Hydrogeology and Water Quality at the Tater Hill Groundwater Monitoring and Research Station, Watauga County, North Carolina

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2014 - 01

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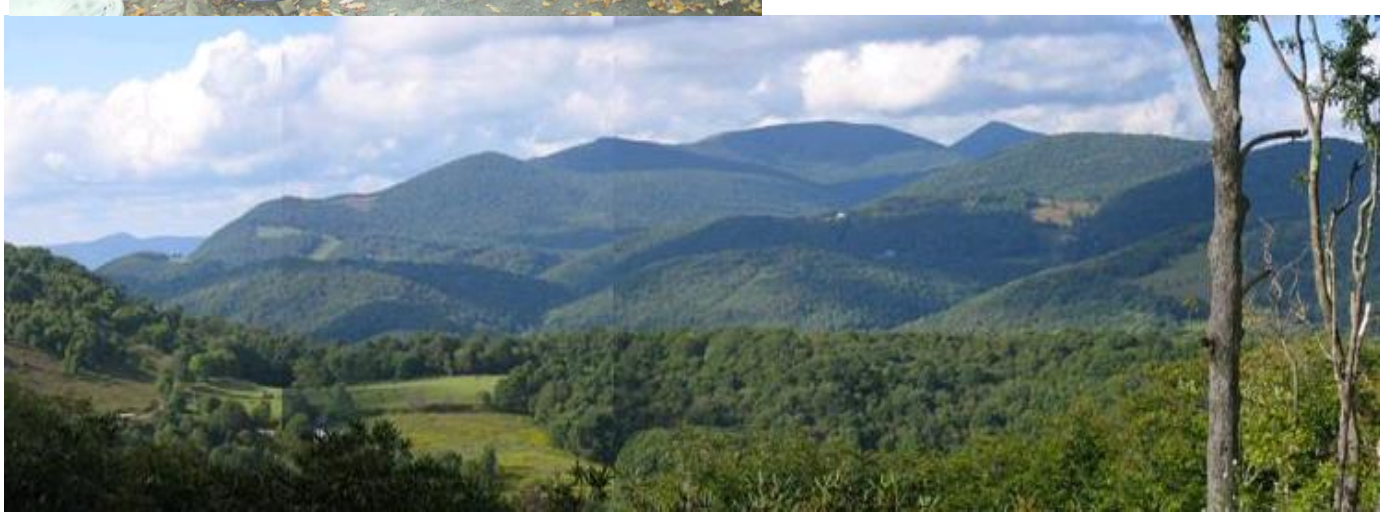

N.C. DEPARTMENT OF ENVIRONMENT AND NATURAL RESOURCES
DIVISION OF WATER RESOURCES

Prepared in cooperation with the Appalachian State University Department of Geology

Hydrogeology and Water Quality at the Tater Hill Groundwater Monitoring and Research Station, Watauga County, North Carolina

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Prepared in cooperation with the Appalachian State University Department of Geology

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Conversion Factors, Vertical Datum, Temperature, and Definitions

Multiply	By	To Obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square mile (mi2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
	Flow	
Gallon per minute (gpm)	3.785	liter per minute (Lpm)
	Radioactivity	
Picocurie per liter (pCi/L)	3.785	becquerel per liter
	Pressure	
Pound per square inch (psi)	6.895	kilopascal

Temperature: In this report, water temperature is reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = (1.8 \times °C) + 32$$

Water-quality measurements and groundwater hydraulic conductivity units:

µS/cm microsiemens per centimeter at 25°C
µg/L microgram per liter
mg/L milligram per liter
ft/day feet per day
m/day meter per day

Acronyms and abbreviations:

ASU Appalachian State University
BLS Below land surface
BMP Below measuring point
BDL Below detection limit
DWR Division of Water Resources
EPA U.S. Environmental Protection Agency
GNM Mafic gneiss hydrologic unit
MCL Maximum Contaminant Level
MW Monitoring well
NCDENR North Carolina Department of Environment and Natural Resources
NCGS North Carolina Geological Survey
NWIS National Water Information System
OTV Optical televiewer
PVC Polyvinyl chloride
PMGREP Piedmont and Mountains Groundwater Resource Evaluation Program
THGMRS Tater Hill Groundwater Monitoring and Research Station
USGS U.S. Geological Survey

Hydrogeology and Water Quality at the Tater Hill Groundwater Monitoring and Research Station, Watauga County, North Carolina

Shuying Wang, William Anderson, and Loren A. Raymond

ABSTRACT

Hydrogeology and groundwater quality have been investigated since July 2007 at the Tater Hill Groundwater Monitoring and Research Station (THGMRS) in Watauga County, North Carolina, as part of the North Carolina Department of Environment and Natural Resources Division of Water Resources (NCDENR DWR formerly Division of Water Quality or DWQ) and the U.S. Geological Survey (USGS) cooperative Piedmont-Mountain Groundwater Resource Evaluation Program (PMGREP). The THGMRS was established to evaluate groundwater availability, movement, and quality in a regolith-fractured rock flow system dominated by an amphibolite formation. The site lies within the Blue Ridge Mountains, which are characterized by complex geology consisting of deformed and fractured metamorphosed sedimentary and mafic volcanic rocks. The THGMRS is one of eleven hydrogeologic research stations installed in the Piedmont and Mountains as part of the PMGREP. Due to the high elevation; steeply-sloped, rugged, and forested landscape, limited physical accessibility of the site; and the lack of a shallow regolith aquifer; this station comprises only three wells: two bedrock wells (ASU-1D and TH-1D) and one transition zone well (TH-1I).

Groundwater at the site occurs within a two-part system consisting of a partially weathered transition zone (the interface of regolith and bedrock) and fractured bedrock, and flows primarily along fractures and lesser foliation planes. Pumping of one bedrock well revealed a hydraulic connection with another bedrock well located 20 feet (6.1 m) away, but no connection was observed between the bedrock well and the transition zone well 40 feet (12.2 m) away.

Over the monitored period, groundwater levels varied in the transition zone from about 27.5 to 31.5 feet (8.4 to 9.45 m) below land surface (BLS) and in the bedrock wells from 58 to 66 feet (17.7 to 20.1 m) BLS. Groundwater levels generally decreased from summer to fall and increased from late fall to the following spring. Water levels tended to be lowest in late summer when the evapotranspiration is greater than recharge, and highest in late winter. Generally, no significant water level decline was measured over the course of the seven-year monitoring period.

The dominant water type at the THGMRS is calcium-bicarbonate. Groundwater in the fractured bedrock is relatively soft and of high quality; therefore, it is good for all domestic and industrial usages. Iron and manganese, however, were detected at concentrations exceeding North Carolina groundwater standards in the transition zone well. Concentrations of turbidity, suspended residue, total dissolved solids, total organic carbon, aluminum, and barium were also significantly higher in the transition zone well than those in the bedrock wells. High levels of iron were also detected in samples collected from Howard Creek beside the well site.

INTRODUCTION

It is important to study the quality, occurrence, and movement of groundwater in the North Carolina Blue Ridge Mountains at the headwaters of four major river systems: the Yadkin, New, Catawba, and Watauga Rivers, because collectively these river systems interact with groundwater. The population in the area has been growing and a large portion of the population in the region relies on groundwater. The groundwater quality, in addition to the quantity, has become a public concern in the region. In addition, the movement and occurrence of groundwater in this part of the state is difficult to predict, because the geology and geomorphology in the region are complex and, more specifically, because the rock fractures through which water flows are heterogeneous and unpredictably arrayed (Campbell, 2011). Hydrogeology and groundwater quality studies in the Blue Ridge Mountains region are very limited and many gaps remain in our understanding of the region's groundwater occurrence, flow, and quality. It is essential for the state of North Carolina to fully understand the groundwater resource to ensure the high quality, long-term availability and sustainability of groundwater in this region of the state. Understanding groundwater quality and aquifer characteristics is also important for identifying potential areas or type settings that are suitable for groundwater withdrawal for drinking-water supplies, or for avoiding areas where naturally occurring contaminants may be present at concentrations that are hard to remove or treat for water-supply purposes (Harden and others, 2009).

In response to the public concern and to meet the state's need, the North Carolina Department of Environment and Natural Resources Division of Water Resources (NCDENR DWR) cooperated with the U. S. Geological Survey (USGS) North Carolina Water Science Center together launched a multi-year cooperative investigation. The investigation focused on groundwater quality, occurrence, and movement in different geologic settings across the Piedmont and Blue Ridge Mountains region of North Carolina (Daniel and Dahlen, 2002). This multi-year study has been conducted as part of the Piedmont-Mountains Groundwater Resource Evaluation Program (PMGREP) initiated in 2000. As of the end of 2012, 11 hydrogeologic monitoring and research stations have been established (fig. 1); the Tater Hill Groundwater Monitoring and Research Station (THGMRS) is one of them. This study is also conducted jointly with the Appalachian State University Department of Geology (ASU) in addition to the USGS.

The THGMRS was established because it is located in the mafic gneiss hydrogeological unit, which underlies approximately 18 percent of the Blue Ridge and Piedmont region of North Carolina (Daniel and Payne, 1990). The knowledge and data gained from this site can be compared to the results from other PMGREP sites to improve regional transferability to the same hydrogeologic unit or similar settings. In addition, this site provides a valuable opportunity to study the applicability of the prevailing conceptual model of groundwater recharge and discharge in the Piedmont and Blue Ridge Mountains (Heath, 1980; Harned and Daniel, 1992). The data and knowledge gained from the THGMRS are also valuable to reveal the nature of the groundwater flow system in this part of the state and to redefine the applicability of this conceptual model.

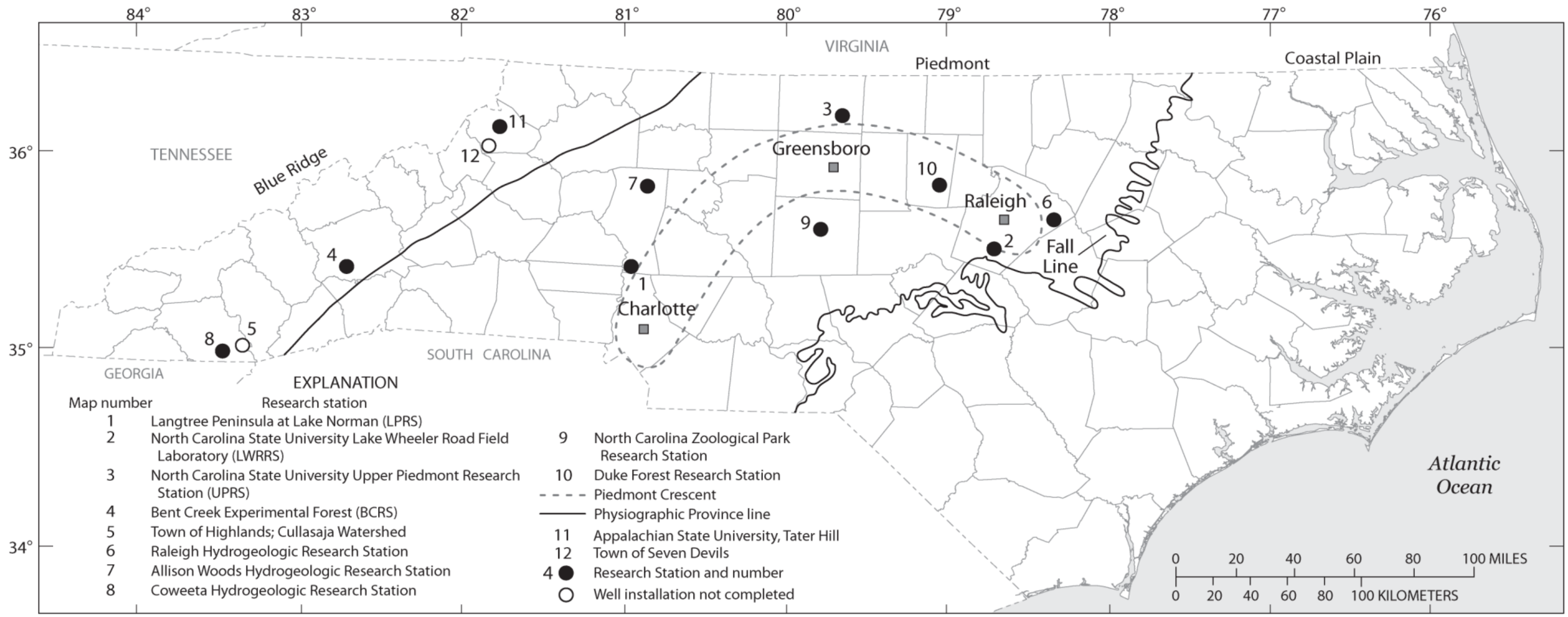

Figure 1. Locations of groundwater monitoring and research stations selected for investigations as part of the cooperative North Carolina Division of Water Quality and U.S. Geological Survey Piedmont and Mountains Resource Evaluation Program in North Carolina (from Huffman and Abraham, 2010).

Background

The groundwater of the Blue Ridge physiographic province of northwestern North Carolina occurs in a complex geologic terrane consisting of metamorphosed igneous and sedimentary rocks that have undergone multiple periods of structural deformation, metamorphism, and igneous intrusion (Abbott and Raymond, 1984; Hatcher et al., 2006; Campbell, 2011). Continual evolution and weathering of the region throughout its geologic history has created a rugged, steep, and dissected landscape. The conceptual model of three-component fractured bedrock aquifer system generalized for the Piedmont-Mountains region (Harned and Daniel, 1992) has been broadly accepted for the region. Based on the conceptual model, two primary components consisting of shallow, weathered regolith and deep, fractured bedrock (Heath, 1980) are commonly connected by a transition zone (fig. 2). The shallow weathered regolith consists of a relatively thin layer of soil and organic material at the land surface that is underlain by saprolite, a highly-weathered soft rock that often retains relict rock structures. Partially-weathered and highly-fractured rock between the saprolite and competent bedrock characterizes the transition zone (Harned and Daniel, 1992). These “layers” are heterogeneous, of variable thickness, and often discontinuous. In some locations, the saprolite and transition zones are interlayered and occur in intermittent, repeating intervals. In others, the transition zone may be absent. Groundwater occupies pore spaces in the regolith, forming a reservoir that stores most of the groundwater in the aquifer system and releases the water to the transition zone, and subsequently the water slowly moves to the underlying crystalline bedrock through fractures, joints, and faults that act as conduits for groundwater movement. The underlying crystalline bedrock has little primary porosity or permeability. Due to the complexities of the geology, hydrogeology, and landforms, the three-component conceptual model that is often applied to the Piedmont-Mountains region may or may not well fit the aquifer system of the northeastern Blue Ridge of North Carolina, where conditions need to be studied further. Recharge and discharge processes in the fractured-bedrock aquifers of this region are not well understood, but significant connection to the shallow aquifer system and surface waters may exist. Recent research indicates that a deeper aquifer exists in thrust-faulted areas of the Blue Ridge Mountains, such as the THGMRS site (Seaton and Burbey, 2005).

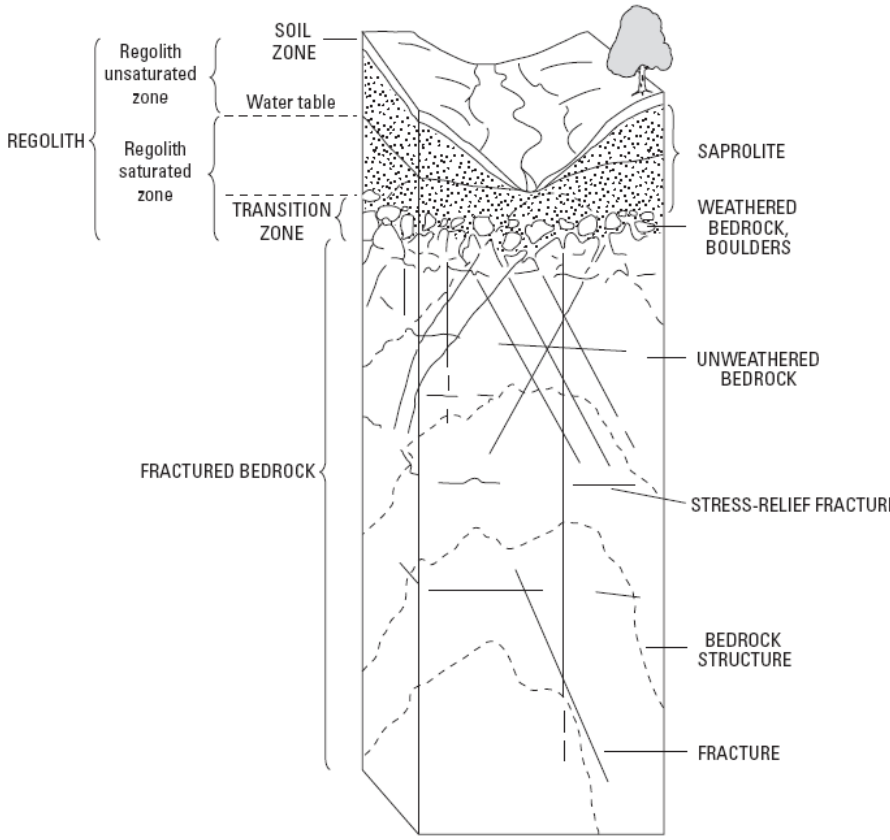

Figure 2. Conceptual model of the Piedmont-Mountains aquifer systems of central and western North Carolina (from Harned and Daniel, 1992).

The hydrogeologic properties of the regolith-fractured bedrock aquifer systems in the northern Blue Ridge are poorly constrained and detailed hydrogeologic information on local groundwater conditions is lacking. Only very limited hydraulic testing of local aquifers has been conducted. The lack of this type of information is problematic, because water resources, including groundwater, are becoming stressed due to population growth, especially in the “High Country” region of Ashe, Avery, and Watauga Counties of North Carolina. Increased urbanization increases runoff and reduces recharge to bedrock fractures that supply water to wells. Interference from pumping may occur if wells are drilled in close proximity to each other or if higher pumping rates become more common and drawdown areas expand (Webb, 2005). If unsustainable stresses on groundwater resources occur, local streams that form the headwaters of four major drainages, including the New River, Watauga River, Yadkin River, and Catawba River basins, may be stressed (fig. 3). Furthermore, the presence of naturally-occurring contaminants such as lead, arsenic and radionuclides in the northern Blue Ridge of North Carolina is poorly documented. Prior to the installation of the first fractured bedrock monitoring well at Tater Hill by the ASU in 2005, there was no groundwater monitoring well installed in this region to document the groundwater quality, and there were no Climate Response Monitoring Network wells in the region (fig. 3). In an effort to mitigate the knowledge deficit to ensure the long-term availability, sustainability, and quality of the region’s groundwater supply, in 2006 PMGREP joined the collaboration with ASU and USGS and completed the THGMRS.

