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Hydrogeology, Groundwater Seepage, Nitrate Distribution, and Flux at the Raleigh Hydrogeologic Research Station, Wake County, North Carolina, 2005–2007

Scientific Investigations Report 2013–5041

U.S. Department of the Interior
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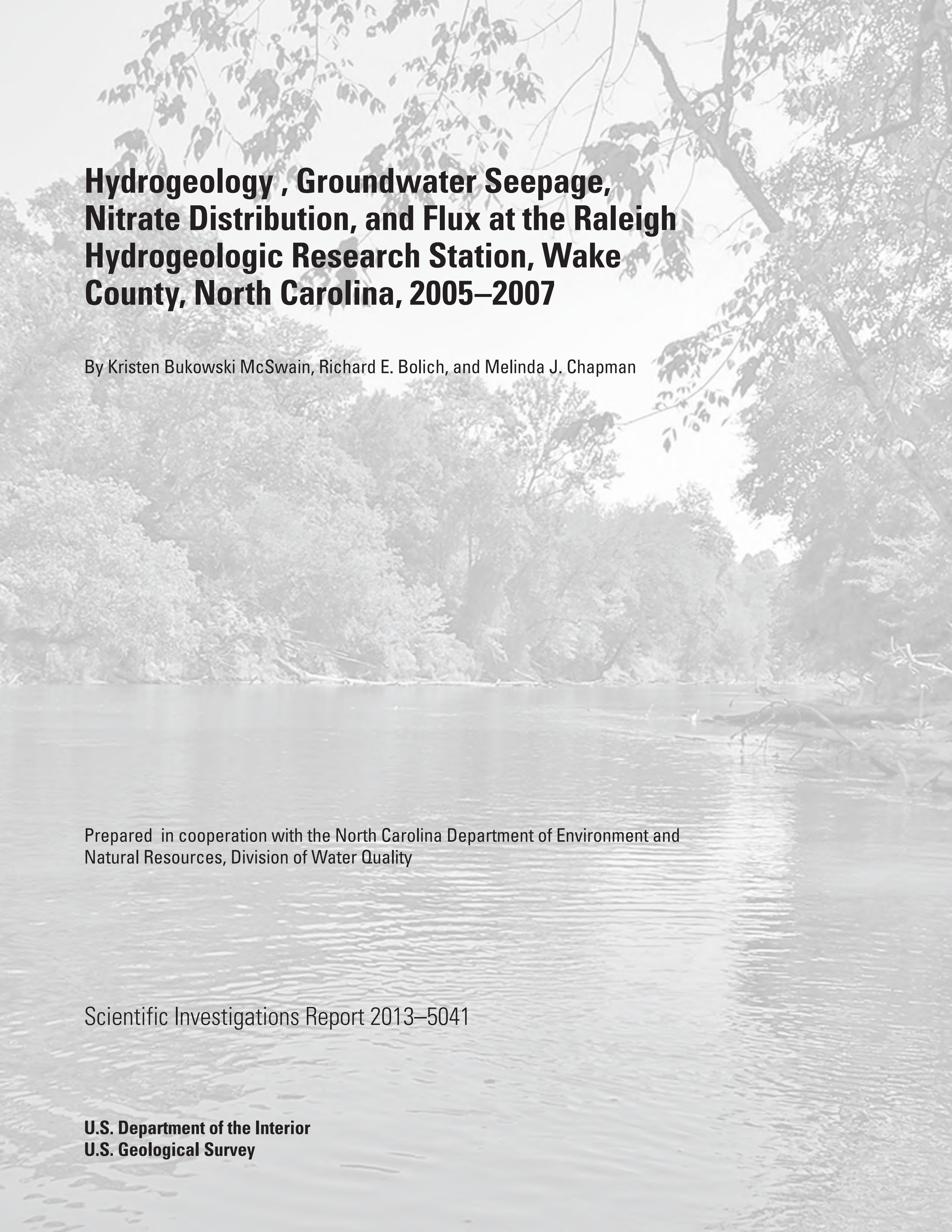
Cover photograph. Neuse River at USGS streamgaging station 0208739677 below SR2555 near Auburn on the Raleigh hydrogeologic research station, Wake County, North Carolina. Photo by Kristen Bukowski McSwain, U.S. Geological Survey.



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

U.S. Department of the Interior
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Conversion Factors and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
	Volume	
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day (m/d)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Volume	
liter (L)	0.2642	gallon (gal)
	Mass	
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

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

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area [(ft^3/d)/ft^3]. In this report, the mathmatically recuced form, feet per day (ft/d), is used for convenience.

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

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

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

Hydrogeology, Groundwater Seepage, Nitrate Distribution, and Flux at the Raleigh Hydrogeologic Research Station, Wake County, North Carolina, 2005–2007

By Kristen Bukowski McSwain,[1] Richard E. Bolich,[2] and Melinda J. Chapman[1]

Abstract

From 2005 to 2007, the U.S. Geological Survey and the North Carolina Department of Environment and Natural Resources, Division of Water Quality, conducted a study to describe the geologic framework, measure groundwater quality, characterize the groundwater-flow system, and describe the groundwater/surface-water interaction at the 60-acre Raleigh hydrogeologic research station (RHRS) located at the Neuse River Waste Water Treatment Plant in eastern Wake County, North Carolina. Previous studies have shown that the local groundwater quality of the surficial and bedrock aquifers at the RHRS had been affected by high levels of nutrients. Geologic, hydrologic, and water-quality data were collected from 3 coreholes, 12 wells, and 4 piezometers at 3 well clusters, as well as from 2 surface-water sites, 2 multiport piezometers, and 80 discrete locations in the streambed of the Neuse River. Data collected were used to evaluate the three primary zones of the Piedmont aquifer (regolith, transition zone, and fractured bedrock) and characterize the interaction of groundwater and surface water as a mechanism of nutrient transport to the Neuse River.

A conceptual hydrogeologic cross section across the RHRS was constructed using new and existing data. Two previously unmapped north striking, nearly vertical diabase dikes intrude the granite beneath the site. Groundwater within the diabase dike appeared to be hydraulically isolated from the surrounding granite bedrock and regolith. A correlation exists between foliation and fracture orientation, with most fractures striking parallel to foliation. Flowmeter logging in two of the bedrock wells indicated that not all of the water-bearing fractures labeled as water bearing were hydraulically active, even when stressed by pumping.

Groundwater levels measured in wells at the RHRS displayed climatic and seasonal trends, with elevated groundwater levels occurring during the late spring and declining to a low in the late fall. Vertical gradients in the groundwater discharge area near the Neuse River were complex and were affected by fluctuations in river stage, with the exception of a well completed in a diabase dike.

Water-quality data from the wells and surface-water sites at the RHRS were collected continuously as well as during periodic sampling events. Surface-water samples collected from a tributary were most similar in chemical composition to groundwater found in the regolith and transition zone. Nitrate (measured as nitrite plus nitrate, as nitrogen) concentrations in the sampled wells and tributary ranged from about 5 to more than 120 milligrams per liter as nitrogen.

Waterborne continuous resistivity profiling conducted on the Neuse River in the area of the RHRS measured areas of low apparent resistivity that likely represent groundwater contaminated by high concentrations of nitrate. These areas were located on either side of a diabase dike and at the outfall of two unnamed tributaries. The diabase dike preferentially directed the discharge of groundwater to the Neuse River and may isolate groundwater movement laterally.

Discrete temperature measurements made within the pore water beneath the Neuse River revealed seeps of colder groundwater discharging into warmer surface water near a diabase dike. Water-quality samples collected from the pore water beneath the Neuse River indicated that nitrate was present at concentrations as high as 80 milligrams per liter as nitrogen on the RHRS side of the river. The highest concentrations of nitrate were located within pore water collected from an area near a diabase dike that was identified as a suspected seepage area.

Hydraulic head was measured and pore water samples were collected from two 140-centimeter-deep (55.1-inch-deep) multiport piezometers that were installed in bed sediments on opposite sides of a diabase dike. The concentration of nitrate in pore water at a suspected seepage area ranged from 42 to 82 milligrams per liter as nitrogen with a median concentration of 79 milligrams per liter as nitrogen. On the opposite side

[1] U.S. Geological Survey.

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

of the dike, concentrations of nitrate in pore water samples ranged from 3 to 91 milligrams per liter as nitrogen with a median concentration of 52 milligrams per liter. At one of the multiport piezometers the vertical gradient of hydraulic head between the Neuse River and the groundwater was too small to measure. At the multiport piezometer located in the suspected seepage area, an upward gradient of about 0.1 was present and explains the occurrence of higher concentrations of nitrate near the sediment/water interface.

Horizontal seepage flux from the surficial aquifer to the edge of the Neuse River was estimated for 2006. Along a 130-foot flow path, the estimated seepage flux ranged from –0.52 to 0.2 foot per day with a median of 0.09 foot per day. The estimated advective horizontal mass flux of nitrate along a 300-foot reach of the Neuse River ranged from –10.9 to 5 pounds per day with a median of 2.2 pounds per day. The total horizontal mass flux of nitrate from the surficial aquifer to the Neuse River along the 130-foot flow path was estimated to be about 750 pounds for all of 2006.

Seepage meters were deployed on the bed of the Neuse River in the areas of the multiport piezometers on either side of the diabase dike to estimate rates of vertical groundwater discharge and flux of nitrate. The average estimated daily seepage flux differed by two orders of magnitude between seepage areas. The potential vertical flux of nitrate from groundwater to the Neuse River was estimated at an average of 2.5 grams per day near one of the multiport piezometers and an average of 784 grams per day at the other. These approximations suggest that under some hydrologic conditions there is the potential for substantial quantities of nitrate to discharge from the groundwater to the Neuse River.

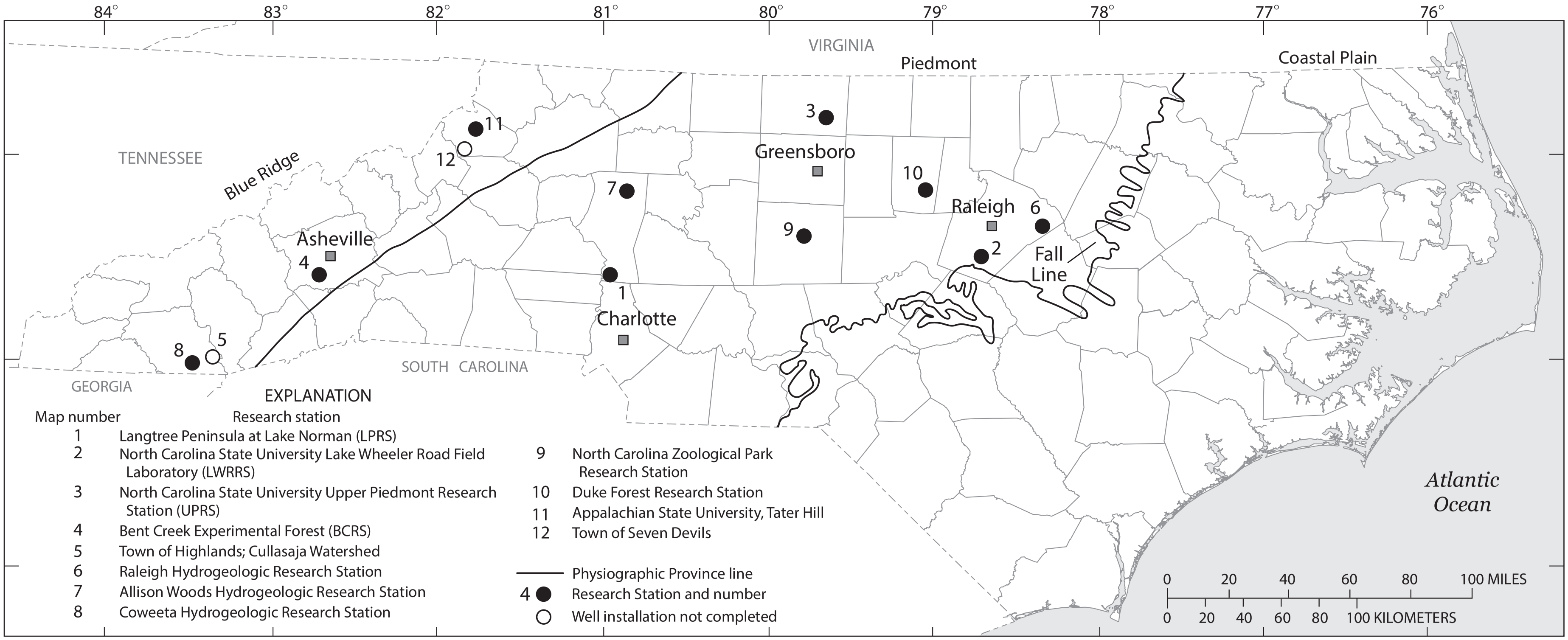
Introduction

The groundwater-flow system in the piedmont and mountains of North Carolina is complex, consisting of numerous geologic units that form fractured-bedrock aquifers. These aquifers are recharged locally and are susceptible to contamination. In order to better protect and manage the groundwater resource, the North Carolina legislature established the Piedmont and Mountains Resource Evaluation Program (PMREP) to ensure long-term availability, sustainability, and quality of groundwater in this area of the State. In 1999, the U.S. Geological Survey (USGS) and the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality (DWQ), began a multiyear cooperative study to measure ambient groundwater quality and describe the groundwater-flow system at selected research stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina (Daniel and Dahlen, 2002). Included in the study was an evaluation of spatial and temporal variations of ambient groundwater levels and quality across the Piedmont and Blue Ridge Physiographic Provinces. A primary goal of the PMREP was the investigation of the vulnerability of the groundwater system to contamination (Chapman and others, 2005).

The PMREP was designed to be an intensive field investigation at individual research stations established in representative hydrogeologic settings across the State. Twelve research stations have been selected for study in the Piedmont and Blue Ridge Physiographic Provinces (fig. 1), and wells have been installed at 10 of these research stations. Data collected as part of the PMREP provide information to refine the historical conceptual groundwater-flow models for the Piedmont and Blue Ridge Physiographic Provinces in North Carolina and the southeastern United States. The work conducted as part of this study supports the USGS mission of understanding processes in complex groundwater systems to aid water-resource managers in the protection and management of the resource. A detailed description of the PMREP study design and implementation is discussed in Daniel and Dahlen (2002).

Purpose and Scope

In 2005, the USGS began investigations at the Raleigh hydrogeologic research station (RHRS). This report presents the results of a 2 ½-year study to describe the hydrogeologic framework, water quality, groundwater flow, and groundwater/surface-water interactions at the RHRS. The hydrogeologic framework was described by integrating new geophysical and subsurface drilling data with previous studies conducted at the RHRS (ENSR Consulting and Engineering, Inc., 2002, 2003). To characterize the water quality at the RHRS, groundwater from 12 wells and a tributary were sampled for major inorganic ions and nutrients. The interaction of groundwater and surface water was evaluated by measuring temperature and nitrate concentration at two depths beneath the Neuse River as well as nutrient concentrations at a groundwater seep that may provide a mechanism for preferential transport to the Neuse River. The lateral and vertical distribution of nitrate and ammonia in shallow pore water up- and downgradient from the seep are described and discussed as evidence of the transport of nutrients from the aquifer to the river. Hydrologic and physical properties of the seep are examined as they related to the hydrogeology of the overall study area. Additionally, horizontal and vertical nitrate flux in groundwater from the RHRS to the adjacent Neuse River are discussed, using the spatial distribution of nitrate concentrations and the groundwater discharge estimated from seepage measurements and groundwater flux calculated from measured hydraulic heads and hydraulic conductivities.



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 investigation as part of the cooperative U.S. Geological Survey and North Carolina Division of Water Quality Piedmont and Mountains Resource Evaluation Program in North Carolina.

Description of Study Area

The RHRS lies in the eastern part of the Piedmont Physiographic Province within the Raleigh Belt, a litho-tectonic terrane, and is located about 9 miles east-southeast of Raleigh in Wake County, North Carolina (fig. 2). The RHRS encompasses about 60 acres within the city of Raleigh's Neuse River Waste Water Treatment Plant (NRWWTP) site. The east and west edges of the study area are bounded by two unnamed tributaries that drain the study area and discharge to the north into the Neuse River, which makes up the northern boundary of the study area (fig. 3). The Neuse River and the two unnamed tributaries that border the study area are separated from the agricultural areas by a mature forested riparian buffer the width of which generally exceeds stream buffer regulations emplaced by the State of North Carolina (North Carolina Department of Environment, Health, and Natural Resources, 1997) (later State rule 15A NCAC 2B .0238). The riparian buffer ranges in width from about 75 to 125 feet (ft) near the Neuse River and from 0 to more than 1,000 ft near the unnamed tributaries. Land use in the study area consists of agricultural areas of seasonally planted row crops, such as corn, interspersed with buffers of grassy and wooded areas.

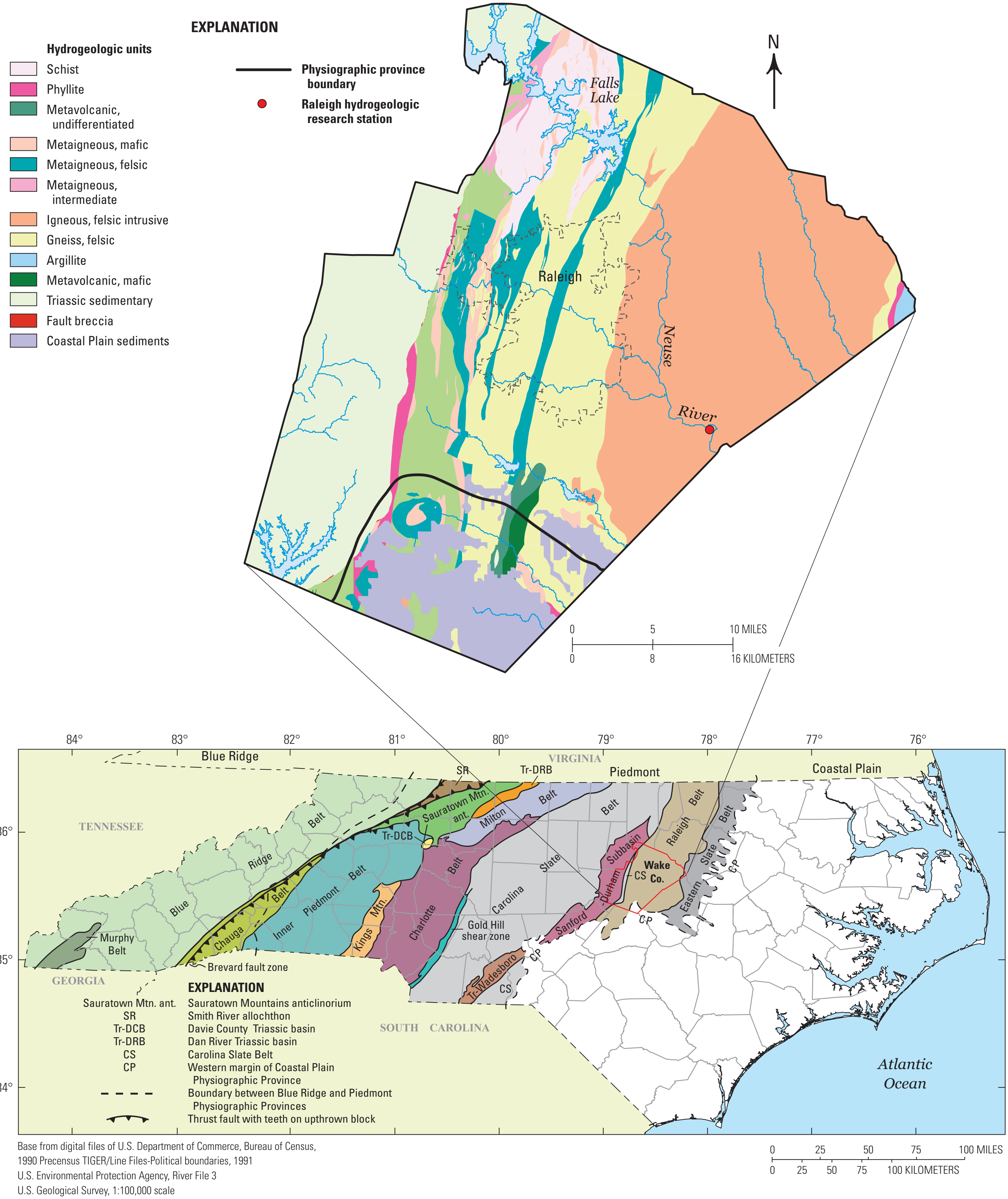


Figure 2. Locations of Raleigh hydrogeologic research station, hydrogeologic units in Wake County, and geologic belts delineated in the Piedmont Physiographic Province of North Carolina (map and hydrogeologic units from North Carolina Geological Survey, 1985; Daniel and Payne, 1990; modified from Camp Dresser and McKee, 2003).

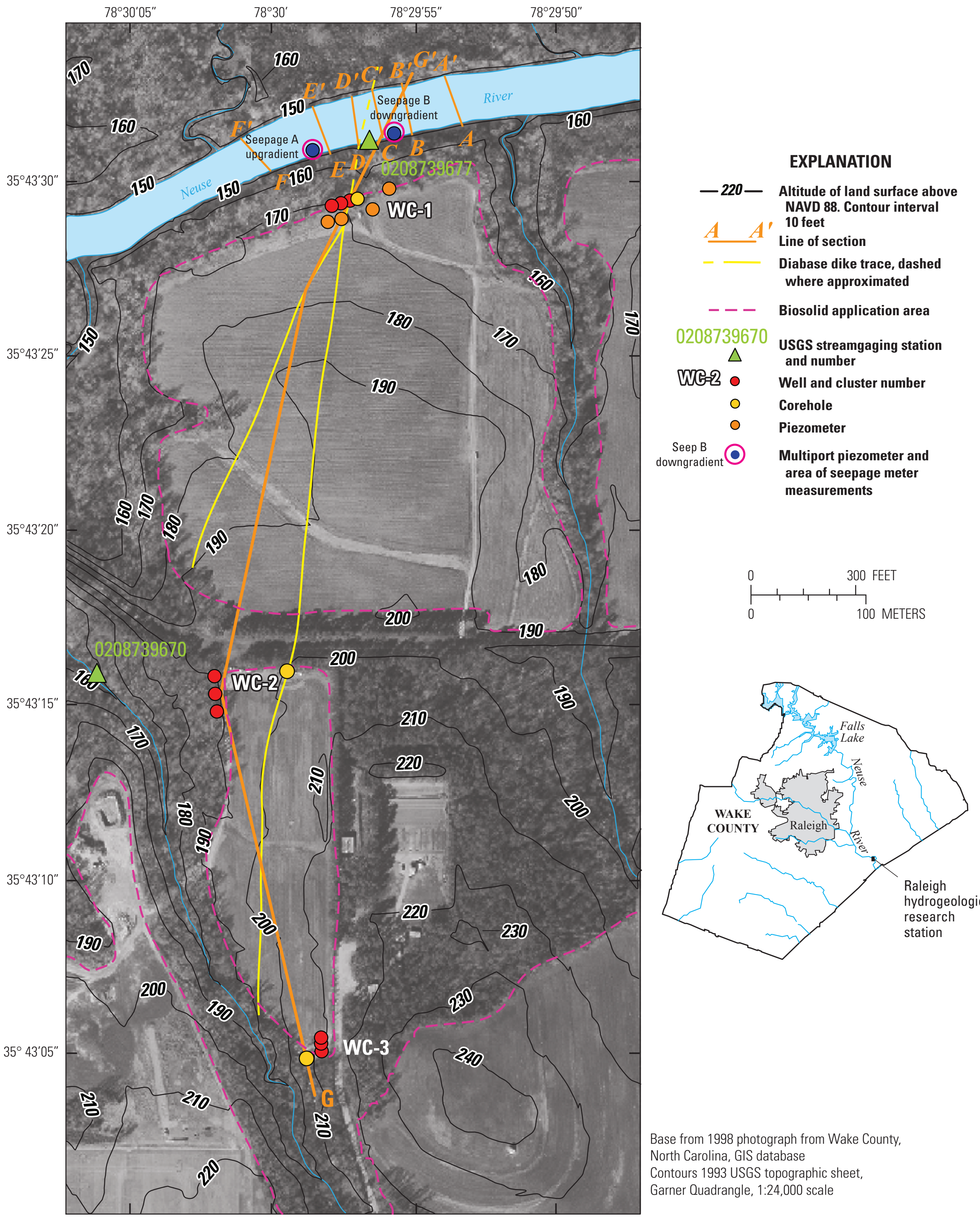


Figure 3. Aerial photograph of the Raleigh hydrogeologic research station, Wake County, North Carolina, overlaid with topographic features showing locations of well clusters, streamgages, piezometers, areas of seepage meter measurements, and lines of section.

Hydrogeologic Setting

Groundwater flows through fractures within metamorphic, igneous, and sedimentary (Triassic basins) bedrock in the Piedmont and Blue Ridge Provinces. Weathered regolith, composed of soil residuum, saprolite, alluvium, and colluvium, may overlie the fractured bedrock. Groundwater flow is complex, consisting of an interconnected, but distinct, two-component groundwater system, in which the regolith provides storage for the underlying fractures in the bedrock (Heath, 1980). The PMREP investigations include a third component of the groundwater-flow system, the transition zone (fig. 4), an area commonly present between the regolith and bedrock (Harned and Daniel, 1992).

The RHRS (fig. 2) is located in the igneous felsic intrusive (IFI) hydrogeologic unit, which represents approximately 5 percent of the area of the Piedmont and Blue Ridge Provinces in North Carolina (Daniel and Dahlen, 2002). The RHRS was selected to evaluate the effects of felsic intrusive rocks with local shearing and jointing, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures on the groundwater-flow system and groundwater quality.

