Geology, Hydrogeology, and Groundwater Quality at North Carolina Zoo Groundwater Monitoring and Research Station Asheboro, North Carolina, 2007-2013

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Conversion Factors, Datum Reference, and Temperature

Multiply	By	To Obtain
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow	
Gallon per minute (gal/min)	0.06309	liter per minute (L/min)
	Radioactivity	
Picocurie per liter (pCi/L)	3.785	becquerel per liter (Bq/L)

Mean Sea Level: refers to the North American Vertical Datum of 1988 (NAVD 88), the vertical control datum established for vertical control surveying in the United State; NAVD was created by the NGS to replace the NGVD 29, a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Horizontal coordinates: Horizontal coordinates (latitude and longitude) in this report are referenced to the North American Datum of 1983 (NAD 83).

Temperature: The following equations can be used to make temperature conversions between degrees Celsius (˚C) and degrees Fahrenheit (˚F):

$˚F = (1.8 \times ˚C) + 32$
$˚C = 5/9\ (˚F - 32)$

Acronyms and Abbreviations:

bls	below land surface
bmp	below measure point
cu	color unit
DO	dissolved oxygen
DWR	Division of Water Resources
ft	foot/feet
ft/day	feet per day
gpm	gallon per minute
hr	hour
MP	measure point
µS/cm	microsiemens per centimeter at 25˚C, unit of specific conductance
µg/L	micrograms per liter
mg/L	milligram per liter
msl	mean sea level

NCDEQ	North Carolina Department of Environmental Quality (the former Department of Environment and Natural Resources, DENR)
NCGS	North Carolina Geological Survey
NCZGMRS	North Carolina Zoo Groundwater Monitoring and Research Station
NWIS	National Water Information System
OTV	Optical Televiewer
PMREP	Piedmont and Mountains Resource Evaluation Program
PVC	Polyvinyl Chloride
REE	Rare Earth Elements
SC	Specific Conductance
SOP	Standard Operating Procedures
TDS	Total Dissolved Solids
USGS	U.S. Geological Survey

ABSTRACT

The North Carolina Zoo groundwater monitoring and research station (NCZGMRS) is located at the southernmost part of the North Carolina Zoo in Asheboro, Randolph County, North Carolina. The station was established as part of the North Carolina Piedmont and Mountains Resource Evaluation Program to evaluate groundwater flow and quality within the felsic metavolcanic hydrogeologic unit that composes the geologic setting of more than six percent of the Piedmont and Mountains region of the state. In order to study the subsurface geology, hydrogeology, and groundwater quality at the NCZGMRS, a well transect, including a well cluster in the recharge area (topographic high), another in the midslope area, and a third in the discharge area on the toe-slope, was carefully designed and constructed. A total of 458 feet of soil and rock cores were collected from three coreholes with one at each well cluster site. Based on the information obtained from geologic coring, a total of ten monitoring wells and five piezometers were installed.

Observations of the geological cores and the examination of the petrographic thin-section samples from this study confirm the mildly metamorphosed felsic lapilli tuff unit of the Uwharrie formation at the NCZGMRS. A minor interlayer of mafic metavolcanic rock was encountered in only one of the three coreholes. Whole-rock geochemical analyses confirm both felsic metatuff and mafic metavolcanic rock compositions of the Uwharrie formation. When compared to average concentrations of metal elements found in granite, the whole-rock analytical results of felsic metatuff samples indicate higher levels of manganese (Mn), calcium (Ca), iron (Fe), lead (Pb) and arsenic (As). When compared to average values for basalt, levels of Ca and Fe in the mafic metavolcanic sample were lower but Mn, Pb and As were higher. Six of seven felsic metatuff samples have a higher ratio of Na_2O/K_2O than typical granite, while the mafic metavolcanic sample has a lower ratio of Na_2O/K_2O compared to the average for gabbro/basalt. Arsenic was more enriched in the mafic metavolcanic sample and the felsic metatuff sample that has a normal Na_2O/K_2O ratio.

Geological coring and geophysical logging conducted at this station indicate that the bedrock fractures are small and localized, but are interconnected to some degree. Most fractures are either sub-vertical to steeply dipping foliation partings or sub-horizontal to medium angled stress-relief fractures that cut the foliation. The transition zone has more low-angle fractures that are often open or slightly open. Steeply dipping fractures found at deeper depths are generally not displaced, but can exhibit chemical weathering. Only one or two relatively significant transmissive fractures were found in each corehole. The transmissive fractures typically have sub-horizontal to medium dip angles (less than 50 degrees).

Groundwater levels measured from April 2007 to October 2013 at the station fluctuated seasonally and responded to both long- and short-term climatic conditions. Generally, groundwater level in wells at the toe-slope in or near the discharge area fluctuated less than at upgradient locations. In shallow regolith zone, groundwater level fluctuated most at the middle slope, but in the bedrock, groundwater level fluctuated most in the well at the upland. During the seven-year monitoring period, the groundwater level decreased about three feet in the shallow zones and five feet in the bedrock well at the upland. An approximately one-foot decrease was also observed in the shallow well at the midslope. No change was found in the bedrock well in

the discharge area. Increases from one-quarter foot to approximately one-foot were measured in other wells.

Throughout the monitoring period, downward head gradients were found in the well clusters at the upland and the midslope sites, indicating recharge conditions. An upward head gradient was measured between the shallow well and bedrock well at the toe-slope, which is consistent with a discharge area. Aquifer testing results suggest an average horizontal hydraulic conductivity of 0.39 ft/day and an average transmissivity of 29.25 ft^2/day at the toe-slope site, and 0.47 ft/day and 89 ft^2/day at the midslope site. Results of slug tests conducted at all three well locations suggest horizontal hydraulic conductivity values ranging from 0.33 to 3.25 ft/day in the regolith and from 0.63 to 23 ft/day in the transition zone.

The groundwater water chemistry at the NCZGMRS is affected by rock type, mineralogy, and weathering processes. The groundwater geochemical signature varied primarily from sodium-bicarbonate type in the recharge area to calcium-bicarbonate type in the discharge area. The same change was found from the shallow regolith to the deep bedrock. The median values of groundwater pH varied from 5.21 to 7.42; pH was generally lower in shallow regolith wells than in deep bedrock wells and higher in the discharge area than in the recharge areas. The groundwater from monitoring wells in the discharge area has the highest mineralization. Iron (Fe) was detected at concentrations exceeding the state groundwater quality standard of 300 µg/L in all shallow monitoring wells and some deeper wells. Manganese (Mn) was also detected above the state standard of 50 µg/L in most of monitoring wells. Zinc was only detected in two of three bedrock wells at concentrations exceeding the state standard of 1000 ppb. Arsenic (As) was detected by USGS laboratory in most samples collected by USGS at concentrations well below the standard, but was not detected in any samples by the DWR laboratory.

INTRODUCTION

The North Carolina Zoo groundwater monitoring and research station (NCZGMRS) was established as part of the North Carolina Piedmont and Mountains Resource Evaluation Program (PMREP) that was conducted cooperatively by the North Carolina Department of Environmental Quality (NCDEQ, the former North Carolina Department of Environment and Natural Resources, NCDENR) Division of Water Resources (DWR, the former Division of Water Quality) and the U.S. Geological Survey (USGS). To evaluate groundwater flow and quality of the Piedmont and Mountains Physiographic Provinces of North Carolina, groundwater monitoring and research stations were installed at select sites considered to be "type" localities for hydrogeological conditions, with the intent of transferring the knowledge gained from these sites to other regions of the state in similar hydrogeologic settings. The NCZGMRS was selected because it is located in felsic metavolcanic rocks of the Carolina terrane. The felsic metavolcanic rocks compose the geologic setting of about 6.3 percent of the Piedmont and Blue Ridge Mountains Physiographic Provinces in North Carolina (Daniel and Payne, 1990 and Daniel and Dahlen, 2002), so the knowledge and information on groundwater conditions at this site would be transferable to a considerable portion of the Piedmont and Blue Ridge region in North Carolina. In addition, groundwater quality data collected from this station will be useful to broaden the PMREP's assessment on the extent and occurrence of arsenic in the groundwater system in the Carolina terrane, from the southwestern portion to the central portion of the terrane in North Carolina.

Another important aspect of the PMREP is to provide educational outreach to the citizens of North Carolina. The North Carolina Zoo is an optimal location for this type of effort, since it already had a strong educational focus and has hundreds of thousands of visitors each year. The information obtained from this geologic and hydrogeological study could be incorporated into future earth science and/or water resource exhibits, providing valuable educational benefits for numerous visitors to the Zoo.

Background of the Study

The Piedmont and Blue Ridge Mountains Physiographic Provinces in North Carolina extend over roughly 30,544 square miles and include 65 counties (fig. 1). In 2005, the population of the region was approximately 6.66 million, and it is estimated that about one-third of this population relies on groundwater for a variety of uses, including commercial, industrial, and most importantly, potable supplies (Huffman and Abraham, 2010). Naturally-occurring chemicals such as arsenic and radon are common in the Piedmont and Blue Ridge Mountains provinces, and may potentially exceed recommended levels for human consumption in groundwater. Because groundwater is the primary source of drinking water for most rural and some suburban households in the region and population increases promote further development of groundwater resources, it is critically important to understand and study the water quality and flow system.

To address these issues, in 1999, the NCDEQ DWR and the USGS began a multiyear cooperative study to measure ambient groundwater quality and describe the groundwater flow system in the Piedmont and Blue Ridge Mountains Physiographic Provinces in North Carolina. This cooperative program was funded by the North Carolina Legislature in 2000-2001 to ensure the long-term availability, sustainability, and quality of groundwater in the state. Ten groundwater monitoring and research stations were established (fig. 1) for this intensive study, in addition to several other focused groundwater quality projects. The NCZGMRS is one of these stations and one of two that were installed in the Carolina terrane. Data collection from this site began in April 2007.

Due to the complexity of the geology of the Piedmont and Blue Ridge Mountains Physiographic Provinces of North Carolina, the hydrogeology of these physiographic provinces is also complex. In the Piedmont region, aquifers generally consist of a basic two-component groundwater system with the regolith providing storage to the underlying fractures in the bedrock; however, a third component, the transition zone, is often present near the top of bedrock (fig. 2), which is often more conductive and plays an important role in transmitting contaminants (Daniel and Dahlen, 2002). Groundwater occurs in pore spaces and fracture networks, and aquifers are relatively shallow in this region. Groundwater in bedrock can be susceptible to contamination from activities on the land surface because of its connection to the shallow regolith aquifer. Geology is an important control on the groundwater movement and often has a direct effect on ambient groundwater quality. Therefore, geologic controls on the groundwater quality and the role of the transition zone in the groundwater system flow have been investigated through PMREP studies.

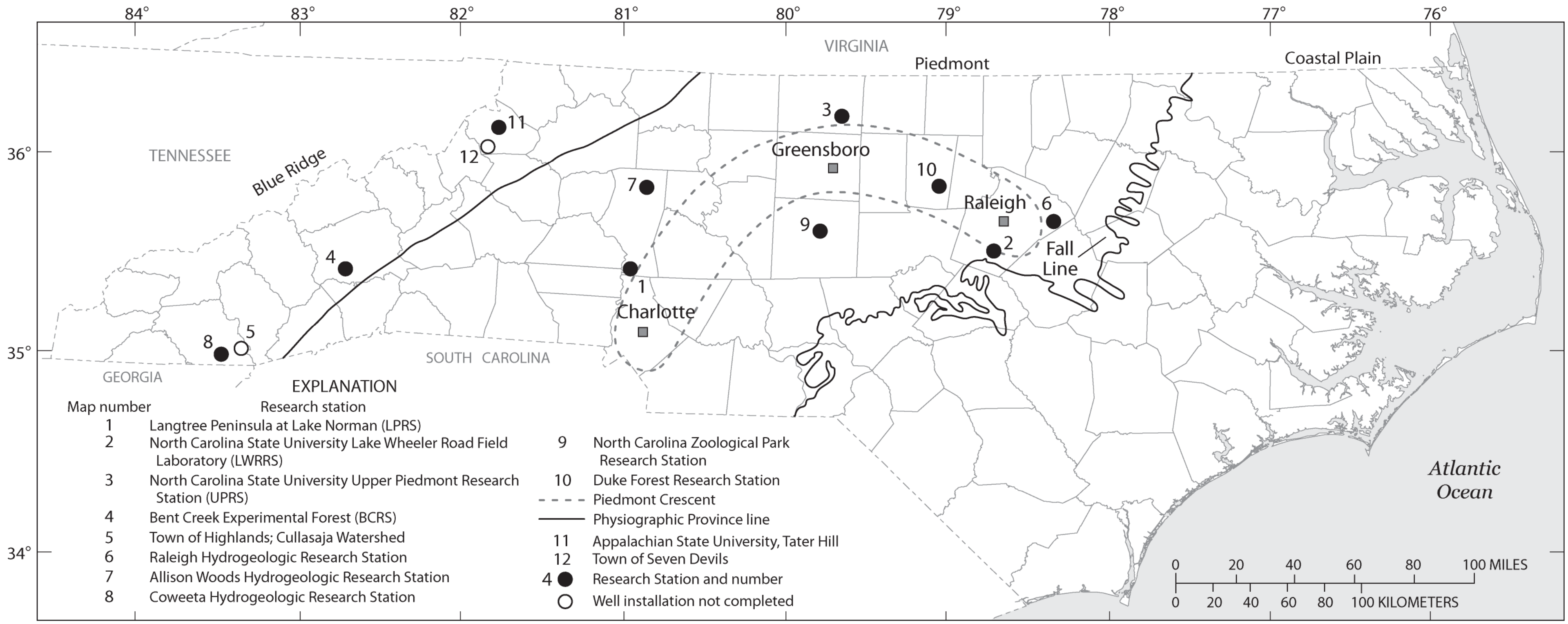
Objectives of the Study

Primary objectives of the groundwater study at the NCZGMRS are to:

1. characterize the site geology and the geochemistry, quality, and hydraulics of groundwater in the felsic metatuff unit of the Uwharrie formation in the Carolina terrane,
2. monitor changes in hydraulic gradients and groundwater quality and track water level fluctuations over time,
3. refine the present understanding of recharge and discharge processes and their role in determining groundwater quality, and
4. collect groundwater data from this station to develop a comprehensive groundwater database for the Piedmont and Mountains region of the state.

Scope and Purpose of the Report

The NCZGMRS was designed to distinguish and evaluate groundwater quality and flow in primary zones of the Piedmont and Mountains groundwater system, including (1) the upper shallow regolith, (2) the intermediate transition zone, and (3) the deeper fractured crystalline bedrock (fig. 2). The evaluation was done through geologic coring, periodic water quality sampling, monthly water level measurements, geophysical logging, and hydraulic testing. Data from geologic cores collected at the NCZGMRS and petrographic thin sections provide fundamental information on the site geology and mineralogy. Core logs, borehole geophysical logs, water level monitoring, other hydraulic testing, and groundwater chemistry data are analyzed to characterize site hydrogeology, with particular focus on groundwater flow and



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. Locations of groundwater monitoring and research stations selected for investigations as part of the cooperative North Carolina Division of Water Quality and U.S. Geological Survey Piedmont and Mountains Resource Evaluation Program in North Carolina (From Huffman and Abraham, 2010)

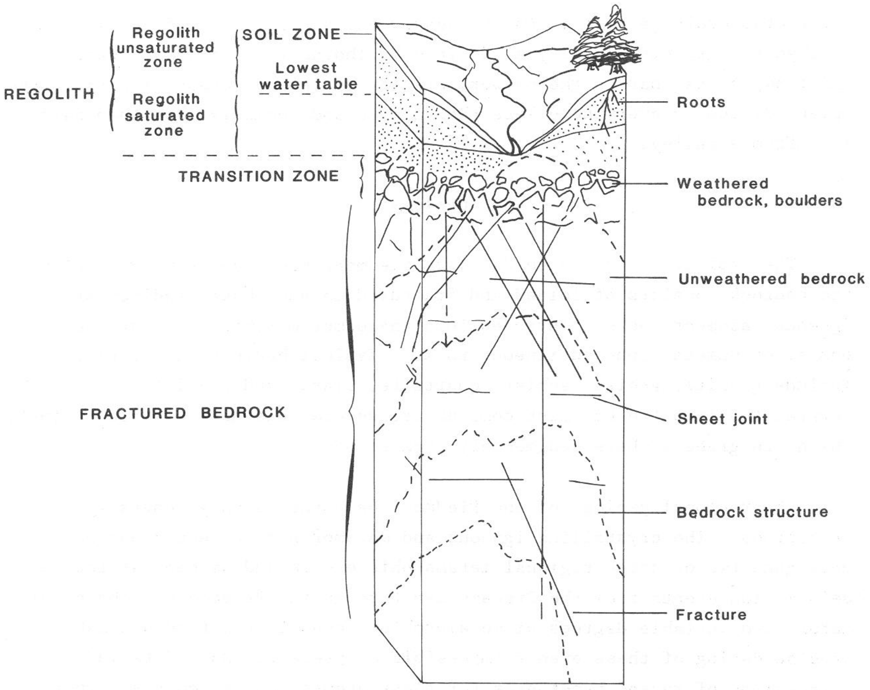


Figure 2. Conceptual components of the Piedmont and Mountains groundwater system (From Harned and Daniel, 1992)

quality. The main purpose of this report is to document and present results and findings of the investigation from April 2007 through October 2013. The report also provides a brief description of the various methods used in this investigation, a short summary of previous studies, and a brief description of the regional and local geology.

Previous Studies

Several geologic studies and mapping projects have been conducted in the Asheboro area and the Piedmont region (Conley, 1962; Conley and Bain, 1965; Seiders, 1971, 1978, 1981, and 1985; Seiders and Wright, 1977; Wright and Seiders, 1980; Butler and Secor, 1991; Hibbard and others, 2002). In addition, a large scale (1:4800) geologic map of the North Carolina Zoo was prepared by Seiders (1985) prior to this study. These previous studies indicate that the NCZGMRS is underlain by felsic lappilli tuff and tuff unit of the Uwharrie Formation. As regional structures, foliation and cleavages with moderate to steep dip primarily strike northeast-southwest.

A few groundwater resource evaluations have been conducted in the region through data collection from water supply wells (Bain and Thomas, 1966; Berry, 1965; Floyd and Peace, 1974), but no specific groundwater or hydrogeologic investigation has been systematically conducted through a designed station consisting of a series of monitoring wells in the area. In Bain and Thomas's (1966) study, groundwater in the Durham area, including Randolph County where the NCZGMRS is located, was evaluated. During their investigation, the yields of 154 water supply wells in Randolph County, including 99 wells constructed in metavolcanic rocks similar to what is underlying the NCZGMRS, were studied with respect to rock type, depth of weathering, and topography. It was found that the average depth of wells constructed in metavolcanic rocks was relatively shallower and the average yield of those wells was generally higher than wells constructed in granite-granodiorite or argillite-graywacke. Depth of weathering was shown to have a greater influence on yields from the metavolcanic unit. The average yield from wells constructed in the metavolcanic unit in Randolph County was 12.9 gallons per minute or 0.13 gallon per minute per foot of well (total well depth). The comparison of yields from different topographic situations indicated that the slopes are the most dependable positions for wells in the area. Their groundwater geochemistry study indicated that groundwater in Randolph County is principally a calcium bicarbonate type, but sodium and magnesium bicarbonate type and calcium chloride type are also present.

Description of the Study Area

The NCZGMRS is located within the North Carolina Zoo property. The North Carolina Zoo is located approximately 5 miles southeast of the City of Asheboro, Randolph County, NC. Randolph County is located in the geographic center of the State of North Carolina. The county has a total area of 505,254 acres, or about 808 square miles (Wyatt, 2006), and a population of 142,577, with 25,559 living in Asheboro (U.S. Census Bureau, 2013). Topographically, the area is characterized as gently rolling to hilly, river valleys, and forestland. The Uwharrie and Deep Rivers and their tributaries form the two major drainage systems within Randolph County. The Uwharrie River drains the western part and the Deep River drains the eastern part of the county. In addition, the Little River, which originates near Asheboro, forms the headwaters of a third drainage basin within the Cape Fear River Basin. Within the area, annual average temperature is 60.2 °F with an average daily high of 71.2 °F and low of 49.2 °F. The total average annual precipitation is approximately 45.5 inches; of this, 24.8 inches, or about 54 percent, usually falls in April through September (Wyatt, 2006).

The Zoo’s property covers approximately 1,500 acres of varied landscape: gently rolling, hilly, and flat; wooded and grassy; stony and fertile. Relief is on the order of 460 feet, with elevations ranging from 500 feet above mean sea level in the northeast corner of the property near Richland Creek, to 960 feet above mean sea level at the top of Purgatory Mountain (fig. 3). Slopes range from less than 10 percent to greater than 20 percent, with three-quarters of the property at less than 20 percent slope (the North Carolina Zoo, 2000, unpublished). Land use in the vicinity of the Zoo is predominantly low density residential and rural.

The NCZGMRS is located on approximately 20 acres of gently sloped and wooded land near the southernmost boundary of the Zoo’s property (fig. 3). The NCZGMRS is bounded on the southwest by a few private residential lots and on the northwest by a gravel driveway through the Zoo recycling drop-off area, on the north-northeast by the parking lot at the Africa Exhibit and the Africa Lake of the Zoo, and on the east-southeast by Panther Creek and its wetland. Surface water drains in south-southeast direction. The station includes three monitoring well clusters installed in a nearly linear well transect parallel to an assumed groundwater flow path (LeGrand and Nelson, 2004), from a topographic high (recharge area) to low (discharge area) setting (fig. 4). Each well cluster has at least three monitoring wells designed to monitor three different groundwater components of the groundwater system.

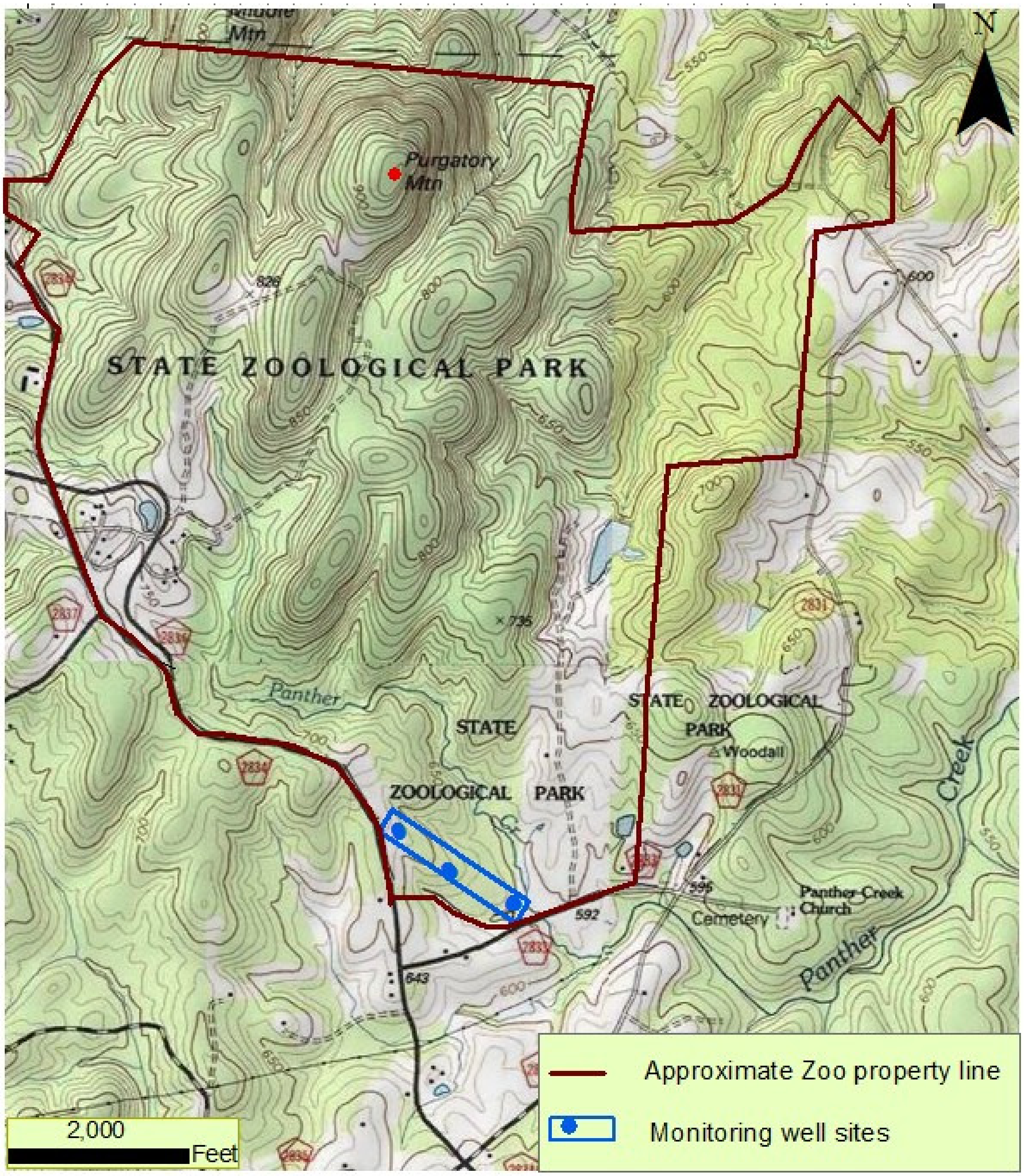


Figure 3. Location of the North Carolina Zoo groundwater monitoring and research station (NCZGMRS) within the Zoo's property, Asheboro, NC