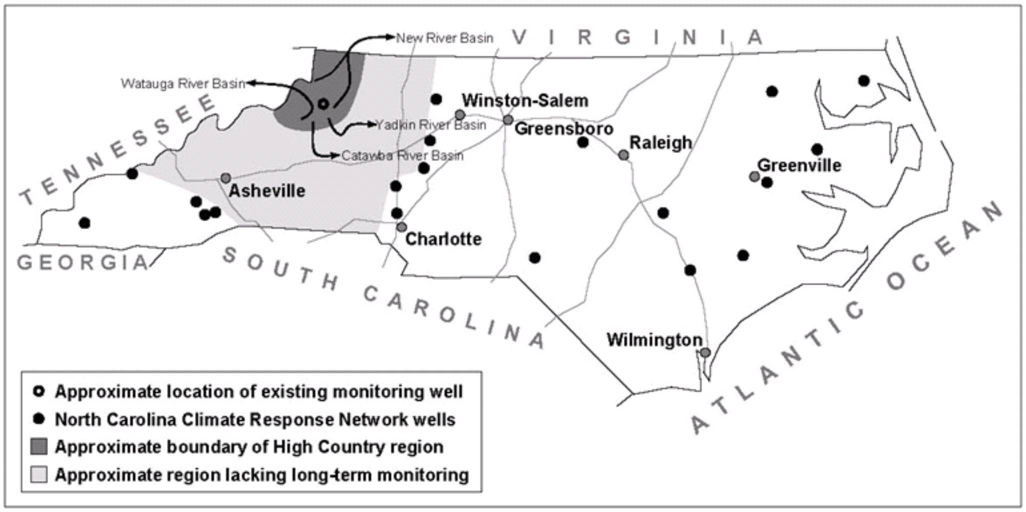

Figure 3. Locations of wells in the USGS North Carolina Climate Response Monitoring Network. The lightly shaded region is the section of western North Carolina lacking climate response monitoring wells; the darkly shaded region is the approximate boundary of the High Country area.

Purpose and Scope

The purpose of this report is to present the findings from a hydrogeologic investigation conducted primarily between July 2007 and July 2012 at the THGMRS within the Howard Creek drainage basin of the New River watershed in the northeastern Blue Ridge of North Carolina. The report outlines the regional and local geologic settings and discusses hydrogeologic properties and groundwater and surface-water quality at the site. The report also includes the results of borehole geophysical logging, groundwater level and temperature measurements, and surface-water temperatures collected by the USGS and ASU from May 2005 through December 2006.

The primary goals of this investigation are to characterize ambient quality and movement of groundwater in one “type area” (mafic gneiss) of the Blue Ridge Physiographic Province of North Carolina and to investigate the vulnerability of the groundwater system to contamination in this part of the Blue Ridge Mountains. The specific goals of the THGMRS monitoring efforts are: (1) to evaluate the relationship between the transition and bedrock zones of the aquifer system; (2) to evaluate the relationship of these components to the hydrologic cycle; (3) to characterize variations in groundwater chemistry between various zones of the aquifer system; (4) to determine the relationship between the aquifer system and surface water; and, (5) to evaluate how well the generalized three-component conceptual model that is widely applied to the Piedmont-Mountains region is applicable to the aquifer system of the northeastern Blue Ridge of North Carolina. To accomplish these goals, borehole geophysical logs and direction adjusted optical televiewer images were collected; stream and groundwater quality samples were collected and analyzed periodically over more than four years; monthly and continuous hourly groundwater level and water temperature data were recorded. In addition, slug tests and partial pumping tests were conducted.

Description of the Study Area

The THGMRS is located in the Blue Ridge Physiographic Province of North Carolina. The Blue Ridge Province is a dynamic and rugged landscape of metamorphosed igneous and sedimentary rocks that has undergone continual evolution throughout its history. The region comprises numerous steep mountain ridges, intermountain basins, and trench valleys. Known as the "High Country", the region contains the highest mountains in the Appalachian Mountain system of eastern North America, with the highest being 6,684 feet (2037 m) above mean sea level (N.C. Geological Survey, 1991). The Blue Ridge physiographic province is bordered to the northwest by the Valley and Ridge Province of Tennessee and Virginia and to the east-southeast by the Inner Piedmont Province, which is delineated by the escarpment of the Blue Ridge front. Major rock formations in this region have been folded and faulted into northeastern-trending belts (Rankin et al., 1973; Hatcher et al., 2006).

Geologically, the THGMRS lies in the eastern Blue Ridge belt in northwestern North Carolina, a region containing the headwaters of four major river systems: the Yadkin, New, Catawba, and Watauga Rivers (fig. 3). THGMRS is underlain predominately by an amphibolite unit of the Ashe Metamorphic Suite (AMS) within a thrust sheet above the Gossan Lead Fault. The study area is in northern Watauga County within the Howard Creek drainage basin of the New River watershed. The site is approximately six miles upstream of the water-supply reservoir that serves as a back-up water source for ASU.

The THGMRS consists of three monitoring wells installed beside an existing access road along a small trough at a low-middle slope of a rugged, forested area near Howard Creek, a classified trout stream that lies approximately 1,640 feet (500 m) down-gradient of the Tater Hill bog. This bog is the former site of Potato Hill Lake, which was a small reservoir prior to a dam failure in 1978 (fig. 4). The relief in the area is about 800 feet (244 m) with elevations ranging from 4,000 feet (2037 m) above mean sea level (AMSL) adjacent to Howard Creek to more than 4,800 feet (1463 m) AMSL at Harmon Knob. The yearly average temperature is between 40°F and 58°F (4.5 to 14.5°C) with average monthly highs of 76°F (24.5°C) in July and lows of 21°F (-6.1°C) in January (Weatherbase.com). The average annual precipitation is approximately 65.3 inches (1660 mm).

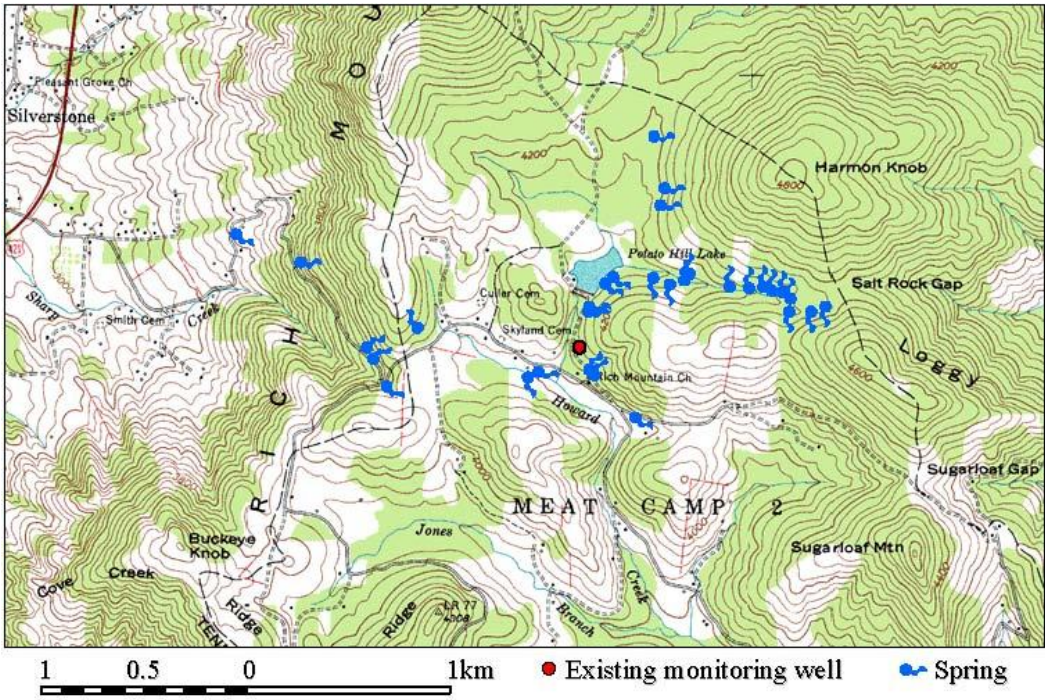

Figure 4. Location of the THGMRS with known springs and initial monitoring well, Watauga County, North Carolina. Base map from the United States Geological Survey Zionville, North Carolina, 7.5-minute quadrangle. Note the location of Potato Hill Lake, which no longer exists after a dam failure in 1978. The lakebed is now occupied by a bog, called Tater Hill bog.

METHODS OF DATA COLLECTION

Most of the methods used in this investigation are documented in the Standard Operating Procedures (SOP) for Groundwater Research Stations (NCDENR DWQ, unpublished, 2008). Site specific methods are briefly described below.

Monitoring Well Installation and Numbering

Three monitoring wells were installed at the THGMRS. The first deep bedrock well, hereafter referred to as ASU-1D, was drilled with an air-rotary drilling rig in April 2005, prior to DWR joining the investigation. This well is 345 feet (105 m) in depth and is cased within the upper 23 feet (7 m). The second bedrock well (TH-1D) and the transition zone well (TH-1I) were installed by the DWR Groundwater Investigation Unit staff, using a Schramm T-450 air-rotary drilling rig, to depths of 350 feet (106.7 m) and 40 feet (12.2 m), respectively, at 20 feet (6.1 m) and 40 feet (12.2 m), respectively, north of the first bedrock well ASU-1D. The location and depth of TH-1D was determined based on hydrogeologic conditions found in ASU-1D and new conditions encountered in the borehole of TH-1D. Due to lack of water in the regolith zone, no shallow well was installed. TH-1I was screened from 20 to 40 feet (6.1-12.2 m), where competent rock was encountered. Upon completion, the wells were developed by direct pumping. The wells were also surveyed to determine the horizontal position and relative elevation. The wells were protected by locked steel outer well casing, 1.35 feet (0.4 m) to approximately 3 (0.9 m) feet above the land surface (fig. 5).

The wells drilled by DWR were numbered as TH-1D and TH-1I, with TH standing for Tater Hill, D for deep bedrock, and I for intermediate or transition zone. It should also be noted that ASU-2D and ASU-1I may be used in place of these names in other reports or publications. In addition, each well and the surface-water sample location were also assigned a unique 10-digit location identification number to easily track DWR laboratory results (table 1).

Table 1. Well construction data and well and stream sampling location ID at the THGMRS, Watauga County, North Carolina.

Location ID (for lab)	40004000001	40004000002	40004000003	40004000004
Well or surface-water ID	ASU-1D	TH-1D	TH-1I	Howard Creek
Date drilled	5/13/2005	7/13/2007	7/13/2007	n/a
Total well depth, feet bls[1]	345	350	40	n/a
Casing/riser depth, feet bls[1]	23	27	17	n/a
Casing type	PVC	GALV	PVC	n/a
Well diameter, in.	6 1/8	6 1/8	4	n/a
Screened/open interval, feet bls[1]	23 – 345	27 – 350	17 – 40	n/a
Screened or open borehole	Open	Open	Screened	n/a
Aquifer zone monitored	Bedrock	Bedrock	Transition	Surface water
Measuring point relative elevation[2], feet	116.152	117.971	117.362	n/a
Measuring point height, feet als[3]	1.35	2.99	3.16	n/a
Land surface relative elevation, feet	114.55	114.97	114.36	n/a
Latitude, NAD83	N36° 16’ 45.98’’	N36° 16’ 45.9’’	N36° 16’ 46.3’’	N36° 16’ 48.6’’
Longitude, NAD83	W81° 43’ 03.7’’	W81° 43’ 03.7’’	W81° 43’ 03.5’’	W81° 43’ 04.8’’
Well yield[4], gpm	60 gpm, ~258 ft. bls	3-5 gpm, ~30 ft. bls	Minimal, ~29 ft. bls	n/a

Notes:
1- Feet below land surface
2- A temporary benchmark of 100.0 feet based on the elevation of a bolt drilled into a rock in Howard Creek is used.
3- Feet above land surface.
4- Well yield estimated during drilling or development.

Figure 5. A view of the THGMRS site from Rich Mountain near Boone, Watauga County, North Carolina (left panel) and the well cluster at the THGMRS (right panel).

Borehole Geophysical Logging

Borehole geophysical logging was conducted and interpreted by the USGS for monitoring wells ASU-1D and TH-1D. Geophysical measurements included caliper; natural gamma; and short-normal, long-normal, and lateral resistivity logs; fluid-temperature and fluid-resistivity logs; and an oriented digital borehole image using an oriented digital camera with optical televiewer (OTV) manufactured by ALT© Geophysics. The OTV images and associated interpretation software enable direct observation of the lithology type (felsic or mafic), rock-foliation (fabric) and fracture orientation. The orientation data of fractures and foliations are displayed in tadpole plots, where dip angle is plotted as a circle and azimuth direction is plotted as a line segment. The OTV data were corrected for magnetic declination and borehole deviation (azimuth and inclination angle). All geophysical logs collected from this study were depth-referenced to feet below land surface. In addition, in order to provide qualitative and quantitative aquifer characteristics, electromagnetic flowmeter (EMFM) logs including ambient and pumping (3 gpm or 11.4 Lpm) conditions were also conducted in ASU-1D.

Water Level and Temperature Monitoring

Water levels in three monitoring wells were measured continuously and/or periodically to identify daily and seasonal groundwater fluctuations in different flow zones and to evaluate vertical hydraulic gradients between the monitoring wells. In addition, continuous groundwater level and temperature data were collected hourly, primarily, with submersible pressure transducers (An In-Situ Level Logger, Aqua Troll ®200 in ASU –1D and YSI Level Scout sensors in TH-1D and TH-1I) and were downloaded periodically. Monthly to quarterly, hand measurements were conducted to check the accuracy of the data collected with the pressure transducers. The hand measurements of groundwater levels were measured to an accuracy of 0.01 feet (3 mm) using an electronic water-level meter referenced to a surveyed measuring point at the top of the casing. The elevations of the measuring points were determined with leveling upon well completion; however, it should be noted that these relative elevations have not been tied to a benchmark.

Groundwater levels and temperatures at ASU-1D have been monitored hourly at the site since June 2005. Between December 2006 and September 2009, the monitoring was part of the

USGS real-time groundwater monitoring network. The data were recorded on a data-collection platform (DCP) and then transmitted by satellite every 4 hours to the USGS National Water Information System (NWIS) database for processing. These data were made accessible from the USGS North Carolina Water Science Center's webpage (http://waterdata.usgs.gov/nc/nwis/uv). Periodic water-level measurements from June 2007 to October 2009 were manually entered into the USGS Groundwater Site Inventory (GWSI) database, and are available online as part of the NWIS (http://nwis.waterdata.usgs.gov/nc/nwis/gwlevels). In addition to groundwater levels and temperatures, water temperature in Howard Creek was monitored by ASU with a submersible temperature datalogger at 30-minute intervals between May and November 2006 to evaluate potential interactions between the surface-water and groundwater systems.

Aquifer/Slug Tests

In order to evaluate the hydraulic connectivity between the two bedrock wells (ASU-1D and TH-1D) and between the pumped bedrock well (ASU-1D) and the transition zone well (TH-1I), drawdown in all three wells was measured during a 2.5-hour well-purging that was conducted during a water-quality sampling event. The purging rate was set at 2.5 gpm (9.5 Lpm). Groundwater-level changes were recorded with an YSI Level Scout transducer and manually verified with an electronic water-level meter.

In addition, a rising head slug test (Butler, 1998) was performed at each monitoring well in order to assess the horizontal hydraulic conductivity of the aquifer tapped by the wells. PVC bailers were used to displace water from the wells. The bailers were rinsed with distilled water prior to use. A submersible pressure transducer with an integrated electronic datalogger measured changes in groundwater levels during each test. Groundwater level data recorded on the dataloggers were verified by manual water-level measurements. The tests were terminated once groundwater levels recovered to 95 percent of the pre-test level or within a reasonable time period if recovery was otherwise extremely slow. Efforts were made to avoid splashing effects during the displacement of water from the well. Slug test analyses utilized the Bouwer and Rice (1976) method spreadsheets developed by Halford and Kuniansky (2002). Assumptions inherent in the method are that the aquifer is porous and isotropic (no directional variation in properties), elastic storage is negligible, and the water table is static. Water-column height represented the aquifer thickness for tests in the transition zone well, while the length of the open borehole represented aquifer thickness for tests in the bedrock wells.

Water-Quality Sampling

Monitoring wells and Howard Creek were sampled four times, corresponding to different seasons, in the first two years of the study and then annually for the subsequent years. Standard procedures (NCDENR DWQ, unpublished, 2008) were followed for sample collection during the investigation. Due to extremely slow recovery in TH-1I, only one well volume of water was removed and samples were collected on the following day. For 6-inch diameter deep open-borehole bedrock wells, removing three well volumes of water prior to sample collection was also impractical when purging at a rate for sampling. Therefore, a minimum of one well volume of water was removed or field parameters became stabilized prior to sample collection. Groundwater samples collected from bedrock wells are considered as composite samples because water may be from multiple fractures. Field parameters including temperature, pH, specific conductance, and dissolved oxygen (DO) were monitored during well purging. Samples were collected for laboratory analyses of major ions, nutrients, trace elements, and selected inorganic parameters seven times during the study period for two bedrock wells and Howard Creek. Samples for fecal coliform, pesticides, herbicides, volatile and semi-volatile organic compounds, and radon analyses were only collected once. The analyses were performed by DWR laboratory following the adopted EPA standard protocols. During the first sampling event, the USGS also collected samples for USGS laboratory analyses of major ions, nutrients, and trace elements in accordance with the USGS Quality Assurance/Quality Control standard protocols.

Analysis of Water-Quality Data

Water-quality data collected for major ions are plotted using Piper trilinear diagrams (Piper, 1953) and Stiff diagrams (Stiff, 1951) in order to analyze the geochemical variability in the groundwater-quality data from the THGMRS. In a Piper diagram, the percentages of cations are plotted in the left trilinear diagram, and the percentages of anions are plotted in the right trilinear diagram. The diamond shaped middle diagram plots the cations and anions together. In a Stiff diagram, a polygonal shape is created from four parallel horizontal axes extending on either side of a vertical zero axis. Cations are plotted in milliequivalents per liter on the left side of the zero axis, one to each horizontal axis, and anions are plotted on the right side. Like Piper diagrams, Stiff diagrams can be used to characterize the composition of groundwater and interpret groundwater flow paths. In addition, X-Y charts were plotted to display seasonal variations of temperature, dissolved oxygen, pH, specific conductance, and selected constituents of water samples. For all other parameters, groundwater quality data collected from this study were compared to the 2L state groundwater quality standards or EPA drinking water standards to determine the quality of groundwater in the study area.

HYDROGEOLOGIC CHARACTERISTICS

Regional Geologic Setting

The THGMRS is located within the Blue Ridge geologic belt (NCGS, 1985) of northwestern North Carolina. This part of the Blue Ridge Belt is bounded on the southeast by the Brevard fault zone and on the northwest by various Blue Ridge fault systems. These fault systems transported crystalline thrust sheets composed of Precambrian basement gneisses and metaplutonic rocks, late Precambrian-early Paleozoic metasedimentary and metavolcanic rocks, and Paleozoic plutons northwestward over Paleozoic sedimentary rocks of the Valley and Ridge belt. Middle Proterozoic basement gneisses, late Proterozoic plutons, late Proterozoic metavolcanic and metasedimentary rift sequences, and thick Paleozoic rifted continental margin and platform rocks are well exposed in this part of the Blue Ridge Belt. In general, this part of the Appalachian Orogen has gone through multiple events of folding and faulting from Proterozoic through Paleozoic time, and its structure is dominated by the series of large westward-vergent thrust faults of different ages and different characters, with major rock units occurring as northeast-trending belts (Hatcher and Goldberg, 1991; Hatcher et al., 2006). The THGMRS lies within the Ashe Metamorphic Suite (Abbott and Raymond, 1984; Hatcher and Goldberg, 1991), part of the Ashe and Alligator Back Metamorphic Suite of figure 6.

