Evaluation of Spring Discharge for Characterization of Groundwater Flow in Fractured Rock Aquifers: A Case Study from the Blue Ridge Province, VA

W. Miles Gentry

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Thomas J. Burbey (Chair)

Madeline Schreiber

John A. Hole

Virginia Polytechnic Institute and State University,

Blacksburg, VA

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Abstract

Recent models of groundwater flow in the Blue Ridge Province suggest multiple aquifers and flow paths may be responsible for springs and seeps appearing throughout the region. Deep confined aquifers and shallow variably confined aquifers may contribute water to spring outlets, resulting in vastly different water quality and suitability for potable water supplies and stock watering. A new Low Flow Recording System (LoFRS) was developed to measure the discharge of these springs that are so ubiquitous throughout the Blue Ridge Province.

Analysis of spring discharge, combined with electrical resistivity surveying, aquifer tests, and water chemistry data reveal mixed shallow and deep aquifer sources for some springs, while other springs and artesian wells are sourced only in the deep aquifer. The technique is suitable for rapid characterization of flow paths leading to spring outlets. Rapid characterization is important for evaluation of potential water quality problems arising from contamination of shallow and deep aquifers, and for evaluation of water resource susceptibility to drought. The spring discharge technique is also suitable for use in other locations where fractured rock and crystalline rock aquifers are common.

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Background

Low discharge springs with flow of less than seven gallons per minute are ubiquitous in the Blue Ridge Province of Virginia. Many have served and continue to serve as the sole source of potable water for stock watering and residential use at many sites. Table 1 shows drinking water sources for the two counties containing the study areas in this investigation (Floyd and Grayson) and a reference urban/suburban county (Warren) near Washington, D.C. These data categorize residential water supplies as public (more than five homes connected to a single source such as a well or public water main), individual drilled or dug well; and other, which includes springs, creeks, cisterns, rivers, and lakes (United States Census Bureau, 1990). In Floyd and Grayson counties a large percentage of water supplies are classified as "Other Source" the counties also have few rivers and lakes suggesting that springs are important source of water in these rural counties.

	Public	**Drilled Well**	**Dug Well**	**Other Source**	**Total**
County					
Floyd	8.01%	54.59%	4.34%	33.06%	100.00%
Grayson	12.59%	54.91%	4.18%	28.32%	100.00%
Warren	48.69%	44.36%	2.22%	4.72%	100.00%

Table 1 - Water Sources for Floyd, Grayson and Warren Counties, Virginia. Data from U.S. Census Bureau, 1990.

A recent drought in the southeastern United States has focused attention on water resources in the Blue Ridge and Piedmont physiographic provinces. These provinces comprise a large portion of the southeast, including significant population centers at Washington, D.C and Winston-Salem, N.C. These provinces are notoriously difficult for siting viable wells; in some areas 10-15% of wells drilled are dry holes (Seaton, 2002).

The drought and ongoing difficulties of finding sites that yield appropriate quantities of water to wells stress the importance of water-resource evaluation in the Blue Ridge region. Another looming problem for regional water resources is the ongoing expansion of Washington, D.C. suburbs into the Blue Ridge. Expansion of residential neighborhoods and subsequent increased need for potable water supplies are evident. Because little is known about the available quantity of water resources in the Blue Ridge, recommendations regarding volumes of water that can be safely withdrawn from aquifer systems in this region are guesses at best. Springs are vital water sources in this region, but there are few methods for analyzing and quantifying water resources that are associated with these springs.

Traditional pumping aquifer tests are the classic method used to characterize aquifer systems. The method requires numerous monitoring wells to measure draw down and recovery and may not be suited for the fractured crystalline rocks in this region. Pumping aquifer tests can also incur significant costs associated with drilling and constructing the wells necessary for completing the aquifer test.

Recently, much consideration has been given to a technique known as springflow hydrograph analysis for evaluating aquifer properties based on analysis of spring discharge records. Hydrograph analysis consists of fitting curves to records of spring discharge after precipitation events, then using the calculated slope of these curves to compute aquifer properties such as transmissivity or specific yield. Baedke and Krothe (2001), Amit et al (2002) and others have shown the technique to be quite useful for characterization of karst spring systems. Karst terrains are known to have many different water reservoirs including large solution openings (conduits), smaller fractures, and traditional porous media diffuse flow through sediments and rocks. The calculated recession coefficient, computed using a curve fitting algorithm, is the exponential term that describes the steepness of the curve fit to the hydrograph. Larger values of recession coefficient indicate steeper curves, while small values indicate shallower curves. Steepness of hydrograph recession curve slopes after rainfall events have been correlated to specific flow systems with the steepest slopes representing conduit type flow and the shallowest slopes representing diffuse flow. Baedke and Krothe (2001) used the method to describe a spring system located at the Crane Naval Surface Warfare Center, Indiana. Their study focused on the use of hydrographs to calculate the ratio of transmissivity to specific yield, which was later used to determine transmissivity and specific yield parameters for conduit and diffuse flow systems in karst terrains. Results obtained from their hydrograph study are consistent with data obtained from traditional aquifer tests and dye-trace studies performed in the same aquifer system. Baedke and Krothe (2001) concluded that two different flow systems, conduit and porous media, were responsible for the multiple slopes recorded in their hydrographs. They also found that an intermediate hydrograph slope was probably a result of a mixing of water from the two main reservoirs, rather than a third flow system.

Amit et al. (2002) suggested that the interpretation of spring recession curves may be valid for many lithologies other than karst, including terrains composed of fractured rock. They applied the hydrograph method to karst springs in Israel, which have significantly lower discharges than those reported by Baedke and Krothe (2001). Their analysis included springs with discharges of 0.16 to 37 gallons per minute, implying the method is valid even at extremely low discharge rates. The authors also report that recession coefficients are nearly constant from event to event for individual springs and the recession curves are influenced by geology and geometry of the flow system supporting the spring. Results are consistent with Baedke and Krothe's findings that the unique recession curve slopes in the analyzed hydrographs can characterize different flow regimes.

The evaluation of Blue Ridge springs investigated in this study is especially important in light of the new conceptual model for Blue Ridge aquifers developed by Seaton (2002). In this model (shown in Figure 1), the Blue Ridge aquifer systems at the Floyd site are represented as complex, heterogeneous hydrostratigraphic units composed largely of fractured granulite gneisses associated with local, but ubiquitous, thrust faulting. These aquifer systems tend to be confined vertically and laterally by mica-schists associated with fault planes or by other lineaments and faults. Local compartmentalization of confined aquifers is possible, with hydraulic heads in these aquifers locally rising above the ground elevation, resulting in springs and seeps. Previous research (Seaton, 2002; Seaton and Burbey, 2000) has shown Blue Ridge aquifers may be divided into two groups: localized, confined deep aquifers and shallow unconfined aquifers. The deep aquifers typically contain relatively clean water, and are associated with fracture systems in the crystalline bedrock. The shallow aquifers are the result of groundwater stored in the shallow soil and saprolite, above the bedrock and may contain surface contaminants. These aquifer systems are referred to as "shallow" and "deep" in this study. Flow between the deep and shallow aquifers is limited, and may occur only in rubble zones or vertical fracture zones that communicate the deep and shallow aquifers.

The new model described by Seaton (2002) also proposes several different flow pathways that may be important, especially with regard to groundwater recharge. Distinct flow pathways in the Blue Ridge may include: flow through shallow saprolite and regolith, flow through bedrock fractures, and flow along highly permeable zones typically found above fault planes and referred to as shear zones or fault zones. Direct connection of these flow pathways to spring outlets may be revealed by springflow hydrographs. This study expands on the conceptual model proposed by Seaton (2002) in an attempt to characterized the flow path ways associated with the complex aquifer systems described in the Blue Ridge.

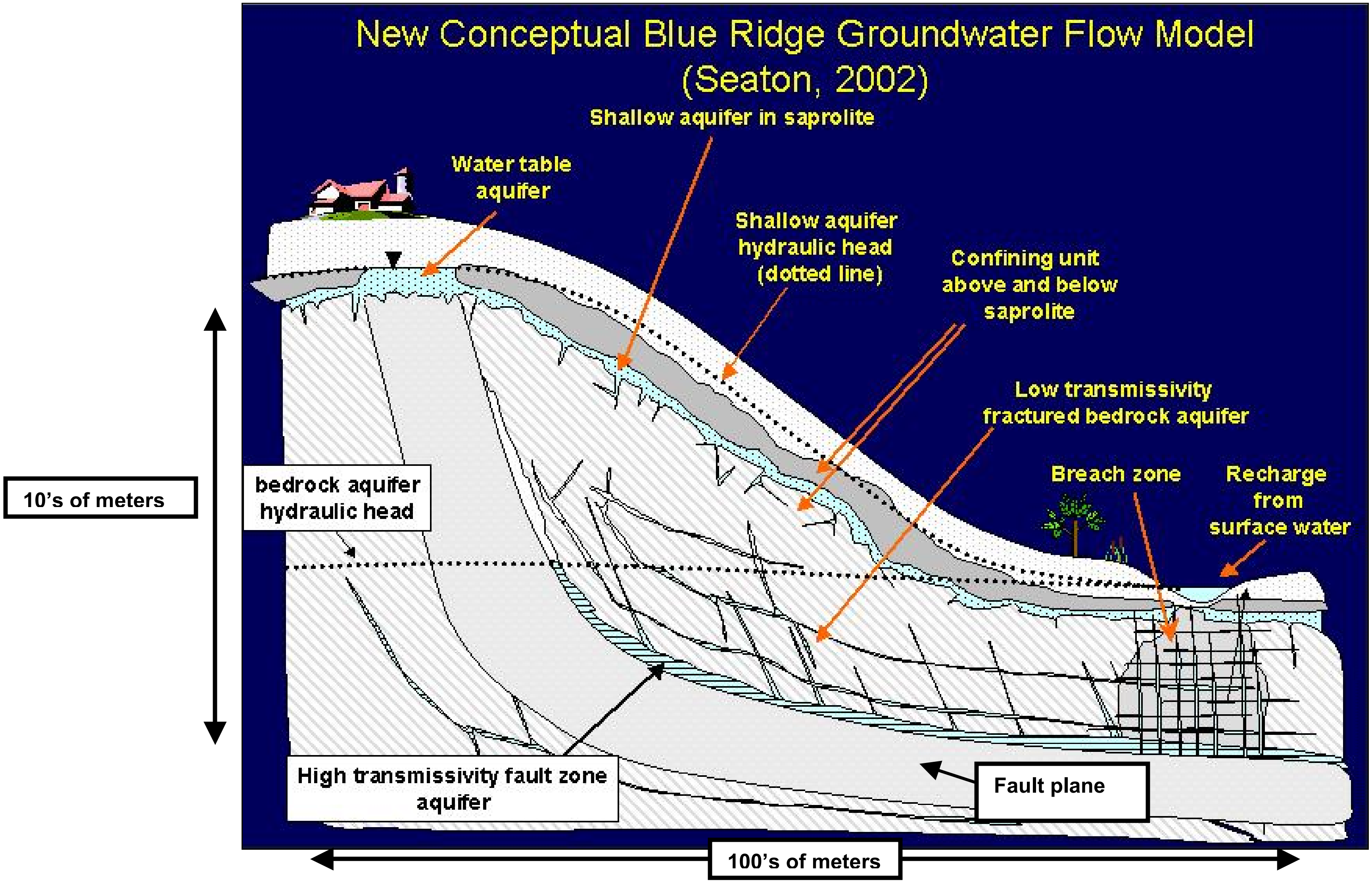

Figure 1 - New Blue Ridge Conceptual Model Proposed by Seaton (2002).

Objectives of this Investigation

The objective of this investigation is to correlate spring discharge with different types of groundwater flow systems supplying water to the springhead at two sites in Floyd and Grayson counties, Virginia. The Floyd County site is used to refine the springflow hydrograph analysis technique and the Grayson County site is used to test the method during one season of fieldwork. A combination of hydrophysical and hydrochemical analyses with surface geophysics is used to ascertain the flow regimes that influence the nature and character of Blue Ridge springs. A new device capable of measurement of low discharge associated with the springs in each of these locations was also developed as part of this study. If the springflow hydrograph technique proves valid, it can be used to assess spring discharge sustainability and water, which are vitally important when springs are used as potable water sources and sustainable yields are necessary.

Geology, Physiography, and Geomorphology

The locations of the field sites discussed in this investigation are shown in Figure 2. The Floyd and Grayson County sites are located on the Western edge of the Blue Ridge Physiographic Province in Southwest Virginia.

The Blue Ridge Physiographic Province is an elongated band of exceptionally complex geology stretching from central Pennsylvania to Georgia (Dietrich, 1959). Composed of complexly faulted, fractured, and metamorphosed rocks, it is amongst the most geologically and hydrogeologically complex area in the eastern United States. The Blue Ridge is generally divided into two sections: a narrower, northern section extending from the area north of Roanoke, VA, and a nearly 70 mile wide band south of Roanoke, extending into North Carolina and Georgia (Clark et al., 1989). The field sites are located in the southern section of the Blue Ridge.