The groundwater system in the study area has two primary components: the shallow, weathered regolith (the surficial aquifer) and the deeper, unweathered fractured bedrock (the fractured bedrock aquifer). Based on observed rock outcrops and the core samples collected during installation of wells at the RHRS, the study area is underlain by a regolith composed of poorly consolidated saprolite, alluvium, and soil residuum, which overlies granite of the Rolesville batholith (McSwain and others, 2009). The regolith is the shallow component of the piedmont groundwater system and, in this report, refers to all unconsolidated or poorly consolidated materials overlying the crystalline bedrock. At the RHRS, the regolith ranged in thickness from 28 to 48 ft. The alluvium material in the regolith was found primarily near the banks of the Neuse River and its tributaries and consisted of a brown silty fine sand to coarse gravel with some cobbles, clay, and organic matter. The saprolite, formed by weathering of bedrock, typically was characterized as a light yellowish brown silty fine to coarse sand with trace amounts of mica. Generally, granitic texture from the underlying bedrock was well preserved within the saprolite, and grain size increases with depth. The Rolesville batholith is a granitic intrusion that is massive to weakly foliated (Hibbard and others, 2002) and commonly intersected by diabase dike intrusions (tabular basaltic bodies with a near vertical orientation).

Groundwater occupies pore spaces in the shallow, weathered regolith. The groundwater stored within the regolith is then conveyed to numerous fractures within the Rolesville batholith. Because the bedrock has little primary porosity or permeability, groundwater in the bedrock occupies secondary fractures and discontinuities. Groundwater flow within the regolith (surficial aquifer) at the RHRS generally followed the topography (ENSR Consulting and Engineering, Inc., 2002).

The channel of the Neuse River was highly incised with the river bank on the RHRS side exceeding a vertical height of 10 ft. The bottom of the Neuse River typically is covered with a silty sand that contains little organic matter. Sediment thickness ranged from less than 1 ft near the river's edge to more than 4 ft in the center (McSwain and others, 2009). There were no exposed granite or diabase outcrops within the Neuse riverbank in the area of the RHRS, likely because of the presence of thick flood-plain sediments built up over many years.

Nutrient Plume Summary

From 1980 to 2002, the NRWWTP disposed of approximately 7,000 tons per year of treated biosolids onto 1,030 acres of fields that surround the plant, including the 60 acres that make up the RHRS (ENSR Consulting and Engineering, Inc., 2003). The application of biosolids was halted in 2002 when studies indicated that the local groundwater of the surficial aquifer contained high levels of nutrients (ENSR Consulting and Engineering, Inc., 2002 , 2003).

Groundwater monitoring in wells at the RHRS from 2005 to 2007 revealed high concentrations of dissolved nitrite plus nitrate as nitrogen, ranging from 69 to 119 milligrams per liter as nitrogen (mg/L as N) in the shallow groundwater (surficial aquifer) and from 4 to 130 mg/L as N in the deep groundwater (fractured bedrock aquifer) (McSwain and others, 2009). These elevated concentrations do not represent background conditions and were a result of calculation errors in biosolid application rates that lead to over application (ENSR Consulting and Engineering, Inc, 2003). ENSR Consulting and Engineering, Inc. (2003), estimated nitrogen loading to the Neuse River from groundwater discharge across the NRWWTP by using a MODFLOW groundwater flow and MT3D nitrogen transport model and assuming no further land application of nitrogen in biosolids after 2002. The model indicated that across the entire NRWWTP site, nitrogen loading would equal 122,294 pounds per year (lbs/yr) in 2006 and decrease to 3,743 lbs/yr in 2050 as a result of natural attenuation processes (ENSR Consulting and Engineering, Inc., 2003).

From June through December 2007, Showers (2008) calculated a total nitrate flux of 28,651 pounds (lbs) (about 57,000 lbs/yr) in four primarily groundwater-fed tributaries on the NRWWTP site. Each of the tributaries monitored by Showers (2007) discharged directly into the Neuse River and had elevated nitrate concentrations in the surface water primarily due to the base flow of groundwater. The drainage basin for each tributary contained between 43 to 219 acres of biosolid application fields, in total covering about 50 percent of the NRWWTP site. The nitrate flux in the basin that drains the RHRS was 10,945 lbs over the same June to December 2007 time period (about 22,000 lbs/yr) and was reported as fairly constant (Showers, 2007).

Groundwater contributions to the Neuse River at the NRWWTP site were investigated by two graduate students

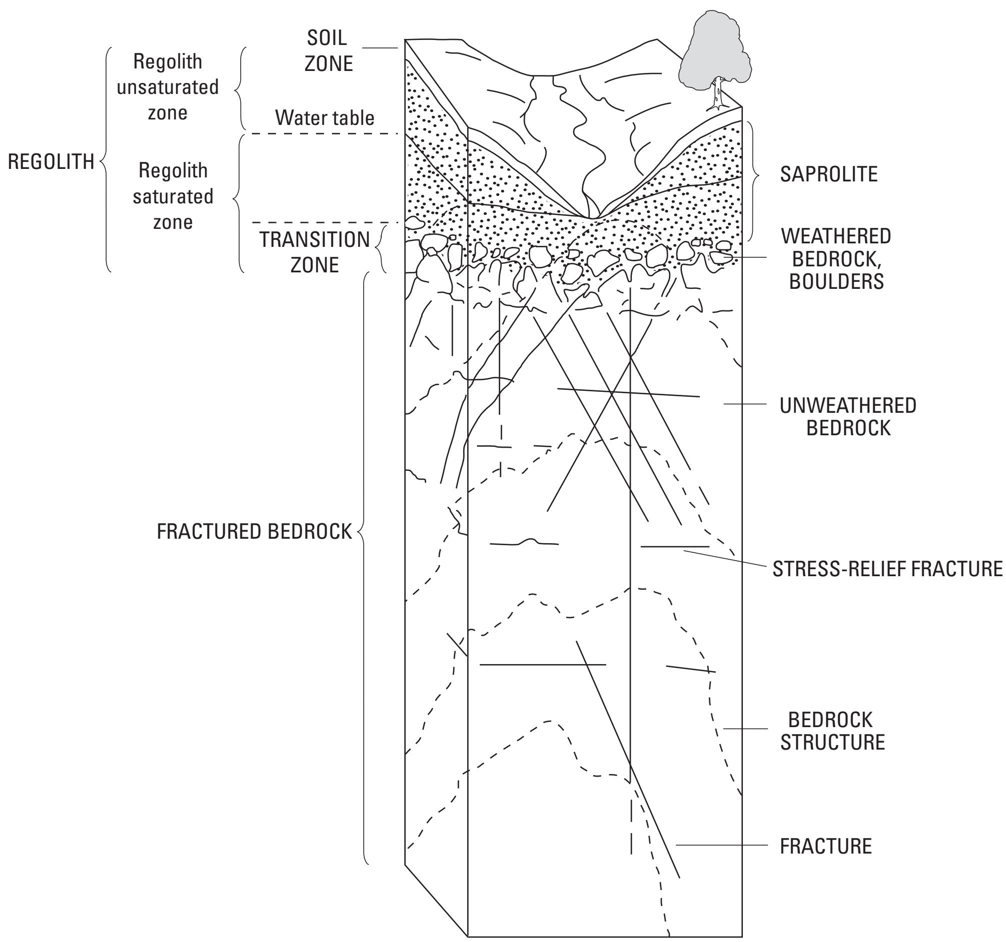


Figure 4. Conceptual components of the piedmont and mountains groundwater system (from Harned and Daniel, 1992).

in the North Carolina State University Marine, Earth, and Atmospheric Sciences Department under Dr. William Showers. Fountain (2006) installed monitoring well transects to determine the effectiveness of nitrate removal as groundwater was transported through a riparian buffer. Fountain (2006) concluded that efficient denitrification was occurring within the riparian buffer zones as nitrate concentrations in shallow groundwater were reduced by 99.1 percent, after factoring in rainwater dilution. Reyes (2009) investigated the presence of diabase dikes crossing the Neuse River on the NRWWTP site and mapped the spatial and temporal variability of groundwater discharge and nitrate concentration at a depth of 30 centimeters (cm; 11.8 in), downstream from a diabase dike, over four seasons. Reyes (2009) concluded that nitrate concentrations varied seasonally and were limited by the concentration of dissolved organic carbon. Over an area of 1,181.25 square meters (12,714.9 square feet), Reyes measured discharge amounts of nitrate as high as 27 kilograms of nitrate per day.

Several reaches of the Neuse River above and below the NRWWTP site are listed on the North Carolina 2008 303(d)-Impaired Waters List (North Carolina Department of Environment and Natural Resources, Division of Water Quality, 2009). Because groundwater is classified as a nonpoint source for surface-water contamination, subsurface discharge of nutrient-rich groundwater from the NRWWTP site has the potential to affect surface-water quality within the adjacent Neuse River. Imbalanced proportions of nitrogen and phosphorus within the river can increase algal production and lead to excessive growth of marine plant life, such as phytoplankton.

Well and Surface-Water Station Numbering System

Wells and surface-water stations monitored by the USGS are given unique identification numbers using geographic location. A latitude-longitude system is used for wells and drive points, and a downstream-order system is used for surface-water stations. The latitude and longitude of each well cluster and the surface-water station at the RHRS were determined by using a differential global positioning system (DGPS) receiver and are considered accurate to within a few feet (Chapman and others, 2005). Wells were assigned a 15-digit site number based on latitude and longitude. The latitude and longitude constitute the first 13 digits, respectively, and are followed by a 2-digit sequence number used to distinguish among wells clustered closely together. 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 at each cluster. Thus, the deeper the well, the higher the sequence number (Chapman and others, 2005).

In addition to the standard USGS well-numbering system, the wells in this study also were assigned a local identifier, which consists of a two-letter North Carolina county code followed by a three-digit sequence number. For example, wells in Wake County are identified by the prefix “WK” followed by three numbers that are assigned sequentially. The station name includes the site identifier (Raleigh hydrogeologic research station [RS]), well descriptor, and number. The well descriptors used in this study were “WC” for monitoring well and “PZ” for piezometer. Following the well descriptor is a cluster number and a letter, which indicates the aquifer section or zone that was being monitored: “S” for shallow zone (regolith), “I” for intermediate zone (transition), and “D” for deeper zone (bedrock). Corehole borings that were converted into bedrock monitoring wells upon the completion of coring have the designation “CH.” For example, well WC-1S is a monitoring well in cluster 1 completed in the shallow regolith zone.

The drive-point locations used to sample pore water within the Neuse River bed sediments were assigned a 15-digit site number based on the latitude and longitude of the transect anchor point on the south bank (to the right when facing downstream) of the Neuse River. The latitude and longitude constitute the first 13 digits and are followed by a 2-digit sequence number used to distinguish between drive-point locations following the same line of transect. Each drive point in a transect has the same site identification number except for the last two digits, which incrementally increased with distance along the transect. Thus, the farther away a drive point was along the line of section from the first point in the transect, the higher the sequence number. The station name includes the site identifier (Raleigh RS), the transect identifier (F–F′), and the distance, in feet, from the right bank of the Neuse River where the drive point was inserted. Transect samples were collected while moving in an upstream direction, with the first transect sampled (east) designated as A–A′. Subsequently sampled transects were labeled in increasing alphabetical order with the most upstream (west) transect designated F–F′.

The multiport piezometer locations in this study were assigned a 15-digit number based on location. The latitude and longitude constitute the first 13 digits and are followed by a 2-digit sequence number used to distinguish between the sampling port depths. Each of the eight ports in a multiport piezometer has the same site-identification number except for the last two digits, which incrementally increased with depth of placement below the riverbed.

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 mainstem of the stream. The first 2 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-digit number is added at the end of the station number in areas of high station density (Chapman and others, 2005).

Methods of Data Collection

From May 2005 through December 2007, an investigation was performed to describe the hydrogeologic framework, groundwater quality, groundwater flow, and groundwater/surface-water interaction at the RHRS. Three monitoring well clusters containing a total of 12 wells and 4 piezometers that monitor the shallow regolith, transition zone, and deep bedrock were installed at the RHRS along a conceptual high to low topographic profile parallel to a flow path from recharge to discharge areas (fig. 3) in a "slope-aquifer system" (LeGrand, 2004). A continuous soil and bedrock core was collected using wire-line coring methods at each of the monitoring well cluster locations. The coreholes provided continuous samples resulting in soil-to-bedrock profiles at each well cluster that were used to determine construction requirements for the monitoring wells. Borehole and surface geophysical methods were used to delineate the hydrogeologic framework. Additional characterization of the interaction between groundwater and surface water was conducted by evaluating the hydrologic and geochemical properties within the hyporheic zone of the Neuse River.

Geophysics

Geophysical methods provide information about subsurface structure, lithology, and fluid chemistry, by measuring the physical and chemical properties of the aquifer material, borehole fluid, and pore fluid. At the RHRS, a suite of conventional and advanced borehole geophysical logs was collected in each borehole open to the bedrock. Graphs of processed borehole geophysical data collected in bedrock wells at the RHRS can be found in McSwain and others (2009). In addition, waterborne continuous resistivity profiling was conducted on the Neuse River in the vicinity of the study area to measure the apparent resistivity distribution of the sediments, bedrock, and pore-water fluid beneath the streambed.

Conventional borehole geophysical logs collected included natural gamma, caliper, long and short normal resistivity, fluid temperature, and fluid conductance. Details about conventional borehole-geophysical methods are given in Keys (1990). The advanced geophysical logs collected included optical-televiewer (OTV) imaging and electromagnetic flowmeter logs (under ambient and pumping conditions). Advanced borehole-geophysical logs were used to determine the location and orientation of foliation in the bedrock and of fractures intersected by the borehole as well as the movement of water within the borehole. A brief description of the optical televiewer and electromagnetic geophysical tools is provided.

Optical-televiewer logging records a magnetically oriented, 360 degree (°) optical image of the borehole wall (Williams and Johnson, 2000). The vertical and horizontal sampling intervals for the OTV images were 0.01 and 0.008 inch (in.), respectively. Fractures and other planar features nearly as small as the sampling interval can be detected. The location and orientation of fractures, foliations, and lithologic changes were interpreted from OTV data by using computer software. The OTV logs were analyzed to confirm lithology and to determine the physical characteristics and orientation of foliation and fractures. Because the OTV is an optical system, low optical contrast features, such as small fractures in dark rocks, can be difficult to delineate. Generally, fracture characteristics, such as the presence of iron oxidation or fracture infilling, can be visually confirmed and provide information on the potential of a fracture to carry groundwater. Flowmeter logging is used to measure the direction and rate of vertical movement of water in a borehole. When used in conjunction with the other geophysical logs, individual fractures or fracture zones where water enters or exits the borehole can be identified. Differences in hydraulic head between two transmissive fractures produce vertical flow in the borehole under ambient conditions. Water enters the borehole at the fracture zone with the higher head and flows towards and out of the fracture with the lower head.

Stationary flow measurements were made under ambient and stressed (pumping) conditions between fractures or fracture zones that were identified as potentially water bearing in the caliper, resistivity, and OTV logs. Flowmeter logging also was conducted under low-rate pumping conditions to identify the least transmissive zones, including those with similar ambient heads that would not be identified without stressing the aquifer. The electromagnetic (EM) flowmeter used in this study is capable of resolving vertical flows from 0.05 to 10 gallons per minute (gal/min). Water levels were recorded during pumping, and EM flowmeter measurements were made after the borehole reached a near steady state in which the amount of water coming out of storage was less than the measurement resolution of the tool. In this investigation, the fractures in the bedrock were described with the terms "water bearing," "secondary," and "sealed," using characterization from caliper and resistivity logs, fluid resistivity and temperature logs, flowmeter logs, and oriented OTV images.

Waterborne continuous resistivity profiling was conducted following methods similar to those outlined in Day-Lewis and others (2006). Apparent resistivity data were collected using an 8-channel resistivity system and an electrode streamer with 11 electrodes at a 5-meter (16.4-ft) spacing. These apparent resistivity data were inverted using software to develop a geomodel of the subsurface structure and stratigraphy in terms of the electrical properties (Snyder and Wightman, 2002).

Water-Level Monitoring and Water Quality

Monitoring of water levels, stream stage, and water quality was conducted at selected sites at the RHRS. Water-quality samples were collected twice from each monitoring well at each cluster and from one unnamed tributary to the Neuse River (fig. 3). The water-quality constituents analyzed include major ions, nutrients, metals, radon 222, radiochemicals, and dissolved gases. Of these, only samples for major ions and nutrients were collected during both sampling events. Water samples for all other constituents were collected intermittently or one time only. Temperature measurements and drive-point water-quality samples were collected in the riverbed to better understand the movement of groundwater to and from the Neuse River. A detailed description of the methods used to collect the water-level, stream-stage, and water-quality data at the RHRS is presented in McSwain and others (2009). The USGS National Water Quality Laboratory in Denver, Colorado, analyzed all water-quality samples.

The nitrate concentration values presented in this report were measured as dissolved nitrate plus nitrite in milligrams per liter as nitrogen. Because nitrite typically represented a small fraction of the total concentration, the reported values are presented and discussed as nitrate. All data were collected following the standard operating procedures of the PMREP (North Carolina Department of Environment and Natural Resources, Division of Water Quality, Groundwater Sciences Unit, and U.S. Geological Survey, Water Resources Division, North Carolina District, 2008). Data collected at the RHRS are accessible in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2006b). Continuous groundwater and water-quality data collected at the RHRS during water years[*] 2005, 2006, and 2007 were published in the USGS annual data reports (U.S. Geological Survey, 2006a, 2007, and 2008).

A multifunction bedrock-aquifer transportable testing tool (BAT^3) was used in one sampling event to collect water-quality samples in the open-hole wells at the RHRS. The BAT^3 allows discrete intervals of a borehole to be isolated hydraulically for geochemical sampling by using two inflatable packers that seal against the borehole wall. The spacing between the two packers defines the test interval in the borehole. The equipment is configured with a submersible pump located between the packers to withdraw water from the test interval in order to collect water-quality samples. The length of the test interval and the depth at which water-quality samples were collected were determined on the basis of the location of the fractures intersecting the borehole as identified in the borehole geophysical logs. A complete discussion of the down-hole components of the BAT^3 and its operation is given in Shapiro (2001).

Daily rainfall data were calculated for the RHRS site by the State Climate Office of North Carolina, using gage-calibrated radar estimates known as multisensor precipitation estimates (MPE) (Mark Brooks, State Climate Office of North Carolina, written commun., October 2008). MPE combines National Weather Service weather surveillance radar 88 Doppler (WSR-88D) precipitation estimates with locally available hourly surface-precipitation gages. This combination provides the spatial resolution of radar with the increased accuracy of surface-gage networks. A study by the State Climate Office of North Carolina indicates that MPE compares well with the independent daily precipitation-gage network over North and South Carolina (Boyles and others, 2006).

[*]Water year is the period October 1 through September 30 and is identified by the year in which the period ends. For example, the 2005 water year is October 1, 2004, through September 30, 2005.

Multiport Piezometers

Pore-water samples from sediments below the river/riverbed interface can be difficult to collect. In the permeable sediments beneath the Neuse River, large changes in the chemical composition of the pore water could, theoretically, occur over short distances. In order to consistently collect multiple samples from a single location at different depths, two multiport piezometers, each containing eight sampling ports, were constructed in a manner similar to that described in Martin and others (2003; fig. 5).

The two multiport piezometers were installed beneath the bed of the Neuse River by hydro-jetting (using high-pressure water to liquefact the sediment). The general stratigraphy observed during jetting was recorded. The piezometers were allowed to settle and equilibrate with the streambed sediments for 3 months before water-quality samples were collected. Locations of the installed piezometers are shown in figure 3.

To collect samples from the screened piezometer ports, each tube was pumped with a peristaltic pump at a rate of about 1 milliliter per second (mL/s). The pumping rate differed slightly from port to port based upon the sediment permeability near the port. Pore water was pumped into a 100-mL container that was allowed to overflow and was monitored continuously for temperature and conductivity by using a calibrated portable field meter. Field properties were recorded, and the pore-water samples were filtered using an in-line 0.45 micron filter and decanted into a bottle.

Seepage Meters

Seepage meters provide a method to measure losses or gains associated with groundwater flux across a streambed surface. The conventional seepage meters used for this study were inexpensive and simple to fabricate. To fabricate a seepage meter for this study, a bottomless cylinder was formed by inverting a 5-gallon polyvinyl chloride (PVC) bucket, which had been trimmed to leave a wall about 3 in. deep. A fitting was installed in the top of the inverted bucket to allow the connection of a discharge tube and sample-collection bag. A second fitting was installed to allow for gas escape, if present. The cross-sectional area of each meter used in this study was 0.573 square foot (ft^2).

To measure vertical groundwater seepage (flux) to or from the Neuse River, the seepage meter was pushed into the bed sediment, and a collection bag containing 0.5 liter (L) of water was attached to the discharge tube. The collection bag was removed after a period of time ranging from 15 minutes to 1 hour, a time period long enough for there to be a measurable change in the volume of water contained in the bag. An increase in the volume of water contained in the bag indicated groundwater discharging to the Neuse River, and a decrease

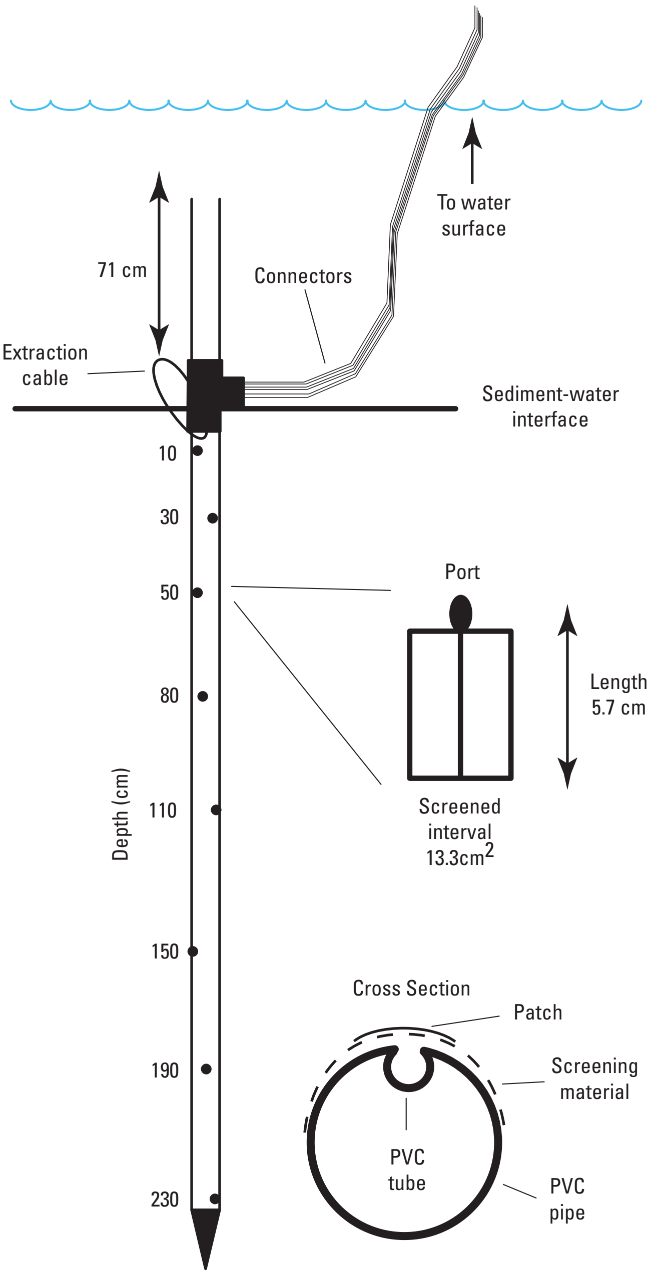


Figure 5. Schematic construction diagram of a multiport piezometer installed at the Raleigh hydrogeologic research station, Wake County, North Carolina (modified from Martin and others, 2003).

in the volume of water contained in the bag indicated a loss of water from the Neuse River to the underlying sediments. Two different seepage meters were used to measure vertical groundwater seepage, and multiple measurements were made by relocating each seepage meter to a different area in the vicinity of each site. The rate of vertical groundwater flux through the area of the streambed was calculated by a relation between the area of the streambed enclosed by the seepage meter, the volume of water lost or gained from the bag, and the length of time of collection as defined in equation 1 below (Majcher and others, 2006).

$$q_v = Q/A, \tag{1}$$

where

q_v is seepage flux (units of length per time),

Q is volume of seepage into or out of the bag divided by the time interval of collection (units of cubic length per time), and

A is cross-sectional area of the seepage meter (units of square length).

Neuse River Stage

The river stage at USGS station 0208739677 (Neuse River below SR 2555 near Auburn, N.C.) was recorded in 15-minute intervals from April to June 2006, but the stage recorder was discontinued because it was destroyed by Tropical Storm Alberto on June 14, 2006. Stage measurements were collected using a submersible pressure transducer to the nearest 0.01 ft and recorded by a data-collection platform (DCP). The pressure transducers were field checked periodically and corrected to measurements read from a staff plate following methods described in Freeman and others (2004).

Hydrogeologic Characterization

Groundwater at the RHRS occupies pore spaces in the shallow, weathered regolith and fractures and discontinuities below the weathered regolith. The regolith serves as the primary storage reservoir and is the source of recharge to the bedrock fractures (Chapman and others, 2005). The three well-cluster locations at the RHRS were located geographically to provide water-quality and water-level data along a topographic transect, spanning areas of recharge and discharge. A total of 3 coreholes, 12 wells, and 4 piezometers were installed at the RHRS during this investigation (table 1). A conceptual hydrogeologic cross section (G–G′; fig. 3) was constructed along the well transect from cluster WC-3 (presumed recharge area) to cluster WC-1 (presumed discharge area; fig. 6) using descriptions obtained from continuous core borings and geologist’s logs collected at each cluster site. The Neuse River incises the regolith on the northern edge of the RHRS and also serves as a groundwater-discharge area. Detailed core descriptions for each core boring at the RHRS can be found in McSwain and others (2009).

Regolith

The regolith at the RHRS is the shallowest component of the groundwater system and includes all soil residuum, alluvium, and saprolite that overly the transition zone and competent crystalline bedrock. 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, while weathering of feldspars and micas produces clay as residuum.

