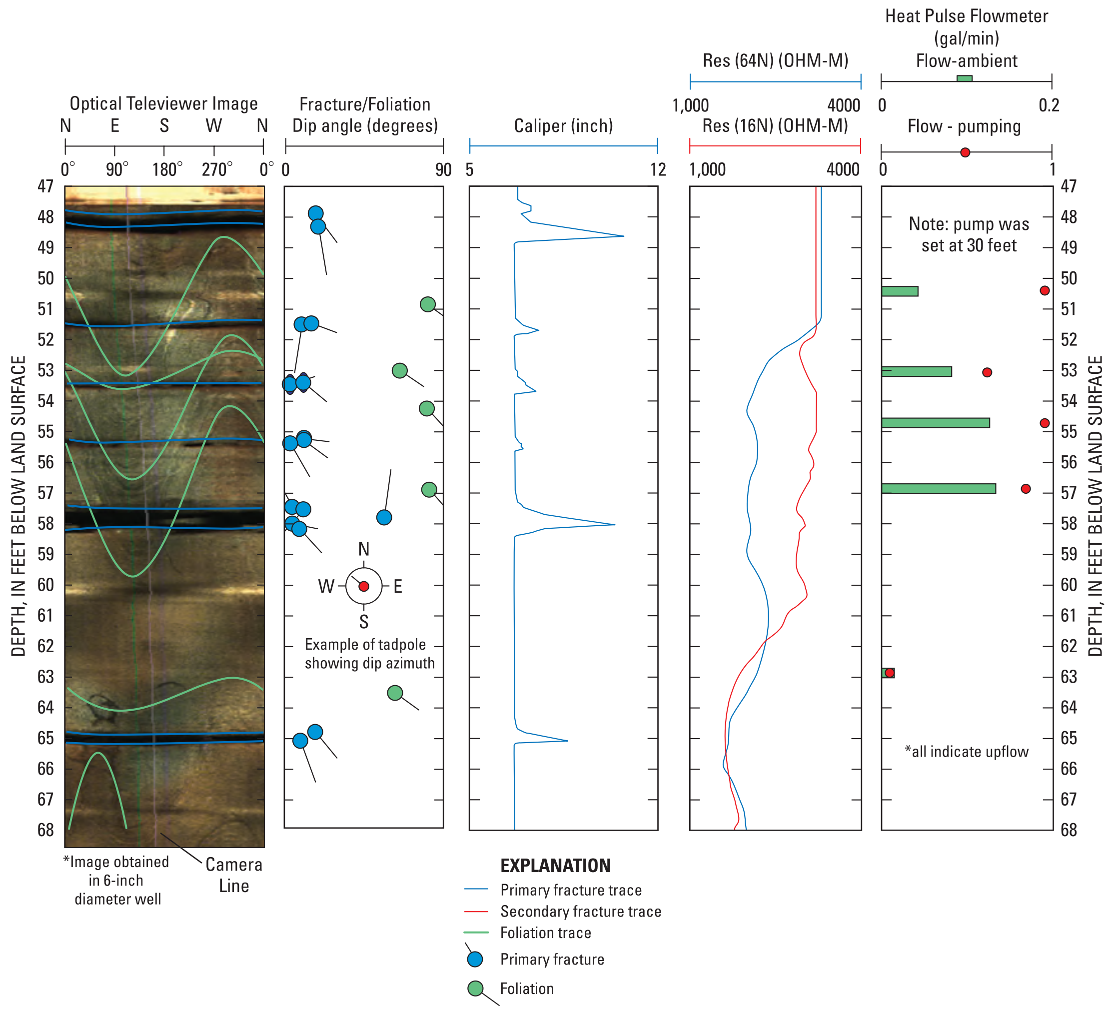


Figure 7. Optical televiewer image, tadpole diagram, caliper, resistivity, and heat-pulse flowmeter logs of the transition-zone fractures (MW-1DUZ) in well MW-1D at the Lake Wheeler Road research station, North Carolina.

of these fractures is about N. 60° E., dipping to the southeast (fig. 7).

Well MW-2T

The characteristics of the weathered bedrock, including numerous open fractures in well MW-2T, are similar to the shallow fractures tapped in the upper section of the borehole in bedrock well MW-1D (MW-1DUZ). Well MW-2T, located in well cluster MW-2, was completed as an open borehole from about 50 to 80 ft below land surface in the transition zone (fig. 6; table 1); fractures were noted in the core log (appendix 2) from about 51 to 69 ft (fig. 8). This well taps two large, open to partially open fracture zones at 52.5–54.5 ft and 59.5–62.5 ft. Smaller fracture zones were noted at 51.2 ft, just below the casing, and at 66–68.4 ft (fig. 8).

Fractures zones in well MW-2T were observed near lithologic contacts with pegmatites or at the boundaries of feldspathic zones, and are more variable in orientation and dip angle compared to the transition-zone fractures in well MW-1DUZ. These fracture zones are open to partially open, complex, and consist of both low-angle and high-angle fracture sets (fig. 8). Partial weathering of the bedrock and oxidation (iron staining) are evident in the OTV image. Overall, the fractures delineated in transition-zone well MW-2T strike nearly due north and dip to the east, parallel to foliation. Of the steeply dipping fractures that are parallel to foliation, the average strike is about N. 1° E., and the dip angles are nearly 80°. Strike for the lower angle fractures (19° to 56° dip angles) averages N. 4° E.

Bedrock

Bedrock lithology and fractures at the LWRRS were described from core samples and geophysical logs and images. The interpretations of bedrock lithologies were based on descriptions from geologic core and drill cuttings, natural

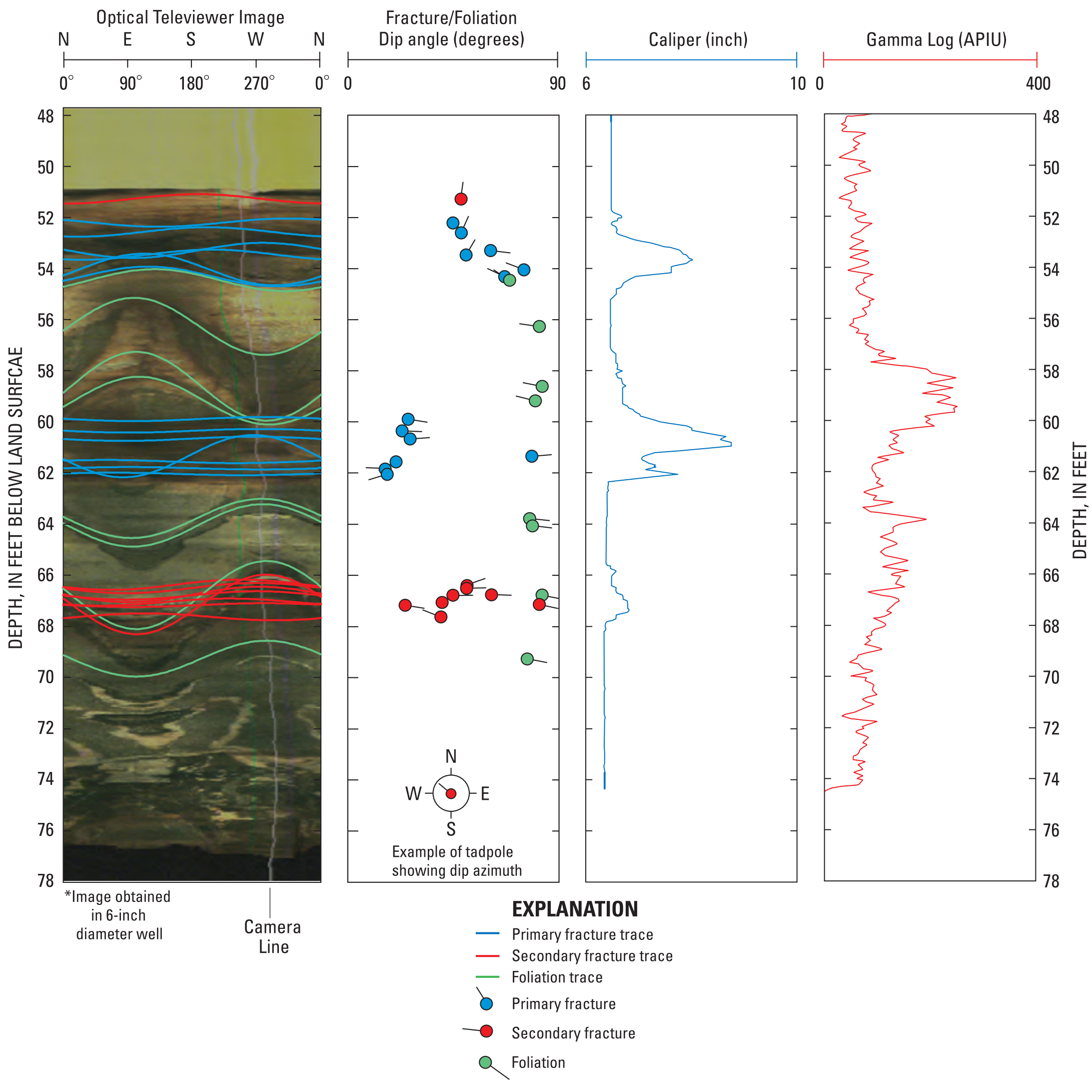


Figure 8. Optical televiewer image, tadpole diagram, caliper, and natural gamma logs of transition-zone well MW-2T at the Lake Wheeler Road research station, North Carolina.

gamma logs, and oriented OTV images. Fractures in the bedrock were first described from the core samples and then characterized using caliper and resistivity logs, fluid resistivity and temperature logs, heat-pulse flowmeter logs, and oriented OTV images.

Lithologies tapped by the four bedrock wells at the LWRRS were interpreted from geologic cores, drill cuttings, OTV images, and natural gamma logs. The Raleigh Gneiss below the LWRRS is represented primarily by biotite gneiss and granitic gneiss. From the core logs (appendixes 1–3), the biotite gneiss is well foliated, locally migmatitic rock containing biotite, amphibole, feldspar, and quartz with trace amounts of pyrite and chlorite. The granitic gneiss is a weakly foliated rock containing pink potassium feldspar, quartz, and trace amounts of pyrite. OTV images were used to delineate the downhole lithology (biotite and granitic gneiss contacts) and measure the orientation of foliation in the bedrock wells.

From the core samples, the mineralogic composition of the gneiss was fairly consistent within and among the coreholes (appendixes 1–3). The biotite gneiss is composed primarily of quartz, feldspar (microcline and plagioclase), and biotite. Minor amounts of hornblende, pyrite, and epidote also were noted in the core samples. The pronounced gneissic banding noted in the majority of the rock core samples appears to be a result of varying amounts of biotite. Migmatitic banding structure was more pronounced in coreholes RAL-2 and RAL-3 (drilled near clusters MW-2 and MW-3, respectively, fig. 4). The migmatitic structure in places appeared to be oriented parallel with the regional strike and dip of the foliation, or roughly striking N. 10° E. and dipping approximately 70° to 80° SE. The orientation of foliation was consistent at the site, indicating the possibility of hydraulic anisotropy created by the bedrock fabric. Delineated joint sets typically strike N. 50° W. and N. 70° W. (Heller, 1996).

All of the bedrock core samples revealed evidence of ductile deformation in response to compressional and(or) shear stresses (such as gneissic banding). The two core samples at 63 and 77 ft in RAL-1 (drilled near cluster MW-1, fig. 4) showed evidence of ductile to brittle transformation along a preexisting fracture (Dr. E.F. Stoddard, North Carolina State University, Department of Earth and Atmospheric Sciences, written commun., 2002). The cores at this location displayed slickensided, oxidized (iron-stained) fractures parallel to foliation in response to a change to a highly fractured biotite-rich zone between 66 and 77 ft. Thin section photomicrographs show the presence of iron oxide and clay particles in the slickensides at 63 ft.

After the initial core collection, four open-borehole bedrock wells were drilled; one at each well cluster, and one west of cluster MW-2 (PW-1, fig. 4). Three of the four wells were completed to a depth of about 300 ft below land surface; the fourth well (MW-2D) was drilled to a depth of about 600 ft. Depth to bedrock (excluding transition-zone fractures) ranged from about 66 to 77 ft at the LWRRS (fig. 6).

The biotite gneiss is described in the geologic core logs (appendixes 1–3) as gray with migmatitic amphibole or biotite laminae up to 0.8 inch thick with trace amounts of pyrite and chlorite. When observed on the OTV image, the biotite gneiss appears dark, indicating a larger percentage of mafic minerals (most likely biotite), and has alternating bands of lighter feldspathic layers. Pyrite also is noted in the biotite gneiss unit as yellow in color on the OTV images. Greater quartz content noted in the descriptions of the biotite gneiss unit could not be delineated in the OTV images. Foliation is readily interpreted in the biotite gneiss unit because of the alternating color bands, which are easily visable in the OTV images.

In the OTV image, the granitic gneiss appears to have only a weak foliation, primarily because of the lack of mafic minerals in contrast to the overall color of the image. Zones of pink potassium feldspar noted in the core logs of this unit were recognizable in the OTV image and as increased overall readings on the natural gamma log. Pyrite also was recognizable as yellow color variations but was not thick enough to be delineated in the borehole lithologic logs.

The interlayering of the biotite gneiss and granitic gneiss is variable across the study area. Lithologies interpreted from the core samples and OTV images indicate biotite gneiss from land surface to a depth of about 260 to 450 ft along the transect in wells MW-1D, MW-2D, and MW-3D (figs. 9–11). The granitic gneiss was delineated in the lower part of each bedrock well along the transect. In bedrock well PW-1, however, the granitic gneiss was delineated much closer to land surface, extending from the top of bedrock to a depth of about 200 ft (fig. 12). The biotite gneiss was delineated in the lower part of well PW-1. The difference in delineation of rock types near the surface at well PW-1 supports a vertical orientation of lithologies. The well transect roughly parallels the strike of lithologies and should have similar rock types. Whereas, if the lithologic units are relatively thin (few hundred feet thick) and steeply dipping, one would expect a different lithologic sequence at well PW-1, which is located perpendicular to the transect to the west.

Interpretations of the orientation of the rock foliation from the OTV images were consistent in three of the four bedrock wells. In general, foliation strike ranged from N. 10° E. to N. 30° E. with dips between 70° and 80° SE. (fig. 13A, 13D, 13E). This average foliation strike is comparable to surface geologic-mapping data, which indicated a strike range of N. 5° to 17° E., dipping 76° to 90° SE. (Heller, 1996). In bedrock well MW-2D, the dominant foliation strike is about N. 20° W. to N. 40° W. from 81 to 400 ft (fig. 13B). From 400 to 600 ft in bedrock well MW-2D, the orientation of foliation shifts to a near east-west (N. 70° to 80° E.) strike (fig. 13C), indicating that a structural feature, such as faulting or folding, has altered the foliation trend in the subsurface. Heller (1996) described brittle faults having a trend of N. 70° W. to N. 80° E. in this area.

In general, with the exception of the upper part of well MW-1D, most fractures in the bedrock wells at the LWRRS were relatively small, having low estimated and measured yields. Depths to fracture zones in the bedrock wells were determined using caliper and resistivity logs (figs. 9–12). Comparisons of fracture zones within each well were made by using fluid logs (temperature and fluid resistivity) and heat-pulse flowmeter logs. Fracture orientations were determined from the OTV image of the open-borehole bedrock well and are included as tadpole diagrams. Overall, the fractures could be separated into two groups: low-angle, stress-relief fractures and high-angle, steeply dipping fractures roughly parallel to foliation. A comparison of the fractures measured in the four bedrock wells can be made from the stereonet structural diagrams shown in figure 14. The three coreholes (RAL-1, RAL-2, and RAL-3) were not oriented; therefore, no specific interpretation of fracture orientations could be made.

Well MW-1D

The lithology of bedrock well MW-1D is interpreted primarily as biotite gneiss to a depth of about 260 ft. Granitic gneiss was delineated in the remainder of the borehole from 260 to 302 ft (fig. 9). Lithologic interpretation of this well was difficult because of the limited depth of the corehole (RAL-1, 137 ft, appendix 1) and the coating of iron and manganese oxides along the borehole (MW-1D) wall, which obscured the OTV image. Interpretations of foliation orientation from the OTV (fig. 13A) indicate that the dominant foliation strike is about N. 10° E. to N. 20° E., with a dip of about 75° SE. for this well.

The description of the fractures observed in bedrock well MW-1D include low-angle, stress-relief fractures in shallow bedrock and steeply dipping fractures that are parallel to foliation and(or) lithologic contacts. The depth and orientation of fractures tapped by well MW-1D are shown in figure 9; descriptions from the core log are included in appendix 1. Transition-zone fractures were delineated to a depth of about 67 ft in this well (see Packer Zone MW-1DUZ).

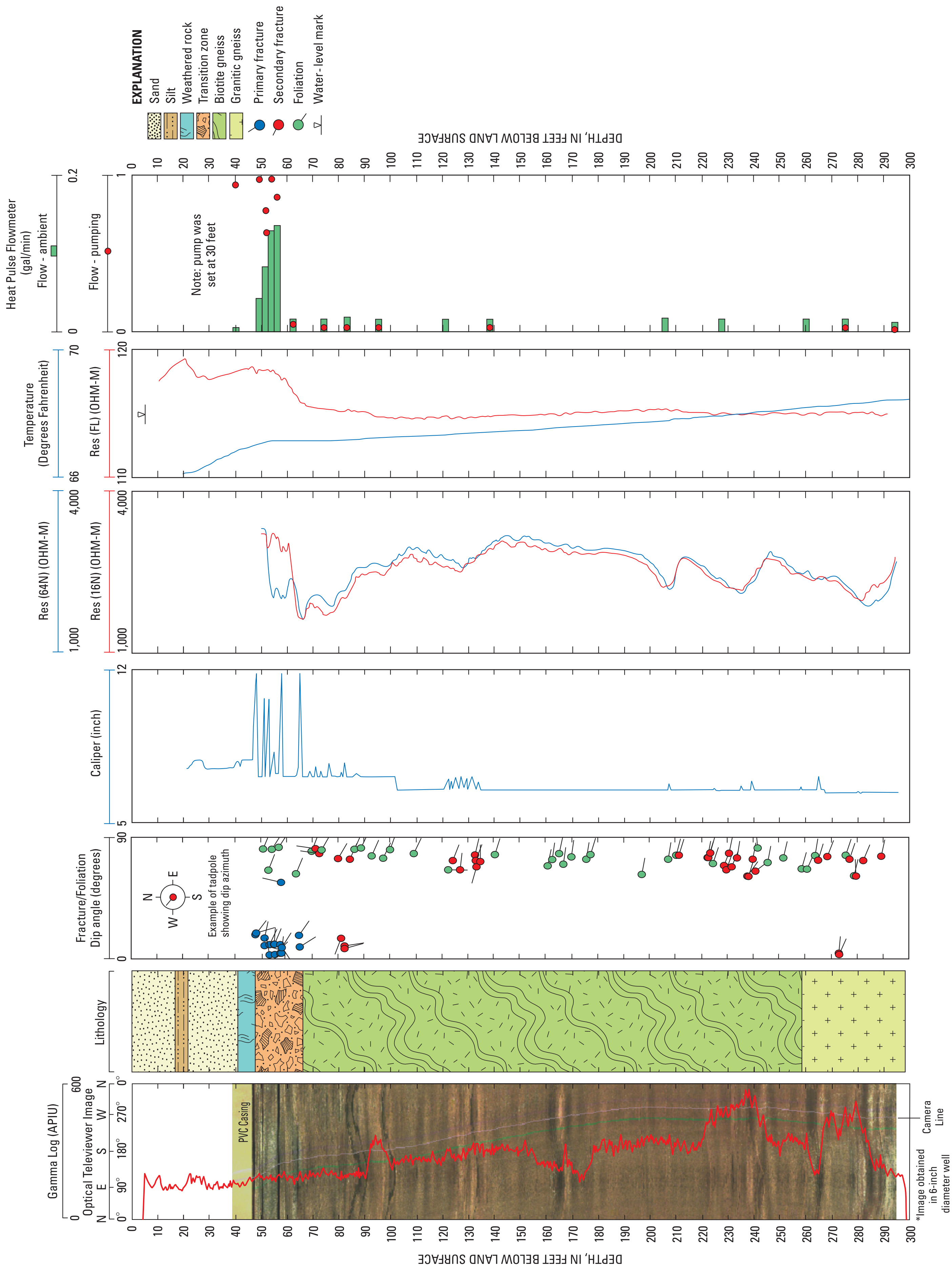


Figure 9. Geophysical logs showing lithologies and fracture zones in bedrock well MW-1D at the Lake Wheeler Road research station, North Carolina.

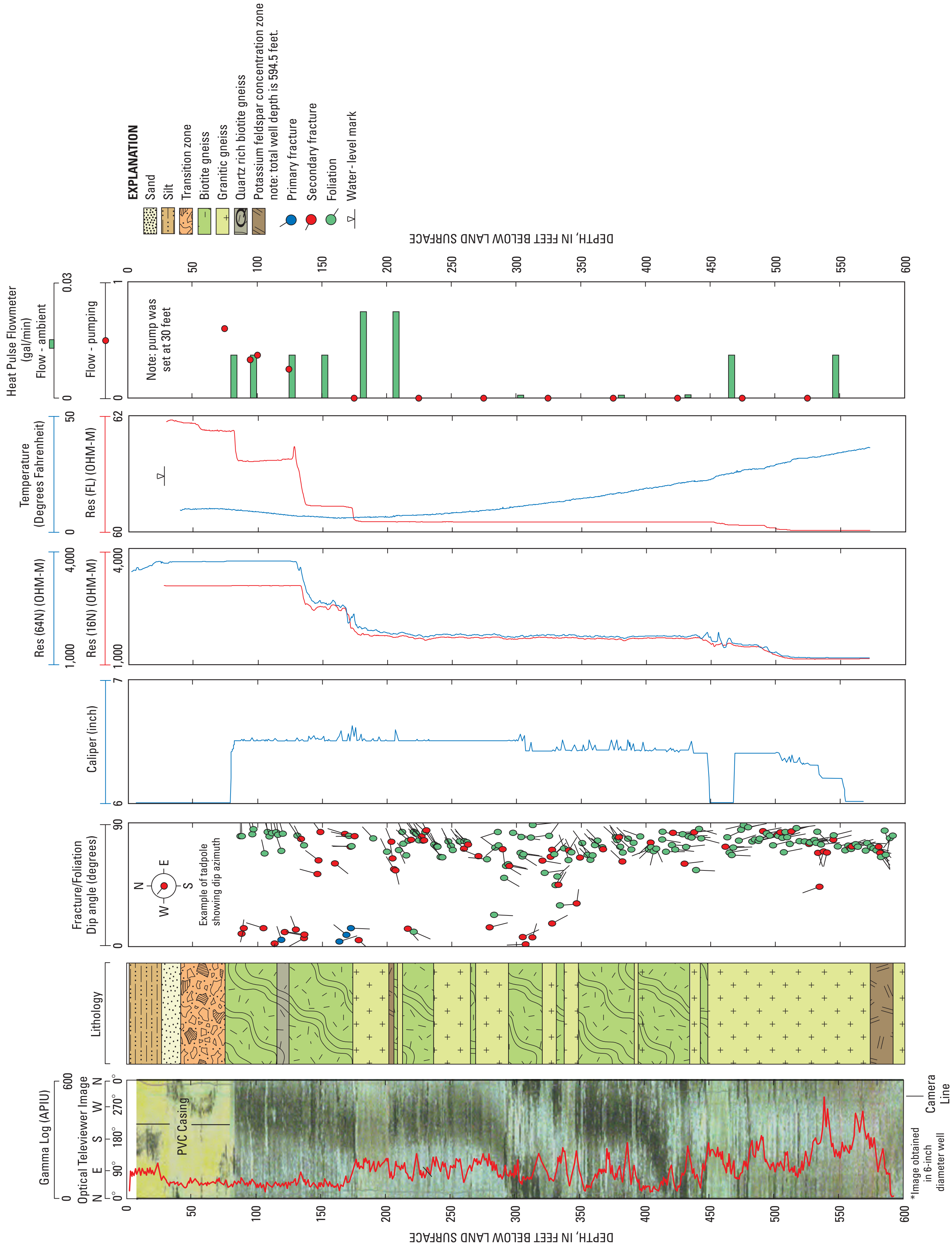


Figure 10. Geophysical logs showing lithologies and fracture zones in bedrock well MW-2D at the Lake Wheeler Road research station, North Carolina.

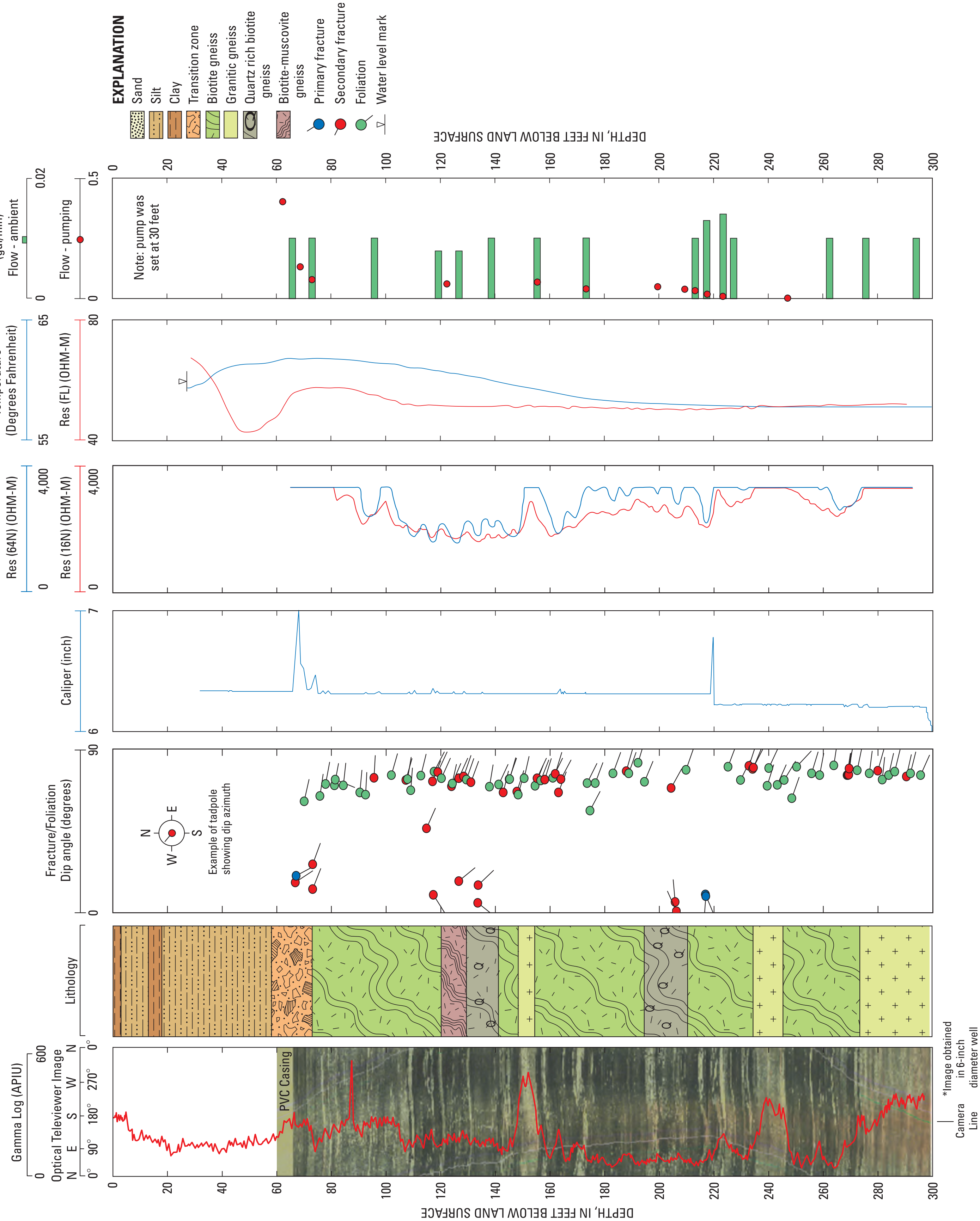


Figure 11. Geophysical logs showing lithologies and fracture zones in bedrock well MW-3D at the Lake Wheeler Road research station, North Carolina.