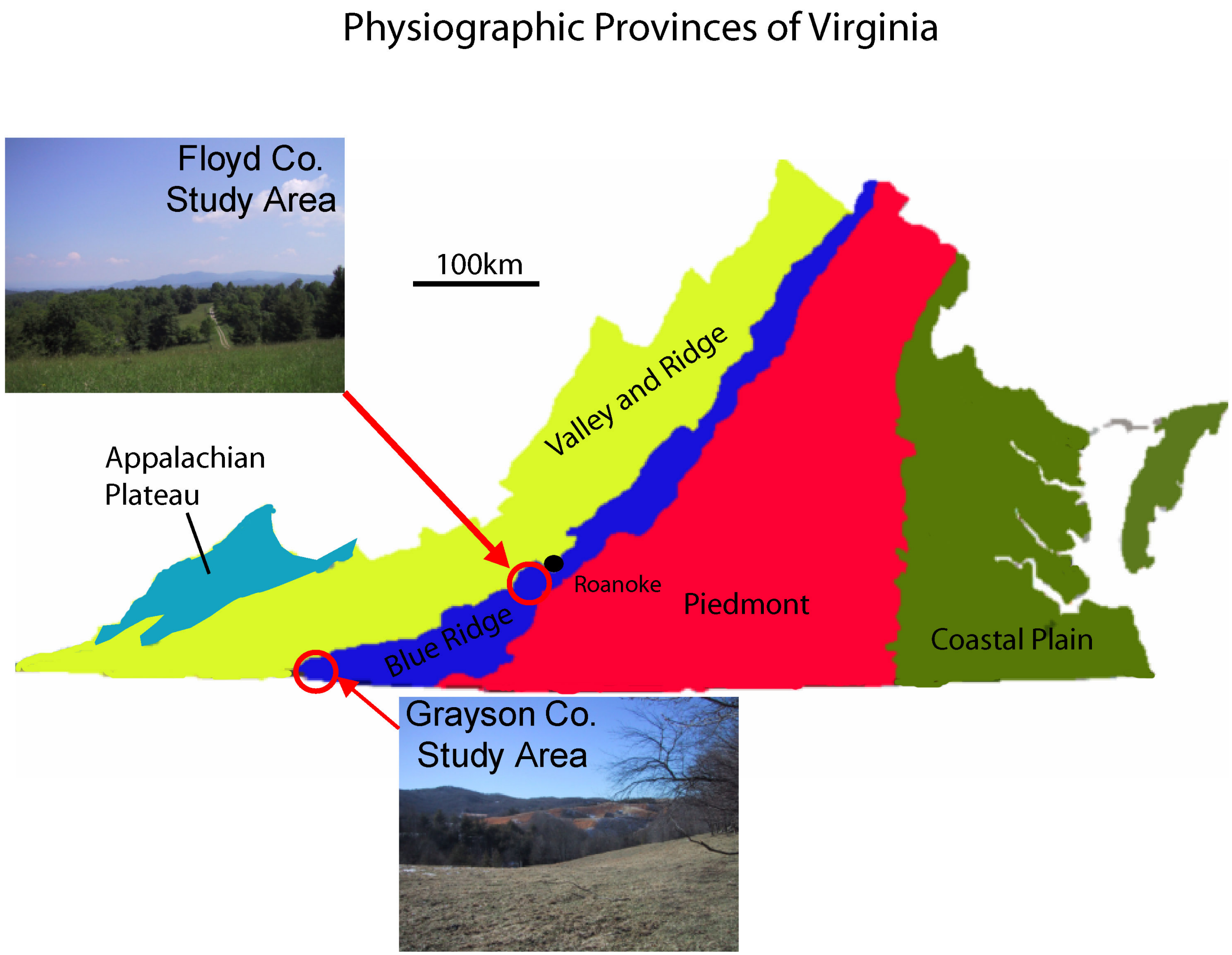

Figure 2 - Map showing physiographic provinces of Virginia

The Northern Blue Ridge is typically a single ridge, surrounded by smaller outlying isolated mountains. Some peaks in the Northern Blue Ridge exceed 1200 m, and most of the drainages flow east to the Atlantic Ocean. The Southern Blue Ridge, morphologically distinct from the Northern Blue Ridge, is typified by higher elevations, multiple ridges, a large escarpment to the east, and drainage that flows west to the Gulf of Mexico (Thornbury, 1965).

Geology and stratigraphy of the Blue Ridge are poorly documented in the area between Roanoke and the North Carolina border. Geologic maps are sparse to non-existent; state level mapping efforts are ongoing, but are still quite limited in extent.

Floyd County Field Site Description

The first field site location (hereafter referred to as the Floyd County site) is located in southwest Virginia along Virginia route 810, 6 km west of Check, VA and 30 km south of Roanoke, VA. The field site is situated on the eastern rainwater divide, which is an imaginary dividing line that separates overland flow so that rainfall on the west side of the line flows into the Gulf of Mexico and rainfall on the east side of the line flows into the Atlantic Ocean. The site is located in the Check quadrangle, near the western edge of the Blue Ridge Physiographic Province.

Several different names have been given to the geologic formations underlying Floyd County, the most recent and accepted being the Ashe Formation suggested by Rankin (1970). The Ashe Formation consists of mica-schists, gneiss, and granites all of metamorphic or igneous origin (Rankin, 1970; Seaton, 2001). Numerous overprinted tectonic episodes have resulted in the fractured, faulted and metamorphosed geology exposed at the field sites (Seaton, 2001).

Topography in Floyd County is highly variable, ranging from relatively flat to rolling lowlands around the western county border near Montgomery County to high plateaus in the central portion of the county (Figure 3). The Blue Ridge Escarpment defines the eastern boundary of Floyd County. The Blue Ridge Escarpment is represented by an abrupt change in topography that is defined by the transition from the Blue Ridge Province to the Piedmont Physiographic Province (Dietrich, 1959).

The average elevation in the Check quadrangle is 750.2 m, the minimum is 444.4 m and the maximum is 984.4 m occurring at an unnamed mountaintop in the northeast corner of the quadrangle. A map showing the topography in the vicinity of this field site is shown in Figure 3. Slopes in the Check quadrangle range from 0° near the South Fork of the Roanoke River to a maximum of 58° in the more rugged portion located along the Northwestern edge of the quad. The Floyd County site is characterized by fractured and layered granulite gneiss bedrock typical of the Ashe Formation (Virginia Division of Mineral Resources, 1993). Granulite gneiss typically has a very low hydraulic conductivity (nearly impermeable). Local and regional faulting and fracturing have created zones with high hydraulic conductivities within gneiss units. The permeable granulite gneiss units are separated into individual hydrostratigraphic units by confining units defined by mylonitic schists or unfractured gneiss (Seaton and Burbey, 2000).

Grayson County Field Site Description

The Grayson County site, located in Southwest Virginia along Virginia route 665 2.5 km southwest of Elk Creek, and 9.2 km northwest of Independence, is shown topographically in Figure 3. The site is located in the Elk Creek quadrangle, near the western edge of the Blue Ridge Physiographic province. The average elevation on the Elk Creek Quadrangle is 928.0m, the minimum elevation is 741.4m and the maximum is

1403.0m occurring at Buck Mountain. Slopes in the Elk Creek Quad range from 0° in the north central part of the quad to 54° near the mountains and more rugged terrain in the southern part of the quad (Figure 3).

The Grayson County site is underlain by a biotite augen gneiss and represents part of the Elk Park Plutonic Group which has previously been described as the Grayson Gneiss (Popek, 1974). The Elk Park Plutonic Group outcrops west of the longitudinally extensive Ashe Formation. While lithologically distinct from the Ashe Formation, the Elk Park Plutonic Group contains many of the same overprinted tectonic events, resulting in rocks that are faulted, and fractured similarly to the rocks at the Floyd County site.

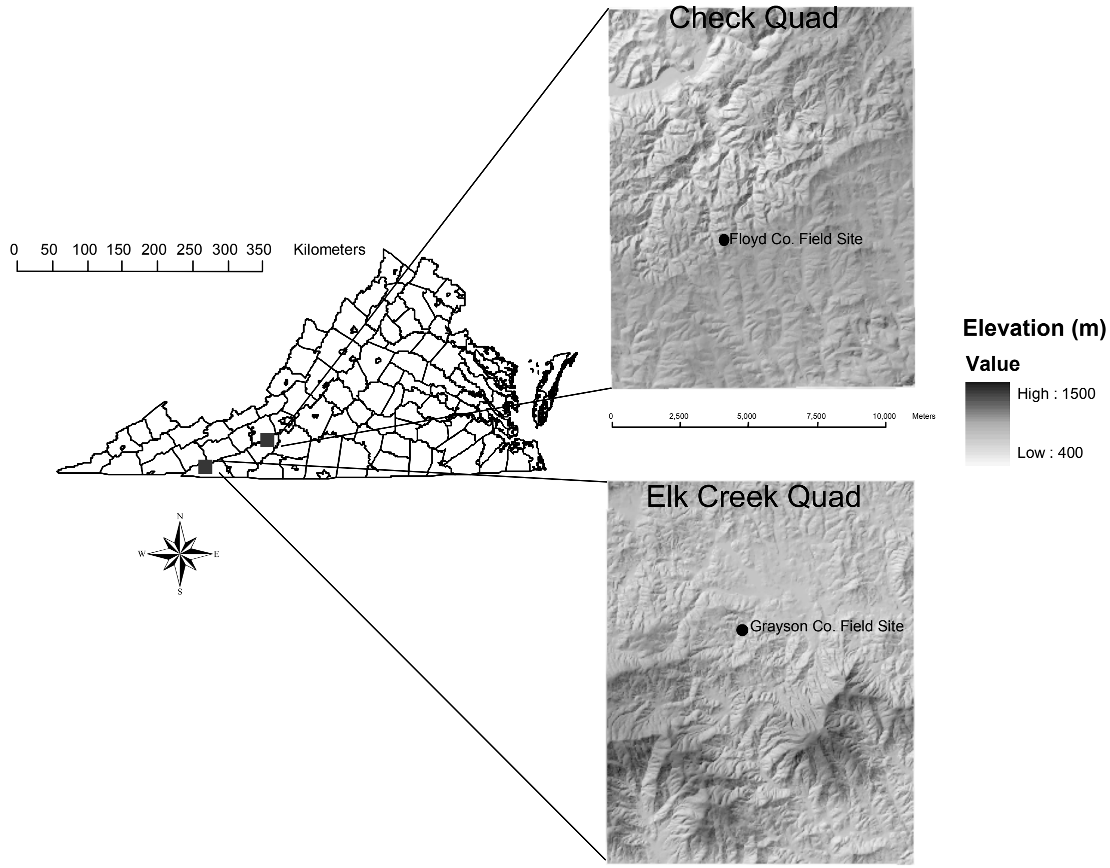

Figure 3 - Locality map showing locations of Floyd and Grayson County sites, with topography. Topgraphic data from U.S. Geological Survey (2001).

Climate

Climate in Virginia is controlled primarily by distance from the Atlantic Ocean and secondarily by topography (Crockett, 1971). The state is divided into three topographic regions: Coastal Plain, Piedmont, and Western Mountain. Both field sites mentioned in this study fall into the Western Mountain region. The Western Mountain region is significantly cooler than locations in the Piedmont and Coastal Plain. Rainfall is also influenced by proximity to the ocean and topography. Most significant rainfall occurs on the southeastern and southwestern parts of the state with lesser amounts of rain in the mountainous regions because of rainfall 'blocking' provided by the mountains (Crockett, 1971). Annual rainfall for Virginia is dependent on the topographic region and ranges from 36 to 52 inches. Long-term annual precipitation averages reported in 1985 for the two study areas in Floyd and Grayson counties are approximately 44 inches per year (Moody et al., 1986). Rainfall is evenly distributed month-to-month throughout the entire year, without significant wet or dry seasons. However, excessive rainfall occasionally occurs during the fall months as infrequent hurricanes and tropical storms pass over or near the state. The past four years (1998-2002) have been marked by significant rainfall deficit with substantial departures from normal rainfall amounts. Occasional droughts on the order of months are common in Virginia's rainfall record, however most are short lived and typically do not result in significant declines in aquifer water levels. Longer-term droughts, on the order of several years, occur periodically and may result in decline of aquifer water levels (Crockett, 1971).

Hydrogeology

Previous Work

Characterization of Blue Ridge hydrogeologic resources has not been a focus of research in the past. Other studies in similar fractured rock aquifers have focused on characterization of individual fractures and fracture geometry (Johnson, 1999; Karasaki et al., 2000), but do not focus on flow pathways and aquifer characterization as a complete unit. Recent water shortages and drought conditions have encouraged new research into water sources and resource availability in the hydrogeologically complex Blue Ridge and Piedmont regions (e.g., Seaton and Burbey, 2002). LeGrand's USGS circular (1967) is one of the first comprehensive synopses of groundwater systems in the Blue Ridge. LeGrand mentions low-flow springs that vary little in yield, even during prolonged dry spells. More recently, Seaton and Burbey (2000) have investigated water resources in the Blue Ridge using numerous geophysical techniques, including surface electrical resistivity and borehole logging. Seaton (2002) describes a new model of Blue Ridge aquifer systems where clayey-schist layers confine hydrogeologic units and recharge may occur along very permeable zones above fault planes. Long-term research initiated by Seaton at the Floyd County site resulted in installation of 10 water-level monitoring wells into the shallow and deep aquifers. The Floyd County site has a well field containing ten wells, divided into two general groups, shallow and deep. Shallow wells are drilled or augured to a depth of only a few meters, deep wells are drilled into bedrock and are 30-300 m deep (Figure 4). The deep wells at the site include two deep very (approximately 100 m, W-03 and 300 m, W-10) wells which were used as a part of an aquifer test to further characterize the aquifer systems of the local area (Seaton, 2001).

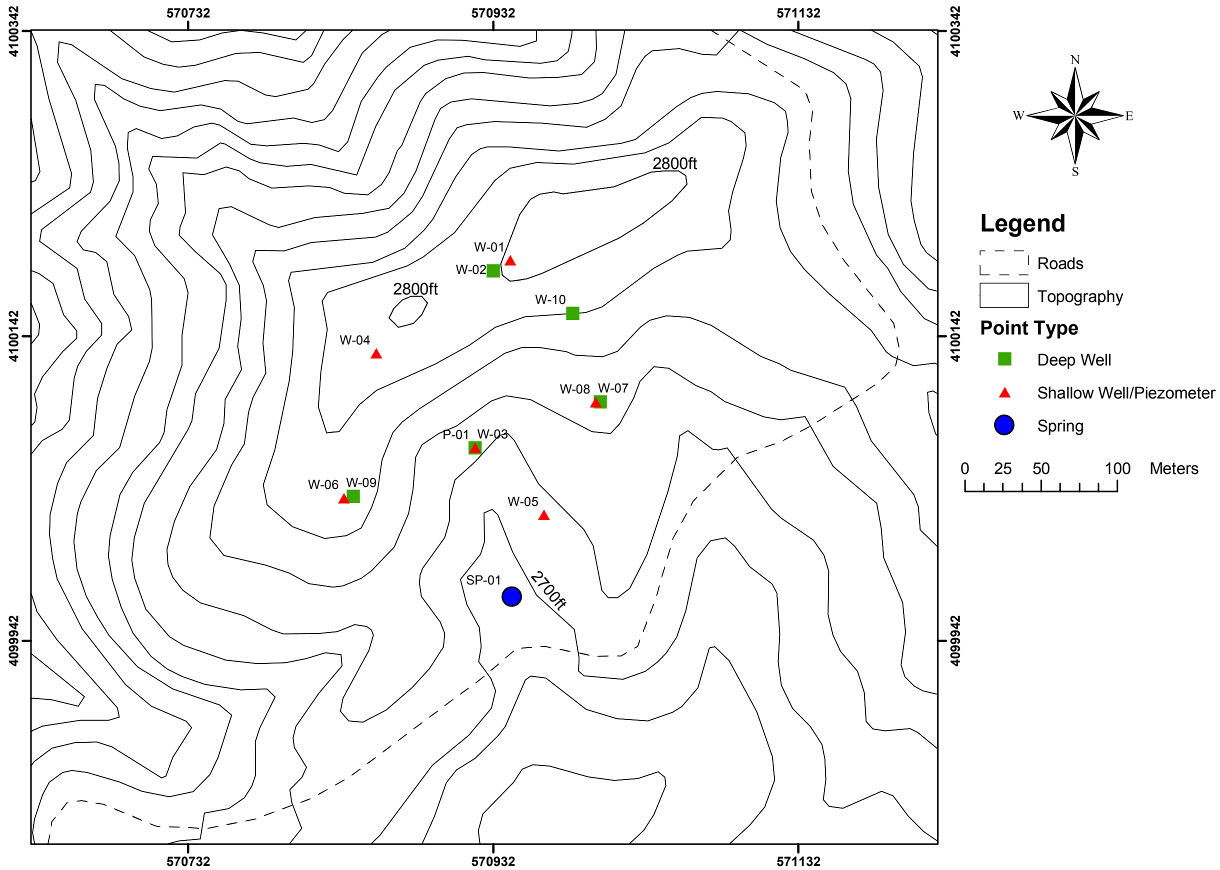

Figure 4 - Diagram showing well, piezometer and spring locations at Floyd county site.