The composition and thickness of the regolith varies along the well transect. About 33 ft of regolith was encountered in corehole WC-1CH in the lowest topographic area, the majority of which was described as alluvium consisting of grayish brown, reddish brown, or yellowish brown silty fine sand to coarse gravel with some cobbles, trace clay, and organic matter (McSwain and others, 2009). The thick alluvium encountered at corehole WC-1CH was because of the close proximity of the boring to the Neuse River, where scouring and deposition of alluvial material had occurred in the past. At coreholes WC-2CH and WC-3CH, about 48 and 33 ft of regolith were encountered, respectively (fig. 6). The regolith in these two coreholes consists of saprolite characterized as a light yellowish to grayish brown fine to very coarse sand with trace amounts of silt, vermiculite, and biotite (McSwain and others, 2009).

Three shallow wells were completed in the regolith—one at each of the three clusters (fig. 6; table 1). These shallow (“S”) wells were completed at depths of about 13 to 28 ft below land surface in the shallow part of the regolith within the alluvium and (or) saprolite. Additionally, four piezometers (“PZ” wells; table 1) were completed at similar depths within the regolith at well cluster WC-1 for use in an aquifer test. Because of difficulties encountered during drilling, well WC-2S and piezometers PZ-3 and PZ-4 were likely screened in the regolith or alluvium and uppermost part of the transition zone. In the alluvium, soil residuum, and saprolite, groundwater flows through intragranular pore spaces or through relict fractures, and these materials typically have high porosity values. However, alluvium and soil residuum commonly have low to moderate hydraulic conductivity compared to saprolite. Slug tests conducted on wells completed within the saprolite at the RHRS yielded hydraulic conductivity values of 6 to 7 feet per day (ft/d) at wells WC-2S and WC-3S. In contrast, the hydraulic conductivity calculated at well WC-1S, which was completed primarily in alluvium, was 0.8 ft/d (McSwain and others, 2009).

Table 1. Characteristics of the monitoring wells and the surface-water sites at the Raleigh hydrogeologic research station, Wake County, North Carolina.

[NAVD 88, North American Vertical Datum of 1988; WC, well cluster; S, shallow regolith; I, intermediate zone regolith; D, deep; CH, core hole; PZ, piezometer; PVC, Schedule 40 polyvinyl chloride casing; Galv. steel, galvanized steel; R, regolith; B, bedrock; T, transition zone; SW, surface-water site; unk, unknown; na, not applicable]

Site identification	Station name	Latitude ddmmss.ss	Longitude ddmmss.ss	Construction date	Land-surface altitude (feet above NAVD 88)	Top of casing altitude (feet above NAVD 88)	Casing material	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
									From	To		
354328078295701	WK-328 Raleigh RS WC-1S	354328.83	782957.83	3-30-2005	171.24	173.74	PVC	4	13	28	0.01 in. slotted PVC	R
354328078295702	WK-329 Raleigh RS WC-1I	354328.86	782957.66	3-29-2005	170.90	173.62	PVC	4	24	39	0.01 in. slotted PVC	T
354328078295703	WK-330 Raleigh RS WC-1D	354328.95	782957.3	4-06-2005	169.27	172.07	Galv. steel	6	82	342	Open hole	B
354328078295704	WK-331 Raleigh RS WC-1CH	354329.12	782956.93	1-12-2005	165.48	167.88	Galv. steel	6	21	90	Open hole	B
354328078295705	WK-369 Raleigh RS PZ-1	354328.38	782958.2	2-14-2005	172.23	174.73	PVC	1	14.5	24.5	0.01 in. slotted PVC	R
354328078295706	WK-370 Raleigh RS PZ-2	354328.52	782957.65	2-15-2005	171.37	173.87	PVC	1	17.5	27.5	0.01 in. slotted PVC	R
354328078295707	WK-371 Raleigh RS PZ-3	354328.74	782956.7	2-15-2005	165.32	167.82	PVC	1	19	29	0.01 in. slotted PVC	R
354328078295708	WK-372 Raleigh RS PZ-4	354329.33	782956.07	2-15-2005	166.94	169.44	PVC	1	16	26	0.01 in. slotted PVC	R
354315078300101	WK-332 Raleigh RS WC-2S	354314.77	783001.87	3-31-2005	189.64	192.33	PVC	4	13.5	28.5	0.01 in. slotted PVC	R
354315078300102	WK-333 Raleigh RS WC-2I	354315.74	783001.92	4-05-2005	189.95	192.46	PVC	4	27	42	0.01 in. slotted PVC	T

Table 1. Characteristics of the monitoring wells and the surface-water sites at the Raleigh hydrogeologic research station, Wake County, North Carolina.—Continued

[NAVD 88, North American Vertical Datum of 1988; WC, well cluster; S, shallow regolith; I, intermediate zone regolith; D, deep; CH, core hole; PZ, piezometer; PVC, Schedule 40 polyvinyl chloride casing; Galv. steel, galvanized steel; R, regolith; B, bedrock; T, transition zone; SW, surface-water site; unk, unknown; na, not applicable]

Site identification	Station name	Latitude ddmmss.ss	Longitude ddmmss.ss	Construction date	Land-surface altitude (feet above NAVD 88)	Top of casing altitude (feet above NAVD 88)	Casing material	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
									From	To		
354315078300101	WK-332 Raleigh RS WC-2S	354314.77	783001.87	3-31-2005	189.64	192.33	PVC	4	13.5	28.5	0.01 in. slotted PVC	R
354315078300102	WK-333 Raleigh RS WC-2I	354315.74	783001.92	4-05-2005	189.95	192.46	PVC	4	27	42	0.01 in. slotted PVC	T
354315078300103	WK-334 Raleigh RS WC-2D	354315.28	783001.91	2-17-2005	188.49	191.28	Galv. steel	6	59	440	Open hole	B
354315078300104	WK-335 Raleigh RS WC-2CH	354316.1	782959.35	2-08-2005	199.50	202.22	PVC	4	70	85	0.01 in. slotted PVC	B
354305078295802	WK-337 Raleigh RS WC-3I	354305.59	782958.14	2-09-2005	210.27	212.96	PVC	4	34	49	0.01 in. slotted PVC	T
354305078295803	WK-338 Raleigh RS WC-3D	354305.72	782958.13	1-13-2005	209.83	212.58	Galv. steel	6	40	300	Open hole	B
354305078295804	WK-339 Raleigh RS WC-3CH	354305.24	782958.67	12-14-2005	206.27	208.69	PVC	4	40	125	Open hole	B
0208739670	Neuse River tributary near Auburn, NC	354316.17	783006.24	4-15-2006	unk.	na	na	na	na	na	na	SW
0208739677	Neuse River below SR2555 near Auburn, North Carolina	354330.61	782956.52	2-28-2006	142.65	na	na	na	na	na	na	SW
02087500	Neuse River near Clayton	353850	782419	8-01-1927	128.41	na	na	na	na	na	na	SW

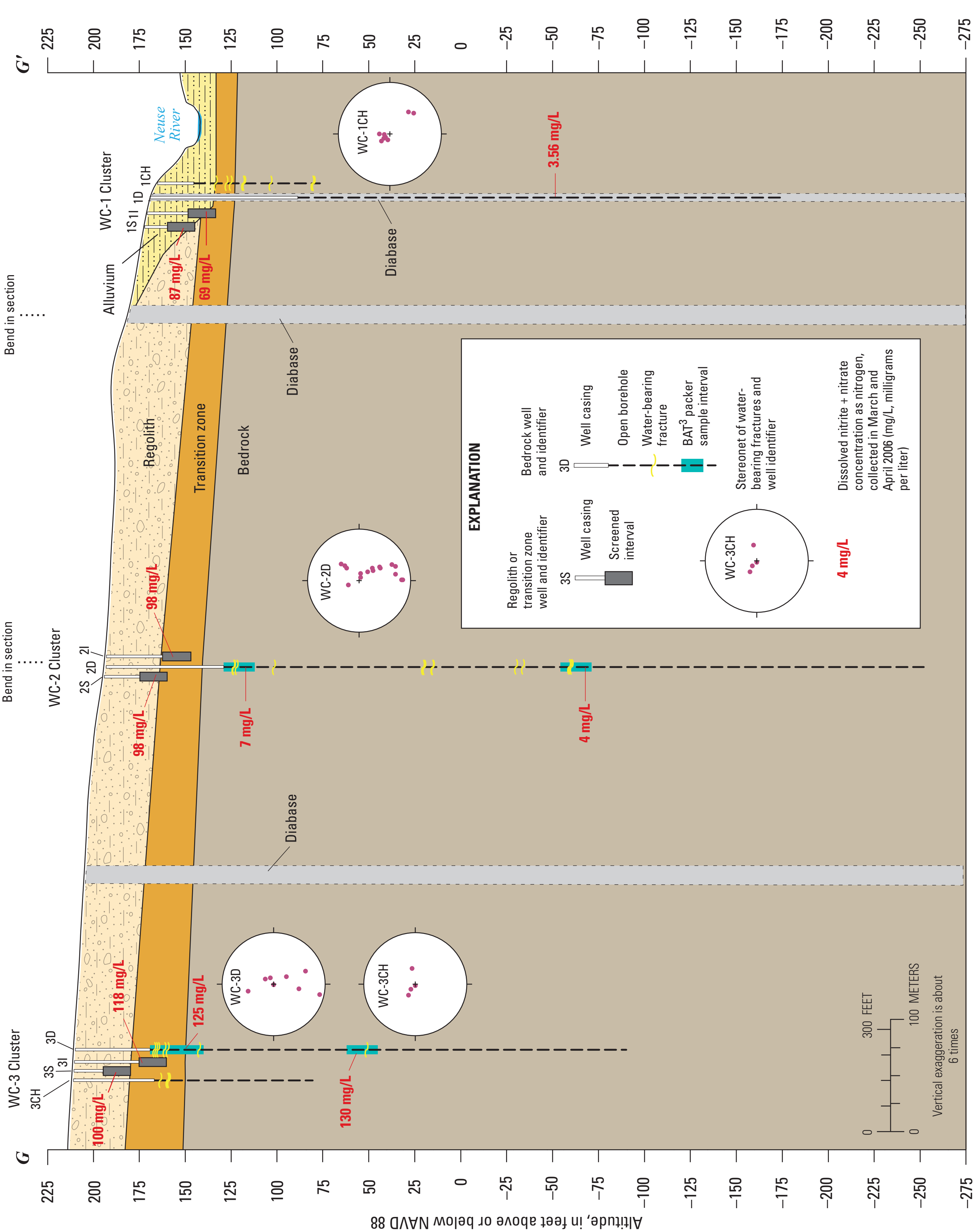


Figure 6. Generalized hydrogeologic cross section G–G′ at the Raleigh hydrogeologic research station, Wake County, North Carolina, with well-construction, equal-area stereonets showing orientation of water-bearing fractures, altitude of water-bearing fractures and BAT[3] packer sample intervals, and dissolved nitrate + nitrite as nitrogen concentration. Location of section G–G′ is shown in figure 3.

Transition Zone

A zone of slightly weathered granite bedrock and numerous open near-horizontal fractures near the top of the bedrock at the RHRS separate the overlying highly weathered regolith from the competent bedrock. Within this transition zone, the bedrock is weathered and altered, but not to the degree necessary to create substantial amounts of clay minerals. At the RHRS, the thickness of the transition zone increases with higher altitude along the well transect, with about 11 ft encountered at corehole WC-1CH, 22 ft at WC-2CH, and 30 ft at WC-3CH.

The weathered rock in the transition zone at coreholes WC-1CH and WC-3CH was characterized as light gray, yellowish brown, and in some places orange granite, weathered to fresh, containing biotite, feldspar, and quartz with well-preserved granitic texture and mineral grain sizes ranging from medium to coarse. Quartz-filled and open fractures within the core samples were common and were predominantly near horizontal in orientation. In corehole WC-2CH, some of the rock in the transition zone differed markedly in color and composition from that encountered at coreholes WC-1CH and WC-3CH. Transition zone material in a portion of corehole WC-2CH (48 to 86 ft) was characterized as olive to dark gray or dark reddish brown, slightly plastic clayey silt to slightly weathered diabase, with poorly preserved relict laminations. This portion of corehole WC-2CH transected a diabase dike that had intruded through the granite. Iron oxide-infilled fractures were common, but the orientation of the fractures appeared to be random for the most part.

Three intermediate wells were completed in the transition zone—one at each of the three clusters (fig. 6; table 1). These “I” wells were completed in the deepest part of the regolith across the saprolite and bedrock interface. Groundwater flows through pore spaces and open fractures within the saprolite and partially weathered bedrock. Slug tests conducted on wells completed within the transition zone at the RHRS yielded hydraulic conductivity values ranging from 2 ft/d at well WC-1I to 5 ft/d at wells WC-2I and WC-3I (McSwain and others, 2009).

Bedrock

Bedrock lithology and fractures at the RHRS were described from core samples and geophysical logs and images. Lithologic interpretations were based on descriptions from geologic core and drill cuttings, natural gamma logs, and oriented optical televiewer images. Fractures in the bedrock were first noted from the core samples and then further characterized by using caliper and resistivity logs, fluid resistivity and temperature logs, flowmeter logs, and oriented optical televiewer images.

Six wells were completed in the bedrock—two at each of the three clusters (fig. 3; table 1). The “D” wells were completed as open-hole wells within the bedrock, and the “CH” wells were completed as open-hole bedrock wells upon completion of the coreholes, with the exception of well WC-2CH, which was installed with a screen. Wells WC-1CH, WC-3D, and WC-3CH are also open to the bottom part of the transition zone. Slug tests conducted on five of the wells completed within the bedrock (well WC-1D was not tested) yielded hydraulic conductivity values that ranged from 0.4 ft/d at well WC-3CH to 10 ft/d at well WC-2D (McSwain and others, 2009).

Lithology

Based on observed rock outcrops, bedrock-core samples, and geophysical logs from the RHRS, the site is underlain by granitic rocks of the Rolesville granite batholith, the largest granitic body in the Eastern United States. The Rolesville batholith is reported to be composed of at least three distinct intrusions, based on geochemical and textural indications (Schneider and Samson, 2001). Core borings at WC-1CH and WC-3CH predominantly encountered the finer grained Rolesville granite “main phase” intrusion, which at the RHRS is described as a gray and pink, fine to medium grained biotite granite with some megacrystic feldspar. The granitic rock outcrops and core specimens from the RHRS show very weak foliation that appear to be striking to the northeast and steeply dipping to the southeast.

Tabular basaltic diabase dike intrusions with a near vertical orientation are commonly found in the Rolesville granite and several are noted on the North Carolina State Geologic Map (North Carolina Geological Survey, 1985). Surface geophysical mapping of the RHRS using a magnetometer revealed the presence of at least two unmapped diabase dikes that appear to strike roughly due north (fig. 3; McSwain and others, 2009). The diabase dikes at the RHRS are highly vertically jointed, mafic, fine grained diabase with some chlorite. Well WC-1D at well cluster WC-1 and WC-2CH at well cluster WC-2 were completed within one of the diabase dikes. The exact dip angle of the diabase dikes is unknown, but appeared to be nearly vertical.

Well WC-1D was completed entirely within a diabase dike to a depth of 342 ft below land surface. Drilling through the weathered diabase while boring WC-1D was difficult because of the extreme degree of vertical fracturing that hampered drill progression. Even though the diabase bedrock is highly fractured at this location, well WC-1D yielded essentially no water as the fractures within the diabase dike appear to be isolated from the surrounding granite bedrock and the overlying alluvium. Because of the highly fractured nature of the diabase, it was impossible to collect optical televiewer logs to determine orientation of fractures even though the well was completed with an open hole.

Well WC-2CH was completed within corehole WC-2CH at cluster WC-2, which transected a diabase dike as delineated by magnetometer survey, and is located about 300 ft to the east of the other wells located in cluster WC-2. The corehole at WC-2CH penetrated through the top of the dike at a depth of about 48 ft and came out through the bottom of the dike at a depth of about 86 ft. The top of the diabase dike in corehole WC-2CH was visible within the core samples as a dense, plastic olive-green clay saprolite that was distinct from the light colored sandy granitic saprolite on top of the dike. The granite encountered below the diabase dike in corehole WC-2CH was slightly weathered and highly fractured at the contact with the diabase. No diabase or granite saprolite was noted at the lower contact between the dike and the granite. Optical televiewer logs were not collected in this well because the highly friable nature of the diabase in this borehole necessitated completing the well with a screen.

Interpretation of Geophysical and Hydraulic Logs

Geophysical logs were collected at all the open-hole bedrock wells at the RHRS, with the exception of WC-1D because of the unstable nature of the diabase. An integrated analysis of geophysical logs was used to identify the location and distribution of fractures within the bedrock of each well. Fracture orientations were determined from the OTV image of the borehole wall and are plotted as tadpole diagrams (figs. 7–10).

Fractures noted from an integrated analysis of borehole geophysical logs collected in wells WC-1CH, WC-2D, WC-3D, and WC-3CH were separated into three groups "water bearing," "secondary," and "sealed." Water-bearing fractures were delineated on the basis of the presence of visible iron or biological staining on the OTV log and anomalies in the caliper and resistivity logs that may indicate the probability of water flowing within the fracture. A total of 36 water-bearing fractures were identified along with 198 discrete separations or discontinuity planes within the bedrock that did not appear to be water bearing and were identified as secondary fractures. Seventeen fractures with partings that have been partially or completely joined together by the deposition of crystalline material were identified as sealed fractures.

The orientation of planar features interpreted from the OTV logs have been plotted in the form of rose diagrams and lower hemisphere equal-area stereonets, both of which provide a graphical method for assessing the pattern of planar features (figs. 11, 12). Rose diagrams are histograms for which the orientation axis is transformed into a circle to give a true angular plot. As used here, the strike of a foliation or fracture is plotted as pie-shaped segments of a circle in its true orientation, and the length of the radius is proportional to the frequency of occurrence of that orientation. Although a rose diagram is limited to displaying only one aspect of a planar feature, a stereonet can be used to graphically display both the strike and dip of a planar feature. A stereonet reduces each fracture plane to a point that represents the intersection of a pole, perpendicular to a fracture plane, with the lower hemisphere projected onto the equatorial plane of the hemisphere. Stereonets provide a graphical method for assessing the clustering or variability of the poles to planes.

A graphical comparison of the foliations measured in the four bedrock wells with OTV logs was made from the rose diagrams and stereonets shown in figures 11 and 12. About 470 foliations were observed in the boreholes. The foliations varied in both strike and dip and collectively appear to be scattered (figs. 11*A*, 12*A*). The orientation of foliations were difficult and somewhat subjective to interpret using OTV logs, but are presented here for comparison to the fracture orientations. The mean principal orientation of all foliations was north 80° east (N. 80° E.) with a dip of 15° south, which was seemingly much shallower than the steeply dipping foliations observed in the core. The rose diagram (fig. 11*A*) indicated that nearly 25 percent of the foliations measured had a strike between N. 60° E. and N. 90° E., which is consistent with the observed outcrop measurements of orientation.

Although the orientation of fractures varies within individual boreholes and across the site, some patterns can be detected within the different fracture types when examined as a whole. The rose diagrams of the water-bearing, secondary, and sealed fractures indicate a predominantly northeast to east-northeast strike (fig. 11*B*–*D*). On the stereonet (fig. 12*B*), poles to water-bearing fractures cluster in two sets—one set strikes east-northeast and dips shallowly to the south, and the second set strikes northeast and dips moderately to steeply to the northwest. Stereonets and altitudes of water-bearing fractures for individual bedrock wells are shown in figure 6.

Poles to secondary fractures appear to be scattered but cluster in four sets—one set strikes generally east-northeast and dips very shallowly to moderately to the south-southeast, a second set strikes northwest and dips moderately to the southwest, a third set strikes north and dips steeply to the west, and a fourth set strikes east-northeast and dips moderate to steeply to the north-northwest. Over half of the poles to sealed fractures cluster in the middle of the stereonet, indicating a very shallow dip.

A correlation exists between foliation and fracture orientation (fig. 11), with most fractures striking parallel to foliation. Nearly 60 percent of water-bearing fractures have shallow dips (less than 30°) (fig. 12*B*) and are likely stress-relief fractures caused by unloading of the granite. Within the secondary fractures there appears to be a conjugate joint that includes fractures with a north strike, but very few water-bearing fractures have similar orientations, which suggests little influence of the conjugate set on groundwater flow. There is more uncertainty and variability in the poles that plot in the center of the stereonet, because of the inherent difficulty of determining the direction of strike and dip on shallow features (with dips less than 30°). As a nearly vertical borehole is more likely to intersect the shallow dipping fractures than the steeply dipping fractures, it is likely that the quantity of steeply dipping fractures occurring within the Rolesville granite at the RHRS has been under sampled.

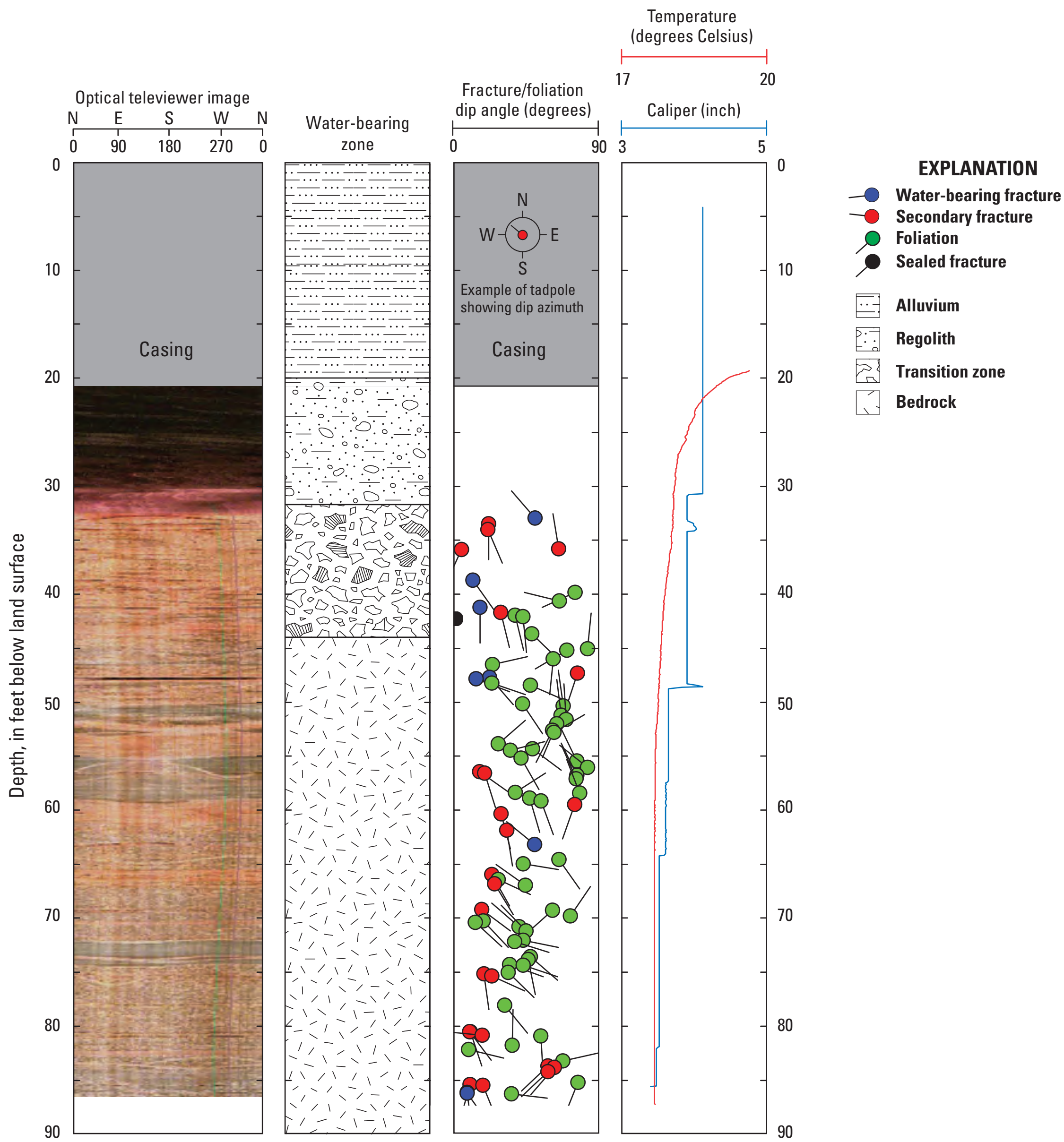


Figure 7. Geophysical logs and interpreted fractures, foliations, and water-bearing zones in bedrock well WC-1CH at the Raleigh hydrogeologic research station, Wake County, North Carolina.