Structurally, two major northwest-vergent thrust faults, the Gossan Lead Thrust Fault and the Fries Thrust Fault, occur to the west of and underlying the THGMRS area (Rankin et al., 1973; Raymond, 1998 and 2000; Wooten et al., 2008). The Gossan Lead Fault separates the Ashe

Metamorphic Suite (AMS) of the Tater Hill area from the structurally underlying and older Pumpkin Patch Metamorphic Suite. Beneath the latter suite is the Fries Fault, which separates the Pumpkin Patch Metamorphic Suite from the underlying Cranberry Gneiss *sensu lato* within the Fork Ridge and Linville Falls blocks. The Gossan Lead Fault, the upper of the two faults, occurs about one mile (1.6 km) west of the Tater Hill area and projects beneath the THGMRS at a depth of between 3000 and 5100 feet (914 and 1555 m) (Hatcher and Goldberg, 1991). In general, the Blue Ridge Belt consists of felsic gneiss, mafic gneiss, schist, metaquartzite, phyllite, and numerous minor rock types (Rankin et al., 1973; Abbott and Raymond, 1984; Daniel and Payne, 1990). The THGMRS lies in a mafic gneiss unit of the Ashe Metamorphic Suite (massive/foliated crystalline rocks) that is mantled by a thin regolith.

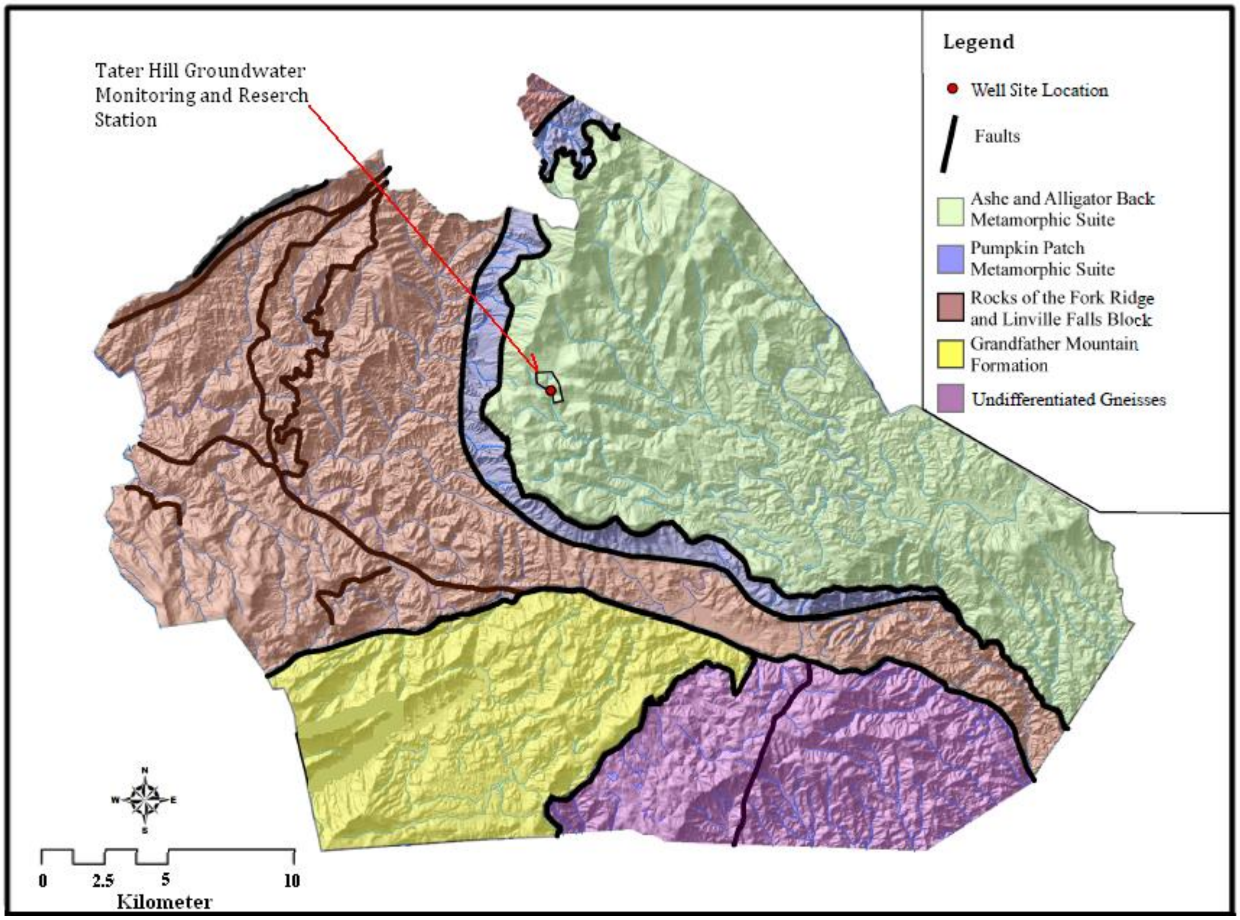

Figure 6. Geologic map of Watauga County showing the location of the THGMRS, major rock units and major faults (From Wooten et al., 2008).

Local/Site Geology

The quality, occurrence, and movement of groundwater is largely dependent on the regolith and rock through which it flows, therefore it is important to study geology at the local scale to understand, as much as possible, the local hydrogeologic framework. Field mapping in the THGMRS area was conducted specifically for this study. The rock structure and mineralogy were not only measured and observed in the field, but also analyzed in the laboratory. The mapping indicates that the THGMRS is underlain by two bedrock subunits of the AMS, including a dominant amphibolite (hornblende gneiss and schist) unit that occupies the eastern and central parts of the mapped area and a less dominant mica schist unit that underlies the northwestern part of the study area (fig. 7). The latter unit was not identified in any previous mapping. In addition to the above rock units, one narrow zone of pegmatitic granitic rock occurs just west of the former Potato Hill Lake dam area, within the amphibolite unit. Overlying the bedrock are five types of Quaternary sediments, including recent surficial deposits.

The amphibolite unit consists primarily of fine- to coarse-grained rocks with up to 80 percent hornblende, lesser amounts of plagioclase and quartz, and minor garnet, epidote, clinopyroxene and pyrite. Foliation in this unit is obvious. Light colored bands consist predominantly of plagioclase feldspar and quartz with less than 40 percent hornblende and minor amounts of epidote and pyrite. Local layers of epidote-rich rock also form lighter bands and contain up to 75 percent epidote with subordinate quartz and minor hornblende and pyrite. The deeply-weathered mica schist unit consists predominantly of biotite with modest amounts of quartz and feldspar and minor amounts of garnet and some white mica. Interlayered in the schists are a few thin layers of hornblende schist and semischist and some white mica-quartz-feldspar semischist.

The observed mineral assemblages, combined with those from other studies in the local area (Abbott and Raymond, 1984 and 1997), indicate that some rocks might be initially metamorphosed under Eclogite Facies conditions; however subsequently, the rocks were recrystallized and deformed under Amphibolite Facies conditions, and were then retrograde metamorphosed under Greenschist Facies conditions. Quartz-epidote bands and veins appear to characterize the Greenschist Facies event. The last metamorphism was probably associated with thrust faulting during the Alleghanian Orogeny at the end of the Paleozoic Era.

Surficial deposits include colluvium and alluvium near the former Potato Hill Lake and along stream valleys, recent lake deposits upstream from the dam, debris flow deposits along stream valleys and gullies, and float blocks up to 15 feet (4.6 m) across that have moved downhill under the influence of gravity. These deposits have mixed grain sizes with the exception of lake deposits and float blocks. A layer of reddish brown silty clay mixed with small rock fragments to clay-rich saprolite was observed at the well site from the land surface to a depth of 15 to 16 feet (4.6-4.9 m) during well installation. The depth to competent bedrock varies from 23 to 30 feet (7-9 m) and the thickness of the transition zone varies from 10 to 20 feet (3-6 m).

Structurally, the AMS rocks contain both faults and folds, in addition to foliations. The dominant structure in outcrops of AMS rocks is metamorphic foliation. The trend of strikes of foliation planes is generally in the N0°-30°E range and dips are highly variable, reflecting folding. Some minor ductile shear zones occur in outcrops, but no significant faults are evident in the mapped patterns of the bedrock in the well site area. Extensive arrays of springs may, however, suggest that up to five faults striking NNE, E-W, NW, WNW, and NE, respectively exist outside of the area mapped in detail (fig. 4).

The poorly exposed contact between the mica schist and amphibolite units at the surface, as revealed by mapping, indicates a strike of about N10°W. A fault zone contact between the two units was penetrated at a depth about 258 feet (78.7 m) in monitoring well ASU-1D (fig. 8) that is approximately 400 feet (122 m) east of the projected surface contact of the two units. The geometry suggests a dip to the east of about 32°ENE, which would be compatible with the 30° E dip measured in the mica schist near the east edge of the detailed geologic map (fig. 7). The OTV image (fig. 8), however, logged in ASU-1D revealed this contact dipping to the North (N1°W) at about 45°. This contrast in strike and dip of the geologic contact of the two bedrock units suggests either (1) that faulting of the contact, not present at the surface, has modified the contact at the well site, or (2) that some fracture(s) and/or fold(s) exist between the outcrop of the contact and the subsurface contact at the well site. Truncation of folds in the amphibolite above the contact (fig. 8) suggests a ductile condition, but a major water-producing (brittle) fracture occurred at this fault contact in monitoring well ASU-1D. The geologic contact was also encountered in TH-1D at a depth of 289 feet (88.1 m) below land surface, but the brittle fracture was not encountered in TH-1D nor was significant water encountered at this depth, in contrast to the significant flow above 258 feet (78.7 m) in ASU-1D, although TH-1D is only 20 feet (6.1 m) north of ASU-1D. If the strike and dip of the contact did not change from ASU-1D to TH-1D and TH-1D is vertical or without any deviation, the contact should be encountered at a depth of about 278 feet (84.8 m), instead of 289 feet (88.1 m), in TH-1D, because it is about 20 feet (6.1 m) north of ASU-1D and the contact dips to the North at about 45° at ASU-1D. The depth of the contact in TH-1D does indicate that the contact (fault) is not strictly planar, but may have local broad folds or irregularities in its surface. The absence in TH-1D of a fracture like that in ASU-1D also suggests that a local fracture that developed near the contact in ASU-1D took advantage of and formed locally at the weak zone of the contact, but did not follow the contact zone down to 289 feet (88.1 m) in TH-1D nearby and is not coplanar with the contact fault.

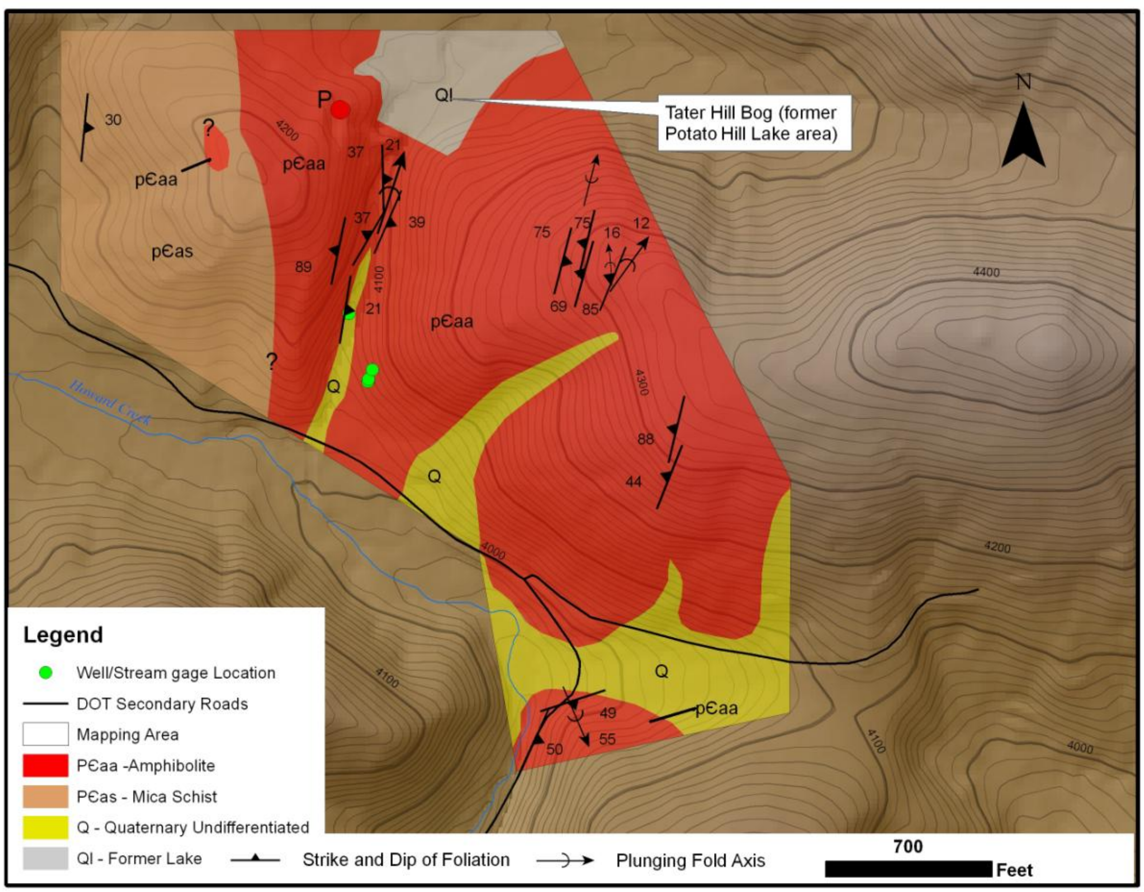

Figure 7. Geologic map of the THGMRS area showing major geologic units, well and stream sampling locations, and secondary structures in the area. P = location of local pegmatitic granite outcrops.

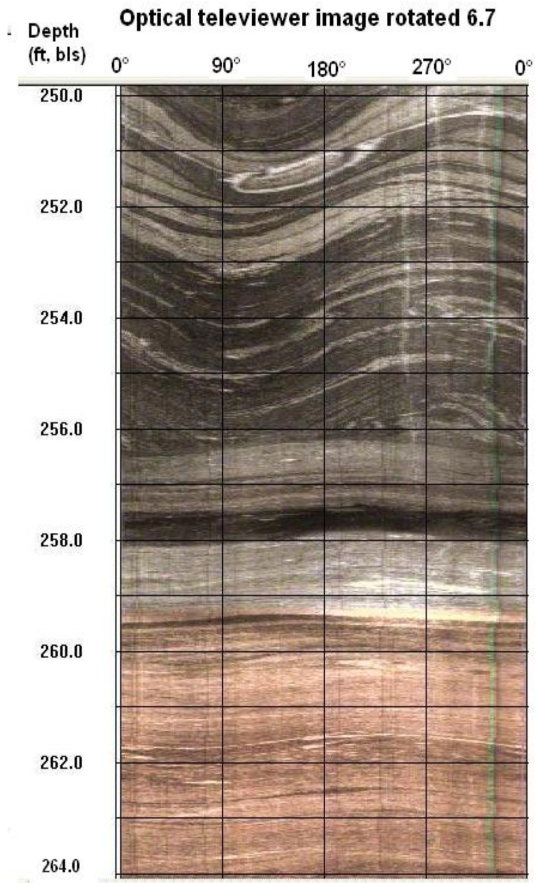

Figure 8. Optical televiewer image of the contact between the amphibolite and mica schist units in ASU-1D at the THPMGRS. The depths listed on the side of the borehole image are in feet below land surface.

Sixteen joint and fracture sets (table 2) are present in the area based on field observations made for this project and additional data collected by Anderson and Raymond (unpublished, 2005). Joint and fracture sets trending N82°E, N46°E, N2°E, N51°W, and N69°W appear to be transmissive, as indicated by the distribution of known springs in the area. Four of these — the N82°E, N46°E, N2°E, and N51°W — dip steeply, 83°SE, 86°NW, 88°NW, and 87°NE, respectively and are unlikely to be the joint sets with which the ASU-1D fracture is associated, but the N82°E set is the closest in strike to the fracture in ASU-1D. The fifth set, the N69°W set, dips 36°SW, opposite the direction of dip of the ASU-1D well fracture.

An inferred fault exists a short distance north of the THGMRS, as marked by an extensive array of springs, extending to the east through Salt Rock Gap (fig. 4). The dip appears to be high-angle. The strike of this high-angle fault zone does not closely correspond with those of any of the 16 known joint sets in the area (see joint set explanation above and table 2), but appears to be approximately parallel to the strike of the fault represented by the mica schist-amphibolite contact encountered at depth in ASU-1D. The dip of the inferred E-W fault is undetermined, because the fault is not exposed within the mapping area; however, if topography accurately reflects the orientation, the dip should be steep (>70°) and to the South, which is opposite to that of the water producing fracture encountered in ASU-1D.

Table 2. List of joints measured in the THGMRS area, Watauga County, North Carolina.

J1	J2	J3	J4	J5
N5°E 71°NW	N74°W 84°SW	N65°W 73°SW	N47°E 85°NW	N45°E 25°NW
N1°W 81°SW	N73°W 78°SW	N55°W 81°SW	N45°E 79°NW	N33°E 13°NW
N5°E 84°NW	N69°W 76°SW	N64°W 90°SW	N40°E 87°NW	N28°E 12°NW
N11°E 80°NW	N87°W 66°SW	N65°W 69°SW	N58°E 71°NW	N32°E 20°NW
N1°E 72°NW		N49°W 80°SW	N46°E 89°SE	N50°E 34°NW
N6°W 80°SW		N50°W 65°SW	N40°E 75°SE	
N1°W 70°SW				
Mean=N2°E 88°NW	Mean=N76°W 76°SW	Mean=N58°W 76°SW	Mean=N46°E 86°NW	Mean=N38°E21°NW
J6	**J7**	**J8**	**J10**	**J11**
N9°E 40°SE	N5°E 30°NW	N63°E 63°SE	N10°E 54°SE	N89°W 17°SW
N12°E 34°SE	N10°E 40°NW	N67°E 57°SE		
N0°E 40°E		N54°E 65°SE		
Mean=N7°E 38°SE	Mean=N8°E 35°NW	Mean=N61°E 62°SE	Mean=N10°E 54°SE	Mean=N89°W 17°SW
J12	**J13**	**J14**	**J15**	**J16**
N73°E 85°SE	N70°W 34°SW	N45°W 80°NE	N23°W 76°NE	N55°E 45°NW
N85°E 88°SE	N68°W 39°SW	N62°W 79°NE	N11°W 78°NE	N49°E 44°NW
N90°E 64°S		N55°W 83°NE	N25°W 85°NE	
N82°E 90°SE		N46°W 88°SW	N16°W 87°NE	
N80°E 88°SE		N40°W 86°SW		
N85°E 83°SE		N56°W 86°SW		
N81°E 80°SE				
Mean=N82°E 83°SE	Mean=N69°W 36°SW	Mean=N51°W 87°NE	Mean=N19°W 81°NE	Mean=N52°E 44°NW

The local AMS rocks are folded at various scales that reflect multiple folding events. Observed folds are tight to isoclinal and upright to overturned. Meter-scale mesoscopic folding exposed near the former Potato Hill Lake and along the headwaters of Howard Creek, appears to be upright and tight to isoclinal. Folds with wavelengths and amplitudes at the centimeter scale observed throughout the hornblende schist and gneiss subunits are generally isoclinal to tight northwest-vergent recumbent to upright structures. Some centimeter-scale folds are southeast vergent. Folds of this scale are evident in amphibolite above the contact in the optical image of well ASU-1D (fig. 8). Stereographic analysis of data collected for this project suggests that most centimeter-scale folds that gently plunge about N11.5°E are crudely coaxial with the dominant folds that plunge 4° to S12°W (fig. 9). Attitudes of foliations and centimeter to meter scale folds along Howard Creek Road indicate a second, younger folding event that produced folds plunging approximately 50° to S38°E.