Evidence of Multiple Flow Regimes

Many different tools can be used to characterize aquifer systems and flow paths. Chlorofluorocarbons (CFC's) can be used to date groundwater and can thus be used to provide evidence of groundwater mixing. Geophysical well logs provide evidence of fractures through interpretation of resistivity logs, and flow between fracture sets through interpretation of borehole flowmeter data. Basic anion-cation water chemistry provides evidence of groundwater mixing through concentration and dilution of specific anions and cations. Surface electrical resistivity data results the yield information on the geometry of the shallow subsurface; including fracture zones and possible aquifers. A variety of tools were used by Seaton (2002) to characterize the hydrogeology of the Floyd County site and suggest multiple flow regimes within the shallow and deep aquifers as discussed below.

CFC Data

CFC age dating is a relatively common method used to obtain groundwater ages of relatively young water (<60 years) by providing an approximate date since the occurrence of groundwater recharge. CFC ages are dependent upon atmospheric concentrations of CFC gases, their associated partial pressures, and recharge temperature. The recharge temperature is typically quite stable because recharge takes place in the soil where temperature fluctuations are minimized. Multiple CFC's, such as CFC-11, CFC-12, and CFC-113, are typically measured in each water sample to corroborate results and provide a check against sample contamination by modern atmospheric air (Kozar et al., 2000). Several wells at the Floyd County site were sampled for CFC's, tritium/helium, and SF_6 (sulfur hexafluoride) as part of a regional groundwater age-dating study performed by the U.S. Geological Survey in 1999. Results are described in detail in Seaton (2002).

The CFC data collected by the U.S. Geological Survey yield evidence of two distinct ages of water at the Floyd County site. The water is divided into two groups: young, which has been in contact with the atmosphere within the past thirty years; and old which has been isolated from the atmosphere for approximately thirty years or more. Interpretation of the estimated dates obtained from the CFC data indicates that the groundwater is 70-75% 60-year-old water mixed with 25-30% modern (<30 years old) water. However, the data do not yield any information about the flow pathways or mechanisms that may be allowing modern water to infiltrate and mix with the water in the deeper, confined system.

Well Log Data

Geophysical well logging is a well-known technique for characterizing the formation and formation fluids intersecting a borehole. Detailed geophysical well logging was performed at the Floyd County site by Seaton (2002). Well logs for gamma ray, spontaneous potential (SP), resistivity, caliper, fluid resistivity, temperature, and heat-pulse flow meter were collected at each of the ten wells and at discrete depth intervals. Geophysical logs, when interpreted together, can yield a host of information about the subsurface including: probable lithologies, stagnant and flowing fracture zones, saturated and unsaturated zones, and confining units. The heatpulse flow meter data show distinct, flowing fracture zones associated with intensely fractured granulites, above fault planes. Resistivity, gamma ray, and caliper logs show mica-schist aquitards (confining units), and similar data from multiple wells scattered over the entire field area suggest vertical fracture zones that communicate and allow flow between the deeper aquifer system and shallower aquifer system. The same combined well-log data also indicate changes in regolith and saprolite thickness associated with structural features that may allow recharge to occur more readily in certain areas of the field site near fault subcrops and associated highly permeable, fractured granulite zones (Seaton, 2002).

Chemistry

Water chemistry, analyzed as mean equivalent cations and anions, can indicate relative water residence times. The longer groundwater is in contact with rock surfaces, the higher the concentration of mean equivalent cations and anions. Other water chemistry data, such as nitrate and phosphate concentrations, can indicate inputs of nutrients from surface sources including fertilizers or septic drain fields and may act as conservative or non-conservative tracers for tracking of groundwater. Seaton (2002) describes the concentrations of cations and anions in wells completed in deep aquifers, which indicates that concentrations are approximately double of those for wells completed in the shallow aquifer system.

In this study, water samples were collected, filtered with a .45µm nylon filter and analyzed for major anions at each spring and from wells in the vicinity of the springs at both field sites. Initial water quality sampling (Summer 2001) consisted of analysis for only nitrate and phosphate concentrations using a Hach DR/890 colorimeter. Later (2002) water quality sampling consisted of an analysis for major anions (Br, Cl, NO_3,PO_4, SO_4) using ion chromatography. Figure 5 shows average anion concentrations from groundwater and spring samples collected at the Floyd County site. Seaton (2002) describes two distinct nitrate concentrations at the field area, which are comparable to the values reported in this study (Figure 5). Deep wells have lower nitrate concentrations while shallow wells have nitrate concentrations on the order of 1-3 parts per million. The data shown in Figure 5 reflect a trend of lower nitrate concentrations in deeper wells and higher concentrations in shallow wells. Concentrations of chloride and sulfate show the opposite relationship with higher levels in the deep wells and lower levels in the shallow wells. Phosphate concentrations in all samples were near or below detection limits for the methods used. Concentrations of ions in water sampled from the spring, presented in Figure 5, reflect a shallow source of water with higher concentration of nitrate and lower concentrations of sulfate and chloride. These results suggest water at the spring outlet is primarily sourced from the shallow aquifer. The next section, *Spring Observations*, provides evidence to the contrary.

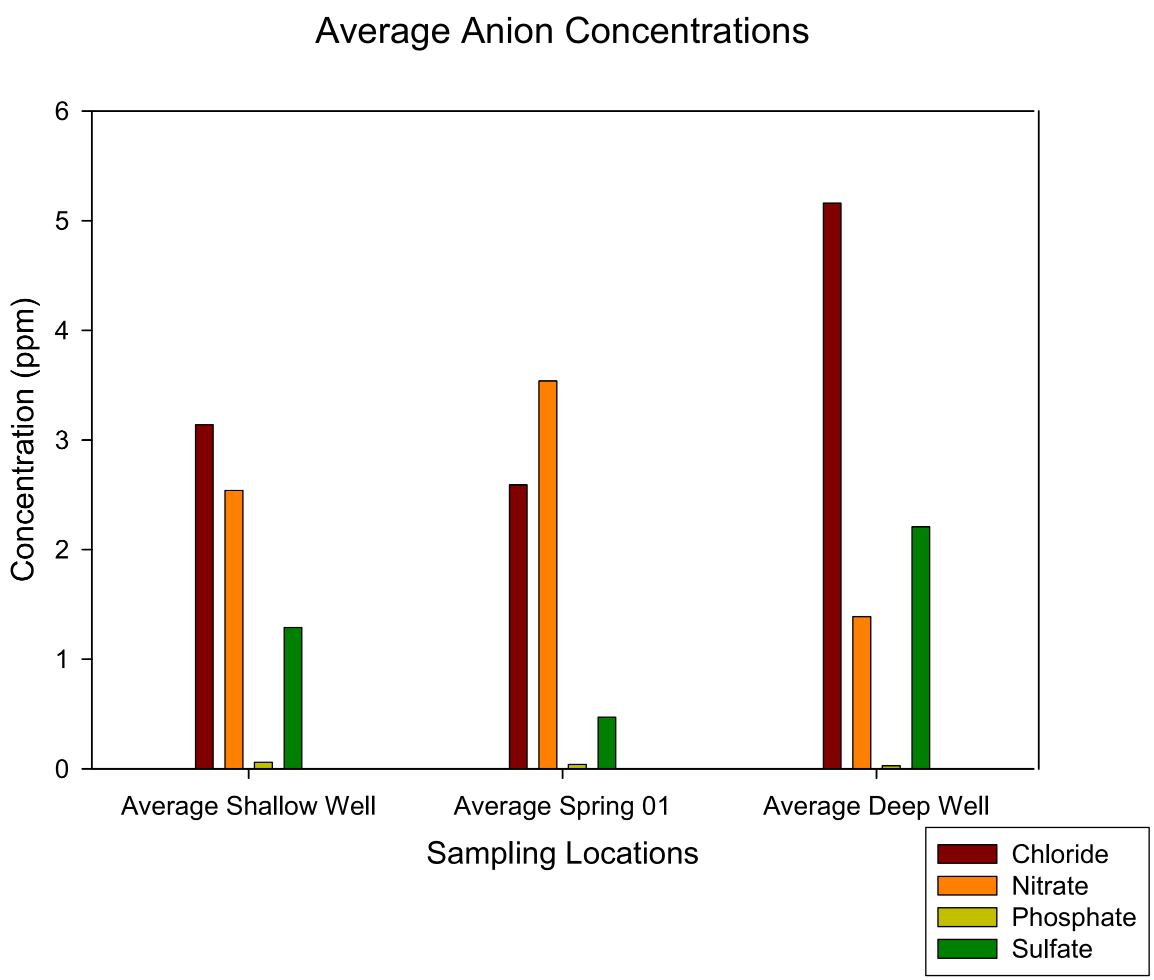

Figure 5 - Plot of Average Spring-Summer Anion Concentrations at Floyd County Site

Spring Observations

The CFC, geophysical well logs, and water chemistry data provide evidence of multiple flow paths to the springhead at the Floyd site. The evidence of multiple flow paths is corroborated by conversations with residents of the area who have used local springs as sources of water for many years. Most residents have noted that some springs go dry from year to year while others consistently discharge water at a constant rate for years, or even decades. Some residents have noted that although springs may 'cloud up' with large amounts of sediment after rain events, the same springs discharge even during drought conditions. The author also observed this phenomenon. Sediment is believed to come from the shallow zone and is another indicator of a possible complex inter-aquifer flow. Springs discharging perennially without significant variation in discharge, despite long-term drought, suggest that they are at least partially connected to a deep flow path with a more distant source of recharge and having long residence times. The combination of both observations at a single spring outlet suggests a mixed deep and shallow source.

Spring Discharge Measurements and Their Correlation to Rain Events

The springflow hydrograph analysis method of aquifer characterization requires a record of spring discharge over time (a hydrograph) and a record of rain events for correlation of discharge peaks and lag times. The period of discharge monitoring required to adequately characterize a spring and the associated flow paths depends entirely on rainfall. Widely separated rainfall events with easily correlated peaks give the best results. Closely spaced rainfall events that result in complex overlapping peaks where the spring discharge does not return to baseflow after each rainfall event provide little help for analyzing hydrographs. However, good (easily interpreted) analysis results can be obtained for hydrographs with widely separated rainfall events over a monitoring period of weeks to months.

To measure precipitation, both field sites were each instrumented with data loggers connected to tipping bucket rain gauges capable of measuring individual rain events as small as 0.01 inches. Spring discharge is typically measured with a flume or weir and a pressure transducer that records variations in water levels through the flume or weir as discharge volumes increase or decrease. This method was not deemed feasible at either field site because of low discharges associated with springs at each of the sites. Discharges from springs at all field sites are typically below the lowest flow calibration for flumes and weirs currently on the market. Development of a new system for measurement of spring discharge was determined to be necessary to accurately monitor the low discharge of the springs at each field site.

A new self-powered system (Low Flow Recording System, LoFRS) was designed and built for use at the Floyd and Grayson sites. The system measures flow using off-the-shelf manufacturing process control equipment including: a paddlewheel flow sensor, a proprietary flow transmitter that converts the output of the flow sensor into a current loop signal, and a data logger to record measurements made by the discharge-measurement system. This system is shown in Figure 6 and diagrammed in Appendix I.

Solar cells and small voltage regulators provide controlled voltages and currents for charging the batteries and powering the discharge-measurement system. The data-logging system also records water temperature using a small stainless steel encased thermistor probe. Multiple channels are available on the logging system, allowing for future expansion of additional probes such as dissolved oxygen, pH, fluid conductivity, and fluid pressure. Field calibration of the flow system was not necessary, the manufacturer supplies a lab-calibrated tee fitting with the flow measurement system that allows for conversion of fluid velocity to flow rate. The calibration is valid for fluid velocities in which the probe is capable of producing an output.

A table containing dates of the spring monitoring periods is shown below (Table 2). Field equipment at the Floyd County site experienced substantial downtime due to damage caused by grazing livestock in the field area. Field equipment could not be left to record discharge in the colder months because freezing water would destroy the flow sensor. The flow monitor requires springflow to be through a pipe to allow for connection of the discharge sensor. Springs at the Grayson County site, GSP-04 and GSP-05, are discussed later in the section titled *Applications to Other Locations.*

Spring	Location	Monitoring Period
SP-01	Floyd County site	6/18/01-8/1/01, 6/28/02-8/1/02, & 9/22/02-10/5/02
GSP-04	Grayson County site	5/22/02-6/11/02
GSP-05	Grayson County site	6/11/02-11/11/02

Table 2 - Spring discharge monitoring periods

Several reference measurements of winter spring flow were recorded in the winter of 2001 and 2002 at SP-01. Winter discharge measurements were recorded with a gallon jug and stopwatch. Typical winter discharge for spring SP-01 is approximately 3 gallons/minute.