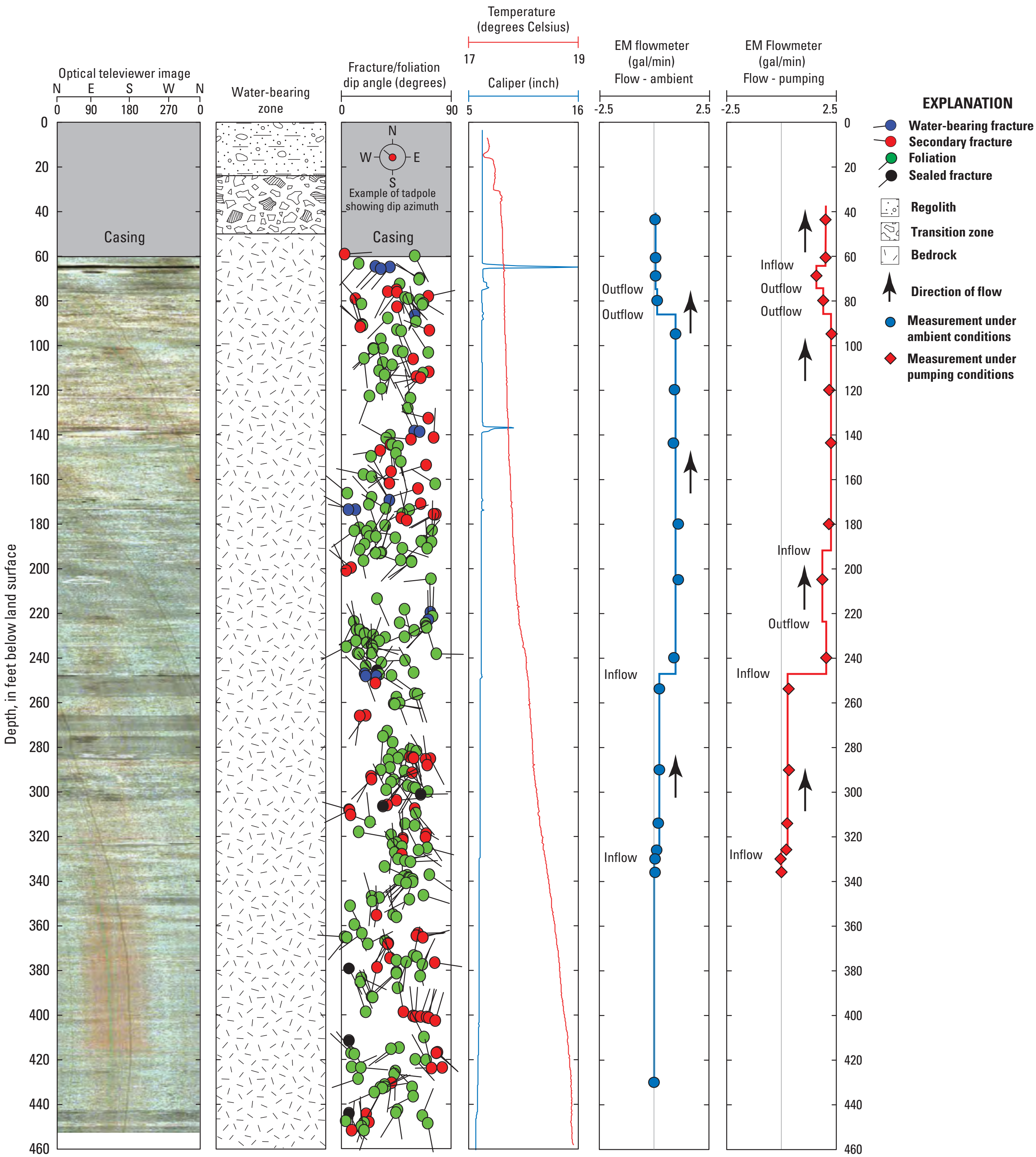


Figure 8. Geophysical logs and interpreted fractures, foliations, and water-bearing zones in bedrock well WC-2D at the Raleigh hydrogeologic research station, Wake County, North Carolina.

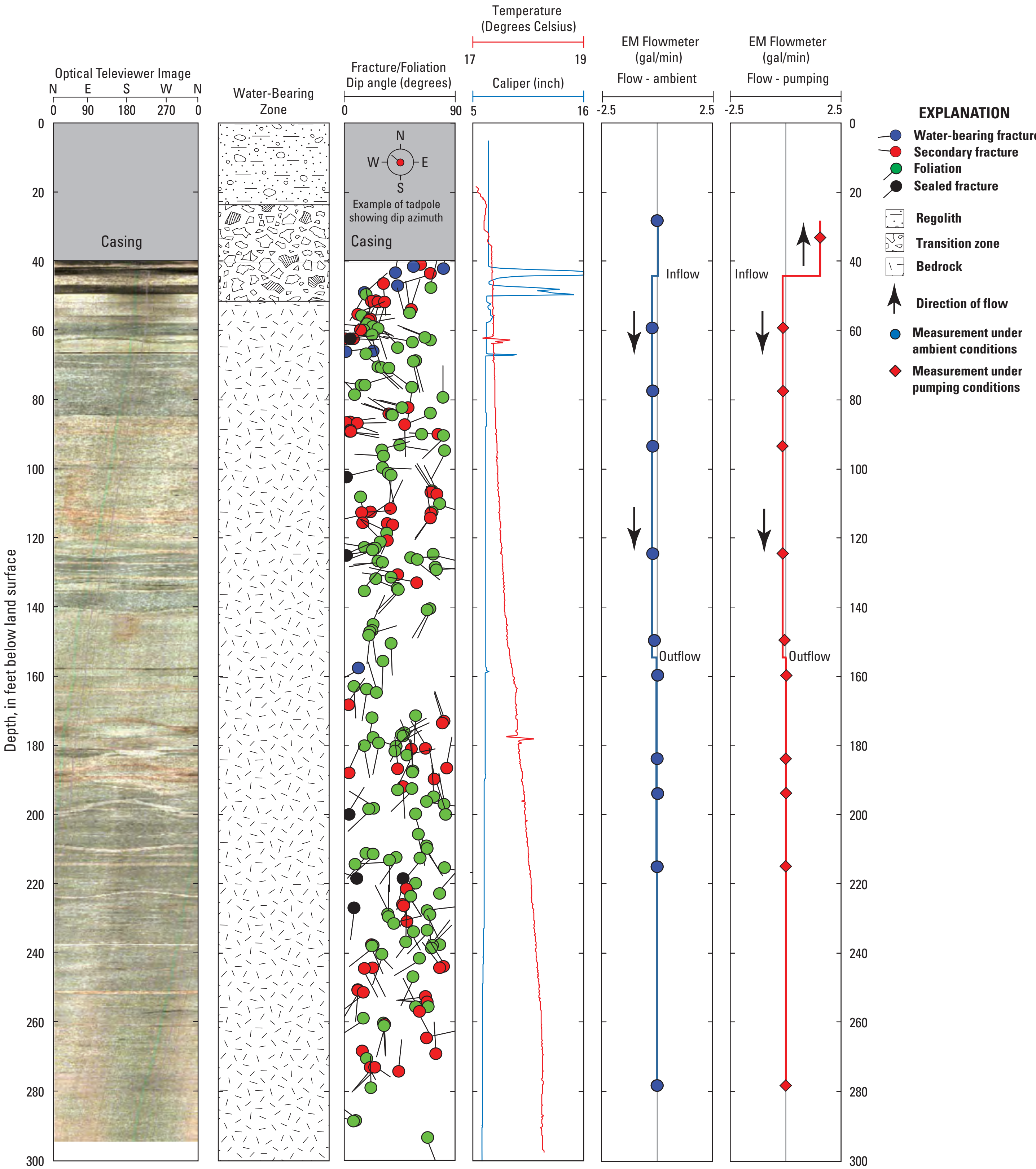


Figure 9. Geophysical logs and interpreted fractures, foliations, and water-bearing zones in bedrock well WC-3D at the Raleigh hydrogeologic research station, Wake County, North Carolina.

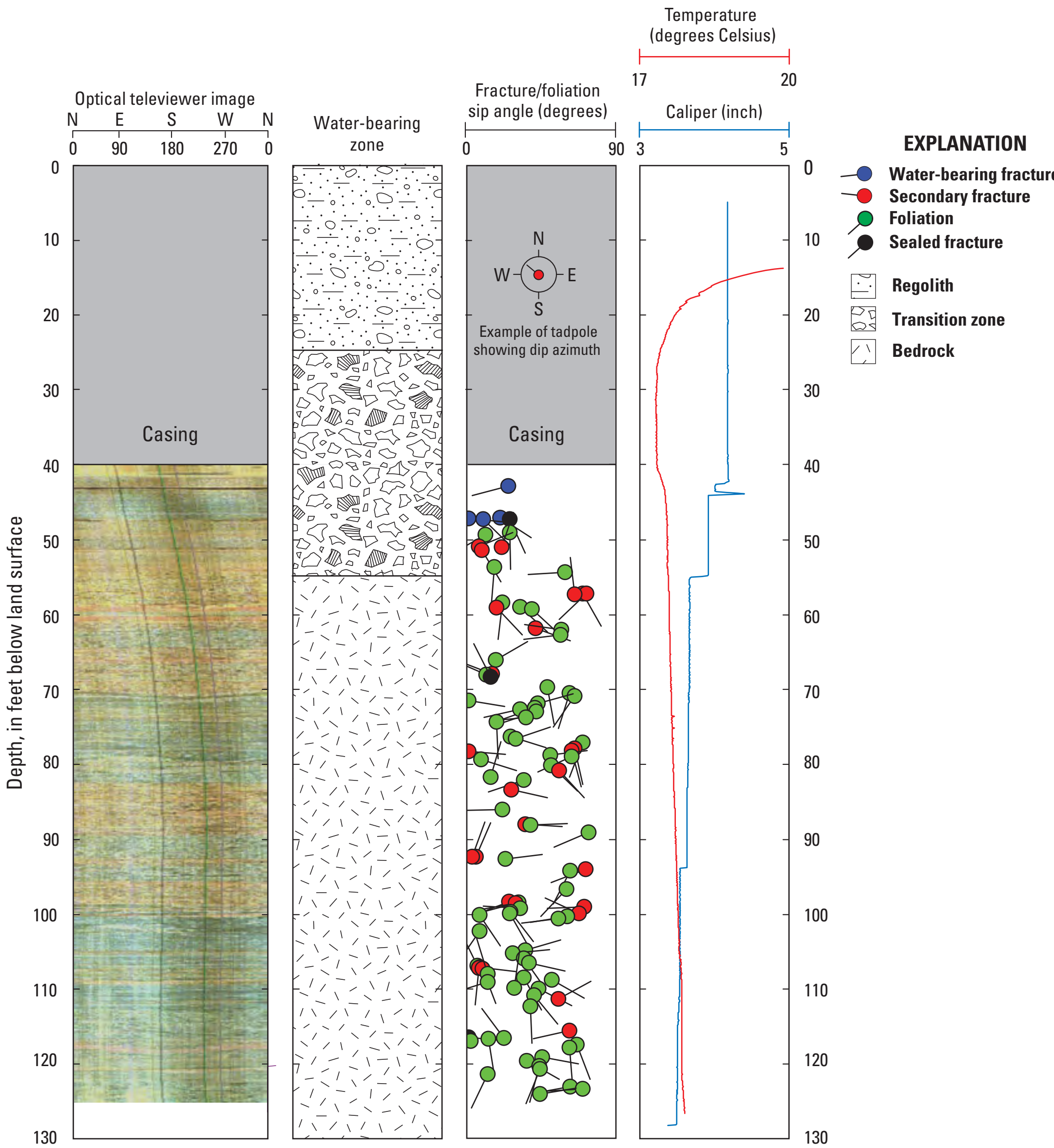


Figure 10. Geophysical logs and interpreted fractures, foliations, and water-bearing zones in bedrock well WC-3CH at the Raleigh hydrogeologic research station, Wake County, North Carolina.

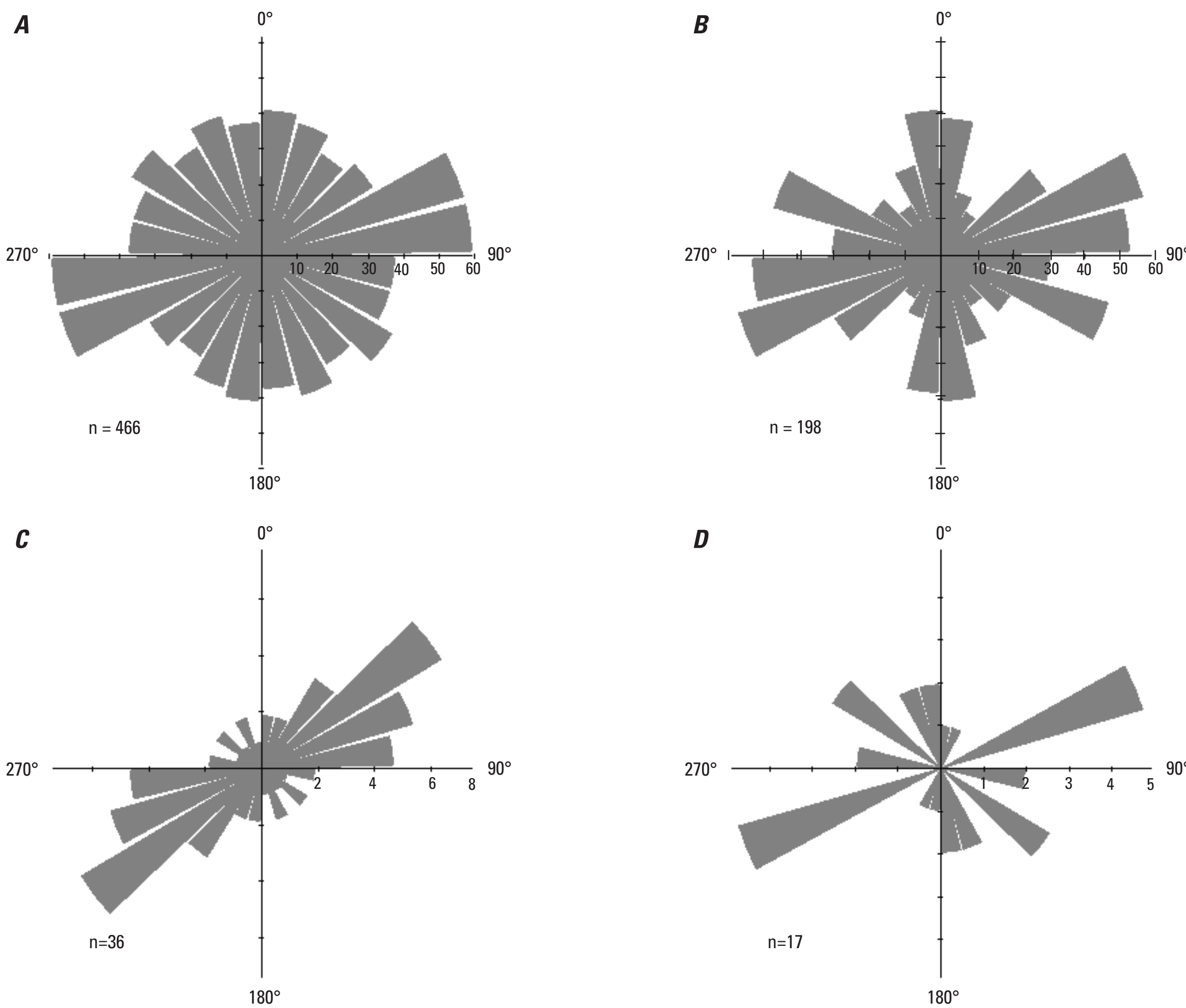


Figure 11. Rose diagrams of (*A*) foliations, (B) secondary fractures, (*C*) water-bearing fractures, and (D) sealed fractures in bedrock boreholes in the Raleigh hydrologic research station study area, Wake County, North Carolina.

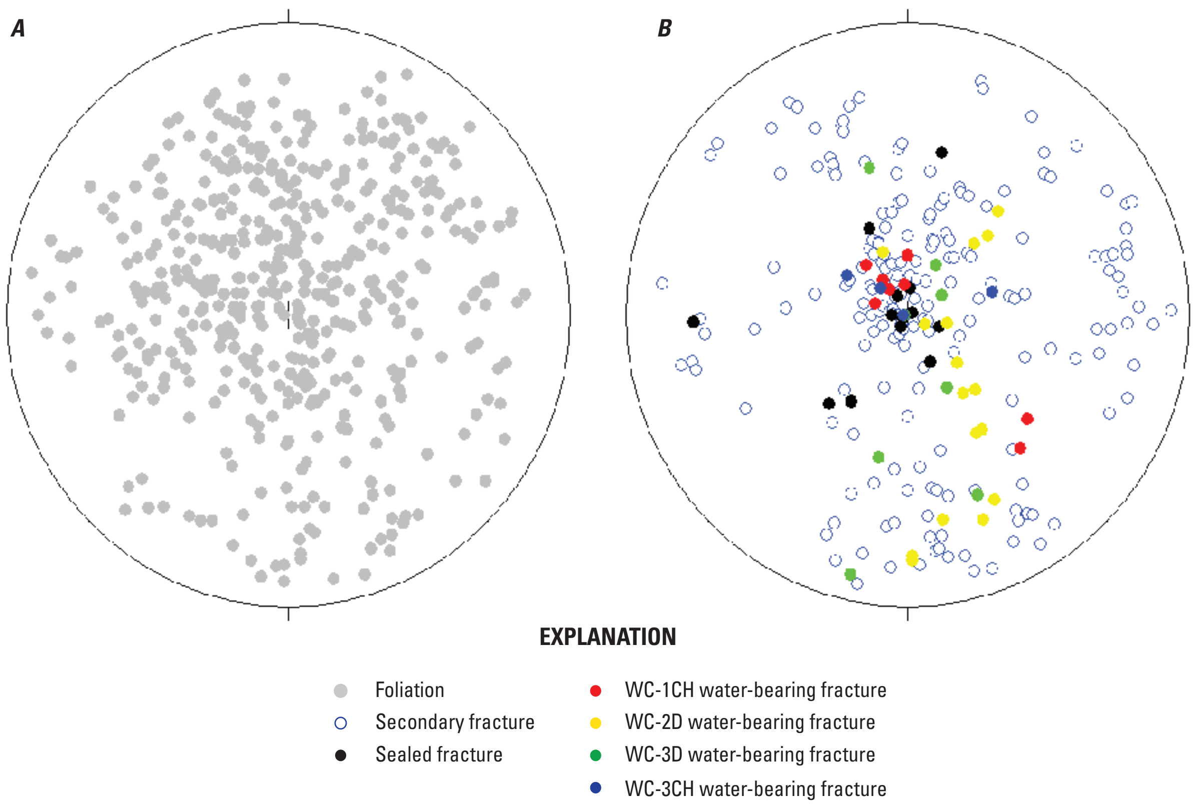


Figure 12. Lower hemisphere equal-area stereonet showing poles to planes of (*A*) foliations and (*B*) fractures in bedrock boreholes in the Raleigh hydrologic research station study area, Wake County, North Carolina.

Flowmeter logging under ambient and stressed conditions was conducted in wells WC-2D and WC-3D to determine the relative contribution of water from transmissive fractures to the well. Individual stereonets displaying the orientation of the transmissive fractures are shown on figure 6. The EM flowmeter surveys results are shown in figures 8 and 9. By convention, upward flow in a borehole is designated with a positive value and downward flow with a negative value. A change in the measured rate of vertical flow in the borehole indicates an addition or removal of water between the two measurement locations. Because vertical flow in a borehole is controlled by the relation of hydraulic heads of groundwater within each fracture, the transmissivity of the fractures that intersect the borehole, and the variation of hydraulic heads over time, the magnitude and direction of ambient flow may vary temporally.

In well WC-2D under ambient conditions, four shallow dipping transmissive fractures at a depth of about 248 ft contributed the majority of water to the well (fig. 8). Water flowed upward within the borehole until it exited through a steeply dipping transmissive fracture at 86 ft. When pumped at 1 gal/min, the contributions of the fractures in well WC-2D were similar to ambient conditions, with the exception of a gain of about 0.4 gal/min from three fractures at a depth of about 64 ft that were inactive under ambient conditions. Under both ambient and stressed conditions, the higher hydraulic head of the deep transmissive fractures within the borehole caused water to flow upward to the transmissive fractures with lower hydraulic heads that occur at shallower depths.

Under both ambient and pumping conditions in well WC-3D, two shallow dipping transmissive fractures at about 66 ft contributed about 0.2 gal/min of water to the well (fig. 9). Water flowed downward within the borehole and out through transmissive fractures at about 158 ft. When pumped at 1.5 gal/min, the transmissive fractures at 66 ft continued to lose water downward at the same rate as under ambient conditions, while moderate to steeply dipping fractures at a depth of about 43 ft began supplying nearly all of the water to the borehole. Unlike in well WC-2D, under both ambient and stressed conditions in well WC-3D the hydraulic head of the shallower transmissive fractures was higher than that of the deeper transmissive fractures. This negative head difference within the borehole indicates a downward vertical gradient that can allow water to pass from shallower fractures to deeper fractures and facilitate the transport of surface contaminants to deeper zones within the bedrock.

Neuse River Stage

Fluctuations in the stage of the Neuse River control groundwater movement near well cluster WC-1. In order for groundwater to discharge into the Neuse River, the altitude of the water table near the river must exceed the stage of the river. If the altitude of the Neuse River is lower than the altitude of the water table, surface water will seep through the river bank and become groundwater. Thus, the altitude of the Neuse River stage is necessary to understand the interaction between groundwater and surface water in the area of well cluster WC-1. Locations of surface-water gages located near the RHRS within the Neuse River Basin are shown in figure 13.

The Neuse River at the RHRS (station 0208739677 Neuse River below SR 2555 near Auburn, NC; hereafter called the “Auburn” station) was ungaged for the majority of the study. A number of methods can be used to estimate stage for an ungaged site by using gaged sites; however, the direct measurement of river stage is preferable. About 2 months of continuous river stage levels were collected at the Auburn station during the study and were used to verify stage estimates at the Auburn station that were calculated by using other gaged sites.

Data for two long-term USGS gaging stations above and below the RHRS on the Neuse River were used to estimate river stage at the Auburn station. Station 02087500, Neuse River at Clayton, NC (hereafter called the “Clayton” station), has monitored river stage since 1927, and station 02087183, Neuse River near Falls, NC (hereafter called the “Falls” station), has monitored river stage since 1960. Two other River Net stations operated by North Carolina State University that monitor river stage and discharge are located upstream (at Auburn-Knightdale Road in Garner, North Carolina) and downstream (at Mial Plantation Road in Clayton, North Carolina) from the Auburn station (North Carolina State University, 2000). At the time of writing of this report, however, data for both of the River Net stations were unavailable for comparison purposes.

The Falls station is located about 22 river miles upstream from the RHRS, has a drainage area of about 771 square miles (mi^2), and is located just downstream from the Falls Lake dam. Stream stage measurements at the Falls station were not used in calculations because of the artificially controlled nature of the Neuse River near the dam. The Clayton station is downstream from the RHRS by about 10 river miles and has a drainage area of 1,150 mi^2, which is similar in size to that of the Auburn station (1,084 mi^2) making it a better choice to use in estimation of river stages near the RHRS. There are two major inputs to this reach of the Neuse River between the RHRS and the Clayton station, the outfall of the NRWWTP and Marks Creek. Both inputs are relatively small compared to the Neuse River discharge.

The Auburn station at the RHRS was monitored every 15 minutes for river stage from April 19, 2006 through June 14, 2006, when it was destroyed by floodwater from Tropical Storm Alberto. To estimate the difference in travel time between the Auburn and Clayton stations, the 15-minute river stage data for both stations were plotted against time. A travel time of 4 hours from the Auburn to Clayton stations was calculated by correlating river stage peaks that occurred during the data-collection period. River stage data at the Clayton station was then time shifted by -4 hours and plotted against stage data collected at the Auburn station to allow discrete comparison. Linear regression was applied to the data, a coefficient of regression (R^2) was calculated, and a mathematical

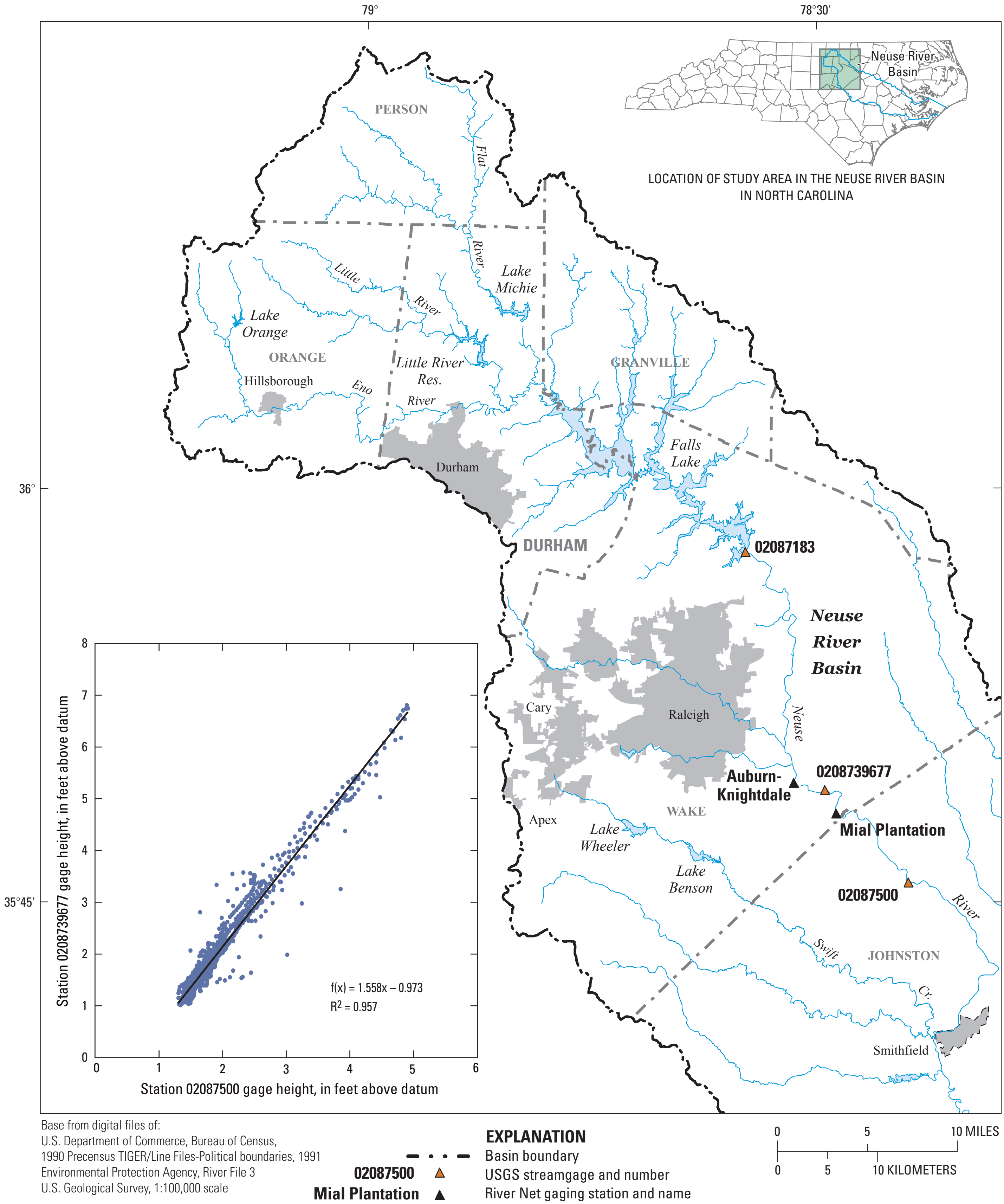


Figure 13. Locations of selected surface-water gages within the Neuse River Basin and linear regression of gage height measured at surface-water gaging stations 0208739677 (Neuse River below SR 2555 near Auburn, North Carolina) and 02087500 (Neuse River at Clayton, North Carolina) in Wake and Johnston Counties, North Carolina.

relation was determined (fig. 13). The R^2 for the plotted stage data was 0.957, indicating that stage data collected at the Clayton station was highly correlated with stage data collected at the Auburn station and could be used to estimate river stage at the Auburn station with relative certainty. The measured and estimated gage heights for the Auburn station were plotted over the same time period to validate that the estimated gage heights were similar to those measured (fig. 14). The gage height for the Auburn station was then estimated for the entire study period, May 2005 to September 2007, by applying the equation determined by linear regression to the 15-minute gage height data collected at the Clayton station and shifting the time by –4 hours (fig. 15).