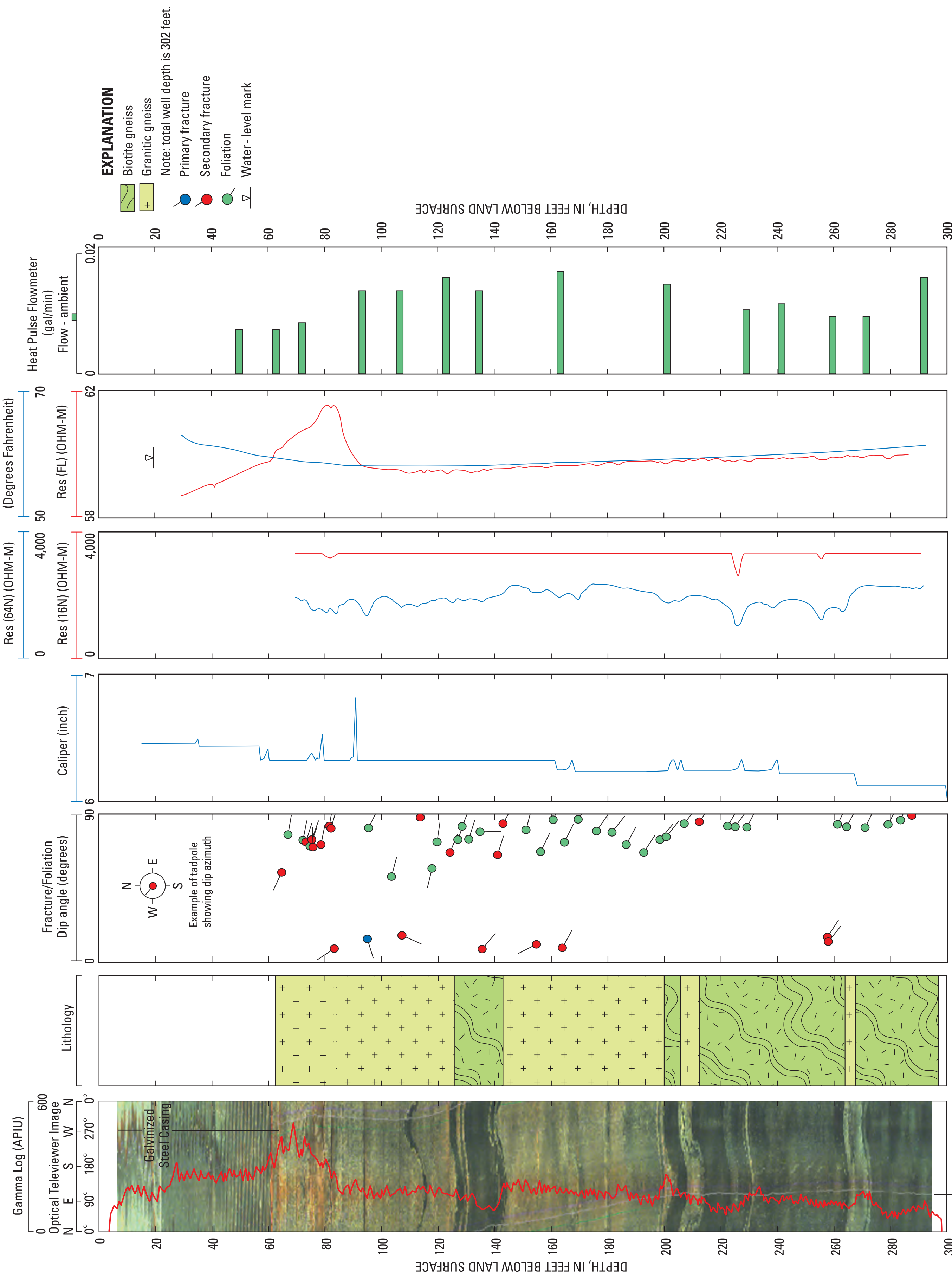


Figure 12. Geophysical logs showing lithologies and fracture zones in bedrock well PW-1 at the Lake Wheeler Road research station, North Carolina.

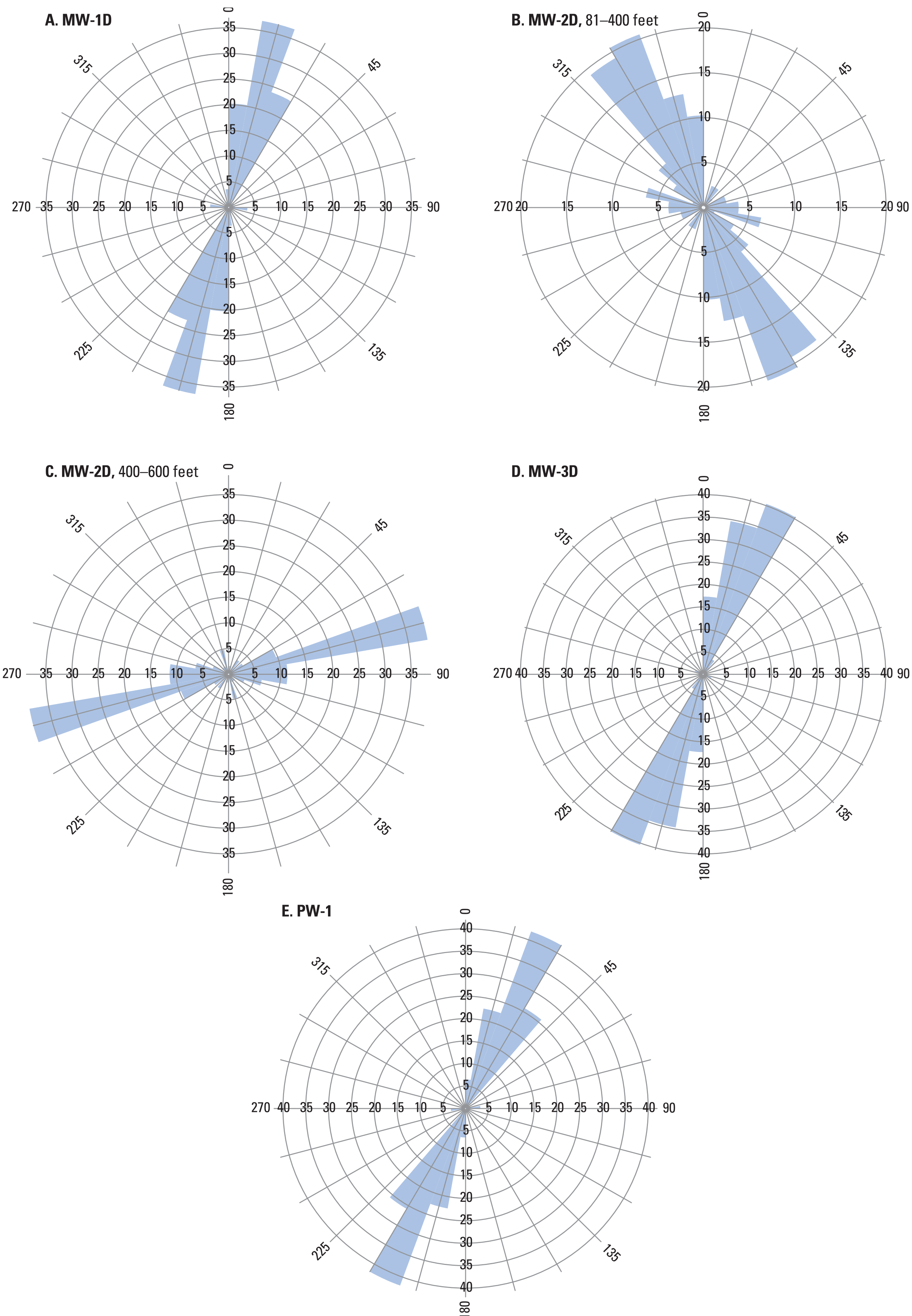


Figure 13. Strike orientation of bedrock foliation interpreted from optical televiewer images of (A) well MW-1D; (B) well MW-2D, 81–400 feet; (C) well MW-2D, 400–600 feet; (D) well MW-3D; and (E) well PW-1 at the Lake Wheeler Road research station, North Carolina.

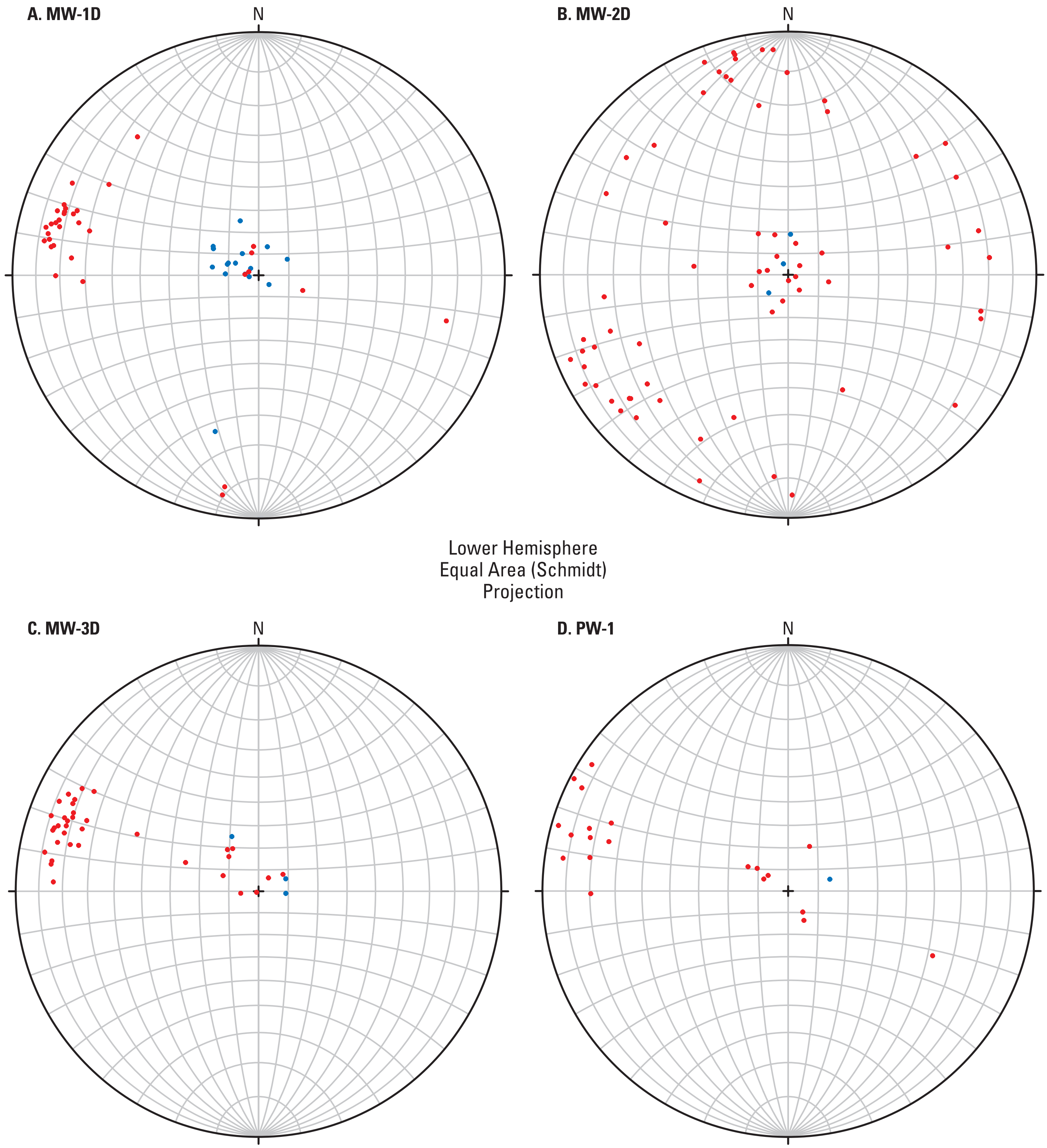


Figure 14. Orientation of primary (blue) and secondary (red) fractures in bedrock wells (A) MW-1D, (B) MW-2D, (C) MW-3D, and (D) PW-1 at the Lake Wheeler Road research station, North Carolina.

The steeply dipping fractures parallel to foliation strike and dip were most commonly delineated in borehole MW-1D (fig. 14A). Oxidation and weathering were noted in fractures as deep as about 282–284 ft (fig. 9), indicating chemical weathering from ground-water flow. The deepest fracture is parallel to foliation and near a pegmatite (feldspathic) zone. The orientation of the steeply dipping fractures parallel to foliation generally is about N. 12° E., dipping 72° SE. (fig. 14A).

Well MW-2D

Well MW-2D has a total depth of 601 ft and is the deepest bedrock well at the LWRRS (table 1). The yield of this well was estimated to be about 15 gal/min. Core samples were collected from land surface to a depth of about 188 ft (see appendix 2 for detailed descriptions). Interpretations of lithology from the core samples, natural gamma log, and OTV image indicate alternating zones of biotite gneiss and granitic gneiss (fig. 10). The estimated thicknesses of the lithologies range from about 20 to 130 ft. From the pink color noted on the OTV image and increased gamma counts, potassium feldspar-rich zones may be present within the lowermost granitic gneiss unit. The strike of foliation interpreted from the OTV image shifted about 90° near a depth of about 400 ft. From about 81 to 400 ft, the dominant strike of foliation was about N. 20° W. to N. 40° W., with a dip of about 70° SW.; however, from 400 to 600 ft, the dominant strike of foliation was about N. 70° E. to N. 80° E, dipping about 75° SE. (figs. 10, 13B, 13C). This deeper strike orientation is similar to the brittle fault orientation trend of N. 70° W. to N. 80° E. described by Heller (1996).

Analysis of caliper log data indicates that no large, open fractures are tapped by bedrock well MW-2D (fig. 10). Individual fractures were noted in the OTV image at depths of about 163 ft, 169 ft, 172 ft, 429 ft, and 544–545 ft from the OTV image; only the shallower three fractures were partially open. The major set of fractures delineated were steeply dipping and parallel to foliation (figs. 10, 14B). Low-angle stress-relief fractures had dominant orientations parallel to foliation (southeast dip direction, fig. 14B). Low-angle fractures were noted at depths as great as about 328 ft; however, most fractures were not open. Steeply dipping foliation-parallel fractures were noted throughout the borehole; from 81 to 400 ft, orientations averaged N. 63° W., dipping 74° SW., and from 400 to 600 ft, orientations averaged N. 9° E., dipping 69° SE.

Well MW-3D

Bedrock well MW-3D was drilled to a depth of 301 ft and had an estimated yield of about 2 gal/min. The core collected at corehole RAL-3 (total depth of about 148 ft, appendix 3) is described as regolith to a depth of about 50 ft, with a transition zone of weathered gneiss from about 50 to 73 ft. The bedrock is light gray granitic gneiss and medium gray biotite and biotite-muscovite gneiss with zones of increased amounts of quartz and biotite. Both horizontal and vertical fractures are delineated at various depths (appendix 3; fig. 11). Open horizontal fractures (transition zone) were observed in the core samples or OTV image between 58 and 60 ft, and vertical fractures with iron and manganese staining were observed at 63 ft. From the OTV image, the dominant rock type in the MW-3D well is biotite gneiss (fig. 11). The granitic gneiss was interpreted to be near the bottom of the well at a depth of about 275 ft for the remainder of the well depth (fig. 11). Zones of granitic gneiss or increased feldspar content were observed in the OTV image and correlated with increases in the natural gamma log response (fig. 11). The dominant strike of foliation orientation interpreted from the OTV image was about N. 10° E. to N. 30° E., with a dip of 75° SE. (fig. 13D).

The most notable fracture zones identified in the geophysical logs and OTV images are low-angle, stress-relief fractures at depths of about 64 ft, 73 ft, and 217–218 ft (fig. 11). The uppermost set of fractures at 64, 67, and 73 ft were delineated as part of the transition zone (fig. 6). These fractures are not open, but are weathered. The strike orientation of the shallow transition-zone fractures are N. 64° E. and N. 22° E. (67 ft and 73 ft, respectively, figs. 11, 14C) both dipping at about 20° SE. Orientation data from the 217–218 ft fracture zone indicate a strike of about N. 10° W., dipping at about 10° SW. During drilling, the uppermost fractures yielded only 1–2 gal/min, and the lowermost fracture yielded less than 1 gal/min. The 217–218 ft fracture zone was confirmed in the OTV image as having a subhorizontal dip that cuts across foliation. Steeply dipping breakouts, or secondary fractures parallel to foliation, were noted throughout the borehole (fig. 11) and have an average strike orientation of about N. 20° E., dipping 73° SE. (figs. 13D, 14C).

Well PW-1

Bedrock well PW-1, located about 235 ft northwest of well cluster MW-2 (fig. 4), was drilled as a dedicated pumping well for aquifer tests, and the casing material was galvanized steel instead of PVC (table 1). The initial air-lift yield of this bedrock well was estimated to be about 3–5 gal/min. An aquifer test conducted during April 2–5, 2002, confirmed a yield of 3 gal/min with 57 ft of drawdown.

No core was collected at this location; therefore, the lithologic description of well PW-1 is based on correlation with other bedrock wells at the LWRRS, interpretation of the OTV image, and natural gamma log. The PW-1 well penetrates a different lithologic sequence compared with the other three bedrock wells. In this well, the granitic gneiss was delineated near the top of bedrock to a depth of about 210 ft (fig. 12). The biotite gneiss was delineated in the remainder of the borehole to a depth of 302 ft (table 1). Foliation interpretations from the OTV image suggest the dominant strike of foliation to be about N. 20° E. to N. 30° E., with a dip of about 75° SE. (fig. 13E).

From the geophysical logs, no large fractures were delineated in bedrock well PW-1 (fig. 12). The most notable fracture zone from the caliper log and the OTV image is at a depth of about 94–95 ft. This fracture is open, cross cuts foliation, and has a strike orientation of about N. 16° W., dipping 14° SW. A second fracture zone was delineated at a depth of about 80–84 ft from the OTV image and caliper log (fig. 12). This fracture zone includes both steeply dipping foliation-parallel fractures (average strike orientation N. 11° E. 82° SE.), and low dip angle stress-relief fractures (strike orientation N. 55° E. 9° NW.; fig. 12). A response in the fluid-resistivity log is noted near these two fracture zones (fig. 12). The fluid-resistivity log indicates potential inflow of water with lower specific conductance from these fractures. The ambient heat-pulse flowmeter log shows a slight reduction in flow above the 94- to 95-ft zone, indicating the movement of water away from the borehole at about the 80- to 84-ft fracture zone. Numerous small, steeply dipping fractures were noted having an orientation (both strike and dip angle) parallel to foliation, most likely as a result of partial drilling breakouts. The general orientation of the foliation-parallel fractures is about N. 31° E. and 76° SE. (figs. 12, 13E, 14D).

Ground-Water Levels

Ground-water levels at the LWRRS for the three components of the ground-water system responded to both long- and short-term climatic conditions. Long-term trends were affected by drought conditions during the first 18 months of the study. Seasonal trends were evident during the drought (water years 2001 and 2002), but rose throughout water year 2003 as a result of above-average rainfall. Ground-water levels also responded to individual rainfall events, evapotranspiration, and barometric pressure. The frequency and data-collection period for ground-water-level data are listed in table 2.

Seasonal Trends and Water Year Comparisons

From May 2001 through September 2003, ground-water levels at the LWRRS had climatic and seasonal trends typical of fluctuations in the Piedmont region (fig. 15). Higher water levels generally occur during the early spring following winter precipitation. During the summer months, rainfall becomes more sporadic and generally shorter in duration. In addition, evapotranspiration (ET) rates increase during the spring and summer months. As a result of reduced precipitation and increased ET rates, ground-water levels decline. This decline generally continues through the fall.

During the study period, typical seasonal trends were affected by extreme climatic conditions. Water years 2001 and 2002 were the last 2 years of a 4-year drought that affected most of central and western North Carolina (Weaver, 2005). In contrast, above-normal rainfall occurred in water year 2003. Ground-water-level data recorded in the LWRRS wells are summarized in the USGS annual data reports for North Carolina (Howe and others, 2002, 2003, 2004).

The contrast between drought conditions (water years 2001 and 2002) and above-normal precipitation (water year 2003) is evident in the ground-water levels at the LWRRS. Precipitation at the site was 29.51 inches for water year 2002 compared with 52.55 inches for water year 2003 (State Climate Office of North Carolina, 2004). In water year 2002, the highest water levels generally occurred in the fall (October 2001), and water levels declined throughout the remainder of the water year (fig. 15). In water year 2003, the lowest water levels occurred in the fall (October 2002) at the end of the drought period. Ground-water levels began to rise in November 2002 and continued to rise during the remainder of water year 2003; the highest levels were recorded in the late summer (August and September) during months in which the lowest water levels typically occur. The above-normal precipitation during water year 2003 resulted in a marked increase in ground-water levels of as much as 3 ft in the regolith (including the intermediate zone) and bedrock wells in cluster MW-3 in the recharge area (fig. 15C).

Regional Comparison

Water levels in the regolith wells at the LWRRS were compared to long-term water-level records for a regolith observation well in Davie County, North Carolina (Mocksville well NC-142, station number 355359080331701, DV-025; fig. 16A), which had similar climatic and seasonal trends as those recorded in regolith well MW-1S during water years 2002 and 2003 (fig. 16B). In water year 2002 during the drought, water levels in well DV-025 were routinely at period-of-record lows (fig. 16A). In water year 2003 following the drought, ground-water levels in the Mocksville well recovered to average conditions within about 7 months.

Response to Rainfall

Recharge to the Piedmont and Mountains ground-water system is a complex process affected by several factors (Heath, 1994; Heath and Jennings, 1995). The amount and seasonal distribution of precipitation determine the amount of water available for recharge. The permeability of the regolith together with the intensity of precipitation determine the amount of precipitation that (1) percolates into the ground and (2) runs off overland and infiltrates through the soil. The type, density, and growth of vegetative cover determine how much precipitation is used for transpiration. The air temperature and amount and intensity of sunlight control surface heating and water evaporation from wet surfaces (ponding) and the soil zones. Finally, the duration and intensity of individual rainfall events affect recharge to the ground-water system (Heath and Jennings, 1995).

Antecedent soil-moisture conditions also affect how much rainfall infiltrates to the water table. In the winter

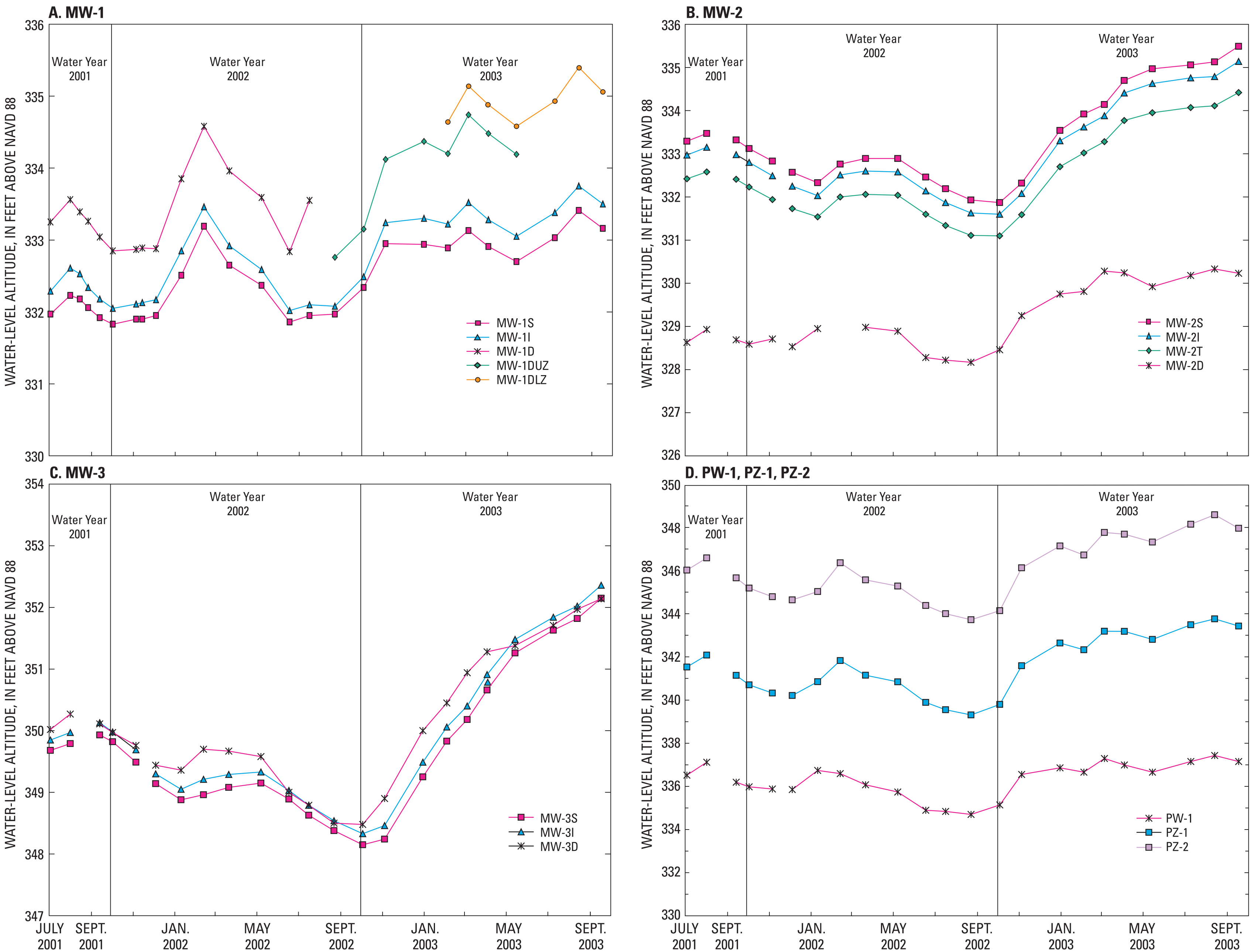


Figure 15. Periodic ground-water levels recorded in (A) well cluster MW-1, (B) well cluster MW-2, (C) well cluster MW-3, and (D) wells PW-1, PZ-1, and PZ-2 at the Lake Wheeler Road research station, North Carolina, during water years 2002–03.