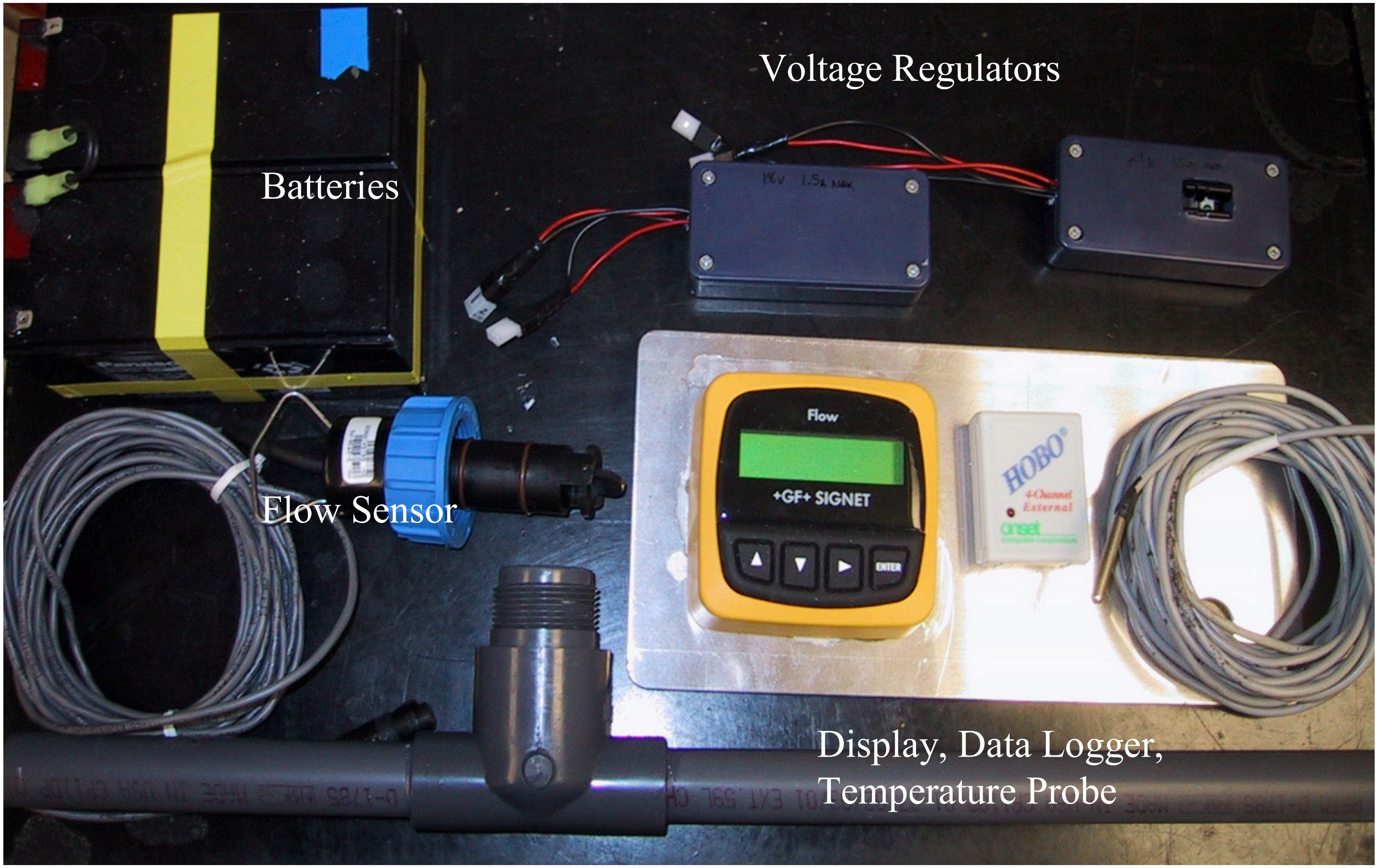

Figure 6 - Flow monitoring field equipment for measuring low discharge.

In order to begin a quantitative comparison of spring discharge and rain input, it is necessary to obtain an isolated rain event and a corresponding discharge peak. A dataset of this type shows the lag time between the two events, which is necessary for correlation of future, more complex hydrographs with multiple overlapping rain events and discharge peaks. Data of this nature were recorded at the Floyd County Site in late September, 2002. Shortly after re-installation of the equipment, remnants of a small tropical storm passed over the field site and resulted in several inches of rain over several days (Figure 7).

Figure 7 represents the SP-01 hydrograph during the event, which is shown as one rain event and one hydrograph peak (circled). An approximate 3-day lag exists between the rain events and the resulting increase in recorded spring discharge at SP-01. Typical multiple rain event/multiple hydrograph peak plots for SP-01 are shown in Figures 8 (2001) and 9 (2002). In most cases there are correlating hydrograph peaks approximately 3 days after rain events. Figure 8 shows NOAA (National Oceanic and Atmospheric Administration) rain gauge data from the Copper Hill weather station a few miles from the Floyd County site. During the monitoring period shown in Figure 8 the on-site rain gauge was not functioning correctly, and alternate data were used from the weather observation station.

Figures 8 and 9 show multiple rain events and peaks with interpreted event-peak pairs shown in circles on Figure 9. Note that different-sized rain events produced notably different peak shapes. Some rain events also produce very sharp, spiked discharge peaks that may be interpreted as very rapid flow (quickflow) through soil, saprolite or possibly fractures close to the spring outlet. The peaks labeled 1, 2 and 3 in Figure 9 will be analyzed in detail in the section titled *Determination of Recession Curve Parameters and Flow Paths*. Despite differences in peak shapes, the peaks consistently occur three days after the peak rainfall, suggesting that the quickflow pathway behaves very consistently. There are several possible explanations for the three day lag between rainfall events and an increase in spring discharge: (1) rainfall infiltration in the unsaturated zone near the springhead; (2) time and a corresponding distance from a specific fracture zone in the unconfined shallow aquifer; or (3) flow driven by hydraulic head piston flow through the deep confined aquifer. It is unlikely the spring discharge increase is due to discharge from the deep confined aquifer, as connections between the shallow and deep aquifers are weak (as will be discussed in the section titled *Aquifer Tests*), and head changes in the deep system (measured by Seaton, 2002) are gradual, taking months-years to respond to drought and rainfall. Interpretations (1) and (2) are more difficult to disprove. However, (2) is unlikely because of the narrow width of most hydrograph peaks. Flow through a high permeability zone connected to the surface would likely produce much broader peaks than those seen on the hydrographs. Rainfall on a high permeability zone would like result in a large volume of water being transmitted through the aquifer materials, and would produce a much broader peak than those recorded in the hydrographs. A detailed study of recharge at the field site is necessary to further characterize flowpaths and recharge zones to the deep and shallow aquifers. Spring discharge may be related to a combination of (1) and (2) and cannot be proven as exclusive flow through the near springhead unsaturated zone or specific shallow fractures with the data presented in this study.

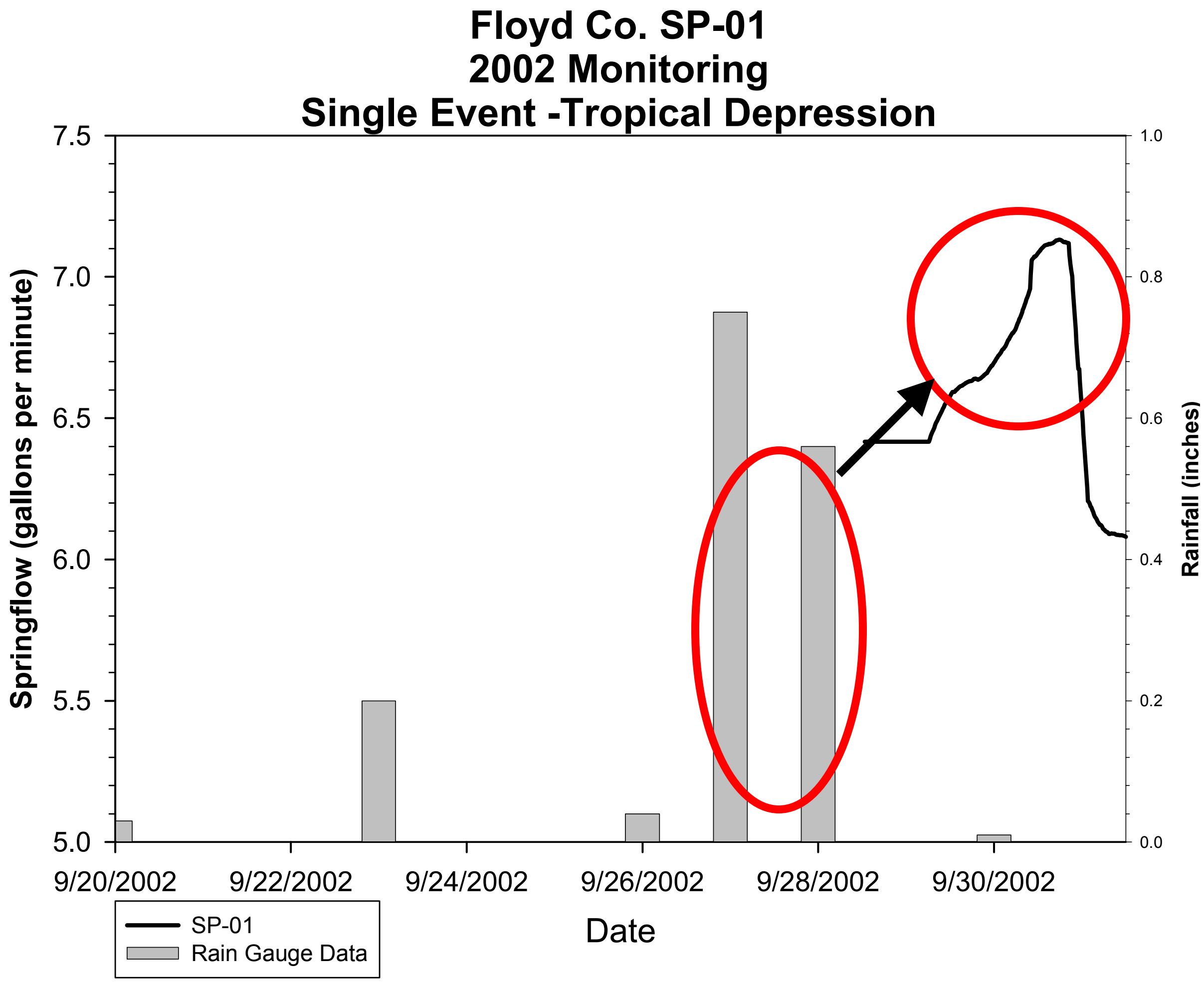

Figure 7 - Plot of spring discharge and rain for an isolated rain event at the Floyd County site.

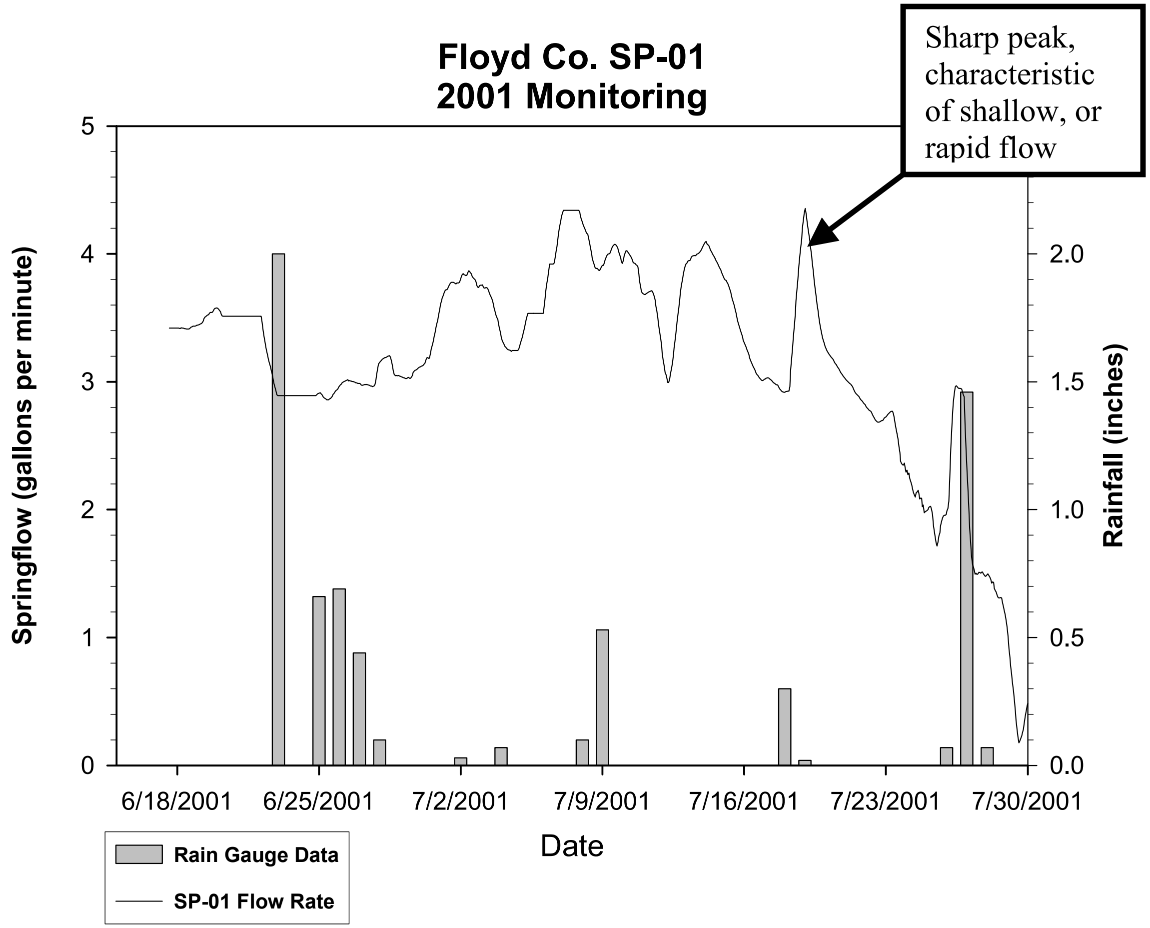

Figure 8 – Plot of spring discharge and rain at the Floyd County site. Rain data from NOAA (on-site rain gauge malfunctioned)

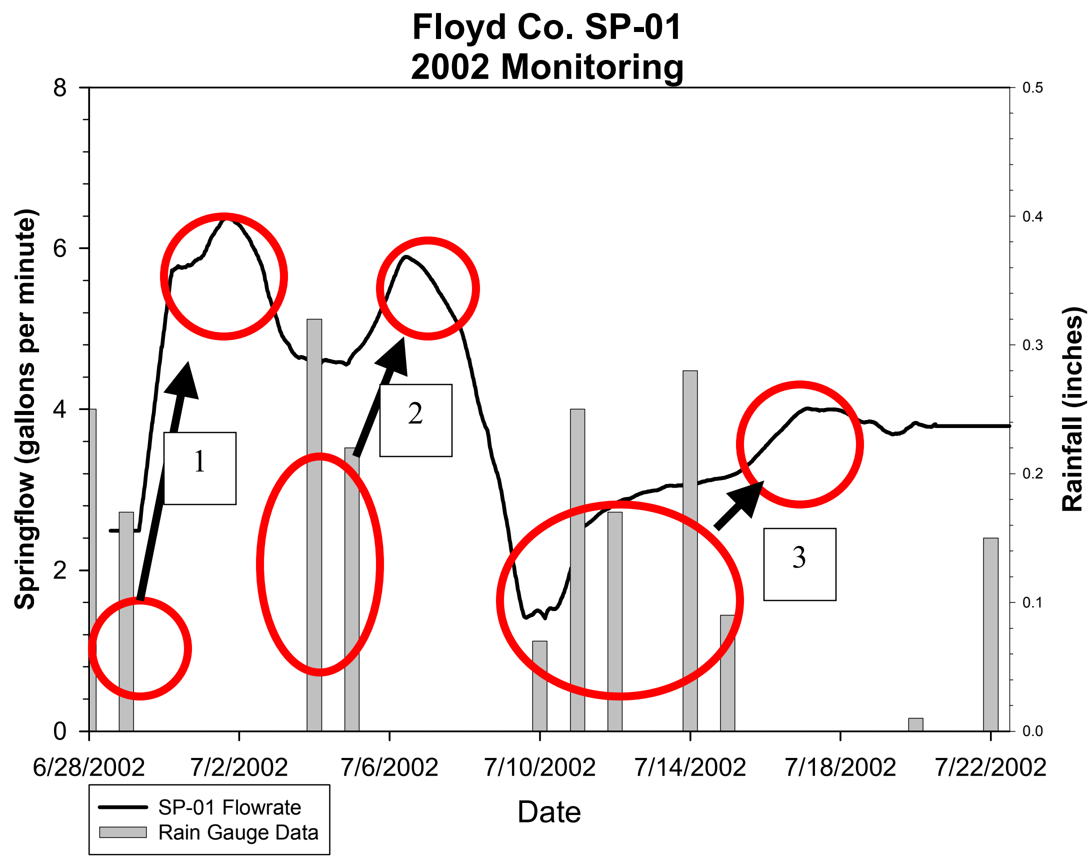

Figure 9 - Another typical multiple rain event, multiple hydrograph peak plot from the summer of 2002 at the Floyd County