Groundwater Levels

From May 2005 to September 2007, groundwater levels were continuously monitored in eight wells at well clusters WC-1 and WC-2 and recorded periodically in four wells at well cluster WC-3. Groundwater levels in the piezometers were measured periodically from February to July 2006.

Seasonal Trends

Groundwater levels measured at the RHRS had climatic and seasonal trends similar to fluctuations observed across the piedmont in the Southeastern United States (U.S. Geological Survey, 2007). Elevated groundwater levels generally occurred during the late spring or early summer following winter precipitation. As a result of increased evapotranspiration (ET) rates and reduced precipitation during the summer months, groundwater levels declined to a low in late fall. During the study period, typical seasonal trends were affected by persistent drought.

At well cluster WC-1, water levels in all wells and piezometers, with the exception of well WC-1D, were affected to some degree by their close proximity to the Neuse River (fig. 15). The water level in well WC-1D did not fully recover until 4 months after drilling was completed. Despite the interaction caused by the Neuse River (storm peaks can be seen in groundwater levels), there was a dampened seasonal trend in the water levels in the wells at well cluster WC-1, which was reflected to a lesser extent in base-flow trends in the river. In wells WC-1S and WC-1I, the typical range of seasonal groundwater-level fluctuation was about 5 ft, with the groundwater low occurring in November. As the groundwater high was directly linked to the stage of the Neuse River, it did not necessarily correlate to the late spring or early summer high typical for piedmont wells. In December 2006 and January 2007 the highest groundwater levels were measured in the wells at well cluster WC-1 because of a series of winter storm events that flooded the upper part of the Neuse River Basin.

Groundwater levels at well clusters WC-2 and WC-3 showed a more typical piedmont seasonal trend during the monitoring period, with the highest groundwater levels occurring about late May and the lowest in November (fig. 15). At well clusters WC-2 and WC-3, the typical range of seasonal groundwater-level fluctuation was about 4 ft. After the occurrence of rainfall during the study period, unlike at well cluster WC-1, all of the water levels in the continuously monitored wells at well cluster WC-2 rose gradually. This delayed response was likely due to the high storage capacity of the silt and clay present in the shallow regolith, retarding rapid recharge, coupled with a more than 15 ft depth to the water table at well cluster WC-2. Rainfall events with a long duration and moderate intensity had the greatest effect on recharge to the groundwater system, especially during the winter months when ET rates were low and soil moisture was high, allowing more rainfall to infiltrate to the water table. This occurred most notably in November 2006 when the area received more than 7 in. of rain, which caused a rise in the water table (fig. 15).

Groundwater-Level Altitudes and Relative Vertical Gradients

Throughout the study period, the water-level altitudes in the regolith, transition zone, and bedrock were variable between well clusters. An accurate calculation of vertical hydraulic gradients between the regolith, transition zone, and bedrock was not possible because of a well spacing of 20 ft between wells. Because there is generally little altitude difference between the wells at each cluster, it is possible to examine the position of water-level altitudes in each monitoring zone in relative terms. In comparing water-level altitude among the three zones of the groundwater system, well cluster WC-3 was consistent with the conceptual slope-aquifer system model, but well clusters WC-1 and WC-2 were more complex. At well cluster WC-3, located in the upgradient recharge area, water levels had lower hydraulic heads with increasing well depth (fig. 15). This downward hydraulic gradient supports the conceptual model theory that recharge occurs in areas of topographic highs.

Well cluster WC-2 is topographically mid-slope and should be in a recharge area based on the conceptual model. An accurate calculation of vertical gradients between all the wells at the WC-2 well cluster was not possible because well WC-2CH is located about 200 ft east of the other wells in the cluster and was completed partly within a diabase dike (fig. 3). Additionally, well WC-2CH is about 10 ft higher in land-surface altitude than the other wells in well cluster WC-2. This vertical and horizontal separation from well WC-2D, coupled with its completion in the diabase dike, was likely the reason that the water-level altitude in well WC-2CH was consistently about 5 ft higher than the other bedrock well in the cluster (fig. 15). If vertical gradient comparisons are made between the remaining three wells at well cluster WC-2, the bedrock has a water-level altitude that was consistently higher than those measured in the transition zone and regolith, indicating an upward gradient (discharge) from the bedrock aquifer to the

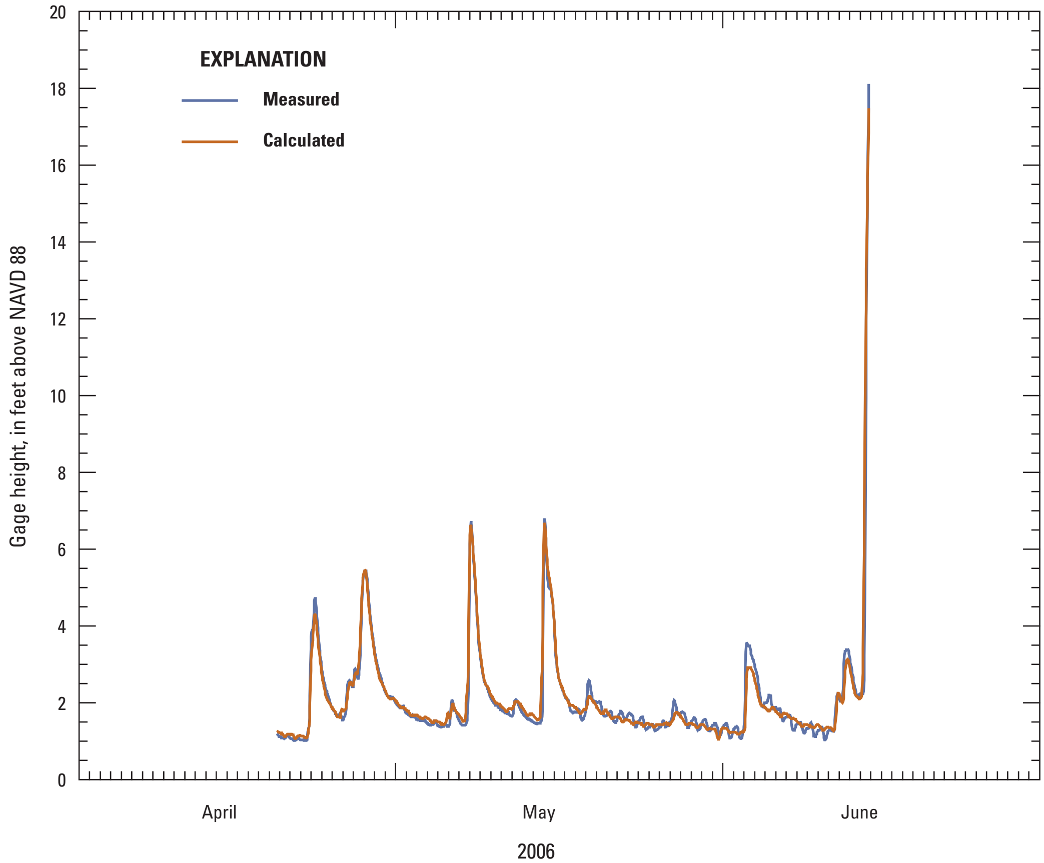


Figure 14. Measured and estimated gage height at station 0208739677 (Neuse River below SR 2555 near Auburn, North Carolina) in Wake County, North Carolina.

surficial aquifer. Conversely, within the surficial aquifer at the WC-2 cluster, the regolith generally had a higher water-level altitude than that of the transition zone, indicating a downward gradient (recharge).

Water levels at well cluster WC-1 were affected by interaction with Neuse River water levels and are, therefore, more complex than those found at well clusters WC-2 and WC-3 where the relative position of hydraulic heads to one another was relatively consistent. Under typical hydrologic conditions at well cluster WC-1, the water-level altitudes of the well and the two piezometers completed in the regolith (well WC-1S and piezometers PZ-1 and PZ-2) were higher than that of wells and piezometers partially or fully completed within the transition zone and granite bedrock (wells WC-1I and WC-1CH, and piezometers PZ-3 and PZ-4) (fig. 16), indicating a local downward gradient. However, all regolith, transition zone, and deeper bedrock aquifer water levels generally were higher than the river stage, indicating that groundwater generally has the potential to discharge to the Neuse River except during particularly wet periods. When the stage of the Neuse River rises as during Tropical Storm Alberto on June 15, 2006, the gradient reverses, and the water levels in wells and piezometers that are partially or fully completed within the transition zone are higher than those wells and piezometers that are completed within the regolith (fig. 17). The concurrent responses of the transition zone wells in cluster WC-1 to changes in river stage and the approximate altitude of the river sediments indicate that the Neuse River has incised through the saprolite, and the alluvium is hydraulically connected to the transition zone (figs. 6, 17).

The degree of vertical gradient reversal among the regolith, transition zone, and bedrock was dependent upon the stage of the Neuse River. The rapid rise and fall of water levels indicated a pressure response as a result of stage changes in the Neuse River. These hydraulic head differences also affected the horizontal flow of water into and out of the Neuse River through bank storage effects (fig. 17). When the stage of the Neuse River was low and head in the aquifers exceeds the river stage, groundwater can discharge readily to the river. Conversely, when the stage of the Neuse River was high because of rainfall or releases from the upstream Falls dam, surface water moved into the river bank reducing the potential for groundwater discharge.

Water-Quality Data

Water-quality data from the wells and surface-water sites at the RHRS were collected continuously and during periodic

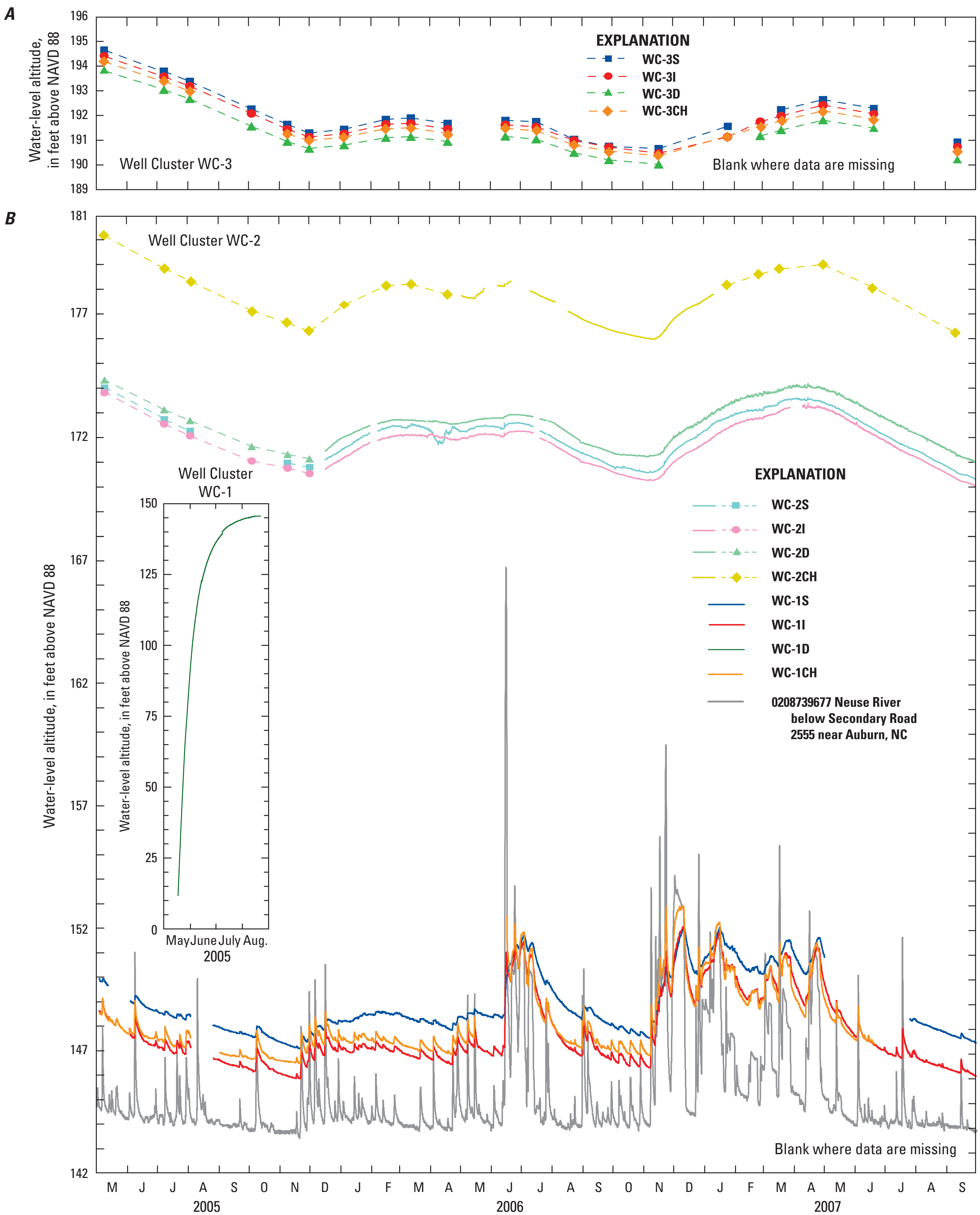


Figure 15. Periodic and continuous hourly groundwater levels and continuous 15-minute stage recorded at the Raleigh hydrogeologic research station, North Carolina, in (*A*) well cluster WC-3 and (*B*) well clusters WC-1 and 2 and surface-water station 0208739677 from May 2005 to September 2007.

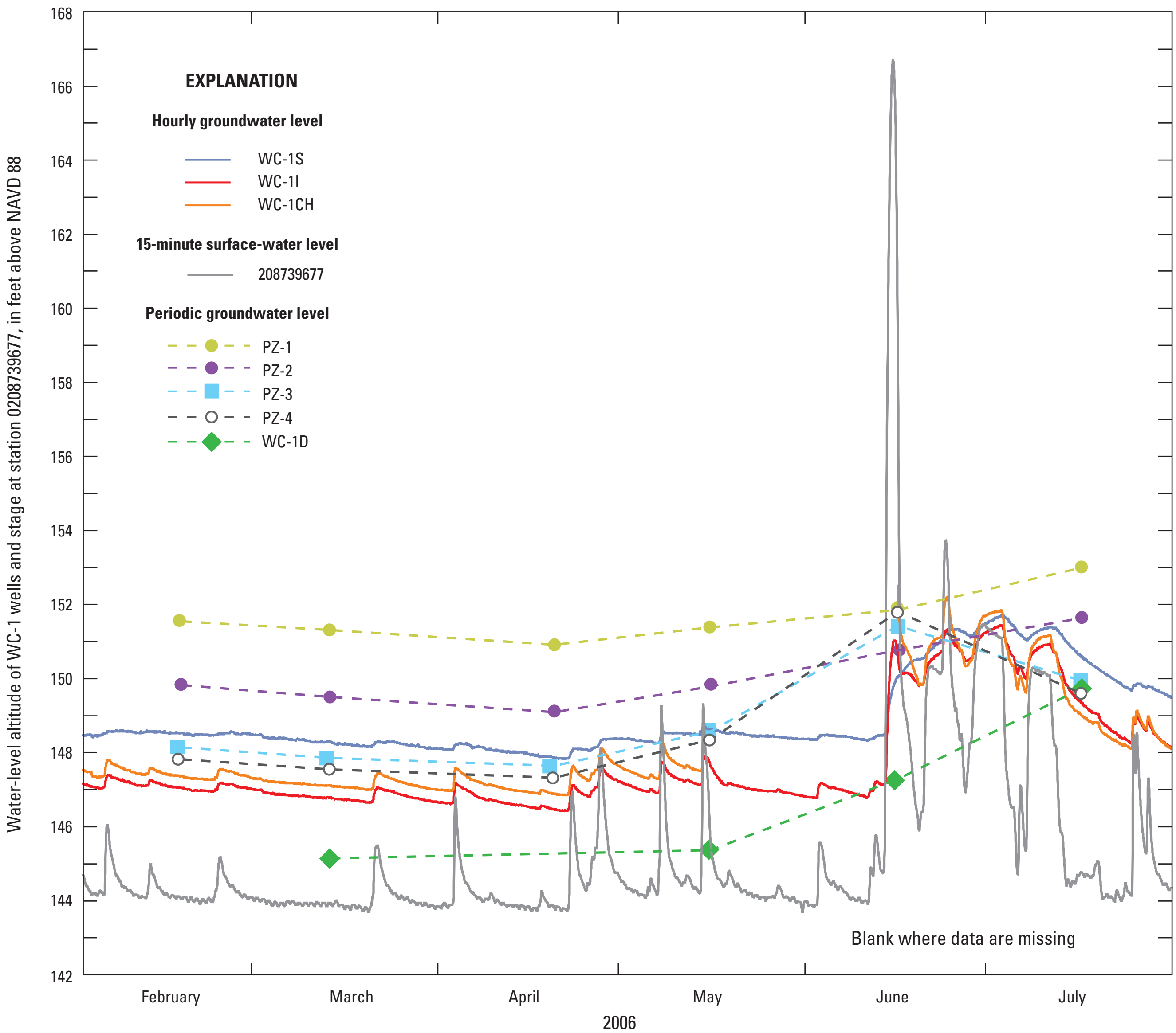


Figure 16. Periodic and hourly groundwater levels recorded in well cluster WC-1 and hourly stage recorded at surface-water station 0208739677 at the Raleigh hydrogeologic research station, North Carolina, from February to July 2006.

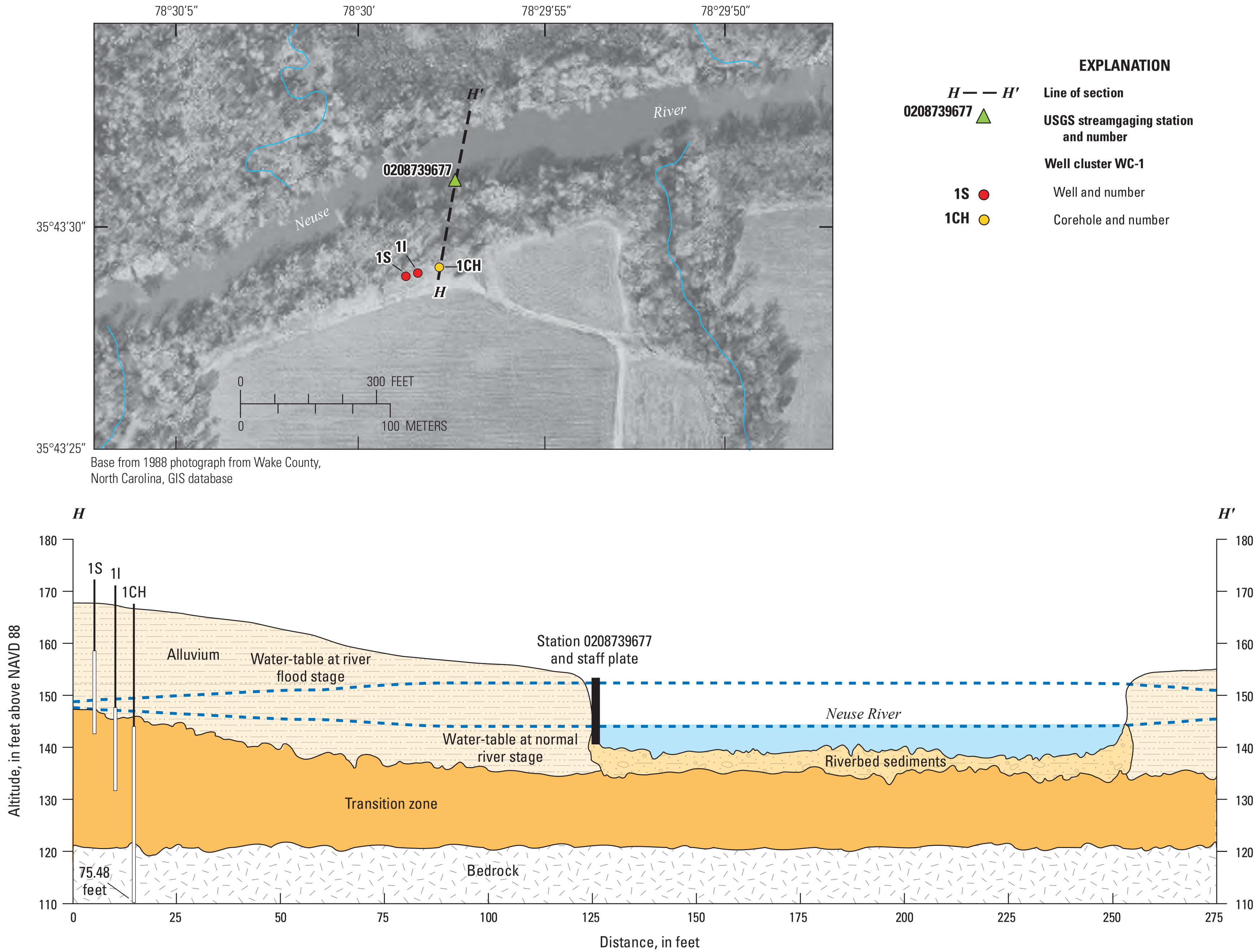


Figure 17. Generalized hydrogeologic cross section *H–H'* at the Raleigh hydrogeologic research station, Wake County, North Carolina.

sampling events. Continuous water-quality monitoring consisted of recording the physical properties of temperature, pH, specific conductance, and dissolved oxygen (DO) in three wells at well cluster WC-2. Only temperature, specific conductance, and pH were recorded at USGS station 0208739670 on an unnamed tributary to the Neuse River near Auburn, North Carolina (hereafter called the "tributary" site location shown in fig. 3).

Periodic water-quality samples were collected during two sampling events in October 2005 and March-April 2006 from all wells except WC-3CH and the tributary site. The core borings were not intended to be sampled for water quality, but the wells completed in the core holes at the WC-1 and WC-2 well clusters were sampled to investigate groundwater in the diabase dikes at these locations. The BAT^3 packer system was used in March 2006 during the second sampling event to isolate individual fracture zones and collect water-quality samples in two of the open boreholes at the RHRS (McSwain and others, 2009). The EM flowmeter logs collected in wells WC-2D and WC-3D (figs. 8, 9) were used to select the BAT^3 packer intervals for sampling. Packer intervals and the location of fractures sampled within that interval are shown on figure 6. Sampling locations, constituents, and dates of collection for water-quality samples are listed in table 2.

A graphical analysis of the periodic water-quality data using Piper diagrams (Piper, 1953) and Stiff diagrams (Stiff, 1951) is presented in figures 18 and 19, respectively. Further description of the methods used to create the diagrams as well as box plots of the water-quality data are presented in McSwain and others (2009).

The dissolved nitrate concentrations from samples collected during the March and April 2006 samplings are shown in figure 6. When examined spatially, the nitrate concentrations affirm that the hydraulic gradient at well cluster WC-3 was downward from regolith to bedrock, but upward from bedrock to regolith in well cluster WC-2. At well cluster WC-1, the nitrate concentration at well WC-1D in the diabase dike was much less than in the other cluster wells, supporting the idea that the diabase dike is hydraulically isolated from the granite bedrock. In the three remaining wells at well cluster WC-1, the nitrate concentration was lowest in the transition zone (well WC-1I) likely because of mixing with water from the Neuse River. In whole, the nitrate concentrations measured in groundwater during the March and April 2006 samplings confirm the general validity of the slope-aquifer concept as applied at the RHRS.

Quality of Water in the Regolith, Transition Zone, and Tributary

Constituent concentrations in samples collected from wells within the regolith and transition zone showed little variability between sampling events, with the exception of well WC-1S (fig. 18*A*). This variation occurs in nitrate and chloride sample values, and likely was due to the interaction of the shallow groundwater with the Neuse River. In general, groundwater in the regolith and transition zone was a calcium-magnesium/chloride-nitrate type, with the exception of wells at well cluster WC-1, which were calcium-magnesium/bicarbonate-nitrate (fig. 19). The elevated chloride (up to 34 mg/L) and nitrate (up to 130 mg/L as N) anion concentrations were a result of the historic biosolid applications and do not represent background conditions, which would be less than 10 mg/L of chloride and less than 1 mg/L as N of nitrate, respectively. Magnesium and bicarbonate concentrations increased with distance along the flow path from recharge at well cluster WC-3 to discharge at well cluster WC-1.

Table 2. Sampling locations, constituents, and dates of collection for water-quality samples collected at the Raleigh hydrogeologic research station, Wake County, North Carolina.