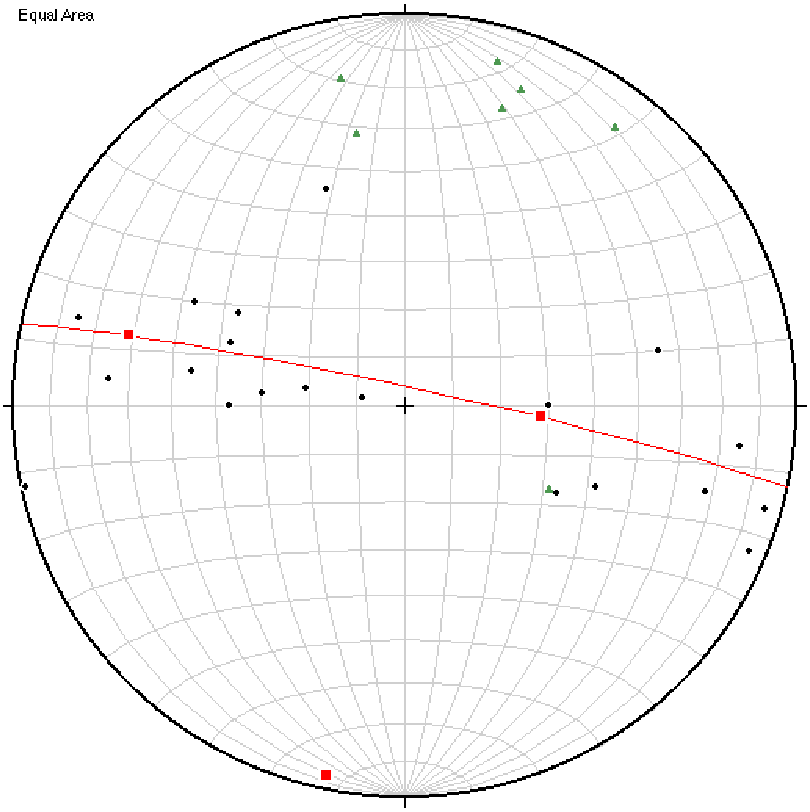

Figure 9. Stereogram showing orientation of foliations and folds in the THGMRS area, Watauga County, North Carolina. Black dots = poles to foliations. Green diamonds are plunges of lineations of mesoscopic folds. The red square in the southwest represents the computed axis of the major fold defined by foliations. The red girdle is the plane perpendicular to the major fold axis.

Borehole Geophysical Properties

Bedrock fractures were further characterized from borehole geophysical logs and optical televiewer (OTV) images. A high-resolution OTV log was collected from ASU-1D to identify lithology as well as to determine the orientation of foliations and fractures. As discussed in a previous section, the OTV image (fig. 10A) shows a fracture developed along the contact between amphibolite and mica schist at a depth of 258 feet (78.7 m) below land surface as an abrupt change in color. Based on the OTV image, the hydraulically-conductive fracture at the contact of two different rock units is interpreted to dip to the North at approximately 45°. The only joint set with a dip similar to this is J16, which has a dip of 44°NW and a strike of N52°E (table 2). No joint set of this dip has a strike that approaches approximately E-W and no single joint measured in nearby creek exposures had a similar attitude. The borehole geophysical logs in TH-1D vary from those of ASU-1D. Natural gamma values increase dramatically at about 290 feet (88.4 m) below land surface, and the fracture at this depth is not as significant in the caliper log (fig. 10B). Observations obtained during the well construction concur with these findings. For instance, a high yield of 60 gal/min (227 L/min) was estimated at the contact between amphibolite and mica schist in well ASU-1D during the well construction, while no water was found at the geologic contact found in well TH-1D.

Conventional borehole-geophysical logs including caliper and natural gamma logs were collected from ASU-1D to study geophysical properties of the rocks. The data show an abrupt and significant increase in natural gamma radiation at the depth of 258 feet (78.7 m) and below (fig. 10A). This increase corresponds with the large fracture (noted above) that was also detected by the caliper log at the same depth. In addition, EM-flowmeter logs were collected under hydraulically-stressed and ambient conditions from ASU-1D to determine the hydraulic properties of the fractures open to the borehole. There was not any borehole flow under ambient conditions, but upward flow at the pumping rate occurred above the large fracture at the depth of 258 feet (78.7 m), suggesting that this is the only hydraulically-conductive fracture in the borehole.

Dips of foliation planes observed in the monitoring well vary regularly from primarily northeast to the east, and to a lesser degree to the southeast with moderate dip angles of 35° to 45°, but dominantly near 45°E in the amphibolite unit and lower dip angles between 10° and 25° in the mica schist unit (fig. 10A). Only few amphibolite foliation attitudes vary substantially from the near 45° cluster. In contrast, foliation attitudes in amphibolite exposed on the surface vary widely, reflecting folding within the unit. The set of twenty attitudes measured in surface outcrops contained nine with dips within 35° to 60°, five greater than 60°, and six less than 25° (figure 9). Twelve of the twenty attitudes dip east (including SE and NE), as do all of those in ASU-1D, whereas eight dip west. Unlike the OTV record, which showed no dips to the northwest, six of the 20 attitudes measured in amphibolite on the surface dip to the northwest.

The well site for ASU-1D was selected on the basis of the intersection of two joint sets — N51°W (J14) and N82°E (J12) — thought to be hydraulically conductive on the basis of known well and spring sites. The fracture present in ASU-1D may represent a local deviation of J12 from its normal dip and strike and water may enter the observed fracture in the well from this or both of these fractures where they intersect nearby. Field measurements show that single joints can vary as much as 30° or more in dip and strike within approximately 30 feet along the fracture surface.

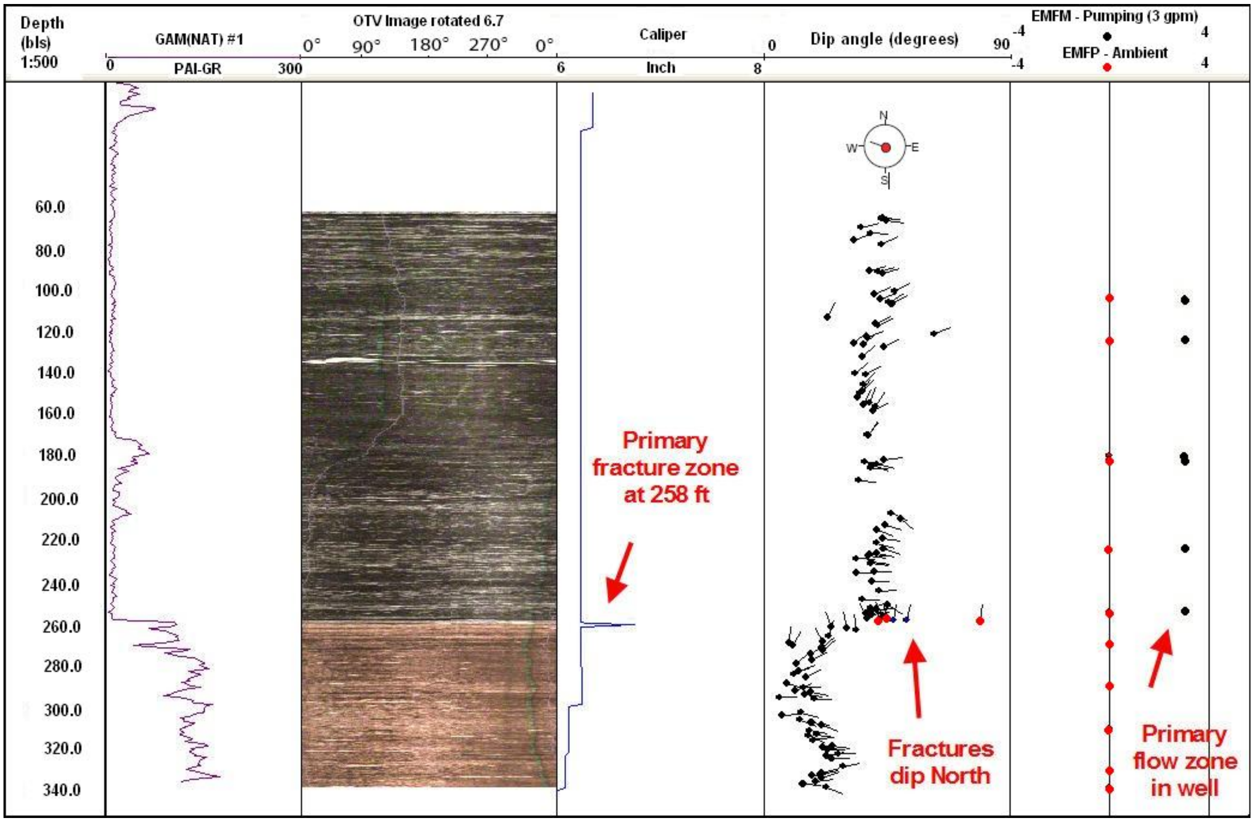

Figure 10A. Natural gamma, OTV image, caliper, tadpole, and EM-flowmeter logs from ASU-1D.

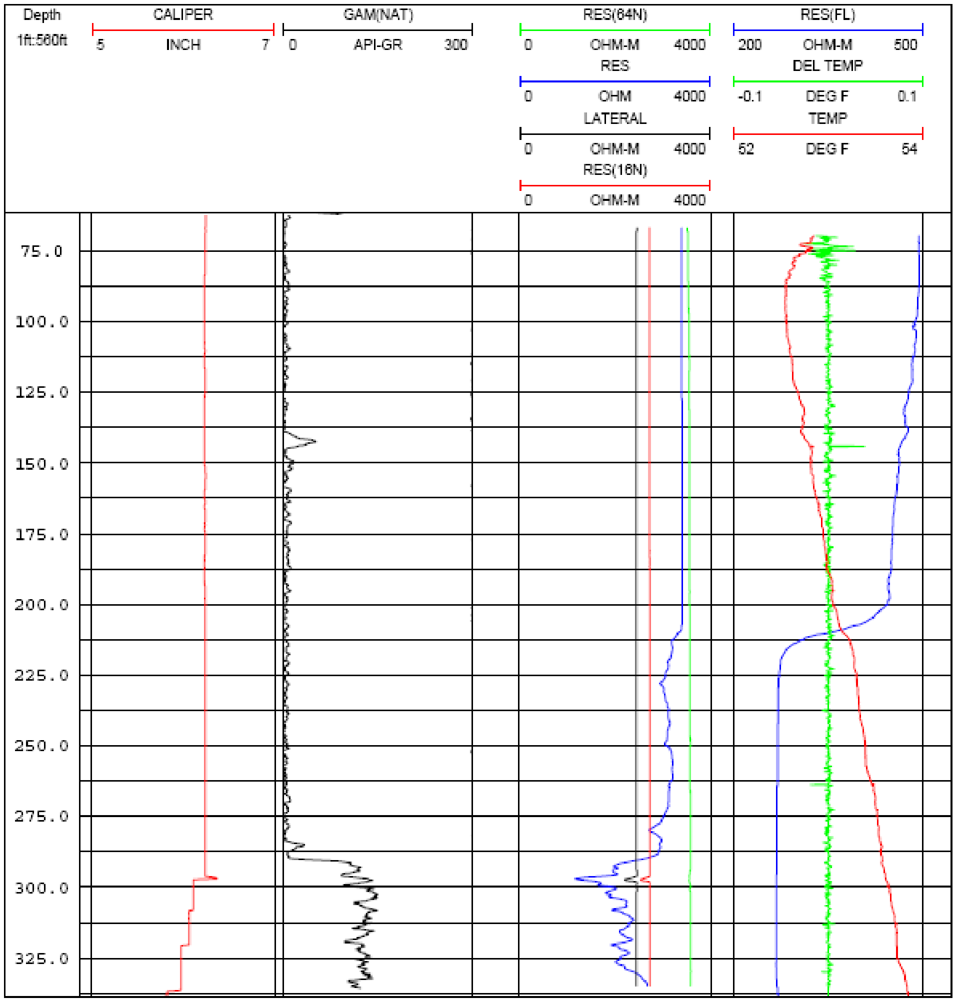

Figure 10B. Caliper, natural gamma, fluid resistivity, and temperature logs from TH-1D.

Hydraulic Properties

<u>Slug test results</u>

The results of slug tests indicate a hydraulic conductivity, *K*, of 0.5 ft/day (0.15 m/day) at ASU-1D, 0.02 ft/day (0.006 m/day) at TH-1D and 0.007 ft/day (0.002 m/day) at the transition zone well TH-1I. The hydraulic conductivity in TH-1D is 25 times lower than ASU-1D, but both fall within the range of hydraulic conductivity for fractured igneous-metamorphic rocks (Halford and Kuniansky, 2002). The hydraulic conductivity of the transition zone, however, is less than the minimum expected value of 0.05 ft/day (0.015 m/day), which could be due to poor well development, in addition to the nature of site conditions. The steeply dipping joints (table 2) present in the THGMRS area can strongly affect horizontal groundwater movement and may account for the extremely low hydraulic conductivity of the transition zone. The higher hydraulic conductivity in ASU-1D is expected, given the single fracture zone in well ASU-1D and its non-vertical northward dip of 45°.

Hydraulic connectivity between different zones and wells

To determine the presence of a hydraulic connection between ASU-1D and TH-1D, which are only 20 feet (6.1 m) apart, groundwater levels in ASU-1D were monitored when drilling TH-1D. Water levels in ASU-1D dropped more than one foot（fig. 11）as the drilling rig penetrated through the contact of two major rock units identified from the borehole geophysical logs (fig. 8).

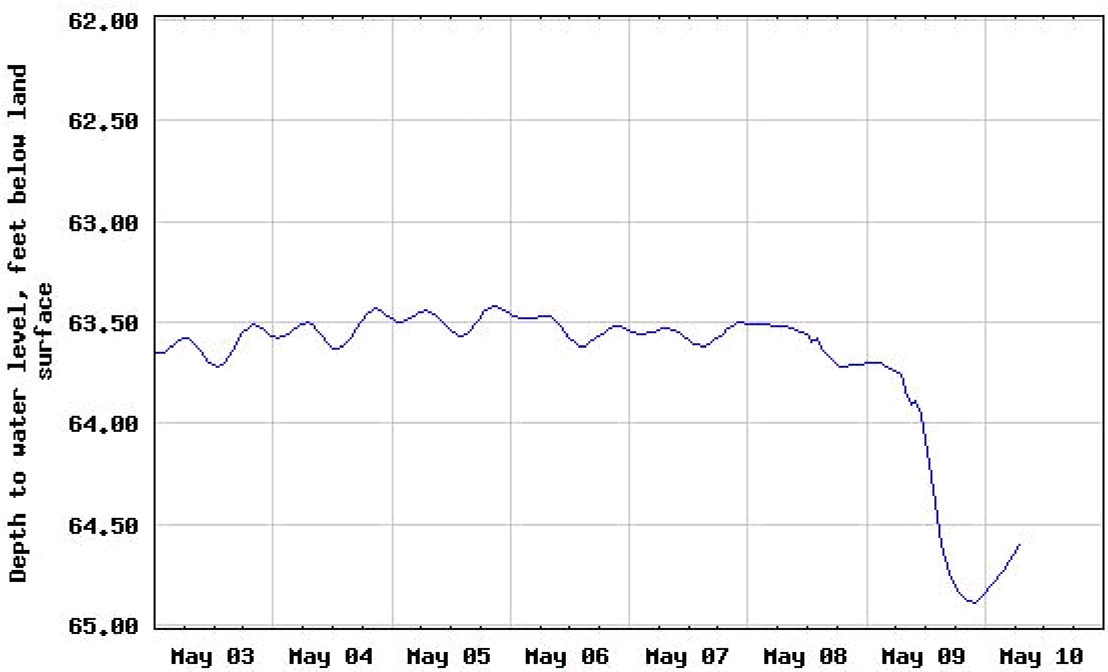

Figure 11. Water level change in ASU-1D during well construction of TH-1D at the THGMRS on May 9, 2007.

To further characterize the hydraulic connectivity among the three wells in the fractured bedrock aquifer system at the THGMRS, water levels were monitored in all three monitoring wells during well purging for sample collection. During several sampling events, hydraulic connection between two bedrock wells was observed; that is, pumping one bedrock well resulted in drawdown to the other, and vice versa. For example, on July 27, 2011, the water level in TH-1D dropped 4.4 feet (1.3 m) from 68.4 to 72.8 feet (20.9 – 22.2 m) below the measuring point during a 2-hour purge of ASU-1D at a rate of 2.5 gpm (9.5 Lpm). Drawdown in ASU-1D was 10.06 feet (3.1 m) at the end of purging. However, no drawdown was observed in the transition zone well, which may indicate no direct hydraulic connection between the transition zone and the producing zone or fracture in the bedrock well. The monitoring well responses to the purging are shown in Figure 12. If an assumption of steady drawdown is made at the end of the two-hour pumping event, a simple calculation using the Thiem Equation suggests that the aquifer transmissivity in the vicinity of the THGMRS is 373.5 ft^2/day (34.7 m^2/day). The borehole geophysical logging further suggests that this flow occurs in the single transmissive fracture at 258 feet (78.7 m) in depth. Also, assuming that the single fracture zone is approximately one foot in thickness (OTV image, fig. 10A), the hydraulic conductivity of the fracture zone approaches 373.5 ft/day (114 m/day), which is a very high value for discrete fracture zones.

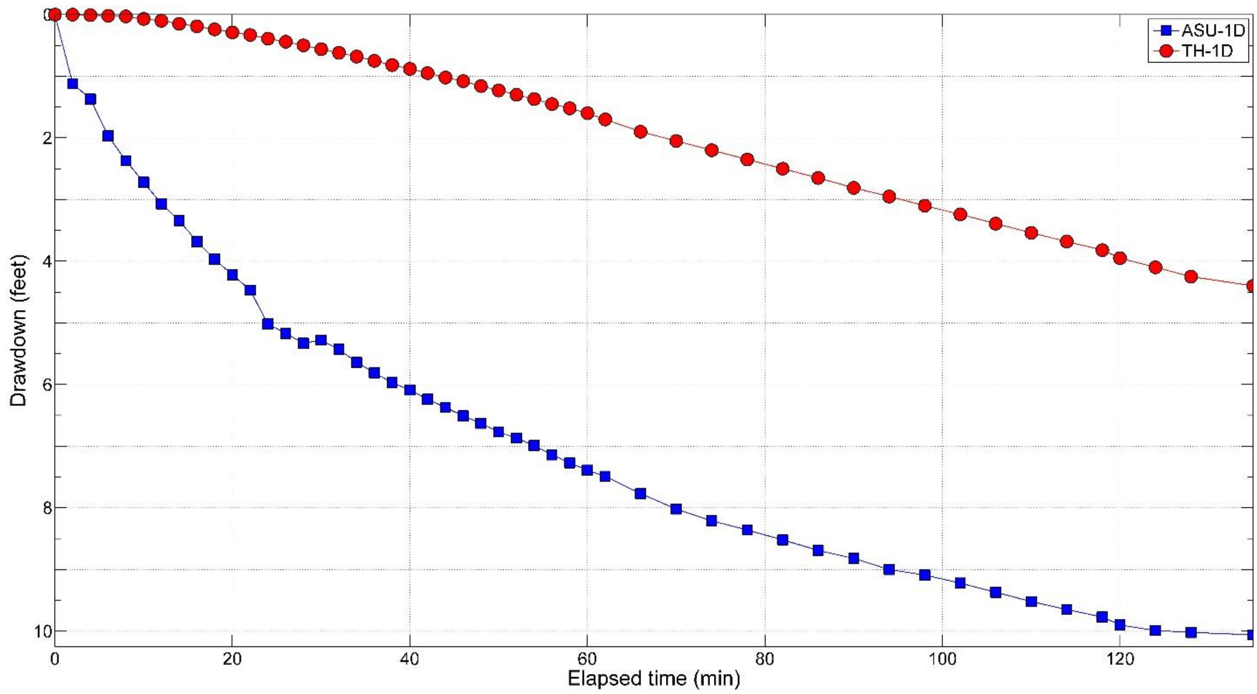

Figure 12. Water-level response of TH-1D to pumping from ASU-1D at the THGMRS.