Determination of Recession Curve Parameters and Flow Paths

One benefit of the springflow hydrograph method is its ability to reveal quantitative data about the aquifer and/or flow path providing water to the spring outlet. Analysis of recession curves can yield values for transmissivity or specific yield if storativity and distance to groundwater divide are known *apriori*. In this investigation, these aquifer parameters are not known. Analysis of the recession curve parameters is thus limited to calculation of recession curve slope, which indicates the relative speed that water drains from flow paths supplying the spring outlet. Steeper slopes are correlated to rapid drainage of flow paths and higher hydraulic conductivities; shallower slopes are correlated to slower drainage of flow paths and lower hydraulic conductivities. Figure 8 (data from 2001) was not fit with recession curve slopes because of the very closely spaced rain events, and the difficulty of interpreting rainfall/hydrograph peak pairs. The difficulty in finding correlated peaks may be related to the offsite raingauge data used for this time period. Rainfall at the Copper Hill weather station may not accurately reflect the rainfall at the Floyd site only a few kilometers away. The three peaks circled and labeled in Figure 9 (data from 2002) were analyzed to determine the recession curve slopes. Each peak was isolated from the time series discharge data shown in Figure 9 and an exponential decay curve in the form of the Boussinesq Equation (2) was fit using SigmaPlot's (2001) regression function in a method similar to that applied by Amit et al (2002).

$$Q = Q_0 e^{-\alpha t} \qquad (2)$$

Where Q is the discharge at the end of the recession, Q_0 is the discharge at the beginning of the recession, α is the recession coefficient, and t is the duration of the recession (time). The parameter of interest is α. α describes the steepness of the recession curve slope after a rainfall event. Large values of *α* are indicative of recession curves with steep slopes, and subsequently indicate a flow path that water moves through very quickly after a rain event and may be associated with solution openings in karst, high permeability fracture sets in fractured rocks, or rapid flow through soil materials very close to the springhead. Smaller values of α are associated with slow flow, and produce very shallow recession slopes on a hydrograph. The results of the recession analysis are presented in Table 3, along with reference values of *α* for several springs of similar discharge in karst and chalk lithologies.

Location	Lithology	Average Discharge (gallons/min)	α (1/day)
Middle East	Dolomite	4.4	0.0514
Middle East	Dolomite	25.4	0.0283
Middle East	Dolomite	18.7	0.0284
Middle East	Dolomite	4.0	0.0601
Middle East	Chalk	1.5	0.1052
SP-01 Peak 1	Soil/Saprolite	3.5	0.1201
SP-01 Peak 2	Soil/Saprolite	3.5	0.1719
SP-01 Peak 3	Soil/Saprolite	3.5	0.0423

Table 3 -Table showing calculated recession alpha values and comparison values. Middle East values from Amit, et al. (2002).

The values reported for the recession curves analyzed at the Floyd County site are comparable to those reported by Amit et al. (2002) for a spring fed by a chalk aquifer. The author of this study beleives that these short-term discharge peaks are due only to flow through the shallow aquifer system surrounding the spring outlet. This is suggested by Seaton's aquifer test data (see the section titled *Aquifer Tests*) that show little connection between the deep and shallow aquifers except near a zone of intense fracturing located approximately 25 m upgradient from the spring. The short total duration (magnitude and width) of discharge peaks, which can be correlated to source areas, also suggests that the peaks are related to flow only through the shallow zone. Sharp discharge peaks are typical of a small source area. If an assumption is made that the area under a hydrograph peak is related to the total rainfall during an individual rainfall event, the area of the location where the rainfall infiltrated can be calculated. This calculation is performed by integrating the area under a hydrograph peak to obtain the total discharge for a single rain event, then dividing the discharge volume by rainfall depth to obtain an estimate of the area where the rainfall infiltrated. The amount of water discharged from the spring outlet must be compensated for losses such as evaporation and runoff and is multiplied by 150% (an approximation). Performing this analysis on the spring at the Floyd site, for the single even isolated in Figure 7 yields a recharge area of only a few hundred square feet. Peaks from flow through a deeper system, with a larger recharge area would likely be much broader because of the likely larger volume of water that would enter the aquifer from a larger recharge area. SP-01 Peak 3 shows a different recession mode, approximately 1/3 of the slopes from peaks 1 and 2. This could be due to the extended rainfall associated with the peak, and subsequent saturation and slower flow along longer paths in the unsaturated zone. To use the recession method for determination of deep aquifer parameters, a record of spring discharge during baseflow conditions would be necessary. The spring at the Floyd site typically shows a baseflow response only during extended droughts (months without rain) during the summer and during the winter when precipitation (snow) evaporates before it can enter the shallow aquifer. Such a record was not recorded because of concerns about freezing temperatures and possible subsequent damage to the flow sensor.

Identification of specific flow paths requires additional information. The hydrographs clearly reveal the influence of rapid flow through the shallow aquifer, but provide less evidence of possible flow through the deeper fault zone aquifer. Electrical resistivity was implemented to evaluate other possible flow paths, including those through the deeper fault zone aquifer.

Resistivity Characterization of Geology and Hydrology

Electrical resistivity surveying is a geophysical technique used for investigation of shallow anomalies such as changes in rock or moisture conditions (Seaton and Burbey, 2002). The technique consists of a numerous measurements of potential (voltage) between two electrodes while a constant current is applied between two other electrodes. The points at which the potential is measured and the current is applied are systematically widened, resulting in deeper, longer current flow paths that sample more of the subsurface. The electrodes are placed at known spacings (geometry shown in Appendix II) and the current supplied is known, making calculation of apparent earth resistivity quite simple using the following equation for the dipole-dipole array which was used for this study (Sharma, 1997):

$$\rho_a = \pi \cdot a \cdot n \cdot (n+1)(n+2)\frac{\Delta V}{I} \qquad (1)$$

Where ρ_a is the calculated resistivity, a is the electrode spacing, n is an incremented variable, ΔV is the potential difference measured, and I is the input current. The measured potential and calculated resisitivities are the result of the interaction of the supplied constant current and the electrical resistivity of the flow path along which the electric current has traveled and incorporates all resistivity heterogeneities along the flow path into the recorded measurement. It is necessary to invert the dataset to calculate a resistivity model of the subsurface that incorporates the heterogeneities measured as the current flows through the subsurface. Inversion of resistivity data is typically completed with a non-linear inversion-modeling program, such as RES2DINV (Loke, 2002; Loke and Barker, 1995).

Resistivity Techniques and Interpretation

Surface geophysical resistivity imaging was used for characterization of the aquifer systems surrounding the springheads at both study sites. A Campus Geopulse 25 electrode system records 178 measurements using a dipole-dipole array (see Appendix II). The dipole-dipole array provides the best compromise between depth and resolution in the geologic medium present at both the Floyd and Grayson sites (Seaton and Burbey, 2002). The measurements taken by the geopulse unit are recorded together with electrode spacing and are referred to as a resistivity line.

Transitions between typical Blue Ridge Province media (soil, saprolite, etc.) affect the resistivity of the matrix material, and result in imageable resistivity changes. Large resistivity transitions, on the scale of several orders of magnitude, occur in saturated zones due to the significantly higher conductivity of water containing dissolved ions. Similar transitions occur at the regolith bedrock interface where resistivity increases, again by several orders of magnitude, at the transition between soil and solid bedrock.

2-dimensional resistivity models computed for each resistivity line were optimized for minimum root mean square (RMS) error between the observed data and calculated data obtained from forward modeling. In most cases RMS error values of less than 10% exist between observed resistivity sections and earth resistivity calculated from the final models. The most important inversion modeling parameter for model optimization is the “robust constraint” option provided in RES2DINV. The traditional least-squares inversion method attempts to minimize the error by minimizing the squared difference of measured and calculated data, but is quite susceptible to “noise” in the field dataset. The “robust constraint” attempts to minimize the absolute difference (rather than the squared difference of the least squares method) to optimize the model. Consequently, the “robust constraint” is less susceptible to noise spikes or shallow electrode-related spikes that are prevalent in Blue Ridge resistivity data. The robust constraint results in reduced model resolution because of the ‘blocky’, large model cells that result from the use of the “robust constraint” (Loke, 2002). Electrical resistivity is ideal for use in the Blue Ridge because of the large resistivity change between shallow soil, deeper crystalline bedrock, fractures, variably saturated soil and saprolite, and fault zones. Misfits between the modeled and observed data remaining after processing may be remnants of small heterogeneities in the shallow subsurface.

Figure 10 shows the approximate locations and lengths of resistivity lines 1 and 2 at the Floyd County site. Resistivity line 1, shown in Figure 11, was recorded approximately west to east, with a dipole-dipole array incorporating 178 measurements along the resistivity line. This line was recorded several meters north of the actual spring outlet, because of fences and other obstacles close to the spring. Once the field data were checked for errors, the data were then imported into RES2DINV program and inverted to obtain the minimum RMS error.

Figures 11 and 12 each show several anomalies that are of interest in this study. Figure 11 has a distinct high resistivity anomaly near the left center portion of the section. This anomaly is modeled as having a constant resistivity, and is homogenous. The right side of the section shows a lower resistivity anomaly that is roughly 'U' shaped containing a roughly circular low resistivity body and bounded by the high resistivity, homogenous anomaly on the left side of the survey and a few model cells shown as higher resistivity on the right side. Two elliptical high resistivity anomalies are shown in the upper left portion of the model with the rest of the shallow portion of the model having a relatively low, variable resistivity. Figure 12 is a crossline of Figure 11, crossing Figure 11 at approximately 120m from the left end. Figure 12 shows a homogenous, roughly elliptical body near the center of the model that is bounded on all sides by lower resisitivities. The zone below this large, homogenous body is modeled as having a lower resistivity similar to that of the shallow (first few meters) of the model above the homogenous body. A low resistivity, homogenous body is located just left of the elliptical, high resistivity body. The remainder of the shallow portion of the model is modeled as having relatively low, variable resistivity.

Interpretation of the Figures 11 and 12 is based on outcrops, water-level observations collected by the author and by Seaton (2002), and based on fracture zones previously documented by Seaton and Burbey (2002). Generally, decreases in resistivity are correlated with increases in soil/rock saturation. The addition of water to the soil or bedrock increases the conductivity. Bedrock in the area is crystalline, and when intact (containing no fractures) has a very high resistivity. This is confirmed by resistivity well logs, collected by Seaton (2002). Fractures and fracture zones in bedrock generally result in lower resisitivities than bedrock alone because of water or air that are present in the fracture or fracture zone. Other features, such as quartz veins and boulders, are easily identified in outcrop. The resistivity data are also interpreted in the context of Seaton's (2002) model (discussed below). Using multiple data allow the author to make precise interpretations of anomalies appearing in the modeled electrical resistivity data.

Figures 11 and 12 show the anomalies marked with probable interpretations, based on the field evidence mentioned above. Possible flow pathways are marked, and will be discussed later.

Numerous surface electrical resistivity surveys have been performed at the Floyd site by Seaton (2002; Seaton and Burbey, 2002) and by the author of this study. The analyses of the surveys conducted by Seaton and Burbey (2002) were instrumental in the development of the new Blue Ridge conceptual model. The model, presented in Figure 1 (Seaton, 2002), is largely dependent on electrical resistivity imaging of fracture zones. Fracture zones are not always imaged as low resistivity anomalies because of limited resolution of electrical resistivity surveys. Minute fractures are well below the size of features that can be characterized by resistivity imaging. However, large fractures zones with intensely fractured rocks are imageable because of large volume of rock affected by the fracturing.

Seaton and Burbey (2002) present evidence of a high-permeability horizontal fracture zone, represented by intensely fractured rocks and their subsequent lower resistivity, these high permeability zones above the fault plane are referred to here as a fault zone or shear zone. Other dispersed fracture zones are scattered throughout the field site (see Seaton, 2002). The fracture zone is believed to represent the deep aquifer system at the site. The resistivity data interpreted by Seaton indicate that these fracture zones may be saturated, moist, or dry, depending on climate conditions and it is probable that they may become saturated and transmit water during rainfall events.

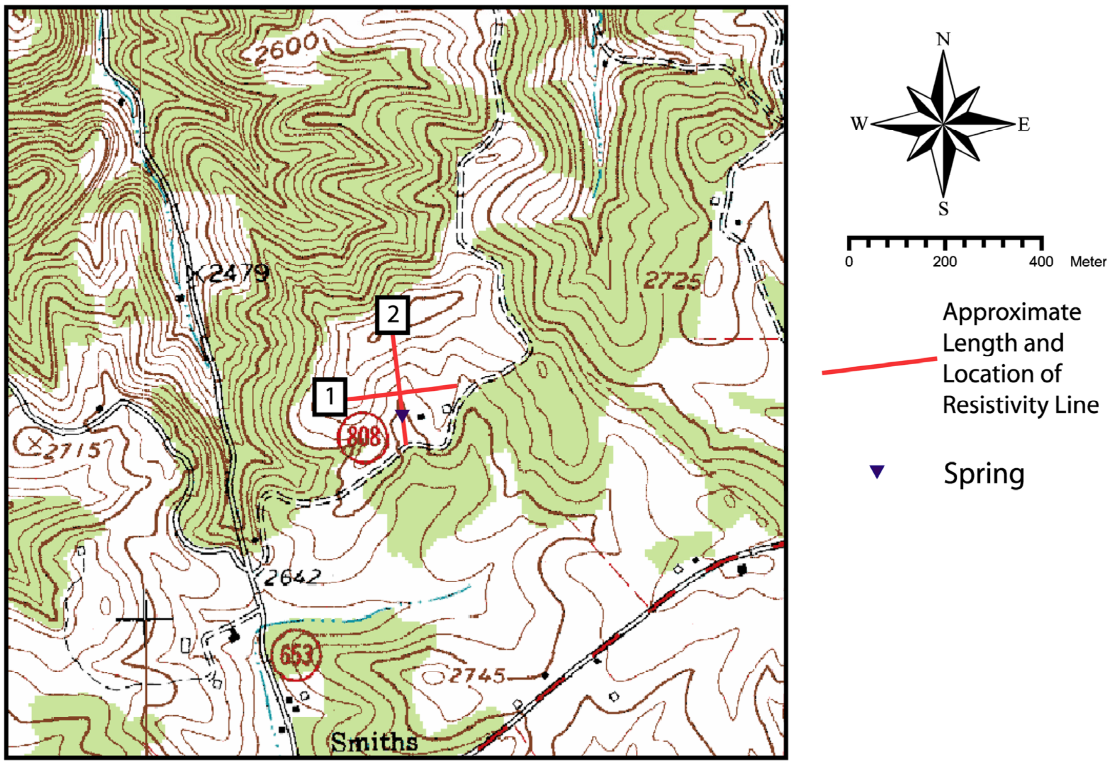

Figure 10 - A portion of the Check, VA topographic map showing approximate resistivity line locations and the spring being investigated (United States Geological Survey, 1963).