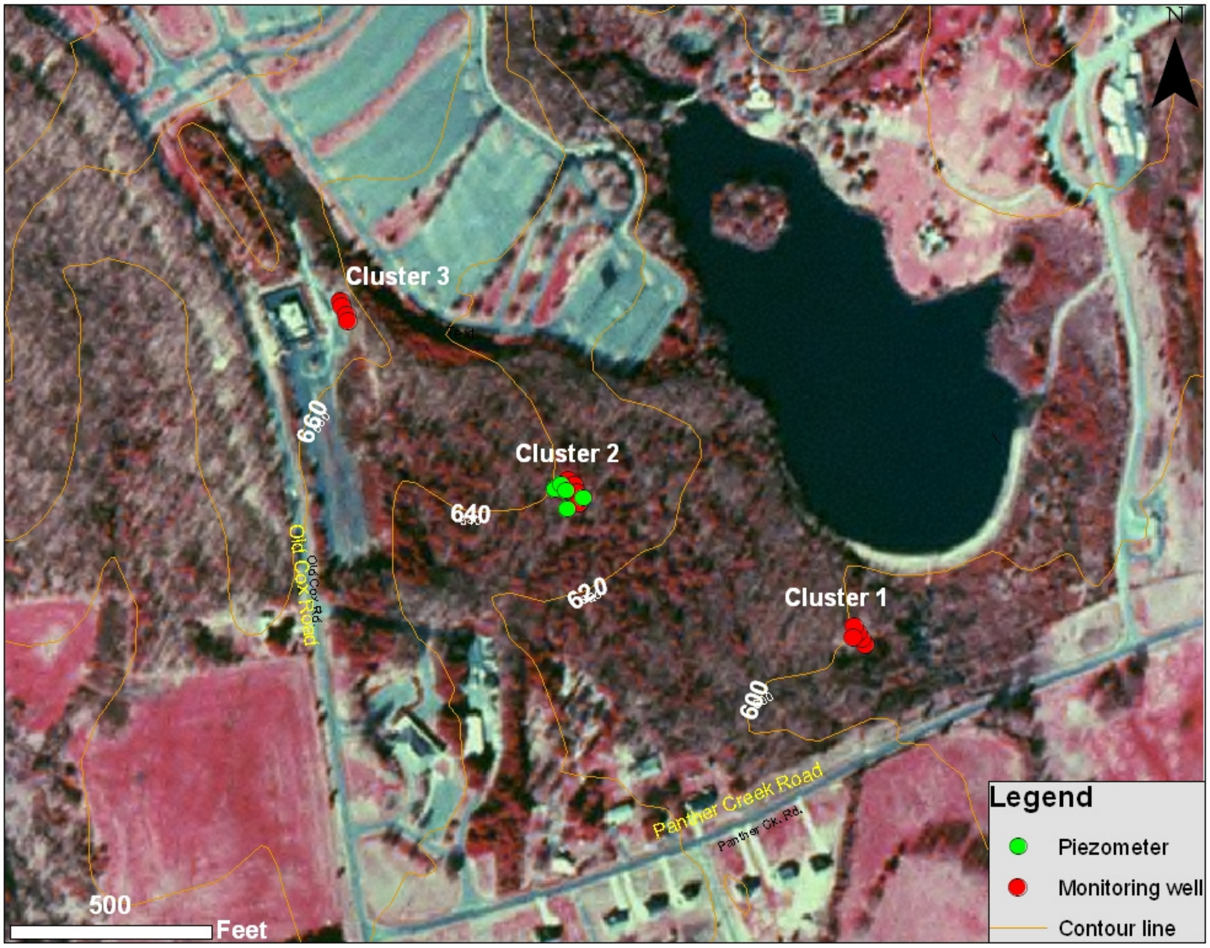


Figure 4. Site map of the NCZGMRS, Asheboro, NC (Base map from NCDOT 98ColorIRTile77)

METHODS OF INVESTIGATION

Since the geology of the Zoo property was previously mapped in detail (Seiders, 1985), no further geologic mapping was conducted for this study. Previous studies described bedrock types and their origin and distribution in the area, but these studies did not provide much data on discontinuities (e.g., fractures and other openings in subsurface rock), which are of utmost importance for groundwater studies in crystalline bedrock terrane. Therefore, to investigate the detailed subsurface geology and hydrogeology, several techniques were used, including geologic coring and groundwater monitoring well installation. These methods are briefly described below. For specific details, please refer to Standard Operating Procedures (SOP) for Groundwater Research Stations (NCDENR DWQ, 2005 and 2008, unpublished).

Geologic Coring and Well Construction

The DWR Field Investigations Unit staff members conducted all drilling for this study using state-owned equipment. Activities of establishing the research station were conducted in two phases: (1) collecting continuous soil and bedrock cores using a wire-line coring rig

(CME-75 drilling rig) and (2) installing monitoring wells and piezometers using a Schramm T450 drilling rig with varying diameters of air-rotary bits.

Geologic coring

Continuous soil and rock core was collected at each proposed well cluster location with a wire-line retrieval system using a 5-foot long and 3 ¼ -inch diameter core barrel sampler. A carbide-tipped soil-sampling core barrel bit was used to penetrate the unconsolidated material, and a diamond-tipped bit was used to penetrate the competent bedrock. The project hydrogeologist logged the cores retrieved from the sample barrel, documenting soil and rock type, fracture type and orientation, and other geologic features. The cores were then marked for section correlation and placed in core boxes for storage (fig. 5). After sample collection and geological logging were completed, the corehole was converted to a monitoring well for use in aquifer testing and other hydrogeologic characterization.

Well-numbering system

The three well clusters were named cluster 1 (or lower cluster), cluster 2 (or mid cluster), and cluster 3 (or upper cluster), respectively, from the topographic low to high setting. The coreholes, wells, and piezometers were numbered with a system similar to the one described by Chapman and others (2005). The numbering system consists of letters (well descriptors) and numbers. The well descriptors used in this study include “MW” for monitoring well, “CH” for corehole, and “PZ” for piezometer. For monitoring wells, following the well descriptor is a number indicating the well cluster in which the well is located and a letter indicating the aquifer section or zone to be monitored: “S” for shallow zone (regolith), “I” for intermediate or transition zone, and “D” for deeper zone (bedrock). For example, well MW–1S is a monitoring well in cluster 1 and is completed in the shallow regolith zone. In addition, letters U and L are used to distinguish either upper or lower section of the transition zone to be monitored if there is more than one intermediate well installed in a well cluster. For example, MW-1UI is an intermediate well in cluster 1, which is completed in the upper section of the transition zone.

Figure 5. Example of core: Core sample from CH-2 at the NCZGMRS showing fracture characteristics and weathering conditions of the bedrock

However, for the five piezometers, following the well descriptor is a letter and then a number. The letter means the same as for monitoring wells described above, the aquifer section or zone to be monitored, but the meaning is different for the number following the letter. For example, PZ-S1 indicates the first piezometer completed in the shallow regolith zone and PZ-D2 means the second piezometer completed in the deep bedrock.

Monitoring well installation

The number and depth of monitoring wells and piezometers to be installed in each cluster were determined based on the information obtained from the geologic core. Monitoring wells and piezometers were completed with a Schramm T450 drilling rig with different diameters of air-rotary drilling bits.

Shallow and intermediate wells: A 12-inch-diameter air-rotary drilling bit was used to set a surface casing up to 20 feet deep, then an 8 5/8-inch diameter bit was used to drill to the prescribed depths through the surface casing. After a boring reached the prescribed depth, a 2- or 4-inch-diameter schedule 40 polyvinyl chloride (PVC) well casing with a 0.01-inch machine-slotted well screen at the base was placed in the boring for monitoring wells. For piezometers, a 2-inch-diameter PVC well casing and screen were used while 4-inch-diameter PVC well casing and screen were used for the monitoring wells. The length of the screen varied from 10 to 20 feet (table 1). Clean sand was gradually poured into the annular space between the PVC screen and the wall of the boring up to approximately one foot above the top of the well screen. A two-feet-thick dry bentonite chip seal was placed on top of the sand filter pack and hydrated. Above the hydrated seal, bentonite chips were used to fill the annular space between the PVC casing and the borehole wall up to approximately three feet below the land surface. Cement grout was then used to fill the top three feet of annular space.

Deep bedrock wells: To install deep bedrock monitoring wells, the 12-inch diameter air-rotary bit was also used to set a 20-foot surface casing first. A smaller air-rotary drilling rig was then used to drill an 8 5/8-inch diameter boring to a depth at the least 5 feet into competent bedrock. After the 8 5/8-inch diameter boring was completed, 6 1/4-inch-diameter galvanized steel casing was lowered into the boring and the annular space was sealed with bentonite up to three feet below the land surface. A smaller diameter (6 1/8 inches) air-hammer was then lowered through the 6 1/4-inch diameter galvanized steel casing to drill the open portion of the borehole. Finally, cement grout was then used to fill the top three feet around the well casing.

Table l. Characteristics of monitoring wells and piezometers at the NCZGMRS, Asheboro, NC

Well ID	**Date of Completion**	**Total Well Depth, ft. bls[1]**	**Casing /Riser Depth, ft. bls[1]**	**Casing Type**	**Borehole Diam., in.**	**Casing Diam., in.**	**Screened/ Open Interval, ft. bls[1]**		**Screened or Open**	**MP Elev. ft. above msl[2]**	**Height of MP ft. als [3]**	**Land Surface Elev. ft. above msl[2]**
CH-1	7/25/06	185	30	PVC	3 ¼	4	30	185	Open	602.02	3.17	598.85
CH-2	10/31/06	98	37	PVC	3 ¼	4	37	98	Open	639.47	3.38	636.09
CH-3	10/4/06	175	53	PVC	3 ¼	4	53	175	Open	668.78	3.25	665.53
MW-1S	3/7/07	23	8	PVC	12	4	8	23	Screened	599.86	2.93	596.93
MW-1UI	3/28/07	43	28	PVC	8 5/8	4	28	43	Screened	602.25	3.00	599.25
MW-1LI	4/3/07	70	50	PVC	8 5/8	4	50	70	Screened	602.34	3.00	599.34
MW-1D	3/21/07	300	85	GALV	6 1/8	6 ¼	85	300	Open	601.13	3.01	598.12
MW-2S	2/20/07	35	25	PVC	12 – 8 5/8	4	25	35	Screened	639.96	2.91	637.05
MW-2I	2/20/07	58	38	PVC	8 5/8	4	38	58	Screened	640.83	3.15	637.68
MW-2D	12/11/06	260	69.9	GALV	6 1/8	6 ¼	70	260	Open	641.94	2.97	638.97
MW-3S	12/5/06	36	16	PVC	12	4	16	36	Screened	668.24	2.94	665.30
MW-3I	11/29/06	63	43	PVC	8 5/8	4	43	63	Screened	668.09	2.91	665.18
MW-3D	11/28/06	180	74.5	GALV	6 1/8	6 ¼	74.5	180	Open	668.10	2.96	665.14
PZ-S1	2/27/07	30	15	PVC	12 – 8 5/8	2	15	30	Screened	639.35	3.25	636.10
PZ-S2	2/28/07	30	15	PVC	12 – 8 5/8	2	15	30	Screened	641.85	3.03	638.82
PZ-I1	2/28/07	60	40	PVC	6 1/8	2	40	60	Screened	643.23	2.93	640.30
PZ-D1	2/27/07	90	70	PVC	6 1/8	2	70	90	Screened	642.50	2.69	639.81
PZ-D2	3/5/07	100	70	PVC	6 1/8	2	70	100	Screened	640.52	3.02	637.50
1-feet below land surface; 2-feet above Mean Sea Level NAVD 88; 3-feet above land surface												

Coreholes: To convert coreholes to monitoring wells, four-inch diameter of PVC casing was lowered into each corehole until competent bedrock was reached; then bentonite was placed in the annular space between the casing and the core-hole wall from the top of the bedrock to three feet below the land surface. The top three feet were cemented.

Upon completion, all wells were developed, protected by locked outer steel casing approximately three feet above the land surface, and surveyed to determine the horizontal position and elevation. The elevations were derived by tying well heads to USGS benchmark Zoo AZMK that is located along Zoo Parkway at North America Bridge at the North Carolina Zoo; the benchmark elevation is 748.60 feet above mean sea level, NAVD 88.

Borehole Geophysical Logging

Borehole geophysical logging data were collected by USGS from each bedrock well to characterize subsurface geologic fractures and lithology. Caliper, natural gamma, electrical (resistance, short-normal, long-normal, and lateral resistivity), and fluid (temperature, fluid resistivity) logging data were collected using a single or a combination Century Geophysical© borehole logging tool. In addition to the above traditional logs, an optical televiewer (OTV) manufactured by ALT© Geophysics was used to obtain an oriented digital image of the borehole. The OTV image and associated interpretation software permits direct observation of lithology and the orientation of rock foliation (fabric) and fracture. The OTV data are corrected for borehole deviation (azimuth and inclination angle) and magnetic declination.

Petrographic Thin-Section

A total of seven petrographic thin-section samples were collected from representative, fresh-looking rock cores from the NCZGMRS to study microscopic characteristics of the rock cores. The photo-microscopic examination was primarily performed by Dr. Rick Abbott at the Appalachian State University Geology Department and Phil Bradley of the North Carolina Geologic Survey.

Whole-Rock Geochemical Analyses

Eight representative unweathered bedrock samples (seven from the rock cores where the thin-section samples were collected and one from drilling cuttings of fresh bedrock) were collected for whole-rock geochemical study. The USGS Mineral Resources Team in Lakewood, CO performed analyses. Analyses for major elements (oxides) were made using wavelength-dispersive X-ray fluorescence (WDXRF) spectrometry (Taggart and Siems, 2002); concentrations of Ag, As, Ba, Bi, Br, Cd, Ce, Cr, Cs, Cu, Ga, Ge, La, Mo, Nd, Nb, Ni, Pb, Rb, Sb, Se, Sn, Sr, Th, U, V, W, Y, Zn, and Zr were determined by energy-dispersive X-ray fluorescence (EDXRF) spectrometry (Siems, 2002); analyses of Fe, Ca, Na, K, Rb, Sr, Cs, Ba, Th, U, La, Ce, Nd, Sm, Eu, Gd, Tb, Ho, Tm, Yb, Lu, Zr, Hf, Ta, W, Sc, Cr, Co, Ni, Sn, As, Sb, and Au were analized using instrumental neutron activation analysis (INAA; Budahn and Wandless, 2002); carbonate carbon was determined using coulometric titration, while total carbon and total sulfur were determined by combustion (Brown and Curry, 2002).

Periodic Water-Level Measurements

Groundwater levels were measured monthly at all wells including monitoring wells, coreholes, and piezometers at the NCZGMRS to identify seasonal and long-term groundwater level variations in each of the three monitored zones (regolith, transition zone, and bedrock) and to qualitatively describe the vertical hydraulic gradient at each of the three well sites. Groundwater levels were collected using an electric water-level meter in reference to a specified measuring point (MP) on top of the well casing and following methods described in the SOP. The MP at each well was surveyed and the elevation was related to a USGS benchmark located in the area to determine water-level altitudes above mean sea level. The water levels were initially recorded in feet below land surface. The data collected before 2009 was entered into the USGS Ground Water Site Inventory (GWSI) database, and are available online at http://nwis.waterdata.usgs.gov/nc/nwis/gwlevels. All data collected from the site are available in the DWR Water Quality Regional Operations Section Winston-Salem Regional Office.

Slug Tests

Falling head (slug in) and rising head (slug out) slug tests were attempted on all shallow regolith wells and intermediate or transition zone wells except for MW-2S that did not have enough water to be tested to estimate the horizontal hydraulic conductivities of the regolith and transition zone tapped by the wells. A five-foot long, 2-inch diameter solid slug (a segment of PVC pipe filled with clean sand) was used to displace water in the wells. It was rinsed with distilled water before use in each well. A submersible pressure transducer with an integrated electronic data logger was used to measure water-level fluctuations during each test. Water-level data recorded on the transducer data logger were verified by manual water-level measurements. The falling head slug test measured the rate at which water levels returned to static conditions after the introduction of the solid slug. The rising head test measured the recovery of water levels to static conditions after the slug was removed. Efforts were made to avoid splashing effects during the introduction of the slug below the water level. The tests were terminated after water levels returned or recovered to within 95 percent of the pre-test static water level.

The slug-test data were analyzed using the Bouwer and Rice (1976) method, which accounts for partial penetration effects and changing aquifer thickness (water table conditions). A basic assumption of this analytical method is that the aquifer is representative of a porous medium and is considered isotropic, with no directional variation in hydraulic properties in the zone being tested. Additional assumptions are that the effects of elastic storage can be neglected and that the position of the water table does not change during the slug test (Butler, 1998). Based on the information obtained from the geological coring, these assumptions should be reasonable for this site although they could not be matched exactly. Spreadsheets developed by USGS (Halford and Kuniansky, 2002) were used for analytical interpretations of slug-test data.

Pumping Tests

A pumping test imposes a greater stress of longer duration than a slug test and can provide estimates of hydraulic properties of a larger region around the well than a slug test can. Two pumping tests were conducted to estimate transmissivity and horizontal hydraulic conductivity of the groundwater system at the NCZGMRS. A step-drawdown test was conducted a week before each pumping test to determine pumping rate. An electric submersible pump was installed in the pumping wells (MW-2D for the first test and MW-1D for the second test) at depths determined by step drawdown tests and the depth of the major water producing zone or fracture zone in each pumping well. Care was taken to ensure that a steady flow rate was maintained throughout the tests. The pumping rate was measured by a flow meter. A plastic gate valve was installed at the wellhead to regulate the pump discharge rate. The flow meter was calibrated by a graduated bucket and stopwatch at regular intervals throughout the tests. The pump discharge was directed to a natural drainage about 200 feet side-down gradient from well MW-2D for the first test and to a natural drainage about 100 feet downgradient of well MW-1D. During the testing (from before pumping to the end of recovery), groundwater levels were measured at all wells at the tested sites using In-Situ Hermit Data Logger transducers in observation wells, an In-Situ mini-troll in the pumping well, and selected wells in outlying well clusters with hand-held electric water-level meters at different designed intervals. To check whether the transducers worked properly, hand measurements were also performed at the on-site monitoring wells. In addition, the pressure transducers were placed in the wells a few days before the aquifer test to allow time for the transducers and water levels to stabilize and to determine effects of atmospheric pressure changes on groundwater levels in monitoring wells. The pressure transducers were attached to an electronic data logger. The data were displayed on laptop computers.

The pumping test data were analyzed with the Cooper-Jacob straight-line time drawdown method analysis spreadsheets developed by USGS (Halford and Kuniansky, 2002). The Cooper-Jacob method, commonly referred to as the straight-line method, is a simplification of the Theis solution. For most applications, the straight-line method is valid as long as $u < 0.1$(u, dimensionless, = $r^2S/4Tt$, where T is the transmissivity, S is the aquifer storativity, r is the radial distance to the pumping well, and t is the time since pumping started). Well losses and partial-penetration have a minimal effect on transmissivity values that are estimated using the Cooper-Jacob method. If there is any effect, well losses and partial penetration affect drawdowns by a fixed amount that changes very little after a well has been discharging for minutes to hours after discharge begins. Additional drawdown at later times is due to declining heads in the aquifer and the rate of decline is controlled mostly by the transmissivity of the aquifer. Analyzing the change in drawdown at later times negates the effect of a fixed offset due to well losses and partial-penetration on the determination of transmissivity. Therefore, the Cooper-Jacob straight-line method is exclusively for estimating T (Halford and Kuniansky, 2002). The same assumptions apply to the Cooper-Jacob method as to the Theis solution. The assumptions and conditions include: the aquifer has a seemingly infinite areal extent; the aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test; prior to pumping, the piezometric surface is horizontal over the area that will be influenced by the test; the aquifer is pumped at a constant discharge rate; and, the well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow. It should be understood that fractured bedrock aquifer systems cannot meet these assumptions and there is no other simple way to handle fractured systems. However, because fractures found in bedrock during the onsite geologic coring are small and developed relatively evenly throughout the area, the method discussed here should be the best approach.

In the Cooper-Jacob straight-line method spreadsheets, a semi-log plot of the field drawdown data (linear scale) versus time (normal log scale) is made. A straight line is then drawn through the field-data points and extended backward to the zero-drawdown axis. The value of the drawdown per log cycle of time, (h_0-h), is obtained from the slope of the graph. Then, transmissivity (T) is estimated from the pumping rate (Q) and the change in drawdown per log-cycle (h_0-h) from the following equation: $T=2.3Q/4\pi(h_0-h)$. The horizontal hydraulic conductivity, K is computed by dividing T by aquifer thickness through the spreadsheets. Well losses and partial-penetration have a minimal effect on transmissivity values that are estimated using the Cooper-Jacob method (Halford and Kuniansky, 2002).

Water-Quality Sampling

Water-quality samples were collected from all monitoring wells semiannually during the first two years and then annually in the following years from 2007 through 2013 for most parameters monitored with submersible pumps following the methods described in the SOP. Purging rate, water levels, and field water-quality properties (pH, SC, DO, and temperature) were monitored and documented during well purging. The field water-quality properties were measured every 10 to 30 minutes using a multi-parameter water-quality instrument. Prior to sample collection, three well volumes of water were removed from the 4-inch diameter screened wells completed in the regolith and transition zone. However, only one well volume of water was removed for a slow recovery well. For 6-inch diameter deep open-borehole bedrock wells, extracting three well volumes of groundwater prior to sample collection was impractical when purging at a rate for sampling. Therefore, for the deep bedrock wells, a minimum of one well volume of water was removed or field parameters were allowed to stabilize prior to sample collection. Pump intakes were placed near the more dominant fracture zones whenever feasible. Samples were collected with bottles, jars, or vials supplied by the analytical laboratories. Radon samples were collected following a special procedure designed to prevent aeration. Specifically, 40-milliliter (or similar) glass radon vials were carefully submerged, filled, and sealed inside a 2-liter plastic beaker or similar container that had been slowly filled with well water. Panther Creek adjacent to the lower well cluster was also sampled following the SOP at the same frequency and for the same parameters with an exception of radon gas.

The water-quality constituents including physical parameters, alkalinity, total organic carbon, cyanide, major ions, trace metals, nutrients, volatile and semivolatile organic compounds, pesticides, and herbicides were analyzed by the DWR laboratory in Raleigh NC; dissolved radon was analyzed by the DWR laboratory in Asheville, NC; fecal coliform samples were analyzed by R&A Laboratories, Inc., a DWR contracted lab, in Kernersville, NC. In order to ensure the quality of the sampling results, a trip blank for volatile samples and a duplicate sample for metals and other parameters were collected and submitted to the DWR laboratory along with other samples.

In addition, water samples were also collected by the USGS following their standard protocols (U.S. Geological Survey, 2006) from selected monitoring wells and coreholes at the NCZGMRS. The water quality constituents analyzed by the USGS National Water Quality Laboratory (NWQL) in Denver, CO, include major ions, nutrients, radon 222 (gas), and trace metals by using methods outlined by Fishman (1993). Bacteria samples were processed locally in the USGS North Carolina Water Science Center laboratory in Raleigh, NC using methods described in USGS water sample collection document (U.S. Geological Survey, 2006).

Analyses of Water-Quality Data

Water quality data were analyzed to determine if there was any element or compound in the samples collected exceeding the 15A NCAC 2L .0202 Groundwater Quality Standards (the state groundwater standards). The data were graphed to assess the variation in groundwater quality. Column bars, scatters, and Piper diagrams (Piper, 1953) were plotted to help evaluate trends and differences of the water quality and type at each well location, and for each component of the groundwater system. Unless otherwise noted, evaluations and discussions are based on the median values of data collected by DWR at a given well or stream site as determined from all values measured over multiple sample dates (appendix 5-1). Data collected by USGS are compiled and presented in appendix 5-2. When medians were calculated, if a parameter was not detected at the detection limit, 50% of the value of the detection limit was used; however, if a parameter was never detected in a given well or the stream site, the value "0" was used to plot figures. Analytical results from each well and from each component of the aquifer system were compared to the state groundwater standards and the EPA secondary drinking water standards (U.S. Environmental Protection Agency, 2003) to determine if any constituents in the groundwater exceed the standards.

In this report, water-quality data are grouped for discussion by well cluster, surface water, and groundwater-system components (regolith, transition zone, and bedrock).

GEOLOGIC SETTING AND ROCK CHEMISTRY

Regional Geologic Setting

The Piedmont Physiographic Province of North Carolina is primarily underlain by metamorphic and igneous rocks, with metamorphic rocks being more dominant. Sedimentary rocks are locally present in limited Triassic basins in the province. Rocks in this region have undergone mild to intense metamorphism, folding, faulting, and igneous intrusion from the Early Cambrian through the end of the Paleozoic. The metamorphic-grade facies in the region ranges from greenschist to amphibolite. The regional sequences of rocks can be grouped into a series of belted terranes with a northeast trend. The study area is located within the Carolina terrane (also known as the Carolina slate belt) of the Carolina Zone (NCGS, 1985 and Hibbard et al., 2002). Generally, the rocks in the study area are composed of approximately 550 million year old volcanic rocks assigned to the Uwharrie formation consisting primarily of slightly metamorphosed felsic lavas and tuffs, lesser interlayered mafic lavas and tuffs and meta-sedimentary rocks (Seiders, 1981). A portion of the geologic map of North Carolina (fig. 6) indicates the approximate extent of the Uwharrie formation and the location of the NCZGMRS.