It is unclear what structures facilitate the connectivity. No single, large fracture (joint) is evident that connects the two wells. A connection between the two wells may be provided by limited flow along the contact and the foliation.

Water Level and Temperature Data

Water Levels

Groundwater levels ranged between 27.5 to 31.5 feet (8.4-9.6 m) below the land surface (BLS) in the transition zone well and from 58 to 68 feet (17.7-20.7 m) BLS in the bedrock wells (fig. 13). Generally, groundwater levels fluctuated seasonally, declining during the summer and early fall when atmospheric conditions enhance evaporation and plants transpire substantial quantities of water, and then rising during the winter and early spring when trees are dormant each year. No decrease was observed over the monitored period in the transition zone well. Water levels in the bedrock wells were consistently lower but fluctuated in much wider ranges than in the transition zone well, and show a trend of slight decrease over the monitoring period (fig. 13).

Continuous groundwater levels were recorded with data-logging pressure transducers, most of the time on an hourly basis, in three THGMRS monitoring wells. Between March 2010 and March 2011, water-level data from the three monitoring wells were collected hourly; however, the datalogger in the transition zone well, TH-1I, failed to record water levels for two short periods during this one-year duration. The results (fig. 14) are consistent with the finding from the periodic manual measurements as shown in Figure 13. The range of groundwater fluctuation in TH-1I was within one foot (0.3 m) and there was not a significant decline in groundwater level during this period (fig. 14, upper panel). In the bedrock wells, however, groundwater levels showed a much larger range of fluctuation and more rapid variations, especially in monitoring well TH-1D, which

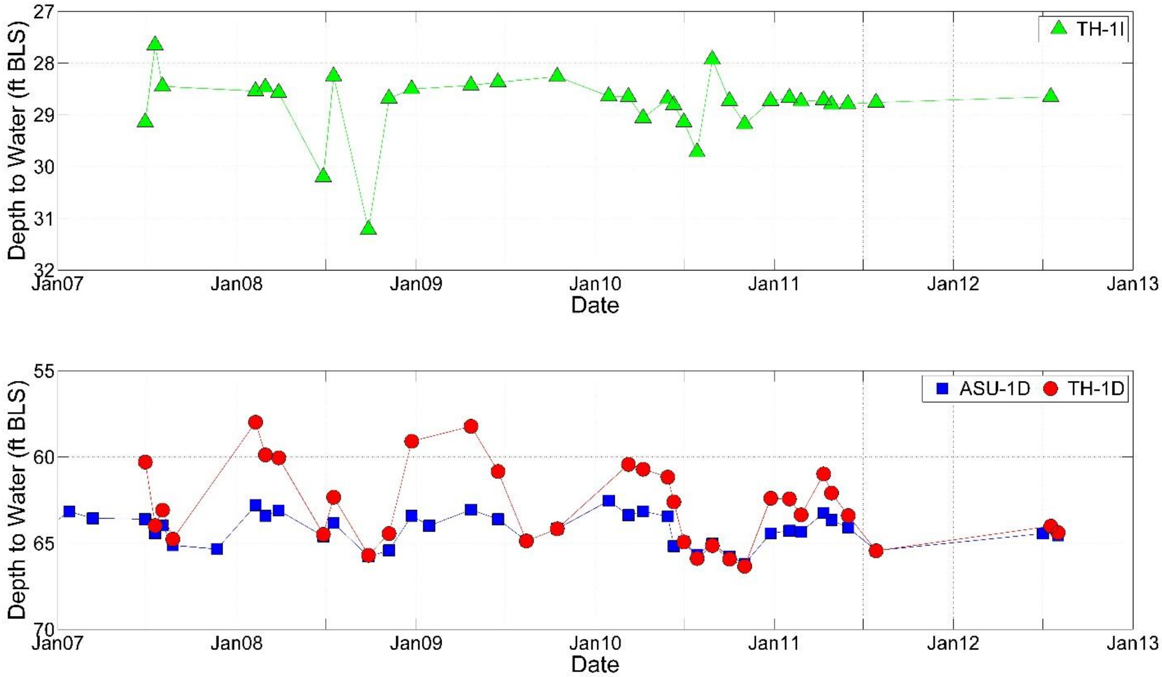

Figure 13. Periodic groundwater level data from TH-1I (upper panel) and ASU-1D and TH-1D (lower panel: ASU-1D, blue squares and TH-1D, red circles) at the THGMRS from June 2007 to July 2012.

varied by approximately 16 feet (4.9 m), as compared with monitoring well ASU-1D, which varied by approximately six feet (fig. 14, middle panel). The data also show that water levels in both bedrock wells were lower but less variable in summer and fall than in winter and early spring, which demonstrates the effects of evapotranspiration in the summer and early fall and high recharge rates in later fall through early spring in the following year. The inference of high recharge rates occurred from later fall through early spring is supported by continuous water level data collected from the headwaters of Howard Creek from October 2007 to February 2008 (fig. 14, lower panel). The stream stage increased several inches during the monitored period, which was directly affected by precipitation and the runoff from land surface during each precipitation event.

Unlike the trends indicated by the data collected from monitoring well TH-1I, the bedrock water-level data show the effects of wet (2010) and dry (2011 late winter-early spring) conditions on recharge rates. Wet winter-spring conditions in 2010 promoted higher recharge rates, thus raising water levels in the bedrock monitoring wells to their highest levels of the measurement period. This is most prominently displayed in monitoring well TH-1D, which peaked at levels shallower than 51 feet (15.5 m) BLS. Although monitoring well ASU-1D displayed less fluctuation, it still was affected by the wetter conditions in 2010, when water levels were shallower than 62 feet (18.9 m) BLS. The effects of the wet and dry conditions on water level changes in bedrock wells also may be interpreted as responses to water level changes in the regional stream network, because at the THGMRS, there is no water in the shallow regolith zone and little connection between the transition well and the two bedrock wells.

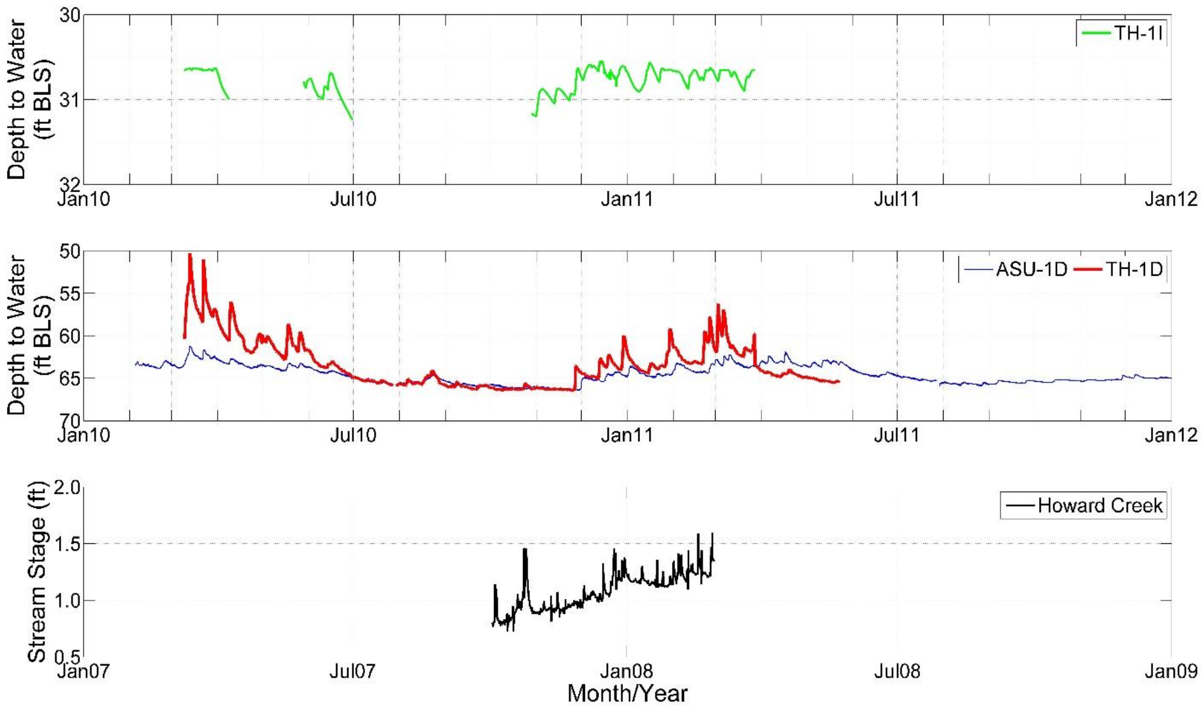

Figure 14. Continuous groundwater level data from TH-1I (upper panel), ASU-1D and TH-1D (middle panel – ASU-1D, thin blue line and TH-1D, thick red line) and Howard Creek (lower panel) at the THGMRS. Stream stage was measured from the surface of water to the streambed directly below the point measured.

Water level data collected from ASU-1D between 2005 and 2012 are shown in Figure 15. A few interesting features of the dataset are immediately apparent. First, wet conditions between the installation of the well and the winter of 2007 kept groundwater levels at their highest values. 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 winter highs. This is consistent with the drought-like conditions that have affected North Carolina for much of the past five years. The effect of the dry winter in 2011-12 resulted in a significantly depressed water level hydrograph in the upper panel of the figure, during which time water levels did not rise above 64.5 feet (19.7 m) BMP. Equipment failure in August 2012 has temporarily halted further water-level data collection.

Another property of the water-level dataset from ASU-1D is the effect that earth tides have on short-term water-level fluctuations. A single hydraulically-conductive fracture supplies water to this monitoring well. The coherence of the bedrock bounding this fracture enables the earth tide influence to vary the fracture's aperture; thus, water levels fluctuate at the same periodicity as would a coastal monitoring well. The middle panel of Figure 15 shows this effect during June 2010. While the temporally-varying influence of recharge events is present in the plot, twice-daily oscillations in the hydrograph are evident. The fact that the amplitude of the oscillations varies suggests that not only is the well tidal, but it also displays spring and neap tidal variations in amplitude. The lower panel of Figure 15 applies a filter to the data in the middle panel by subtracting a 12-hour centered-in-time moving average from each data point, thereby giving groundwater oscillations about a mean of approximately zero. As is evident in the plot, not only do the data show tidal periodicity, but they also show much larger spring tide amplitudes of nearly 0.10 feet (3 cm) than neap tide amplitudes

(0.03 feet/0.9 cm). This property exists throughout the entire seven years of data for ASU-1D. Analysis of the groundwater-level data in the other wells suggests that those wells, especially monitoring well TH-1D, also show tidal effects. The upper panel of Figure 16 shows the same dataset as is in Figure 15. The middle panel of this figure shows data from June 2010 for TH-1D. While not showing amplitudes as high as ASU-1D, TH-1D still displays spring and neap variations. The dataset from TH-1I (lower panel) is much noisier; although the signal is two orders of magnitude smaller than in the other two wells, there are clearly two peaks per day in the signal.

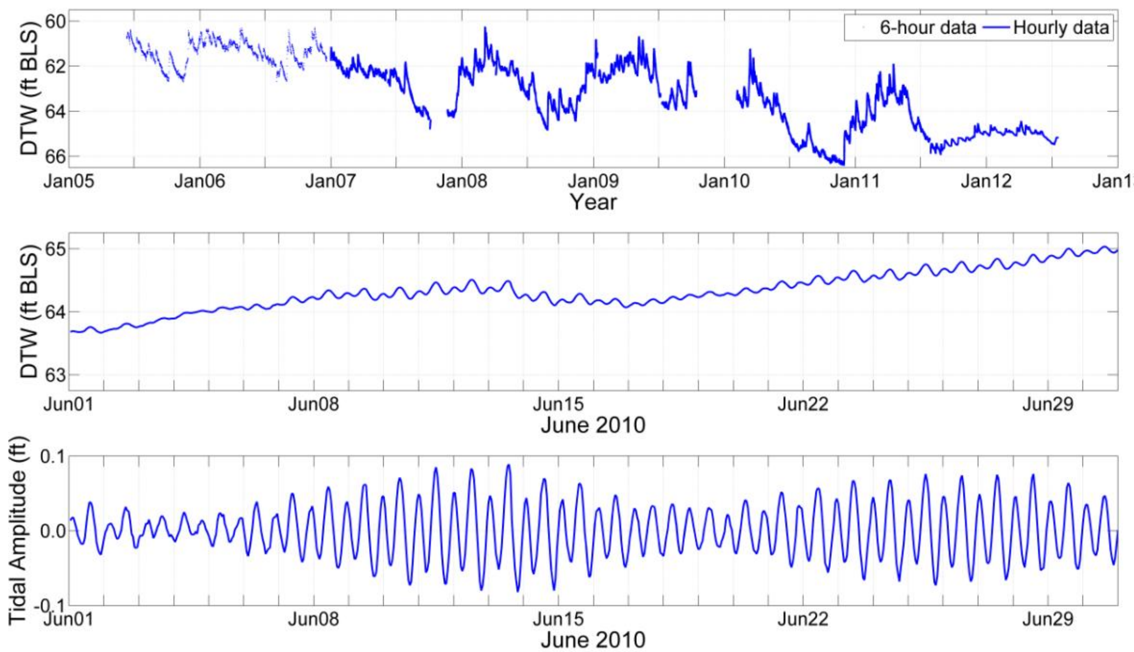

Figure 15. Continuous groundwater level data from ASU-1D at the THGMRS. Upper panel: Groundwater levels from June 2005 to July 2012 (data were collected every six hours from June 2005 through December 2006; the rest were hourly). Middle panel: Detail of water-level data from June 2010, showing the tidal signal superimposed upon the temporal trend of rising water levels. Lower panel: Filtered data over the same time window in which 12-hour centered-in-time averages were subtracted from water levels, showing the spring and neap earth tide signals in the groundwater signal.

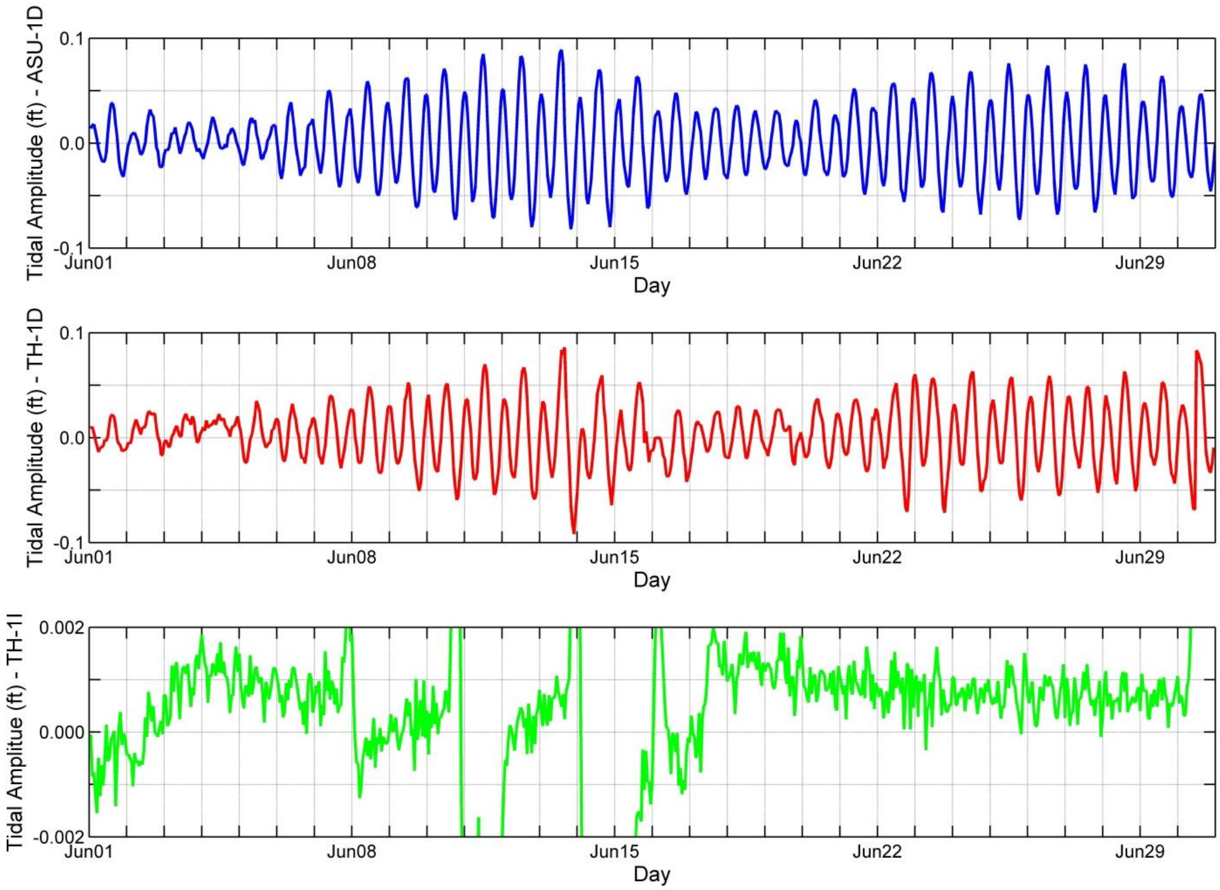

Figure 16. Continuous groundwater level data from the THGMRS during June 2010. Upper panel: Groundwater levels in ASU-1D, as shown in Figure 15, showing the spring (centered on 13 June and 26 June) and neap (centered on 04 June) earth tide signals in the groundwater signal. Middle panel: Groundwater levels in TH-1D showing filtered tidal signal. Lower panel: Filtered data from TH-1I showing the potential tidal nature of this well.

Water temperatures

Groundwater temperatures, as measured in the monitoring wells, are shown in Figure 17. Temperatures in the two bedrock wells, ASU-1D (upper panel) and TH-1D (middle panel), do not fluctuate diurnally, suggesting that there is minimal high-frequency thermal input to the aquifer. In addition, neither well displays lagged seasonality, such as would be expected in most groundwater conditions. This probably indicates that groundwater flow paths to the wells are considerably long. Groundwater temperatures in both bedrock wells show a temporally decreasing trend. It should be noted that this temperature decline correlates with temporally decreasing groundwater levels (fig. 13, lower panel, and fig. 14, middle panel), so it may indicate a gradual deepening of the source water to the wells. Groundwater temperatures in the transition-zone well, TH-1I (fig. 17, lower panel), lag seasonal variations in atmospheric temperatures by about 6 six months, which is expected given the insulating effects of the approximately 30 foot (9.1 m) thickness of the overlying material. The small dips (small and frequent fluctuations) in water temperature data graphs are more likely indicative of the level of accuracy of the temperature sensors.