[ft BLS, feet below land surface; WC, well cluster; S, shallow regolith; I, intermediate zone regolith; D, deep; CH, core hole; CFC, Chloroflourocarbon; na, not applicable; –, not sampled]

Site identification number	Station name	Packer interval sampled (ft BLS)	Bacteria	Major inorganic ions	Nutrients	CFC	Tritium	Helium	Dissolved gasses	Radon	Wastewater compounds	Trace metals	Pharmaceuticals
354328078295701	WC-1S	na	Oct. 2005	Oct. 2005 Apr. 2006	Oct. 2005 Apr. 2006	Apr. 2006	Apr. 2006	–	–	–	–	–	–
354328078295702	WC-1I	na	Oct. 2005	Oct. 2005 Apr. 2006	Oct. 2005 Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	–	–	–	–
354328078295703	WC-1D	na	Oct. 2005	Oct. 2005	Oct. 2005 Apr. 2006 Sept. 2007	–	Apr. 2006	Apr. 2006	–C	Sept. 2007	–	–	–
354328078295704	WC-1CH	na	Oct. 2005	Oct. 2005 Apr. 2006	Oct. 2005 Apr. 2006 Sept. 2007	Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	Sept. 2007	–	–	–
354315078300101	WC-2S	na	Oct. 2005	Oct. 2005 Dec. 2005 Apr. 2006	Oct. 2005 Dec. 2005 Apr. 2006 Sept. 2007	Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	Sept. 2007	Dec. 2005	Dec. 2005	Dec. 2005
354315078300102	WC-2I	na	Oct. 2005	Oct. 2005 Apr. 2006	Oct. 2005 Apr. 2006 Sept. 2007	Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	Sept. 2007	–	–	–
354315078300103	WC-2D	na	Oct. 2005	Oct. 2005	Oct. 2005 Sept. 2007	–	–	–	–	Sept. 2007	–	–	–

Table 2. Sampling locations, constituents, and dates of collection for water-quality samples collected at the Raleigh hydrogeologic research station, Wake County, North Carolina.—Continued

[ft BLS, feet below land surface; WC, well cluster; S, shallow regolith; I, intermediate zone regolith; D, deep; CH, core hole; CFC, Chloroflourocarbon; na, not applicable; –, not sampled]

Site identification number	Station name	Packer interval sampled (ft BLS)	Bacteria	Major inor-ganic ions	Nutri-ents	CFC	Tritium	Helium	Dissolved gasses	Radon	Wastewater compounds	Trace metals	Pharmaceuticals
354315078300103	WC-2D	59-77	–	Mar. 2006	Mar. 2006	Mar. 2006	Mar. 2006	–	Mar. 2006	–	–	–	–
354315078300103	WC-2D	244-260	–	Mar. 2006	Mar. 2006	Mar. 2006	Mar. 2006	–	Mar. 2006	–	–	–	–
354315078300104	WC-2CH	na	Oct. 2005	Oct. 2005	Oct. 2005 Sept. 2007	–	–	–	–	Sept. 2007	–	–	–
354305078295801	WC-3S	na	Oct. 2005	Oct. 2005 Apr. 2006	Oct. 2005 Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	–	–	–	–
354305078295802	WC-3I	na	Oct. 2005	Oct. 2005 Apr. 2006	Oct. 2005 Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006	Apr. 2006				
354305078295803	WC-3D	na	Oct. 2005	Oct. 2005	Oct. 2005 Sept. 2007	–	–	–	–	–	–	–	–
354305078295803	WC-3D	41-70	–	Mar. 2006	Mar. 2006	Mar. 2006	Mar. 2006	–	Mar. 2006	–	–	–	–
354305078295803	WC-3D	148-164	–	Mar. 2006	Mar. 2006	Mar. 2006	Mar. 2006	–	Mar. 2006	–	–	–	–
354305078295804	WC-3CH	na	–	–	–	–	–	–	–	–	–	–	–
0208739670	Neuse River tributary near Auburn, North Carolina	na	Oct. 2005	Oct. 2005	Oct. 2005 Sept. 2007	–	–	–	–	Sept. 2007	–	–	–

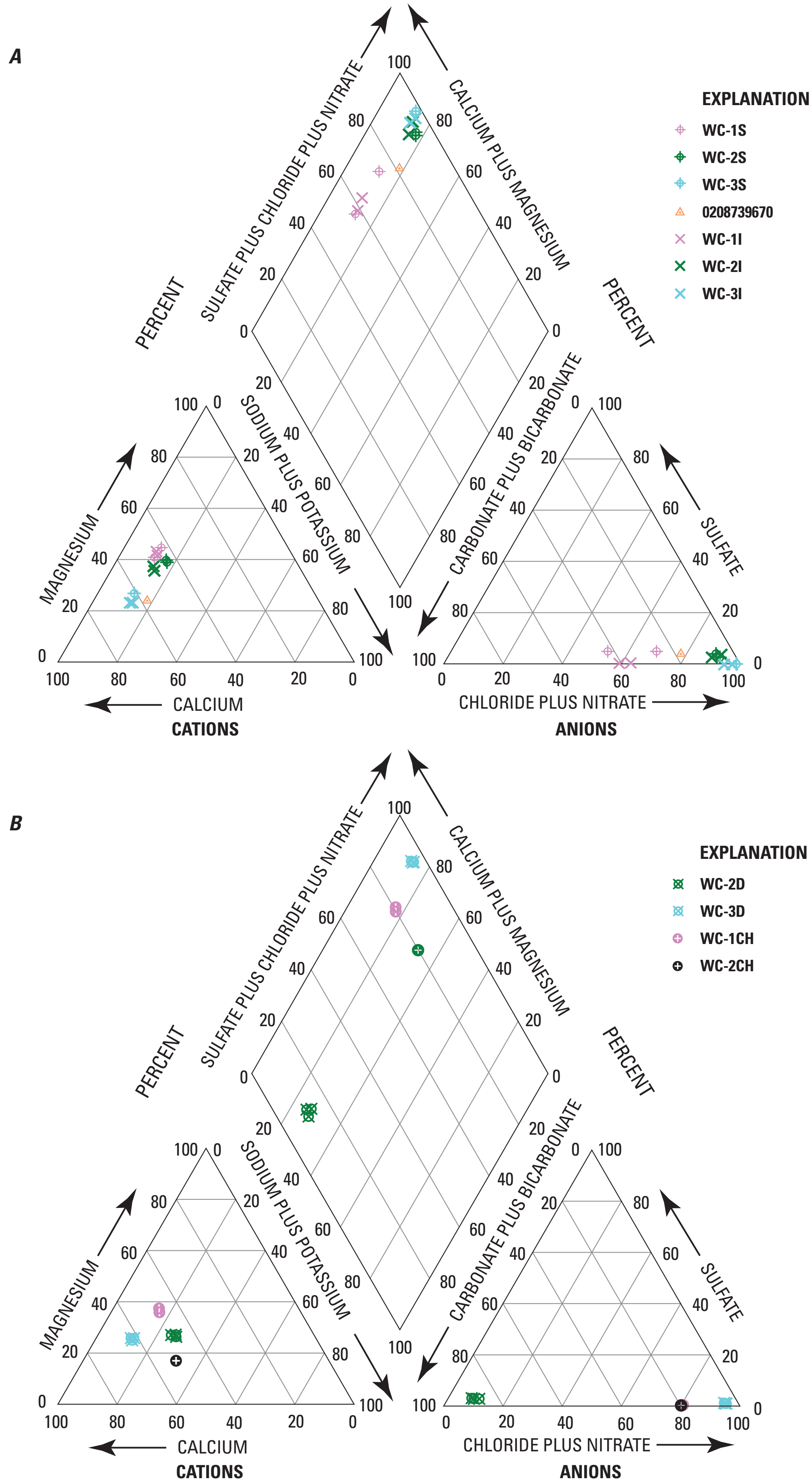


Figure 18. The water chemistry of samples collected October 2005 and April 2006 from the (*A*) regolith and transition-zone wells and the tributary site (station 0208739670), and (*B*) bedrock wells at the Raleigh hydrogeologic research station, Wake County, North Carolina.

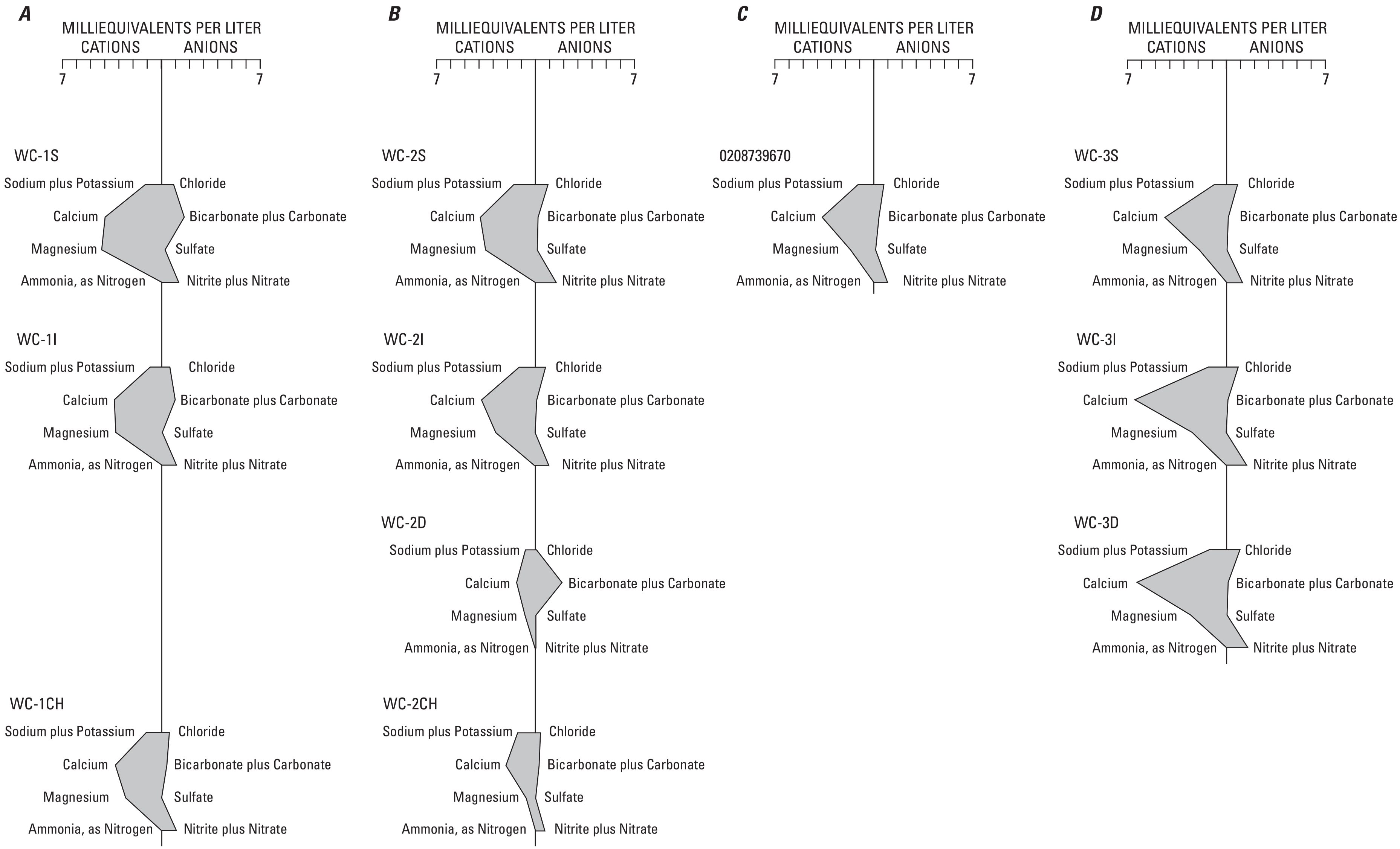


Figure 19. Major ion milliequivalents in water samples collected in October 2005 from (*A*) well cluster WC-1, (*B*) well cluster WC-2, (*C*) a Neuse River tributary (station 0208739670), and (*D*) well cluster WC-3 at the Raleigh hydrogeologic research station, Wake County, North Carolina.

Water-quality data collected from continuous monitors installed in the regolith in well WC-2S and in the transition zone in well WC-2I displayed seasonal fluctuations in groundwater chemistry (fig. 20). The regolith and transition zone had similar seasonal hydrographs, with water levels generally peaking in the spring and declining to a low in the late fall. Differences in seasonal groundwater chemistry existed between the regolith and transition zone, and these differences did not follow the same seasonal cycle as the water levels. In the regolith (well WC-2S) when the groundwater level was high in June 2006, the water temperature and specific conductance were seasonally low. Conversely, in the transition zone (well WC-2I) in June 2006, the water level was seasonally high and the water temperature was seasonally low, but the specific conductance did not reach a seasonal low until August 2008. Groundwater in the transition zone displayed a greater range in specific conductance than in the regolith. Dissolved oxygen was higher in groundwater within the regolith than in the transition zone. Aerobic conditions dominated within the regolith and transition zone and were likely a factor in the persistence of high nitrate concentrations in the groundwater. The pH in the regolith and transition zone groundwater was acidic and increased slightly with depth. The inverse response of specific conductance and pH between the regolith and the transition zone was likely an effect of surface recharge.

Surface water collected from the tributary site was intermediate in relative ion composition compared to groundwater in the regolith and transition zone at well clusters WC-2 and WC-3 (fig. 18*A*) but most resembled wells WC-3S and WC-3I in major ion concentration (figs. 19*C*, *D*). In October 2005, water from the tributary site had a nitrate concentration of 74 mg/L as N. In comparison, water from well WC-2I in October 2005 had a nitrate concentration of 80 mg/L as N and at well WC-3I the concentration was 114 mg/L as N. Because the tributary is topographically downgradient from both well clusters WC-2 and WC-3, it was likely that the tributary received groundwater discharge from the regolith and transition zones in both areas.

The surface-water quality continuous monitor in the tributary site was operated for about a month before it was destroyed by Tropical Storm Alberto in June 2006. However, some trends can be inferred from the limited data collected (fig. 21). The surface-water temperature was highly variable and fluctuated diurnally in response to air temperature and insolation. Specific conductance was elevated because of the high nitrate and chloride concentrations in the discharging groundwater and, though generally stable, decreased markedly in response to rainfall events. This decrease was most likely due to dilution with less conductive runoff caused by the rainfall event. The pH was stable and neutral.

Quality of Bedrock Groundwater

Major ion concentrations in the open-borehole bedrock wells and individually sampled fractures showed little variability between sampling events but considerable variability from well cluster to well cluster (fig. 18*B*). Elevated alkalinity, calcium, and sulfate concentrations as well as pH values above 8 measured in well WC-1D indicate the well likely was grout contaminated, and samples from this well were omitted from further data analysis. The type of water sampled from the open-borehole well generally was calcium-magnesium/chloride-nitrate type in the bedrock with the exception of well WC-2D, which was calcium/bicarbonate (fig. 19). Even though they are completed within the same well cluster, the groundwater chemistry from well WC-2CH differed from WC-2D in that it had a higher calcium concentration, lower bicarbonate plus carbonate concentration, and much higher nitrate concentration (51 mg/L as N in WC-2CH as opposed to 5 mg/L as N in WC-2D). These chemical differences likely were due, in part, to the geology near the open hole or screened interval of the well, the 200-ft horizontal separation of the two wells, and hydraulic differences within the fracture zone tapped by each well. Well WC-2CH was partially completed within a diabase dike, whereas well WC-2D was completed solely within granite.

Whole rock analyses on the cores collected at the RHRS indicated that the diabase contains about 7 percent calcium as opposed to about 1 percent in the granite (McSwain and others, 2009), making geologic differences the likely source of the disparity in calcium concentrations within the water samples. Wells WC-2D and WC-2CH probably intersect different fracture sets, in part because of their 200-ft horizontal separation. Because the source of the dissolved nitrate was a land-applied biosolid, it is likely that the fractures within well WC-2CH tap a shallower, more nitrate-laden fracture set than those intersected by well WC-2D.

In March 2006 the BAT^3 packer system was used to collect samples from discrete fracture zones within wells WC-2D and WC-3D. Samples were collected at depths of 59 to 77 ft and 244 to 260 ft within well WC-2D and at depths of 41 to 70 ft and 148 to 164 ft within WC-3D (fig. 6).

Once the BAT^3 system was installed, hydraulic head was monitored above, below, and within the isolated fracture zone to establish vertical gradients within the borehole. At well WC-2D, the deepest fracture set at 244 to 260 ft had a higher head than the shallower fracture set at 59 to 77 ft, indicating upward flow within the borehole and confirming measurements collected with the borehole flowmeter (fig. 8). This upward flow within the borehole retarded the downward migration of contaminated groundwater and was likely why water-quality samples collected from well WC-2D had nitrate concentrations that were much lower than those found in well WC-2CH as well as the regolith and transition zone wells in the same well cluster (fig. 6).

Because fractured-rock flow systems are complex, it is unknown if this condition of deep upward discharge exists throughout the flow system in the area of WC-2 or if it is an artifact caused by connecting the fractures within the borehole during the drilling process. The opposite hydraulic condition existed at well WC-3D where the deepest fracture set at 148 to 164 ft had a lower head than the shallower fracture set at

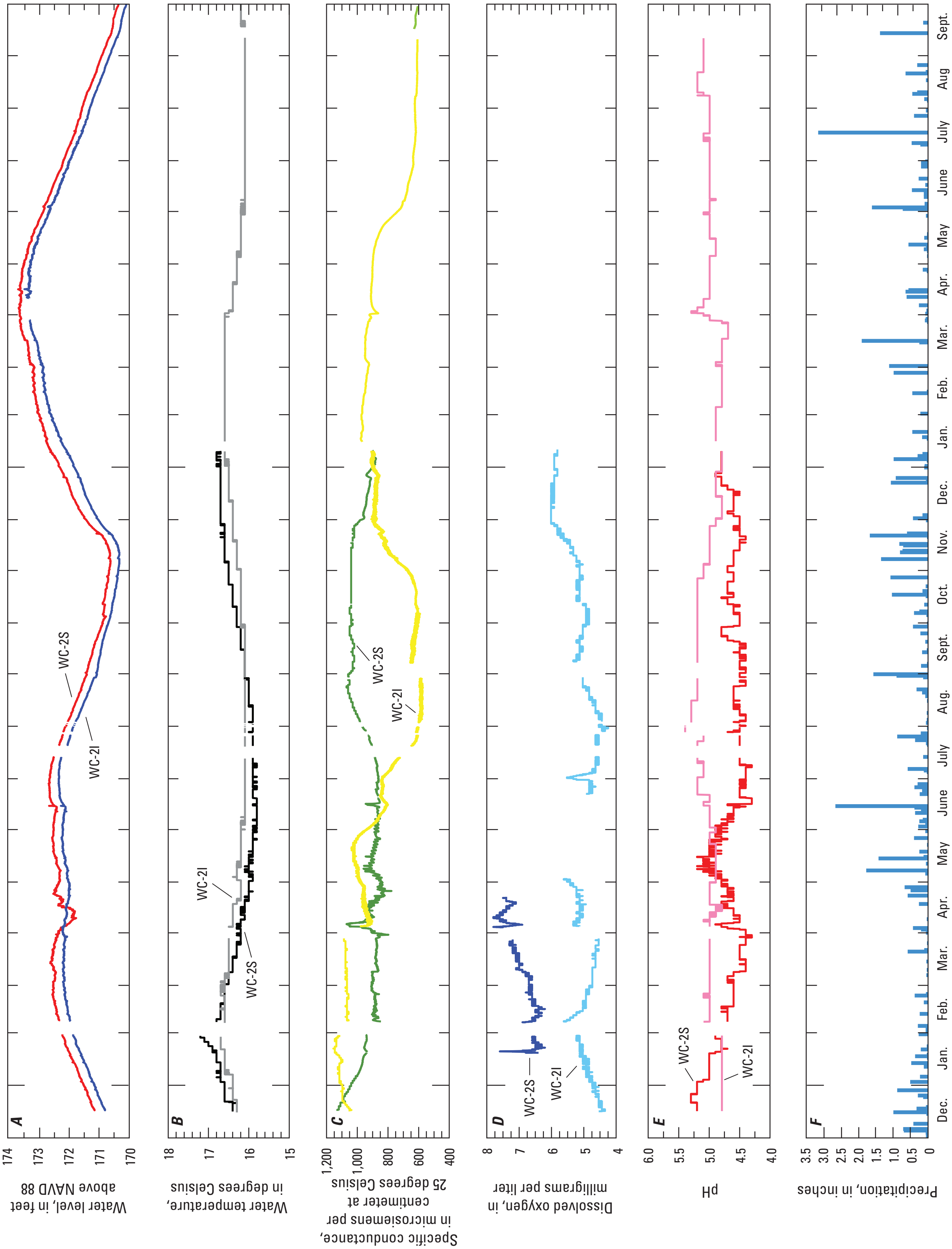


Figure 20. Hourly record of (*A*) water level, (*B*) temperature, (*C*) specific conductance, (*D*) dissolved oxygen, (*E*) pH in wells WC-2S and WC-2I, and (*F*) daily precipitation at the Raleigh hydrogeologic research station, North Carolina, December 2005 through September 2007.

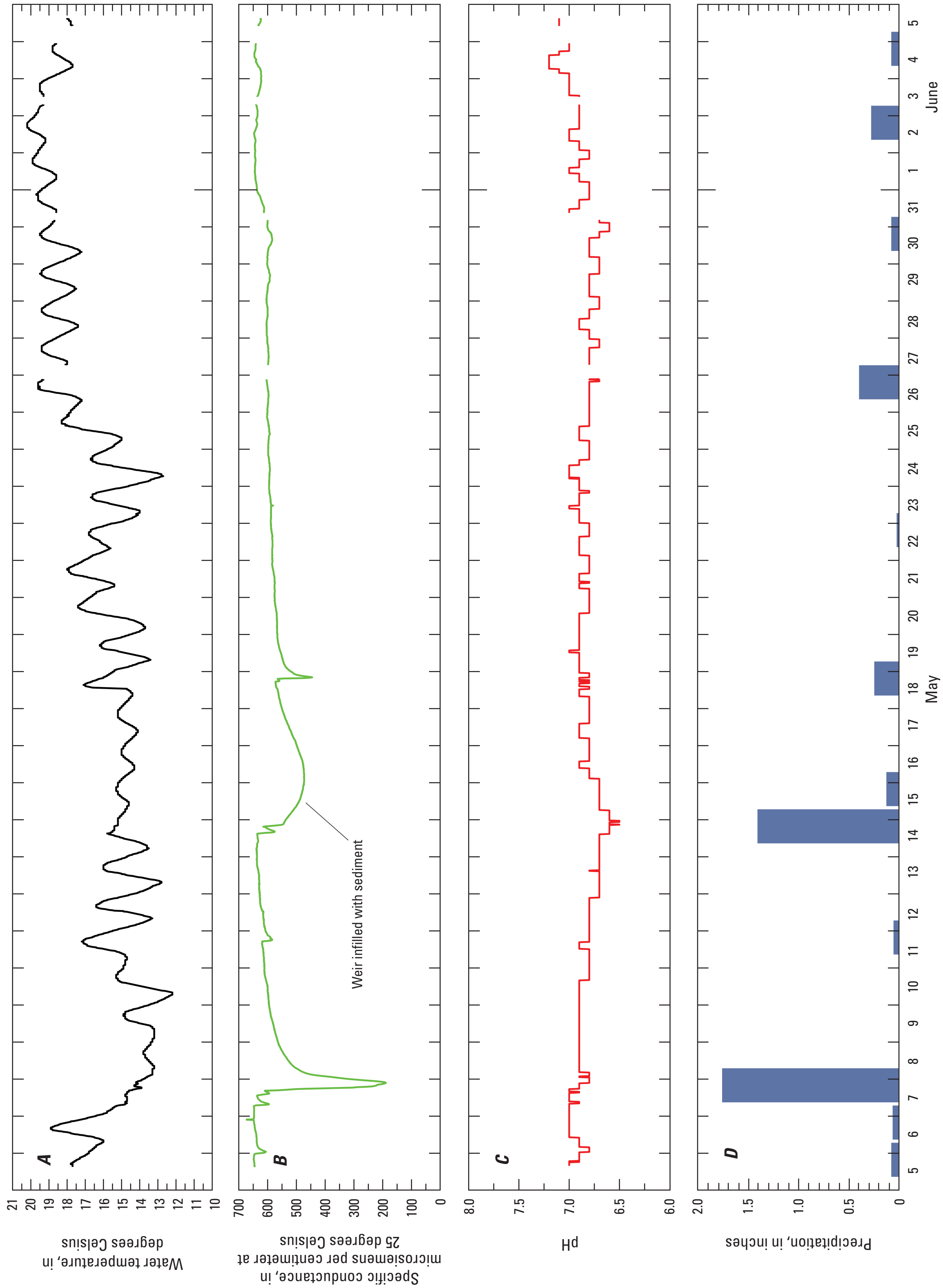


Figure 21. Fifteen-minute record of (*A*) temperature, (*B*) specific conductance, (*C*) pH, and (*D*) daily precipitation at station 0208739670 Neuse River tributary near Auburn, North Carolina, May 5 to June 5, 2006.

41 to 70 ft, indicating downward flow within the borehole as was measured by the borehole flowmeter (fig. 9). This downward flow allowed the migration of contaminants from the shallow fracture set to the deeper fracture set and was likely why water-quality samples collected from WC-3D had concentrations of nitrate that were greater than those measured within the regolith and transition zone at well cluster WC-3. Water-quality samples collected from well WC-3D had concentrations of nitrate that were greater than those measured within the regolith and transition zone at well cluster WC-3 (fig. 6). As the RWWTP ceased land application of biosolids in 2002 and because well cluster WC-3 is in a recharge area, it was likely that rainfall flushed the nitrate deeper into the groundwater system.

In contrast to the groundwater levels, seasonal fluctuations in groundwater chemistry were not measured by the continuous water-quality monitor in the bedrock well WC-2D (fig. 22). Groundwater temperature and specific conductance steadily increased over the 1-year monitoring period, but pH remained stable at a neutral 7.5. DO levels were low, indicating anaerobic conditions, but increased markedly because of mixing each time the monitor was serviced, generally taking weeks to return to an ambient level. The lack of seasonal changes in groundwater chemistry coupled with a neutral pH and very low DO levels suggest a longer residence time for groundwater in the bedrock near this well than in the regolith or transition zone. The groundwater in the bedrock near well WC-2D has largely not been affected by the nitrate-laden groundwater in the regolith and transition zone. However, the slight rise in groundwater temperature and specific conductance suggests that a source of nitrate was affecting at least one of the fractures intersecting the open-hole well WC-2D.