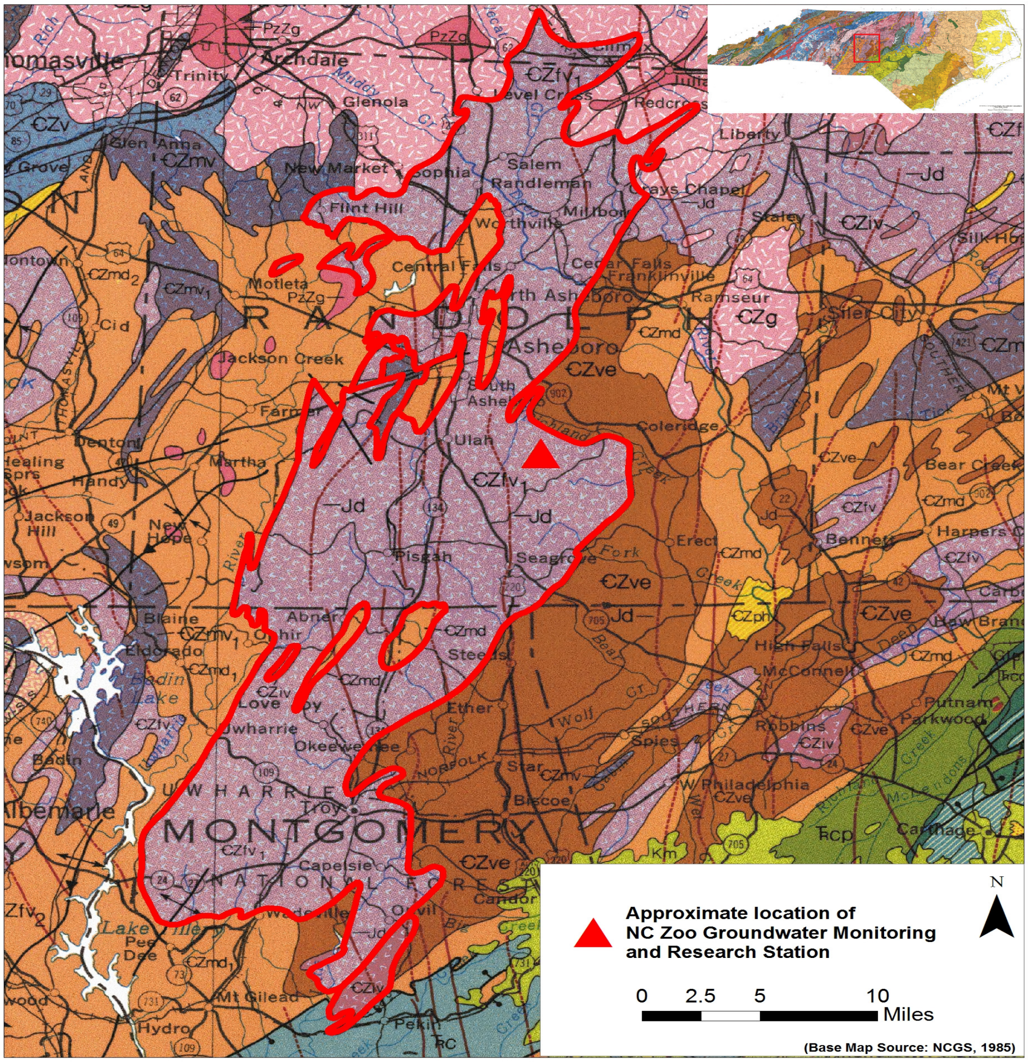


Figure 6. Portion of 1985 Geologic Map of North Carolina, indicating the approximate extent of the Uwharrie formation (outlined in Red) and location of study area (produced by Phil Bradley, North Carolina Geological Survey from North Carolina Geological Survey, 1985, Geologic Map of North Carolina, 1:500,000)

Site Specific Geology

The NCZGMRS is underlain by the Uwharrie formation that has been folded into open folds causing original depositional layering to be inclined from 15 to 80 degrees from the horizontal. The rocks in the vicinity of the study site include metamorphosed felsic tuffs and felsic volcanic rocks and lesser interlayered mafic lavas and meta-sedimentary rocks. The metamorphic foliation or cleavage of the rocks is generally steeply dipping, ranging from 60 degrees to almost vertical from the horizontal (Seiders, 1981). Metamorphic foliation and cleavage is typically northeast/southwest trending. The trend of original depositional layering is widely variable depending on local geologic structures (i.e. anticlines and synclines). Structural data is sparse and the identification of original depositional layering is difficult in the metamorphosed tuffs and lavas of the Uwharrie formation. The metamorphic foliation is the most prominent planar feature observed at the outcrop scale.

A Preliminary Geologic Map of the North Carolina Zoological Park, Randolph County, NC was prepared by Seiders (1985). Based on this map, the monitoring wells and coreholes of the NCZGMRS were all installed within the mildly metamorphosed felsic lapilli tuff and tuff unit (fig. 7). Seiders (1985) described this unit as massive to weakly foliated rock composed of tightly compacted sand- and silt-sized volcanic rock fragments and quartz and feldspar grains, commonly with scattered volcanic rock fragments larger than 4 mm (lapilli), generally without visible bedding, and rarely thin to thick bedded. An outcrop with primary layering was identified northwest of the groundwater monitoring and research station (fig. 7). Structural data indicates that primary layering is oriented in a northeast (approximately N22E) trend and steeply dipping (87^{o}) toward the southeast. Structural data for metamorphic foliation and cleavage indicates a northeast strike (N20E to N30E) with steep dips (approximately 60 to 90 degrees) toward the southeast or northwest.

Soil and geologic core description

A continuous soil-bedrock corehole was advanced at each of the three monitoring well cluster sites. Corehole CH-1 was drilled at cluster 1 or the lower cluster; CH-2 was drilled at cluster 2 or the mid cluster; CH-3 was drilled at cluster 3 or the upper cluster; the cores were advanced to 185, 95, and 175 feet below land surface (bls), respectively. A soil transect from CH-3 to CH-1 was surveyed. The soil and rock cores are briefly described as follows, but detailed logs and photographs are included in appendix 1.

Regolith

The term "regolith" used in this report includes all unconsolidated and poorly consolidated weathered materials that can be either soil or saprolite overlying bedrock. Regolith characteristics described below are primarily based on the information obtained from the geologic coring, but information from the soil survey transect performed for this study is also incorporated into the description. The properties of the shallow soils were mainly observed during the soil survey conducted before the geological coring.

The thickness of regolith decreases from 50 feet at CH-3 in the upper topographic area to 27 feet at CH-1 in the lower topographic area (fig. 8), while the land surface altitude drops more than 60 feet from CH-3 to CH-1. The recovery rate of soil core from the topmost few feet of each corehole was very low due to the nature of the soil and coring technique.

Lignum Series soil, a clayey soil with light yellowish brown to brownish gray color in B to Bt horizons, was found at the top portion of CH-1 as well as in the vicinity of the toe-slope landscape. Intersected quartz vein fragments were cemented into the top foot of the soil, and some quartz vein boulders floated on surface in the area. The moderately sticky consistency of the soil implies a parental material of mafic to intermediate composition. Redoxomorphic condition (as evidenced by the transformation of iron species colors) in the soil morphology was observed at two feet bls. Dark yellowish brown fine silty-sand grained saprolite was encountered at 10 feet bls. Relict rock texture becomes more evident with depth increasing. The saprolite became rockier at 27 feet bls, and weathered fractured bedrock was encountered at about 30 feet bls.

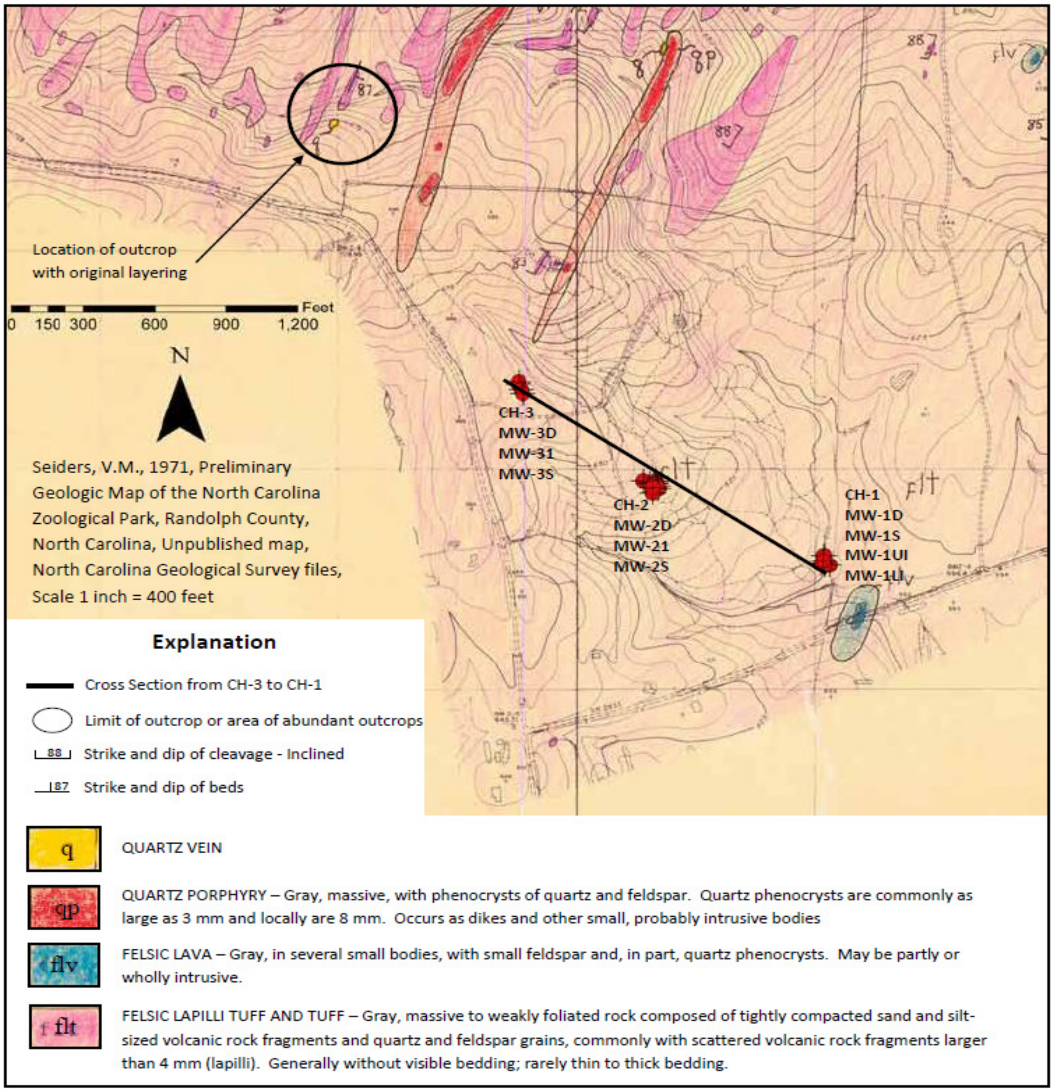


Figure 7. Portion of the geologic map of Seiders (1971) indicating the geology of NC Zoo area and locations of groundwater monitoring wells and coreholes at the NCZGMRS, Asheboro, NC

At the middle slope position where CH-2 was cored, Herndon Series soil, a typical yellowish red (5 YR) slightly plastic clayey and well-drained deep soil was found on the land surface and at the top portion of corehole CH-2. Horizon B extends to a depth of about eight feet from the land surface with clay content increasing. Occasional gravel-sized quartz fragments mixed into the soil were also found on or near the land surface. The kaolinitic clay mineralogy and its slightly sticky to non-sticky consistence imply a felsic volcanic parental material. From eight to 37 feet bls, light yellowish red to variegated saprolite was observed, which also indicates a felsic volcanic parental material. Weathered and fractured bedrock was encountered at 37 feet bls in CH-2.

Georgeville Series soil, a clayey soil with distinctive 2.5YR red color, was identified in CH-3 at a broad upland position. This soil is very similar to Herndon Series except for the color and landscape. The hematitic color (2.5YR) resulted from the oxidation condition at the broad upland position is an indicator of well-drained hydrology. The slightly sticky wet consistency of the soil is an indicator of kaolinitic clay mineralogy that reflects felsic metavolcanic parental rocks of the Uwharrie formation. The soil at the surface was influenced or intersected by some quartz boulders or fragments. The soil consistency changed at about 12 feet bls and saprolite was encountered from 15 to 45 feet bls. At 51 feet bls, weathered and fractured bedrock was clearly encountered.

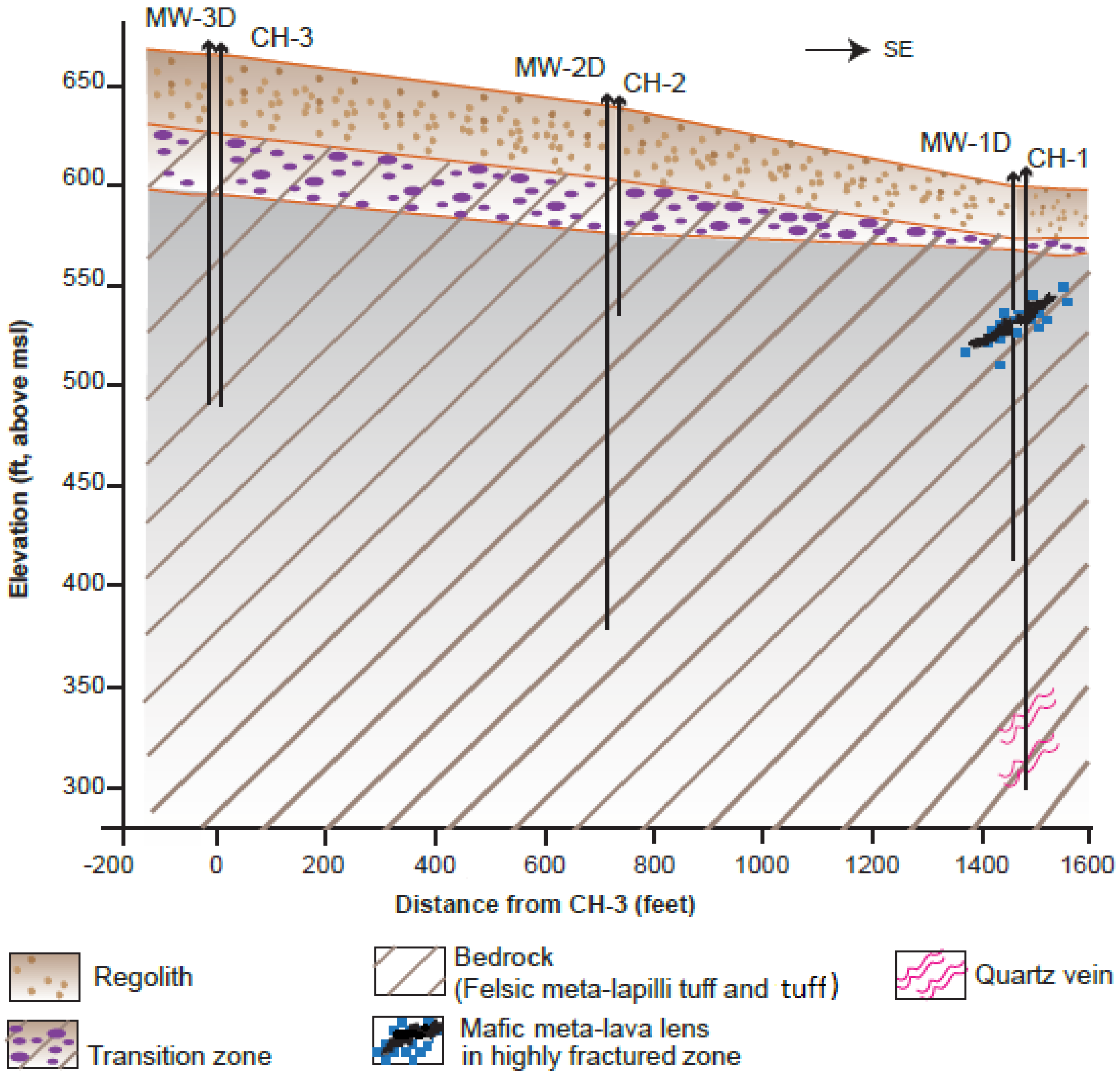


Figure 8. Cross section from CH-3 to CH-1, showing thicknesses of the regolith and transition zone, and depth to competent bedrock at the NCZGMRS, Asheboro, NC

Transition zone

The lowermost portion of the saprolite and the upper portion of the highly weathered and fractured bedrock are together referred to as the transition zone. The estimated thickness of the transition zone across the NCZGMRS is shown in figure 8. It varies from approximately 30 feet in CH-3 to a few feet in CH-1, suggesting that the thickness of transition zone decreases from the upland position to the toe slope. The thickness of the lowermost part of saprolite portion of the transition zone is only one to several feet, and it is characterized by relatively coarse and incompletely weathered metavolcanic rock fragments and clay minerals. Relict texture, such as foliation, of the metavolcanic rock was well preserved in this section. The upper fractured bedrock section (or the lower portion of the transition zone) is characterized by highly weathered and fractured bedrock, but not to the degree necessary to form sand and gravel size particles and/or significant clay minerals. The rock cores from the uppermost fractured bedrock portion of the transition zone remained wet or damp for more than a day after extraction, suggesting that there is some degree of primary and/or secondary porosity in this zone.

Bedrock

Competent bedrock was encountered in all three coreholes at varying depths. Observations on the bedrock cores confirm that in the NCZGMRS area the metavolcanic rocks are chiefly felsic, composed of nonfoliated to weakly foliated metamorphosed lapilli tuff and tuff. Weakly foliated to foliated felsic lapilli metatuff (fig. 9 A and B) is common throughout the rock cores. Interlayers of nonfoliated feldspar crystal rich metatuff or metalava are also present (fig. 9 C). Its groundmass appears to be altered and weathered. This type of rock is relatively soft and porous. Iron-leaching stain on the samples is common. Mafic metavolcanic rock (fig. 9 D) was found at the interval from approximately 70 to 75 feet bls in CH-1. In addition, small intervals of felsic metatuff breccia were found in all the cores (fig. 9 E). There is not a distinctive contact between the breccia and more common felsic metatuff or lapilli metatuff, indicating that the lithologies are closely interlayered and have gradational contacts. Two small quartz veins/dikes with a thickness of one to two feet were penetrated at depths of 265 feet and 295 feet bls, respectively, during the construction of monitoring well MW-1D.

Feldspar and quartz were identified as the primary minerals in bedrock core samples. Secondary minerals, such as calcite, pyrite, and hematite, were found on some of the fracture planes of the cores. Irregular, white colored, and aphanitic textured veinlets that are possibly composed of siliceous minerals from hydrothermal alteration were often found on the cylinder surface of the rock core samples. Detailed lithologic logs for the cores are provided in appendix 1.

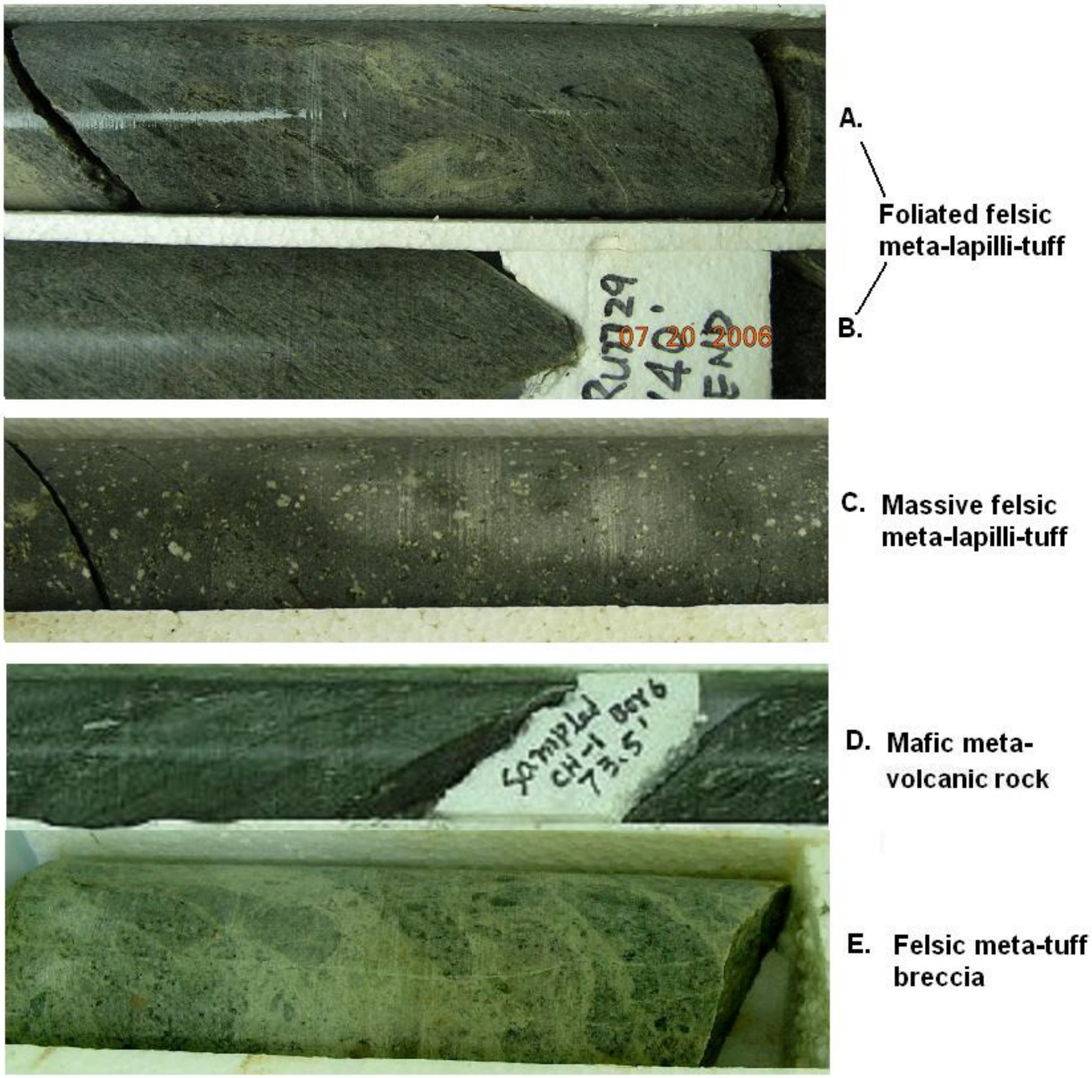


Figure 9. Types of metavolcanic rocks from geologic coreholes at the NCZGMRS, Asheboro, NC

Geophysical logs and fractures in bedrock

Geophysical logging data obtained from this study (appendix 2) and observations from outcrops and geologic core samples collected during this study indicate that the metamorphic foliation mainly strikes northeast (NE), with moderate to steeply dipping angles (50-70 degrees) mainly towards the northwest (NW). Fractures and cleavages are either parallel to the foliations or intersected them at a low angle; some fractures dip more steeply at angles greater than 80 degrees. The quartz veins appear to be parallel to foliation and dip to the northwest with a moderate dipping angle.

As indicated in figure 10, each tadpole represents a structural feature (such as fracture, foliation, or quartz vein); each color represents a different type structure: blue for primary fractures bearing water, red for fractures bearing a little or no water, green for foliations, and black for quartz veins. The horizontal gridlines of the tadpole log portion of the figure are divided and marked by vertical lines from 0 to 90 degrees from left to right. Therefore the dip angle of a structure feature is indicated by a tadpole's position related to the vertical lines of the log diagram. The pole or tail of each tadpole depicts each feature's dip direction, similar to reading a map: up is north, down is south, left is west, and right is east. For example, in MW-1D there is a blue tadpole at about 100 feet bls, which means a fracture bearing water at about 100 feet bls. This tadpole falls near the fifth vertical line (from left to right), which means that its dip angle is approximately 50 degrees. The pole of the blue tadpole points to the left, which means the fracture dips to west. In summary, figure 10 shows that (1) generally fracture density decreases with increasing depth, (2) foliation is the dominant feature (neither primary nor secondary fractures were well developed), (3) dip angles of foliations are generally steeper in MW-2D than those in MW-3D and MW-1D, with the least steep in MW-1D, (4) most foliations dip in a westerly direction, from NW to WNW, but opposite directions were also measured, (5) primary (water bearing) fractures developed at approximately100 feet and 136 feet bls in MW-1D, about 195 feet bls in MW-2D, and about 80-90 feet bls in MW-3D, and (6) the dip angle of water bearing fractures in MW-1D is steeper than that in MW-2D.