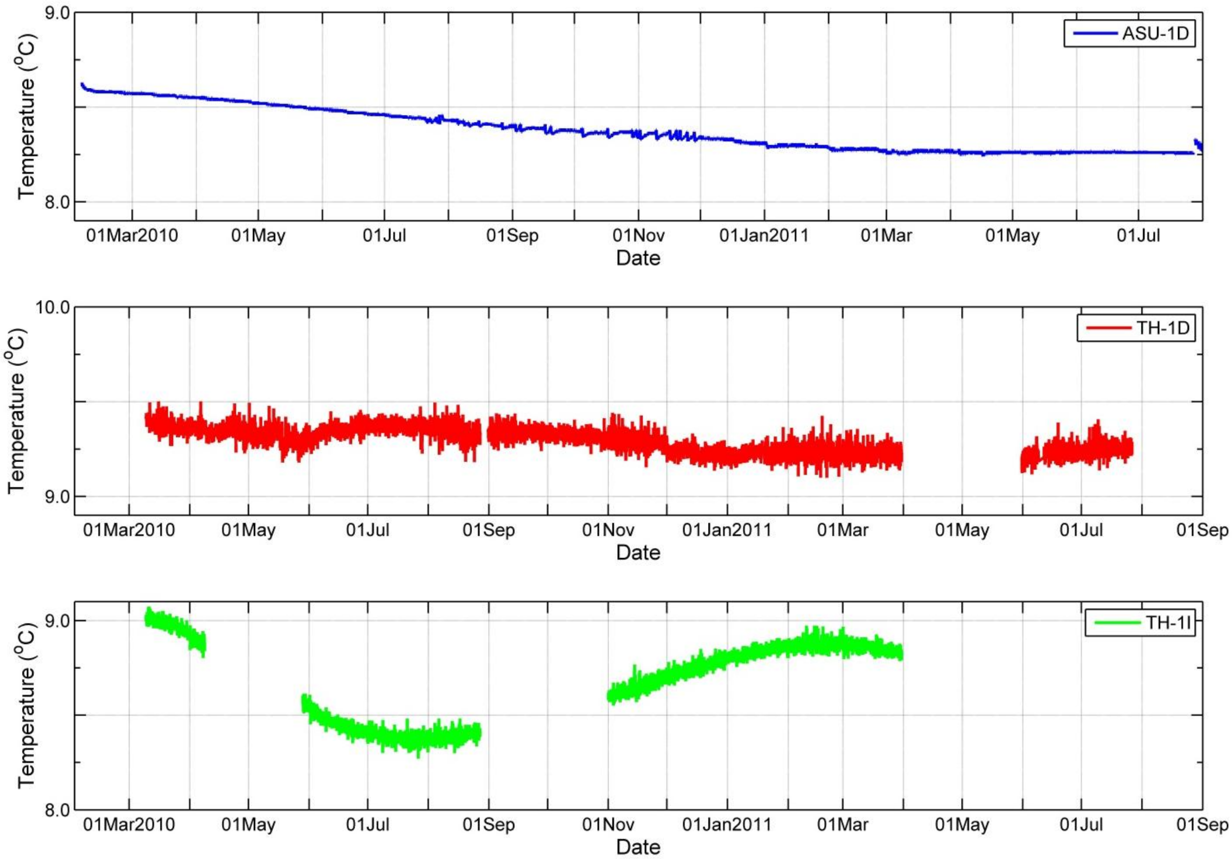

Figure 17. Groundwater temperatures at the THGMRS from February 2010 through July 2011. Upper panel: Groundwater temperatures in ASU-1D. Middle panel: Groundwater temperatures in TH-1D. Lower panel: Groundwater temperatures in TH-1I. An In-Situ Level Logger was used in AUS-1D, while YSI Level Scout sensors were used in TH-1I and TH-1D to collect data.

Figure 18 compares groundwater temperatures in ASU-1D with surface-water temperatures as measured in the adjacent Howard Creek located approximately 150 feet (45.7) away. As is evident in the upper panel, stream temperatures in Howard Creek show long time-scale seasonal fluctuations as well as diurnal oscillations in response to air temperature fluctuations. Noteworthy in this panel, and the other two panels of this figure, is the near-constant temperature of the groundwater in ASU-1D. This suggests again a relatively long travel path to intersection with the monitoring well, so that there has been enough time for the groundwater to equilibrate with mean annual air temperatures. The middle panel shows a larger-scale plot of August 2006 temperatures. Diurnal oscillations in stream temperatures are obvious, as is the fact that mean stream temperatures are much higher than deep groundwater temperatures. The opposite is the case in the lower panel, which shows a month of temperatures during November 2006. By November, stream temperatures have cooled in response to the decline in air temperature. Groundwater, however, is insulated from seasonal effects and continues at approximately the same temperature as during the summer.

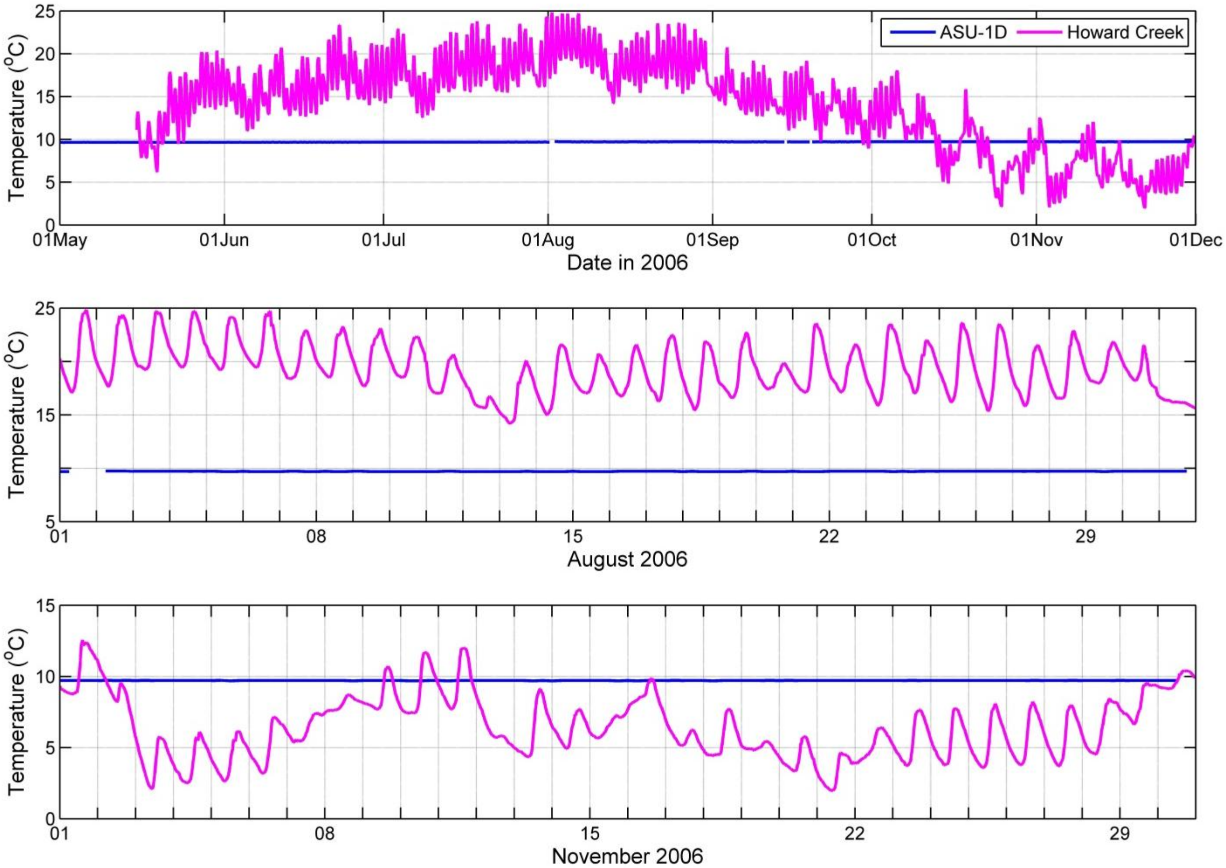

Figure 18. Comparison of stream and groundwater temperatures at the THGMRS. Upper panel: Groundwater temperatures in ASU-1D (blue line) show no change, especially when compared with stream temperatures (magenta line). Middle panel: August 2006 temperatures measured in Howard Creek show diurnal oscillations and values typical of warm summer conditions, while groundwater temperatures remain below 10°C, likely reflecting mean air temperatures. Lower panel: November 2006 temperatures measured in Howard Creek are lower than the groundwater temperatures that remain at mean air temperature.

WATER QUALITY

Water quality in each component of the aquifer system at the THGMRS was characterized by periodic field measurements of pH, specific conductance (SC), water temperature (WT), and dissolved oxygen (DO) and sample collection for laboratory analyses. From 2007 to 2012, water-quality samples were collected from the three THGMRS monitoring wells and Howard Creek eight times to characterize groundwater chemistry at the site (Note: the results from July 2012 sampling event are not discussed in this report, but presented in the compiled table, Appendix 1). The specific objectives of the sampling were to (1) study the quality of groundwater associated with the amphibolite and mica schist units of AMS, (2) determine the "water type" or groundwater geochemistry within these types of rock and the differences in water quality among different components of the groundwater flow system, (3) compare the results to the quality of regional groundwater, (4) evaluate seasonal changes in water quality over the monitored period, and (5) determine the presence or absence of naturally occurring and anthropogenic contaminants at the THGMRS.

Water temperature, pH, DO, and SC were measured in the field during each sampling event before samples were collected for laboratory analyses. Laboratory analytes including major ions (calcium, magnesium, potassium, sodium, bicarbonate, carbonate, chloride, sulfate, and fluoride), metals (silver, aluminum, arsenic, barium, cadmium, chromium, copper, iron, lead, manganese, selenium, nickel, and zinc), nutrients (ammonia, nitrate + nitrite, and phosphorus), and alkalinity were tested in each of seven sampling events. Dissolved metals, turbidity, suspended residue, color, total dissolved solids, specific conductance, and total organic carbon were sampled four or five out of the seven sampling events. Mercury and volatile organics were sampled twice. Fecal coliform, cyanide, semivolatile organics, herbicides, pesticides, and dissolved radon were sampled only once. The analytical data are compiled and presented in Appendix 1. Sampling results from the first two years are also available at http://portal.ncdenr.org/web/wq/aps/gwp/groundwater-monitoring. In addition to the sampling by DWR, on October 2, 2007, USGS personnel also collected water samples from the two bedrock wells (TH-1D and ASU-1D) and analyzed for major ions, nutrients, and trace metals. These results are provided in Appendix 2.

Analytical Results

Field parameters

Water temperature, pH, and DO are important parameters that define and affect the chemical state of waters. Because groundwater recharge to transition-zone well TH-1I was very slow and the quantity of water available was not enough for field measurements, these four field parameters were only measured once for this well.

The data collected from this study show that variations or ranges of WT and DO in the adjacent surface water (the headwaters of Howard Creek) are wider to much wider than in groundwater, probably due to direct and instantaneous atmospheric influence (fig. 19, upper left panel). Much higher DO levels were measured in TH-1D than in ASU-1D although these two bedrock wells, only 20 feet (6.1 m) apart, were constructed to almost the same depth. The difference in DO in these two bedrock wells suggests that their recharge sources and flow paths could be different (Briel, 1997). pH measurements from the THGMRS are within the range of North Carolina groundwater quality standards. Overall, the highest pH value was measured in ASU-1D, the lowest in TH-1D, and almost neutral in Howard Creek (fig.19, lower right panel).

Specific conductance 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. It is an indirect measure of the presence of dissolved ions such as Cl^-, NO_3^-, HCO_3^-, SO_4^{2-}, PO_4^{3+}, Na^+, Ca^{2+}, Fe^{2+}, in addition to others. Factors that control 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 water. SC sometimes can be used as an indicator of water pollution. The results from this study show that the concentration of SC was generally low at THGMRS, but high values of SC were measured in the transition zone well TH-1I (fig. 19, lower left panel). It should be noted that only one sample was collected from this well.

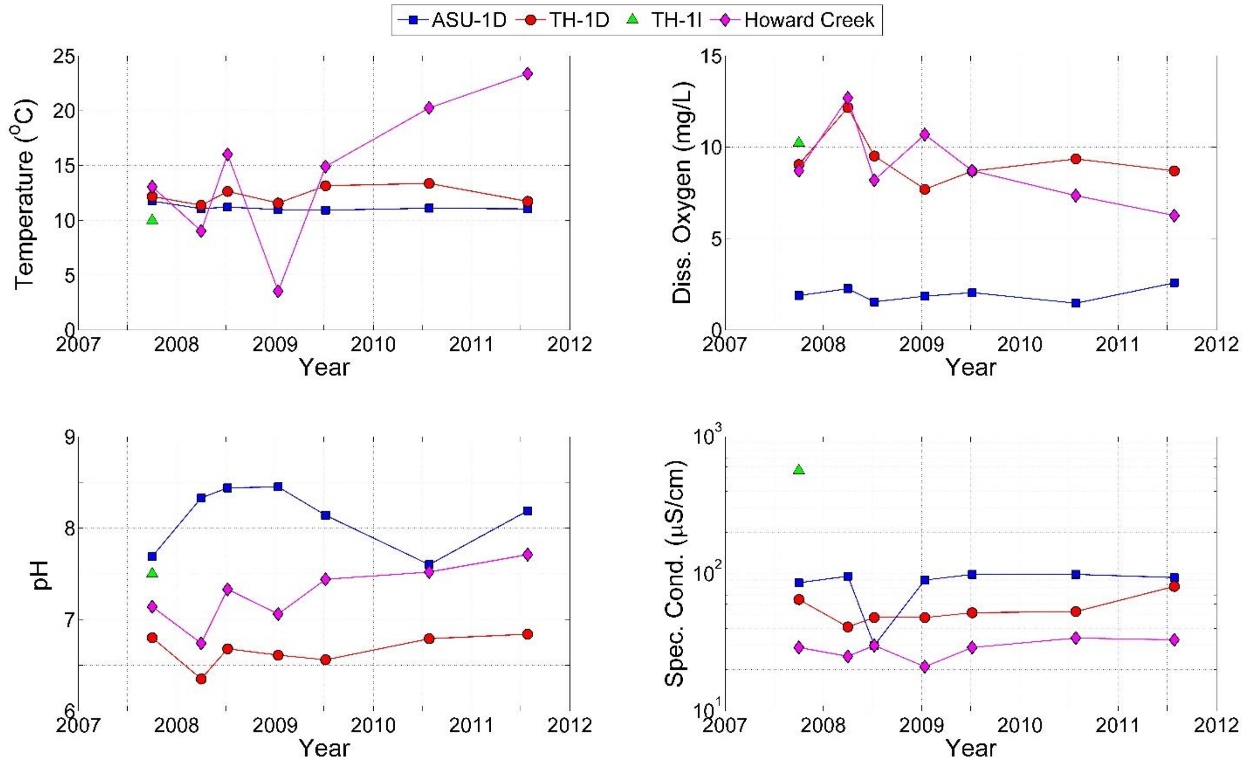

Figure 19. Results of water-quality sampling at the THGMRS site: Temperature (upper left panel), dissolved oxygen (upper right panel), pH (lower left panel), and specific conductance (lower right panel). Note that water quality was sampled only one time from the TH-1I monitoring well due to low flow conditions.

Alkalinity, TDS, SR, SC, TOC and color

Alkalinity, total dissolved solids (TDS), suspended residue (SR), turbidity, specific conductance (SC), total organic carbon (TOC), and color were analyzed in the laboratory. Table 3 shows the median concentrations of these parameters measured from the THGMRS.

Alkalinity is the buffering capacity of a water body or aquifer. Without this buffering capacity, any acid added to a body of water would immediately change its pH (Addy and others, 2004); thus, it measures the ability of waters to neutralize acids or bases, thereby enabling it to maintain a fairly stable pH. Alkalinity is reported as mg/L of $CaCO_3$ and is measured as the amount of acid needed to bring the water sample to a certain level of pH. Alkalinity is not the same as pH because water does not have to be strongly basic (high pH) to have high alkalinity. The alkalinity of samples collected from the station varied with the highest measured in the transition zone well. Relatively low alkalinity levels were reported in the bedrock wells and the lowest level was measured in Howard Creek (Table 3). Based on the EPA's Classification of lakes and ponds based on alkalinity as measured in terms of calcium carbonate ($CaCO_3$), the headwaters of Howard Creek at the THGMRS is a sensitive to highly-sensitive stream.

Total dissolved solids is the residue left behind after a given volume of water has been evaporated and dried at a given temperature. It has the same pattern as SC because both are controlled by the dissolved minerals or ions in the water sample. Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates. Water with high levels of suspended particulates looks cloudy and has a high turbidity value. Natural turbidity in groundwater generally is less than 5 turbidity units (Anderson, 2005). 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 the water. The color of natural water usually results from leaching of organic debris, but can also be from iron and manganese leaching.

High levels of SR in the water samples were most likely caused as water in the well or stream was disturbed during the sampling process. Because only a limited volume of water was in well TH-1I and the recovery rate of the well was extremely slow, the well was purged to dry conditions. When the well was purged until it was completely emptied, sediments at the bottom of the well were disturbed; thus, both SR and turbidity were high in TH-1I. This was not the case for the two bedrock wells. TDS, SR, Turbidity, and SC were also measured at higher levels in TH-1I than in the two bedrock wells and Howard Creek. In addition, elevated TOC and color were measured in the transition zone well, but these values were normal in the other samples (Table 3).

Table 3. Median concentrations of selected water quality parameters at the THGMRS.

Field Sample ID	Alkalinity to pH 4.5 (mg/L)	TDS (mg/L)	SR (mg/L)	Turbidity (NTU)	SC (µS/cm)	TOC (mg/L)	PT Color (c.u.)
TH-1D	20	35	<6.2	2.50	50	<2	<5
ASU-1D	36	66	<6.2	<1	94	<2	<5
TH-1I	290	404	389	500	445	9	26
Howard Creek	11	30	14	8.2	29	2.9	28
NCAC 15A 2L Standards		500					15

Fecal coliform

Fecal coliform was not detected in any well samples at the THGMRS, but was detected at a low level (19 colonies/100 ml) in the Howard Creek sample. The presence of fecal contamination in streams is not uncommon. Fecal coliform is a specific subgroup of the total coliform bacteria. Its presence in the creek indicates contamination from human or animal waste or by pathogens or disease-producing bacteria or viruses that can exist in human or animal wastes.

Major ions

The quality, types of chemical constituents, and other properties of groundwater are the result of aquifer minerals and processes that take place in 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 to study the water type or geochemical signature of the groundwater flow system. The median concentrations of these ions are shown in Table 4. To this end, a Piper diagram (fig. 20) was plotted with the results.

Table 4. Median concentrations of major ionic compositions (mg/L) at the THGMRS.

Sample ID	Bicarbonate, HCO_3^-	Carbonate, CO_3^{2-}	Chloride, Cl^-	Sulfate, SO_4^{2-}	Calcium, Ca^{2+}	Potassium, K^+	Magnesium, Mg^{2+}	Sodium, Na^+
ASU-1D	36	<1	0.5	9.2	13.5	1.20	1.80	4.40
TH-1D	18	<1	1.1	3.9	7.0	0.45	1.40	1.35
TH-1I	290	<1	3.5	46.5	77.0	3.20	22.00	61.00
Howard Creek	11	<1	1.2	0	2.9	0.36	1.45	1.15

As shown in the table and Figure 20, the distribution of ions in the diagram indicates that the anionic composition is dominated by HCO_3^- in all groundwater samples and Howard Creek. The cationic composition is dominated by Ca^{2+} in bedrock wells, while, Na^+ and Mg^{2+} are proportionately high in the transition zone well. In the Howard Creek sample, there is no dominant cation but a mix of Ca^{2+}, Mg^{2+}, Na^+, and K^+. Therefore, the groundwater in the fractured bedrock aquifer is classified as calcium/bicarbonate-type water, while water in the transition zone is calcium mixed with sodium and magnesium/bicarbonate-type water. The stream water is similar in composition to the transition-zone water, but ionic concentrations in the stream water are much lower. This groundwater geochemical property is more clearly revealed by a Stiff diagram (fig. 21). The Stiff diagram also shows that much higher ionic concentraions were measured in the transition zone well, TH-1I.