Neuse River Resistivity Profiling

In November 2005, waterborne continuous resistivity profiling was conducted on the Neuse River in the area of the RHRS to measure the apparent resistivity distribution of the sediments, weathered rock, and pore-water fluid beneath the streambed (McSwain and others, 2009). Composition of the sediment and weathered rock, amount of water in the pore space and fractures, ionic concentration of the pore fluid, and variations in pore space affect resistivity. A processed inversion of one continuous resistivity profile section of the Neuse River near the study area is presented in figure 23.

Resistivity is a measure of the ability of a fluid to conduct electrical current. Because conductivity is the reciprocal of resistivity, one interpretation of the continuous resistivity profile in figure 23 was that the areas of low resistivity (dark blues) were areas beneath the streambed that contain fluids with high specific conductance, while the areas of high resistivity (reds) delineated areas with low specific conductance fluids or more competent bedrock. In the processed inversion, the low resistivity areas to the west and east sides of the profile were located where both of the unnamed tributaries discharge to the Neuse River. As the unnamed tributaries were reported to have base-flow nitrate concentrations ranging from 30 to 60 mg/L as N in 2005 and 2006 (Fountain, 2006), the low resistivity measurements in the area of the unnamed tributaries on the continuous resistivity profile most likely represented groundwater contaminated by high concentrations of nitrate with the potential to discharge into the Neuse River.

Based on groundwater sampling at well cluster WC-1, high concentrations of nitrate were present in the regolith and alluvium (greater than 80 mg/L as N), with a much lower concentration of nitrate (6 mg/L as N) detected in groundwater within the diabase dike. The small, isolated high resistivity area in the middle of the profile is likely the diabase dike, while the low resistivity areas located on either side of the dike represent shallow groundwater contaminated with nitrate. It appears that the diabase dike acts as a barrier that preferentially directs the discharge of groundwater to the Neuse River and at depth may isolate groundwater movement laterally across the dike.

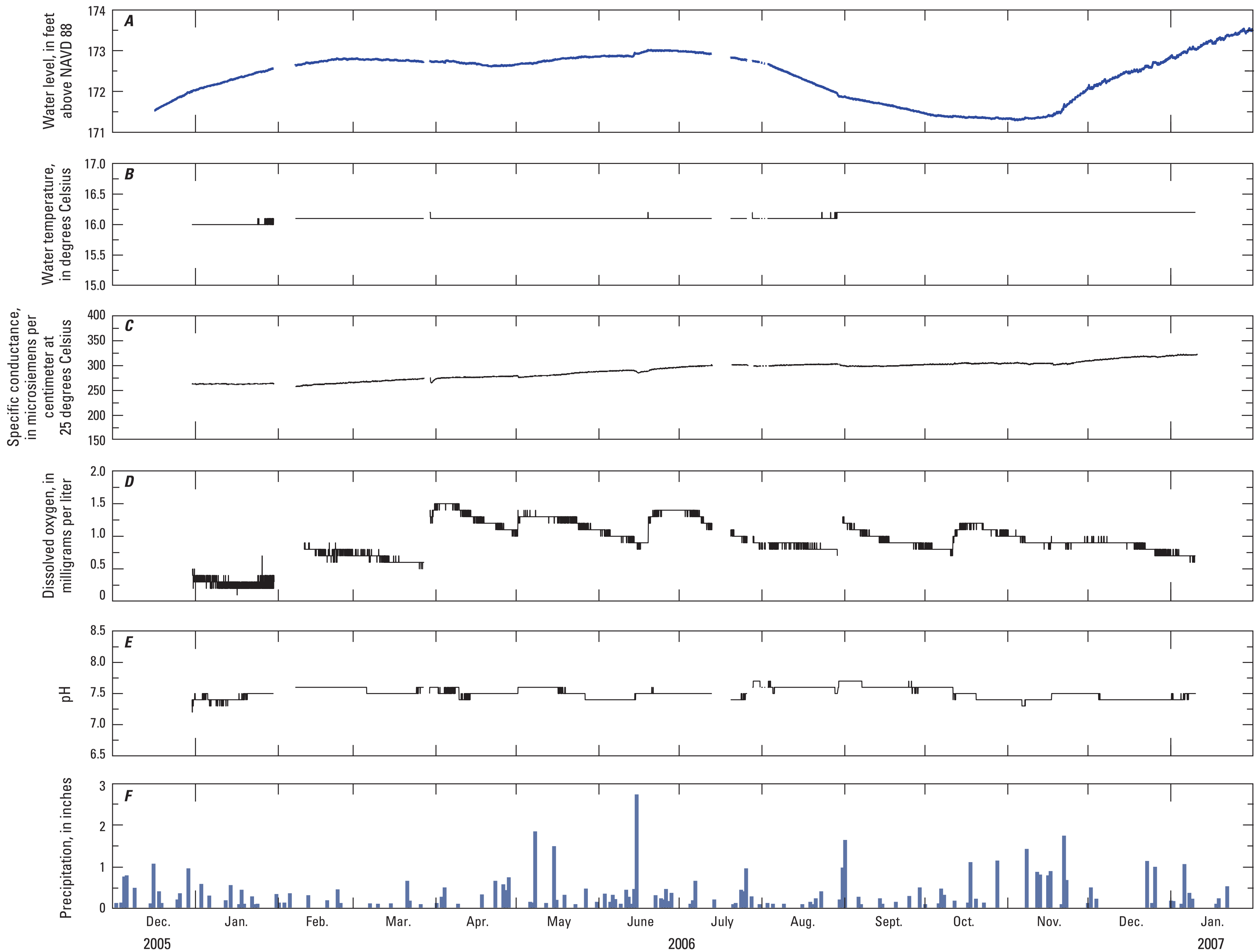


Figure 22. Hourly record of *(A)* water level, (*B*) temperature, (*C*) specific conductance, (*D*) dissolved oxygen, (*E*) pH in well WC-2D, and (*F*) daily precipitation at the Raleigh hydrogeologic research station, North Carolina, December 2005 through January 2007.

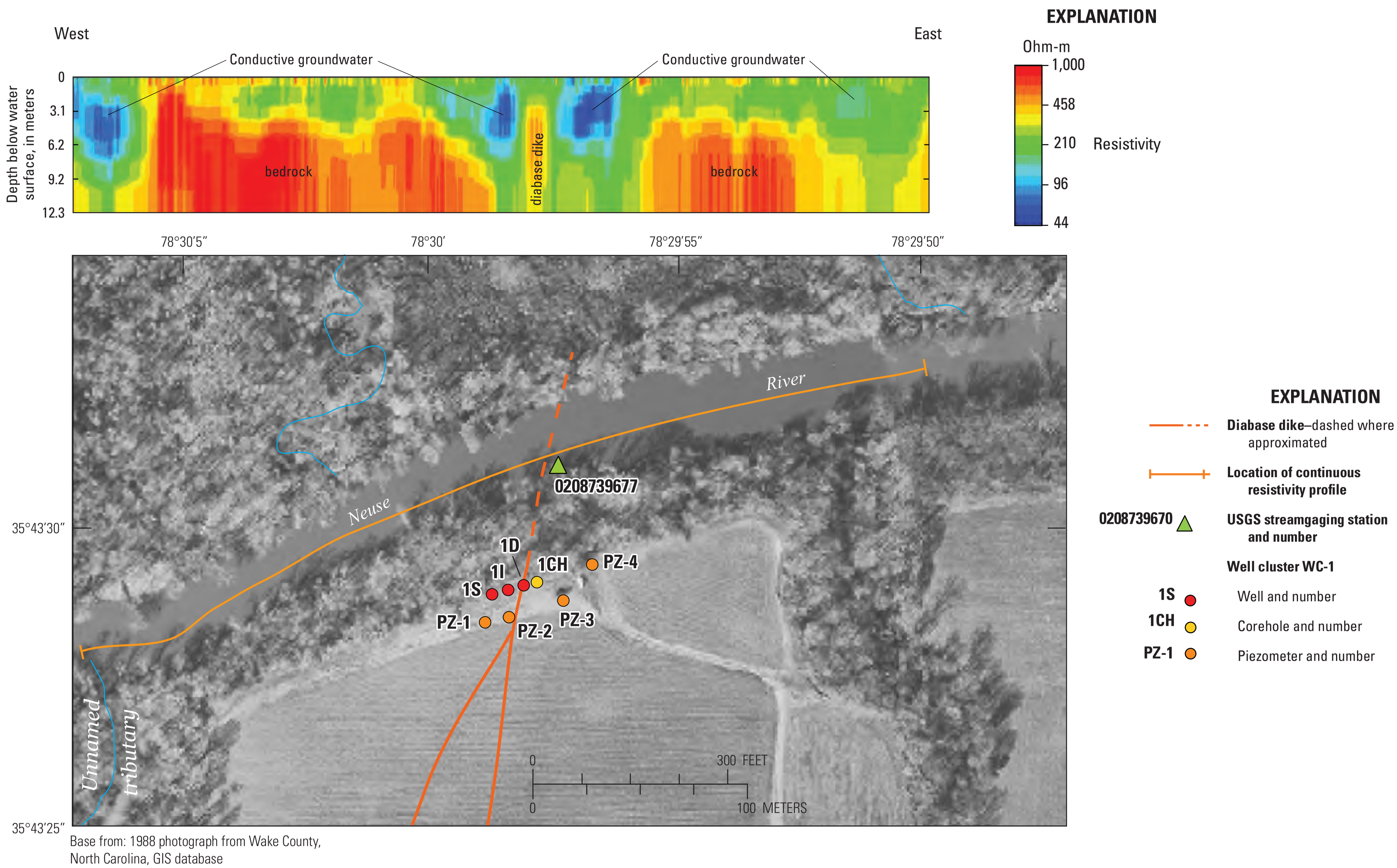


Figure 23. Processed continuous resistivity profile (CRP) inversion and location of CRP survey with approximate projected surface location of diabase dikes from magnetometer data overlaid on an aerial photograph of the Raleigh hydrogeologic research station, Wake County, North Carolina.

Characterization of Groundwater Seepage to the Neuse River

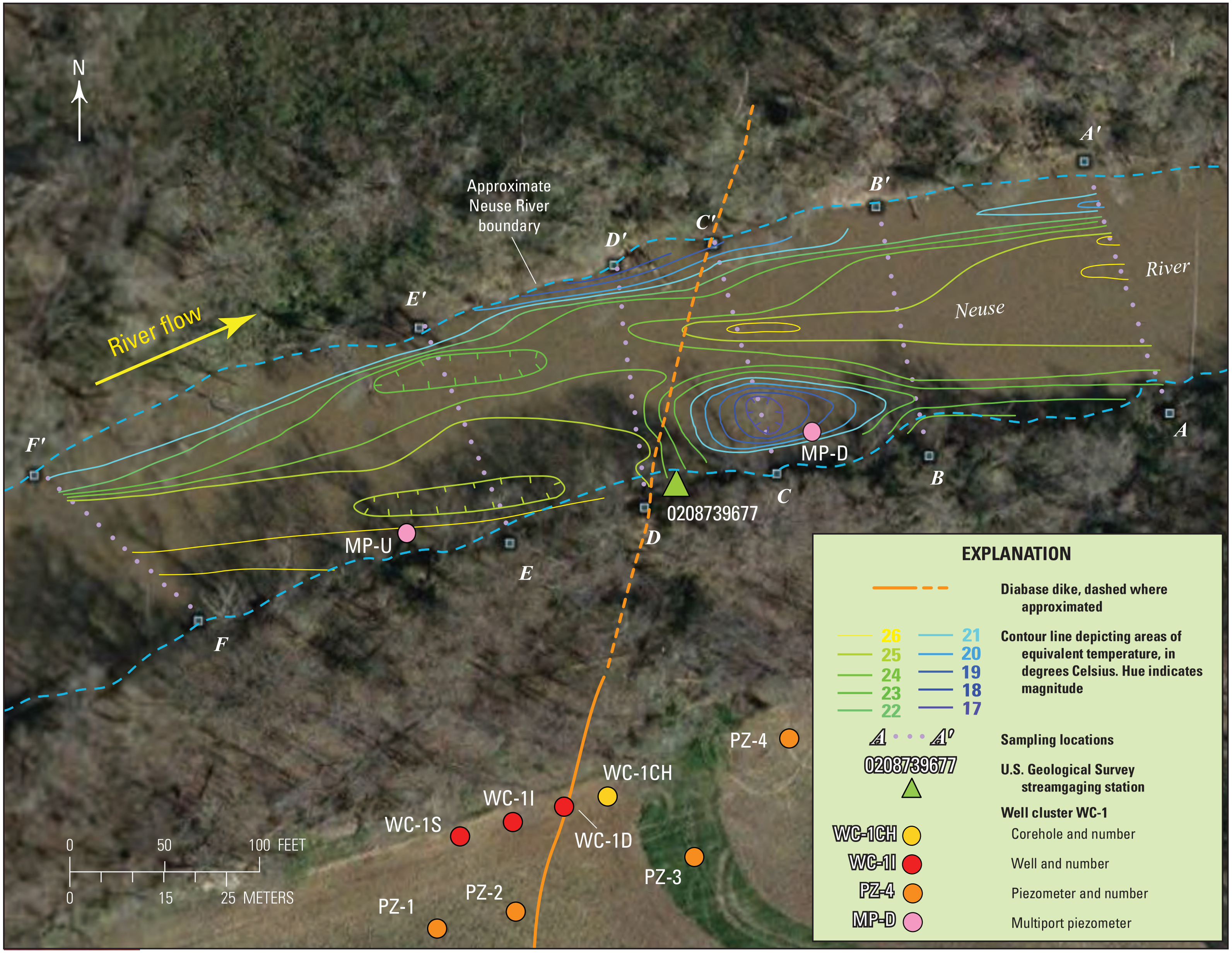
The extent of discharge from the groundwater beneath the RHRS to the Neuse River was determined by the use of physical and chemical methods. Areas of preferential groundwater discharge (seeps) were identified using temperature and water-quality methods. Seepage meters were used to quantify the movement of water vertically between the groundwater/surface-water interface, while samples of the pore water at two locations beneath the Neuse River were used to characterize nitrogen concentrations in the seepage.

Temperature Distribution in Pore Water Beneath the Neuse River

Differences in temperature can be an indication of groundwater seepage, especially if measurements are taken when the contrast between groundwater and surface-water temperatures are at their greatest. Water-quality monitoring at the RHRS indicated that the groundwater temperatures were fairly stable year round at about 16 degrees Celsius (°C; figs. 20, 22). Generally the maximum temperature difference between groundwater and surface water occurs twice a year, during the late summer when surface-water temperatures can exceed 25 °C and during the winter when surface-water temperatures approach 0 °C.

To locate possible seepage of groundwater, 80 instantaneous temperature measurements were made within the pore water beneath the Neuse River across six lines of section (fig. 3) on August 8, 2006, at depths of 0.5, 2.5, and 4.5 ft. A detailed description of the methods used to collect the temperature measurements can be found in McSwain and others (2009). Temperature measurements were also collected from within the Neuse River immediately above the riverbed to create an upper boundary and for comparison purposes. Because the temperature measurements were collected throughout an 8-hour period during a hot day in August (maximum air temperature of 35 °C), an increase in the temperature measured within the Neuse River was to be expected as the surface-water temperature rose in response to day time heating. However, the pore-water measurements at 2.5 ft or deeper were unlikely to be affected by day time heating.

To examine the distribution of the pore-water temperatures, contour maps were created from the transect data. A general trend toward cooler pore-water temperatures occurred with increasing depth. A contour map displaying the aerial distribution of pore-water temperature at a depth of 2.5 ft below the bed of the Neuse River is shown in figure 24. The north bank of the Neuse River opposite the RHRS between lines of section A′ and F′ likely was a groundwater discharge area based on the cool isotherms that parallel the bank. Additionally, two seeps discharging much colder groundwater were noted, one on the south bank of the Neuse River near section C–C′ and a second on the north bank of the Neuse River near section D–D′ to the northwest of the first seep (fig. 24). When the trace of one of the diabase dikes was overlain on the contour map, the seeps occurred on opposite sides of the dike. The presence of these seeps supports the concept that the diabase dike may act as a subsurface barrier that preferentially directs the discharge of groundwater to the Neuse River. Although continuous resistivity profiling (CRP) profiling (fig. 22) suggested that shallow groundwater on both the east and west sides of the diabase dike was nitrate laden, the temperature distribution survey did not locate a groundwater seep on the western side of the dike on the south bank of the Neuse River. It is probable that a seep did exist at that location at that time, but was not identified by temperature signature because it was located between sections D–D′ and E–E′.



Base from 1998 photograph from Wake County, North Carolina, GIS database
Contours 1993 USGS topographic sheet, Garner Quadrangle, 1:24,000 scale

Figure 24. Contour map of pore-water temperature measured at 2.5 feet below the Neuse River bed at the Raleigh hydrogeologic research station, Wake County, North Carolina.

Nutrient Distribution

On August 15-17, 2006, water-quality samples were collected from the pore water beneath the Neuse River at a total of 47 locations across sections A–A′, C–C′, and F–F′ by using a retractable drive-point piezometer (McSwain and others, 2009). Profiles of the contoured concentrations were generated (fig. 25) for each line of section in order to examine the distribution of the nitrate and ammonia concentrations. Elevated nitrate concentrations of about 65 mg/L as N near the RHRS on section A–A′ occurred downstream from the RHRS on the south side of the Neuse River. At section C–C′, groundwater with a nitrate concentration of about 80 mg/L as N was present at depth within the seep on the RHRS side of the Neuse River. Higher than background concentrations of nitrate (about 10 mg/L as N) extended to the north into the center of the river along section C–C′, indicating the discharge of nitrate by deeper flow paths within the aquifer. At section F–F′, upstream and to the west of the diabase dike, nitrate with a concentration of about 56 mg/L as N occurred at depth, but there was little lateral extent to the plume. Ammonia was present in relatively high concentrations in the center of the Neuse River at sections A–A′ and F–F′, but was not present at section C–C′.

To further characterize the nitrate distribution in the pore water beneath the Neuse River, two multiport piezometers were installed in bed sediments approximately 20 ft off the south bank of the river in September 2007 (locations shown in fig. 24). Multiport piezometers MP-U and MP-D were installed on opposing sides of the diabase dike to determine if the quality of water in the seepage area on one side of the dike differed from the non-seepage area on the other side of the dike. The multiport piezometers were used to assess the vertical distribution of nitrate concentrations in the pore water of as much as 140 cm (about 4.6 ft) beneath the Neuse River bed (table 3). Piezometer MP-U on the western side of the diabase dike was completed near line of section E–E′ in sediments described as silty sand grading to a silty sand with few cobbles. Piezometer MP-D, on the eastern side of the diabase dike, was completed near line of section C–C′ within the boundary of the previously identified seep in sediments described as a clayey silt grading to a silty sand.

After installation, the multiport piezometers were allowed to equilibrate for several months. On December 14, 2007, a pore-water sample was collected from each port within both of the multiport piezometers and analyzed for nutrients, temperature, and specific conductance. Dissolved oxygen was measured only in water samples collected from the 20-cm (about 0.3 ft) and 140-cm (about 4.6 ft) sampling ports of piezometers MP-U and MP-D. Samples of the water in the Neuse River were collected near both multiport piezometer sites from just above the sediment/water interface for comparison purposes. Results of the pore-water sample analyses are shown in table 3.

Pore-water samples collected from multiport piezometer MP-U had specific conductance and nitrate concentrations that gradually increased with depth below the sediment/water interface, while ammonia concentrations decreased with depth. Water temperature varied, but generally was about 14.1 ºC (the same as the temperature of the water in the Neuse River), with the exception of the two deepest sampling ports, which had slightly warmer temperatures. Nitrate concentrations in pore water collected from multiport piezometer MP-U ranged from about 3 mg/L as N in the 10-cm (about 0.3 ft) deep port to 91 mg/L as N in the 140-cm (about 4.6 ft) deep port, with a median concentration of about 52 mg/L as N. The nitrate concentration just above the sediment/water interface in the Neuse River was about 0.4 mg/L as N. It is likely that the increasing concentration of nitrate with depth was due to mixing of groundwater and surface water within the hyporheic zone in the area of multiport piezometer MP-U as aerobic conditions predominated at and below a depth of 20 cm (about 0.6 ft).

In contrast to the multiport piezometer MP-U, pore-water samples collected from multiport piezometer MP-D located in the previously delineated seep, were warmer in temperature and had little measurable ammonia. Specific conductance and nitrate concentrations rapidly increased with depth below the sediment/water interface (table 3). Water temperature ranged from 14.7 to 15.6 ºC and increased with depth. Nitrate concentrations in pore water ranged from about 42 mg/L as N in the 10-cm (about 0.3 ft) deep port to about 82 mg/L as N in the 40-cm (about 1.3 ft) port, but varied less than 2 mg/L as N from the 20-cm (about 0.6 ft) to 140-cm (about 4.6 ft) ports. The median pore-water concentration of nitrate in multiport piezometer MP-D was about 79 mg/L as N, while the concentration in the Neuse River just above the sediment/pore-water interface was about 0.5 mg/L as N. The occurrence of high concentrations of nitrate at such a shallow depth beneath the sediment/water interface suggests that little denitrification or mixing with surface water was occurring in the hyporheic zone in the area of multiport piezometer MP-D.

Vertical Gradients

Hydraulic head was measured in multiport piezometers MP-U and MP-D on December 14, 2007, at the time of sampling to determine the vertical gradient between the Neuse River and the groundwater during a period of low flow in the river. The stage of the Neuse River at the time of the hydraulic head measurement was used as a datum and the measurements are listed in table 3. In piezometer MP-U, the hydraulic head measured to 0.01 ft in all the ports was equivalent to the Neuse River stage, indicating that little measurable vertical gradient was present. It is probable that there was a slight gradient, but it was too small to quantify. This lack of vertical gradient coupled with the gradual downward increase in nitrate concentrations and aerobic conditions indicates that in the area of the multiport piezometer, little vertical movement of groundwater was occurring at 140 cm (about 4.6 ft) below the sediment/water interface, and the gradual downward increase of nitrate concentrations may have been the result of the lateral mixing of surface water with groundwater. However, this condition

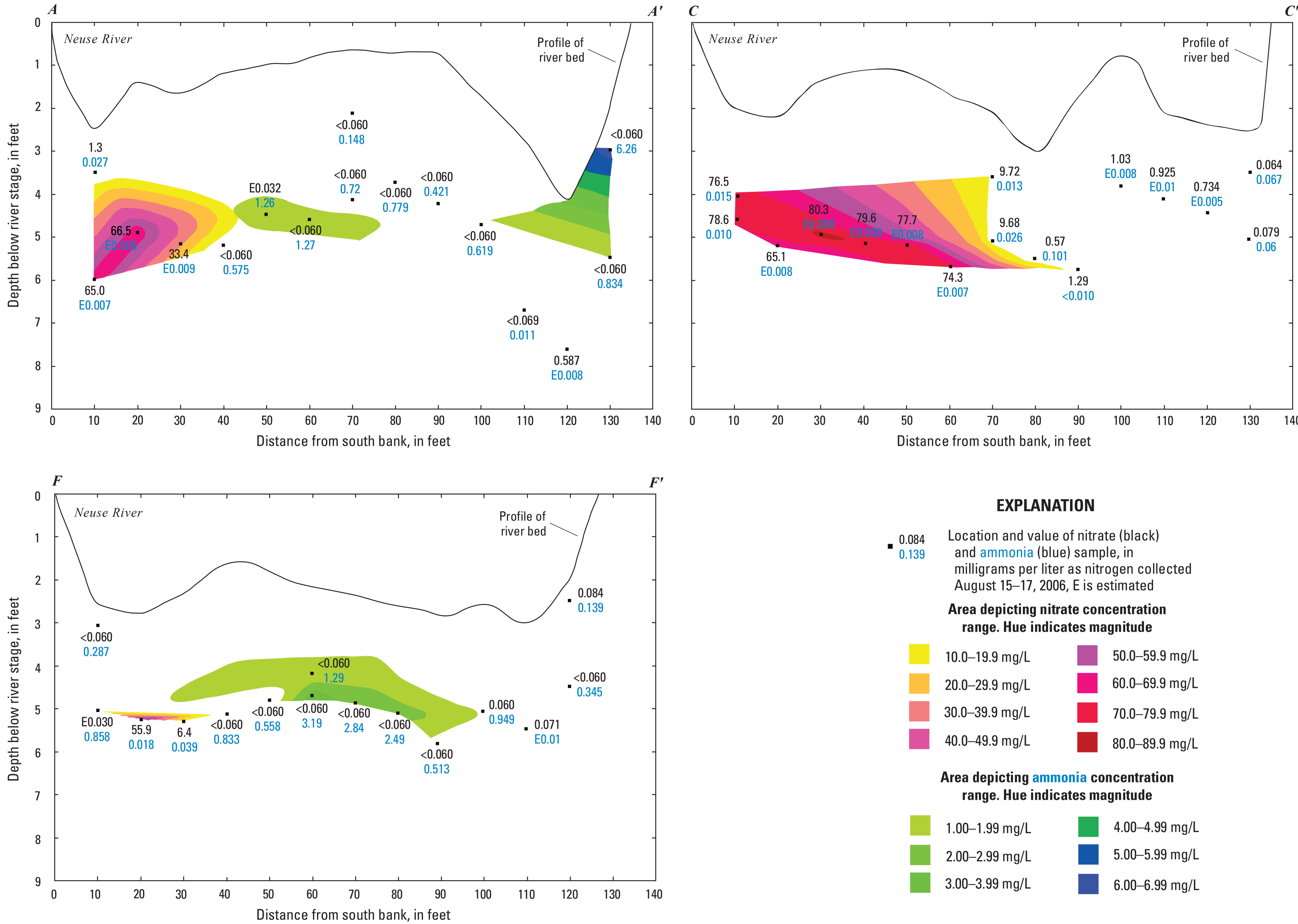


Figure 25. Contoured concentration of nitrite + nitrate, as nitrogen, and ammonia beneath the Neuse River at lines of section *A–A′*, *C–C′*, and *F–F′* at the Raleigh hydrogeologic research station, Wake County, North Carolina (see figs. 3 and 24 for line of section locations).