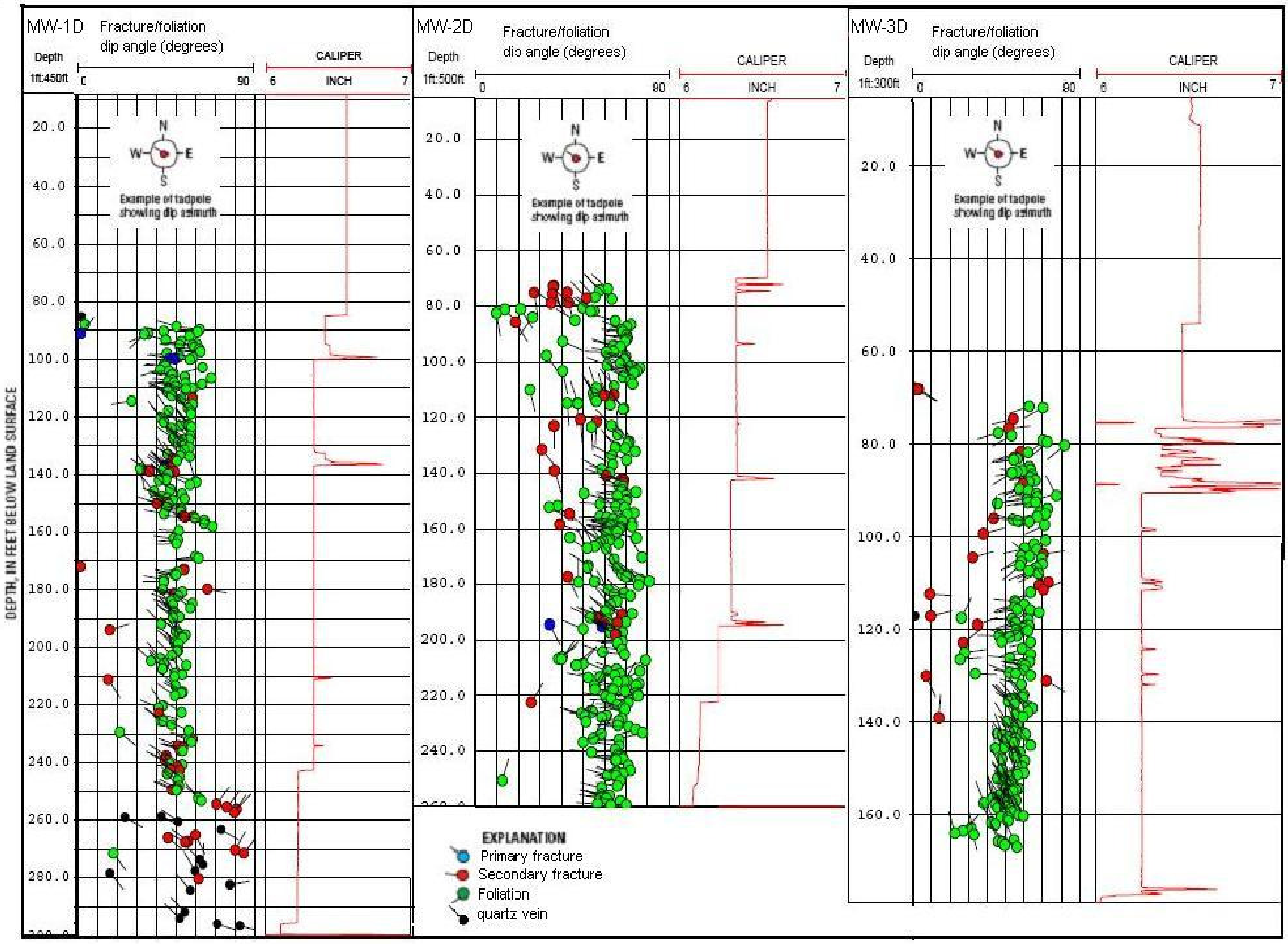
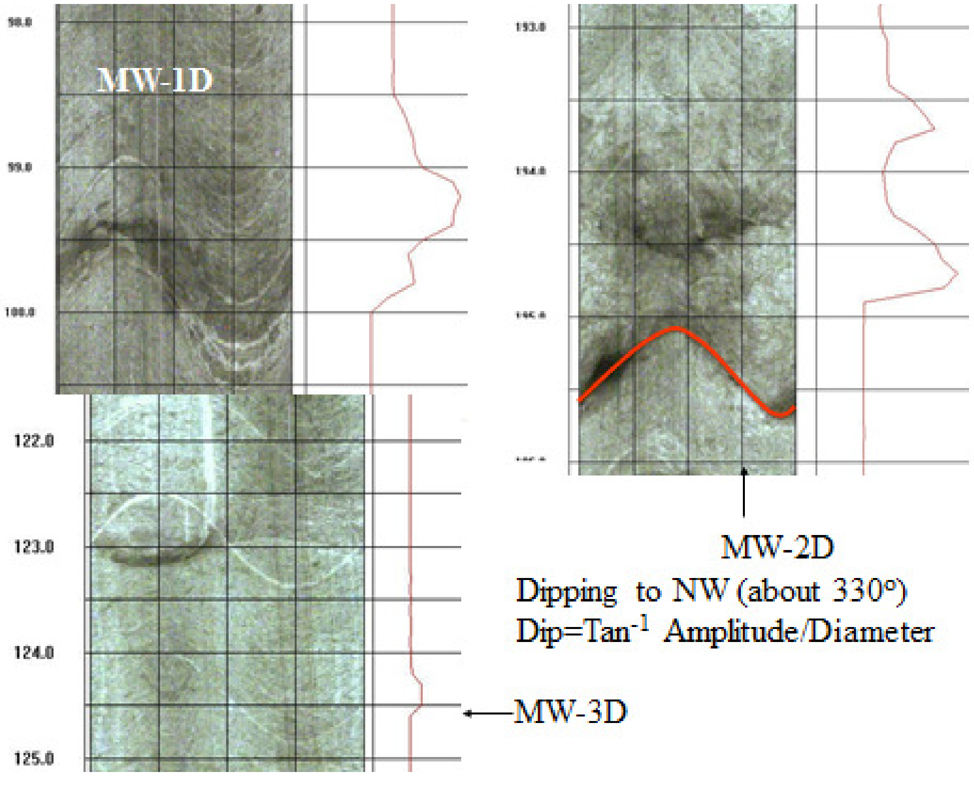


Figure 10. Tadpole diagrams and caliper logs from the NCZGMRS, Asheboro, NC

Figure 11 shows three pieces of OTV images collected from three bedrock wells respectively. The OTV data are corrected for borehole deviation (azimuth and inclination angle) and magnetic declination. An OTV image is a flatted digital image of the inside of wall of a borehole. The image and associated interpretation software allows direct observation of lithology. In addition, orientation of fractures and foliations can be interpreted based on their shapes, positions, and the relationships with gridlines of the image. For example, the orange sine wave in figure 11 is the trace of a fracture. Since the lowest point of the sine wave (MW-2D) is in the portion between West (W) and North (N), the fracture dips to NW. The dipping angle can be determined based on the amplitude of the sine wave and the diameter of well MW-2D (Dip = Tan^{-1} Amplitude/Diameter). In the OTV images, the light colored sine wave lines are foliations, cleavage partings, or annealed fractures. Dark and wider sine wave strips are most likely open fractures bearing some water. The amplitude of the sine wave of water producing fracture in MW-1D is higher than those in other wells. Therefore, we can determine that its dip angle is steeper than those of water producing fractures in other wells, which is consistent with what was found from the tadpole diagrams and may explain why the yield and hydraulic conductivity of MW-1D is less and lower than that of MW-2D.



MW-2D
Dipping to NW (about 330°)
Dip=Tan^{-1} Amplitude/Diameter

MW-3D

Figure 11. OTV images showing foliation and fractures in bedrock at the NCZGMRS, Asheboro, NC

Based on the bedrock core samples (figs. 5 and 9, and appendix 1) and geophysical logs (figs 10 and 11, and appendix 2), most fractures encountered at the NCZGMRS are either (1) medium to steeply-dipping foliation partings and small fractures that are generally parallel to foliation or (2) low to medium angle stress-relief fractures that intersect the foliation and may bear water. Very often, two groups of fractures crosscut each other. The foliations are oriented consistently, with up to 80 degrees of dip that appear to be relatively parallel to the original bedding, and are often defined by aligned, elongated or flattened pumice and glass shards ranging from 1x2 mm to 2x10 mm in size.

Water-bearing fractures or small fractured zones were often developed in the uppermost part of bedrock, the transition zone. However, in CH-1, a more fractured bedrock water-bearing zone (55-75 feet bls) is separated by a relatively fresh and competent bedrock zone from the upper transition zone. At the base of this zone, a fracture filled with saturated silty clay/angular gravels: 50/50 developed between 74.5 and 75 feet bls. Another fractured zone formed by groups of intersected joints at the interval of 97-102 feet bls was also found in this corehole. Below this depth, the rock appeared to be very competent and less fractured, and almost no water bearing fractures that were developed. CH-2 was advanced to 98 feet only; the density of open fractures in this hole definitely decreased with depth; no significant fractured-zone was encountered beyond the transition zone (37-65 feet bls) although some evidence of water activity was observed on rock core samples. In CH-3, beyond the transition zone (51-77 feet bls), two fractured zones developed at intervals of 126 -130 feet and 154-162 feet bls (appendix 1), respectively, which appeared to bear water. Please note that depths of the fractured intervals found in coreholes may be different from those encountered in the monitoring wells.

Microscopic characteristics of petrographic thin-sections

The study of petrographic thin-sections confirms the presence of rock types described by Seiders (1985). The felsic metatuff can be further classified as metamorphosed crystal tuff, lithic tuff, and lithic-crystal tuff. Minerals including quartz, feldspar, sanidine, sericite, muscovite, biotite, and epidote were identified in felsic metatuff thin-section samples. The interlayer of mafic metavolcanic rock present at CH-1-73.5 contains abundant plagioclase crystal laths typical of lava. Examples of photomicrographs of the petrographic thin-sections are attached in appendix 3.

Results of whole-rock geochemical analyses

The USGS Mineral Resources Team in Lakewood, CO conducted whole-rock analyses of eight bedrock core samples collected from the NCZGMRS. The tabulated analytical results of major elements, trace elements, and rare earth elements are included in appendix 4. The geochemical data from this study are consistent with the rock types indicated by Seiders (1985). The felsic metatuff samples (except for sample CH-1-182) plot in the dacite field of a QAP (quartz- alkali feldspar-plagioclass feldspar) diagram (fig. 12); sample CH-1-182 plots in the rhyodacitic field. The mafic metavolcanic rock sample CH-1-73.5 plots in the latite field. Based on the rock chemistry and the texture and minerals observed from the petrographic thin-section, the protolith of sample CH-1-73.5 was likely of basaltic composition and has been altered.

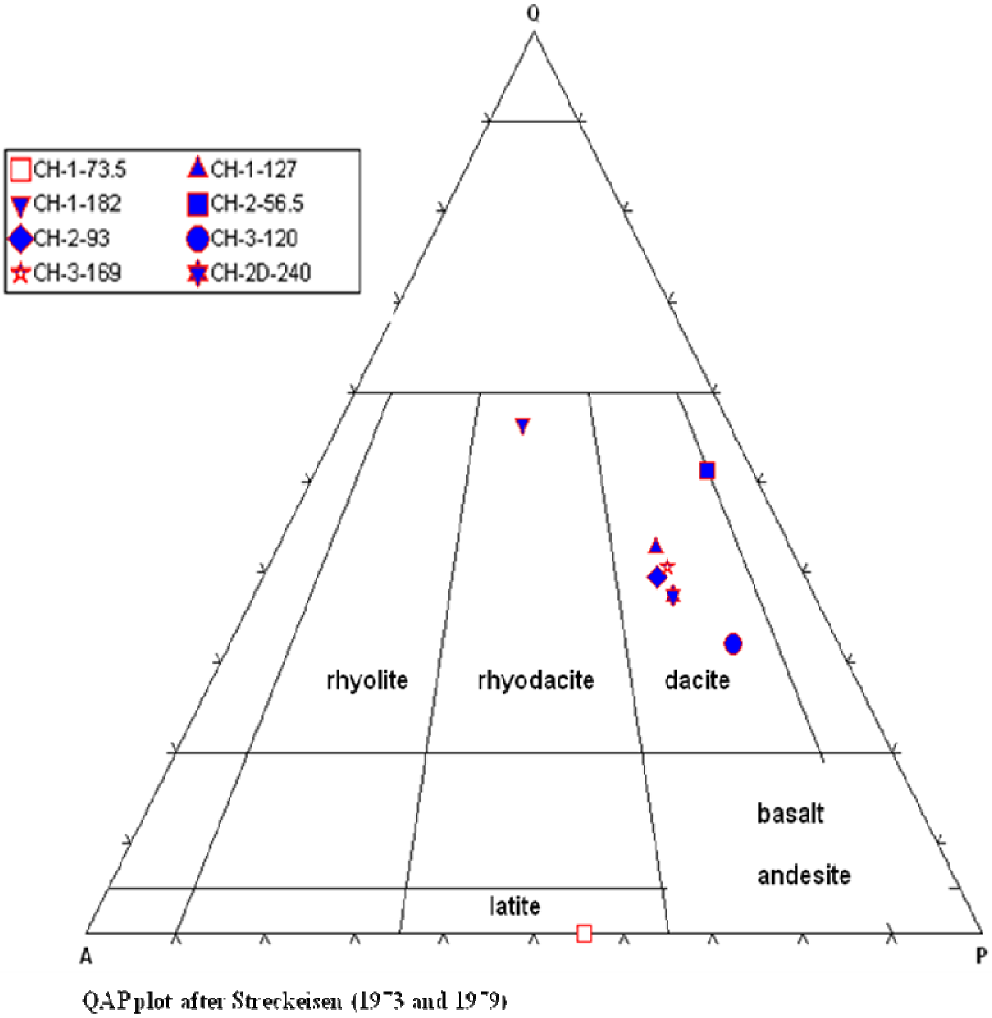


Figure 12. Plot of felsic metatuff and mafic metavolcanic rock samples from the NCZGMRS in QAP diagram (Plotted by Phil Bradley, North Carolina Geological Survey)

Analytical results of major oxides indicate an abnormal ratio of Na_2O/ K_2O in a majority of the samples (higher in felsic metatuff samples except for one (CH-1-182) and lower in the mafic metavolcanic sample (CH-1-73.5)) because the concentration of K_2O is lower in all felsic metatuff samples, but much higher in mafic metavolcanic rock sample than the averages found in common granite and gabbros, respectively. Additionally, Na_2O is higher in almost all (with one exception – CH-1-182) felsic metatuff samples, but normal in the mafic metavolcanic sample (fig. 13). FeO is generally lower in most felsic metatuff samples and higher in the mafic metavolcanic sample comparing to its average in granite and gabbros, respectively (Ehlers and Blatt, 1982). CaO is relatively higher in felsic metatuffs than the average in granite and lower in mafic metavolcanic rock than the average in gabbros. MgO concentration is close to normal in all samples, while MnO concentration is notably higher in all samples (appendix 4).

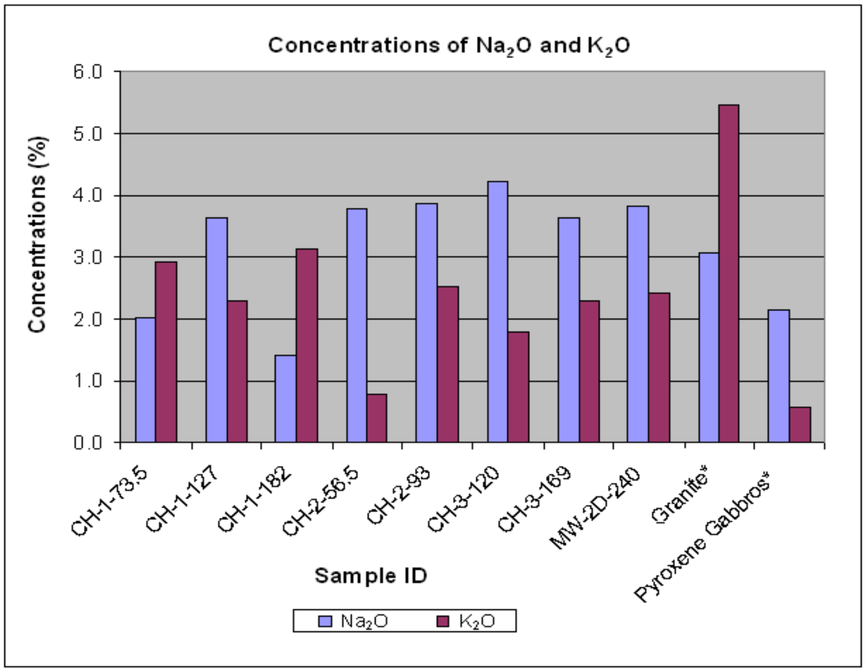


Figure 13. Concentrations of Na_2O and K_2O in rock samples from the NCZGMRS vs. their averages in granite and gabbro (* Ehlers and Blatt, 1982)

In addition, the results also show that nickel (Ni) in most felsic metatuff samples and vanadium (V) in two samples are higher than their averages in granite (Krauskopf and Bird, 1995); chromium (Cr) and Ni are higher in the mafic metavolcanic sample than their averages in basalt; lead (Pb) and arsenic (As) are higher in all samples than the average in basalt or granite. Arsenic was definitely enriched in two samples (CH-1-73.5 and CH-1-182) with a lower ratio of Na_2O/K_2O. The concentrations of Rb, Cs, Pb, and Ba are higher in the mafic metavolcanic sample than their averages in basalt or diabase (appendix 4).

HYDROGEOLOGIC CHARACTERISTICS

Groundwater Occurrence and Movement

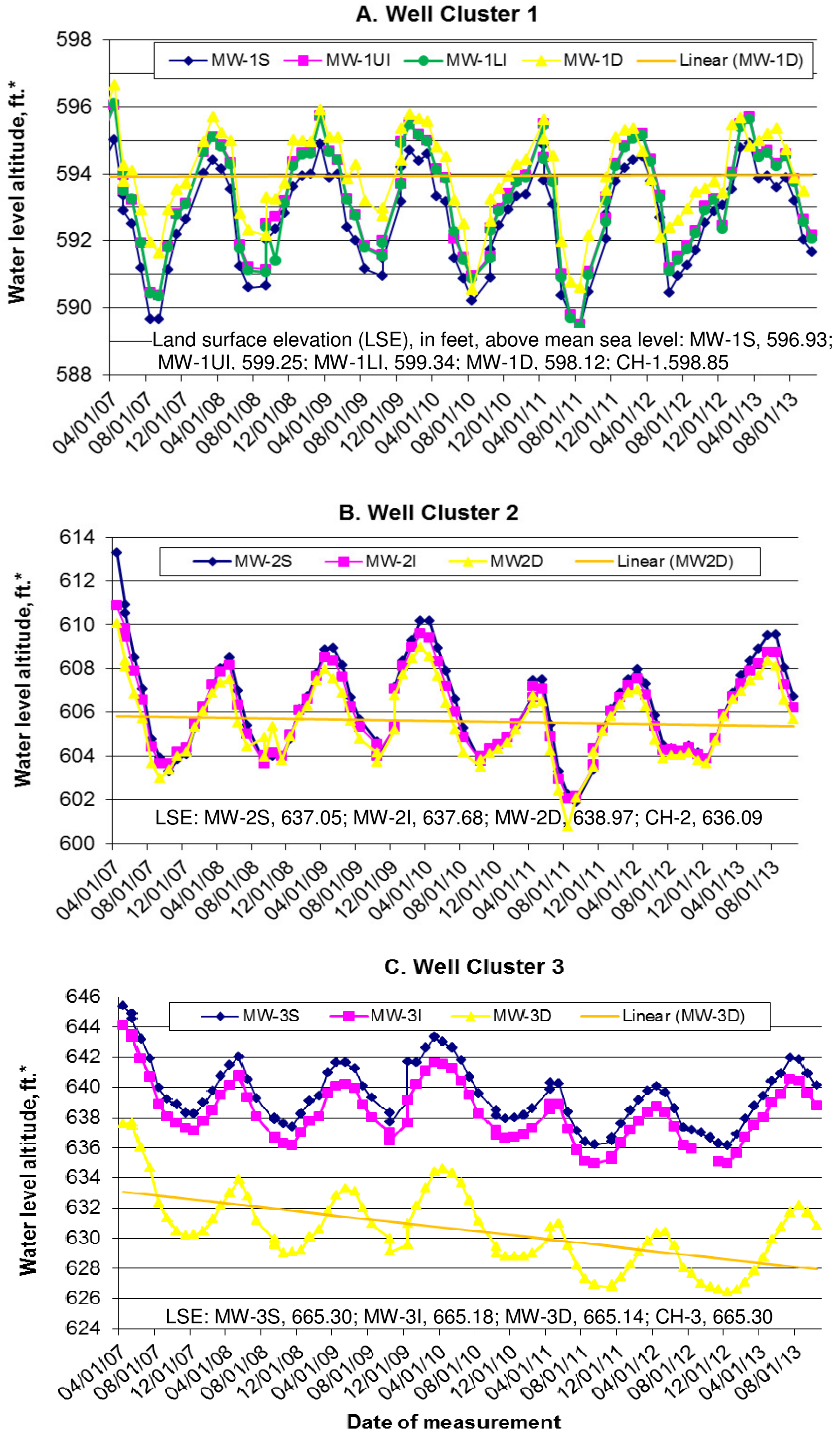
Occurrence

The groundwater system at the NCZGMRS is similar to that found regionally. It generally consists of three components including regolith, bedrock, and a transition zone between the regolith and bedrock (fig. 2) as described by Harned and Daniel (1992). The regolith zone consists of soil residuum and saprolite, which is approximately 30 to 50 feet in thickness, overlying the felsic metavolcanic rocks at NCZGMRS. Saprolite retains much of the fabric of the underlying parental rock. This layer has high porosity values but low to moderate hydraulic conductivity due to the clay content. The transition zone is composed of the lowest portion of saprolite and the top portion of bedrock; this zone is partially weathered, highly fractured, and generally more transmissive than the saprolite or the bedrock (fig. 8). The fractures are usually considered secondary and often connect with each other, and the density of these fractures typically decreases with depth. The secondary fracture network plays an important role in bedrock aquifers (Chapman et al., 2005). Water from precipitation enters the groundwater system in recharge areas and moves through the saturated zone vertically into fractures in the underlying bedrock, and laterally to discharge areas including the surface waters and the floodplain adjacent to the site. The pore spaces in regolith serve primarily as a reservoir, while secondary fractures in bedrock serve mainly as conduits (Daniel and Dahlen, 2002).

Movement

Groundwater flows from high pressure to low pressure, and in unconfined systems this correlates to flow from high to low elevation; gradients in energy potential drive groundwater flow. In the Piedmont of North Carolina, groundwater flow is generally described by the slope-aquifer conceptual model (LeGrand and Nelson, 2004). Conceptually, topographic highs are recharge areas, while topographic lows, particularly areas near streams, are groundwater discharge areas. Groundwater flows from recharge areas to discharge areas, roughly following surface topography. This conceptual model is particularly applicable to the regolith and transition zone, but often applies to bedrock conditions as well. However, groundwater water flow direction in fractured bedrock generally is more complex and is especially affected by the density, scale, continuity, orientation, and interconnectivity of fractures.

The groundwater level data (fig. 14) collected from the NCZGMRS supports the slope aquifer conceptual model. At the topographic low (well cluster 1 area), water level in the deep well MW-1D tends to be closer to land surface than water level in the shallow well (MW-1S) most of time (fig. 14A), which indicates an upward vertical gradient and is representative of discharge conditions. The upward vertical gradient could reverse before and after a rainfall. At the upland (well cluster 3) and the midslope (well cluster 2), water levels in shallow wells tend to be closer to the land surface than water levels in their nested counterpart deep wells (fig. 14. B and C), representing downward vertical potentiometric head gradients and recharge conditions. The downward vertical gradient was consistent at the upland or the midslope, but the vertical gradient at the midslope was much smaller than at the upland. From the upland well cluster to the toe-slope well cluster, the groundwater horizontal gradient is approximately 4% in the regolith and transition zone and about 3% in the fractured bedrock. The hydraulic gradients in all three components of the groundwater flow system are less steep than the slope of the land surface, which is roughly 6%. Generally, the groundwater flow at the NCZGMRS follows the land slope from higher elevation to lower elevation primarily to the southeast, but some influential local flow paths also exist. For instance, the groundwater flow direction could be influenced by northeastern and southern components of horizontal flows prior to moving to the southeast toward Panther Creek (fig. 4). Although the direction of groundwater movement in fractured bedrock is more complex than in regolith, based on the geologic core, fracture analysis, and results of pumping tests, the three components of the groundwater system at the NCZGMRS are well connected. Groundwater surface altitude in the bedrock wells also follows topography; therefore, groundwater flow in the fractured bedrock should be generally toward the southeast as well.



* feet above mean sea level (msl), NAVD88

Figure 14. Periodic groundwater levels recorded in monitoring wells at the NCZGMRS from April 2007 through October 2013

Groundwater Levels

Groundwater Level Data

Groundwater levels were manually recorded from all monitoring wells at the NCZGMRS from April 2007 through October 2013 on a monthly basis. The results indicate that groundwater level attitude declined from the upland (well cluster 3) to the toe-slope (cluster 1) and continuously fluctuated. Larger fluctuations were measured at the upland or the recharge area and the midslope than at the toe-slope or the discharge area. The largest fluctuation was measured in shallow well MW-2S at the midslope or in the deep bedrock well, MW-3D, at the upland, while the smallest was measured in MW-1S, the shallow well at the toe-slope. Please refer to table 2 and figure 14 for specific groundwater level changes measured in each monitoring well.

Table 2. Groundwater level fluctuation data from the NCZGMRS, Asheboro, NC (From April 2007 to October 2013)

Well ID	Land position	Highest level, ft*	Date measured	Lowest level, ft*	Date measured	Max. fluctuation, ft	Change over time**, ft
MW-1S	Toe-slope	595.01	04/15/07	589.37	08/29/11	5.64	0.2
MW-1UI	Toe-slope	596.06	04/15/07	589.51	08/29/11	6.55	0.25
MW-1LI	Toe-slope	596.09	04/15/07	589.42	08/29/11	6.67	0.25
MW-1D	Toe-slope	596.67	04/15/07	590.55	08/26/10	6.12	unchanged
CH-1	Toe-slope	596.62	04/15/07	590.33	08/29/11	6.29	unchanged
MW-2S	Midslope	613.29	04/15/07	601.9	09/28/11	11.39	-1
MW-2I	Midslope	610.86	04/15/07	602.07	08/29/11	8.79	0.5
MW-2D	Midslope	610.04	04/15/07	600.78	08/29/11	9.26	0.5
CH-2	Midslope	612.31	04/15/07	601.43	09/29/11	10.88	0.9
MW-3S	Upland	645.35	04/15/07	636.14	12/27/12	9.21	-3
MW-3I	Upland	644.13	04/15/07	634.94	12/27/12	9.19	-2.5
MW-3D	Upland	637.69	05/17/07	626.4	12/27/12	11.29	-5
CH-3	Upland	645.28	04/15/07	636.09	12/27/12	9.19	-3

* Above mean sea level, NAVD88

** Estimated based on trend-lines of groundwater levels plotted in figure 14 generated from Excel spreadsheets.

The groundwater level data also show that depth to water surface from the land surface in the regolith zone and transition zone wells (MW-2S and MW-2I) at the midslope were deeper than those in wells (MW-3S and MW-3I) at the upland, and the difference was larger in summer than in winter, which is contrary to the concept of the slope-aquifer model in the Piedmont region. More large trees around the well site at the midslope than at the upland location were observed, which suggests transpiration has an important effect on the groundwater table and the larger fluctuations in summer. In addition, the landscape and surface water features may also have effects. The well transect was designed along a gently sloped ridge running from northwest to southeast with the upland being relatively flat but the midslope area being relatively steep and sloping in three directions. Consequently, the midslope area would be subject to more runoff and less recharge. Furthermore, water supply well use in the vicinity and/or a subsurface geologic structure, such as a steeply dipping fault or a diabase dike between the two well clusters, may also result in such a phenomenon.