The water types described above appear to be consistent with the lithology found at the THGMRS. Calcium is the principal cation in the water samples. The source of dissolved calcium is the dissolution of calcium-bearing minerals such as plagioclase feldspar, amphibole, epidote, and garnet from rocks of the AMS at the site. The main rock unit identified at the THGMRS is amphibolite that contains significant amounts of plagioclase feldspar, amphibole, and garnet. The geochemistry of Howard Creek is more influenced by atmospheric conditions and surface runoff than is the groundwater which has had a long time to react with the rock units.

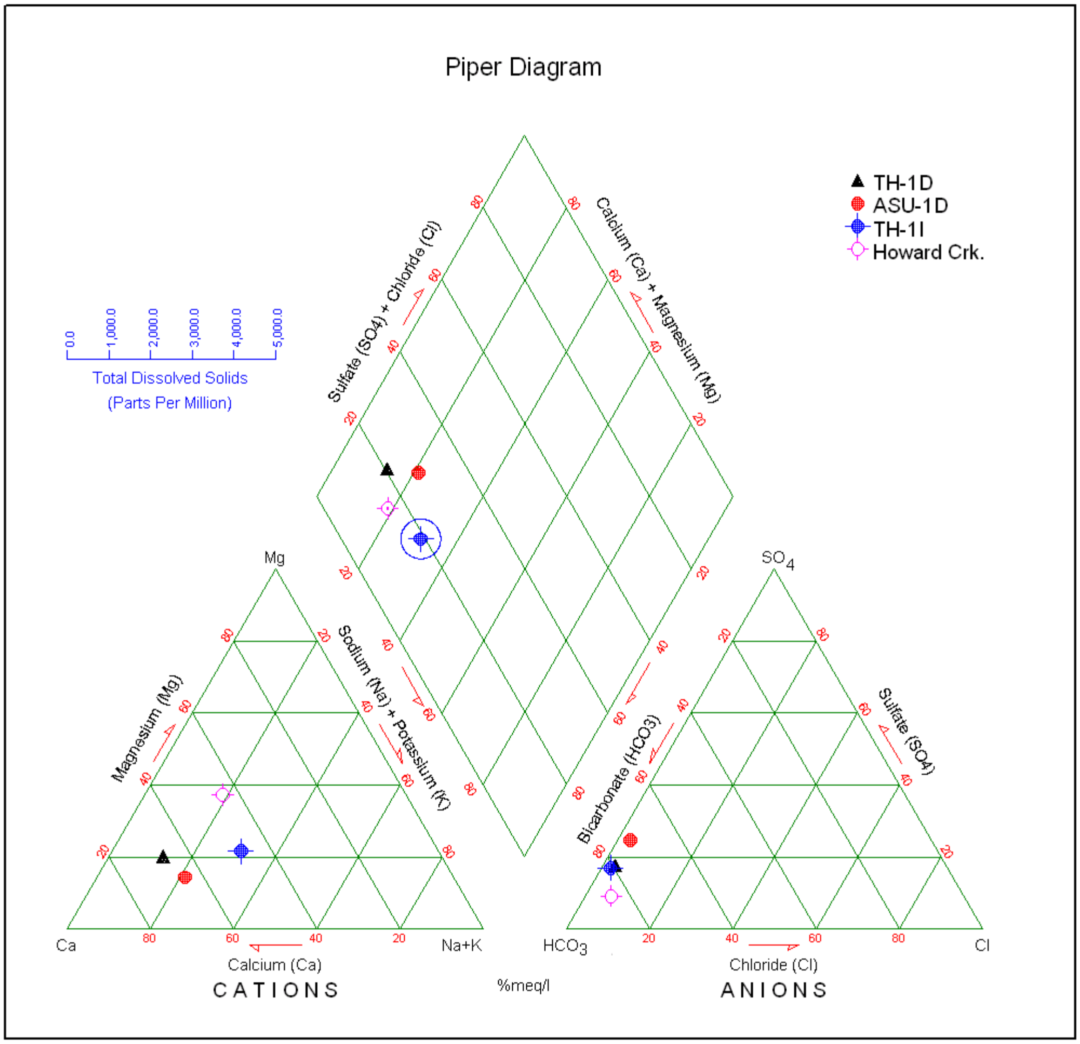

Figure 20. Piper diagram showing the geochemistry of water samples from monitoring wells and Howard Creek at the THGMRS.

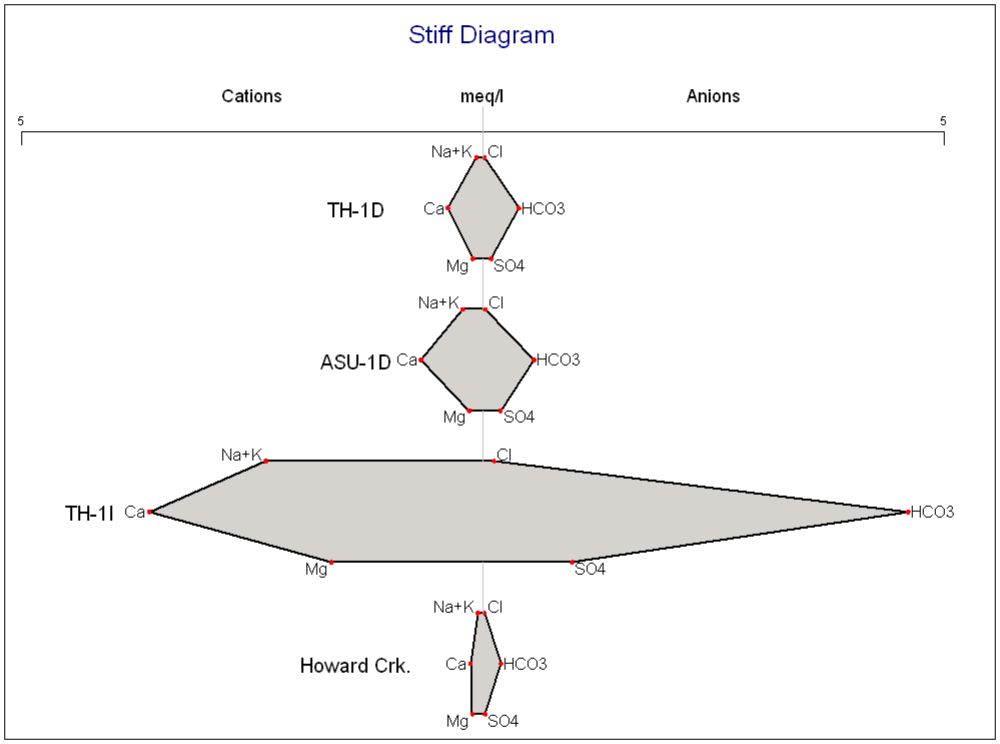

Figure 21. Stiff diagram showing major ion milliequivalents in water samples collected from monitoring wells and Howard Creek at the THGMRS.

In addition to the major ions used to determine the water type, fluoride and silica were also analyzed. Dissolved silica is derived from weathering and decomposition of mineral silicates. Its concentration varies generally from 1 to 30 mg/L, but can be up to more than 100 mg/L naturally in groundwater (Hem, 1985). Silica was detected at concentrations within its normal natural range at THGMRS. 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). Fluoride was not detected in any samples collected from the THGMRS.

<u>Trace metals</u>

Trace metal analytes 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), mercury (Hg), selenium (Se), and zinc (Zn). Both dissolved (filtered) and total concentrations (unfiltered) were analyzed to determine if these metals were associated with suspended solids. The analytical results are compiled and presented in Appendix 1. Because the North Carolina groundwater quality standards (15A NCAC 2L, also referred to as 2L) pertain to total recoverable (unfiltered) constituent concentrations, discussions and comparisons made in this report focus primarily on the total recoverable constituent concentrations.

Aluminum (Al) was detected in groundwater samples collected from TH-1D, TH-1I and Howard Creek, but levels were elevated only in TH-1I and the creek. No Al was detected in samples collected from ASU-1D. Cu and Zn were detected in both TH-1I and Howard Creek, but concentrations were below 2L standards or North Carolina’s fresh surface-water quality standards for Class C waters (15A NCAC 2B). Cu and Zn were not detected in bedrock wells. Neither Fe nor Mn was detected in ASU-1D, but low levels of Fe and Mn were detected in TH-1D. Both Fe and Mn were detected in TH-1I at concentrations exceeding the 2L standards, which is more likely affected by high turbidity of the water samples because no dissolved Fe was detected at the laboratory detection limit. Dissolved phase of Mn was detected in this well at concentrations exceeding the standard, but the concentrations were much lower than its total recoverable constituent concentrations. Iron exceeding 15A NCAC 2B was also detected in Howard Creek. Ba, Cr, and Ni were detected in TH-1I at concentrations below the 2L standards, but not detected in groundwater samples from the bedrock wells.

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 unless pH is very low (Bain and Thomas, 1966). Fe is also very common in many rocks, especially those containing high percentages of ferromagnesian minerals, as is the case at THGMRS, and it is soluble in groundwater when pH is low. Analytical results from this site are consistent with these characteristics and show high levels of suspended Fe and Al in the shallow transition zone well, and both suspended and dissolved Fe and Al in Howard Creek.

Although Fe and Mn are not uncommon in the Piedmont and Mountains groundwater, data from bedrock wells ASU-1D and TH-1D show that neither Fe nor Mn was elevated in the bedrock aquifer within the mafic gneiss hydrogeologic unit. The geochemical behavior of Mn in water is similar to that of Fe, although it is much less abundant in rocks and its concentration in groundwater is generally lower than Fe. Mn does substitute for iron in notable amounts in ferromagnesian minerals, such as hornblende and biotite. Therefore, elevated Fe and Mn may occur together in groundwater. Ag, As, Cd, Pb, Hg, and Se were not detected in any form in any samples, including surface water samples, from October 2007 and July 2011.

In addition to the trace metals discussed above, the USGS also sampled the two bedrock wells for laboratory analysis of antinomy, beryllium, boron, cobalt, and molybdenum. All metal elements USGS sampled were detected above laboratory detection limits, but below 2L or EPA standards (Appendix 2).

<u>Nutrients</u>

Nutrients including ammonia (as nitrogen, N), nitrate and nitrite (as N), and phosphorus (as P) were sampled in this study. Ammonia was not detected in ASU-1D and TH-1D, but low levels (<0.02 – 0.46 mg/L) were detected in TH-1I and Howard Creek. Nitrate and nitrite were detected at typical levels in all monitoring wells and Howard Creek, with concentrations ranging from <0.02 to 0.30 mg/L. Nitrate is highly-soluble and mobile in groundwater and it is the final oxidation product of nitrogenous organic materials, while nitrite is an intermediate in the oxidation process and rapidly converts to nitrate in the subsurface. Therefore, the value of nitrate and nitrite together should be nearly equal to nitrate. The 2L standard for nitrate is 10 mg/L. Very low levels (<0.02 - 0.8 mg/L) of phosphorous were detected in water samples from the THGMRS. The highest level was detected in TH-1I. The nutrients detected in the bedrock wells more reflect their ambient conditions.

Cyanide, volatile and semivolatile organics, herbicides, and pesticides

To measure ambient groundwater quality and evaluate potential anthropogenic impacts, samples were also collected for cyanide, volatile and semivolatile organic compounds, herbicides, and pesticides. As expected, these parameters were essentially absent from all samples collected in this study (Appendix 1). With the exception of a very low level of one volatile organic compound (toluene at 0.18 µg/L) and three semivolatile organic compounds at insignificant levels in TH-1I, no volatile or semivolatile organic compounds were detected. Herbicide compounds were absent in all samples, and only one pesticide compound (4-nitropheno at 1µg/L in the stream sample) was detected during this study.

Dissolved radon and uranium

Naturally occurring radionuclide contaminants, radon and uranium, were sampled once at the THGMRS. Radon (Rn^{222}) is a chemically inert and radioactive gas that is an intermediate product of the decay of U^{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 (Campbell, 2008). Dissolved radon was detected in TH-1D and ASU-1D at concentrations of 90 and 1120 pCi/L, respectively. The EPA proposed a maximum contaminant level (MCL) of 300 pCi/L and an alternate MCL of 4000 pCi/L[2] for radon in drinking water (Federal Register, 1999). Radon is a known human carcinogen and presents a potential health risk to well owners exposed via ingestion and, to a much greater degree, inhalation of gassing. Uranium was detected at 0.07µg/L and 0.25µg/L in bedrock wells TH-1D and ASU-1D, respectively. These levels are well below the 2L or EPA drinking water standard of 30 µg/L for uranium. TH-1I was not sampled for radon or uranium because there was not enough water to be sampled.

Changes in Groundwater Quality with Season

No significant seasonal variations in water quality were observed at the THGMRS from October 2007 to July 2011(figs. 19 & 22). Specific conductance and total dissolved solids measured in bedrock well ASU-1D appear to be lower in winter than in other seasons. To determine whether this could be a trend, additional seasonal sampling should be conducted. This change could also be due to variations in the depth of the pump placed during different sampling events.

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[2]The alternate standard applies to suppliers who also have an indoor radon mitigation program in place; neither standard has been enacted to date.

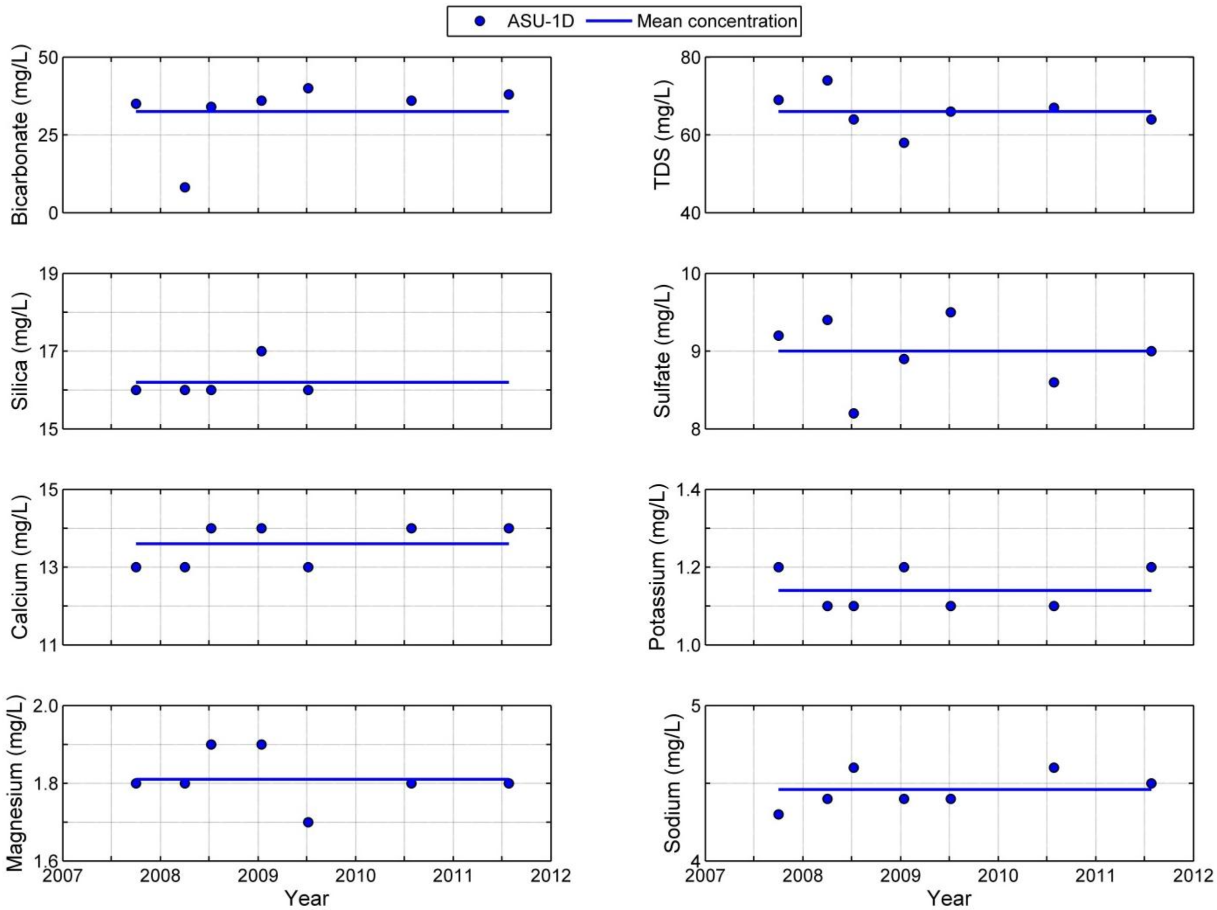

Figure 22. Analytical results for selected parameters measured from 2007 to 2011 in bedrock well ASU-1D at the THGMRS. Samples were collected in July 2007, April and October 2008, January and July 2009, July 2010, and July 2011.

Changes in Groundwater Quality with Groundwater Level Fluctuation

Continuous (hourly) water-level and specific conductivity data from bedrock well ASU-1D show that the specific conductivity of groundwater increased in winter and spring when water levels rose and decreased in summer and fall when water levels dropped (fig. 23). This suggests that recharge had at least some effect on groundwater quality. Concentrations of other constituents or parameters sampled in this study do not show any obvious relationship with groundwater level changes.