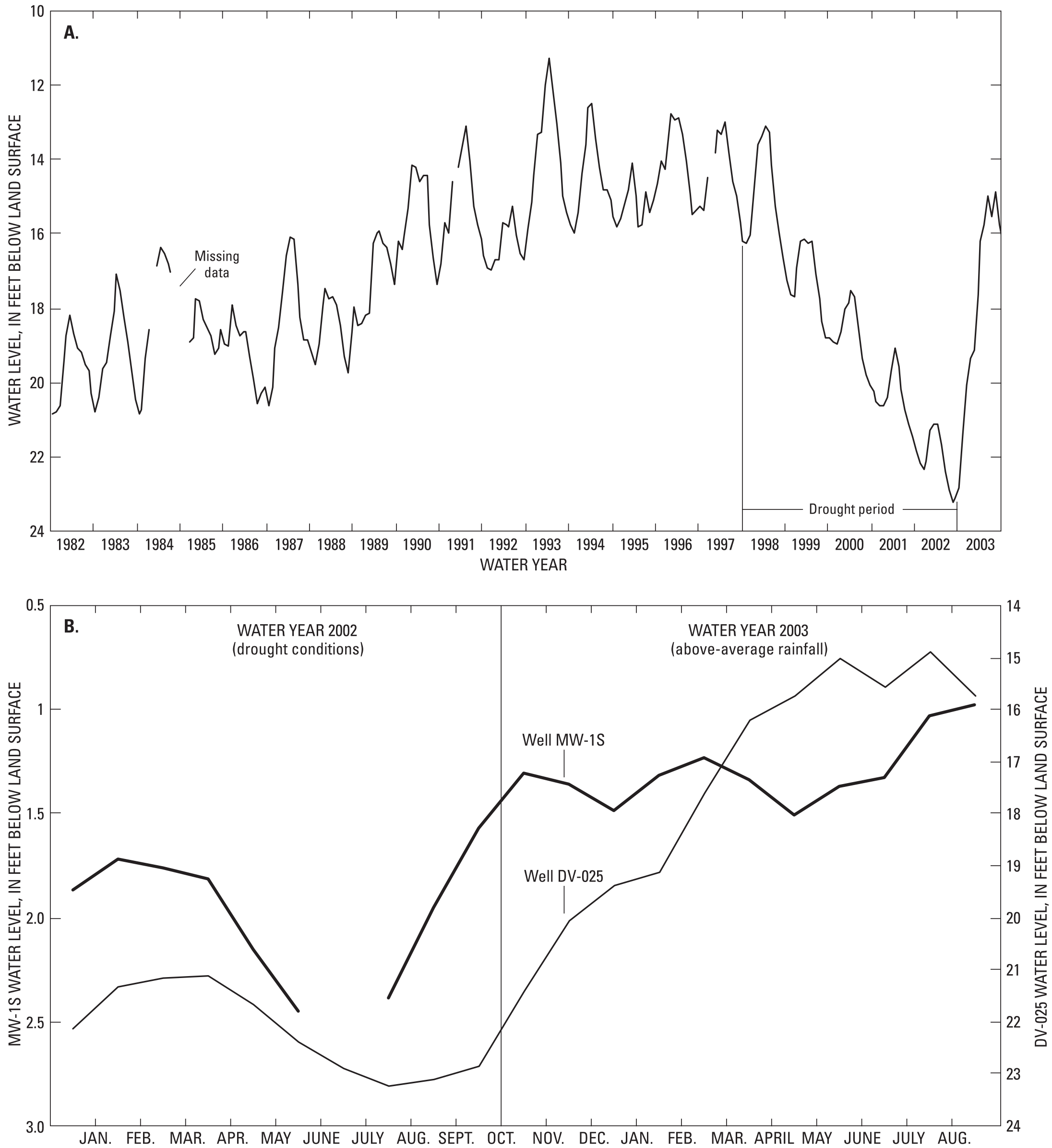


Figure 16. Monthly mean water levels in (A) well DV-025 near Mocksville, North Carolina, during water years 1982–2003, and (B) well DV-025 and well MW-1S during water years 2002–03.

months, the soil moisture generally is high because plant moisture intake decreases, less evapotranspiration occurs, and more rainfall readily infiltrates to the water table. During the summer months, however, the soil moisture is low because of more isolated rainfall, increased plant growth and water intake, and increased evapotranspiration in response to higher temperatures.

Ground-water levels in all of the MW-1 cluster wells rose within a few hours after the occurrence of rainfall during the study period (fig. 17A). Continuously measured (hourly) water levels in well cluster MW-1 were compared to hourly precipitation data recorded at the climate station (fig. 4; State Climate Office of North Carolina, 2004). These data were used to evaluate the response of surface-water stage and ground-water levels during rainfall. The magnitude of the water-level rise generally decreased with depth; the water-level rise in the deeper bedrock (MW-1DLZ) had less magnitude than the shallow regolith water level (MW-1S, fig. 17A). Water levels in well MW-1S rose within 1–3 hours after the onset of rainfall.

The rise in ground-water levels in all three zones in well cluster MW-1 may not be the result of direct infiltration of rainfall. Because of the proximity of this well cluster to a surface-water drainage (unnamed tributary to Swift Creek near Yates Mill Pond, fig. 4), the water-level rises may be a response to a hydrologic boundary condition. Water-level

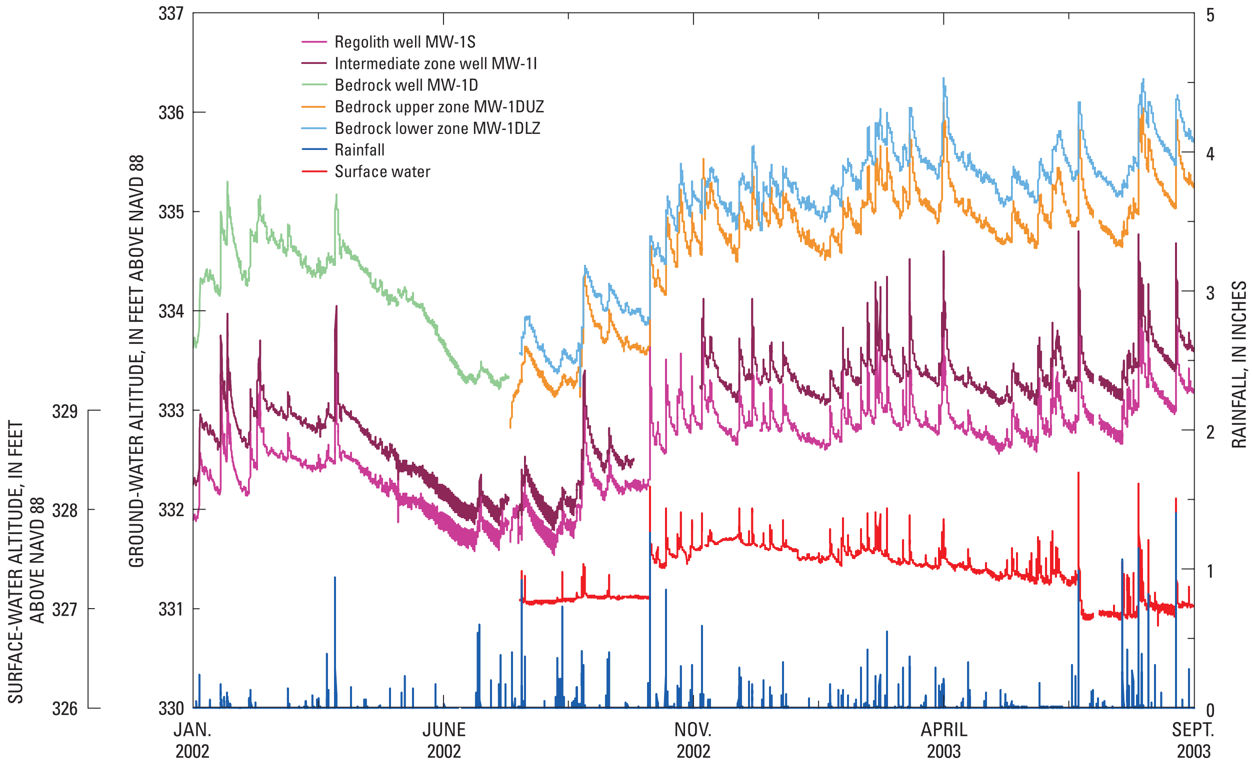


Figure 17A. Continuous ground-water levels recorded in well cluster MW-1, surface-water stage at the tributary site, and hourly precipitation at the climate station, January 2002–September 2003, Lake Wheeler Road research station, North Carolina.

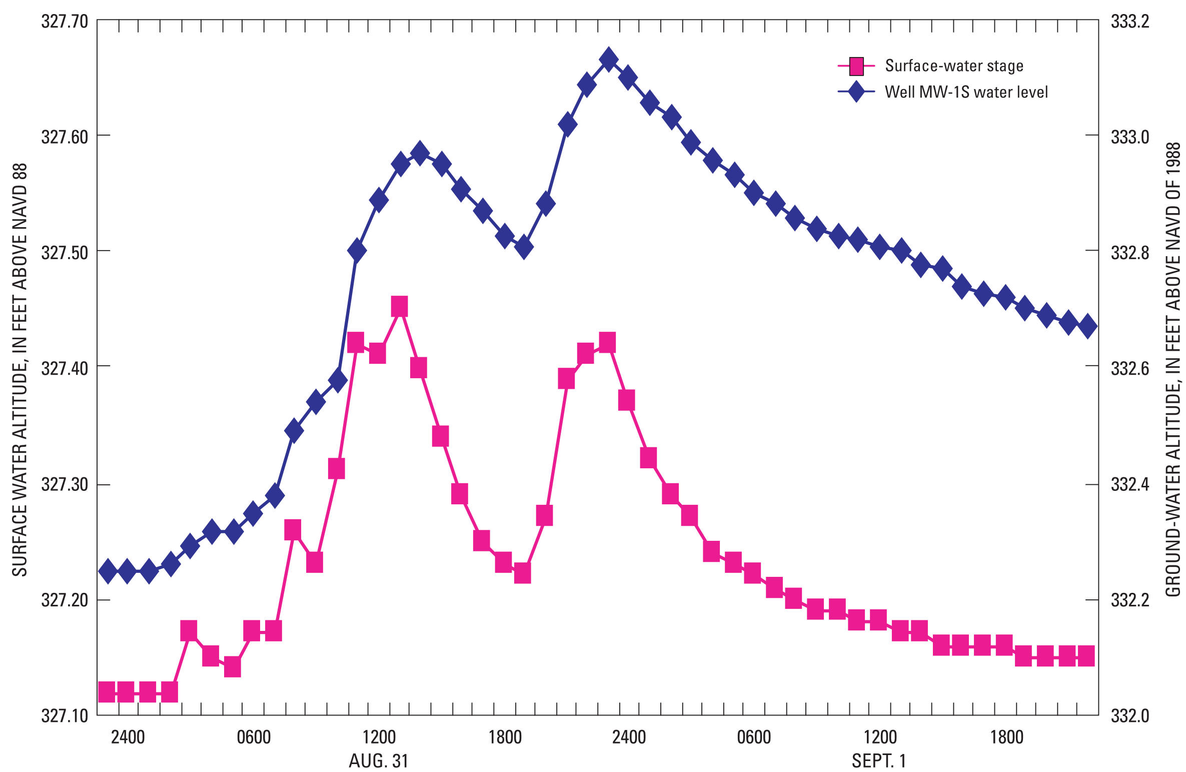


Figure 17B. Corresponding fluctuations in surface-water stage at the tributary site and ground-water levels in well MS-1S during recorded rainfall, August 31–September 1, 2002, Lake Wheeler Road research station, North Carolina.

gradient reversals, however, were not observed between regolith well MW-1S and the surface-water gage. (The location of the surface-water gage 200 ft downstream and beneath a culvert may have been a factor in the interpretation of these data.) An example of the response of water levels in well MW-1S and tributary stage during a rainfall event in August 2002 is given in figure 17B. The rise and fall of the shallow ground water and surface water occurred at similar times and similar magnitudes. Additionally, the rise of water levels in all ground-water zones at depth, including the lower fracture zone in well MW-1DLZ where direct infiltration of rainfall is unlikely, indicates a possible pressure response as a result of rising stage in the tributary. In the Piedmont and Mountains region, ground-water levels in discharge areas near streams commonly respond with sharp rises and declines that are similar to the fluctuation of surface-water stage.

Daily Fluctuations

Daily fluctuations of ground-water levels at the LWRRS are affected by earth tides, barometric pressure, and evapotranspiration rates. These short-term fluctuations can be observed in hourly water-level data.

Water levels in bedrock wells MW-2D and MW-3D (fig. 18) had similar patterns of daily fluctuation during water year 2003. Diurnal earth-tide fluctuations on the order of a few hundredths of a foot were observed in both wells. Response to recharge and barometric-pressure fluctuations also was quite similar in the two wells (fig. 18). Both wells are located in ground-water recharge areas, and the observed earth-tide and barometric-pressure fluctuations are typical of confined aquifers. Whereas the Piedmont aquifer system is considered unconfined in the sense that the underlying bedrock is connected to the overlying regolith in some places,

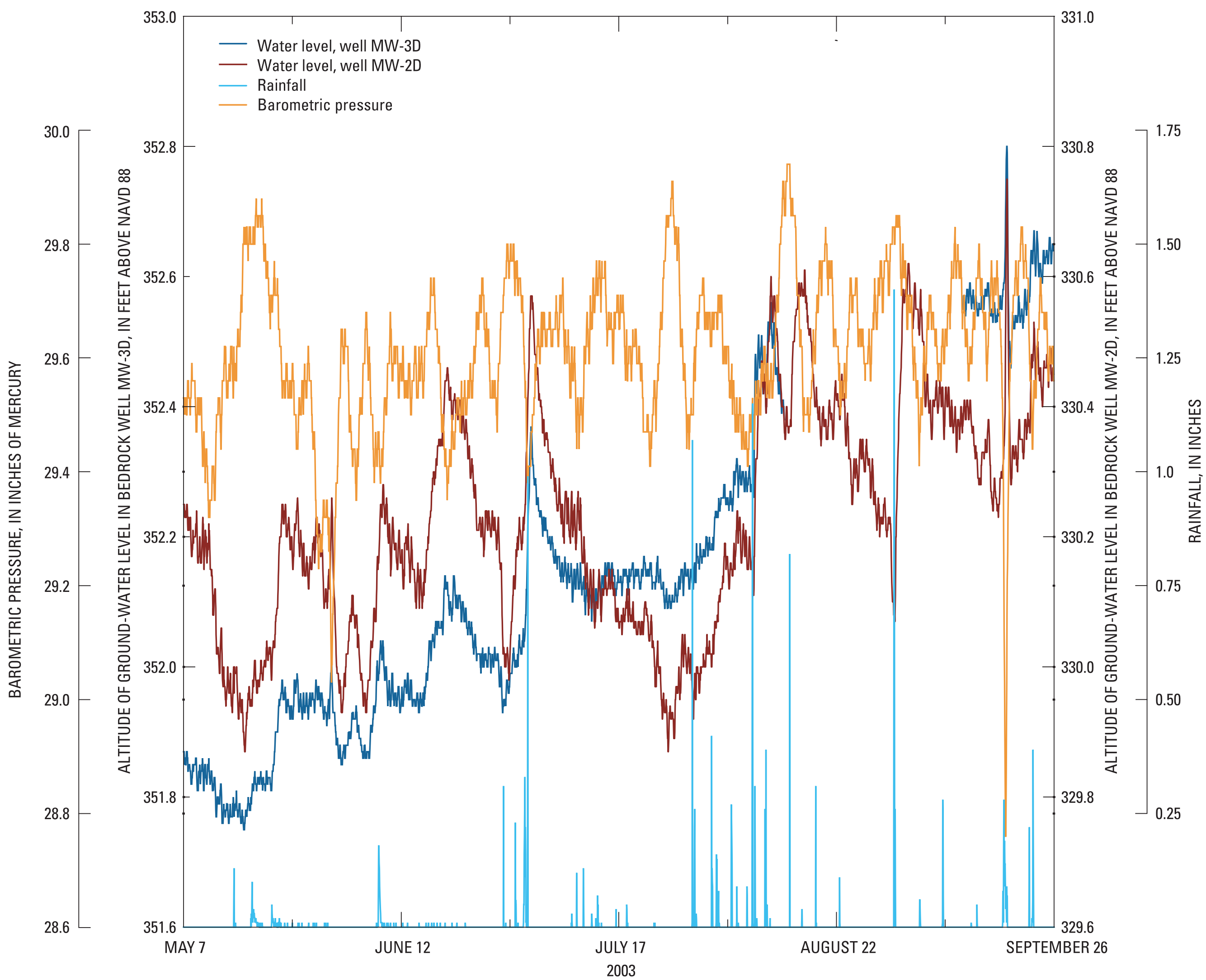


Figure 18. Continuous ground-water levels recorded in bedrock wells MW-2D and MW-3D at the Lake Wheeler Road research station, North Carolina, May 7 to September 26, 2003.

water-bearing fractures in the bedrock are confined by the low-permeability rock mass.

Evapotranspiration

Effects of evapotranspiration (ET) were observed at the surface-water gage and in all MW-1 cluster wells during the growing season from April through mid-October. The ET fluctuations correlated with photosynthetic-activity cycles recorded at the climate station (State Climate Office of North Carolina, 2004). The ground-water-level fluctuations may be a result of transpiration processes or in response to fluctuations in surface-water stage (fig. 19A). Well cluster MW-1 is within 20 ft of a large grove of poplar trees. Diurnal water-level fluctuations of a few tenths of a foot were observed in shallow regolith well MW-1S even in the absence of precipitation (fig. 19). Water levels typically were highest in early morning and lowest in mid-afternoon (fig. 19B) when photosynthesis is at a maximum and vegetation consumes more water, resulting in a decline in ground-water levels. Overnight, when photosynthesis is at a minimum, less water is consumed by vegetation, and water levels rise (fig. 19). Effects of ET on the ground-water levels increased during the warm summer months with increased plant growth.

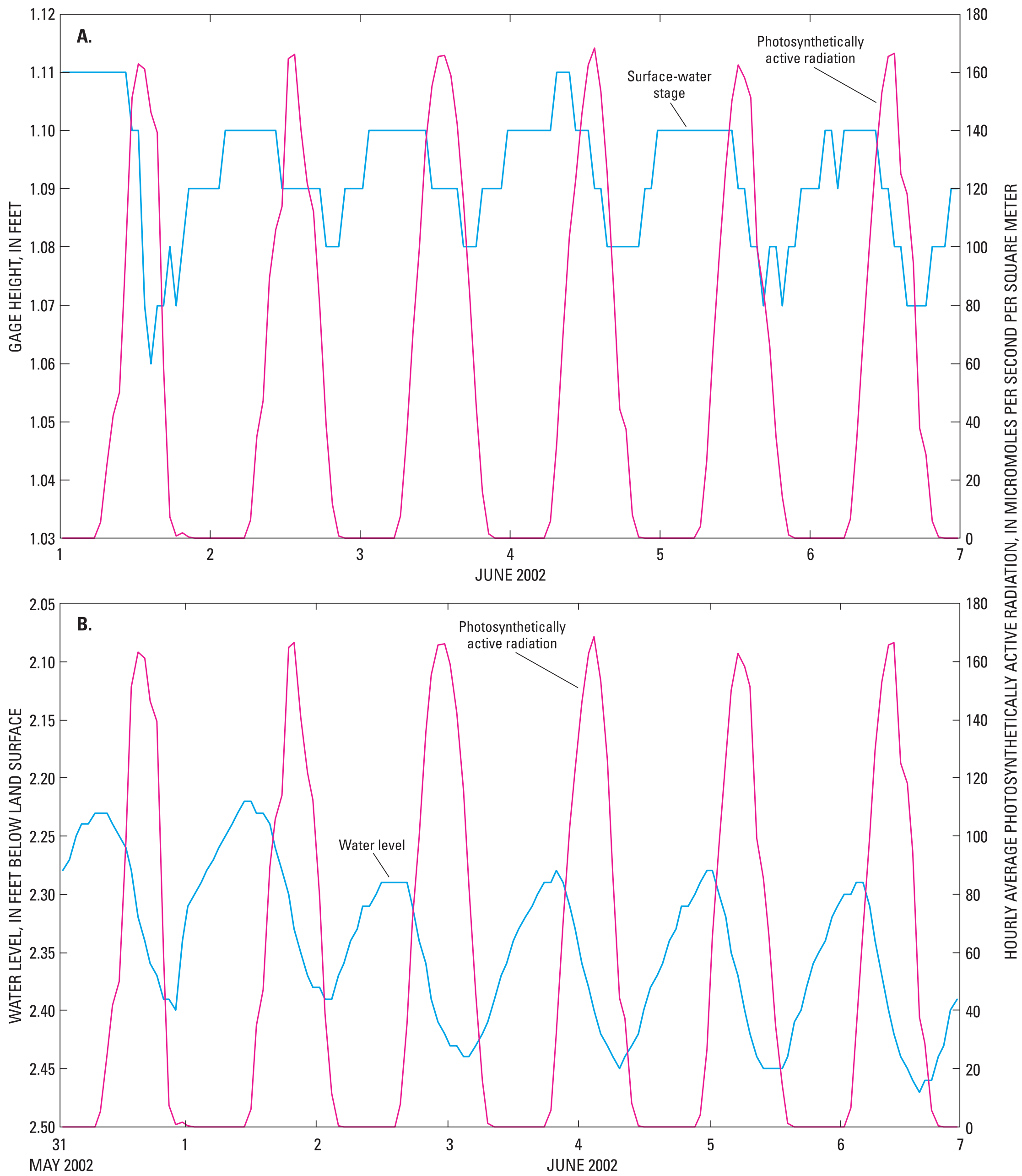


Figure 19. Relation of average hourly photosynthetic activity radiation recorded at the climate station to (A) gage height (stage) at the surface-water station and (B) water levels in regolith well MW-1S, Lake Wheeler Road research station, North Carolina, June 1–7, 2002.

Surface-Water Fluctuations

Although the drainage area of the tributary at the LWRRS is only 0.21 mi^2, the tributary flowed continuously during the study, including the 2001 and 2002 drought years. Base flow in the tributary was maintained by ground-water discharge. Gage height was recorded at 15-minute intervals from April 2002 through September 30, 2003 (table 2; fig. 20A). A stage/discharge rating was developed for the study period (fig. 20B).

Throughout the study period, the altitude of the water level in regolith well MW-1S was higher than the stage of the tributary, which indicates that ground water continually discharged to surface water (fig. 4). Base-flow conditions ranged from about 0.1 to 0.2 cubic feet per second (ft^3/s; fig. 20B). Applying an average of 0.15 ft^3/s to the drainage area (0.21 mi^2), the estimated ground-water recharge for the watershed is about 9.7 inches per year.

Instantaneous discharge (flow) in the tributary ranged from an estimated 0.01 to 60 ft^3/s (fig. 20B) for the study period. Flow in the tributary responded to local precipitation. Because of the small contributing drainage area, however, runoff generally lasted only a few hours.

Daily fluctuations in stage were most evident during the summer months when ET processes were dominant during warmer temperatures. The daily-stage cycles correspond

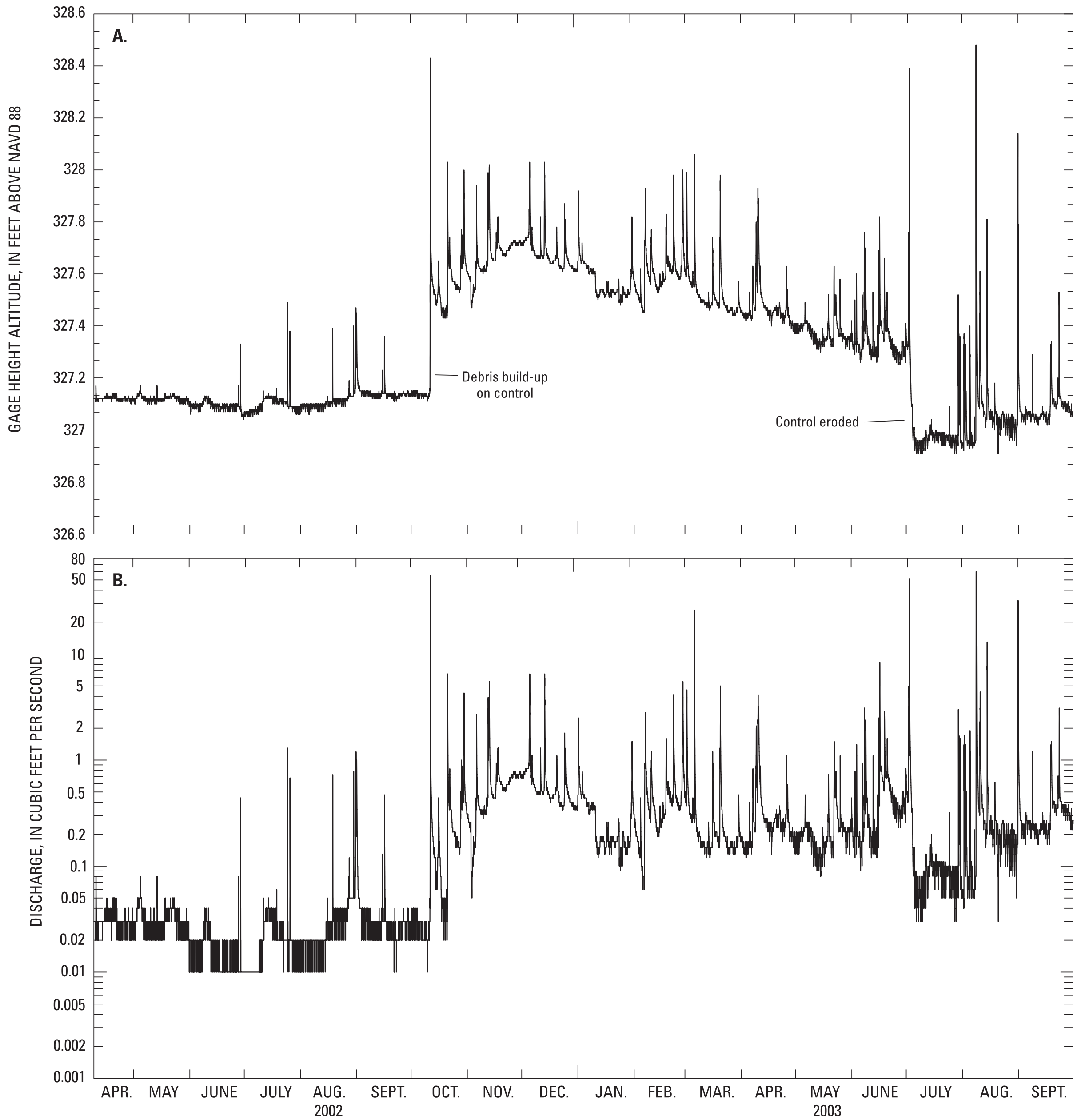


Figure 20. Continuous (A) gage height and (B) discharge recorded at the unnamed tributary at the Lake Wheeler Road research station, North Carolina.

directly with photosynthetic activity (fig. 18). Higher stage was observed in the morning when photosynthetic activity was low. Lower stage was observed during the afternoon when ET processes were most active during the highest temperatures (increased biological activity) of the day.

Ground-Water Flow

Conceptual models of ground-water flow in the Piedmont Physiographic Province of North Carolina assume that water flows from high topographic areas to low topographic areas (fig. 5). Depth to ground water and altitude of water levels are greater in topographically high recharge areas than in the topographically low areas where ground water is discharged at land surface to streams. This system is referred to as a "slope-aquifer system" (LeGrand, 2004; fig. 5). Discussions of conceptual ground-water flow and the influence of topography can be found in LeGrand (1967), Heath (1983, 1984), Harned and Daniel (1992), and Daniel and Dahlen (2002).

Ground-water-level profiles for the LWRRS generally support the slope-aquifer system concept. In general, water levels are closer to land surface at well cluster MW-1, the discharge area, than at well cluster MW-3, the recharge area (figs. 4, 6).