Response to Long Term Climate Change

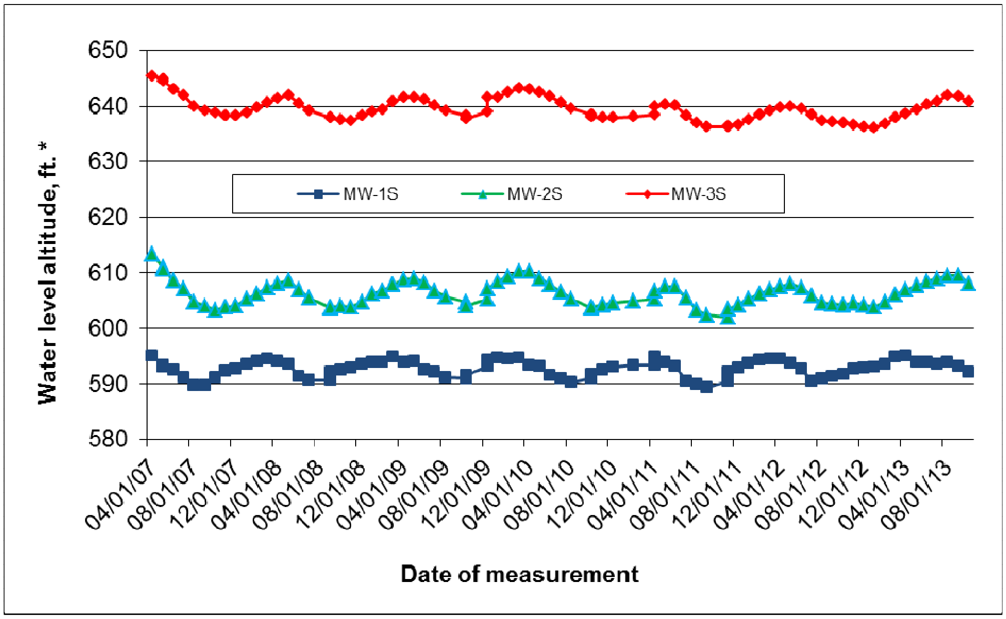
The groundwater level data from the NCZGMRS show typical changes and fluctuations in the Piedmont and reflect the long term climate change in the area and region, which is clearer at well clusters 2 & 3 (fig. 14 B&C). A couple of interesting features of the dataset are immediately apparent. First, wet conditions from 2005 to spring 2007 kept groundwater levels at their highest values when wells were measured for the first time. Please refer to National Oceanic and Atmospheric Administration's National Climatic Data Center website: http://www.ncdc.noaa.gov/cdo-web for the regional precipitation data. Persistent drying conditions beginning in the summer of 2007 produced a general downward decline in water levels in the subsequent years (with the exception of seasonal highs) until late 2009. The wet winter of 2009-2010 promoted higher recharge rates, thus raising water levels to their highest levels since April 2007. The effect of the dry conditions from winter through early fall 2011 resulted in significantly depressed water level hydrographs: water levels dropped to the lowest levels since monitoring began, while more precipitation occurred in the spring and summer of 2013 produced the highest summer groundwater levels in the six years of monitoring.

Over the monitored period, groundwater levels declined about 2.5-5 feet at the upland (well cluster 3) with the steepest decline measured in the bedrock well MW-3D. Smaller declines in groundwater levels were measured at the midslope, but almost no change was noted at the toe-slope.

Seasonal Fluctuation

Generally, groundwater levels at NCZGMRS tended to be highest between April and June each year following winter and spring precipitation events (figs. 14 and 15). The lowest levels occurred between August and November because rainfall in the late summer and early fall is more sporadic, intense, and generally shorter in duration, resulting in less infiltration and more runoff. In addition, evapotranspiration rate greatly increases during this vegetation growth season, which would also result in less recharge to the groundwater. This effect is even more pronounced during drought conditions.

The water level changes in the recharge area (fig. 15, MW-3S) show the same pattern as that in the discharge area (fig. 15, MW-1S), but lagged the discharge area change by approximately two months, suggesting that the groundwater level in discharge area was affected directly by Panther Creek, a nearby surface water. In the discharge area, the groundwater level adjusts quickly by discharging to the surface water if it is elevated relative to the stream, and by recharging from the surface water when stream level is higher. Because of this close connection to surface water, the discharge area wells respond to precipitation events much more quickly than the wells at the recharge areas. The groundwater levels in well cluster 1 at discharge area began to rise in September and October in response to fall precipitation, while water levels in well clusters 2 and 3 in the recharge areas or at the midslope and the upland did not begin to rise until November and December, respectively. It takes longer for the upland and midslope wells to be recharged or to respond to precipitation events than wells in the discharge area because upgradient infiltration from the land surface and groundwater flows are much slower than recharge from the surface water.



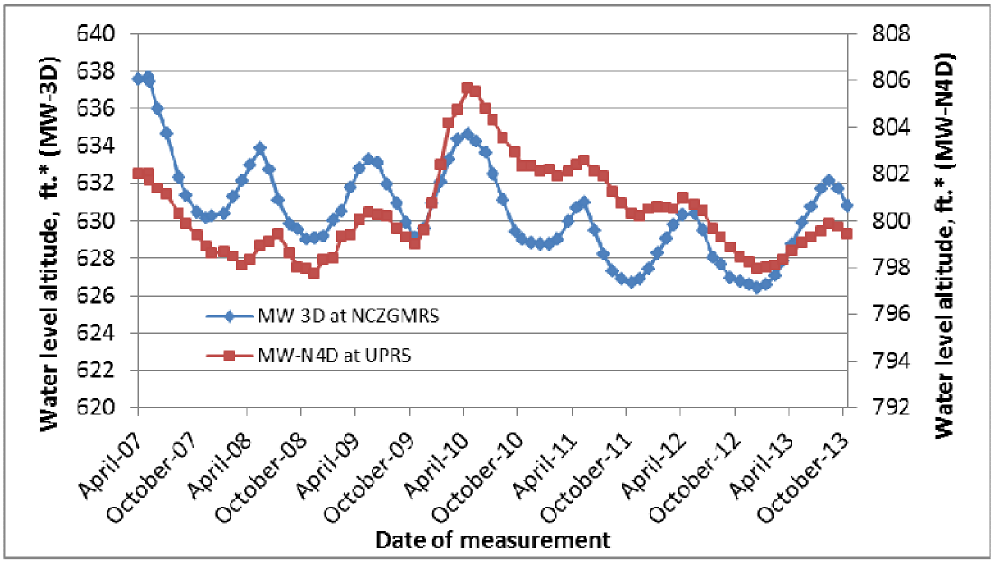
* Above mean sea level, NAVD88

Figure 15. Groundwater levels in regolith wells at the NCZGMRS from April 2007 to October 2013

Regional Comparison

Groundwater level data collected from the NCZGMRS were compared to data collected from the Upper Piedmont Research Station (UPRS), another PMREP groundwater monitoring and research station in the Piedmont region. Groundwater levels at both sites were strongly affected by local and regional precipitation. Seasonal changes in groundwater level at the NCZGMRS appear to be similar to those at the UPRS (fig. 16): high in spring - early summer and low in late summer and fall. The groundwater level change responding to seasonal or climate changes in bedrock or in the recharge area generally lags that in regolith or in the discharge area by a couple of months.

The 2007 regional drought resulted in a groundwater level sharply declining at both stations, but the decline was much sharper and longer lasting at the NCZGMRS than at the UPSR (fig. 16). The wet conditions from fall 2009 to spring 2010 produced a sharp increase in groundwater levels, especially at the UPRS. The weekly seasonal variation in MW-N4D at the UPRS since April 2010 could be the result of relatively wet falls, but the date and time when the groundwater level was measured may also have some effect. In addition, the drying conditions starting early summer 2010 resulted in a continuous decline in groundwater levels at the UPRS. The wetter spring and early summer in 2013 in the NC Zoo area pushed the groundwater level higher at the NCZGMRS than that at UPRS. Please refer to National Oceanic and Atmospheric Administration's National Climatic Data Center website: http://www.ncdc.noaa.gov/cdo-web for precipitation data of the area or region.



(* Above mean sea level, NAVD88)

Figure 16. Comparison of groundwater level changes from April 2007 to October 2013 in MW-3D at NCZGMRS in Asheboro, NC to changes in MW-N4D at the Upper Piedmont Research Station in Reidsville, NC

Aquifer Hydraulic Properties

The yields of bedrock wells at the NCZGMRS were estimated to be 4-9 gallons per minute (gpm)` with an average of 6 gpm. This average yield is somewhat lower than the average yield of 8.6 gpm obtained by Bain and Thomas (1966) from water supply wells in the same lithologic unit in the region. Transition zone well yields were estimated to be 1-5 gpm with an average of 3.5 gpm. The yield of shallow regolith wells was only about 1 gpm. The bedrock wells yielded more water than the transition wells because the bedrock wells were drilled deeper with multiple fractures intersecting the borehole. However, the yield per foot of well or per foot of uncased hole of the bedrock wells was much less than that of the transition zone wells. The shallow wells in regolith zone had the lowest yield because of the high clay content of the regolith.

The hydraulic conductivity and transmissivity of different components of the aquifer system at the NCZGMRS were estimated by analyzing data from rising- and falling-head slug tests and pumping tests. Slug tests were conducted to obtain estimates of the hydraulic conductivity of aquifer materials in the immediate vicinity of the tested wells in regolith and transition zones. Step-drawdown and constant-rate pumping tests were conducted to understand the hydraulic conductivity and transmissivity for the bedrock, transition zone, and regolith in the testing area.

Results of Slug Tests

Rising- and falling-head slug tests were conducted in all regolith and transition zone wells at the NCZGMRS, except for MW-2S, which did not have sufficient water to be tested. Slug tests were not conducted in any bedrock wells because the slug can only displace a relatively small volume of water in comparison to the volume of water in bedrock wells. Data collected from the slug tests were analyzed using Slug-Bouwer-Rice Spreadsheets developed by USGS (Halford and Kuniansky, 2002). The Bouwer-Rice method accounts for water-table condition and partial penetration effects and is suitable for the conditions at this study site. Either the bottom of the well or the top of the transition zone was used as the base of the aquifer for the saprolite wells. The bottom of the transition well was considered the base of the aquifer for the transition wells. The analytical results are summarized in table 3. Hydraulic conductivity values in the saprolite wells ranged from 0.33 to 3.25 ft/day, and generally, the values were higher in transition zone wells, ranging from 0.63 to 23 ft/day. The trend is consistent with the conceptual model that the transition zone material generally is considered more transmissive.

Table 3. Result of slug tests in wells at the NCZGMRS, Asheboro, NC

Well ID	Screened/open interval (feet below land surface)	Hydraulic Conductivity (ft/day)
Saprolite wells		
MW-1S	8-23	3.25
MW-3S	16-36	0.33
Transition-zone wells		
MW-1UI	28-43	0.63
MW-2I	38-58	23*
MW-3I	43-63	0.85

* Only one rising head (slug out) test was conducted.

Results of Pumping Tests

Two pumping tests were conducted at well clusters 1 and 2 (fig. 4) to evaluate: (1) the degree of interconnectivity among the bedrock, transition zone, and saprolite, (2) the degree of heterogeneity and preferential flow paths within the system, (3) the lateral extent of influence of pumping, (4) hydraulic boundaries and how they influence drawdown, (5) the aquifer transmissivity (T) and hydraulic conductivity (K) at each test area, and (6) the degree of heterogeneity of the aquifer system between two test sites. The methods and equipment used in the tests were described in the Methods of Investigation section of this report.

The first test was conducted at well cluster 2 at the midslope setting, about midway between well cluster 1 at the discharge area and cluster 3 at the upland position (fig. 4). Recharge to this test area is from precipitation, groundwater from upslope, and surface water from a constructed pond at the NC Zoo (fig. 4) under the pumped condition. The groundwater in this test area flows from the northwest primarily toward the southeast and discharges to Panther Creek. However, minor components of flow also occur to the northeast and the south prior to moving to the southeast toward Panther Creek. Bedrock well MW-2D (260 feet deep and cased to 70 feet bls) was used as the pumping well. The major water-producing fracture zone is between 190 and 200 feet bls, which was determined with downhole geophysics, OTV and geologic core. Moderately to steeply dipping foliation partings and joints are distributed throughout the borehole.

Five piezometers including two in the regolith, two in the bedrock, and one in the transition zone were installed for this test. In addition, MW-2S, the regolith monitoring well, MW2I, the intermediate well of this cluster, screened across transition zone material, and corehole CH-2 were also used as the observation wells during the test (fig. 17). The depths and screened/open intervals of these wells and their distance from the pumping well are shown in table 4.

The pump was set in MW-2D at a depth of 197 feet bls and pumping began at 8:40 am on May 22, 2007 at a relatively constant pumping rate of 8.5 gallons per minute (gpm). This pumping rate was based on the result of a step drawdown test conducted one week prior to this test with the same well and equipment. Based on the flow meter reading, the pump discharge rate fluctuated between 7.1 to 9 gpm. Frequent adjustments of the gate valve installed at the wellhead were made to maintain the pumping rate as constant as possible. Pressure transducers were placed in the pumping well, MW-2D, and eight observation wells at the testing site. Water level in the pumping well was measured every five seconds constantly. In the observation wells the frequency of water level collection started at every two seconds and subsequently was gradually reduced to every ten minutes at the end of the test. The static water level in the pumping well was 33.86 feet below measurement point (bmp) before pumping. The test was designed to run 72 hours, but was cut off due to the generator and pump problems at 4:20 am on May 23, 2007, after approximately 19.5 hours (1170 minutes) of pumping. Useful information was obtained from the 19-hour test (fig. 18) as described below. Recovery data also were collected, and the test was terminated on May 23, 2007 at 11:40 am when water levels recovered to within 90 percent of the pre-test static water level.

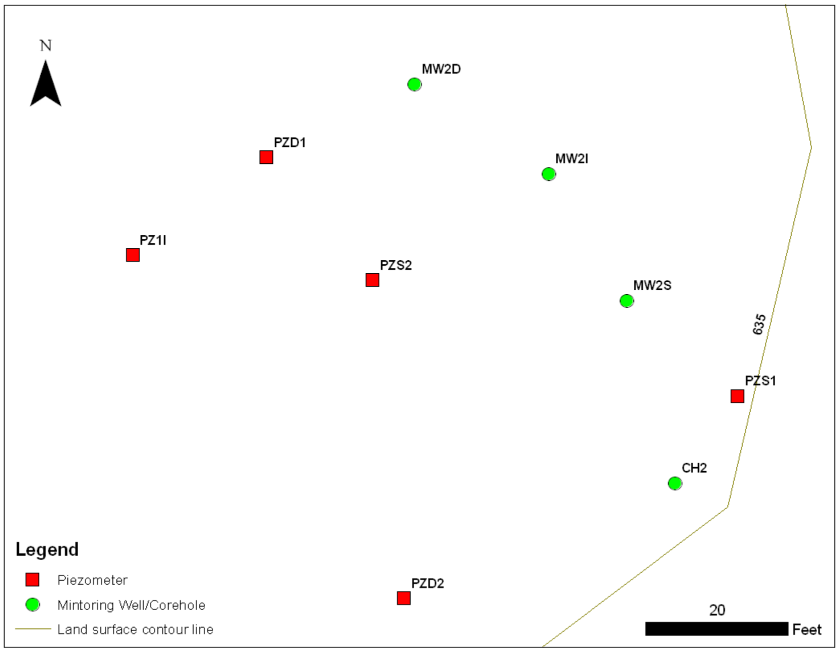
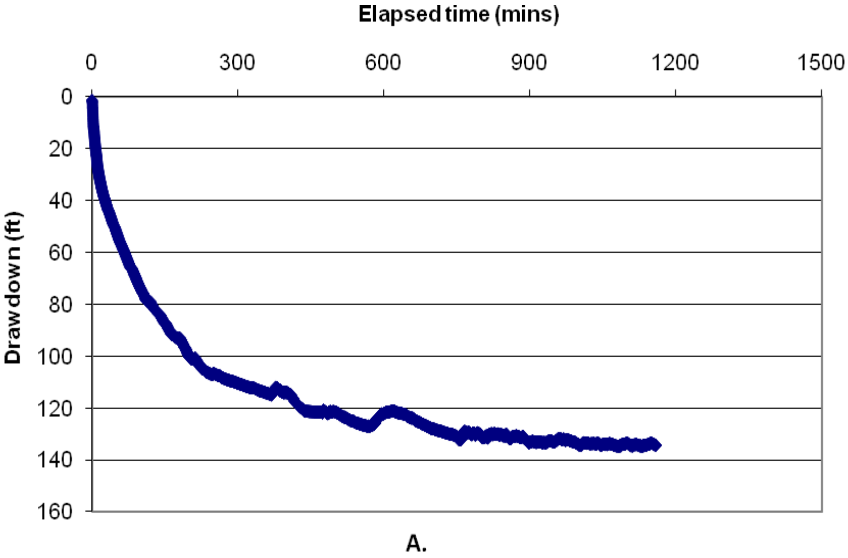


Figure 17. Layout of monitoring wells and piezometers at cluster 2, NCZGMRS, Asheboro, NC

Table 4. Maximum drawdown in each well/piezometer measured during pumping MW-2D at the NCZGMRS, Asheboro, NC

Well ID	**Screened/Open interval (ft. bls[1])**		**Screened or Open**	**Distance from pumping well MW-2D (ft)**	**Bearing from pumping well MW-2D**	**Maximum drawdown (ft)**
	From	**To**				
MW-1S	8	23	SCREEN	>600	SE	NM[2]
MW-1UI	28	43	SCREEN	>600	SE	NM
MW-1LI	50	70	SCREEN	>600	SE	NM
MW-1D	85	300	OPEN	>600	SE	NM
MW-2S	21	35	SCREEN	39	SE	1.53
MW-2I	38	58	SCREEN	19.8	SE	4.76
MW-2D	70	260	OPEN	0	Control well	134.19
MW-3S	16	36	SCREEN	>600	NW	NM
MW-3I	40	63	SCREEN	>600	NW	NM
MW-D	74.9	180	OPEN	>600	NW	NM
CH-1	32	185	OPEN	>600		NM
CH-2	40	98	OPEN	63.1	SE	2.15
CH-3	53	175	OPEN	>600	NW	NM
PZ-D2	70	100	SCREEN	71.3	S	4.23
PZ-S2	15	30	SCREEN	27.6	S	1.66
PZ-I1	40	60	SCREEN	39.6	SW	2.14
PZ-S1	15	30	SCREEN	57	SE	0.63
PZ-D1	70	100	SCREEN	19	SW	15.05

Note: 1. bls = below land surface; 2. NM = not measurable



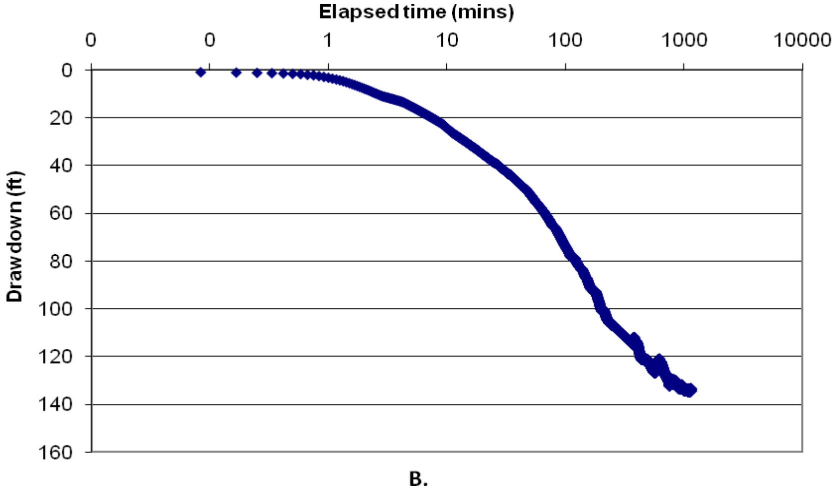


Figure 18. A. Arithmetic time-drawdown and B. Semi-log time-drawdown in pumping well MW-2D at NCZGMRS, Asheboro, NC (Pumping test conducted from May 22 to May 23, 2007)

The maximum drawdown of 134.84 feet was measured in the pumping well. The drawdown measured in the observation wells and piezometers varied from 0.63 to 15.05 feet (table 4). The drawdown was not only measured in the bedrock, but also in the transition zone and the saprolite, which indicates that groundwater in the bedrock is not confined but instead is connected to the overlying components. Among the observation wells, the largest drawdown was measured in the bedrock wells. The limited data also indicate that the drawdown decreased with distance increasing from the pumping well more rapidly in the shallow and transition zones than in the bedrock. Lateral influence of pumping appears to be similar in different directions in each zone (fig. 19). No preferential flow paths or any obvious heterogeneity was identified in any component of the aquifer system from the test.

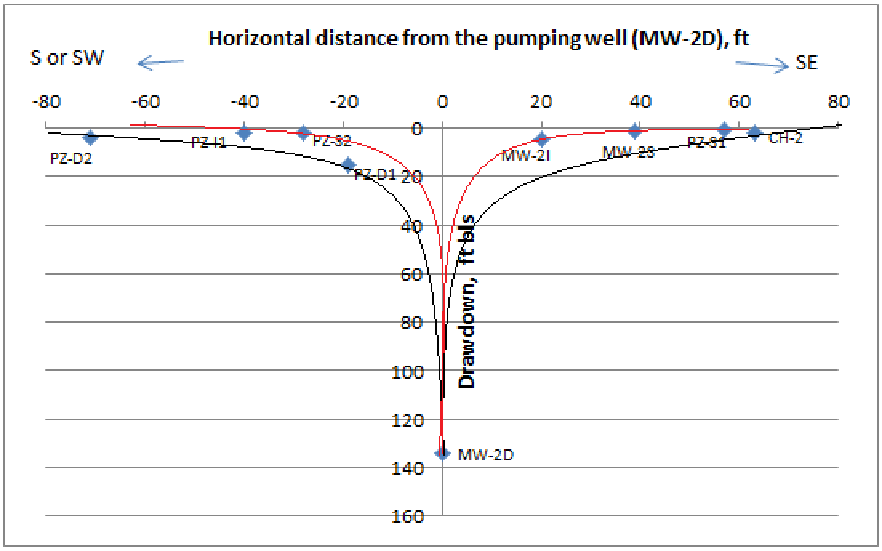


Figure 19. The maximum drawdowns measured from the pumping test conducted at well cluster 2, NCZGMRS, Asheboro, NC (Red lines = drawdown among the pumping well MW-1D and shallow and intermediate monitoring wells/piezometers; black lines = drawdown occurred in bedrock wells).

Only 0.40 - 0.61 inches of water-level decline were measured in the outlying bedrock wells or coreholes located more than 600 feet away from the pumping well. The decline may not be considered a response to pumping effects because two to more than five inches of water-level decline were noted within five days immediately before the test. No water table decline in the outlying regolith wells was observed. The effective radius of the pumping from MW-2D at the pumping rate of 8.5 gpm is greater than 71 feet in the bedrock, an estimated 60 feet in the transition zone, and greater than 57 feet in the regolith (fig. 19).

The test data indicates that the closer to the pumping well and the deeper a well is, the quicker and greater the response of the well to the pumping activity is. For example, PZ-D1, a deep piezometer, 19 feet southwest of the pumping well, responded to the pumping first and had the greatest drawdown (15 feet), while regolith shallow piezometer PZ-S1, 57 feet southeast of the pumping well, showed the slowest response and the least drawdown (fig. 20, upper panel, and table 4). Therefore, there was a positive correlation between the drawdown and the well depth and an inverse correlation between the drawdown and the distance from the pumping well. Because the test was conducted in a bedrock well with a relatively deep fracture, the pressure head in the bedrock aquifer was reduced prior to its reduction in the overlying transition zone and/or saprolite, and reduced in wells near the pumping well prior to its reduction in wells away from the pumping well. The difference in drawdown between any two wells or between any two components of the groundwater system after the first 1000 minutes of pumping is almost constant (fig. 20, lower panel), suggesting a stratified three-component aquifer system with a relatively homogeneous hydrogeology and a recharge boundary for each component.

In summary, the drawdown data did not reveal any obviously preferential flow paths or significant heterogeneity within each component of the groundwater system, but did support that there is connection among the three aquifer components.