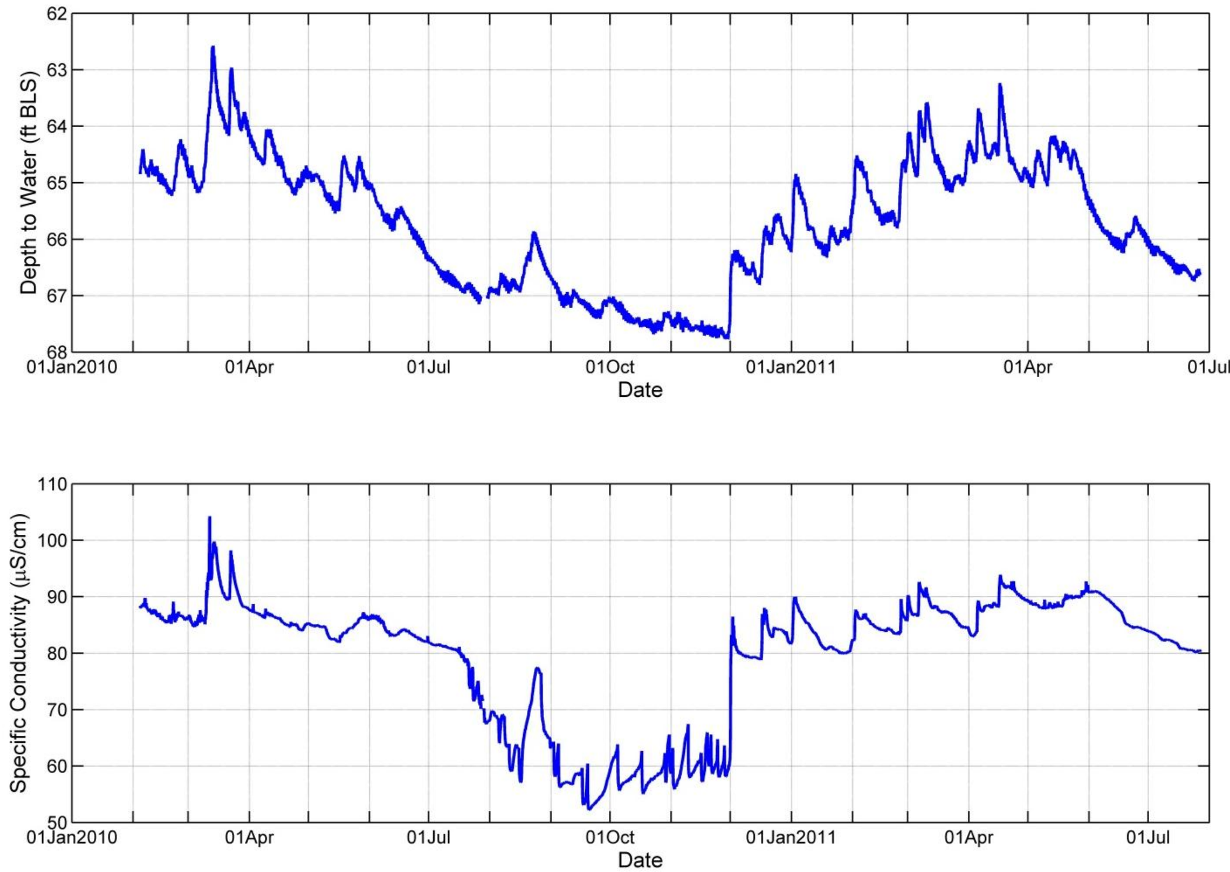

Figure 23. Groundwater level (upper panel) and specific conductivity (lower panel) in ASU-1D at the THGMRS from February 2010 through July 2011.

Comparisons of Water Quality among Different Flow Components

Groundwater in bedrock at THGMRS is calcium/bicarbonate-type water, while the transition zone is of calcium-sodium-magnesium/bicarbonate-type. The stream water is more similar in composition to the transition-zone water, although the stream water contains low ionic concentrations. Much higher ionic concentrations were measured in the transition zone well than in the bedrock wells and the creek (table 4 and fig. 21).

Another notable difference in the water quality among the three different components of the THGMRS flow system is that total recoverable concentrations of iron (Fe) and manganese (Mn) were higher in Howard Creek and much higher in the transition zone well than in the two bedrock wells. In addition, dissolved Fe was measured in Howard Creek, and dissolved Mn was measured in both Howard Creek and the transition zone well; however, neither dissolved Fe nor dissolved Mn was detected in the bedrock wells (table 5). This distribution pattern suggests that Fe and Mn present in soil and regolith at shallow depth as a result of mineral weathering provided the source of Fe and Mn that dissolved in Howard Creek and the transition zone, or these two elements were eroded and deposited as sediment with the subsequent potential for dissolution. As redox potential and soil pH are favorable (low), Fe and Mn leach from soil and rock, and mobilize to the surface water and shallow groundwater (Nadaska and others, 2012). However, since they are redox sensitive elements, their solubility and mobility will be reduced and limited once they move into groundwater in which dissolved oxygen is high and pH is almost neutral. In addition, the solubility of Fe is generally lower than that of Mn, therefore no dissolved Fe was detected in the groundwater, while dissolved Mn was detected in groundwater, but limited within the shallow zone only.

Other parameters or constituents were also higher in the transition zone well than in the bedrock wells, including specific conductance, turbidity, suspended residue, dissolved solids, total organic carbon, aluminum, and barium (tables 3 and 5). The greater mineralization in the transition zone over that of the bedrock flow system is probably attributed to two factors: (1) the transition zone is more weathered so that the minerals would release from the rock to the water more easily than from the competent bedrock and (2) the length of time that groundwater is in contact with minerals is longer. As discussed earlier in this report, the groundwater hydraulic conductivity obtained from the transition zone well was more than 70 times lower than that in the bedrock well ASU-1D. Furthermore, no connectivity between the transition zone well and the bedrock wells was observed during the limited pumping test conducted at the site. High turbidity of the water in the transition zone well is probably another reason for the high total recoverable metals.

Table 5. Median concentrations of aluminum, barium, copper, iron, and manganese at the THGMRS

Flow Components	**Field Sample ID**	**Aluminum (Al, µg/l)**	**Diss. Aluminum (Al, µg/l)**	**Barium (Ba, µg/l)**	**Diss. Barium (Ba, µg/l)**	**Copper (Cu, µg/l)**
Bedrock	TH-1D	100	<50	<10	<10	4.1
	ASU-1D	<50	<50	<10	<10	<2
Transition Zone	HT-1I	18000	<50	72	9	330
Surface water	Howard Creek	500	51	<10	<10	<2
NCAC 15A 2L Standards				2000		1000
NCAC 15A 2B Standards						7
Flow Components	**Field Sample ID**	**Diss. Copper (Cu, µg/l)**	**Iron (Fe, µg/l)**	**Diss. Iron (Fe, µg/l)**	**Manganese (Mn, µg/l)**	**Diss. Manganese (Mn, µg/l)**
Bedrock	TH-1D	2.7	77	<50	<10	<10
	ASU-1D	<2	<50	<50	<10	<10
Transition Zone	HT-1I	20	**12500**	<50	**530**	**84**
Surface water	Howard Creek	<2	**1800**	310	73	38
NCAC 15A 2L Standards			300		50	
NCAC 15A 2B Standards			1000			

Comparisons with Water Quality Standards

Water-quality conditions at the station were also compared to 15A NCAC 2L groundwater standards and EPA drinking water standards (Appendix 1). The comparison shows a high quality of groundwater from bedrock: good pH values, extremely low levels of nutrients, undetectable total organic carbon and fecal coliform, absence of volatile and semi-volatile organics, pesticides, and herbicides. No exceedances of the 2L groundwater standards or EPA drinking water standards were found in the bedrock aquifer, which reflects ambient conditions with no noticeable influence from local land use. In the transition zone, however, iron and manganese were detected at concentrations exceeding the standards. Iron was also detected in the Howard Creek samples at concentrations exceeding North Carolina's fresh surface-water quality standards for Class C waters (table 5). No other targeted parameters were detected in the creek above the North Carolina standards. An average radon concentration of 605 pCi/L was detected in the two bedrock wells at the THGMRS, which is above the EPA MCL (300 pCi/L) but well below the alternative MCL (4000 pCi/L) set for drinking water provided by community water systems .

Comparisons with Regional Groundwater Quality Data

Groundwater in the mafic gneiss bedrock flow system at the THGMRS is a calcium/bicarbonate-type water (fig. 20), which is very similar to the results from Bent Creek Research Station and Allison Woods Research Station, two PMGREP studies conducted within the Blue Ridge geologic belt and the Inner Piedmont geologic belt, respectively. Furthermore, there were no significant differences in overall ionic chemistry when comparing the THGMRS to all of the other PMGREP groundwater monitoring stations located in different geologic belts or hydrogeologic units (fig. 24). Bicarbonate is the dominant anion for most of stations, and calcium is the dominant cation, but more often mixed primarily with sodium and/or magnesium; therefore, the basic ionic compositions of most groundwater samples from the other PMGREP stations are considered either a calcium-sodium/bicarbonate or a calcium-magnesium/bicarbonate water type (Harden and others, 2009). Based on Briel's study (1997) of Piedmont (13,498 wells) and Blue Ridge (776 wells) physiographic provinces of the Eastern U.S., the dominant geochemical type of Blue Ridge groundwater is a mixed water type containing calcium-magnesium/bicarbonate and sodium/chloride.

In Harden and other's study, at some of PMGREP stations, notable changes occurred in the anionic composition of the groundwater in response to anthropogenic effects, such as nutrient inputs from local land use that increased groundwater nitrate concentrations (Harden and others, 2009). This is not the case at the THGMRS.

Although the vertical head gradient is downward at the THGMRS, groundwater chemistry suggests that the bedrock flow system may be recharged by a source other than the transition zone. For example, ionic concentrations were significantly higher in the transition zone than in the bedrock flow system, a finding that runs counter to conditions at other PMGREP groundwater monitoring stations. Concentrations of specific conductance, total dissolved solids, and some trace metals also suggest that the transition zone is not the only or primary source of recharge to the bedrock flow system, probably because of the lack of transmissive fractures. Rather, it seems likely that the bedrock wells are connected horizontally over long distances through shallow-dipping fracture(s). Furthermore, there was no water in the shallow regolith zone and very little water in the transition zone at the THGMRS. The general concept of groundwater flow in the Piedmont and Mountains of North Carolina (precipitation → recharge → shallow regolith → transition zone → bedrock) does not appear to fit the observations at the THGMRS. The data from THGMRS suggest a behavior different from the generalized flowpath and conceptualized three components of the regolith-fractured crystalline bedrock aquifer system model established for the Piedmont and Mountains region of North Carolina (LeGrand, 2004; Daniel and Harned, 1998). This behavior was also found in a couple of mid-slope well clusters at other PMGREP stations, such as 2I, a mid-slope well cluster at the Allison Woods Research Station (Abraham, writing communication, 2013) and N3, a mid-slope well cluster at the Upper Piedmont Research Station. Therefore, the applicability of the conceptualized model perhaps needs to be further evaluated, especially, for using it in the high-country area of the Blue Ridge Mountains of North Carolina.

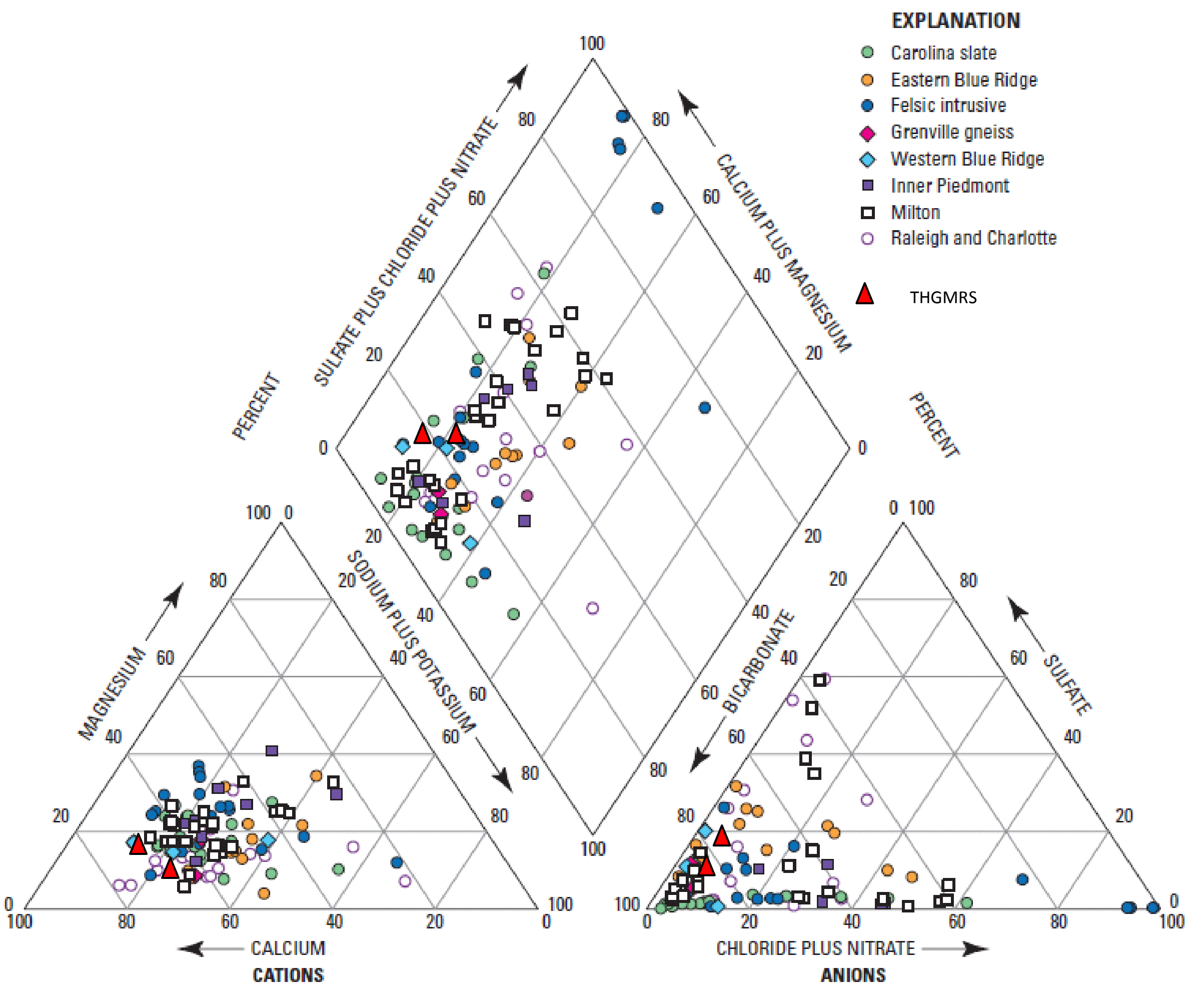

Figure 24. Piper diagram showing comparison of bedrock groundwater ionic composition from the THGMRS to ionic composition of groundwater samples from eight geozones in the Piedmont and Blue Ridge Provinces of North Carolina (from Harden and others, 2009).

It is also noted that the specific conductivity of groundwater in the fractured bedrock aquifer at the THGMRS area is fairly low (median value = 91.5 µS/cm at 25 degrees Celsius). It is similar to what was found at the Allison Woods Research Station (median value = 86 µS/cm) within the Inner Piedmont geologic belt, but it is much lower than the average (220.84 µS/cm) of medium values from eight PMGREP stations and 48 National Water-Quality Assessment Program wells across the North Carolina Piedmont and Blue Ridge region (Harden and others, 2009). The low specific conductivity values generally indicate low total dissolved solids and dissolved metals.

The most common exceedances of 2L water quality standards in bedrock wells at the other PMGREP stations are pH, manganese, iron, and zinc; however, none of these constituents exceeded 2L in the bedrock aquifer at the THGMRS. Dissolved iron and manganese were not even detected in its bedrock wells. Like other PMGREP sites, naturally occurring radon exceeded the EPA proposed standard. The highest level of radon was detected in one of the bedrock wells at a concentration of 1120 pCi/L, which is below the median of 1560 pCi/L from 87 private wells in ten counties in the region (Campbell, 2008).

SUMMARY AND CONCLUSIONS

The Tater Hill Groundwater Monitoring and Research Station (THGMRS) is one of the eleven groundwater monitoring stations installed by the North Carolina Division of Water Resources (DWR) in cooperation with USGS to evaluate groundwater availability, flow, and quality in the Piedmont-Mountains of North Carolina. The station lies in the headwaters of Howard Creek, a classified trout stream, within the New River Watershed in Watauga County, North Carolina. The area is rugged and forested, which is typical of the Blue Ridge Physiographic Province. This terrain was subjected to multiple events of folding and faulting, as the rock units were highly deformed and metamorphosed through its billion-year history. Geologically, the THGMRS is underlain predominately by an amphibolite unit of the Ashe Metamorphic Suite within a thrust sheet above the Gossan Lead Fault in the northeastern Blue Ridge geologic belt of North Carolina.

The drawdown that occurred during groundwater sampling revealed that the two bedrock wells are hydraulically connected. Application of the steady-state Thiem equation to the maximum drawdown in the two wells suggests that the transmissivity and hydraulic conductivity of the single, approximately one-foot (0.3 m) thick fracture zone supplying water to the well ASU-1D are 373.5 ft^2/day (34.7 m^2/day) and 373.5 ft/day (114 m/day), respectively. The transition zone has little water, and there is no water in the shallow regolith. The range of fluctuation of water level in the transition zone well has been smaller than that in two bedrock wells. Although a downward vertical head gradient was measured between the transition zone well and the bedrock wells, it appears that the bedrock aquifer was not recharged from the transition zone directly above, but perhaps through shallow-dipping fractures connecting regional fractures that draw water from shallow regolith or surface waters. The reservoir-pipeline conceptual model (Daniel and Dahlen, 2002) and the three-component conceptual model (regolith saturated zone, transition zone, and fractured bedrock) generalized for the regolith-fractured bedrock groundwater system in the Piedmont and Blue Ridge (Harned and Daniel, 1992) do not appear to fit the observations made from the THGMRS area well. These generalized models describe the shallow regolith saturated zone as a reservoir providing water to the transition zone and bedrock through seepage and fractures. The transition zone at the THGMRS, however, has a very low permeability and no or limited transmissive fractures, which seems to limit its ability to conduct water to the bedrock system**.** Water in the transition zone appears to seep out through the stream bank and discharge to the stream due to the steep landform. Regional flow systems dominated by highly-permeable fracture zones may better describe the groundwater flow in the THGMRS and other areas in the Blue Ridge Mountains of North Carolina. In addition, the groundwater quality data collected from the station indicate that the groundwater in the transition-zone contained higher TDS and SC compared to bedrock water. This appears to contradict with findings from most of other stations in the Piedmont and Mountains region, where groundwater in the bedrock contains higher ionic concentrations.

Periodic and continuous water-level data show that the water level in the transition zone well was at least 30 feet (6.1 m) higher than water levels in the bedrock wells. The water levels in the monitoring wells fluctuated periodically, but there was not a significant decline over the monitored period. The range of groundwater fluctuation was greater in the bedrock wells than in the transition zone well. The largest fluctuation (16 ft/4.9 m) was measured in TH-1D. In the bedrock wells, water levels were higher in winter and spring than in summer and early fall, reflecting higher recharge rates in the late winter and early spring and lower recharge due to evapotranspiration during the summer and early fall. Water levels were deeper in TH-1D than in ASU-1D during the summer, but the opposite in winter, indicating that TH-1D is more affected by evapotranspiration during the growing season and received more recharge from precipitation in winter and early spring. It also suggests that there is a higher storage component in the fracture at ASU-1D than at TH-1D. The groundwater temperature data indicate that groundwater temperatures lag seasonal air temperature by about six months in the transition zone due to the insulating effects of the overlying material. Groundwater temperatures in the bedrock wells did not show any effects of seasonal oscillations because of an extremely long flow path for recharge water, in addition to the insulating effect of overlying material.

Groundwater from the bedrock flow system at the THGMRS is of calcium-bicarbonate type, and the surface water and transition zone groundwater are of calcium-sodium/magnesium-bicarbonate type. When compared with North Carolina groundwater standards and EPA drinking water standards, the bedrock groundwater from the THGMRS area is of high quality and consistent over the monitored period with little seasonal change. No exceedances of North Carolina groundwater or EPA drinking water standards were found in the bedrock wells during this five-year study. The level of naturally-occurring radon was below the median level found in the Piedmont and Blue Ridge Mountains region of North Carolina, but somewhat above the proposed EPA standard. Unlike other sites in the region, the transition zone well has a much lower hydraulic conductivity and yield, and much higher concentrations of aluminum, barium, iron, manganese, specific conductance, and total dissolved solids than the bedrock wells at the THGMRS. Elevated iron and manganese were detected in the transition zone well, and elevated iron was also detected in the headwater of Howard Creek.

Interpretations in the study are based on limited wells and therefore, additional data are needed to confirm some of the observations noted in this study.

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APPENDIXES

Appendix 1. Compiled THGMRS water quality data, Watauga County, North Carolina

Appendix 2. THGMRS groundwater quality data sampled and analyzed by USGS