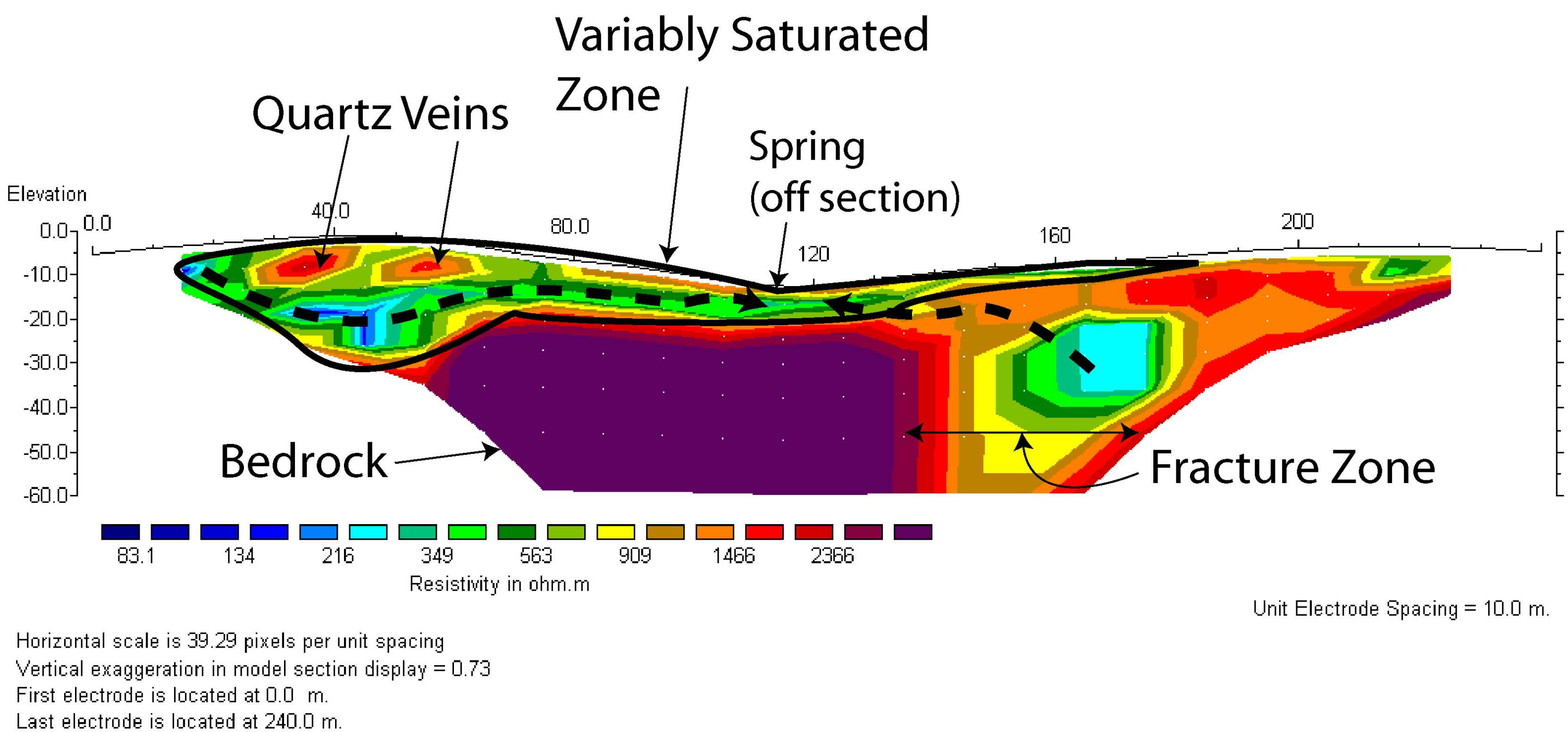

Figure 11 - Interpreted resistivity section (Line 1) from the Floyd County Site. Dashed line indicates possible flow pathways to springhead.

Figure 11 shows several possible flow pathways (marked with dashed lines) for spring SP-01 at the Floyd County site. Of particular interest is the variably saturated zone outlined on the figure. The zone extends from a topographic high on the left (west) side of the survey towards the draw (topographic low) in the center of the survey where the spring is located. This variably saturated zone located near areas of known high permeability suggests that a portion of the water discharged at the spring orifice is provided by the shallow, variably saturated, unconfined aquifer system. And, as suggested by springflow hydrograph analysis and deep aquifer head data collected by Seaton (2002), another possible flow path for spring water originates in the large vertical fracture zone on the east end of the survey where Seaton's (2002) data shows deep aquifer water-levels may rise above land surface. A large low-resistivity anomaly is shown in the fracture zone. This resistivity anomaly probably represents groundwater in the fracture zone, reducing the resistivity of the rocks, soil and saprolite in the zone. There could be a direct connection between the fracture zone and the shallow groundwater system closer to the spring, allowing deep groundwater to discharge to the spring. The low resistivity anomaly may also be directly connected to the shallow groundwater system at the point where this line was recorded. Only two model cells from the shallow system separate the modeled low resistivity body from the spring location. Resistivity data such as those used in this survey are incapable of imaging a feature as small as a single fracture, which is all that is required to transmit volumes of water as small as those recorded at the spring outlet.

Figure 12 shows a dip-line resistivity section (Line 2 from the site map) that crosses Line 1 just north of the spring. The resistivity model images the shallow variably saturated zone, and the deeper aquifer system associated with the fault zone. Missing from this section is the low-resistivity anomaly previously correlated to a groundwater filled fracture zone. It is possible that the fracture is located just out of the plane of the survey, and the low-resistivity zone imaged is the edge of the fracture zone. Figure 12 shows two possible flow paths, one shallow and one deep. The shallow flow path originates at the top of the draw, in a zone characterized by Seaton (2002) as a possible vertical flow/recharge zone . The shallow flow path (or a portion of the flow path) may be responsible for the quick spring response after rainfall events mentioned in the Springflow Hydrograph section. The deeper flow path along the high permeability zone could be responsible for the longterm perennial baseflow discharge at the spring. To confirm a direct connection between the spring outlet and the deeper aquifer system associated with the low resistivity zone, an aquifer test was performed in which water was pumped exclusively from the deep aquifer. Methods and results for the test are included in the next section.

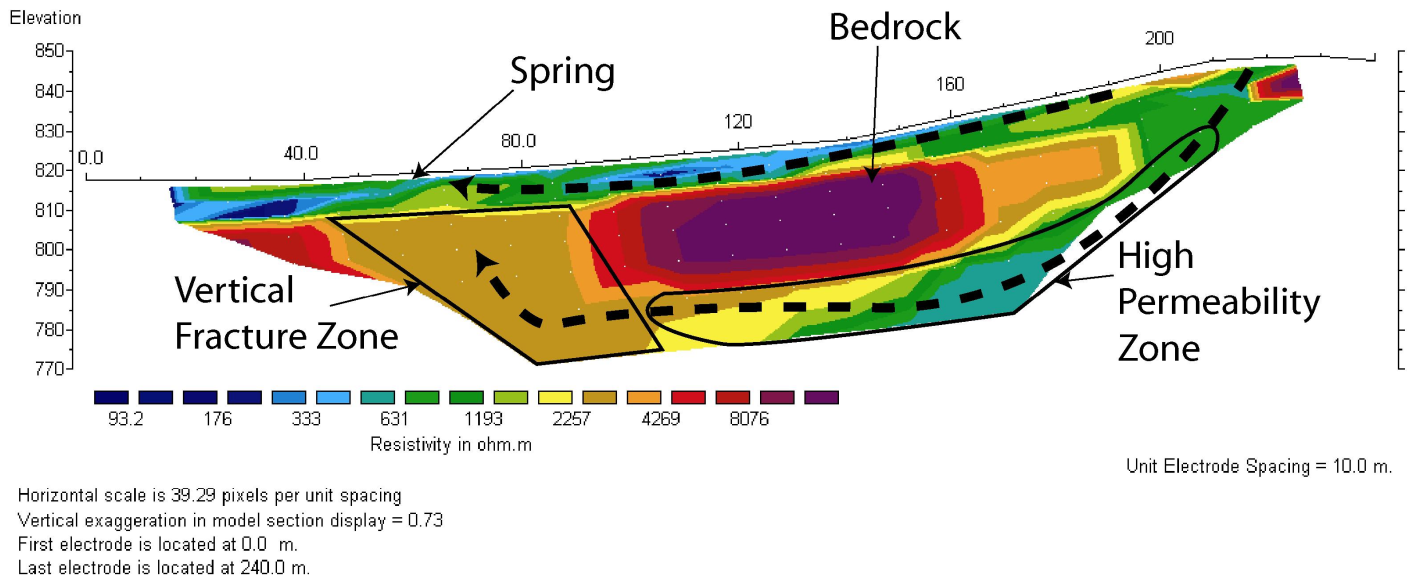

Figure 12 - Interpreted resistivity section (Line 2) from the Floyd County Site. Dashed line indicates possible flow pathways to springhead.

Aquifer Tests

A six-day aquifer test was performed by Seaton (2002) at the Floyd County site in the spring of 2001. Water was withdrawn from deep well W-07 situated near the center of the site to test for fracture connections between wells (Figure 4). The data from the aquifer test show practically no connection between the shallow and deep aquifers. Water level declines in the shallow system were negligible, suggesting no significant flow pathways between the deep and shallow aquifers near the well being pumped. Water-level declines in the well and deep aquifer occurred slowly (over a 6 day period) during pumping with aquifer materials surrounding the well behaving much like an extended well. Analysis of pumping and recovery data suggests that the deep wells are connected by a network of highly transmissive fractures that convey water rapidly to the pumping well, this network of fractures is described as the fault zone aquifer (Seaton, 2002). Interpretation of the data suggests water is flowing in the aquifers on two different times scales. Flow within the deep aquifer is rapid because of the high hydraulic conductivity of the fracture system that comprises the deep aquifer, and flow between the shallow and deep aquifers is very slow because of the low hydraulic conductivity of the confining units separating the two aquifers (Seaton, 2001).

In November of 2002 an additional aquifer test was performed at the Floyd County site by the author of this study to determine a connection between the deep fault zone aquifer and the spring SP-01. The test was designed to evaluate flow between the deep aquifer and the spring outlet and complements the data collected in Seaton's (2002) aquifer test that characterized the flow between the shallow and deep aquifers. Deep well W-03 (Figure 4) was packed off just above the producing fracture zone indicated by Seaton (2002) to ensure only the deep aquifer was pumped and there was no connection with the shallow aquifer. The discharge of SP-01 was monitored through the duration of pumping and for several hours after pumping. W-03 was pumped at 2.5-3.0 gallons per minute for 4 hours resulting in nearly 180 feet of drawdown measured in the pumped well over approximately 3 hours. In addition to monitoring of the pumping well and spring discharge rates during pumping, water samples were taken at half hour intervals from the pumped well and from the spring in an attempt to characterize changes in water chemistry during the pumping test. If the pre-aquifer test spring water is a mix of water from the shallow and deep aquifers, and pumping W-03 reduces the head in the deep aquifer so it no longer provides water to the spring outlet, the water chemistry during and after the aquifer test will resemble the chemistry of the shallow aquifer sampled at P-01. If the pre-aquifer test spring water is solely from the deep aquifer, the water chemistry will no resemble the chemistry of the shallow aquifer during or after the test.

The results of the aquifer test are shown in Figure 13. This figure shows spring discharge and pumping well discharge for the duration of the aquifer test. The results show that spring discharge decreased by more than 50% as the well was pumped. The spring responds almost instantly as pumping begins and the well is water level in the well is lowered. The spring also recovers almost as quickly after pumping ends. This suggests the well and spring are connected by a flow pathway with a very high hydraulic conductivity (such as a fracture, or fracture network). Spring discharge was reduced by approximately 2/3 after 3 hours of pumping. This suggests that a majority of the spring’s discharge was from the deep aquifer pumped at well W-03. The remainder of the discharge may come from another fracture or from the shallow zone.

Figure 14 shows temporal changes in anion water chemistry from the samples collected at half hour intervals during the pumping duration of the aquifer test. Additional samples were collected from a piezometer (P-01) located beside W-03 for comparison of water chemistry from the shallow and deep aquifers. The anomalous data points in the chloride, phosphate and bromide plots (zero or near zero concentrations) may be due to analysis error (incorrect peak picking by the chromatography software). The anion chemistry from the spring does not trend towards the water chemistry of the shallow zone (high nitrate content) sampled at P-01. This suggests the water discharged from the spring outlet, even after significant pumping of W-03 may come from another fracture, rather than the shallow aquifer.

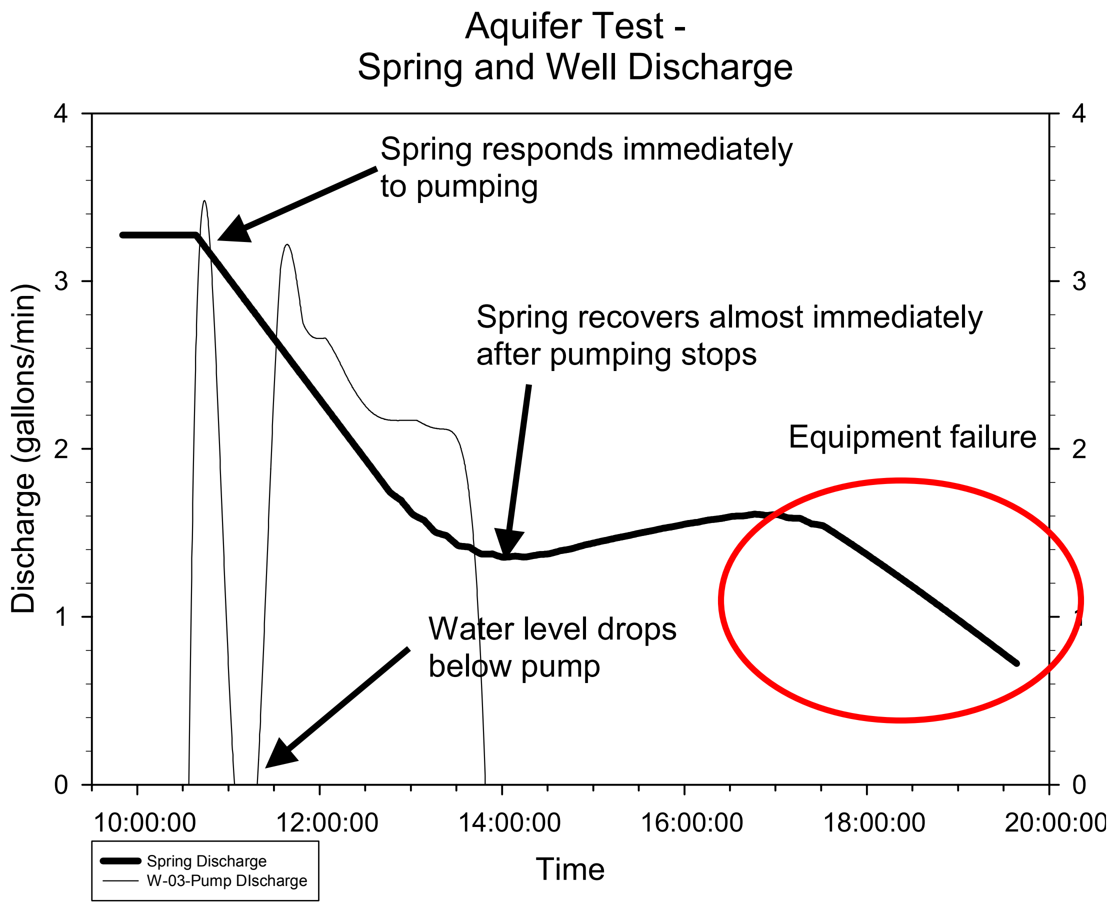

Figure 13 - Graph showing spring and pump discharge during the aquifer test performed in November of 2002. The water level dropped below the pump at approximately 11:05AM and pumping resumed at 11:20 after lowering the pump several more feet.