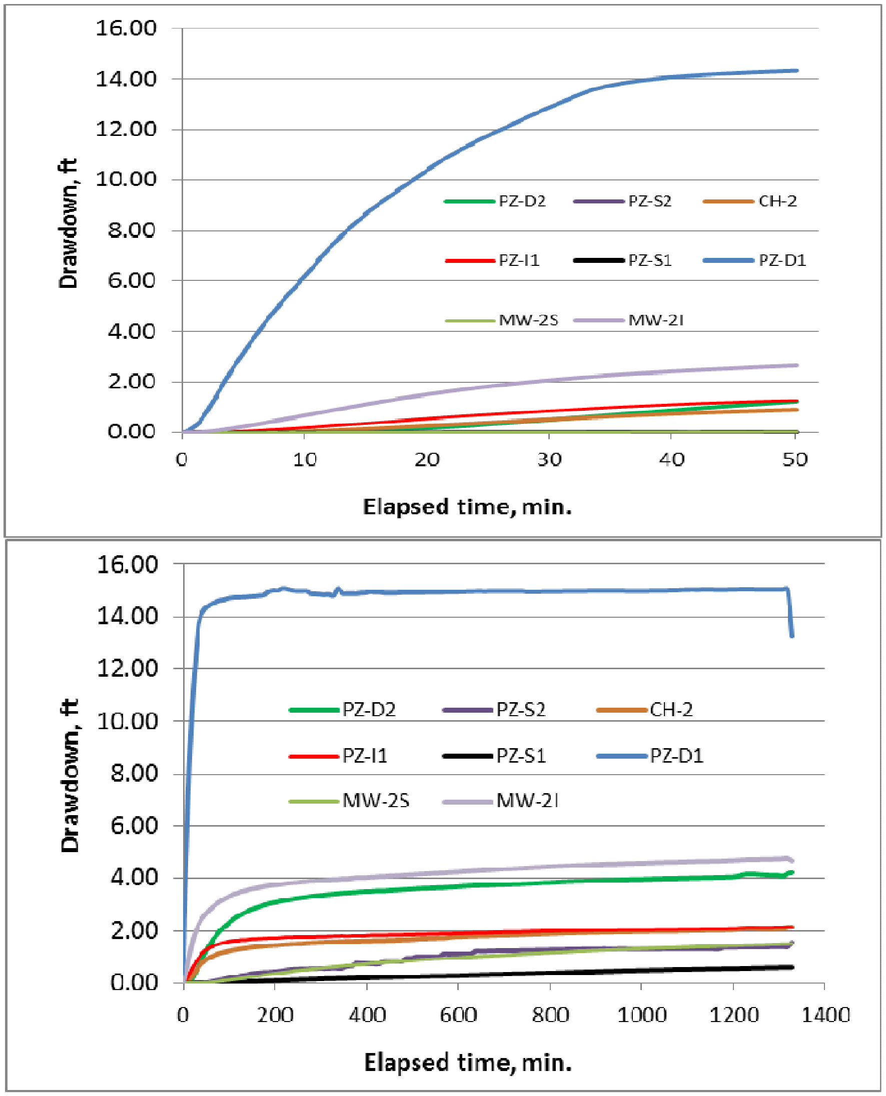


Figure 20. Drawdowns measured in onsite observation wells at NCZGMRS, Asheboro, NC (Upper panel -- Drawdowns within the first 50 minutes of pumping)

The transmissivity (T) of the bedrock and the horizontal hydraulic conductivity (K) of the water bearing fracture(s) were estimated through analyses of time-drawdown data using the Cooper-Jacob straight-line method spreadsheets developed by USGS (Halford and Kuniansky, 2002). To estimate the T and K of the bedrock, the middle time-drawdown data were used (fig. 21) because early data were affected by different factors, such as pumping rate (the pump may not start as expected, or the pumping rate did not reach the designed rate), well-storage effect, and others; while the late time-drawdown curve departed from the theoretical straight line due to the leakage or recharge from the upper regolith layer and transition zone. The drawdown in MW-2I or PZ-D1 was too large, compared to the thickness of the aquifer to use the Cooper-Jacob method; therefore the data were not used to estimate the K and T. The T for the bedrock (felsic metatuffs) and the K of the water producing fracture(s) were calculated with the drawdown data recorded from PZ-D2. The T and K are 89 ft^2/day and 0.47 ft/day, respectively. Higher values of T and K were obtained when drawdown data from the transition zone piezometer PZ-I1 and corehole CH-2 were used for analysis. The highest values were obtained when drawdown data from saprolite wells MW-2S, PZ-S1 and PZ-S2 were used (table 5).

It has been noted that some of the assumptions inherent in the Cooper Jacob method at this site may not be met. For example, the Cooper Jacob equations assume that well discharge is constant and derived exclusively from storage in the aquifer, the well is of infinitesimally small diameter and fully penetrates a homogeneous and isotropic aquifer of uniform thickness and infinite areal extent, and groundwater flow is horizontal. Therefore, the estimates of K and T may not be fully representative of the aquifer system. Nevertheless, when used carefully in conjunction with an understanding of site geologic and hydrogeologic conditions, the Cooper Jacob method was believed to produce useful estimates for the transmissivity and horizontal hydraulic conductivity at the site.

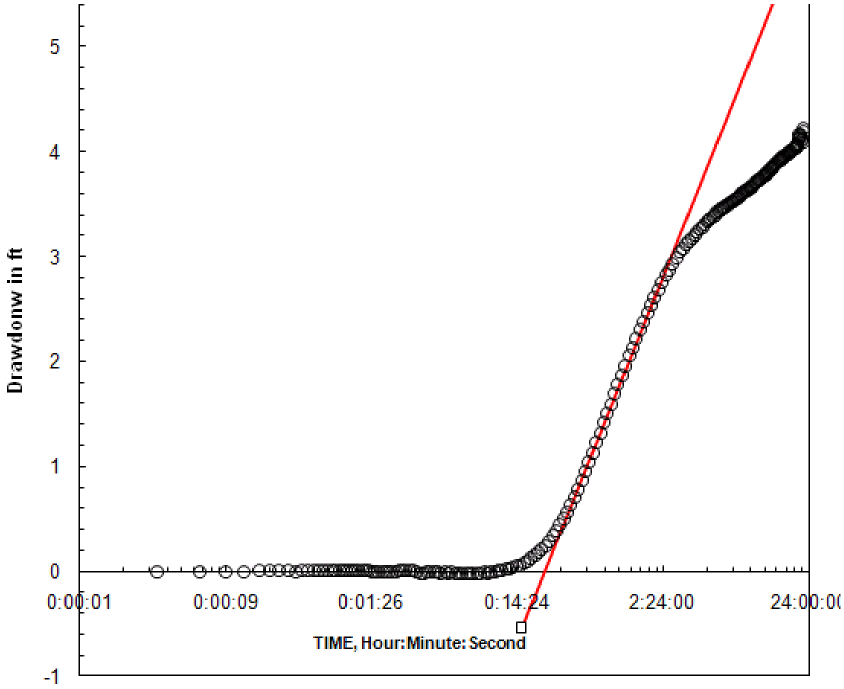


Figure 21. Cooper-Jacob single well aquifer test at NCZGMRS well cluster 2, Asheboro, NC (Pumping from MW-2D and drawdown data from PZ-D2)

To supplement data obtained from the aquifer test at MW-2D and to evaluate the degree of heterogeneity of the aquifer system in the study area, a second test was conducted at well cluster 1 in a topographically low area which slopes a short distance to Panther Creek or the outflow of the constructed pond at the Zoo (fig. 4). Panther Creek flows southeast into the pond and discharges at an outlet at the southeastern end of the pond, about 200 feet from MW-1D, and continues flowing to the south-southeast. The periodic groundwater level data generally showed an upward vertical gradient between the bedrock well MW-1D and the saprolite well MW-1S, which indicates a discharge area. However, during or a short time after a heavy rainfall, the vertical gradient can be reversed, suggesting that groundwater was recharged by surface water from the pond and Panther Creek.

Table 5. Estimated transmissivity (T) and hydraulic conductivity (K) of different components of the groundwater system at the NCZGMRS, Asheboro, NC

Component	T (ft^2/day)	K (ft/day)
Test 1, pumping from MW-2D at Cluster 2		
Bedrock (PZ-D2)	89	0.47
Transition zone (PZ-I1)	170	0.91
Transition + bedrock (CH-2)	190	1.00
Average in regolith/saprolite (MW-2S, PZ-S1 and PZ-S2)	257	1.33
Average	**176**	**0.93**
Test 2, pumping from MW-1D at Cluster 1		
Bedrock (MW-1D)	6.25	0.08
Average in transition zone (MW-1UI & MW-1LI)	29.25	0.39
Regolith/Saprolite (MW-1S)	120	1.6
Average	**51.83**	**0.69**
Note: (1) based on the information from coring and drilling, 75 feet of thickness of aquifer was estimated and used to calculate T and K for test 2 at cluster 1; (2) total open length of MW-1D, 190 feet, was used as the thickness of the aquifer to calculate T and K for test at cluster 2.		

MW-1D, the pumping well, was drilled to 300 feet bls and cased to 85 feet bls. Borehole geophysical logs including OTV revealed a major water-producing fracture at about 100 feet bls and a minor one at about 135 feet. No water-producing fractures were encountered below 160 feet bls. Well yield was estimated about 5 gpm during well installation. A step drawdown test suggested a sustainable pumping rate of about 4 gpm. Therefore, the pump was placed at 100 feet bls and the pumping test began at a rate of 4 gpm. After the first 7 minutes of pumping, due to difficulties in maintaining a constant pumping rate of 4 gpm, MW-1D was pumped at a relatively constant rate of 3.6 (varied from 3.4 to 3.7 gpm, but was adjusted to and kept at 3.6 gpm) for 35.5 hours, followed by 11.5 hours of recovery. In addition to the pumping well, three other monitoring wells (including saprolite well MW-1S and two transition zone wells, MW-1UI and MW-1LI) and corehole CH-1 (open from the transition zone to bedrock) were also monitored for responses to pumping effects by measuring water levels at designed intervals (fig. 22). Outlying bedrock well MW-2D and corehole CH-2 at well cluster 2 were also monitored for responses to the pumping. Equipment and procedures used in the first test were also used in this test. The data loggers were programmed initially to record water levels at two-second logarithmic time intervals and gradually increased to one-hour intervals. Hand measurements of water levels were made every 10 seconds at the beginning of the test to every two hours by the end of the test. Drawdown was observed in all wells at the tested site: 69.44 feet in the pumping well, 29.43 in corehole CH-1, 20 feet north of the pumping well, 5.26 and 5.88 feet in two transition zone wells MW-1UI, 39 feet north-northwest of the pumping well and MW-1LI, 22 feet northwest of the pumping well, and 1.15 feet in the regolith well MW-1S, 15 feet south of the pumping well. In the outlying wells MW-2D and CH-2, greater than 600 feet upgradient of the pumping well, only 1.2 and 1.6 inches of drawdown were measured, respectively. It is uncertain whether the drawdown in the outlying wells was related to pumping or to ambient cyclical fluctuation. It is possibly the result of a natural declination because the weather was dry and hot.

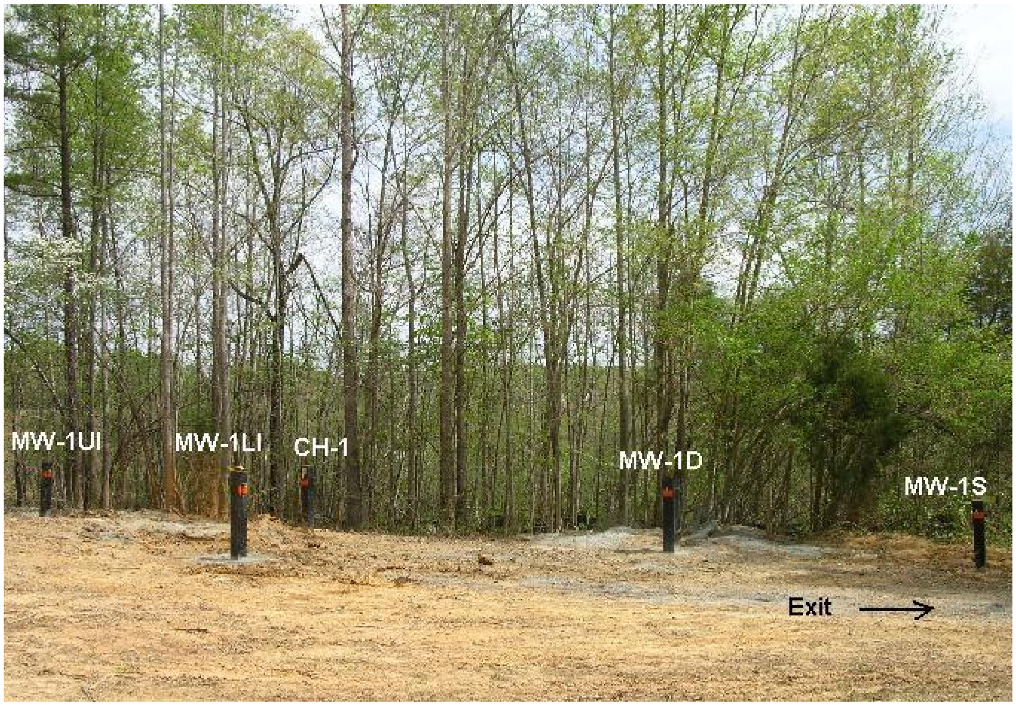


Figure 22. Monitoring wells and well identifications at well cluster 1, NCZGMRS, Asheboro, NC

The drawdown data from this test also indicates that the fractured bedrock aquifer is connected to the overlying transition zone and saprolite, and that the connectivity between the bedrock and the transition zone is much better than between the bedrock and the saprolite. Based on the drawdown data measured from two transition zone monitoring wells screened into the top part of bedrock, the K value of 0.39 ft/day and the T value of 29.25 ft^2/day were estimated using the same Cooper-Jacob strait-line method spreadsheets as used for the first test. This method is more representative because of distances of the two observation wells from the pumping well, the depth of the well screen, and limitations of the Cooper-Jacob strait-line method. The values of K and T estimated with drawdown data from the shallow saprolite well are higher, but lower if calculated with drawdown data from the pumping well (table 5). The estimated values of K and T for the bedrock component of the aquifer system from this test are generally lower than those from the first test. This result concurs with the findings from geologic cores and well installations. For example, the scale and extent of water bearing fractures are small, limited, and varied at the study site. Fewer and smaller water bearing fractures were found in MW-1D than in MW-2D. In addition, the dip angle of each water-bearing fracture may also play a role in the horizontal hydraulic conductivity and transmissivity of the aquifer. The lower horizontal hydraulic conductivity and transmissivity at MW-1D may also be associated with the steeper dip angle of the water bearing fracture.

The test results suggest that K and T vary spatially in the felsic metatuff hydrogeologic unit, depending on the number and scale of water bearing fractures encountered, but are within the reported range of K and T for fractured metamorphic igneous/volcanic rocks (Halford and

Kuniansky, 2002).

GROUNDWATER QUALITY CHARACTERISTICS

The quality of groundwater generally varies in different hydrogeologic settings and environments and along the flow path. It is determined and controlled by its composition and the concentration of each constituent it contains, and in large part is controlled by concentrations of ions (Harden and others, 2009). Water entering the groundwater system as recharge contains dissolved gases (such as O_2, CO_2, etc.) from the atmosphere, soil, and organic matter. As the water slowly moves through the subsurface, it dissolves minerals in the soil and rock. Therefore, older, deeper groundwater that has traveled greater distances is usually more mineralized than younger, shallower groundwater that has traveled a shorter distance. To determine (1) the "type" and the quality of the groundwater associated with the felsic metatuffs of the Uwharrie Formation in the Carolina terrane and any correlation between the groundwater quality and the rock chemistry, (2) the differences of the groundwater type and quality in three different components or zones of the groundwater system, (3) the presence or absence of arsenic and other naturally-occurring contaminants, and (4) if the quality of groundwater in the study area has been impacted by human activities. Water-quality samples were collected from all monitoring wells and Panther Creek at the NCZGMRS eight times from May 2007 to May 2013.

Water temperature, pH, dissolved oxygen, and specific conductance were measured in the field during each sampling event before samples for laboratory analyses were collected. Laboratory analytes include turbidity, suspended residue, color, total dissolved solids, specific conductance, pH, alkalinity, total organic carbon, fecal coliform, major ions (calcium, magnesium, potassium, sodium silica, bicarbonate, carbonate, chloride, sulfate, and fluoride), trace metals (silver, aluminum, arsenic, barium, cadmium, chromium, copper, ion, lead, manganese, selenium, nickel, and zinc), and nutrients (ammonia, nitrate + nitrite, and phosphorus). Most of the constituents were sampled eight times, but fecal coliform, cyanide, volatile and semivolatile organics, herbicides, pesticides, and dissolved radon were sampled only once. Compiled data tables are presented in appendix 5-1 and also available at http://www.ncwater.org/?page=638

Sampling Results and Exceedances of NCAC 15A 2L Standards

Field and Related Parameters

Temperature

Groundwater temperature was measured in the field before water-quality samples were collected. At the NCZGMRS, groundwater temperature was generally higher and more variable (14.62-18.93°C) in the regolith wells than in the transition zone and bedrock wells, which resulted from influences from air and surface water. The groundwater temperature was relatively stable in the transition zone wells (15.35-17.03°C). The larger fluctuation (15.19-18.08°C) was observed in the bedrock wells than in the transition zone wells, but within the normal range.

pH and alkalinity

The pH of groundwater is a measure of the degree of acidity or basicity of the water, expressed as the negative logarithm of the concentration of the hydrogen ion in moles per liter. A pH of 7.0 in water is neutral, lower than 7.0 is acidic, and higher than 7.0 is basic. The pH of pure water at 25 °C is 7.00. The normal range for pH in groundwater lies between 6.5 and 8.5 (Water System Council, Wellcare®, 2004); however, it is not uncommon that groundwater in the Piedmont region of North Carolina has a lower pH value. Groundwater pH is affected by precipitation which strongly affects and is influenced by chemical reactions between the water and aquifer materials. The pH can also change when mixing with different waters occurs, or if high levels of microbial activity are supported.

At the NCZGMRS, groundwater pH values in the regolith or transition zone wells were generally lower than those in paired bedrock wells (fig. 23 and appendix 5-1). The pH values from the wells (cluster 1) in the discharge area were consistently higher than those from wells (clusters 2 and 3) in the recharge and midslope area, which is most likely affected by precipitation, different lithology, and the length of groundwater flow pathway. As mentioned in the Site Specific Geology section of this report, mafic metavolcanic rock was encountered during the geological coring at the well cluster 1 site, but not well clusters 2 and 3. The pH of the surface water (Panther Creek) was lower than groundwater in well cluster 1. The groundwater pH levels were out of the state standard range (6.5-8.5) in five of ten wells and in one of three bedrock wells (fig. 23). pH levels in five nearby water supply wells in a similar geological formation were also lower than the state standard.

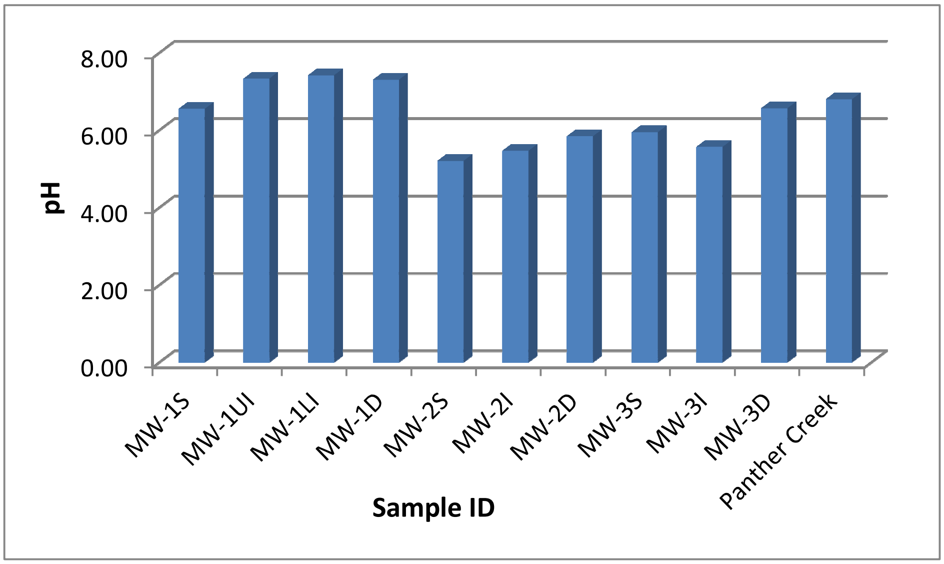


Figure 23. pH levels measured in monitoring wells and Panther Creek at the NCZGMRS, Asheboro, NC (Note, as stated in the Methods of Investigation section of this report, the last letter S, I, or D of sample IDs stands for shallow, a shallow well in regolith, intermediate, an intermediate depth well in transition zone, and deep, a deep well in bedrock, respectively; MW-1 wells are cluster 1 located at the low terrain, the hydraulic discharge area, also called lower cluster; MW-2 wells are cluster 2 located at the midslope, also called mid cluster; MW-3 wells are cluster 3, located at a upland position, the hydraulic recharge area, also called upper cluster. These clarifications apply to all groundwater quality figures.)

Alkalinity measures the ability of water bodies to neutralize acids. It is reported as mg/L $CaCO_3$ and measured as the amount of acid needed to bring the water sample to a certain level of pH. The alkalinity of samples collected for this study varied from 3.3 to 300 mg/L when bringing the pH of the samples to 4.5. The alkalinity values from the NCZGMRS follow the trend of pH, increasing from the shallow regolith zone to the fractured bedrock and from recharge areas to the discharge area. The highest level was measured in MW-1UI of well cluster 1and the lowest level in MW-2I of well cluster 2. Both are transition zone wells.

Dissolved oxygen (DO)

DO was also measured in the field. It was generally higher in regolith and transition zone wells than in bedrock wells and higher in the recharge area than in the discharge area (fig. 24). Most DO contained in water that seeps into the soil is consumed in the oxidation of organic matter as the water moves downward through the oxygenated regolith. Rainfall events also cause higher DO in groundwater of the upland and midslope areas because of increased surface recharge.

Relatively higher levels of in the transition zone or fractured bedrock are likely caused from interconnections to the upper components of the groundwater system. High DO levels were measured in wells of cluster 2 which is near the Zoo's constructed lake, indicating a considerable connection between the groundwater and the lake in addition to its midslope-recharge condition.

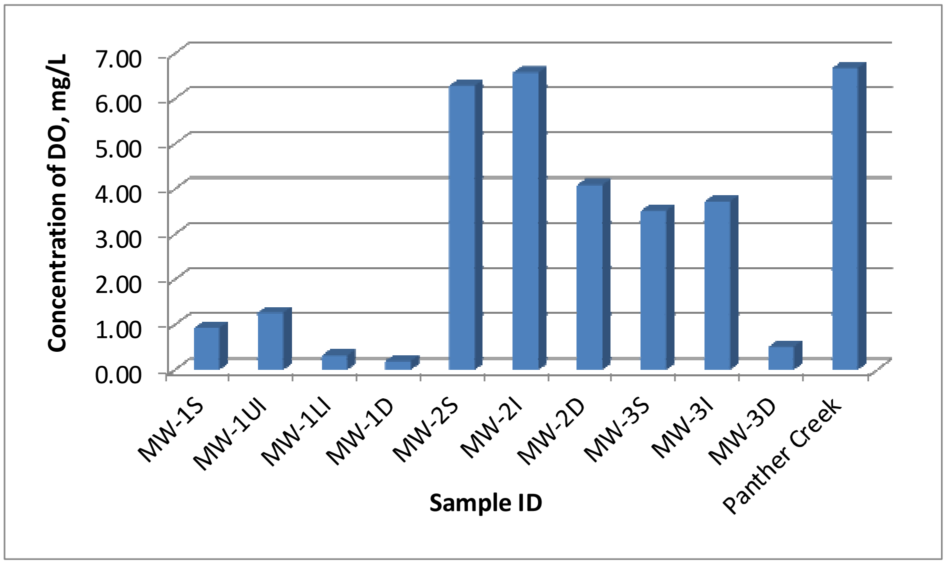


Figure 24. Dissolved oxygen levels measured in monitoring wells and Panther Creek at the NCZGMRS, Asheboro, NC

Total dissolved solids (TDS)

TDS is the residue after a given volume of water has been evaporated and dried at a given temperature. The concentration is controlled by the dissolved minerals or ions. Factors that control the dissolved minerals in groundwater include (1) the types of minerals that make up the aquifer, (2) the length of time that the water is in contact with the minerals, and (3) the chemical state of the groundwater. The results (appendix 5-1) show that generally higher levels were detected in the bedrock wells and wells in the discharge area than in the nested shallow wells and wells in the recharge area. The lowest level was detected at the midslope position where cluster 2 wells, MW-2S, MW-2I and MW-2D, are located (fig. 25). The highest level, 390 mg/L, or the highest mean, 321 mg/L, was detected in MW-1UI, an intermediate well at the discharge area.

Specific conductance (SC)

SC is a measure of the capacity of water to conduct an electrical current and is primarily dependent upon the amount and mobility of ions that come from the breakdown of compounds and dissolved metals. SC is an indirect measure of the presence of dissolved solids such as Cl^-, NO_3^-, HCO_3^-, SO_4^{2-}, PO_4^{3+}, Na^+, Ca^{2+}, Fe^{2+}, etc. and can be used as an indicator of water pollution. As TDS, SC level at the NCZGMRS generally increased with depth and was higher in the discharge area than in the recharge area, which is consistent with the concept that minerals are dissolved along the flow path. Increased contact time along the flow path from the recharge area to the discharge area or from the surface through the regolith and the transition zone to the fractured bedrock provides further opportunity for mineral dissolution, which is reflected in the higher concentrations in the discharge area wells or in the bedrock wells. The highest level of SC was measured in the transition zone well at the discharge area, while the lowest level was measured in the regolith well at the midslope (fig. 25).