Flow in the Shallow Regolith

The general direction of ground-water flow in the regolith below the LWRRS (fig. 6) is consistently toward the south-southeast (fig. 21). This is in general agreement with the conceptual ground-water-flow model; however, depth to ground water (water-level altitude) and direction of flow do not completely correspond to land-surface topography in the immediate area of the well transect. The ground-water-flow direction indicates a discharge area farther downstream in the tributary than the area near well cluster MW-1.

Water-level altitudes measured in wells tapping the shallow regolith generally support the conceptual model; the highest water-level altitudes were measured at MW-3S in the recharge area, and lower water-level altitudes were measured in the recharge area (fig. 21). The representative high (March 5, 2003) and low (August 22, 2002) water-level conditions for the study period are shown in figure 21. Water-level altitudes in wells MW-1S and MW-2S did not follow the topographic profile and were within 1 ft of each other despite the substantial difference in land-surface altitude (about 28 ft; fig. 21; table 1). Conversely, the water-level altitude in well MW-3S followed the topographic profile and was about 16 ft higher than the water levels in wells MW-1S and MW-2S (figs. 15, 21). (Land surface at well MW-3S was about 13 ft higher than at well MW-2S and about 41 ft higher than at well MW-1S.) Additionally, although wells PZ-1 and PZ-2 had a lower land-surface altitude than well MW-2S, water-level altitudes in these two wells were higher than in well MW-2S. Water-level altitudes in wells PZ-1 and PZ-2 were intermediate to those in wells MW-3S and MW-2S, and water levels in PZ-2 were slightly higher than in PZ-1 (about 4.5 ft; fig. 15), which corresponds with the topographic profile.

Flow in the Intermediate Zone of the Regolith

Ground-water flow in the intermediate zone of the regolith at the LWRRS is consistently toward the south-southeast (fig. 22), indicating discharge farther downstream than the area near well cluster MW-1, similar to flow in the shallow regolith. Figure 22 shows representative high (March 5, 2003) and low (August 22, 2002) water-level conditions for the study period. As with the shallow regolith wells, intermediate-zone water-level altitudes were comparable in well clusters MW-1 (well MW-1I) and MW-2 (well MW-2I), resulting in a southeastward bend in the ground-water-flow direction (fig. 22). Water levels recorded in the intermediate zone of the regolith in well clusters MW-1 and MW-2 did not follow the topographic profile and were within 1 ft of each other (wells MW-1I and MW-2I, respectively), similar to water levels in the shallow regolith wells MW-1S and MW-2S. Water-level altitudes in well MW-3I generally followed the topographic profile and were about 17 ft higher than in well MW- 2I (fig. 22).

Flow in the Bedrock

The direction of ground-water flow in the bedrock at the LWRRS, as determined from open-borehole water-level data, is similar to flow in the shallow and intermediate zones of the regolith—consistently toward the southeast, discharging farther downstream in the tributary than the area near well cluster MW-1 (fig. 23). The low water-level altitude measured in well MW-2D largely affects interpretation of the flow direction.

Water levels in the bedrock wells roughly parallel topography (fig. 23). Water levels were highest in the recharge area at MW-3D; however, the lowest water levels were in well MW-2D, topographically uphill from bedrock well MW-1D (fig. 23). Figure 23 depicts representative high (March 5, 2003) and low (August 22, 2002) water-level conditions for the study period. Water levels in MW-2D were almost 5 ft lower than those in MW-1D, despite being topographically higher (about 28 ft; fig. 6). The water-level altitude in well MW-3D generally followed the topographic profile and was about 20 ft higher than in well MW-2D. Water-level altitudes in well PW-1 also did not follow the topographic profile and were about 2 ft higher than in well MW-1D, yet well PW-1 is about 19 ft higher, topographically, than well MW-1D.

One explanation for the lower water-level altitude in well MW-2D (fig. 15) is that this well was drilled about 300 ft deeper than the other bedrock wells (table 1). If hydraulic heads decrease with depth, the composite water level in a deeper well may be affected by these lower hydraulic heads,

Figure 21. Ground-water-level altitudes and flow direction in the regolith at the Lake Wheeler Road research station, North Carolina, (A) August 22, 2002, and (B) March 5, 2003.

Figure 22. Ground-water-level altitudes and flow direction in the intermediate zone at the Lake Wheeler Road research station, North Carolina, (A) August 22, 2002, and (B) March 5, 2003.

Figure 23. Ground-water-level altitudes and flow direction in the bedrock at the Lake Wheeler Road research station, North Carolina, (A) August 13, 2002, and (B) March 5, 2003.

especially in a low-yield well that has a limited number of transmissive fractures. The low water-level altitude in MW-2D indicates a substantial downward vertical gradient (recharge) at this location. Additionally, there is a pronounced foliation strike shift from N. 20° W. to N. 40° W., dipping SW. from 81 to 400 ft, to N. 70° E. to N. 80° E., dipping SE. from 400 to 600 ft. This geologic structural shift in foliation strike (about 90°) also may indicate a distinct fracture network at depth that may have lower hydraulic heads in comparison with the shallower part of the bedrock.

Interpretation of the open-borehole water levels is complex because the data represent a composite of the hydraulic heads in several fractures tapped by the bedrock well. The hydraulic head in a specific fracture may be different from that measured in the entire open borehole. Packers, such as the one installed in well MW-1D, can be used to isolate fracture zones in the open borehole for a more accurate measurement of natural water levels in the fracture network.

Depth to Ground Water and Vertical Gradients

Throughout the study period, the depth to ground water in a well cluster and water-level altitudes in the regolith, transition zone, and bedrock were relatively consistent. An accurate calculation of vertical gradients was not possible because of the distance between wells. (A well spacing of 20 ft was used to avoid potential ground-water-quality problems related to grouting.)

In comparing water-level altitude among the three zones of the ground-water system, some areas were consistent with the conceptual model (fig. 5), but other areas were more complex. For example, in well cluster MW-1 in the discharge area, water levels had higher hydraulic heads with depth (figs. 15A, 17A), which supports the historical conceptual model. In well cluster MW-2, water levels decreased with depth (fig. 15B), indicating a recharge area. In well cluster MW-3, however, which should be in a recharge area according to the conceptual model, water levels had a slight increase in hydraulic head with depth (fig. 15C). Well cluster MW-3 may be affected by well placement; the deepest well (MW-3D) that taps the bedrock is located upslope and has a slightly higher land-surface altitude than the shallower wells. This upslope placement may affect the comparison of water-level altitudes at this well cluster location.

Although the shallow regolith wells near bedrock well PW-1 are spaced farther apart compared with the cluster wells, a downward vertical gradient to the bedrock was observed (fig. 15D). The shallow regolith wells PZ-1 and PZ-2, located downslope and upslope, respectively, from well PW-1 (fig. 4), consistently had higher hydraulic heads than the bedrock well PW-1.

The vertical hydraulic gradient between regolith well MW-1S and the surface-water site was consistently toward the tributary (fig. 21), maintaining a ground-water discharge area. A reversal of the hydraulic gradient was not observed, even during high-stage rainfall events. (If ground-water-level data were collected at 15-minute intervals, as with surface-water stage, gradient reversals may have been observed.) Placement of the streamgage farther downstream also may have affected this comparison.

Aquifer Hydraulic Properties

Aquifer hydraulic properties at the site were computed by analyzing data from rising- and falling-head slug tests and aquifer tests. Slug tests are considered estimates of the hydraulic conductivity of near-borehole aquifer materials. Slug tests were conducted in all wells completed in the regolith (including the intermediate zone), transition zone, and bedrock. A step-drawdown test and a constant-rate aquifer test also were conducted using well PW-1 as the pumping well.

Slug Tests

Slug tests provide a relatively quick and economical method of assessing spatial trends in hydraulic conductivity across a site. Methods and equipment used in conducting the slug tests are described in the Methods of Investigation section of this report.

The slug-test data collected at the LWRRS were analyzed using the Bouwer and Rice (1976) method, which accounts for water-table conditions and partial penetration effects. For the base of the aquifer, the depth to the top of the next zone (intermediate or transition zone) was used. For the shallow (S) regolith wells (table 1), depth to the deeper intermediate zone was used. For the intermediate-zone (I) wells, depth to the delineated transition zone was used. For the bedrock wells, the total depth of the well was used for the base of the aquifer. A summary of the analytical results of the slug-test data is given in table 3.

The slug-test results indicate that the bedrock had the lowest hydraulic conductivity, ranging from about 0.04 to 1.1 feet per day (ft/d). The shallow regolith had a higher overall hydraulic conductivity, ranging from about 0.6 to 3.0 ft/d, than the intermediate zone in the regolith, the transition zone, or the bedrock. The slug-test data generally agree with the conceptual model of ground-water flow in the porous media of the regolith. Flow in the transition zone and bedrock, however, is considered more tortuous and complex, resulting in lower hydraulic conductivity values.

Aquifer Tests

A 55-hour (hr) constant-rate aquifer test was conducted to obtain estimates of transmissivity and storage coefficients for the bedrock, transition zone, and regolith. Equipment and procedures used in the aquifer test are described in the Methods of Investigation section of this report. The pump

Table 3. Analytical results of slug tests in wells at the Lake Wheeler Road research station, North Carolina.

Well number	Total depth (feet below land surface)	Screened/open interval (feet below land surface)	Hydraulic conductivity (feet per day)
Regolith wells			
MW-1S	20	5–20	0.8
MW-2S	40	20–40	0.6
MW-3S	35	20–35	3.0
PZ-1	50	30–50	1.0
Intermediate-zone wells			
MW-1I	41.5	31.5–41.5	1.2
MW-2I	50	40–50	0.5
MW-3I	60	45–60	0.7
Transition-zone well			
MW-2T	80	50–80	0.2
Bedrock wells			
MW-1D	302	47–302	0.3
MW-2D	6	81–601	1.1
MW-3D	301	66–301	0.04
PW-1	302	62.5–302	0.05

was placed near the bottom of well PW-1 at a depth of about 280 ft. The pump discharge was directed toward the tributary, which is downslope and about 300 ft from the pumping well. An initial step-drawdown test (6 hrs in duration) was conducted in PW-1 to obtain an optimum pumping rate to be used during the constant-discharge aquifer test. Pumping rates of 1, 2, and 5 gal/min were evaluated during the step-drawdown test. The results of the step-drawdown test indicated an optimum pumping rate for the constant-rate aquifer test of about 3 gal/min.

Data from the constant-rate aquifer test are not presented in this report because of a lack of measurable drawdown in observation wells tapping the bedrock, transition zone, and regolith. Data collected during this aquifer test indicate a lack of connection with the surrounding bedrock wells. Care must be taken with this interpretation, however, in that if specific fracture zones had been pumped and monitored, compared to the entire open borehole, drawdown in interconnected fracture zones might have been measured. Additionally, pumping well PW-1 is perpendicular to the strike of foliation and the line of bedrock observation wells (well transect; MW-3D, MW-2D, and MW-1D). Conceptually, drawdown would be enhanced along the strike if the fracture systems were parallel to foliation. The most open fracture observed in well PW-1 (94–95 ft depth) had a strike oblique to foliation and a low dip angle.

A total of 10,040 gallons of ground water was pumped from well PW-1 during the study, resulting in an average discharge rate of approximately 3.1 gal/min. Drawdown in the pumping well was about 57 ft, resulting in specific-capacity calculation of about 5 gallons per minute per foot ((gal/min)/ft). The pumping water level, about 78 ft below land surface, was well above the primary water-bearing fracture at 94–95 ft. During the aquifer test, water levels in the pumping well responded to a decrease in barometric pressure, which indicates that the pumping rate may have been too low to create sufficient stress on the bedrock aquifer (fracture network) to generate drawdown in the bedrock observation wells. This response of bedrock ground-water levels to barometric-pressure changes is similar to the response of a confined aquifer, indicating reduced connection with the shallow regolith part of the ground-water system.

Water-Quality Data

Water-quality data from the wells and surface-water site at the LWRRS were collected both continuously and during periodic sampling events. Continuous water-quality monitoring was conducted from December 2001 in the MW-1 cluster wells and from April 2002 in the tributary through September 30, 2003. The continuous monitoring consisted of recording the physical properties of temperature, pH, SC, and DO in the MW-1 cluster wells and in the tributary.

Periodic samples were collected during four sampling events and analyzed for selected major ions, nutrients, metals, radiochemicals, and physical properties (table 4). Physical properties measured in the field included water temperature, pH, SC, DO, and field alkalinity (calculated as total and bicarbonate concentration). Major ion analytes included bromide, calcium, chloride, fluoride, magnesium, potassium, silica (as SiO_2), sodium, and sulfate. Trace metal analytes included aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, uranium, and zinc.

Some samples from bedrock wells may have been affected by grout migration and were omitted from this report. In general, pH values above 8 and elevated alkalinity, calcium, and sulfate concentrations indicated grout effects in the sample. Samples from transition-zone fractures MW-1DUZ and open borehole MW-1D were included in this report to document elevated ammonia concentrations, but likely also were affected by grout migration. As many samples contained elevated nitrate concentrations, these data are not considered to be representative of ambient ground-water-quality conditions. These data are used to characterize the ground-water-flow system and are representative of agricultural areas in similar hydrogeologic settings.

Methods and instrumentation used for both the continuous monitoring and periodic sampling are described in the Methods of Investigation section of this report and in the SOP for this study (North Carolina Department of

Table 4. Water-quality analyses included in periodic sampling events at the Lake Wheeler Road research station, North Carolina.

[nc, not collected]

Sampling date	Major ions[a,b] (dissolved)	Nutrients[a,c] (dissolved)	Metals[a,d] (dissolved)	Radon 222 (gas)[a] (total)	Gross alpha[a] (total)
August 2001[e]	X	X	nc	X	X
November 2001	X	X	nc		
May 2002	X	X	X	X	X
November 2002	X	X	X	X	

[a]Analyzed by STL Richland, Richland, Washington (contracted by U.S. Geological Survey National Water Quality Laboratory).

[b]Analyses for major ions included bromide, calcium, chloride, fluoride, magnesium, potassium, silica (as SiO_2), sodium, and sulfate.

[c]Analyses for nutrients included ammonia, nitrogen as nitrate, nitrogen as nitrite, nitrate plus nitrite, organic nitrogen, orthophosphorus, and orthophosphate.

[d]Analyses for metals included aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, uranium, and zinc.

[e]Only MW-1 cluster wells were sampled in August 2001.

Environment and Natural Resources, 2005). Continuous water-quality data collected during water years 2002 and 2003 are published in USGS annual data reports (Howe and others, 2003, 2004).

Continuous Monitoring Data

An important use of continuous water-quality monitoring data is to evaluate the response of the hydrologic system during seasonal trends, rainfall, and interactions of ground water with surface water. Seasonal trends are a function of recharge from precipitation, which typically is greatest during the winter and early spring months, and evapotranspiration, which is greatest during the late spring and summer months. In general, water levels in the MW-1 cluster wells rose during rainfall, likely from the interaction with the surface-water boundary during rising tributary stage. Interactions with surface water were evaluated by comparing water-quality data from the wells with data from the nearby surface-water site. The relative contribution of surface runoff compared to base flow (from ground-water discharge) was evaluated for the tributary site. The minimum and maximum daily mean values of physical properties are listed for each station in table 5.

Seasonal Trends

Water-quality data recorded in the MW-1 cluster wells and at the tributary site showed seasonal patterns. Specific ranges in daily mean temperature, pH, SC, and DO concentrations during each water year are listed for each well and the tributary site in table 5. Graphs showing trends in the recorded values are given in figures 24–28.

General trends in the ground-water system are evident from a comparison of ground-water quality in shallow regolith well MW-1S (fig. 24), intermediate-zone regolith well MW-1I (fig. 25), and deep bedrock well MW-1D (fig. 26). A further distinction in the ground-water system is made from isolation of the upper fractures in the transition zone in well MW-1D, as MW-1DUZ (fig. 27). In general, pH increases, DO decreases, and temperature becomes stable at increasing depths in the ground-water system. These observations most likely are the result of a lesser degree of infiltration of rainfall at depth over time. An overall increase in SC with depth indicates increased ground-water residence time and exposure to minerals in the bedrock (MW-1D) and the presence of elevated nutrients in the fractures in the transition zone (MW-1DUZ).

Overall, the ground water in shallow regolith well MW-1S exhibited greater seasonal fluctuation in water-quality properties (fig. 24) than was observed in the other wells. The observed seasonal temperature fluctuation in regolith well MW-1S was substantially greater than the temperature range in the deeper bedrock well MW-1D. As expected from the conceptual ground-water-flow model, the pH values increased with depth. In the bedrock, ground water has a long residence time, and the pH increases from dissolution of the minerals. Shallow ground water in the regolith (MW-1S) typically receives large amounts of acidic (lower pH) rainfall.

Table 5. Minimum and maximum daily mean values for physical properties collected during continuous water-quality monitoring in the MW-1 cluster wells and at the tributary site at the Lake Wheeler Road research station, North Carolina.

[°C, degrees Celsius; SC, specific conductance; µS/cm, microsiemens per centimeter at 25 °C; DO, dissolved oxygen; mg/L, milligram per liter; na, not applicable]

Station identification	Physical property	Water year 2002		Water year 2003	
		Maximum	Minimum	Maximum	Minimum
MW-1S	Temperature (°C)	16.9	14.2	17.2	13.9
	pH	6.1	4.8	5.8	4.7
	SC (µS/cm)	258	110	176	115
	DO (mg/L)	4.1	1.8	4.0	2.9
MW-1I	Temperature (°C)	16.0	15.9	16.2	16.0
	pH	5.3	5.2	5.8	5.0
	SC (µS/cm)	144	120	207	132
	DO (mg/L)	3.0	2.1	3.3	1.3
MW-1D[a]	Temperature (°C)	16.1	16.1	na	na
	pH	6.0	5.5	na	na
	SC (µS/cm)	744	647	na	na
	DO (mg/L)	0.9	0.2	na	na
MW-1DUZ[b]	Temperature (°C)	16.1	16.1	16.1	16.1
	pH	5.7	5.5	6.1	5.5
	SC (µS/cm)	702	624	714	554
	DO (mg/L)	0.3	0.2	1.8	0.2
Tributary site[c]	Temperature (°C)	20.8	14.1	22.8	4.4
	pH	6.0	4.9	6.5	5.0
	SC (µS/cm)	436	26	334	41
	DO (mg/L)	8.5	0.3	12.0	0.6

[a]Period of record is December 18, 2001, through July 18, 2002.

[b]Period of record began July 18, 2002.

[c]Period of record began April 9, 2002.

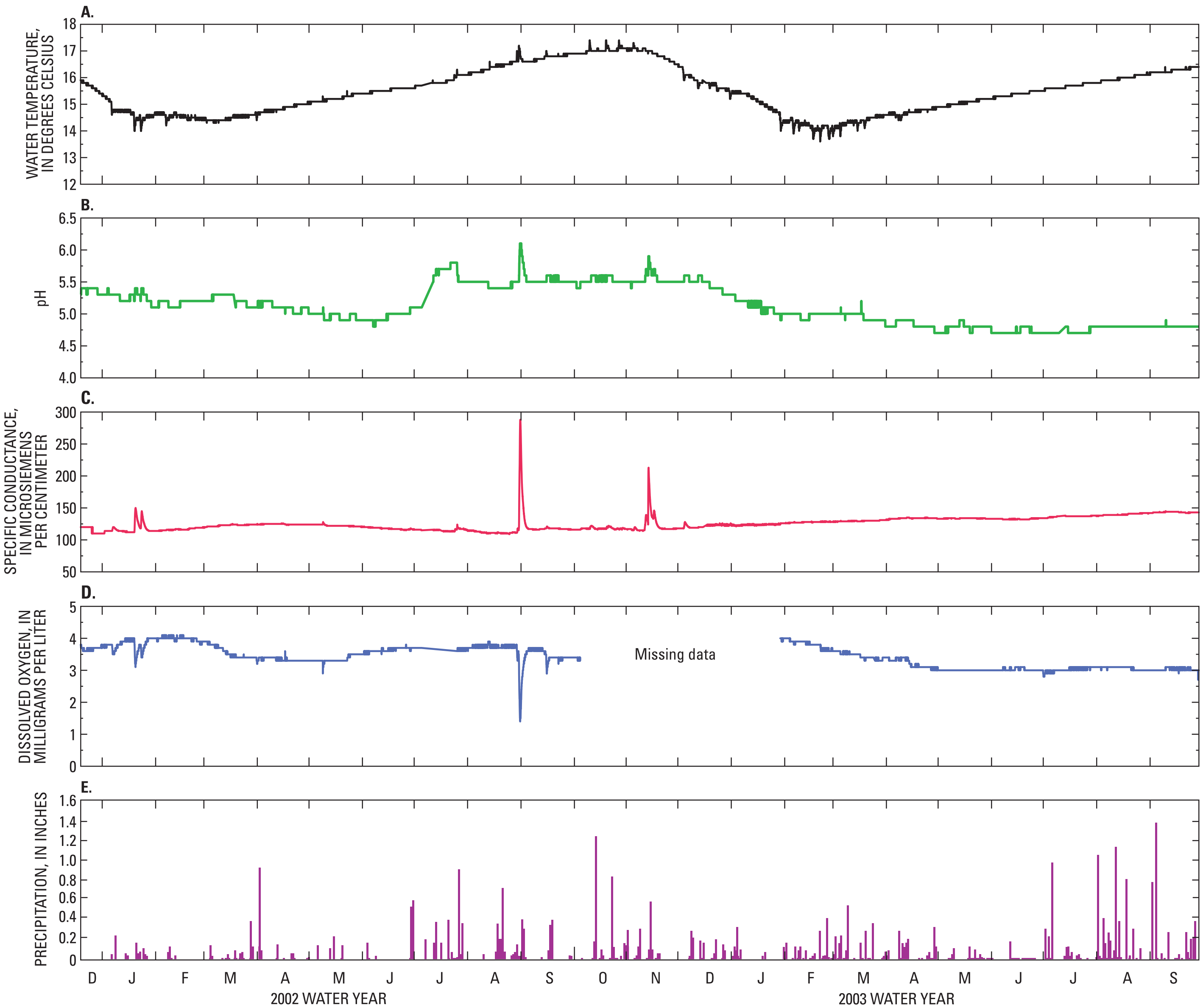


Figure 24. Continuous hourly (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in regolith well MW-1S; and (E) precipitation at the climate station at the Lake Wheeler Road research station, North Carolina, December 2001 through September 2003.

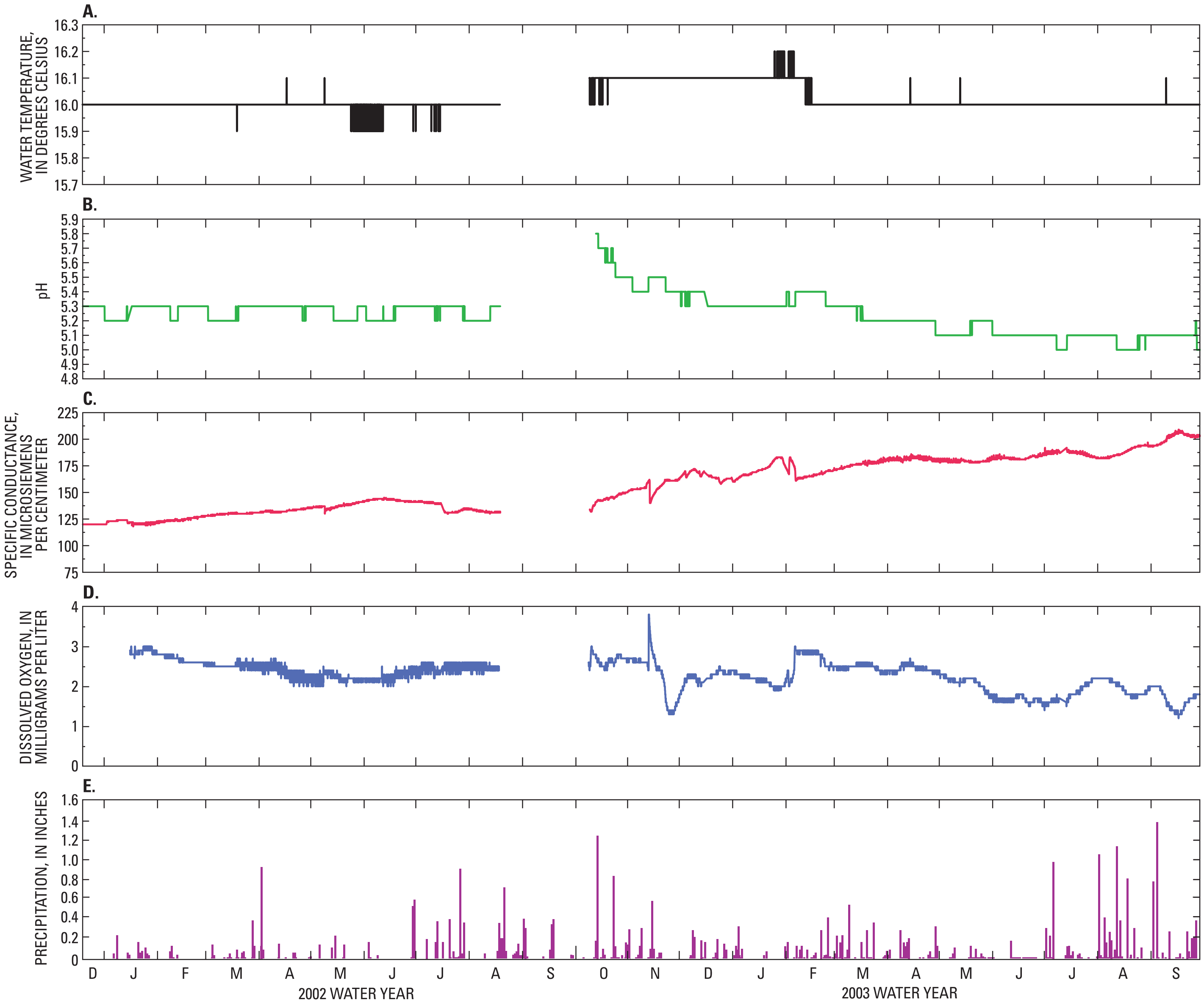


Figure 25. Continuous hourly (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in intermediate well MW-1I; and (E) precipitation at the climate station at the Lake Wheeler Road research station, North Carolina, December 2001 through September 2003. (Gaps indicate missing data.)