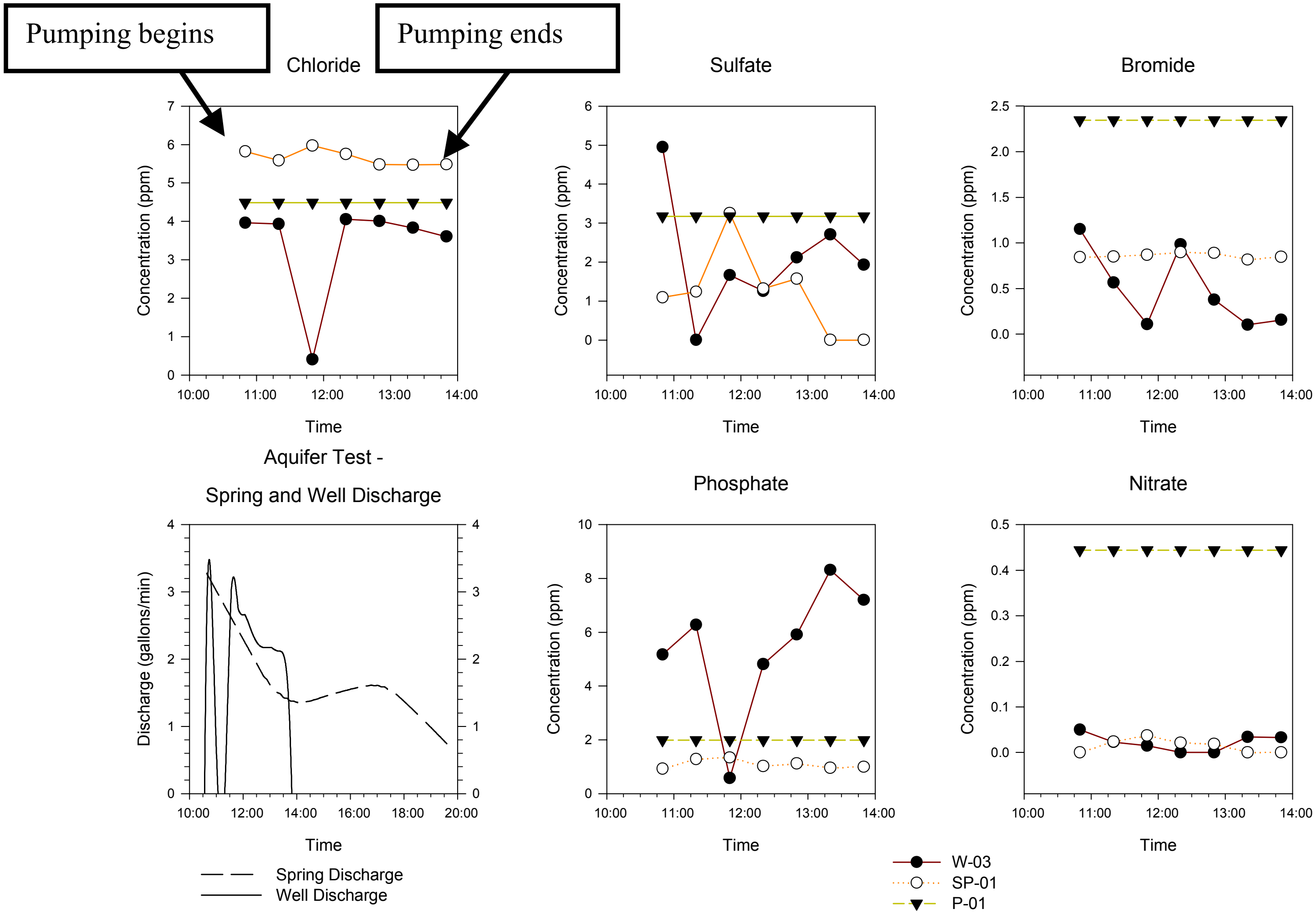

Figure 14 - Graphs showing changes in water chemistry during the aquifer test. A graph showing time of pumping is located in the lower left.

The pumping data, combined with the spring-discharge record during the aquifer test, show a direct connection between well W-03 (deep aquifer) and spring SP-01. Such a rapid change in discharge is not likely if the flow system supplying the spring is a porous media type system. Changes in head would likely take days to correlate to a change in discharge in this kind of system, assuming the cone of depression from the pumping well doesn't reach the springhead. A fracture flow path between the well and the spring outlet could respond within hours and is the likely flow path supplying the spring. The water chemistry data and the lack of trend towards the shallow water chemistry also suggest that the remainder of the spring discharge (approximately 1 gallon per minute) comes from another fracture not connected to well W-03.

This second aquifer test confirmed the direct connection between the deep aquifer and by W-03 and shows that the deep aquifer supplies at least 50%, possibly 100% of the water present at the spring outlet of SP-01. The aquifer test was performed during baseflow conditions, when shallow aquifer contributions to the spring's discharge are minimal. Spring and summer spring discharge rates are typically 200% of those recorded during winter baseflow. This indicates an additional source of water available as spring discharge during these months. This water could come from the shallow aquifer. Had a similar aquifer test been performed in the summer months where spring discharge is 3-4 gallons per minute higher, different results may have occurred. More substantial flow to the spring outlet, possibly from the shallow zone, during the summer months could result in water chemistry more similar to the shallow zone chemistry during a similar pumping test completed during a different season. It is likely contributions from the deep aquifer remain nearly constant year round because of the large head changes in the deep aquifer system necessary to induce a change in the spring's discharge. Spring discharge is likely to be nearly 100% baseflow-deep aquifer water in the winter months, and mixed with approximately 50% deep aquifer groundwater and 50% shallow aquifer groundwater in the spring and summer months.

The data indicate the flow during the summer months, when spring discharge is high, is largely due to rapid flow through the shallow zone. Baseflow recorded during drought and winter is likely from the deep aquifer and reflects slow recharge. All the data indicate a mixed shallow and deep flow paths providing water to the springoutlet.

Applications to Other Locations

The Grayson County site was selected to test the knowledge gained from the investigation at the Floyd County site in order to evaluate the usefulness of springflow hydrograph analysis for evaluating aquifer systems at other fractured rock locations. Located in a geologically similar terrain, analysis of springs using the hydrograph method proceeded as it did at the Floyd County site.

Two springs were investigated at the Grayson County site (Figure 15), and were instrumented with the same equipment used to measure discharge at the Floyd County site. GSP-04 is a perennially flowing spring that was drilled and cased several years ago and was observed to have near constant discharge and may alternately be described as a flowing artesian well. GSP-05 is a perennially flowing spring that fluctuates in flow. The recorded discharge for GSP-04 and precipitation are presented in Figure 16. The spring shows surprisingly little response to rain inputs. Spring discharge remained nearly constant showing no changes during the three relatively large rainfall events that occurred during monitoring. The near constant discharge could be caused by very slow flow of water from the surface to the aquifer supplying the spring outlet. Such a slow flow caused by low hydraulic conductivities would result in a very long lag time between rain event and the corresponding increase in spring discharge and the discharge peak would be very subdued.

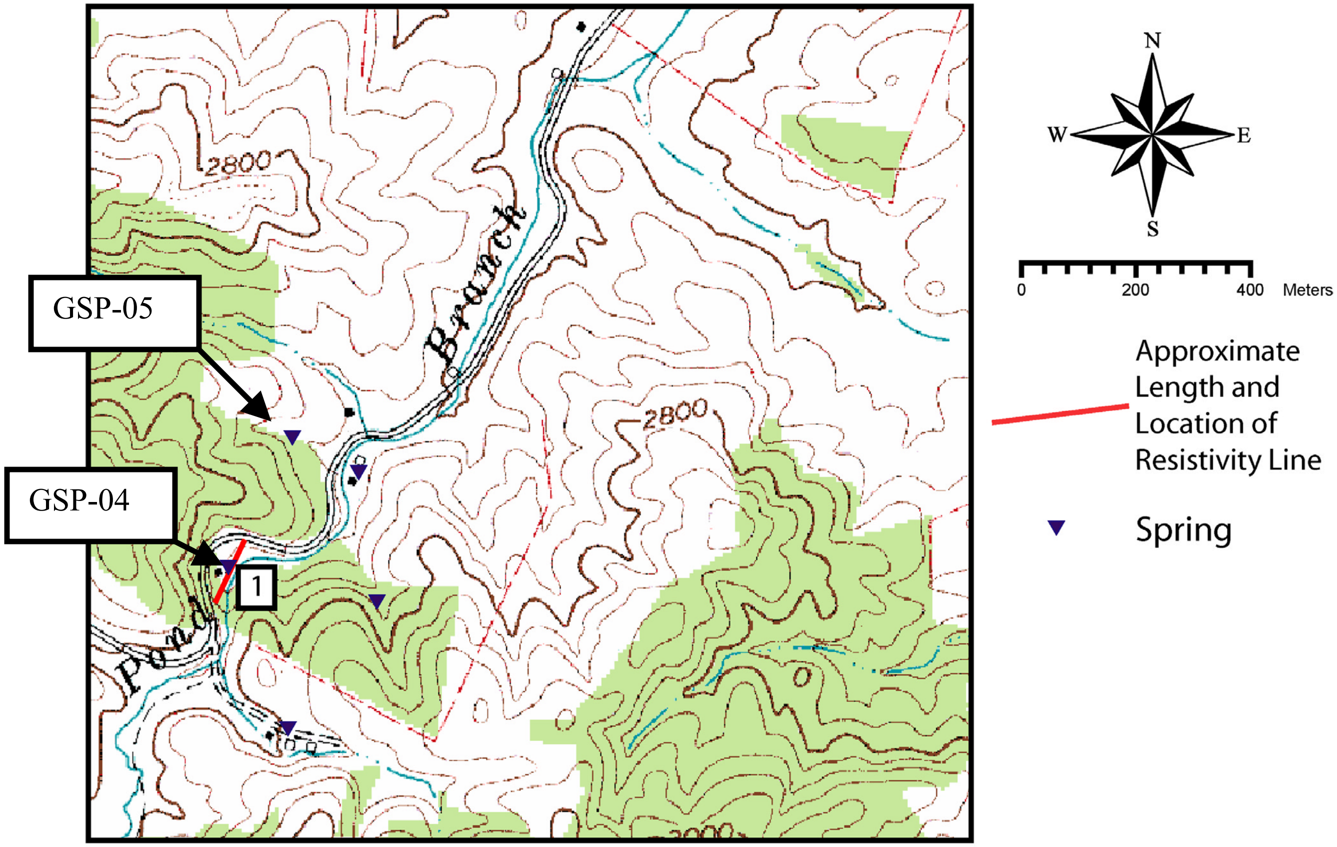

Figure 15 - Map showing locations of springs and a resistivity survey in Grayson County.

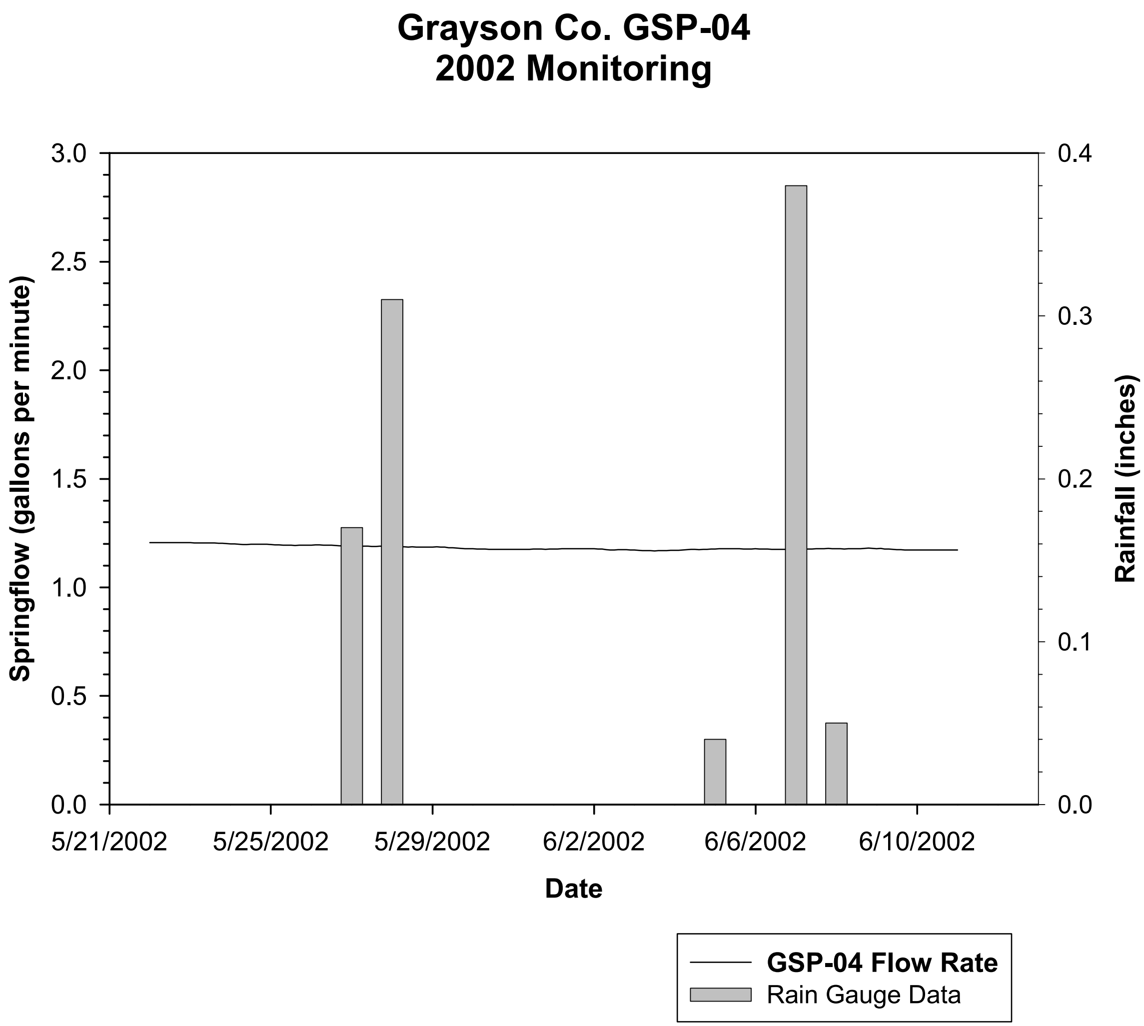

Figure 16 - Spring discharge at Spring #04 at the Grayson County site.