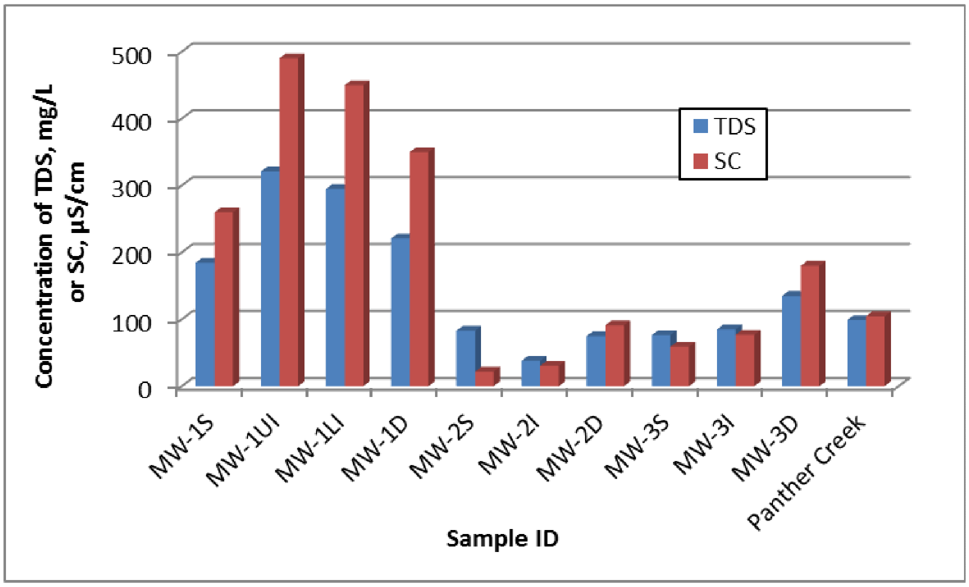


Figure 25. SC and TDS levels measured in monitoring wells and Panther Creek at the NCZGMRS, Asheboro, NC

Turbidity and suspended residue

Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates. Water with higher levels of suspended particulates looks cloudy, and has a higher turbidity. Natural turbidity in groundwater generally is less than 5 turbidity units (Anderson, 2005). Turbidity was measured from less than 1 to 280 NTUs (appendix 5-1) at the NCZGMRS. High levels of turbidity were associated with shallow wells with either an extremely low yield or a very shallow water table. High turbidity occurring in the extremely low yield wells could probably be attributed to the turbulence caused from well purging during sampling, which may have disrupted fine sediments present in the bottom of the well. Generally, the turbidity of groundwater in the transition zone and the fractured bedrock at the NCZGMRS was within 5 NTUs. As turbidity reflects suspended residue in water, the suspended residue in groundwater at the NCZGMRS followed the trend of the turbidity and was low in transition zone and bedrock wells.

Color

The color of natural water usually results from leaching of organic debris, but can also be from iron and manganese leaching, so generally it is an indicator of contamination. Water samples collected from the NCZGMRS were generally clear. Only a few samples from the shallow regolith wells located in the discharge area or at the midslope were reported to have a color level of 2-7 color units, which is below the state groundwater quality standard, 15 color units. The color of samples from Panther Creek ranged much higher, from 37 to71 color units.

Total Organic Carbon and Fecal Coliform

In order to check whether the groundwater at the NCZGMRS area was affected by organic debris or fecal bacteria, TOC and fecal coliform were tested. TOC is a composite measure of the overall organic matter content in a water sample and is used as an indicator of the natural organic matter and/or organic carbon of anthropogenic origin in water. The sampling results show that TOC was only detected in two shallow regolith wells (MW-2S and MW-3S) in two of eight sampling events at low concentrations; no TOC was detected in any other wells.

Fecal coliform is a specific subgroup of the total coliform bacteria. The presence of fecal coliform bacteria in groundwater indicates that the water has been contaminated with the fecal material of man or other animals or by pathogens or disease producing bacteria or viruses that can exist in fecal material. Fecal coliform was not detected in any groundwater samples at the NCZGMRS.

Major Ions

The qualities, types of chemical constituents, and other properties of groundwater are the result of aquifer minerals and processes of the hydrogeologic environment. Dissolution of aquifer minerals is a major geochemical process that controls the major ionic composition. In this study, major ions including cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-) were analyzed in each sampling event to study the water type of the groundwater.

In the Piper diagram (fig. 26), the percentages of dissolved cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) are plotted in the left trilinear diagram and the percentages of anions (HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-) are plotted in the right trilinear diagram; in addition, the diamond shaped middle diagram plots the cations and anions together to determine the water type and specific primary cations and anions. The analysis of ionic composition of groundwater samples from monitoring wells at the NCZGMRS shows a consistent dominant anion (bicarbonate, HCO_3^- dominates in all wells) and a considerable variability of cations (table 6 and fig. 26). Calcium content apparently increased from the shallow regolith zone to the bedrock and from the upland to the discharge area. The predominant ionic composition of water samples from well cluster 1 (MW-1S, MW-1UI, MW-1LI, and MW-1D) at the discharge area indicates a simple calcium - bicarbonate water type. Due to increase in sodium and potassium content and decrease in calcium content, all other wells or samples are calcium sodium mixed - bicarbonate water type. The concentrations of major ions in the surface water at the NCZGMRS are similar to those detected in the groundwater, but the concentrations of potassium, chloride, and sulfate were slightly higher in the surface water than in the groundwater.

Table 6. Median concentrations of major ions, weight %, at NCZGMRS, Asheboro, NC

Sample ID	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}
MW-1S	15.0	3.5	38.5	5.6	3.8	130	<1	1
MW-1UI	27.0	6.2	80.5	13.5	4.5	270	<1	1
MW-1LI	24.0	4.2	72.0	12.0	4.5	250	<1	1
MW-1D	16.0	3.4	55.0	8.4	4.9	180	<1	<2
MW-2S	2.9	2.8	1.3	1.2	2.0	13	<1	<2
MW-2I	3.9	1.1	1.4	0.5	1.9	7	<1	1
MW-2D	6.8	1.3	10.4	1.1	2.4	42	<1	<2
MW-3S	8.5	1.5	4.4	1.1	3.3	24	<1	<2
MW-3I	10.0	1.2	6.2	1.1	3.2	32	<1	<2
MW-3D	14.5	5.4	16.0	5.3	3.1	86	<1	1
Median in regolith	**8.5**	**2.8**	**4.4**	**1.2**	**3.3**	**23.5**	**<1**	**<2**
Median in transition zone	**17.0**	**2.7**	**39.1**	**6.6**	**3.8**	**141.0**	**<1**	**1**
Median in bedrock	**14.5**	**3.4**	**16.0**	**5.3**	**3.1**	**86.0**	**<1**	**<2**
Median at the site	**12.3**	**3.1**	**13.2**	**3.3**	**3.3**	**64.0**	**<1**	**<2**
Panther Creek	8.4	4.0	8.8	1.8	5.9	33	<1	3.9
WSW-Z1	7.5	1.0	4.0	0.7	1.7	24	<1	<2
WSW-Z3	5.2	0.9	2.7	0.6	2.2	31	<1	<2
WSW-O.	7.2	1.0	4.8	1.1	3.2	22	<1	<2
WSW-RTMC	6.7	1.4	5.2	1.4	2.8	24	<1	<2
WSW-S.	11.0	1.7	12.0	1.9	9.0	33	<1	<2
Median in supply wells	**7.2**	**1.0**	**5.0**	**1.1**	**2.8**	**24.0**	**<1**	**<2**

Note: if an ion was never detected in a well, zero value was considered in the calculation

The major ionic composition of bedrock wells at the NCZGMRS is similar to the findings from two other groundwater-monitoring stations (the Duke Forest in Orange County and the Morgan Mill in Union County) in the Carolina terrane. At the Duke Forest station, groundwater in bedrock was characterized as calcium-bicarbonate and mixed-cation-bicarbonate types, while at the Morgan Mill station it was characterized as calcium-bicarbonate type.

Similar low levels of chloride were detected in water supply wells as in the bedrock monitoring wells. Sulfate was only detected at very low levels in the regolith well and transition zone wells of well cluster 1 near the creek and in bedrock well MW-3D at the upland. No carbonate was detected in any samples. All other major ions were detected at much lower levels in the water supply wells than in the bedrock monitoring wells. The groundwater geochemistry at the NCZGMRS appears to reflect ambient groundwater conditions.

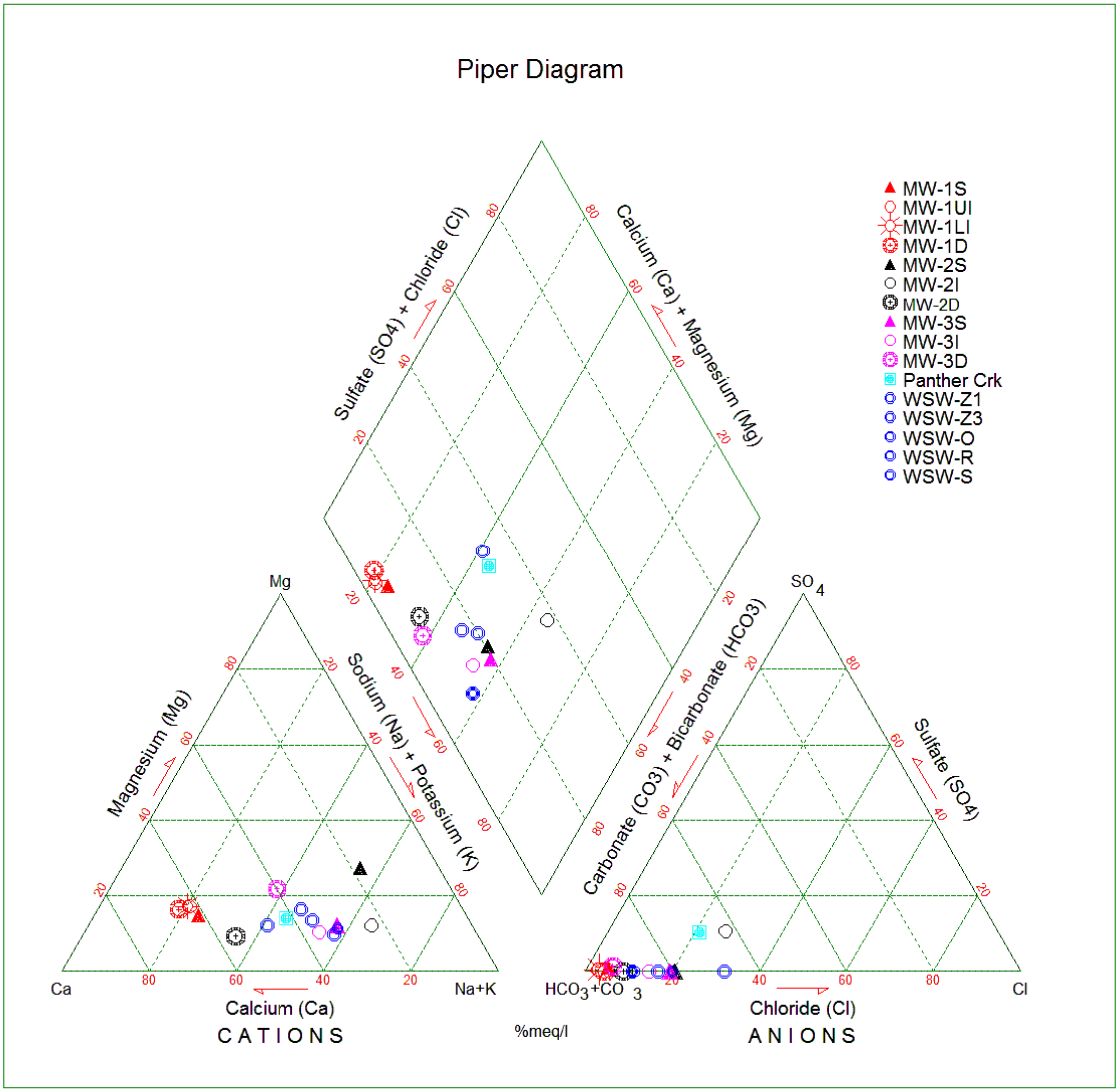


Figure 26. Piper Diagram showing major ionic composition of all samples from the NCZGMRS and five water supply wells nearby

In addition to the major ions used to determine water types, fluoride and silica were also analyzed. Fluoride was not detected in any samples. Silica was detected at concentrations ranging from <2 to 50 mg/L, which is within the range detected in ambient groundwater of Piedmont. Silica is derived from the weathering and decomposition of mineral silicates. Its concentration varies generally from 1 to 30 mg/L, but can be more than 100 mg/L in groundwater (Hem, 1985). Fluoride is decomposed from fluorite and other minerals containing fluoride; the concentration of fluoride in most natural water is less 1 mg/L (Hem, 1985).

Trace Metals

Trace metal analytes sampled in this study include silver (Ag), aluminum (Al), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn). Both dissolved (filtered samples) and total constituent concentrations (unfiltered samples) were analyzed to determine if the metals were associated with suspended solids. Sampling results and averages of concentrations are compiled and presented in appendix 5-1. Since the North Carolina groundwater quality standards (15A NCAC 2L) are set for total constituent concentrations, discussions and comparisons were made only between total constituent concentrations and the state standards.

Ag, Cd, Cr, Ni, and Se were not detected in any samples (filtered or unfiltered) from any of eight sampling events between May 2007 and May 2013. Arsenic (As) was detected, but below the standard, in MW-2S and Panther Creek only once. Pb was detected at concentrations below the state standard in MW-1S and MW-1UI once, and in MW-2S three out of five times. Cu was occasionally detected at concentrations well below the state standard in several unfiltered samples from the regolith and transition-zone wells, but not in any filtered samples or samples collected from the bedrock wells. However, Cu was detected in three of five supply wells sampled (appendix 5-1) in a primarily dissolved phase, which was probably attributable to the home plumbing system and the lower pH of the groundwater.

Fe, Al, Mn, and Zn were detected in several wells (fig. 27) at levels exceeding either the state groundwater quality standards (300, 50, and 1050 µg/L respectively for Fe, Mn, and Zn) or the federal secondary drinking water standard (for Al, 50-200 µg/L).

Aluminum (Al) is one of the most abundant elements in the Earth's crust, but high concentrations of dissolved aluminum are not common in groundwater because this metal is generally retained in the clay minerals formed during the weathering process; the exception is water with very low pH (Bain and Thomas, 1966). Fe is also very common in many rocks, especially those containing high percentages of ferromagnesian minerals. Fe is soluble in groundwater, particularly in acidic groundwater. The analytical results of Fe and Al from this study concur with these observations and show that high levels of Fe and Al occurred in the shallow regolith wells, while only low levels were detected in bedrock wells (fig. 27). Fe and Al closely correlate with the turbidity of groundwater (fig. 28), which indicates these two metals exist primarily in suspended state. Concentrations of Fe and Al in shallow regolith wells and the surface water (fig.29) appear to decrease with the increase of pH value from about 5.5 (acidic condition) to 7. 5 (neutral). The lab results confirmed that Fe and Al, especially Al, in these samples were primarily present as suspended particulate matter (appendix 5-1). Both suspended and dissolved forms of Fe and Al were detected in the creek. The dissolved level of Fe was much higher in the stream than in the groundwater.

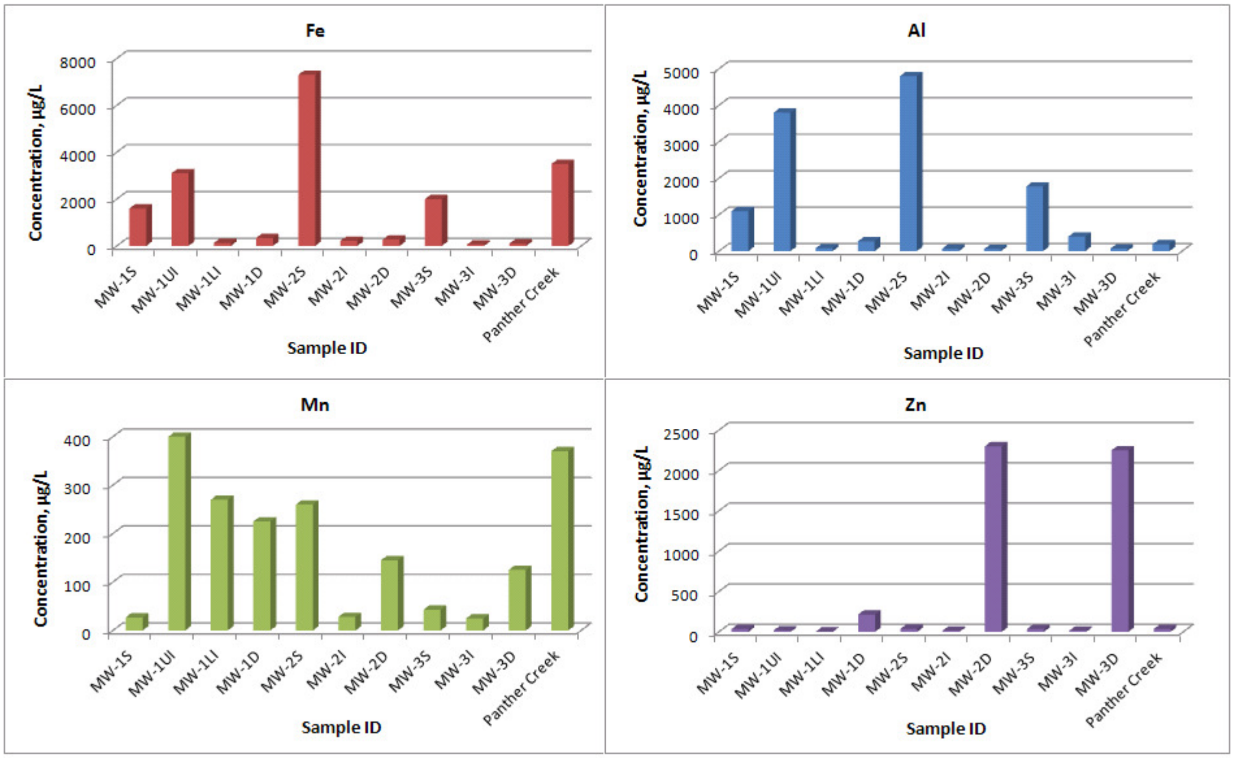


Figure 27. Distributions and concentrations of iron, aluminum, manganese, and zinc in groundwater at the NCZGMRS, Asheboro, NC

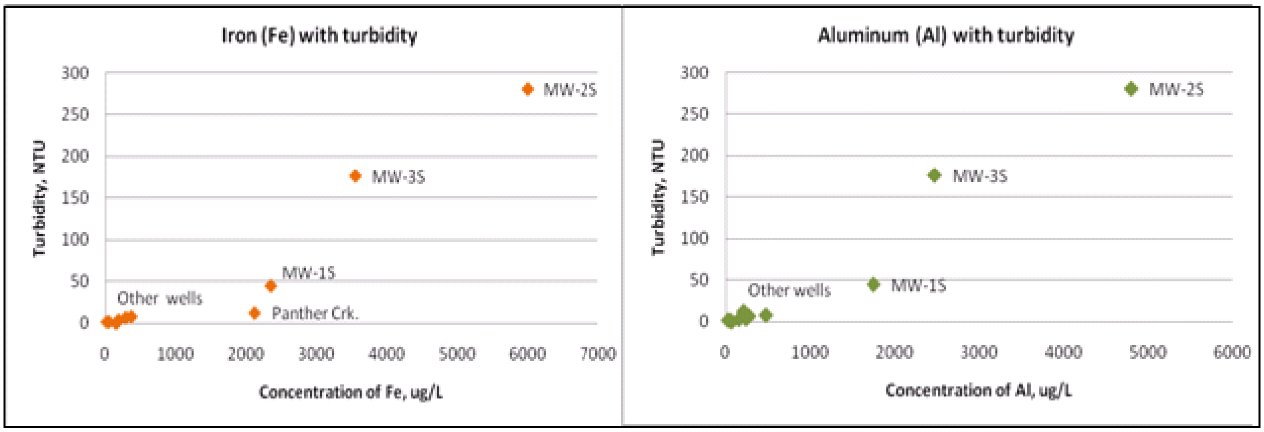


Figure 28. Correlation between concentration of total iron/aluminum and turbidity of groundwater at the NCZGMRS, Asheboro, NC

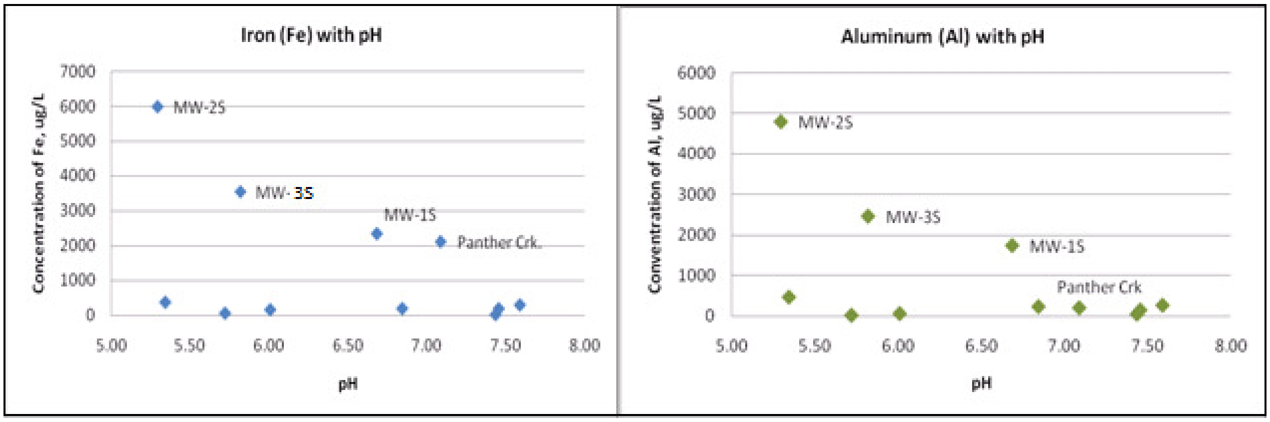


Figure 29. Correlation between concentration of total iron/aluminum and pH of groundwater at the NCZGMRS, Asheboro, NC

The geochemical behavior of Mn in water is similar to that of Fe although it is less abundant in rock and less prevalent in groundwater. Fe and Mn contained in the groundwater originate from rocks rich in iron and manganese under a certain geochemical conditions. The extent to which Fe and Mn dissolve in groundwater primarily depends on the concentration of oxygen and pH value in the water in addition to the rock type of aquifer (Cox, 1995). Mn and Fe are also present in surface waters, usually as organic complexes. Elevated Mn is common in the Piedmont and Mountains groundwater. It was detected in nine out of ten monitoring wells and in all bedrock wells at concentrations exceeding the state standard (>50 µg/L) at the NCZGMRS. Mn was not detected in MW-2I at concentrations exceeding the standard. Due to limited and different sampling conditions (weather, temperature, and sampling equipment and devices), no clear correlation between Mn concentration and dissolved oxygen level was found (fig. 30, left panel). In three shallow wells, the concentration appears to increase with water turbidity (fig. 30, right panel), which is similar to Fe and Al in the shallow regolith wells (fig. 29). However, unlike Fe, Mn was present in the groundwater at the NCZGMRS primarily in the dissolved state.

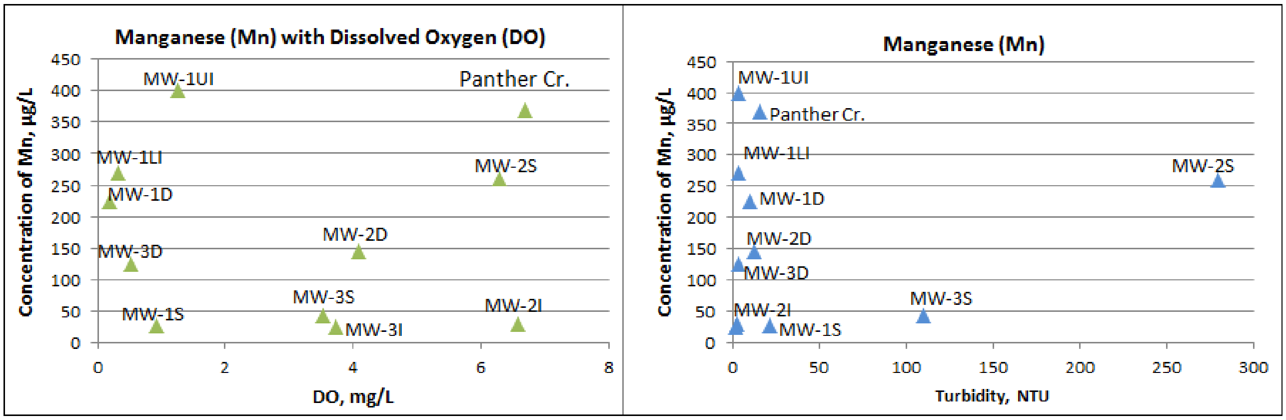


Figure 30. Correlation between manganese and dissolved oxygen (left) or turbidity (right) of groundwater at the NCZGMRS, Asheboro, NC

Zn is a fairly common metallic element and has about the same abundance in crystal rocks as Cu or Ni. However, Zn has only one significant oxidation state, Zn^{2+}, and tends to be substantially more soluble in most types of water than Cu and Ni. At the NCZGMRS, elevated levels of Zn were detected in two of three bedrock wells. No elevated level was detected in shallow or transition zone wells. The state standard for Zn is 1050 µg/L. It has been noted that the concentration of Zn detected in the bedrock wells decreased some over the monitored time, which could indicate that high levels of Zn may be partially attributable to the galvanized well casing that was installed in the bedrock wells. Zn was also detected primarily in the dissolved state in the groundwater at the NCZGMRS.