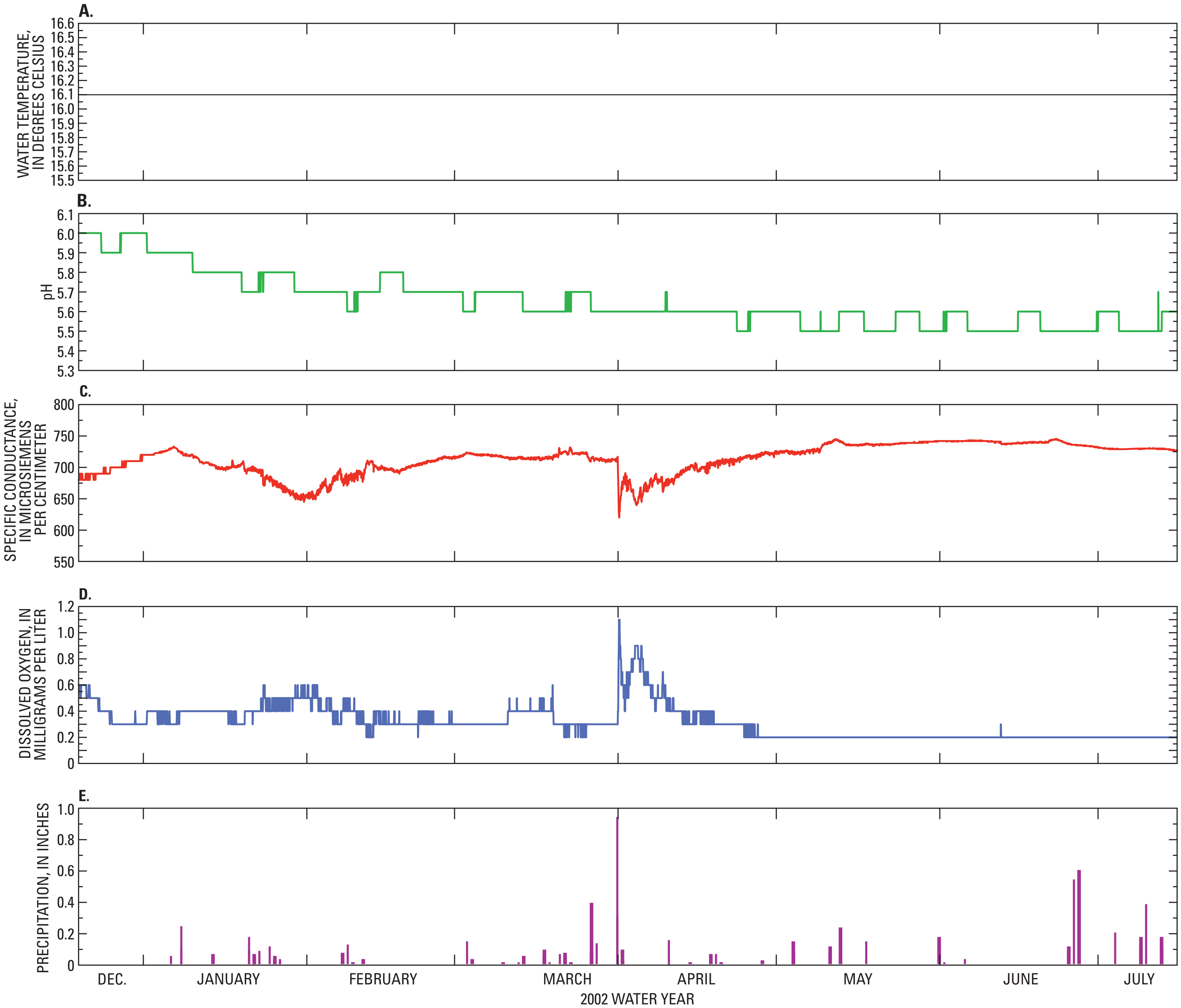


Figure 26. Continuous hourly (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in bedrock well MW-1D; and (E) precipitation at the climate station at the Lake Wheeler Road research station, North Carolina, December 2001 through July 2002.

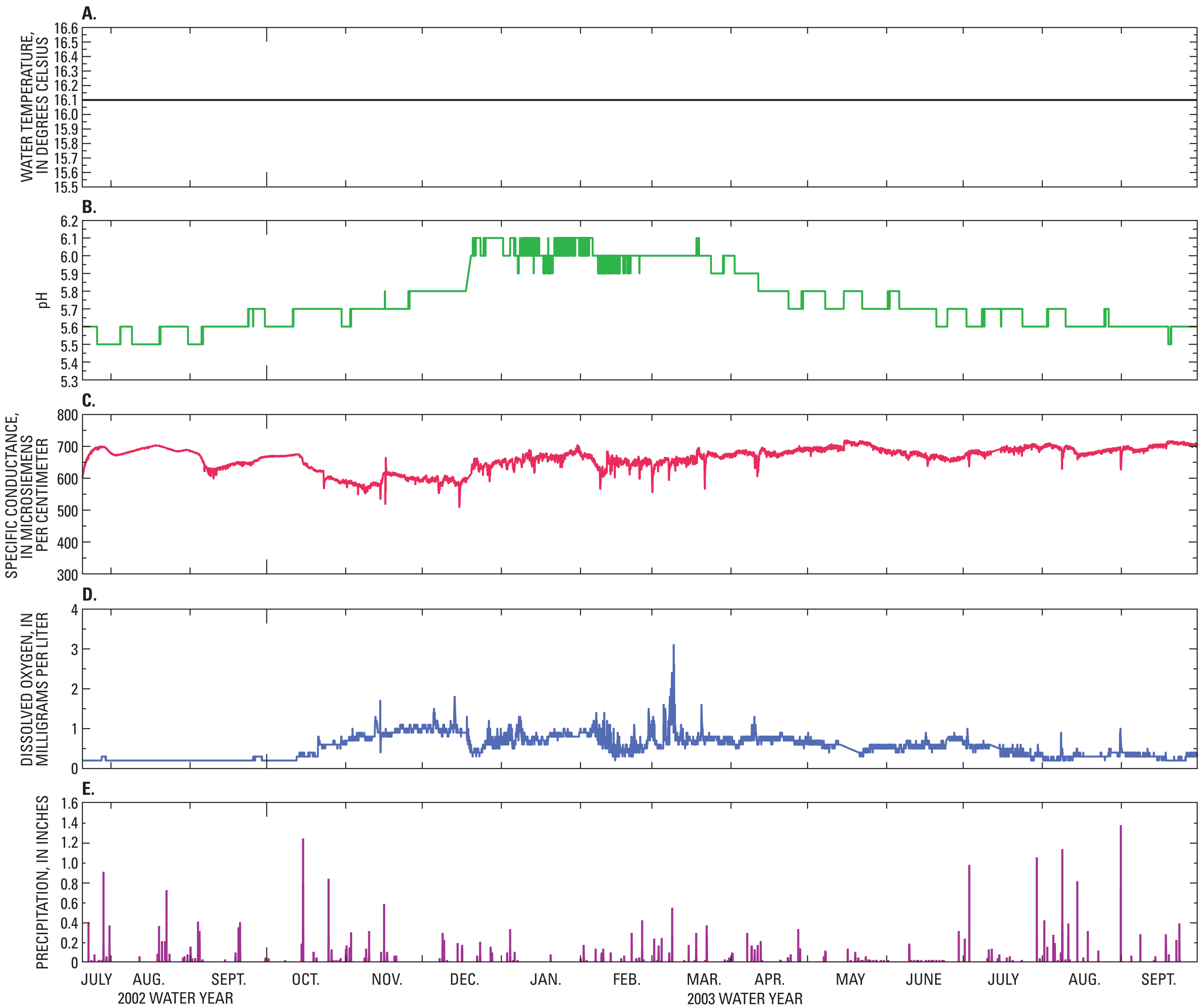


Figure 27. Continuous hourly (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in transition-zone well MW-1DUZ; and (E) precipitation at the climate station at the Lake Wheeler Road research station, North Carolina, July 2002 through September 2003.

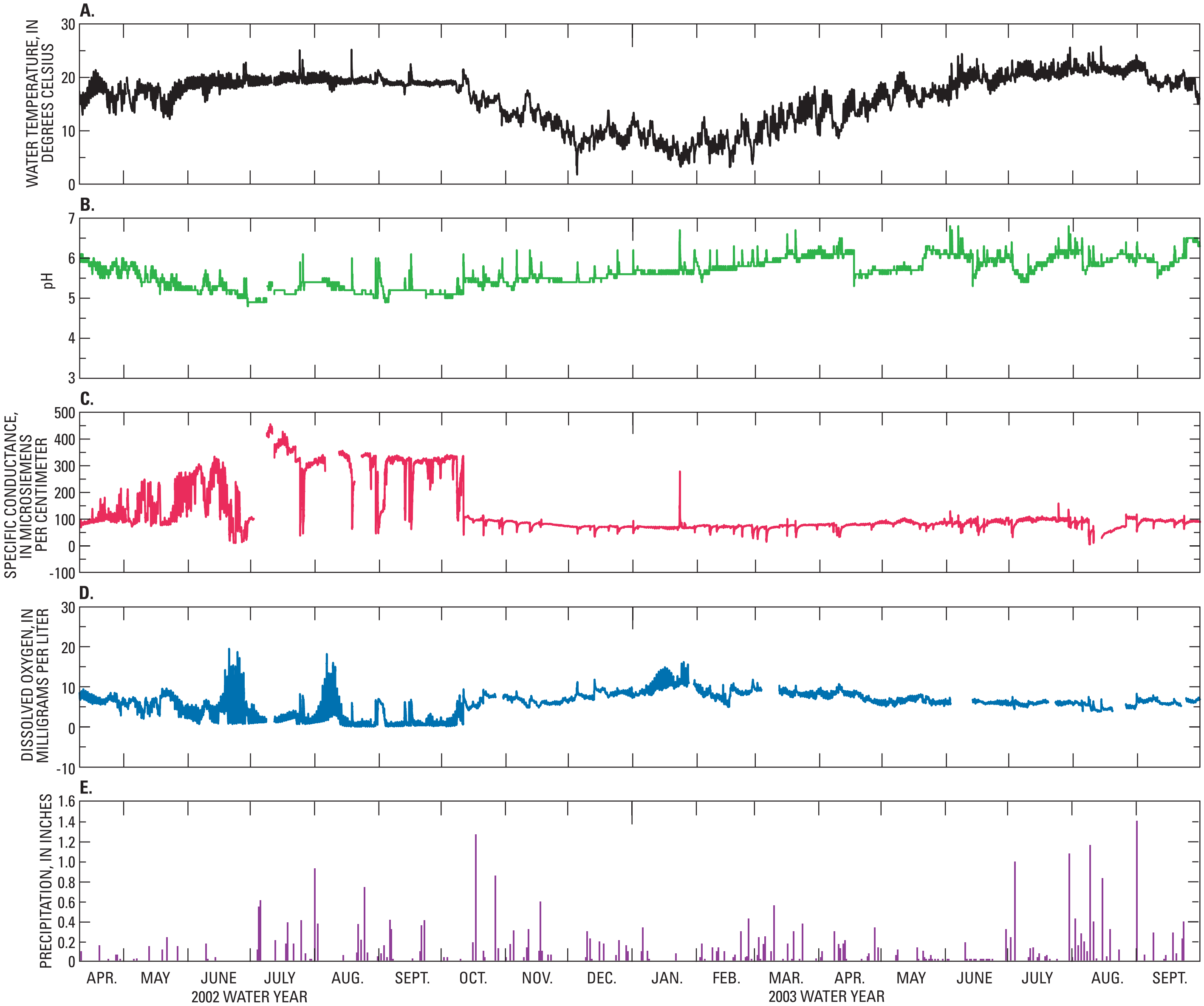


Figure 28. Continuous (15-minute) (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen data in the tributary (station 0208762750); and (E) hourly precipitation data at the climate station at the Lake Wheeler Road research station, North Carolina, April 2002 through September 2003. (Gaps indicate missing data.)

Water Temperature

The seasonal pattern of shallow regolith ground-water temperature generally was lowest during the winter and highest during the fall, indicating a delay compared with air temperature. Concurrent measurements of air temperature at the climate station and shallow ground-water temperature recorded in well MW-1S were available (fig. 29). The lowest ground-water temperatures occurred about 1.5 months after the lowest air temperatures, and the highest ground-water temperatures occurred about 2 months after the highest air temperatures (fig. 29).

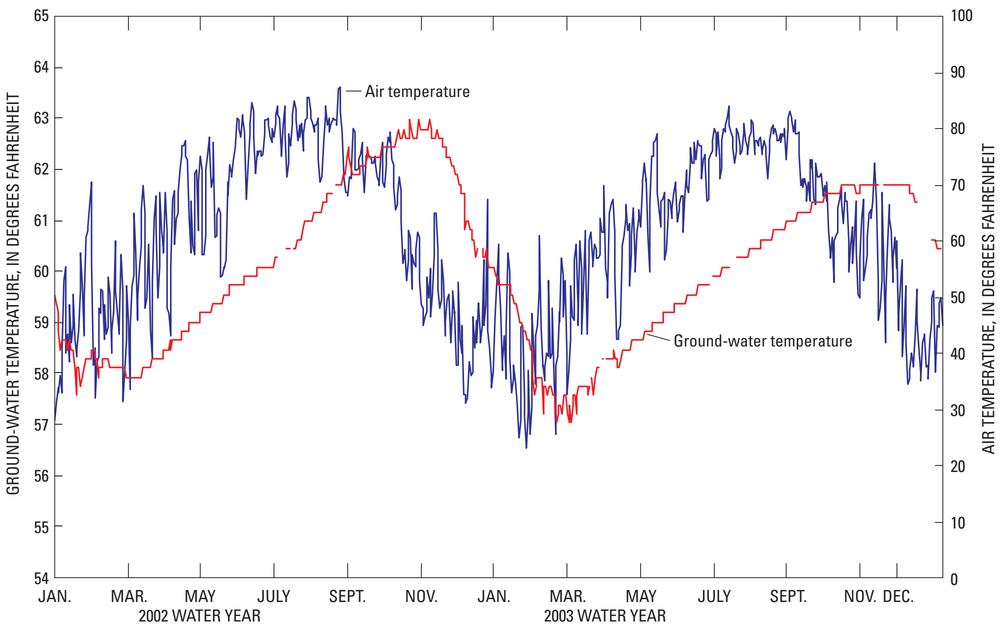


Figure 29. Daily ground-water temperature recorded in regolith well MW-1S in relation to daily air temperature at the climate station at the Lake Wheeler Road research station, North Carolina, January 2002 through December 2003. (Gaps indicate missing data.)

The magnitude of seasonal ground-water temperature fluctuations were substantially less with increasing depth at the LWRRS. Temperatures in the shallow regolith well MW-1S fluctuated about 3° per year (fig. 24A), but water temperatures in the bedrock well MW-1D did not fluctuate (fig. 26A; table 5). Temperatures in the intermediate zone of the regolith (well MW-1I) fluctuated only a few tenths of a degree (fig. 25A).

pH

The pH of ground water in the shallow regolith, transition zone, and bedrock is slightly acidic to acidic, and pH values generally increase with depth (table 5). The lower pH values in shallow zones likely are the result of infiltration of acidic precipitation and the presence of carbonic acid (produced when carbon dioxide from decaying organic matter dissolves in the water table (Drever, 1988)).

Surface water, rainfall (State Climate Office of North Carolina, 2004), and ground water all had similar pH values during the study period. The pH in the tributary was similar to but slightly higher than the pH of the shallow regolith ground water (well MW-1S (figs. 24B, 28B)). The higher pH in the tributary most likely resulted from the uptake of sulfate from biological activity (Drever, 1988). Daily fluctuations were observed in correlation with photosynthetic activities and temperature. The highest pH occurred in the afternoon at the height of photosynthetic activity (warmest temperature), and the lowest values occurred in early morning during plant respiration.

Specific Conductance

As with pH, SC in the ground water generally increased with depth. Daily mean SC for the shallow regolith well MW-1S and intermediate-zone well MW-1I were similar, ranging from about 120 to 258 microsiemens per centimeter at 25° Celsius (µS/cm; figs. 24C, 25C). The higher readings for the regolith well were recorded during rainfall, apparently in response to interaction with deeper ground water. A conceptual model of this deeper ground-water interaction would include a short-term upward mixing of ground water from the transition zone in the discharge area.

The highest SC values (typically more than 600 µS/cm) were recorded in bedrock well MW-1D (fig. 26C) and transition-zone well MW-1DUZ (fig. 27C). In MW-1DUZ, the high SC values may have been affected by elevated ammonia concentrations. The source of ammonia is unknown but most likely is related to agricultural practices (animal operations and crop fertilization) at the study site. In MW-1D, high SC values were affected by ammonia and possibly grout, as indicated by elevated alkalinity and concentrations of calcium and sulfate.

Specific conductance values recorded at the tributary site reflect both runoff and base-flow influences. During the drought in water year 2002, daily mean SC values were high, generally ranging from 26 to 436 µS/cm, which are similar to the SC values in the shallow and intermediate-zone ground water in the regolith (figs. 24C, 25C, 28C). During above-average rainfall that occurred in water year 2003, however, SC values generally were less than 100 µS/cm. Daily fluctuations were noted during the growing season as biological activity increased. The highest daily SC readings were observed in the afternoon during peak temperature and photosynthetic activity.

Dissolved Oxygen

Dissolved oxygen (DO) concentrations in the MW-1 cluster wells decreased with depth. In the shallow and intermediate-zone regolith wells, DO concentrations ranged from about 2 to 4 milligrams per liter (mg/L), representing aerobic conditions, whereas DO concentrations in the deeper transition-zone (MW-1DUZ) and bedrock (MW-1D) wells usually were less than 1 mg/L, representing anaerobic conditions (table 5; figs. 24D–27D). The higher DO concentrations in shallow and intermediate-zone regolith wells indicate a more direct interaction with precipitation. In wells MW-1S and MW-1I, DO concentrations decreased during the drier months when recharge decreased and ground water with lower DO concentrations was more dominant. The lower DO concentrations in the deeper zones may be related to the presence of elevated nutrient concentrations and associated denitrification processes.

The tributary site had daily mean DO concentrations ranging from 0.3 to 12 mg/L (table 5; fig. 28D). Diurnal fluctuations in instantaneous DO concentrations were most pronounced during summer 2002 when biological activity was high. The highest DO readings occurred in the afternoon and, thus, were likely associated with photosynthetic activity by aquatic vegetation. Daily fluctuations in instantaneous DO concentrations of as much as 15 mg/L were observed during the summer (fig. 28D), most likely a result of algal activity in pooled water during low flow.

Response During Rainfall

Continuous water-quality monitoring data provide insight into the processes and interactions of components of the ground-water system during rainfall (recharge). Water levels in all wells in cluster MW-1 rise during rainfall (see Ground-Water Levels section of this report). This water-level rise may be a result of interaction with and hydraulic response to the nearby surface-water boundary.

From the continuous water-quality data recorded at the LWRRS study area, specific trends and responses during large rainfall events were observed. This was especially evident during water year 2002, the last year of a 4-year drought in the area, when dilution from rainfall was minimal and the ground-water components were dominant. For example, the water-quality data from regolith well MW-1S generally indicated increased pH and SC, and decreased DO in response to large rainfall events. This response is more typical of deeper ground water, which indicates that the most likely cause of this response is from upward mixing of water from deeper transition-zone fractures in the discharge area. In transition-zone well MW-1DUZ and bedrock well MW-1D, SC values decreased during large rainfall events, likely from interaction with more dilute surface water. Water-temperature fluctuations in regolith well MW-1S during rainfall indicate that interaction with surface water is likely during high-stage levels in the tributary.

January 2002 Rainfall

During January 2002, as winter recharge began, water-quality properties in shallow regolith well MW-1S had short-term responses to three notable rainfall events (total of 4.83 inches; fig. 30A–C). The responses in this well were consistent during all three rainfall events: pH and SC increased (fig. 30A, B), and DO and temperature decreased (fig. 30B, C). In general, infiltrating rainfall typically interacts with ground water by increasing the DO, lowering the SC, lowering the water temperature (if the air temperature is cooler than the ground-water temperature), and potentially lowering the pH. At the climate station, the pH of rainwater ranged from 4.3 to 5.0 in January 2002 (National Atmospheric Deposition Program, 2002), only slightly lower than the pH of the shallow ground water. In this example, however, most notably with SC and pH increasing and DO decreasing, the responses in MW-1S during rainfall indicate an interaction with deeper ground water (fig. 30D), in which pH and SC values are higher and DO concentrations are lower. This interaction most likely occurs in the transition-zone fractures near the top of bedrock, similar to those observed in well MW-1DUZ. The upward gradient between the transition zone and regolith in this ground-water discharge area, conceptually, would support a mechanism for this type of interaction. Additionally, the sharp rise in water levels in well MW-1D (open borehole including transition-zone fractures) indicates that the decrease in temperature recorded in regolith well MW-1S during rainfall (fig. 30B) most likely indicates a second process, interaction with colder surface water, as direct infiltration of rainwater likely would occur at a much slower rate.

August–September 2002 Rainfall

A similar response in the ground-water system occurred during a large rainfall event in August–September 2002 (fig. 31). From August 31 to September 1, 2002, 2.89 inches of rainfall occurred at the study site, resulting in notable inflections in water-quality monitoring data. Water levels in all four zones — regolith (MW-1S), intermediate (MW-1I), transition (MW-1DUZ), and lower bedrock (MW-1DLZ) — rose during this rainfall event. (Water-quality data for the regolith intermediate-zone well MW-1I were not available because of probe malfunctions.) In well MW-1S, the pH, temperature, and SC increased (fig. 31A, B), and the DO decreased (fig. 31C). The pH of rainwater collected from August 27 through September 3 at the climate station was 5.11 (National Atmospheric Deposition Program, 2002), slightly lower than the pH of shallow ground water. As occurred during rainfall in January 2002, the increase in pH and SC and the decrease in DO indicate interaction with deeper ground water in the transition-zone fractures (well MW-1DUZ, fig. 31D). Additionally, the increase in temperature recorded

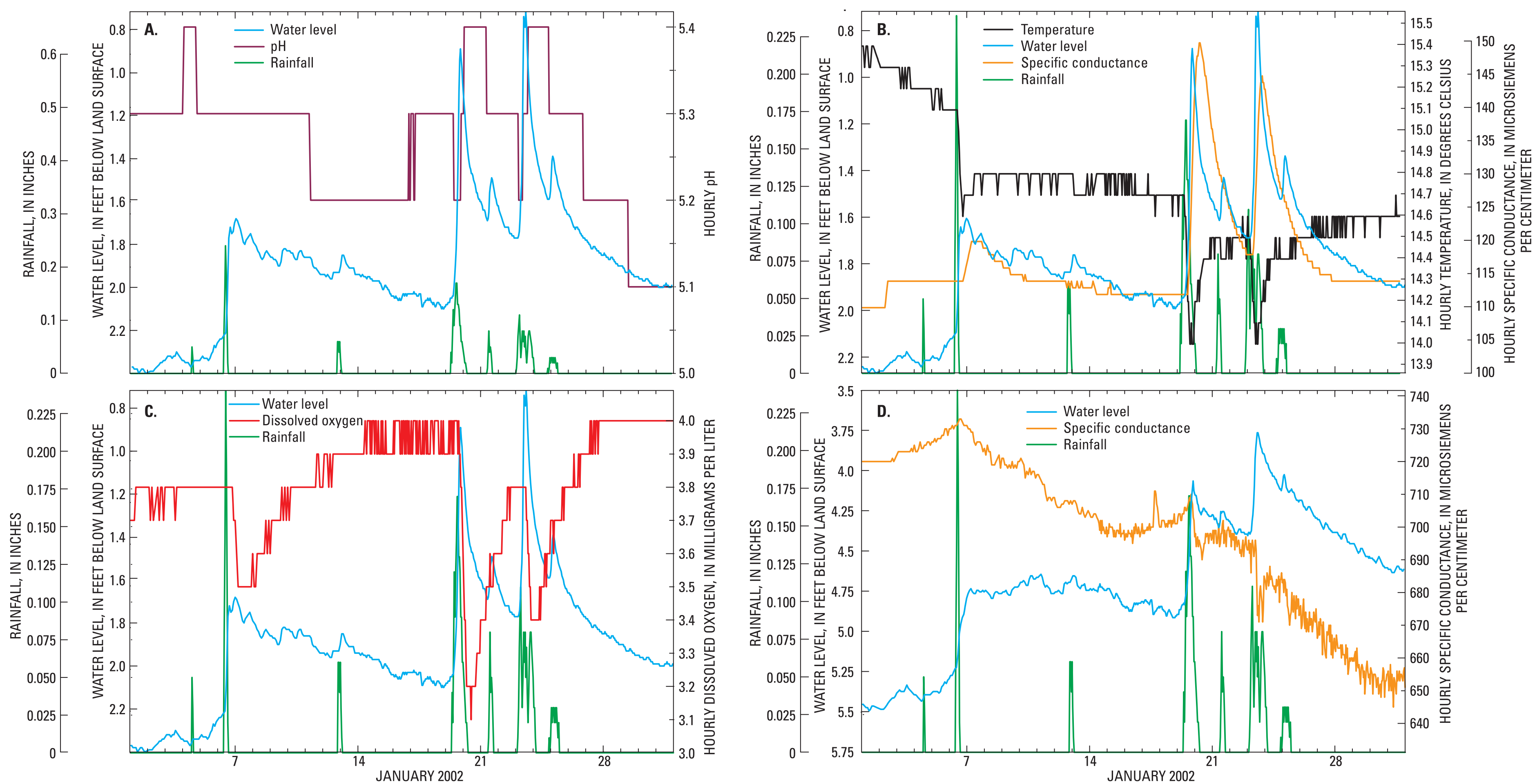


Figure 30. Response of (A) pH, (B) temperature and specific conductance, and (C) dissolved oxygen in regolith well MW-1S; and (D) specific conductance in bedrock well MW-1D to rainfall in January 2002 at the Lake Wheeler Road research station, North Carolina.

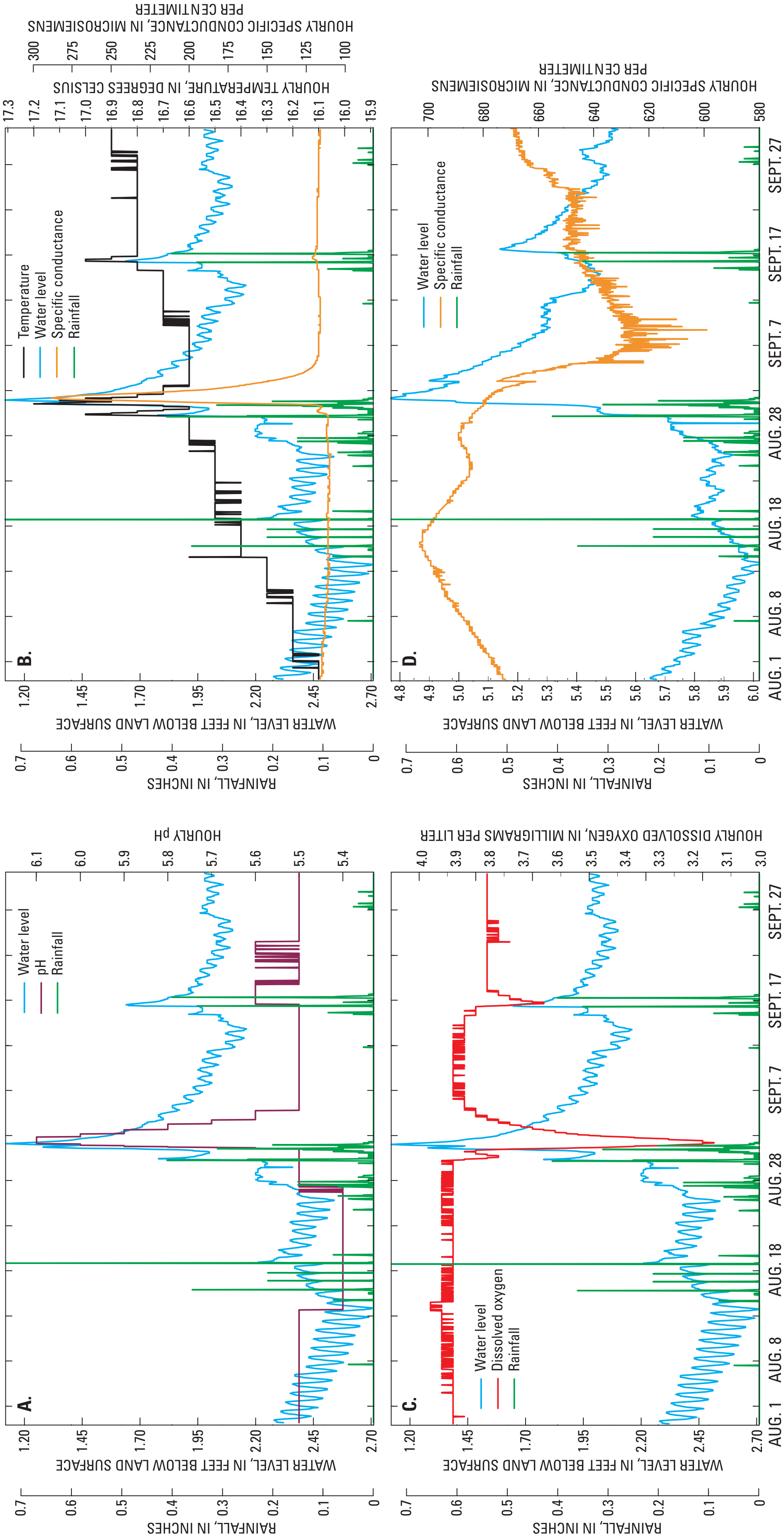


Figure 31. Response of (A) pH, (B) temperature and specific conductance, and (C) dissolved oxygen in regolith well MW-1S; and (D) specific conductance in transition zone well MW-1DUZ to rainfall during August–September 2002 at the Lake Wheeler Road research station, North Carolina.

in regolith well MW-1S during rainfall (fig. 31B) most likely indicates interaction with warmer surface water.