Table 3. Temperature, specific conductance, dissolved oxygen, and nutrient concentrations in pore-water samples collected from multiport piezometers at two locations in the Neuse River, Raleigh hydrogeolgoic research station, Wake County, North Carolina, December 14, 2007. Locations of samples shown in figure 24.

[°C, degrees Celsius; mg/L , miligrams per liter; N, nitrogen; µS, microsiemens; P, phosphorus; cm, centimeter; SR, Secondary Road; NC, North Carolina; –, not measured; E, value estimated]

Site identification number	Station name	Sample date	Sample time	Hydraulic head (feet)	Temperature (°C)	Nitrite + nitrate as nitrogen (mg/L as N)	Specific conductance (µS)	Dissolved oxygen (mg/L)	Ammonia, as nitrogen (mg/L as N)	Nitrite, as nitrogen (mg/L as N)	Orthophosphate as phosphorus (mg/L as P)	Alkaline persulfate nitrogen (mg/L as N)
Upgradient piezometer MP-U												
0208739677	Neuse River below SR 2555 near Auburn, NC	Dec. 14, 2007	1208	1.0	14.1	0.375	154	7.3	E0.010	0.008	E0.004	0.72
354330078295801	WK-352 10 cm	Dec. 14, 2007	1125	1.0	14.1	2.98	170	–	0.043	0.006	0.022	3.39
354330078295802	WK-353 20 cm	Dec. 14, 2007	1131	1.0	14.4	6.41	198	6.4	0.046	0.002	0.017	6.96
354330078295803	WK-354 30 cm	Dec. 14, 2007	1136	1.0	13.8	27.0	370	–	0.055	0.01	0.017	29.0
354330078295804	WK-355 40 cm	Dec. 14, 2007	1141	1.0	14.1	45.5	540	–	0.023	0.021	0.015	47.6
354330078295805	WK-356 50 cm	Dec. 14, 2007	1145	1.0	14.0	58.7	684	–	E0.011	0.027	0.024	61.6
354330078295806	WK-357 80 cm	Dec. 14, 2007	1149	1.0	14.1	65.8	697	–	E0.015	0.017	0.021	67.7
354330078295807	WK-358 110 cm	Dec. 14, 2007	1155	1.0	14.4	81.1	808	–	E0.012	0.004	0.022	84.3
354330078295808	WK-359 140 cm	Dec. 14, 2007	1159	1.0	14.7	91.0	870	5.3	E0.012	0.015	0.021	89.0
Downgradient piezometer MP-D												
0208739677	Neuse River below SR 2555 near Auburn, NC	Dec. 14, 2007	1329	1.0	14.1	0.508	152	7.3	<0.02	0.008	E0.003	0.91
354330078295601	WK-360 10 cm	Dec. 14, 2007	1308	1.0	14.7	41.8	451	–	E0.018	0.012	0.01	43.2
354330078295602	WK-361 20 cm	Dec. 14, 2007	1252	1.2	15.0	80.7	780	6.3	<0.02	E0.001	0.025	84.2
354330078295603	WK-362 30 cm	Dec. 14, 2007	1319	1.2	15.2	79.7	777	–	E0.016	E0.001	0.025	82.5
354330078295604	WK-363 40 cm	Dec. 14, 2007	1302	1.3	15.2	81.8	774	–	E0.014	E0.001	0.022	79.1
354330078295605	WK-364 50 cm	Dec. 14, 2007	1325	1.4	15.2	80.4	777	–	E0.015	<0.002	0.025	79.4
354330078295606	WK-365 80 cm	Dec. 14, 2007	1258	1.4	15.4	79.0	777	–	E0.015	<0.002	0.024	81.4
354330078295607	WK-366 110 cm	Dec. 14, 2007	1245	1.4	15.6	78.9	777	–	<0.02	E0.001	0.026	82.3
354330078295608	WK-367 140 cm	Dec. 14, 2007	1241	1.4	15.6	78.9	776	5.7	E0.013	E0.001	0.022	82.4

most likely did not exist at all depths beneath the sediment/water interface at this river stage in the Neuse River because of the highly elevated nitrate concentrations. Groundwater movement and subsequent discharge probably was occurring along a deeper flow path.

Similarly, hydraulic head was measured in multiport piezometer MP-D, and a vertical gradient was calculated using the stage of the Neuse River as a datum. Measurements are listed in table 3. In piezometer MP-D, the measured hydraulic head in the 140-cm (about 4.6 ft) port was about 0.4 ft higher than the Neuse River. This strong upward vertical gradient of 0.1 and upward flow of groundwater is likely why nitrate concentrations of 80 mg/L as N were found at the shallow depth of 20 cm (about 0.6 ft) beneath the sediment/water interface.

Seepage and Mass Flux

At the RHRS, vertical fluctuations in river stage and the resulting horizontal changes in pressure gradients between the aquifer and the Neuse River made vertical and horizontal seepage velocity and the resulting mass flux of nitrate into the river highly temporal. Solutions to groundwater-flow equations are rarely simple and generally require the use of numerical modeling methods to address complex boundary conditions. However, by examining flow in one direction at a time and assuming an isotropic and homogeneous medium with no dispersion or diffusion of dissolved constituents, it was possible to approximate the rate of groundwater flow (seepage) and mass of nitrate transported through the aquifer.

Horizontal Seepage and Mass Flux

The availability of hourly river stage from the Auburn station at the RHRS and corresponding groundwater level in the wells of well cluster WC-1 allowed for the estimation of horizontal gradients between the aquifer and the river as they changed over time. The horizontal gradient, coupled with hydraulic conductivity and effective porosity of the aquifer sediments, allowed the calculation of a groundwater, horizontal-seepage flux from the aquifer along a tangential flow path to the edge of the Neuse River by using equation 2 (Dominico and Schwartz, 1990).

$$q_h = 1/n_e \times K_h \times dh/L, \quad (2)$$

where

q_h is horizontal seepage flux (units of length per time),

n_e is effective porosity (unitless),

K_h is horizontal hydraulic conductivity (units of length per time),

dh is the change in hydraulic head along the flow path (units of length), and

L is flow path length (units of length).

In order to quantify the horizontal seepage from WC-1I to the Neuse River, a flux was estimated for each day of 2006 using the gradient between the daily-mean water level in well WC-1I and the daily-mean stage of the Neuse River measured at the Auburn station. Well WC-1I was selected for gradient calculation because it responded quickly to changes in river stage due to the transition zone's direct connection with the alluvial bed sediments. Similarly, slug tests conducted in well WC-1I were used to define the horizontal hydraulic conductivity because it is a conservative approximation in comparison to the hydraulic conductivity of the sandy bed sediments. As it is not easy to determine the effective porosity of aquifer sediments, a laboratory-based infiltration value for loamy sand was used (Rawls and others, 1983). A loamy sand texture also has a hydraulic conductivity similar to that measured by slug testing in well WC-1I.

Estimated horizontal seepage fluxes along the 130-ft flow path from well WC-1I to the Neuse River (fig. 26) ranged from a minimum of -0.52 ft/d (June 15, 2006) to 0.20 ft/d (December 13, 2006) with a median value of 0.09 ft/d. A negative seepage flux indicates surface water infiltrating into the aquifer while a positive flux indicates groundwater discharge into the Neuse River. On June 15, 2006, the Neuse River flooded its bank because of Tropical Storm Alberto, causing the gradient to reverse and river water to infiltrate into the aquifer. For a total of 35 days in 2006, the daily-mean stage of the Neuse River was higher than the daily-mean water level in well WC-1I, effectively damming groundwater discharge to the Neuse River. Twenty-four of those 35 days occurred during a 1-month time period from November 11 to December 10, 2006. The maximum seepage flux occurred on December 13, 2006, as a direct result of a rapid decrease in river stage that allowed a large quantity of stored groundwater to quickly discharge to the Neuse River.

Using the estimated horizontal seepage flux and the dissolved nitrate concentration in the groundwater, it was possible to approximate the potential horizontal advective mass flux of nitrate from groundwater to the Neuse River for a given cross-sectional area by applying equation 3 (Dominico and Schwartz, 1990).

$$F = q \times A \times X_c, \quad (3)$$

where

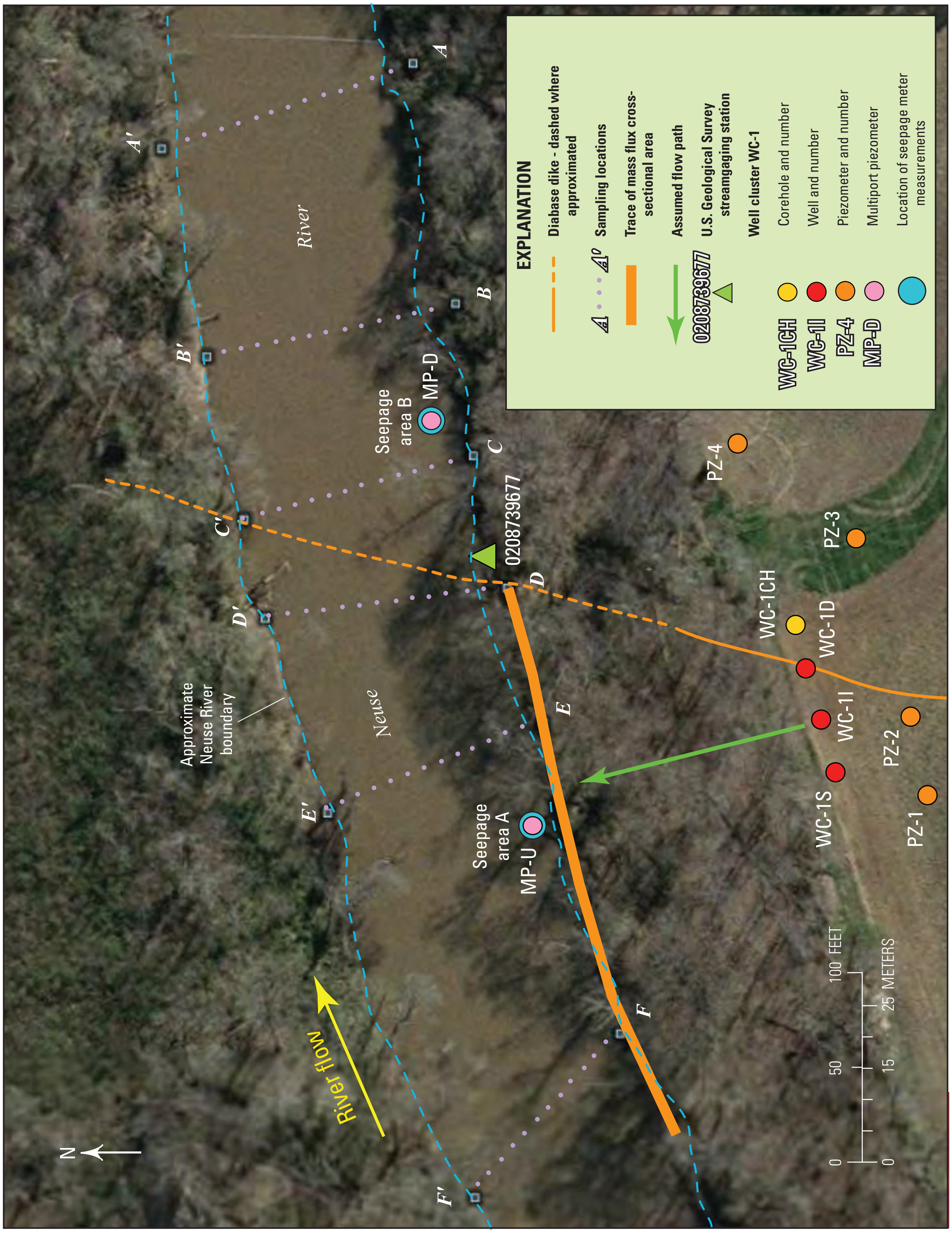
F is mass flux (units of mass per time),

q is seepage flux (units of length per time),

A is cross-sectional seepage area (units of squared length), and

X_c is the concentration of nitrate (units of mass per cubed length).

Equation 3 was used to estimate the potential horizontal discharge of nitrate from groundwater to the Neuse River along a 300-ft long reach near well cluster WC-1 (fig. 26). The daily horizontal mass flux of nitrate for 2006 was estimated by incorporating the daily seepage flux estimated from equation 2.



Base from 1998 photograph from Wake County, North Carolina, GIS database

Figure 26. Area of Neuse River bed sediments investigated with seepage meter measurements at the Raleigh hydrogeologic research station, Wake County, North Carolina, in August 2006 and December 2007.

For each day, the wet cross-sectional area was determined by using the altitude of the bottom of the transition zone (121.5 ft as noted from coring in well WC-1CH) as a lower boundary and the stage of the Neuse River as the upper boundary along a 300-ft reach at the aquifer/river-bank interface (fig. 26). A constant nitrate concentration of 0.0035 pound per cubic foot as N (55.9 mg/L as N) was applied in the calculation. This was the same concentration of nitrate measured in August 2006 from the drive-point sample located 20 ft off the bank in transect F–F′, which was located near the middle of the 300-ft reach.

Estimated horizontal mass flux of nitrate along the 300-ft reach of the Neuse River (fig. 26) ranged from a minimum of –10.9 pounds per day (lbs/d) on June 15, 2006, to 5.0 lbs/d on December 13, 2006, with a median value of 2.2 lbs/d. A negative mass flux indicates the effect of surface water infiltrating into the aquifer and a positive mass flux indicates the discharge of a mass of nitrate into the Neuse River. Mass flux of nitrate was estimated for each day and summed to approximate a total horizontal nitrate flux of about 750 lbs/year in 2006 for this 300-ft reach of the Neuse River. Because area and nitrate concentration were held at constant levels throughout the calculations, the estimation of nitrate mass flux was highly dependent upon the magnitude of the seepage flux. Thus, the dates of minimum and maximum horizontal nitrate mass flux corresponded to the dates of minimum and maximum horizontal seepage flux, with the greatest release of nitrate from the aquifer to the river following a rapid decline in river stage. A substantial limitation of this horizontal mass flux estimation was that it only accounts for fluid movement to the edge of the river and does not quantify the actual discharge into the river. This estimation provides an idea of the potential mass of nitrate that was available to be discharged if hydrologic and geologic conditions within the river sediments were favorable. Although this was an approximation based on many assumptions, it does highlight that over a much larger river reach there is the potential for a substantial amount of nitrate to discharge as a nonpoint source from the groundwater to the Neuse River.

Vertical Seepage and Mass Flux

Seepage meters can be used to determine rates of vertical groundwater flow to surface-water bodies (Lee, 1977). On August 16, 2006, and December 12, 2007, seepage meters were deployed in the bed of the Neuse River in two locations (seepage areas A and B; figs. 4, 26) in close proximity to multiport piezometers MP-D and MP-U. These specific areas were selected to compare vertical seepage flux in an area of probable groundwater discharge (seepage area B near MP-D to the east of the diabase dike) to an area where discharge was likely negligible (seepage area A near MP-U on the west side of the diabase dike) (fig. 26). Vertical seepage flux was estimated using equation 1.

Vertical seepage flux differed markedly from seepage area A to B in both August 2006 and December 2007 (table 4). The average estimated daily seepage flux at seepage area A was about 4.5 ft/d, about 2 orders of magnitude larger than the 0.022 ft/d average estimated at seepage area B over both collection dates. This large disparity in vertical seepage measurements provides further evidence that seepage area B (located near multiport piezometer MP-D to the east of the diabase dike) was an area of preferential groundwater discharge to the Neuse River.

Localized approximations of vertical seepage flux in fluvial environments can be highly variable. At both seepage areas A and B, sources of error were minimized by making repeated measurements with more than one meter, and suspect measurements were not used in vertical seepage estimations. Only two small areas of the heterogeneous streambed were tested with seepage meters. The magnitude of seepage measured in this study at seepage area B was on the high end of values reported in the literature for vertical seepage velocities measured in riverine environments of North Carolina (Kennedy and others, 2008). Although seepage meters are a simple, inexpensive tool to approximate vertical seepage flux, several sources of error could affect the measurements. As seepage meters measure flow across a small area of the river bed, measurement heterogeneities in the seepage direction

Table 4. Summary of Darcian flux and mass flux of nitrite + nitrate, as nitrogen, calculated from seepage measurements in August 2006 and December 2007 near the upgradient and downgradient piezometers, Raleigh hydrologic research station, Wake County, North Carolina.

[ft/d, feet per day; ft^2, square feet; mg/L, milligrams per liter; g/d, grams per day]

Location	Date of measurements	Number of seepage measurements	Average seepage flux (ft/d)	Seepage area (ft^2)	Median nitrite + nitrate concentration (mg/L)	Mass flux (g/d)
Seepage Area A	August 16, 2006	4	0.015	78.56	52	1.74
Seepage Area A	December 12, 2007	4	0.028	78.56	52	3.24
Seepage Area B	August 16, 2006	5	3.8	78.56	79	667.8
Seepage Area B	December 12, 2007	4	5.1	78.56	79	896.3

and rate in fluvial settings can be caused by local variation in sediment hydraulic conductivity and bed topography (Conant, 2004). Also, because it is difficult to seat a seepage meter in an alluvial environment with fast-flowing water, the measurements collected with the seepage meters may be biased high because of scouring of the bed around the meter or by water flowing past the submerged collection bag and inducing water flow into the bag.

An approximation of the contribution of nitrate from vertical groundwater discharge to the Neuse River at seepage areas A and B can made by the calculation of mass flux applying equation 3 but orienting all measurements in a vertical direction. As the true aerial extent of seepage areas A and B has not been mapped, a circular area with a radius of 5 ft (78.5 square feet (ft^2)) centered on MP-U and MP-D was used as an approximation for area in equation 3. This corresponds roughly to the circular area that the seepage meters were moved within to make repeated discharge measurements. For seepage area A mass flux calculations, a nitrate concentration of 52 mg/L as N (1.47 grams per cubic foot as N) was used for X_c as it was the median concentration of the eight samples collected in December 2007 (table 3) from multiport piezometer MP-U. Similarly for seepage area B, a nitrite concentration of 79 mg/L as N (0.22 milligram per cubic foot as N) was used for X_c as it was the median concentration of the eight samples collected in December 2007 (table 3) from multiport piezometer MP-D. Because area and nitrate concentration were held at constant levels throughout the calculations (similar to the horizontal mass flux calculations), the vertical mass flux of nitrate was highly dependent on the magnitude of the seepage flux.

Estimated vertical mass flux of nitrate for seepage areas A and B are listed in table 4. At seepage area A the vertical mass flux of nitrate averaged about 2.5 grams per day (g/d) and at seepage area B, it was 784 g/d. These estimations of vertical mass flux are an approximation and were specific to hydrologic conditions that occurred on August 16, 2006, and December 12, 2007, within the area near where the seepage measurements were made. They do not account for errors that are inherent to data collection using seepage meters or other naturally occurring factors that may play a role in regulating groundwater discharge throughout the year, such as evapotranspiration, recharge, groundwater level, and stream stage. However, these approximations of vertical mass flux of nitrate do indicate that under certain hydrologic conditions, the area of preferential discharge near MP-D at seepage area B east of the diabase dike has the potential to discharge substantial quantities of nitrate to the Neuse River.

Summary

Geologic, hydrologic, and water-quality data were collected from 3 core borings, 12 wells, and 4 piezometers at 3 well clusters, as well as from 2 surface-water sites, 2 multiport piezometers, and 80 discrete locations in the streambed of the Neuse River from 2005 to 2007. Data collected were used to evaluate the three primary zones of the piedmont aquifer (regolith, transition zone, and fractured bedrock) and characterize the interaction of groundwater and surface water as a mechanism of nutrient transport to the Neuse River.

The RHRS is representative of the igneous felsic intrusive hydrogeologic unit in the Piedmont Physiographic Province as it is underlain by the Rolesville granite batholith, a massive to weakly foliated granite intersected by diabase dike intrusions. The regolith varies in composition from a saprolite that was present across most of the RHRS to an alluvium deposited by the Neuse River. A zone of slightly weathered granite bedrock with open near-horizontal fractures near the top of the bedrock separated the overlying highly weathered regolith from the competent bedrock. The thickness of the transition zone increases with higher altitude along the well transect, ranging from 11 to 30 ft. The granitic rock outcrops and core specimens show a very weak steeply dipping foliation with a north-northeast strike. Two previously unmapped north-striking nearly vertical diabase dikes intrude the granite bedrock. The dikes appear to be hydraulically disconnected from the rest of the groundwater system.

Fractures identified within the boreholes were separated into three groups—"water bearing," "secondary," and "sealed"—on the basis of optical televiewer image logs. A correlation existed between foliation and fracture orientation, with most fractures striking parallel to foliation. Water-bearing fractures clustered in two sets: one set strikes east-northeast with a shallow south dip, and the second strikes northeast and dips moderately to steeply to the northwest. The majority of water-bearing fractures have dips of less than 30° and were likely stress-relief fractures caused by unloading of the granite. Secondary fractures had a conjugate joint set with a north strike, but few appeared to be water bearing and thus may have had little influence on groundwater flow.

Groundwater flow and vertical gradients at the RHRS generally supported historical conceptual models, with recharge occurring in areas of topographic high and discharge occurring at topographic lows near streams. The vertical gradient direction at well cluster WC-3 supported the concept of the downward movement of groundwater in recharge areas. In well WC-3D, the hydraulic head of the shallow transmissive fractures was higher than that of the deeper transmissive fractures, facilitating the transport of surface contaminants to deeper zones within the bedrock. In well WC-2D, under both ambient and stressed conditions the higher hydraulic head of the deep transmissive fractures caused water to flow upward to fractures at shallower depths with lower hydraulic heads. Vertical gradients in the discharge area near well cluster WC-1 were variable and highly dependent on the stage of the Neuse River, with gradient reversals common. Continuous groundwater-level data collected in the wells at well cluster WC-1 generally mimicked the surface-water stage of the Neuse River. It appears as though the Neuse River has incised through the alluvium and saprolite, hydraulically connecting it to the transition zone.

Elevated nutrient concentrations were detected in all of the groundwater samples collected from the wells and surface-water sites at the RHRS. Nitrate estimated from nitrite plus nitrate concentrations in the sampled wells and tributary ranged from about 5 to more than 120 mg/L as N. The distribution of nitrate concentrations within individual bedrock fractures isolated using a multifunction bedrock-aquifer transportable testing tool indicated that at well cluster WC-2 little nitrate was detected in the deep bedrock fractures but high concentrations of nitrate were present in deep bedrock fractures at WC-3. At well cluster WC-1, the nitrate concentration at well WC-1D completed in a diabase dike was much less than in the other WC-1 cluster wells, supporting the idea that the diabase dike is hydraulically isolated from the granite bedrock. The tributary topographically downgradient from well cluster WC-2 and WC-3 is a discharge point for regolith and transition zone groundwater originating in both areas. Seasonality in the groundwater temperature and specific conductance in the regolith and transition zone groundwater was not present in the bedrock groundwater. Based on dissolved-oxygen measurements, groundwater in the regolith and transition zone was aerobic, but groundwater in the bedrock tended to be anaerobic.

The extent of preferential discharge from the groundwater beneath the RHRS to the Neuse River was determined by the use of physical and chemical methods. Waterborne continuous resistivity profiling conducted on the Neuse River in the area of the RHRS indicated areas of low resistivity, likely representing groundwater contaminated by high concentrations of nitrate. The low-resistivity areas were concentrated beneath tributaries with high base flow nitrate concentrations and on either side of a diabase dike that transects the Neuse River. Discrete temperature measurements made within the pore water beneath the Neuse River revealed seeps of colder groundwater discharging into warmer surface water near a diabase dike. Water-quality samples collected from the pore water beneath the Neuse River indicated that concentrations of nitrate exceeding 80 mg/L as N were present in some areas on the RHRS side. Multiport piezometers installed in bed sediments on opposing sides of the diabase dike were used to assess the vertical distribution of nitrate in the pore water. Pore-water samples from the multiport piezometer installed in a previously identified seep had a median nitrate concentration that exceeded 75 mg/L as N and a vertical hydraulic gradient of 0.1. Pore-water samples from the multiport piezometer on the opposite side of the diabase dike had a median nitrate concentration of 79 mg/L as N and had no measurable vertical gradient. The disparate temperatures, vertical gradients, and nitrate distribution on either side of the diabase dike are evidence that the diabase dike preferentially directed the discharge of groundwater in the area of well cluster WC-1 to the Neuse River and isolated groundwater movement laterally across the dike.

Vertical fluctuations in the stage of the Neuse River and the resulting horizontal changes in pressure gradients made the calculation of vertical and horizontal seepage velocity and the resulting mass flux of nitrate highly temporal. The potential horizontal seepage and mass flux of nitrate from groundwater to the Neuse River was quantified for 2006 along a 300-ft river reach near well cluster WC-1. For the majority of 2006, the water level in the surficial aquifer was higher than the stage of the Neuse River, allowing groundwater to flux into the river with a median rate of 0.09 ft/d. The total horizontal mass flux of nitrate from the surficial aquifer to the Neuse River was estimated to be about 750 lbs for all of 2006. The flux of vertical groundwater seepage and mass of nitrate to the Neuse River was estimated by the use of seepage meters in the areas of the multiport piezometers on either side of the diabase dike. Seepage meter measurements were markedly different from one side of the diabase dike to the other, with average seepage fluxes of 0.02 ft/d and 4.5 ft/d, respectively. The estimated average daily vertical mass flux of nitrate at each seepage area was 2.5 g/d and 784 g/d over 2 days of measurement. Although these seepage and mass flux approximations are based on many assumptions, they highlight that over a small reach there is the potential for a large amount of nitrate to discharge from the groundwater into the Neuse River as a nonpoint source.

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For additional information regarding this
publication, contact:

Director
USGS North Carolina Water Science Center
3916 Sunset Ridge Road
Raleigh, NC 27607
(919) 571-4000
email: dc_nc@usgs.gov

Or visit the USGS North Carolina Water
Science Center Web site at:
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