Nutrients

Nutrients including ammonia (as nitrogen, N), nitrate and nitrite (as N), and phosphorus (as total P) were analyzed. Ammonia was only detected in the shallow regolith wells and the creek at concentrations from 0.02 to 0.14 mg/L. Nitrate is highly soluble and mobile in groundwater, and is considered to be the final oxidation product of nitrogenous organic materials. Nitrite is an intermediate in the oxidation process, and rapidly converts to nitrate in the subsurface. Therefore, the value of nitrate and nitrite together is relatively equal to nitrate. The state standard for nitrate is 10 mg/L, when reported as N. In this study, nitrate and nitrite as N was detected in all regolith wells, two of four transition zone wells, and one of three bedrock wells at levels from 0.02 to 0.62 mg/L. The highest concentration was detected in a transition zone well (MW-3I). These levels are well below the state standard. Nitrate was also detected in four of the five nearby private supply wells with the highest concentration of 3.4 mg/L, which may indicate pollution by sewage and/or fertilizers.

Phosphorous concentrations in groundwater sampled from wells at the NCZGMRS and the vicinity were low, <0.02-0.28 mg/L. Phosphorous in groundwater may result from the dissolution of apatite and other minerals containing phosphorus or from commercial fertilizers. Phosphorus is one of the key elements necessary for growth of plants and animals and in lake ecosystems. However, overloading phosphate in surface waters will accelerate the aging process of the surface water ecosystem. Unlike nitrogen, phosphate is retained in the soil by a complex system of biological uptake, sorption, and mineralization. Phosphates are not toxic to people or animals unless they are present in very high levels. Therefore, no drinking water standard or groundwater standard is established for phosphorus at the state or federal level.

Cyanide, Volatile and Semivolatile Organics, Herbicides, and Pesticides

To measure the quality of ambient groundwater from the felsic metatuff unit of the Uwharrie Formation, and to determine whether the groundwater in this area of the state has been impacted by any human activities, each monitoring well at the NCZGMRS was also sampled for cyanide, volatile and semivolatile organic compounds, herbicides, and pesticides. Cyanide was not detected in any of the groundwater or surface water samples. Three volatile organic compounds (chloroform, bromodichloromethane, and 1-methyl-Naphthalene) were detected at very low levels in some monitoring wells. Chloroform was detected in MW-3I and MW-3D at concentrations of 2.1 µg/L and 0.42 µg/L, respectively, and similar low levels were also detected in two of five water supply wells sampled and the trip blanks during the same sampling event. Bromodichloromethane was detected at a concentration of 0.23 µg/L in MW-

3I. 1-methyl-Naphthalene was detected in MW-1D at 2.4 µg/L. Neither bromodichloromethane nor 1-methyl-Naphthalene was detected in the trip blank sample. Both chloroform and bromodichloromethane were detected in MW-3I, the transition zone well at the upland where an emergency power station and a large recycle tank used by the Zoo recycling program are located. Only one semivolatile organic compound, bis-phthalate (2-ethylhexyl), was detected at a concentration of 16 µg/L in MW-2S, the shallow well at the midslope. This compound was not detected in the trip blank sample. A herbicide compound, 4-nitrophenol, was detected in MW-3D at 0.19 µg/L. No other volatile/semivolatile organic compounds or herbicides were detected in any samples collected from the NCZGMRS. No pesticides compounds were found in any samples, but four unidentified compounds were detected in MW-1D. None of the detected constituents were above the state standards.

Arsenic and Dissolved Radon

Arsenic and radon are two common naturally-occurring constituents of concern in the region. Pippin (2005) indicated that the groundwater in the study area has greater than 25% probability to contain arsenic at a concentration greater than 1 µg/L. As discussed earlier, arsenic was detected in the whole rock samples at concentrations higher or much higher than the average concentration in the same rock type. However, arsenic was not detected in any groundwater samples collected from the NCZGMRS in the DWR laboratory at detection limit between 2 and 5µg/L. Arsenic was detected by the USGS laboratory in seven of nine groundwater samples at concentrations between 0.1 and 1.1µg/L (appendix 5-2), which were below the state standard of 10µg/L.

Radon (radon-222) is a chemically inert, radioactive gas and an intermediate product of the decay of uranium-238. Radon is common in uranium rich granitic rocks and, to a lesser degree, in other rocks present throughout the Piedmont and Mountains of North Carolina, including felsic metavolcanic rocks as those in the study area. Dissolved radon samples were collected from each monitoring well, but the vials of samples MW-2D, MW-3S, MW-SI, and MW-3D were broken in the shipping process. Low levels of radon, ranging from 130 to 780pCi/L, were reported for the remaining samples. Although special procedures were taken to prevent aeration, it is still possible that some radon gas was lost from groundwater by release to the air during the sample collection, especially since these samples were collected in hot weather. Therefore, actual levels of radon in the groundwater at the NCZGMRS may be slightly higher than reported levels. The EPA proposed a maximum contaminant level of 300pCi/L for radon in water for public water supply and an alternate standard of 4000pCi/L for water suppliers with a radon mitigation and outreach program (http://www.epa.gov/ogwdw000/radon/fact.html), but, to date, neither standard has been promulgated.

Comparisons of Groundwater Quality among Three Components of the Groundwater System: Regolith, Transition Zone, and Bedrock

The analytical data of groundwater samples collected during this study indicate that there are no significant differences in quality among the three components (regolith, transition zone, and bedrock) of the regolith-fractured bedrock groundwater system at the NCZGMRS. However variability and several general trends exist:

1. pH, SC, and TDS of the groundwater generally increase from the shallow regolith to the bedrock with highest concentrations of SC and TDS detected in the transition zone. Temperature, dissolved oxygen, turbidity, and total suspended residue decrease from the shallow to the deep zone of the groundwater system.
2. Predominant water type generally changes from sodium-bicarbonate in the regolith to calcium dominated bicarbonate in the bedrock and from the recharge area to the discharge area.
3. Concentrations of aluminum and iron generally decrease from the regolith to the bedrock while the concentration of manganese appears to increase, and high levels of zinc were only detected in two of three bedrock wells.
4. Phosphorus tends to be more likely detected in the regolith wells than in the transition zone and bedrock wells; nitrate is more likely detected in the regolith and transition zone wells with the highest level in the transition zone.

Comparisons of Groundwater Quality between Recharge Area and Discharge Area

Results of this study show that from the recharge area to the discharge area, levels or concentrations of pH, alkalinity, SC, TDS, Al, Fe, As (based on USGS lab results), Mn, and the ratio of Ca^{2+} to Na^{+} in the groundwater generally increased from the recharge area to the discharge area, which was due to the longer residence time and flowpath for more ion exchange between the groundwater and minerals of the aquifer contains. However the lowest levels or concentrations of these parameters were always detected at the midslope. Additionally, nutrients tended to be detected more frequency at relatively higher concentrations at the recharge area and the midslope than at the discharge area.

Comparisons of Site Groundwater Quality to Regional Groundwater Quality

In addition to the NCZGMRSR, there are two other groundwater monitoring and research stations (the Duke Forest and the Morgan Mill) established by the PMREP in the Carolina terrane. Due to the similar geologic setting, groundwater at the NCZGMRS has similar major ionic compositions as at the other two stations: HCO_3^{2-} is the sole predominant anion; calcium mixed with sodium-bicarbonate water type is predominant at the NCZGMRS and the Duke Forest, but calcium-bicarbonate is the sole groundwater type at the Morgan Mill. Due to the differences in local lithology and rock geochemistry (fig. 31 and table 7), major cations and other quality characteristics of groundwater at the NCZGMRS are distinct (table 8) to some degree from the other two stations. For instance, groundwater pH is lower while Fe concentration is much higher and Mn slightly higher at the NCZGMRS than at two other stations. In addition, arsenic was only detected in bedrock wells at the NCZGMRS at very low concentrations (0.1 to 1.1 µg/L), which is similar to the result at the Duke Forest station. Higher levels (3.8 µg/L average) were detected at the Morgan Mill. Furthermore, based on North Carolina Division of Public Health lab data of private well samples collected from Randolph County in which the NCZGMRS is located, Orange County in which the Duke Forest is located, and Union County in which the Morgan Mill is located, less than 4% of samples in Randolph and Orange Counties exceed the state standard (10 µg/L) while about 20% of private wells throughout Union County exceed the standard and 25% exceed the standard in some area of the county. The data strongly suggest that elevated arsenic in groundwater appears to occur in the Albemarle Group, particularly associated with the meta-mudstones of the Cid Formation, but not typically in the underlying rocks of the Uwharrie Formation.

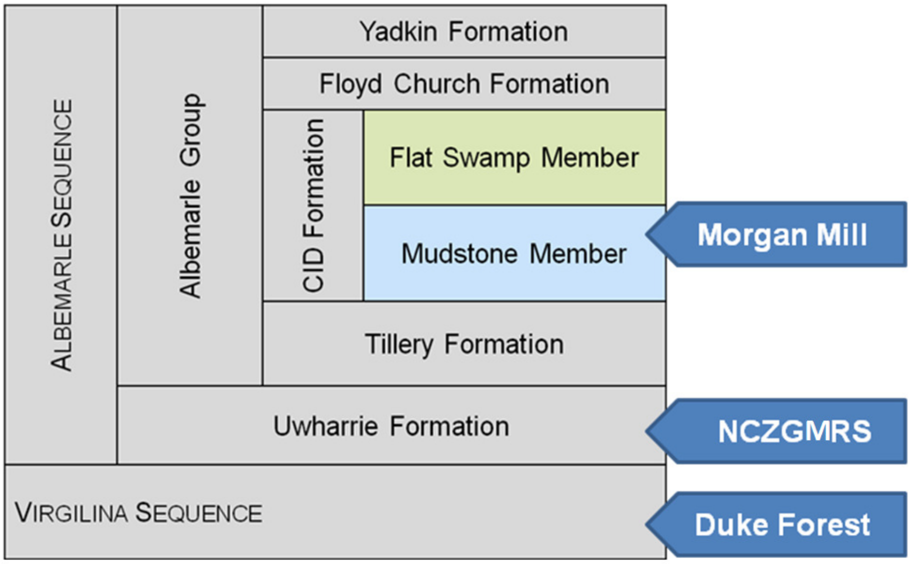
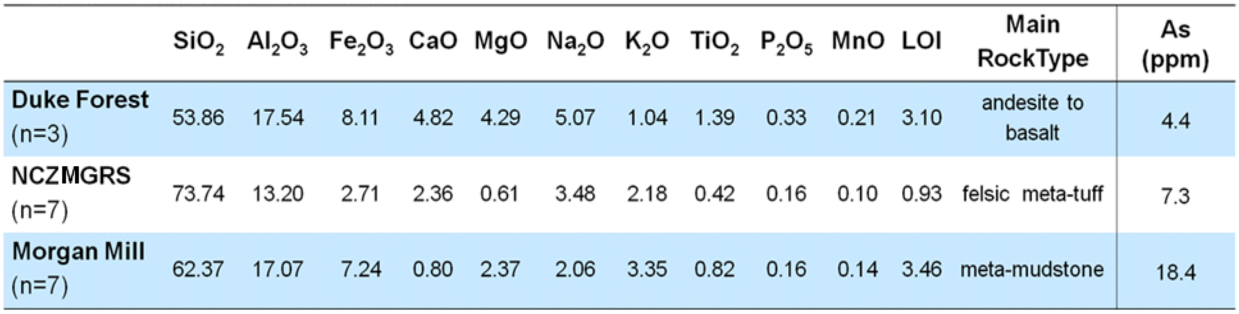


Figure 31. Two lower sequences of the Carolina terrane and the sequence or formation in which a groundwater monitoring and research station is installed (from Abraham and others, 2010)

Table 7. Results of whole-rock analyses in weight % for samples collected from the three groundwater monitoring and research stations in the Carolina terrane (From Abraham and others, 2010)



	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI	Main RockType	As (ppm)
Duke Forest (n=3)	53.86	17.54	8.11	4.82	4.29	5.07	1.04	1.39	0.33	0.21	3.10	andesite to basalt	4.4
NCZMGRS (n=7)	73.74	13.20	2.71	2.36	0.61	3.48	2.18	0.42	0.16	0.10	0.93	felsic meta-tuff	7.3
Morgan Mill (n=7)	62.37	17.07	7.24	0.80	2.37	2.06	3.35	0.82	0.16	0.14	3.46	meta-mudstone	18.4

Table 8. Average concentrations of select groundwater constituents and other characteristics of bedrock aquifers at the three groundwater monitoring and research stations in the Carolina terrane

	pH	**As (µg/L)**	**Fe (µg/L)**	**Mn (µg/L)**	**HCO_3 (mg/L)**	**SC (µS/cm)**	**Water type classification**
Duke* Forest n =15	Near-neutral to slightly alkaline	<1	160	198	113	157	Ca^{2+} - HCO_3^- to mixed cations - HCO_3^-
NCZGMRS n =15	Slightly acidic to neutral	<1.1	527	224	104	203	Ca^{2+} +Na^- - HCO_3 to Ca^{2+} - HCO_3^-
Morgan* Mill n=20	Near-neutral to slightly alkaline	3.8	244	95	119	272	Ca^{2+} - HCO_3^-

*from Abraham and others, 2010

The Piper water type classification analysis indicates that the groundwater at the NCZGMRS has a similar geochemical signature as in water supply wells installed within the metavolcanic rock unit of the Uwharrie formation throughout Randolph County (fig. 32). Samples from the NCZGMRS plot within the sample population. Across the Uwharrie Formation in Randolph County, groundwater may be broadly classified as mixed-cations-bicarbonate type water.

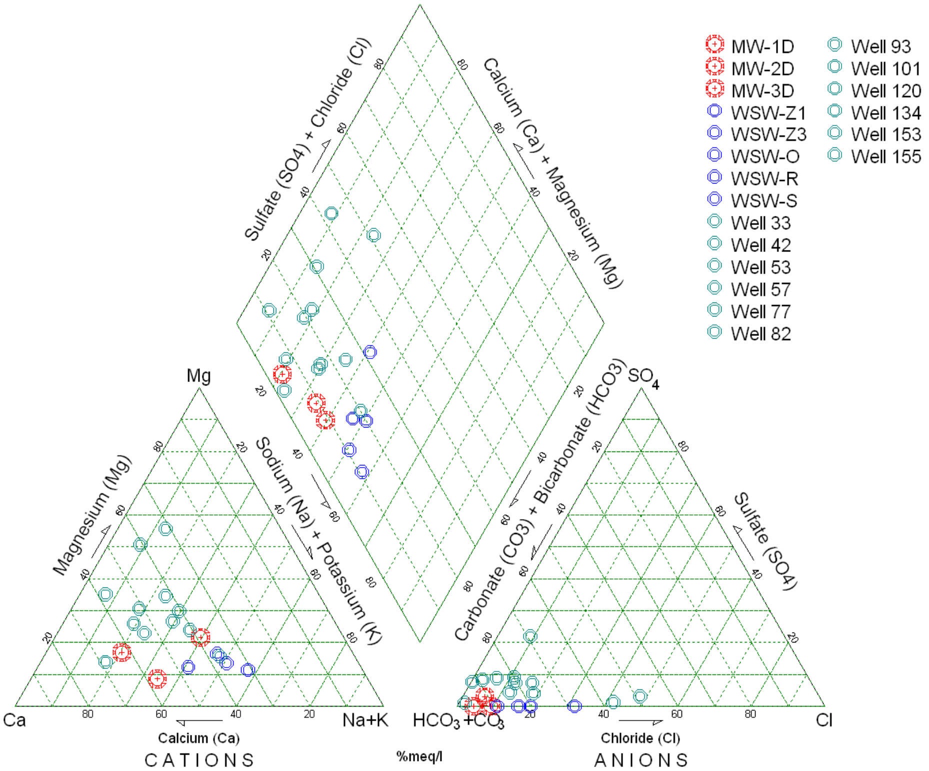


Figure 32. Major ion distribution in groundwater samples from bedrock monitoring wells at the NCZGMRS and metavolcanic bedrock water supply wells surrounding the NCZGMRS and throughout Randolph County (Note: samples with an ID beginning with MW are bedrock monitoring wells at the NCZGMRS; the remaining samples were collected from water supply wells)

Comparisons of Site Groundwater Quality to Rock Chemistry

The geochemistry signature of groundwater to some degree reflects the mineral or chemical composition of the rock with which it has been in contact. During process of weathering of rocks, principally SiO_2, Ca^{++}, Mg^{++}, Na^+, K^+, and $CO_2^=$ are released from minerals to groundwater. For example, granite is composed largely of sodium and potassium feldspars and quartz. These minerals are mainly composed of sodium, potassium and silica. Groundwater from granite or its extrusive equivalent rocks, such as felsic volcanic to volcaniclastic rocks, should have a geochemistry signature of sodium-bicarbonate type. Gabbro and its extrusive type, such as basaltic volcanic rocks, are composed largely of calcium feldspars and ferromagnesian minerals; therefore, water from gabbro and basalts should be a calcium/magnesium-bicarbonate type. However, this relationship could be complicated by mixing of waters from adjacent rock types of different compositions or if the host rock has an intermediate composition.

At the upland and the midslope well clusters of the NCZGMRS, water from shallow and intermediate monitoring wells is sodium-bicarbonate type, which direct reflects dissolution of the felsic metatuffs which have the same chemical composition as granite. While, the water type in the paired bedrock wells alters from the mixed cations-bicarbonate type at the upland to primarily calcium-bicarbonate type at the midslope. The mixed cations-bicarbonate and calcium-bicarbonate water types were found at this felsic metatuff geological setting because the felsic metatuffs found at the NCZGMRS contain higher calcium than normal felsic rocks (appendix 4). The change of water type from sodium-bicarbonate to calcium-carbonate occurred because the relative concentration of calcium increased from the shallow regolith to the deep bedrock at each cluster and from the upland position to the lower areas due to weathering and cation exchange processes in addition to the rock chemistry. Weathering of naturally sodium-rich felsic metatuffs releases abundant Na^+ into the groundwater; Na^+ then exchanges with Ca^{2+} attracted to the surface of clay minerals. The released Ca^{2+} is then transported along the flowpath to the deeper section of the aquifer system. Although generally divalent ions are more strongly bonded and tend to replace monovalent ions, it is a reversible reaction. At high Na^+ activity or concentration, the monovalent cation Na^+ can replace the divalent cation Ca^{2+} (Fetter, 1988). The felsic metatuffs mainly consist of Na rich minerals. As abundant Na^+ releases into the groundwater as a result of weathering, relatively less abundant Ca^{2+} attached on the surface of clay is replaced with Na^+ and moves to the deeper section of the aquifer system and more downgradient area. Therefore, groundwater from the discharge area where well cluster 1 is located became calcium-bicarbonate type. This geochemical signature also reflects the mafic bedrock encountered in the corehole at this location and the surrounding felsic metatuffs that are relatively high in calcium.

Elevated levels of Mn were measured in almost all monitoring wells at the NCZGMRS, which most likely reflects the higher concentrations of Mn present in the whole rock samples (table 7 and appendix 4). Weathering processes also played an important role on concentrations of Fe and Mn in the groundwater. The geological coring logging indicated that Fe-Mn leaching stain was very common on fracture surfaces. Locally existed Fe-Mn rich rocks, such as diabase and basaltic lava, may also contribute Mn to the groundwater at the NCZGMRS.

Although arsenic was detected in both felsic and mafic rock samples at levels higher than the averages in granite and basalt, only very low levels (<1.1 µg/L) of arsenic were detected in groundwater samples collected from this study site. It is noted from the whole rock analysis results that the Na_2O/K_2O ratio is higher than normal in six out of eight samples and the remaining two samples have a normal Na_2O/K_2O ratio (fig. 13 and appendix 4). Much higher concentrations of arsenic were found in these samples with normal Na_2O/K_2O ratio. This may imply that some arsenic re-mobilized along with potassium migrating away from the formation during the metamorphic process and/or hydrothermal liquid activities, which explains why elevated levels of arsenic have been found in a newer metasedimentary formation in Union County and other locations in the Carolina terrane.

SUMMARY AND CONCLUSIONS

The NCZGMRS located in Asheboro, Randolph County was established to evaluate the effects of the felsic metavolcanic rocks characterized by moderately to steeply dipping foliation on groundwater flow and quality in the Metavolcanic, Felsic hydrogeologic unit in the North Carolina Piedmont region. The geologic and lithologic setting at this site is distinguished by slightly metamorphosed felsic tuffs locally interlayered with minor mafic metavolcanic rock within the Uwharrie formation of the Carolina terrane. The Uwharrie formation underlies an extensive portion of Randolph and Montgomery counties in central North Carolina. The felsic metatuffs underlying the NCZGMRS are composed of felsic volcanic ash, lapilli-sized pumice fragments and/or glass charts, and minerals including quartz, feldspar, sanidine, sericite, muscovite, biotitic, and epidotic. Secondary minerals, calcite and pyrite, and Fe-Mn leaching stain, are very common along fractures or on fracture planes, implying hydrothermal liquid and groundwater activities.

Fractures encountered at the NCZGMRS can be divided into two types: (1) sub-vertical foliation and foliation partings and (2) sub-horizontal to medium (20 to 50 degrees) angle shearing and stress-relief fractures that cut the foliation and partings. Generally, the metamorphic foliation is parallel to the regional structures, striking approximately N20°E to about N30°E, dipping primarily NW-W (lesser SE) from 60 ° to sub-almost vertical. Overall, the transition zone or the top portion of bedrock has more low-angle fractures that are often slightly open and water bearing. Steeply dipping fractures found deeper are generally closed, but exhibit chemical weathering. The scale of fractures in the bedrock is generally small and localized, but interconnected to some degree. It is noted that foliations measured in MW-1D and CH-1 at the discharge area are generally less steep than foliations at the other two-well-cluster sites in the recharge area and the midslope. However, the dips of the shearing or stress-relief fractures that produce water in MW-1D are relatively steeper than in the other two wells. Only a few water-bearing fractures were encountered in each corehole or well.

Higher topography and steeply dipping foliation appeared to have some influence on the thickness of regolith at the NCZGMRS. The continuous soil-bedrock core logging indicates that the thickness of regolith decreases from 50 feet at the upland recharge area to about 27 feet at the low or discharge area. The thickness of the transition zone varies from approximately 30 feet thick at the upland recharge area to several feet at the low terrain or discharge area. However, another highly weathered and fractured layer (15 feet in thickness) was found beneath a fresh and less fractured bedrock layer (10 feet in thickness) which is beneath the first highly weathered and fractured bedrock layer in CH-1. This finding reveals the complicated nature of the transition zone in the Piedmont and Mountain regions of North Carolina. Therefore, caution should be exercised when determining the thickness of the transition zone and the depth to base bedrock, especially as it relates to the implications for potential contaminant transport at similar sites within the Piedmont and Mountain regions of North Carolina.

The results of whole-rock geochemical analyses of eight fresh bedrock samples indicate a higher ratio of Na_2O/K_2O in felsic metatuffs. In addition, Ca concentrations are higher in all felsic metatuff samples than the average in granite. Mn concentrations are higher in all samples. These characteristics of rock chemistry directly affect the groundwater quality and water type. For instance, Mn was elevated in nine of ten monitoring wells, including regolith, transition zone, and bedrock wells; the major ionic compositions of groundwater from wells installed in the felsic metatuff bedrock are classified water types from sodium-bicarbonate to calcium-bicarbonate, instead of a sole sodium-bicarbonate type as expected.

The periodic groundwater level data collected from the NCZGMRS generally support the slope-aquifer conceptual model (Legrand and Nelson, 2004) for groundwater in the Piedmont and Mountain regions of North Carolina. The groundwater flow generally follows the surface topography, from the topographic high (well cluster 3) to the topographic low (well cluster 1), from northwest to southeast. Based on downward head gradients, well clusters 2 and 3 are in recharge areas, while well cluster 1 is in a discharge area based on the upward head gradient, which is also consistent with the conceptual model. Results of the slug and aquifer tests conducted in this study indicate that groundwater in bedrock is connected to the shallow, porous regolith aquifer through intersected fractures in the transition zone. The hydraulic conductivity (K) of the fractured bedrock varies from 0.39 to 0.47 ft/day and the aquifer transmissivity (T) ranges from 29.25 to 89 ft/day. The transition zone appears to be the most conductive zone for groundwater movement in the subsurface.

Comparisons of analytical results of groundwater samples to state groundwater quality standards or EPA drinking water standards and EPA secondary drinking water standards indicate that the quality of ambient groundwater from the Metavolcanic, Felsic hydrogeologic unit in the NCZGMRS area is generally good. Concentrations of total dissolved solids, color, nitrate, fecal coliform, chloride, sulfate, fluoride, silver, arsenic, barium, cadmium, chromium, copper, lead, selenium, nickel, cyanide, most volatile and semivolatile compounds, pesticides, and most herbicides were either below laboratory detection limits or state groundwater quality standards. Constituents and properties that exceeded state standards or federal secondary standards are aluminum, iron, manganese, zinc, and pH. Manganese is the most notable element that was detected above the state groundwater standard in nine of ten monitoring wells. Elevated levels of zinc were only detected in bedrock wells, which may be attributable to the galvanized well casing. The other constituents in concentrations above the standards appear to reflect ambient groundwater conditions in this type of hydrogeologic setting.

Naturally occurring radon was detected in all samples at levels ranging from 130 to 780pCi/L with an average of 522pCi/L. The radon level in some samples is likely lower than the actual level because some radon gas may have volatilized from the groundwater into the air during the sample collection.

In addition, TOC, nitrate, and a few volatile and semivolatile organic compounds, including chloroform, bromodichloromethane, 1-methyl-naphthalene, and bis-phthalate (2-ethylhexyl), and an herbicide compound (4-nitrophenol) were detected in some regolith or transition zone wells at very low levels. Based on their distribution, these contaminants could be the result of land use or human activities rather than from a natural source or sampling artifacts. Although both chloroform and bromodichloromethane could be the by-products of chlorine added to water supply systems, both were detected in MW-3I, the transition zone well, at the upland position, but not in the trip blank sample.

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APPENDICES

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