Results from Periodic Water-Quality Sampling Events

Water-quality samples were collected periodically from wells and the tributary site to characterize the water chemistry in wells completed in a felsic gneiss rock type. Results of analyses of water-quality data collected during four sampling events are listed in table 4 and published in Howe and others (2002, 2003). Samples were analyzed for major ions, nutrients, metals, and radon 222 (gas) concentrations and gross alpha activity (table 4). All of the 11 monitoring wells were sampled during the three latter periodic sampling events (November 2001, May 2002, and November 2002); the tributary site was sampled during the latter two sampling events (May and November 2002).

One of the objectives of this study was to compare ground-water-quality data from each water-bearing zone of the ground-water system—the regolith, transition zone, and bedrock. Physical properties measured during periodic sampling events provide a means of comparing geochemical conditions. Generally, observations of trends in physical property measurements made during periodic sampling events were similar to the continuous-monitoring data recorded during the study period (table 5). Comparisons of the range of physical property values recorded and major ion concentrations are shown in the box plots in figures 32–34. Water-quality sampling results presented in this report are representative of agricultural areas in similar hydrogeologic settings.

The standard graphical tools used for the geochemical comparison of ground-water-quality data are Piper trilinear diagrams and Stiff diagrams. The Piper diagram is a multiple-trilinear diagram that segregates analytical data with respect to dissolved major cations and anions in ground water (Piper, 1953). The Stiff diagram is used to display dominant cations and anions (Stiff, 1951). If the ion balance in a sample was determined to be within 10 percent, the data were accepted and analyzed using these diagrams. Figures 35 and 36 display Piper and Stiff diagrams, respectively, for each compartment of the ground-water system in the study area. Specific wells and dates of sampling used for box plots in figures 32–34 are listed on the Piper diagrams in figure 35. The Piper diagrams (fig. 35) include all samples not affected by grout migration except for samples from wells MW-1D and MW-1DUZ, which are presented to document elevated ammonia concentrations. The Stiff diagrams (fig. 36) depict data collected during May 2002, selected as previously stated.

Field properties measured during periodic sampling events were similar to those measured continuously. In the shallow and intermediate zones in the regolith, pH and SC were lower and DO was higher than in the deeper transition zone and bedrock (fig. 32). Concentrations of dissolved

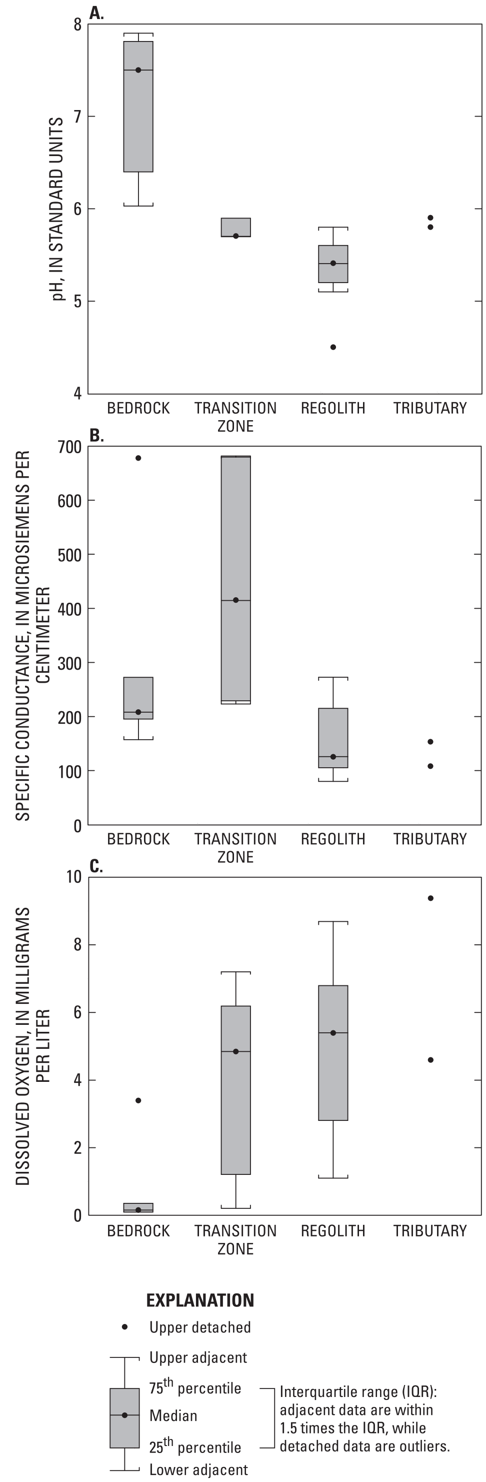


Figure 32. The range, median, and quartile statistical values for (A) pH, (B) specific conductance, and (C) dissolved oxygen data collected from the wells and tributary site during periodic sampling events at the Lake Wheeler Road research station, North Carolina.

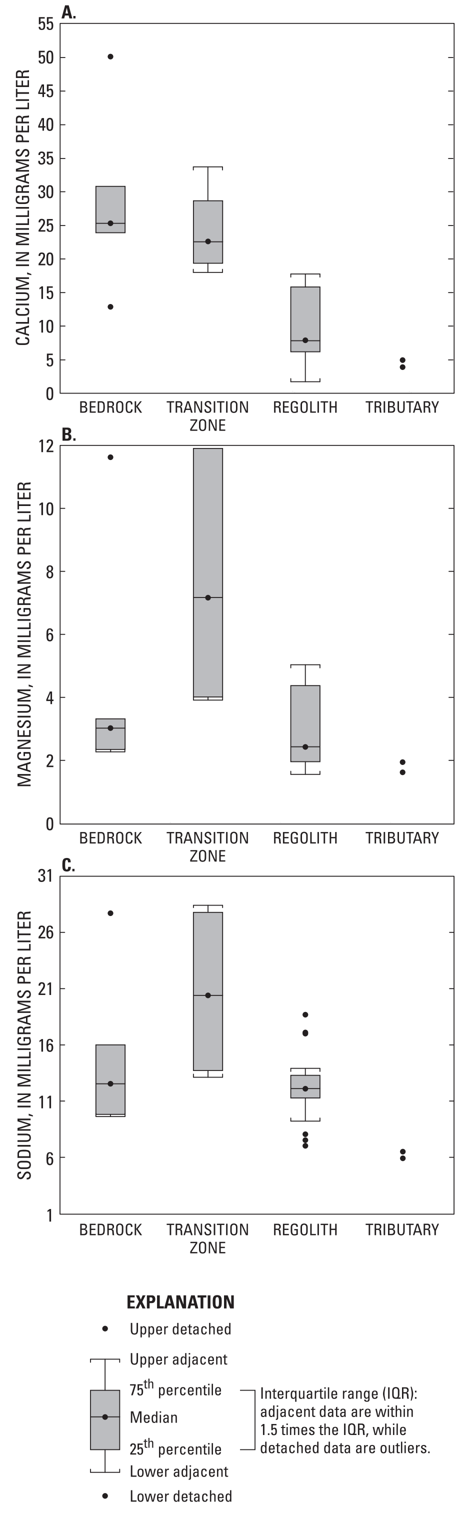


Figure 33. The range, median, and quartile statistical values for (A) calcium, (B) magnesium, and (C) sodium data collected from the wells and tributary site during periodic sampling events at the Lake Wheeler Road research station, North Carolina.

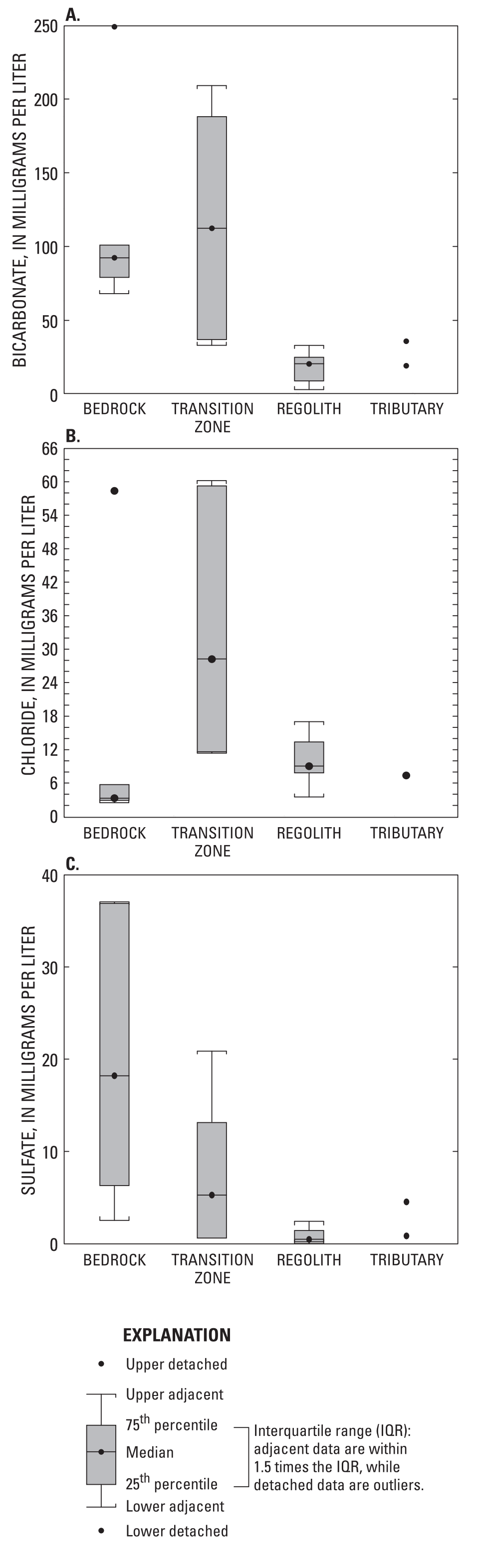
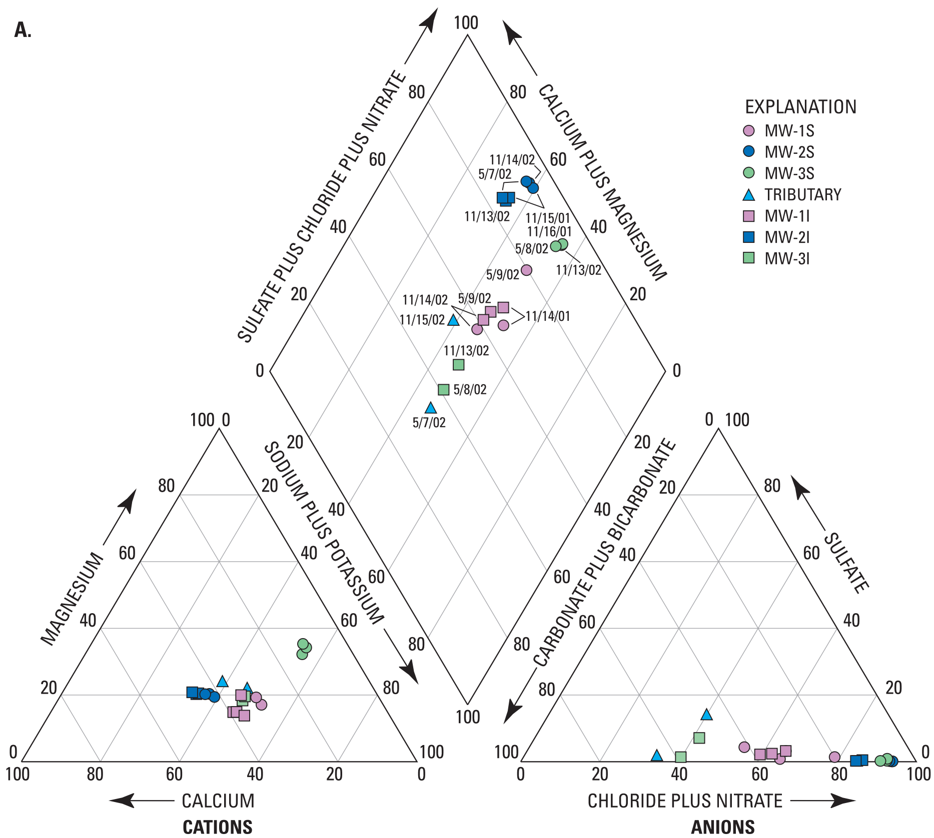


Figure 34. The range, median, and quartile statistical values for (A) bicarbonate, (B) chloride, and (C) sulfate data collected from the wells and tributary site during periodic sampling events at the Lake Wheeler Road research station, North Carolina.



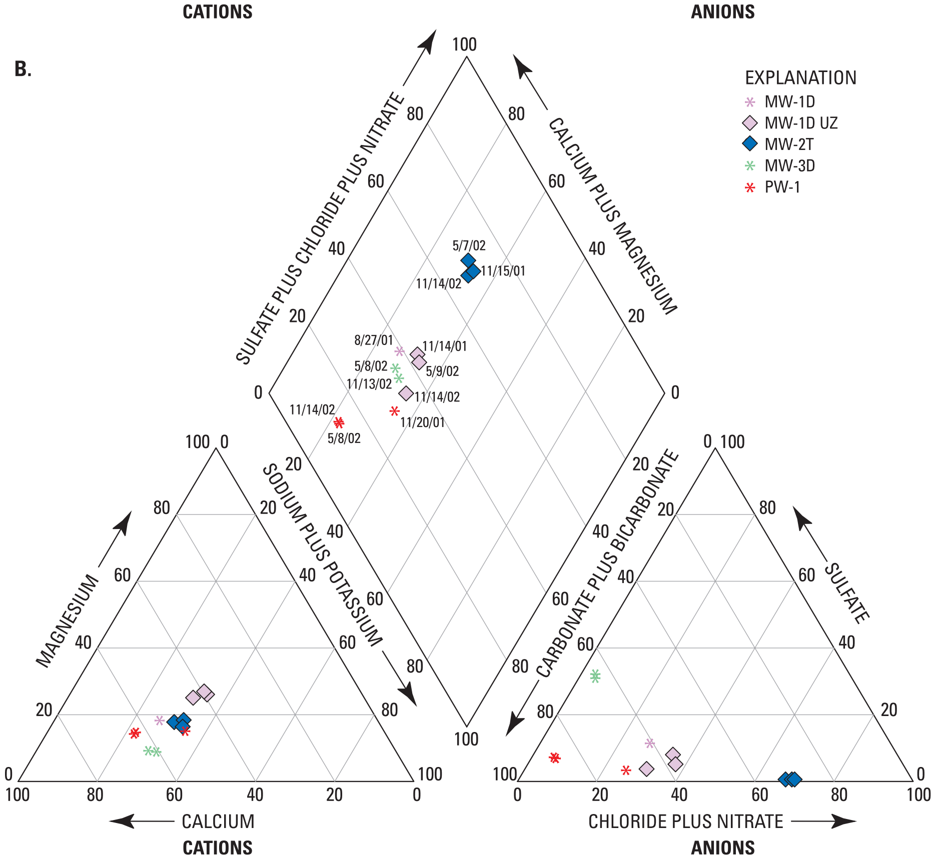


Figure 35. The water chemistry of samples from the (A) regolith and intermediate-zone wells, and the tributary site, and (B) transition-zone and bedrock wells at the Lake Wheeler Road research station, North Carolina.

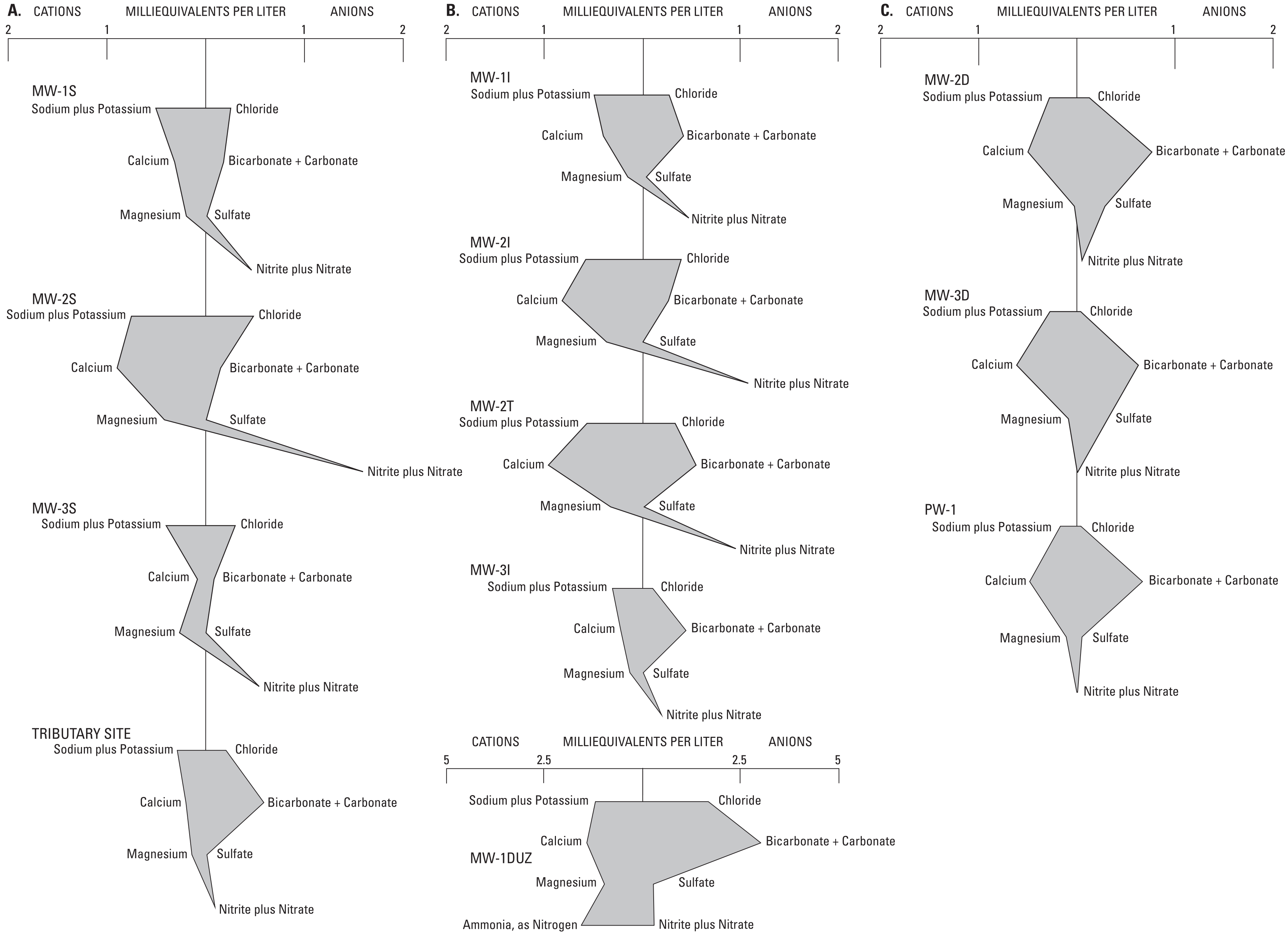


Figure 36. Major ion milliequivalents in water samples collected from (A) the regolith wells and the tributary site, (B) the intermediate-zone and transition-zone wells, and (C) the open-borehole bedrock wells at the Lake Wheeler Road research station, North Carolina, May 2002.

cations and anions also were lower in the regolith compared with deeper parts of the ground-water system (figs. 33, 34).

Quality of Water in the Shallow and Intermediate-Zone Regolith and the Tributary

Constituent concentrations in samples collected from the discharge area (MW-1 cluster wells) and from the tributary site were more variable than in samples from well clusters MW-2 and MW-3 (fig. 35A). This variation, similar to water-level fluctuations, may be the result of ground-water and surface-water interaction in the ground-water discharge area. In general, ground water in the regolith is a sodium-potassium/bicarbonate-nitrate type, and water from well MW-1S is similar in composition to surface water at the tributary site (fig. 36A). Regolith ground water had elevated concentrations of nitrate during the study period, especially in well MW-2S (table 6; fig. 36A).

Major ion concentrations in samples collected from the regolith wells at the LWRRS were variable (figs. 33, 34, 35A). The dominant cations were sodium-potassium in all samples except those from well MW-2S, which had similar milliequivalent concentrations of calcium and sodium-potassium (fig. 36A). The dominant anion was nitrate in the shallow regolith wells (fig. 36A; table 6), indicating the possible effects of agricultural practices. The surface-water samples consistently were sodium-bicarbonate type water. Stiff diagrams of analytical results of samples collected from well MW-1S and the tributary site in May 2002 indicate an overall similarity in chemical composition, although bicarbonate was more dominant in the tributary. Elevated chloride concentrations also were most likely a result of agricultural practices, including animal operations and crop fertilization.

Quality of Transition-Zone Ground Water

Ground-water quality in individual transition-zone wells was relatively consistent on all dates that samples were collected (fig. 35B, 36B). The composition of ground water from this zone generally was similar to that from the regolith (including the intermediate zone), although calcium concentrations increased with depth (fig. 33). The water type of samples from the transition zone was either sodium-potassium/bicarbonate-nitrate or calcium/bicarbonate-nitrate. Also, similar to the regolith ground water, most samples from this zone had elevated nitrate concentrations, and the MW-2 cluster wells had the highest concentrations (table 6).

Table 6. Dissolved concentrations of nitrite plus nitrate and ammonia in water samples collected periodically from wells and the tributary site at the Lake Wheeler Road research station, North Carolina.

[mg/L, milligrams per liter; <, less than; —, not analyzed]

Station name	Date sampled	Nitrite (NO_2) plus nitrate (NO_3), as nitrogen (mg/L)	Ammonia, as nitrogen (mg/L)
MW-1S	8/27/2001	5.6	0.03
MW-1S	11/14/2001	5.9	0.03
MW-1S	5/9/2002	6.4	0.03
MW-1S	11/14/2002	5.6	0.03
MW-1I	8/27/2001	6.7	0.05
MW-1I	11/14/2001	6.1	<0.04
MW-1I	5/9/2002	6.5	<0.04
MW-1I	11/14/2002	6.7	0.09
MW-1DUZ	8/27/2001	3.0	22
MW-1DUZ	11/14/2001	3.1	28
MW-1DUZ	5/9/2002	4.0	28
MW-1DUZ	11/14/2002	4.8	22
MW-1DLZ	5/9/2002	<0.05	0.10
MW-1DLZ	11/14/2002	<0.60	0.08
MW-2S	11/15/2001	22	<0.04
MW-2S	5/7/2002	22	<0.04
MW-2S	11/14/2002	21	<0.04
MW-2I	11/15/2001	17	<0.04
MW-2I	5/7/2002	15	<0.04
MW-2I	11/14/2002	16	<0.04
MW-2T	11/15/2001	15	<0.04
MW-2T	5/7/2002	13	<0.04
MW-2T	11/14/2002	15	<0.04
MW-2D	5/7/2002	1.9	0.07
MW-2D	11/13/2002	1.4	0.03
MW-3S	11/16/2001	—	<0.04
MW-3S	5/8/2002	7.5	<0.04
MW-3S	11/13/2002	5.9	<0.04
MW-3I	11/16/2001	3.0	<0.04
MW-3I	5/8/2002	2.7	<0.04
MW-3I	11/14/2002	2.7	<0.04
MW-3D	11/16/2001	0.04	<0.04
MW-3D	5/8/2002	<0.05	<0.04
MW-3D	11/13/2002	0.06	<0.04
PW-1	11/20/2001	3.4	0.03
PW-1	5/8/2002	0.26	<0.04
PW-1	11/14/2002	<0.06	<0.04
Tributary site	5/7/2002	1.4	0.07
Tributary site	11/15/2002	0.88	0.10

As in the regolith wells, higher concentrations of chloride can be correlated with nitrate concentrations as another indication of the proximity of a nutrient source.

Quality of Bedrock Ground Water

The water type of samples from the open-borehole bedrock wells was generally calcium-bicarbonate (figs. 35B, 36C). The bedrock ground-water samples were collected near the most dominant fracture zone tapped by the well. Unlike the regolith and transition-zone wells, nitrate did not dominate the water chemistry in the bedrock wells (fig. 36C; table 6). A comparison of the physical properties of the shallow (regolith and transition zone) and deeper (bedrock) parts of the ground-water system indicated an increase in pH (fig. 32A) and lower DO concentrations (fig. 32C) with depth. Analytical results indicate that samples from the bedrock wells had higher concentrations of fluoride, calcium, sulfate, molybdenum, uranium, radon, and arsenic (Howe and others, 2002, 2003) than the shallower wells. Samples from bedrock wells also had higher SC and bicarbonate than those collected from regolith wells (figs. 32B and 34A, respectively), which supports the concept of increased residence time for mineral dissolution in the felsic gneiss.

Nutrients

Elevated nutrient concentrations were detected in most of the wells at the LWRRS (table 6). These elevated concentrations most likely are related to agricultural practices, including animal operations and crop fertilization. A history of agricultural practices was not known at the time of this report preparation. Nitrate levels in ground water from agricultural areas near Raleigh may be as high as 4–5 mg/L (Mr. Rick Bolich, North Carolina Division of Water Quality, written commun., 2004). Background nitrate levels for Wake County range from 0.29 to 0.74 mg/L (Daniel and Dahlen, 2002).

Samples from the regolith and transition-zone wells in cluster MW-2 (fig. 4) had the highest nitrate concentrations, ranging from 13 to 22 mg/L (fig. 37; table 6). Samples from the transition-zone well MW-1DUZ had elevated concentrations of ammonia (ammonium ion, NH^{4+}), ranging from about 22 to 28 mg/L (table 6). Concentrations of nitrate

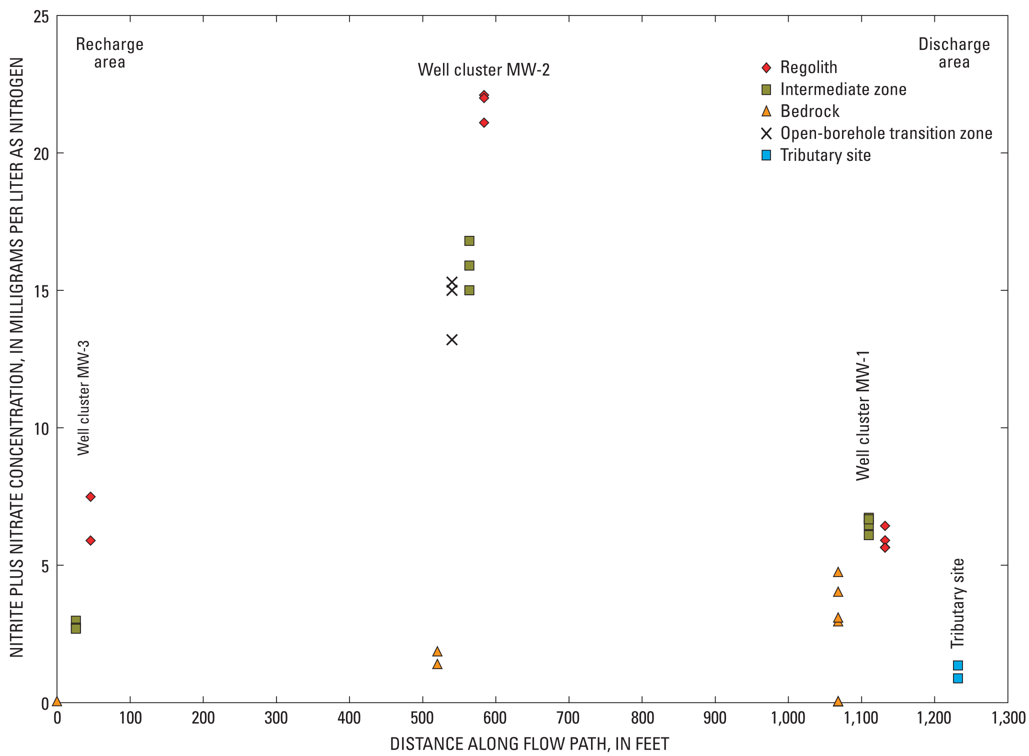


Figure 37. Variation in nitrite plus nitrate concentrations in water samples collected along the well transect and at the tributary site at the Lake Wheeler Road research station, North Carolina.

generally were lower in bedrock wells in each cluster (table 6). Figure 37 shows nitrate concentrations along the well transect from well cluster MW-3 (recharge area) toward well cluster MW-1 (discharge area) and at the tributary site. The high nitrate concentrations near well cluster MW-2 indicate a close proximity to a source area. Because the source areas and history of agricultural practices near the study site are unknown at the time of this reporting, these data are not discussed here in more detail. The higher concentrations of nitrate in the shallow part of the ground-water system supports reduced connection with the deeper part of the system at the study site.

Radiochemicals and Radon Gas

Radiochemicals and radon gas are of interest because natural concentrations can be high in igneous and metamorphic rocks. The concentration of radon gas in ground water has been the subject of much consideration by the U.S. Environmental Protection Agency in establishing public health guidelines. The proposed Federal standards for public drinking-water supplies do not require treatment if radon concentrations are 300 picocuries per liter (piC/L) or lower; however, treatment is required to reduce radon if concentrations are 4,000 piC/L or higher (U.S. Environmental Protection Agency, 2000a). Many of the water samples collected at the LWRRS had radon concentrations that exceeded 4,000 piC/L (Howe and others, 2002, 2003). Concentrations of radon 222 are similar in the bedrock and transition-zone wells. Gross alpha concentrations did not exceed the recommended drinking-water standard of 15 piC/L (U.S. Environmental Protection Agency, 2000b; Howe and others, 2002, 2003; North Carolina Department of Environment, Health, and Natural Resources, 1979). Additionally, following the aquifer test in well PW-1 in April 2002, radon decreased and gross alpha concentrations increased in the pumped well (Howe and others, 2002, 2003). Radon 222 (gas) concentrations increased along the well transect toward the discharge area near well cluster MW-1 (fig. 38). Concentrations of radon 222 gas were higher in the intermediate zone in well clusters MW-1 and MW-2.

Comparisons with Regional Ground-Water-Quality Data

To gain a perspective of how water-quality data from the LWRRS compares with regional water quality, a summary of analytical data for bedrock wells tapping the Raleigh Gneiss was compiled from USGS data, primarily collected in 1963 as part of the study by May and Thomas (1968), and NCDENR data (paper files) collected by the DWQ Raleigh Regional Office. The data include major ion concentrations,

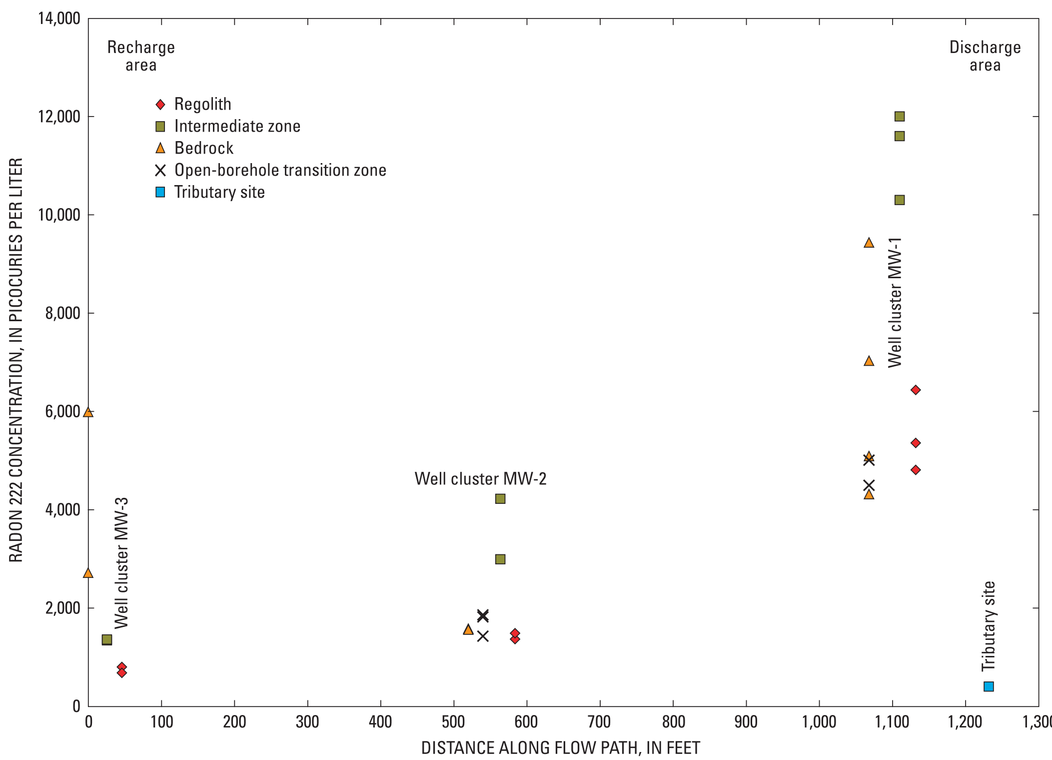


Figure 38. Variation in radon 222 gas concentrations in water samples collected along the well transect and at the tributary site at the Lake Wheeler Road research station, North Carolina.

pH, and SC. Locations of the sampled wells were confirmed to be within the felsic gneiss (GNF) hydrogeologic unit (Daniel and Payne, 1990). A mass balance calculation of cations and anions was made to assure data quality. If the balance was determined to be within 10 percent, the data were accepted. In all, 14 regional data points were used for this analysis.

In general, historical ground-water-quality data compiled for locations in the GNF unit were comparable to the water-quality data for the LWRRS samples (fig. 39). Variability in water types may be the result of local differences in rock composition and possibly land use. The bedrock ground-water composition trends from a calcium-bicarbonate type, similar to the samples from wells PW-1, MW-1D, MW-2D, and MW-3D (figs. 35B, 36C, 39), to a sodium-bicarbonate type. Effects from well construction and the quality assurance of laboratory procedures could not be determined for the historical ground-water-quality data.

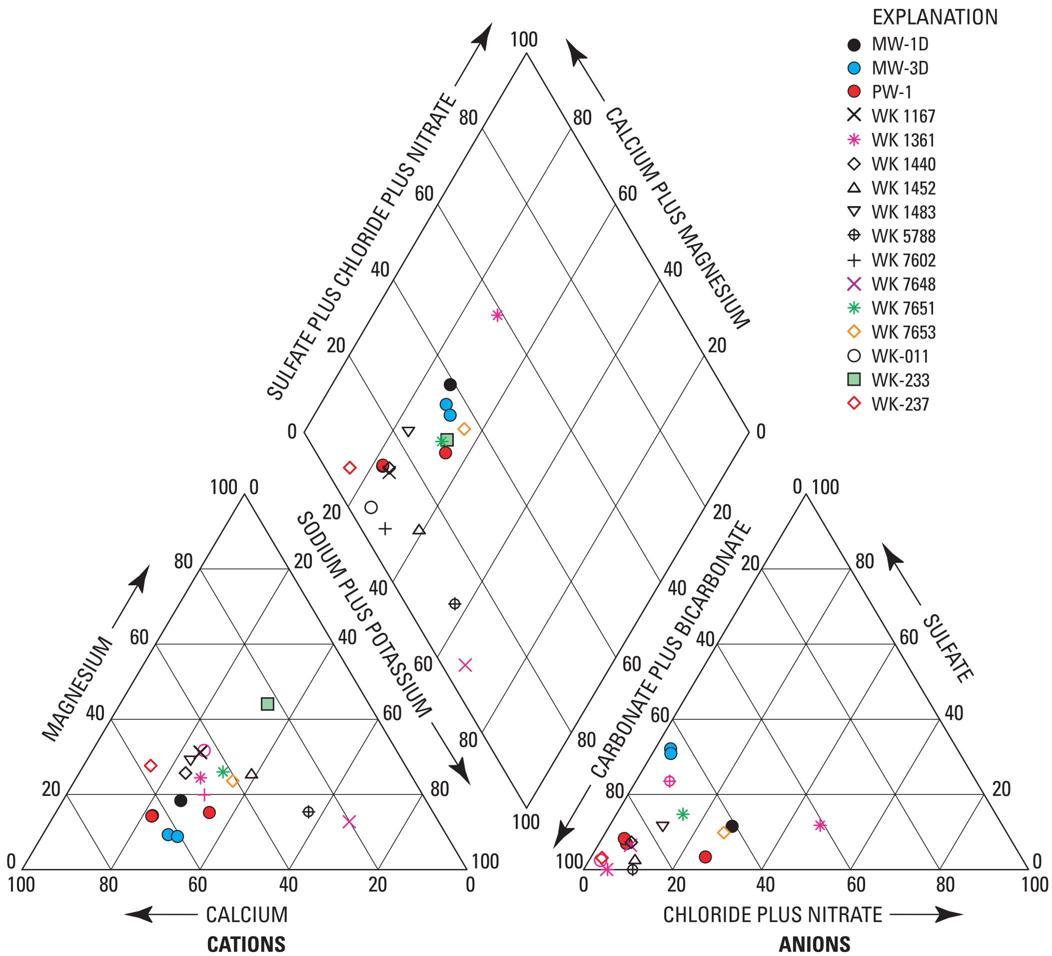


Figure 39. Major ion distribution in regional ground-water samples collected from Raleigh Gneiss bedrock wells in North Carolina.

Comparison to Rock Chemistry

The North Carolina Geological Survey (NCGS) conducted whole-rock geochemical analyses on the bedrock core samples collected from all three coreholes at the LWRRS. Results of the core analyses of bedrock ground-water samples are listed in table 7. The dominant major ion species in core samples from the LWRRS biotite gneiss and granitic gneiss were silicon dioxide (63 percent), followed by aluminum oxide (15 percent), iron oxide (6 percent), calcium oxide (5 percent), and sodium oxide (3 percent; fig. 40; table 7; Mr. Tyler Clark, North Carolina Geological Survey, written commun., 2003). These data compare favorably with regional samples collected from surface outcrops of Raleigh Gneiss in Wake and Franklin Counties, N.C. (Dr. David Blake, University of North Carolina at Wilmington, written commun., 2003). Ground-water samples collected from the wells contained dissolved species resulting from dissolution of the bedrock minerals.

Table 7. Analytical results of average whole-rock core composition from the bedrock and average dissolved major ion concentrations in bedrock ground-water samples collected at the Lake Wheeler Road research station, North Carolina.

[%, sample weight percentage; ppm, parts per million; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Composition of whole-rock core[a]		Major ion concentrations in ground-water samples	
Species	Weight, in percent (%) or concentration (ppm)	Dissolved ion	Concentration (mg/L or µg/L)
SiO_2	62.8%	Silica	27.2 mg/L as SiO_2
Al_2O_3	14.9%	Aluminum	5.2 µg/L as Al
CaO	5.1%	Calcium	23.6 mg/L as Ca
MgO	3.3%	Magnesium	2.8 mg/L as Mg
Na_2O	3.3%	Sodium	12.1 mg/L as Na
K_2O	2.9%	Potassium	2.7 mg/L as K
Fe_2O_3	6.1%	Iron	13.0 µg/L as Fe
MnO	0.1%	Manganese	46.2 µg/L as Mn
Cr_2O_3	0%	Chromium	< 0.8 µg/L as Cr
Ag	< 1 ppm	Silver	< 1 µg/L as Ag
Ba	753.6 ppm	Barium	21.4 µg/L as Ba
Co	20.0 ppm	Cobalt	0.1 µg/L as Co
Cu	17.6 ppm	Copper	0.5 µg/L as Cu
Mo	< 2 ppm	Molybdenum	18.7 µg/L as Mo
Ni	29.3 ppm	Nickel	0.9 µg/L as Ni
Sn	1.7 ppm	Antimony	0.3 µg/L as Sn
U	2.5 ppm	Uranium	21.9 µg/L as U
Zn	96.3 ppm	Zinc	66.3 µg/L as Zn

[a]Mr. Tyler Clark, North Carolina Geological Survey, written commun., 2003.

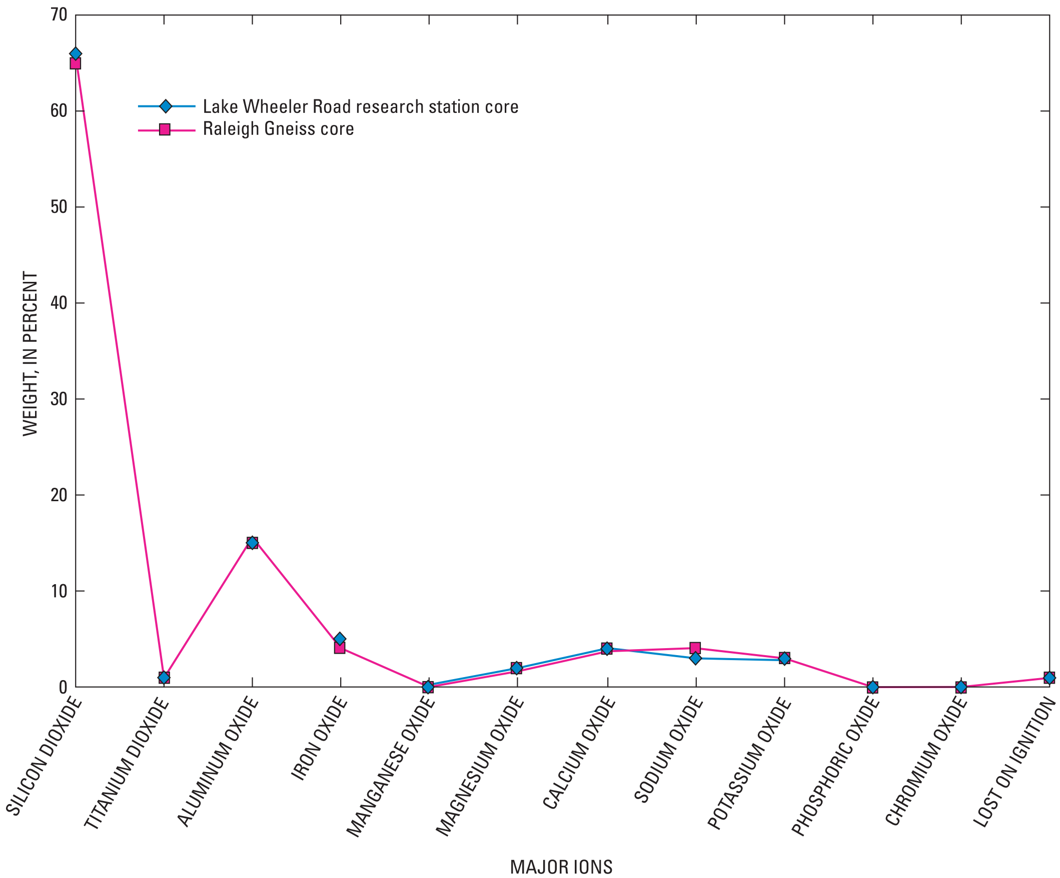


Figure 40. Average weights of major ion and trace metal species in regional whole-rock samples of Raleigh Gneiss and in core samples from the Lake Wheeler Road research station, North Carolina.

Summary and Conclusions

The Lake Wheeler Road research station (LWRRS) in Wake County, North Carolina, is representative of the felsic gneiss hydrogeologic unit in the Piedmont Physiographic Province. The hydrogeologic setting at this site is distinguished by the effects of steeply dipping foliation. The regional geologic unit represented is the Raleigh Gneiss within the Raleigh Belt, a north-northeast trending belt that extends through Wake, Vance, Warren, and Franklin Counties, North Carolina. At the study site, dominant rock types consist of biotite gneiss and granitic gneiss. Foliation strikes N. 10° E. to N. 30° E. and N. 20° W. to N. 40° W., dipping 70° to 80° SE. and NE., respectively, to depths of about 400 ft, shifting to a strike of N. 70° E. to N. 80° E., dipping 70° to 80° SE. from 400 to 600 ft in depth.

Although the rock types are interlayered (biotite gneiss and granitic gneiss) at the LWRRS and land-surface altitude varied more than 40 ft, depth to bedrock and the transition zone was fairly consistent across the study area. Depth to bedrock ranged from about 67 to 77 ft below land surface. Thickness of the regolith ranged from about 42 to 50 ft below land surface. Steeply dipping foliation may contribute to this relatively consistent weathering profile.

Overall, most fractures encountered at the LWRRS were classified as one of three types: (1) shallow, transition-zone stress-relief fractures (dip of less than 30°, opened from the unloading of material as the rock weathers) near the top of bedrock that cross cut foliation and have a dip direction similar to foliation; (2) deeper, low-angle stress-relief fractures that cross cut foliation and have a dip direction similar to foliation; or (3) steeply dipping fractures (dip angle between 70° and 80°) with a strike parallel to foliation. Overall, the transition zone has more open fractures, and the deeper, steeply dipping fractures generally are not considered open but do exhibit chemical weathering at depth.

Ground-water flow at the LWRRS generally supports historical conceptual models developed in earlier studies, but also represents a refinement of those models at the local scale.

General ground-water flow toward a surface-water drainage supports the historical conceptual model. Additionally, the vertical gradient direction at well cluster MW-1 supports the concept of the upward movement of ground water to discharge areas. Vertical gradients in the recharge areas were variable. Near well cluster MW-2, a downward gradient supported the recharge area concept, but water-level altitudes in well cluster MW-3, the highest topographic recharge area, showed a slight upward gradient at depth. Continuous ground-water-level data collected in the discharge area indicate a response to the surface-water boundary. Water levels in the shallow regolith, the transition zone, and the deeper fractured bedrock (the three components forming the ground-water system) mimic the surface-water stage.

Elevated nutrient concentrations were detected in samples collected from most of the wells at the LWRRS. Nitrate (nitrite plus nitrate, as nitrogen) concentrations were as high as 22 mg/L in shallow regolith well MW-2S. Concentrations of ammonia were as high as 28 mg/L in transition-zone well MW-1DUZ. These elevated nutrient concentrations most likely are related to agricultural practices, including animal operations and crop fertilization. A history of agricultural practices was not available at the time of this reporting. The presence of nitrate in the aerobic (higher dissolved oxygen (2–4 mg/L)), shallow (regolith, including the intermediate zone) ground-water system, and ammonia in the deeper, anaerobic (very low dissolved oxygen (0.1 mg/L)) part of the ground-water system (transition zone) indicate the effects of agricultural practices related to animal operations and crop fertilization.

The continuous-monitoring, ground-water-quality data collected at the LWRRS aid in understanding how various components of the ground-water system interact. Evaluation of the response of the water level in well MW-1S in the shallow regolith during rainfall indicates an upward flushing of transition-zone ground water into the overlying regolith in ground-water discharge areas. Dilution of ground water in the transition zone indicates interaction with surface water during high runoff periods.

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Appendixes

Appendix 1. Geologic core descriptions for RAL-1 from the Lake Wheeler Road research station

Appendix 2. Geologic core descriptions for RAL-2 from the Lake Wheeler Road research station

Appendix 3. Geologic core descriptions for RAL-3 from the Lake Wheeler Road research station

Appendix 1. Geologic core descriptions for RAL-1 at the Lake Wheeler Road research station.

REGOLITH LOG SHEET

PROJECT: NCSU Lake Wheeler Road

BORING ID: **RAL-1**

LOGGED BY: Bolich

BEGIN DATE: 12/13/2000

END DATE: 2/19/2001

DRILLING METHOD: wireline coring

CORE DIAMETER: 2.1”

Color descriptions referenced to Munsell soil color charts.

INTERVAL	RECOVERY	DRY/WET	COLOR	UNIFIED CLASS	LAYER	DESCRIPTION
0 TO 7	5.0’	moist	7.5YR 3/2	SM	ALLUVIUM	Brown and yellowish brown SILT and fine to medium SAND; top 0.7 foot abundant organic matter (topsoil); becoming mostly fine micaeous sand; massive.
7 TO 12	1.8’	wet	10YR 6/6	SW	ALLUVIUM	Yellowish brown fine to coarse SAND; little silt; trace mica; homogeneous; well sorted; possible stratified, wet.
12 TO 17	0.2’	wet	2.5Y 7/6	SW	ALLUVIUM	Yellowish brown fine to medium SAND; trace silt; trace mica; sample is poor quality/recovery; loose.
17 TO 22	4.9’	wet	2.5Y 3/3 to 2.5Y 7/4	SM	SAPROLITE	Dark yellowish brown to greyish brown SILT, FINE SAND, and VERMICULITE; occasional MnO staining; very poorly preserved rock texture with relict foliation nearly vertical in orientation.
22 TO 27	0’	wet	2.5Y 6/3	SM	SAPROLITE	Yellowish brown fine to medium SAND; trace silt; no sample recovery in core barrel; sample taken from mud tub.

UNIFIED CLASS: SM, silty sands, sand-silt mixtures; SW, well-graded sands, gravelly sands, little or no fines (ASTM International, 2004).

Appendix 1. Geologic core descriptions for RAL-1 at the Lake Wheeler Road research station.—Continued

REGOLITH LOG SHEET

PROJECT:	NCSU Lake Wheeler Road
BORING ID:	**RAL-1**
LOGGED BY:	Bolich
BEGIN DATE:	3/7/2001
END DATE:	3/22/2001

DRILLING METHOD: wireline coring

CORE DIAMETER: 2.1”

Color descriptions referenced to Munsell soil color charts.

INTERVAL	RECOVERY	DRY/WET	COLOR	UNIFIED CLASS	LAYER	DESCRIPTION
27 TO 32	0’	wet	2.5Y 6/3	SM	SAPROLITE	Yellowish brown fine to medium SAND; trace silt; no sample recovery in core barrel; sample taken from mud tub.
32 TO 37	0’	wet	2.5Y 6/3	SM	SAPROLITE	Yellowish brown fine to medium SAND; trace silt; no sample recovery in core barrel; sample taken from mud tub.
37 TO 41	0’	wet	2.5Y 6/3	SM	SAPROLITE	Yellowish brown fine to medium SAND; trace silt; no sample recovery in core barrel; sample taken from mud tub.

UNIFIED CLASS: SM, silty sands, sand-silt mixtures (ASTM International, 2004).

Appendix 1. Geologic core descriptions for RAL-1 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-1**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	NO. WATER BEARING	LAYERS
41 TO 42	1.2’	Light yellowish grey WEATHERED GNEISS; predominantly quartz and biotite with some orange stained quartz; weak gneissic banding at approximately 80 degrees from horizontal.	V				SAPROLITE
			SV				
			M				
			SH				
			H		1	1	
42 TO 47	4.2’	Light grey WEATHERED GNEISS; becoming very weathered from 45 to 47 feet, with well developed secondary porosity; abundant low angle water bearing fractures; occasional iron and manganese staining on fractures.	V				TRANSITION ZONE
			SV				
			M				
			SH		10	9	
			H				
47 TO 52	4.7’	Light grey weathered biotite GNEISS; becoming slightly less weathered; foliation angle approximately 80 degrees; predominant minerals are quartz and biotite with verry minor feldspar; fractures are semi-horizontal and iron stained.	V				TRANSITION ZONE
			SV				
			M				
			SH		5	5	
			H				
52 TO 57	4.6’	Light grey weathered biotite GNEISS; becoming less weathered; foliation still 80 degrees; fractures have iron/manganese staining, small, discontinuous high angle fracture at 52.5 to 52.8 feet, all other fractures are low angle (stress relief).	V				TRANSITION ZONE
			SV		1	0	
			M				
			SH				
			H		10	9	
57 TO 62	5.1’	Light grey slightly weathered biotite GNEISS; becoming fresh; 80% quartz, 15% biotite, 5% feldspar; complex fracture set at 58.2 feet; most fractures are low angle with some iron staining.	V				TRANSITION ZONE
			SV		1	1	
			M				
			SH		9	7	
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 1. Geologic core descriptions for RAL-1 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:** wireline coring	
BORING ID:	**RAL-1**	**CORE DIAMETER:** 2.1”	
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	NO. WATER BEARING	LAYERS
62 TO 67	5.2’	Light grey quartz-rich BIOTITE GNEISS, as above to 62.7 feet, then slickensided, oxidized fracture parallel to foliation change to medium grey biotite-rich GNEISS with abundant fractures; lost circulation during drilling.	V				TRANSITION ZONE
			SV		2	1	
			M				
			SH		19	10	
			H				
67 TO 72	4.3’	Medium grey biotite-rich GNEISS; slightly weathered; highly fractured; 50% biotite, 40% quartz, 10% accessories; few fractures are slightly mineralized with Si02; foliation is approximately 80 degrees from horizontal.	V				BEDROCK
			SV		5	3	
			M				
			SH		17	13	
			H				
72 TO 77	4.9’	Medium grey biotite-rich GNEISS; slightly weathered; highly fractured; fractures have random orientations but ususally cut foliation planes, some pyrite and quartz on fractures; abrupt, slickensided contact with GRANITIC GNEISS at 76.5 feet; contact is parallel to	V				BEDROCK
			SV		8	4	
			M				
			SH		16	13	
			H				
77 TO 82	5.2’	Light grey and pink GRANITIC GNEISS; fresh; weakly foliated at approximately 70 degrees from horizontal; predominantly quartz and feldspar, approximately 10% biotite; fractures are all low angle and low aperture.	V				BEDROCK
			SV				
			M				
			SH		8	1	
			H				
82 TO 87	5.2’	Light grey and pink GRANITIC GNEISS; fresh; weakly foliated at approximately 70 degrees from horizontal; predominantly quartz and feldspar, approximately 10% biotite.	V				BEDROCK
			SV				
			M				
			SH		3	0	
			H				
87 TO 92	4.7’	Light grey and pink GRANITIC GNEISS; fresh; weakly foliated; solid; no fractures other than drilling breaks; very dense and hard to penetrate; estimate 50% quartz, 40% feldspar, and 10% biotite.	V				BEDROCK
			SV				
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 1. Geologic core descriptions for RAL-1 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:** wireline coring	
BORING ID:	**RAL-1**	**CORE DIAMETER:** 2.1”	
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	NO. WATER BEARING	LAYER
92 TO 97	4.8’	Light grey with pink and orange phenocrysts GRANITIC GNEISS; similar to previous sample; foliation angle approximately 80 degrees; possible water bearing fracture at 92.0 feet.	V				BEDROCK
			SV				
			M				
			SH		3	2	
			H				
97 TO 102	5.0’	Light grey and pink GRANITIC GNEISS; fresh, competent; possible water bearing horizontal fracture at 97.4 feet; foliation angle approximately 70 degrees from horizontal.	V				BEDROCK
			SV				
			M				
			SH	1	2	1	
			H				
102 TO 107	5.0’	Light grey to medium grey GRANITIC GNEISS; lightly metamorphosed; predominantly quartz and feldspar; migmatitic quartz/feldspar vein from 103.2 feet to 104.5 feet; core was hard to extract and many of the fractures may have been created by the extraction process.	V				BEDROCK
			SV				
			M				
			SH		5?	3?	
			H				
107 TO 112	4.9’	Medium grey GRANITIC GNEISS; competent, fresh; probable tight horizontal fracture at 110.8 feet.	V				BEDROCK
			SV				
			M				
			SH		1		
			H		1	1	
112 TO 117	4.8’	Medium grey GRANITIC GNEISS; solid; fresh; steeply dipping (60 degrees) feldspar/quartz vein, 10 millimeters thick, sub-parallel to foliation at 112.1 to 112.6 feet; very hard drilling.	V				BEDROCK
			SV				
			M				
			SH		1	0	
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 1. Geologic core descriptions for RAL-1 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-1**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	**RECOVERY**	**DESCRIPTION**	**DIP ANGLE**	**NO. ANNEALED**	**NO. OPEN**	**NO. WATER BEARING**	**LAYER**
117 TO 122	4.2’	Medium grey GRANITIC GNEISS; predominantly quartz and feldspar, little biotite, trace muscovite; weak foliation at approximately 70 degrees.	**V**				BEDROCK
			SV				
			M				
			SH		2	0	
			H				
122 TO 127	5.4’	Medium grey GRANITIC GNEISS; as previous; medium grained, average feldspar crystal is approximately 2 millimeters in diameter; possible water bearing fracture at 122.0 feet.	**V**				BEDROCK
			SV				
			M				
			SH		2	1	
			H				
127 TO 132	5.0’	Medium grey GRANITIC GNEISS; weakly foliated; probable horizontal water bearing fractures at 128.4 and 128.5 feet, low aperature, slightly mineralized.	**V**				BEDROCK
			SV				
			M				
			SH				
			H		2	2	
132 TO 137	5.0’	Medium grey GRANITIC GNEISS; as previous; fresh; solid; no fractures.	**V**				BEDROCK
			SV				
			M				
			SH			0	
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.

REGOLITH LOG SHEET

PROJECT:	NCSU Lake Wheeler Road
BORING ID:	**RAL-2**
LOGGED BY:	Bolich
BEGIN DATE:	3/7/2001
END DATE:	3/22/2001

DRILLING METHOD: wireline coring

CORE DIAMETER: 2.1”

Color descriptions referenced to Munsell soil color charts.

INTERVAL	RECOVERY	DRY/WET	COLOR	UNIFIED CLASS	LAYER	DESCRIPTION
2 TO 7	3.8’	moist	2.5YR4/8	SM	RESIDUUM	Reddish brown fine to coarse SAND and SILT; some clay; occasional mica; massive; quartz grains sub-angular to angular; increasing sand content with depth.
7 TO 12	3.6’	moist	2.5YR4/8	SM	RESIDUUM	Reddish brown SILT AND FINE TO MEDIUM SAND; little mica (vermiculite); little clay; becoming micaceous at approximately 9 feet; massive; heavy manganese staining at 8.5 feet oriented nearly horizontal.
12 TO 17	1.6’	moist to dry	2.5YR4/6 to 5YR 4/6	ML	SAPROLITE	Reddish brown SILT AND VERMICULITE; little fine to medium sand; relict rock texture beginning to show; friable.
17 TO 22	3.2’	moist	10YR 4/4	SM	SAPROLITE	Dark yellowish brown SILT, FINE SAND, and VERMICULITE; trace fine to coarse quartz gravel; occasional manganese oxide staining; poorly preserved rock texture with relict foliation nearly vertical in orientation.
22 TO 27	1.6’	moist to wet	10YR 4/3	ML	SAPROLITE	Brown VERMICULITE; some fine to medium sand; 4 millimeter thick seam of low angle medium quartz gravel at 0.7 foot into sample; very poorly preserved relict rock texture; 2 centimeter thick zone of manganese oxide staining 1.0 foot into sample.

UNIFIED CLASS: SM, silty sands, sand-silt mixtures; ML, inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity (ASTM International, 2004)..

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

REGOLITH LOG SHEET

PROJECT:	NCSU Lake Wheeler Road
BORING ID:	**RAL-2**
LOGGED BY:	Bolich
BEGIN DATE:	3/7/2001
END DATE:	3/22/2001

DRILLING METHOD: wireline coring

CORE DIAMETER: 2.1”

Color descriptions referenced to Munsell soil color charts.

INTERVAL	RECOVERY	DRY/WET	COLOR	UNIFIED CLASS	LAYER	DESCRIPTION
27 TO 32	3.3’	moist	2.5YR4/8	SM	SAPROLITE	Light greyish brown FINE SAND AND VERMICULITE; little silt; trace clay; relict rock texture becoming better preserved; foliation appears to be approximately 75 to 80 degrees; occasional (kaolinite?) healed sub-horizontal relict fractures.
32 TO 37	4.0’	wet	2.5YR4/8	SM	SAPROLITE	Reddish brown SILT AND FINE TO MEDIUM SAND; little mica (vermiculite); little clay; becoming micaceous at approximately 9 feet; massive; heavy manganese staining at 8.5 feet oriented nearly horizontal.
37 TO 42	3.8’	wet		SW	SAPROLITE	Light yellowish brown to grey FINE TO MEDIUM SAND; some vermiculite; well preserved relict rock texture; becoming dense at 41 feet; increasing sand content; fine to medium quartz gravel zone 10 millimeters thick at 40 feet.
42 TO 44	0.5’	wet			TRANSITION ZONE	Light grey partially weathered granitic bedrock.

UNIFIED CLASS: SM, silty sands, sand-silt mixtures; SW, well-graded sands, gravelly sands, little or no fines (ASTM International, 2004).

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-2**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	WATER BEARING?	LAYER
44 TO 47	0	No Recovery	V				
			SV				
			M				
			SH				
			H				
47 TO 52	3.9’	Light grey slightly weathered GRANITE; non-metamorphosed; transition into a mafic biotite-rich zone at approximately 50 feet; iron-stained weathered fracture zones at 47.5 and 50.0 feet, large aperture, water bearing; migmatitic zone from 51 to 52 feet.	V				TRANSITION ZONE
			SV				
			M				
			SH		2	yes	
			H				
52 TO 57	1.9’	Light grey weathered biotite GNEISS; grades back into brownish grey micaceous SILT and FINE TO MEDIUM SAND in middle of sample, then back into quartz-rich biotite gneiss; foliation appears to be 80 degrees; rock retains water long after removal from core barrel.	V				TRANSITION ZONE
			SV				
			M				
			SH				
			H				
57 TO 62	2.9’	Light grey weathered biotite GNEISS; iron stained fractures; porous; becoming less weathered at the end of run (62 feet); fractures are nearly horizontal; foliation is nearly vertical.	V				TRANSITION ZONE
			SV				
			M				
			SH				
			H				
62 TO 67	5.0’	Light grey biotite GNEISS; fresh; horizontal low angle fracture at 65.5 feet; low angle fracture at 67.0 feet; foliation starts run at about 80 degrees and becomes nearly vertical past 64 feet.	V				TRANSITION ZONE
			SV				
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-2**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	**RECOVERY**	**DESCRIPTION**	**DIP ANGLE**	**NO. ANNEALED**	**NO. OPEN**	**NO. WATER BEARING**	**LAYER**
67 TO 72	2.9’	Fractured quartz-rich GNEISS; weathered fracture interval at 67.2 feet; fractures are near horizontal, abundant iron staining on fractures; fresh pyrite coating on fracture at 72 feet.	V SV M SH H				TRANSITION ZONE
72 TO 77	4.1’	Medium grey quartz-rich GNEISS; note loss of circulation at 73 feet; fresh; foliation angle near vertical; fracture zones at 73.5, 74.3 – 74.6, and 76.8 feet; fractures are small aperture coated with pyrite.	V SV M SH H				TRANSITION ZONE
77 TO 82	5.1’	Grey GNEISS; fresh; no fractures; abundant pyrite in laminae; foliation changing from near vertical at 77 feet to approximately 70 degrees at 81 to 82 feet.	V SV M SH H				BEDROCK
82 TO 87	4.0’	Grey biotite GNEISS with migmatitic amphibole or biotite laminae up to 2 centimeters thick; fresh; no fractures; trace pyrite (intragranular); foliation angle is near vertical at end of run.	V SV M SH H				BEDROCK
87 TO 92	3.1	Grey GNEISS; fresh; horizontal quartz-filled fracture at 90.4 feet; occasional intragranular pyrite; 3 centimeter thick amphibolite/biotite zone at about 91 feet with abundant pyrite; 2 millimeter thick quartz filled fracture at 91.2 feet; nearly horizontal; foliation is nearly vertical.	V SV M SH H				BEDROCK

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:** wireline coring	
BORING ID:	**RAL-2**	**CORE DIAMETER:** 2.1”	
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	**RECOVERY**	**DESCRIPTION**	**DIP ANGLE**	**NO. ANNEALED**	**NO. OPEN**	**NO. WATER BEARING**	**LAYER**
92 TO 97	5.0’	Grey and black BIOTITE GNEISS; fresh; abundant intragranular pyrite; foliation angle is about 80 degrees from horizontal; tight quartz filled fracture at 92.6 feet oriented nearly horizontal.	V				BEDROCK
			SV				
			M				
			SH				
			H				
97 TO 102	5.0’	Grey and black BIOTITE GNEISS; 1 millimeter thick horizontal quartz seam at 98.9 feet, low aperture; some pyrite; fracture zone from 100.8 to 101.2 feet with three moderate aperture horizontal quartz coated fractures; probably water bearing; foliation near vertical.	V				BEDROCK
			SV				
			M				
			SH				
			H				
102 TO 107	5.0’	Grey BIOTITE GNEISS; fresh; pyrite coated fracture at 102.0 feet, otherwise fresh and solid; very tight possible fracture with quartz coating at 104.5 feet; foliation is nearly vertical.	V				BEDROCK
			SV				
			M				
			SH				
			H				
107 TO 112	4.7’	Grey and black BIOTITE GNEISS grading into grey quartzite with migmatitic biotite/ amphibole foliation banding; quartz zones within the migmatitic bands suggest voids filled with quartz from low temperature solutions; foliation nearly vertical.	V				BEDROCK
			SV				
			M				
			SH				
			H				
112 TO 117	5.0’	Grey GNEISS; quartz rich, becoming very micaceous (biotite) from 114 feet; moderate aperture horizontal fracture at 115.5 feet, trace coating of quartz, probably water bearing; almost pure biotite at 116.5 feet; very friable, disintegrated in core barrel	V				BEDROCK
			SV				
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-2**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	NO. WATER BEARING	LAYER
117 TO 122	5.2	Medium grey BIOTITE GNEISS; possible very low aperture fracture at 118.3 feet, trace pyrite coating, nearly horizontal; possible low aperture fracture at 121.5 feet, no mineralization, anastamozing; foliation is vertical.	V				BEDROCK
			SV				
			M				
			SH				
			H				
122 TO 127	3.0	Grey BIOTITE GNEISS; pegmatite vein at 122.1 feet to 123.0 feet, contains quartz and feldspar; 1 millimeter thick fracture/ quartz vein at 125.0 feet, bottom of core sample; last 2 feet of run may still be in core barrel.	V				BEDROCK
			SV				
			M				
			SH				
			H				
127 TO 132	4.8	Grey and black BIOTITE GNEISS; possible low aperture fracture at 130.0 feet, horizontal, coated with quartz; foliation angle decreasing to approximately 70 degrees toward end of run.	V				BEDROCK
			SV				
			M				
			SH				
			H				
132 TO 137	5.1	Grey BIOTITE GNEISS; quartz seams parallel to foliation at 132.2 and 133.0 feet, approximately 10 millimeters thick; small aperture fracture at 133.6 feet, nearly horizontal, some quartz coating on surface; thin horizontal seam approximately 2 millimeters thick at 133.8 feet; foliation becoming near vertical at the end of core.	V				BEDROCK
			SV				
			M				
			SH				
			H				
137 TO 142	5.0’	Grey BIOTITE GNEISS; possible low angle, very low aperture fracture at 139.3 feet, trace quartz coating on fracture; foliation is near vertical.	V				BEDROCK
			SV				
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-2**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	NO. WATER BEARING	LAYER
142 TO 147	3.2’	Grey BIOTITE GNEISS; quartz rich; near vertical, low aperture fracture at 142.0 feet, quartz coated; possible very low aperture fracture, anastamosing horizontal fracture at 144.9 feet. Drilling very slowly now.	V SV M SH H				BEDROCK
147 TO 152	4.8’	Grey BIOTITE GNEISS; quartz rich; no apparent fractures; foliation is nearly vertical. Core taken as two shorter runs.	V SV M SH H				BEDROCK
152 TO 157	6.1’	Grey BIOTITE GNEISS; high angle near vertical water bearing fracture from 150.6 to 156.0 feet, iron oxide stained, trace quartz infilling, low aperture, sub-parallel to foliation.	V SV M SH H				BEDROCK
157 TO 162	5.3’	Grey BIOTITE GNEISS with little to no feldspar, contact change to pink and grey GRANITE GNEISS at 158.3 feet, change marked by large pink feldspar crystals; trace muscovite; pyrite seems to have discontinued.	V SV M SH H				BEDROCK
162 TO 167	5.0’	Grey, black, and pink GRANITIC GNEISS, then change back to black and grey BIOTITE GNEISS as before; possible fractures at 164.0 feet, tight, approximately 20 degrees from horizontal, very light coating of black iron oxide; fracture at contact between units at 164.3 feet is probably water bearing but is obscured because rock disintegrated during drilling; possible tight, low angle fracture at 165.9 feet; tight quartz-coated fracture at 166.8 feet, possible water-bearing.	V SV M SH H				BEDROCK

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 2. Geologic core descriptions for RAL-2 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	**RAL-2**	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	3/7/2001		
END DATE:	3/22/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	NO. WATER BEARING	LAYER
167 TO 172	4.5’	Grey and black BIOTITE GNEISS; abundant quartz; solid with no fractures; foliation is approximately 70 degrees from horizontal; a greenish yellow vein (epidote?) at 68.1 feet approximately 5 – 10 millimeters thick, perpendicular to foliation.	V				BEDROCK
			SV				
			M				
			SH				
			H				
172 TO 177	4.7’	Grey BIOTITE GNEISS; fresh; laminated quartz seam at 173 feet, approximately 10 centimeters thick, not water bearing; horizontal fracture zone at 174.8 to 175.0 feet, core is highly fragmented and some pieces polished.	V				BEDROCK
			SV				
			M				
			SH				
			H				
177 TO 182	6.1’	Grey GNEISS; quartz rich zone at 177.1 to 177.8 feet; tight horizontal fracture at 177.2 feet; water bearing fracture zone 179.0 to 179.2 feet; thin horizontal quartz seam at 181.8 feet.	V				BEDROCK
			SV				
			M				
			SH				
			H				
182 TO 187	5.1’	Grey BIOTITE GNEISS; predominantly biotite and quartz, minor epidote (?); tight, low angle fracture at 183.5 feet, trace quartz and iron oxide coating; fracture set at 186.8 to 187.0 feet, low angle, probably water bearing.	V				BEDROCK
			SV				
			M				
			SH				
			H				
187 TO 188	1.2’	Grey GNEISS; becoming almost pure quartz at bottom of run; terminated boring due to circulation problems.	V				BEDROCK
			SV				
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 3. Geologic core descriptions for RAL-3 at the Lake Wheeler Road research station.

REGOLITH LOG SHEET

PROJECT: NCSU Lake Wheeler Road
BORING ID: **RAL-3**
LOGGED BY: Bolich
BEGIN DATE: 2/20/2001
END DATE: 3/1/2001

DRILLING METHOD: wireline coring
CORE DIAMETER: 2.1”
Color descriptions referenced to Munsell soil color charts.

INTERVAL	RECOVERY	DRY/WET	COLOR	UNIFIED CLASS	LAYER	DESCRIPTION
3 TO 8	4.0’	moist	2.5YR4/8	ML	RESIDUUM	Reddish brown SILT; some clay; little mica; trace fine sand; moist; soft to slightly dense; massive.
8 TO 13	3.1’	moist	2.5YR4/8	ML	RESIDUUM	Reddish brown SILT; some clay; some mica; trace fine sand; grading into 2.5YR 4/6 micaceous SILT; trace fine sand; no apparent relict structure; moist.
13 TO 18	1.5’	moist	2.5YR4/6	SM	RESIDUUM AND SAPROLITE	Reddish brown MICACEOUS SILT; as above, grading into Brown (10Y 4/3) micaceous fine SAND; trace clay trace medium sand; poorly preserved relict granitic texture.
18 TO 23	2.4’	moist	10YR 4/3	ML	SAPROLITE	Brown MICACEOUS SILT; trace fine sand; occasional manganese staining; massive.
23 TO 28	2.1’	moist	10YR 4/3	ML	SAPROLITE	Brown MICACEOUS SILT; trace fine to medium sand; few manganese staining; slightly dense; massive.

UNIFIED CLASS: ML, inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity; SM, silty sands, sand-silt mixtures (ASTM International, 2004).

Appendix 3. Geologic core descriptions for RAL-3 at the Lake Wheeler Road research station.—Continued

REGOLITH LOG SHEET

PROJECT: NCSU Lake Wheeler Road
BORING ID: **RAL-3**
LOGGED BY: Bolich
BEGIN DATE: 2/20/2001
END DATE: 3/1/2001

DRILLING METHOD: wireline coring
CORE DIAMETER: 2.1”
Color descriptions referenced to Munsell soilcolor charts.

INTERVAL	RECOVERY	DRY/WET	COLOR	UNIFIED CLASS	LAYER	DESCRIPTION
28 TO 33	1.2’	moist	2.5Y 4/3	ML	SAPROLITE	Olive brown MICACEOUS SILT; trace fine to medium sand; trace manganese staining; slightly dense; massive.
33 TO 38	0.8’	moist	2.5Y 4/3	SM	SAPROLITE	Olive brown MICACEOUS SILT; as above; some relict foliation; changing to SILTY FINE TO COARSE SAND; some clay at bottom; possible change to PWR at 38 feet.
38 TO 43	2.9’	moist to wet	2.5Y 4/3	SM	SAPROLITE	Mottled olive brown MICACEOUS SILT and FINE TO MEDIUM SAND; 2 centimeter thick layer of coarse quartz gravel at 38 feet; increasing sand content; rock texture better preserved.
43 TO 48	2.2’	wet	2.5 4/3	SM	SAPROLITE	Mottled olive brown MICACEOUS SILT and FINE TO MEDIUM SAND; trace clay; trace coarse sand; poorly preserved relict foliation.
48 TO 53	1.0’	moist	2.5 Y 6/4	SP/GM	SAPROLITE AND TRANSITION ZONE) AT 50 FEET	Light yellowish brown SILT and FINE SAND; becoming fine to medium GRAVEL with limonite filled weathered fractures.
53 TO 58	No data					

UNIFIED CLASS: ML, inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity; SM, silty sands, sand-silt mixtures; SP, poorly graded sands, gravelly sands, little or no fines; GM, silty gravels, gravel-sand-silt mixtures (ASTM International, 2004).

Appendix 3. Geologic core descriptions for RAL-3 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:**	wireline coring
BORING ID:	RAL-3	**CORE DIAMETER:**	2.1”
LOGGED BY:	Bolich		
BEGIN DATE:	2/20/2001		
END DATE:	3/1/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	WATER BEARING?	LAYER
58 TO 63	5.0’	Light grey GRANITIC GNEISS; weathered; porous; foliation approximately 70 degrees; a near vertical fracture with slickensides at 58.0 – 58.8 feet; open horizontal fractures at 58.2, 58.4, 59.2, zone of four horizontal fractures at 59.6 – 59.9 feet, 61.0, 61.3, and 62.8 feet.	V		1	yes	TRANSITION ZONE
			SV				
			M				
			SH				
			H		10	yes	
63 TO 68	4.9	Very light grey GRANITIC GNEISS; slightly weathered; predominantly quartz, biotite, muscovite, and possible serricite; iron and manganese staining on vertical fracture at 63.0 to 63.4 feet; evidence of some slickenside development; foliation at approximately 60 to 70 degrees from horizontal.	V		1	yes	TRANSITION ZONE
			SV				
			M				
			SH				
			H		2	no	
68 TO 73	5.0’	Very light grey GRANITIC GNEISS; slightly weathered; as above; slightly more weathered; foliation at 80 to 90 degrees from horizontal.	V				TRANSITION ZONE
			SV				
			M				
			SH		2	no	
			H		4	yes	
73 TO 78	5.0’	Very light grey to medium grey BIOTITE GNEISS; changes to a biotite-rich gneiss at 74.0 feet; contact zone at 73.5 feet reveals quartz/biotite vein parallel to foliation (about 60 degrees), vug at this transition shows some quartz re-crystallization;core appears to be fresh and non-weathered.	V				BEDROCK
			SV				
			M				
			SH		3	no	
			H		3	yes	
78 TO 83	4.0’	Grey BIOTITE GNEISS; as above; some muscovite; possible serricite; foliation angle = 60 degrees; 2 millimeter thick quartz-healed fracture parallel to foliation at 79.2 feet.	V				BEDROCK
			SV	1		no	
			M				
			SH				
			H		2	no	

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 3. Geologic core descriptions for RAL-3 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:** wireline coring	
BORING ID:	RAL-3	**CORE DIAMETER:** 2.1”	
LOGGED BY:	Bolich		
BEGIN DATE:	2/20/2001		
END DATE:	3/1/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	**RECOVERY**	**DESCRIPTION**	**DIP ANGLE**	**NO. ANNEALED**	**NO. OPEN**	**WATER BEARING?**	**LAYER**
83 TO 88	4.8’	Grey to light grey BIOTITE GNEISS; changing to a lighter, more siliceous light grey biotite gneiss at 84.5 feet, transition is abrupt, parallel to folitation; 5 millimeter quartz filled fracture at 87 to 87.6 feet, parallel to foliation.	**V**				BEDROCK
			SV		1	yes	
			M				
			SH		1	yes	
			H		1	no	
88 TO 93	4.6’	Light grey BIOTITE GNEISS; foliation at approximately 80 degrees to horizontal; fresh; no evidence of water.	**V**				BEDROCK
			SV				
			M				
			SH				
			H		3	no	
93 TO 98	5.4’	Light grey BIOTITE GNEISS; fresh; predominantly quartz and biotite, trace of sericite; 3 millimeter quartz seam at 97.1 to 97.5 feet; parallel to foliation (80 degrees).	**V**				BEDROCK
			SV		1	no	
			M				
			SH		3	no	
			H		2	no	
98 TO 103	5.3’	Light grey GNEISS; un-weathered; foliation is subtle at approximately 70 degrees; predominantly biotite, quartz, and muscovite; thin (2 millimeter) quartz seam at 101.6 feet, parallel to foliation.	**V**				BEDROCK
			SV				
			M				
			SH		1	no	
			H		5	no	
103 TO 108	5.3’	Light grey BIOTITE/MUSCOVITE GNEISS; as above; zone of increased feldspar from 105 – 106 feet, zone appears discordant with rest of sample; thick milky quartz seam starting at 107 feet, thickness unknown.	**V**				BEDROCK
			SV				
			M				
			SH		1	no	
			H		2	no	

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 3. Geologic core descriptions for RAL-3 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:** wireline coring	
BORING ID:	RAL-3	**CORE DIAMETER:** 2.1”	
LOGGED BY:	Bolich		
BEGIN DATE:	2/20/2001		
END DATE:	3/1/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	WATER BEARING?	LAYER
108 TO 113	4.8’	Light grey BIOTITE GNEISS and QUARTZ; quartz vein continues from previous run to 109.6 feet; quartz vein is parallel to foliation at lower contact; note three high angle mineralized (sericite and quartz) fractures not parallel to foliation.	V				BEDROCK
			SV	2	3	no / yes	
			M				
			SH		4	no	
			H				
113 TO 118	5.0’	Light grey BIOTITE GNEISS; foliation at approximately 80 degrees to horizontal, very prominent; 5 millimeter thick quartz vein parallel to foliation at 113.0 to 113.5 feet; fresh.	V				BEDROCK
			SV	1		no	
			M				
			SH				
			H		1	no	
118 TO 123	3.7’	Light grey BIOTITE/MUSCOVITE GNEISS, trace of sericite; foliation 70 to 80 degrees; gneissic banding very prominent in 0.1 to 1.0 millimeter thick bands.	V				BEDROCK
			SV				
			M				
			SH				
			H				
123 TO 128	6.5’	Light grey MUSCOVITE/BIOTITE GNEISS changing to dark grey banded BIOTITE GNEISS; dark gneiss contains abundant biotite and quartz in confused, irregular foliation patterns; small (5 millimeter diameter) open vug in quartz at 127.5 feet.	V				BEDROCK
			SV				
			M				
			SH				
			H		2	no	
128 TO 133	4.9’	Dark grey and black BIOTITE GNEISS; occasional migmatitic quartz bands 0.1 to 3 millimeters thick; predominant foliation is approximately 70 degrees from horizontal; tight, high angle, but sub-parallel to foliation fracture at 133 feet; some chlorite, epidote, and a fibrous radiating mineral (calcite?) coating on fracture surface.	V				BEDROCK
			SV		1	yes	
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

Appendix 3. Geologic core descriptions for RAL-3 at the Lake Wheeler Road research station.—Continued

BEDROCK LOG SHEET

PROJECT:	NCSU Lake Wheeler Road	**DRILLING METHOD:** wireline coring	
BORING ID:	RAL-3	**CORE DIAMETER:** 2.1”	
LOGGED BY:	Bolich		
BEGIN DATE:	2/20/2001		
END DATE:	3/1/2001		

LITHOLOGIC DESCRIPTION			FRACTURE INFORMATION				
INTERVAL	RECOVERY	DESCRIPTION	DIP ANGLE	NO. ANNEALED	NO. OPEN	WATER BEARING?	LAYER
133 TO 138	5.3’	Grey BIOTITE GNEISS, banded; fracture zone at 133.0 feet, low and high angle fractures; foliation becoming more consistent at approximately 70 degrees.	V				BEDROCK
			SV	1	2	no / yes	
			M				
			SH		1	no	
			H		1	yes	
138 TO 143	4.3’	Grey BIOTITE GNEISS, banded; numerous quartz seams/bands up to 5 centimeters thick parallel to foliation; prominent migmatitic banding.	V				BEDROCK
			SV	2	1	no	
			M				
			SH				
			H		3	no	
143 TO 148	5.0’	Medium grey BIOTITE GNEISS; quartz-rich zone from 143 to 146 feet; foliation at approximately 60 degrees; slight expression of migmatitic banding.	V				BEDROCK
			SV				
			M				
			SH				
			H				

DIP ANGLE: V, vertical; SV, subvertical; M, medium; SH, subhorizontal; H, horizontal.

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