Figure 17 shows a hydrograph and precipitation for GSP-05 at the Grayson County site. The second spring shows a much 'flashier' response to rain events, and resembles the hydrographs from the Floyd County site. An isolated rain event was not captured by the discharge monitoring equipment, and subsequent knowledge of lag times is unavailable. Lag times (if the system is consistent with the Floyd County site) of several days are likely. Rainfall events and correlated discharge increases are circled on Figure 17. α values cannot be calculated for this spring since little qualitative data are known about the groundwater system at the springhead. In this case the hydrograph yields only qualitative evidence of a substantial connection to the shallow aquifer through its apparent rapid response after rain events.

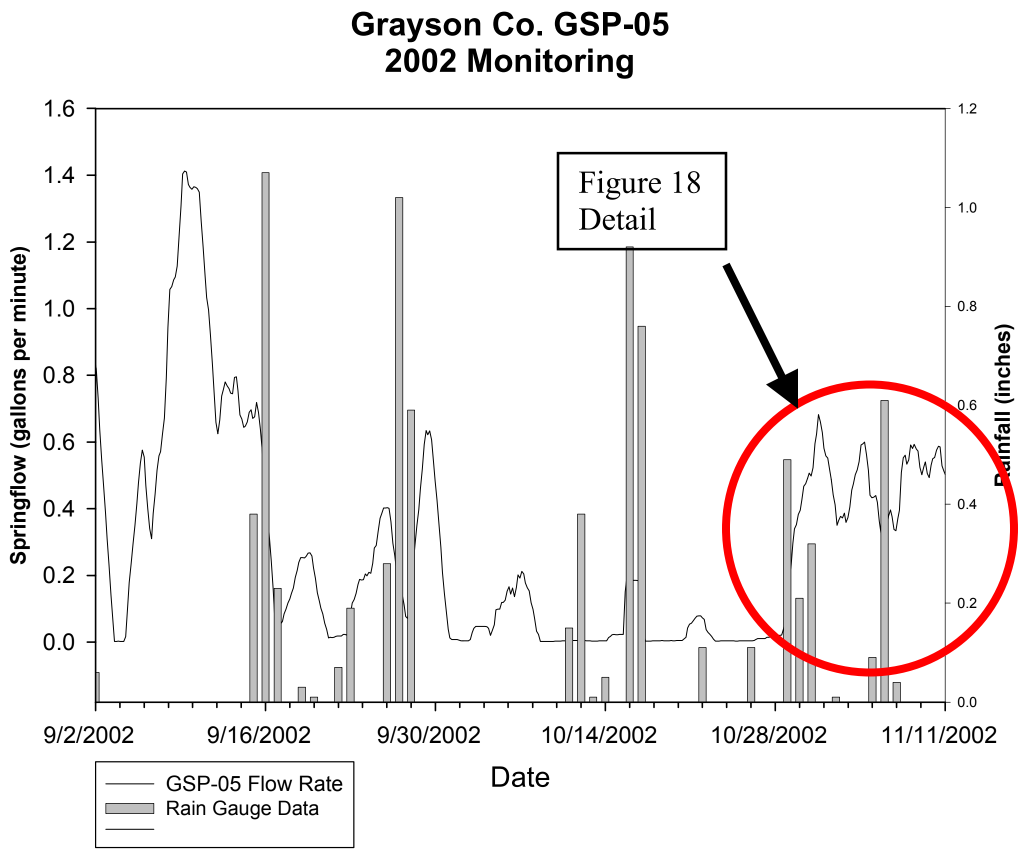

Figure 17 - Springflow and rainfall at GSP-05 in Grayson County

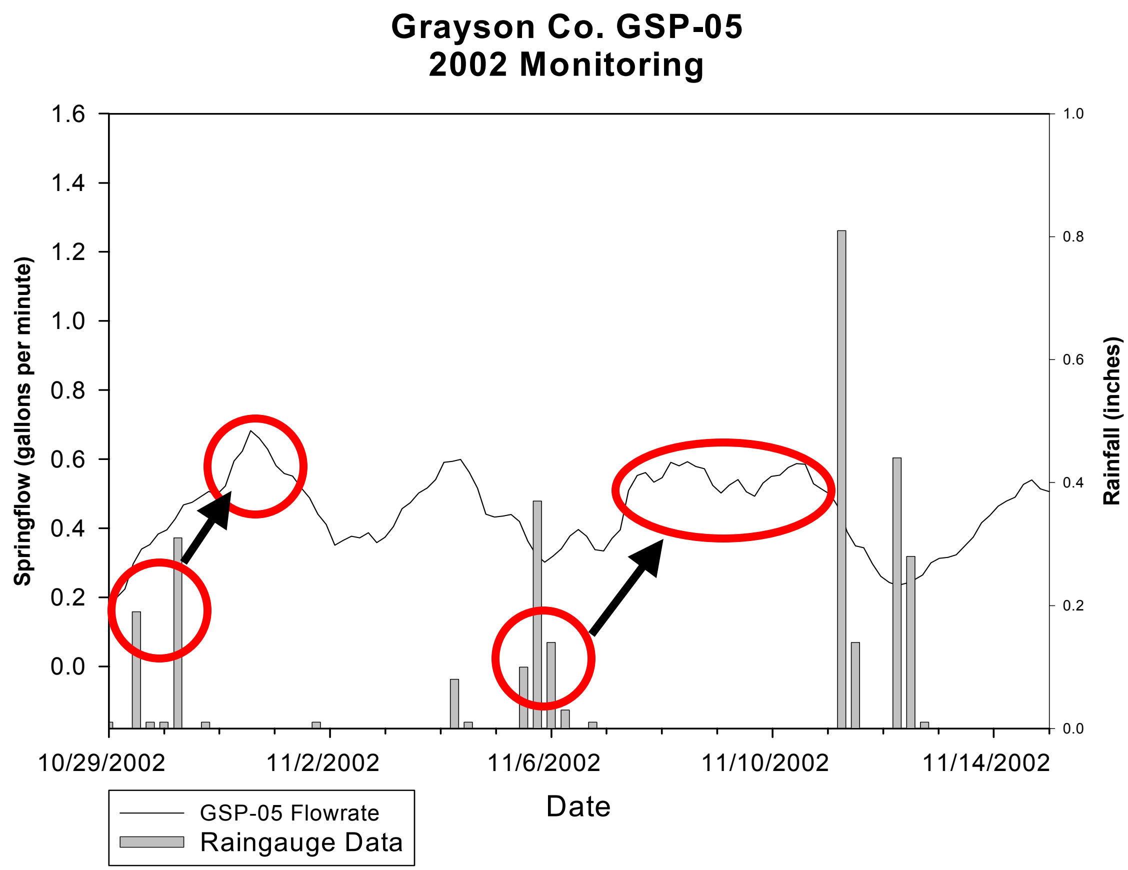

Figure 18 – Figure showing several rain events and probable correlated discharge peaks at GSP-05

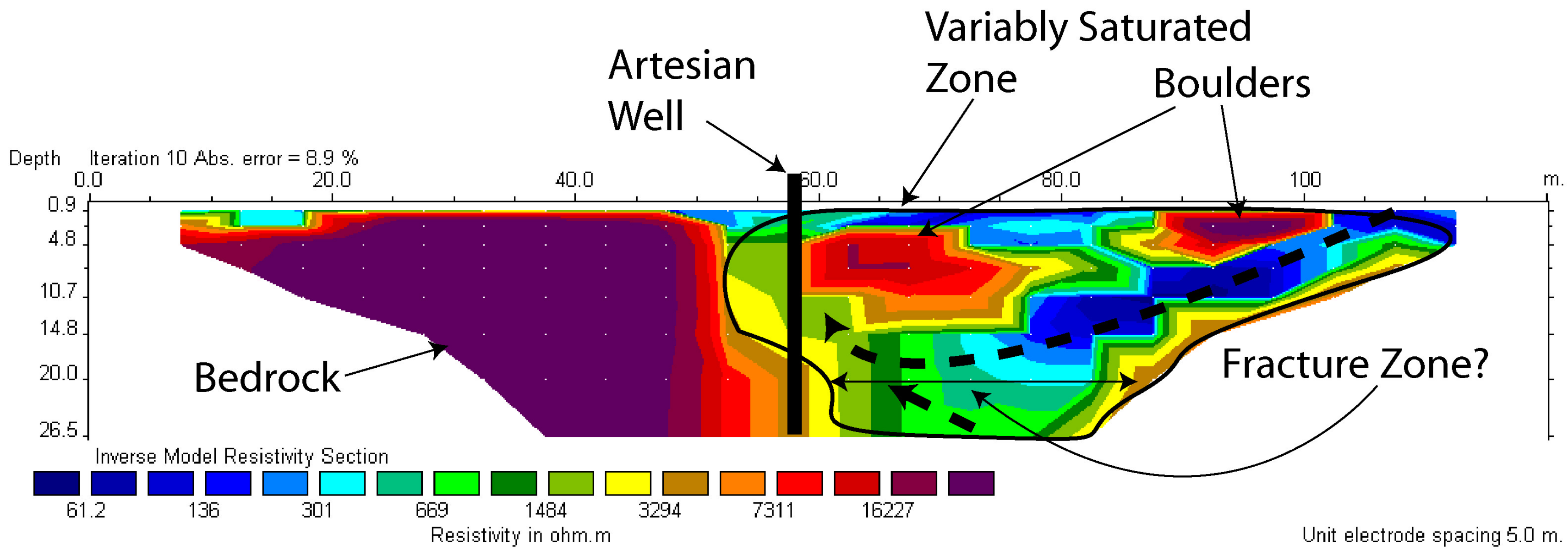

Figure 19 - Interpreted resistivity section from a spring located at the Grayson County Site.
Dashed line indicates possible flow pathway to springhead.

Figure 15 shows the location of a resistivity survey performed in Grayson County, near GSP-04. Only one survey was conducted at the Grayson Site because of very thick briers located around other springs. The resistivity line is oriented perpendicular to the topographic expression of a large fracture/lineament and oriented along the strike of the rocks in the area. Figure 19 shows the interpreted survey with a distinct bedrock high on the left (southwest) end of the section. The northeast side of the section is considerably more complex, showing features such as boulders and a possible fracture zone. The spring is located in the middle of the resistivity section, and was drilled and cased to a depth below the maximum depth of investigation for this resistivity survey. The casing should predetermine the flow path for the spring discharge. If the casing is intact and the recharge to the deep aquifer system is slow, the hydrograph will be predictably flat (as it appears in Figure 16). However, if there is rapid recharge to the aquifer supplying the water to the flowing artesian well, the hydrograph will rainfall related peaks. The northeast side of the section shows a variably saturated zone that extends from the spring location to the northeast end of the survey. This zone may have been a previous contributing flow path for the spring. The casing prevents any fluids from this shallow aquifer from contributing to the spring discharge. The zone below the spring appears to be a vertical fracture zone, a possible connection to a deep aquifer system. Spring discharge data confirm the resistivity observation of no direct connection to a shallow aquifer system.

The hydrograph analysis method has helped determine possible flow paths for springs GSP-04 and GSP-05 in Grayson County. In the case of GSP-04, the flow path was known to be through the deep system, with little to no input from the shallow aquifer. The hydrograph confirmed this, showing a near constant discharge. GSP-05 was believed to be mostly shallow or a mixed shallow and deep system because of its intermittent flow. The hydrograph has provided evidence of a shallow flow path, through the rapid response after a rain event, and a deeper or intermediate flow path by the sustained discharge after rainfall events.

Summary and Conclusions

Perennial springs have been described and used as drinking water supplies for many decades in the Blue Ridge Physiographic Province. CFC data have been used to show that at least two different ages of water exist, modern (less than 30 years old) and old (greater than 30 years old). These two types of groundwater are contained within a shallow and deep aquifer, respectively. Anion and cation concentrations in water samples taken at the Floyd County site confirm this relationship, with higher concentrations of mean equivalent ions in water with longer residence times in the deeper aquifer system. Observations of springs using hydrophysical and hydrochemical tools suggested that some springs may be partly sourced in the shallow aquifer and are susceptible to drought, while others may be sourced in the deep aquifer and are less susceptible to drought. Monitoring of spring discharge at both the Floyd and Grayson sites has shown that some springs display fast (2-4 days) responses to rain events, indicating that water has flowed very quickly to the spring outlet after a rain event, or that the recharge area is in close proximity. Other springs have shown very little change in discharge after rain events, suggesting that their source water flows very slowly to the spring outlet or the recharge zone is far away. Still other springs show a mixed flow system with both shallow and deep sources shown as peaks after rain events, and sustained near constant baseflow discharge, even during drought. Electrical resistivity characterization of geology and hydrology has supported these interpretations. An aquifer test performed at the Floyd County site also confirmed the connection between the deep aquifer system and a spring outlet.

This investigation has shown the springflow hydrograph analysis method is useful for describing different flow paths that may be supplying water to a spring outlet in the Blue Ridge Physiographic. The hydrograph recession analysis method has shown that springs in the Blue Ridge Province, in some instances, behave similar to previously evaluated springs in fractured chalk aquifers in the Middle East, having nearly identical recession coefficients indicating similar recession time periods possibly through hydraulically similar aquifer materials. However, the method is not suited to providing quantitative aquifer parameters in the studied area because of the necessary body of *apriori* knowledge that is necessary to quantitatively analyze hydrographs. However, the hydrograph analysis method can provide substantial qualitative evidence about water sources for spring outlets. The method can be used to show whether a spring source originates from deep aquifers that are less susceptible to surface contamination, or from shallow aquifers and are more susceptible to surface contamination, or from mixed systems. Hydrograph data combined with geophysical data from surface resistivity and borehole logs, chemical data, and physical aquifer test data can be used to describe details of the flow paths, including subsurface geometry.

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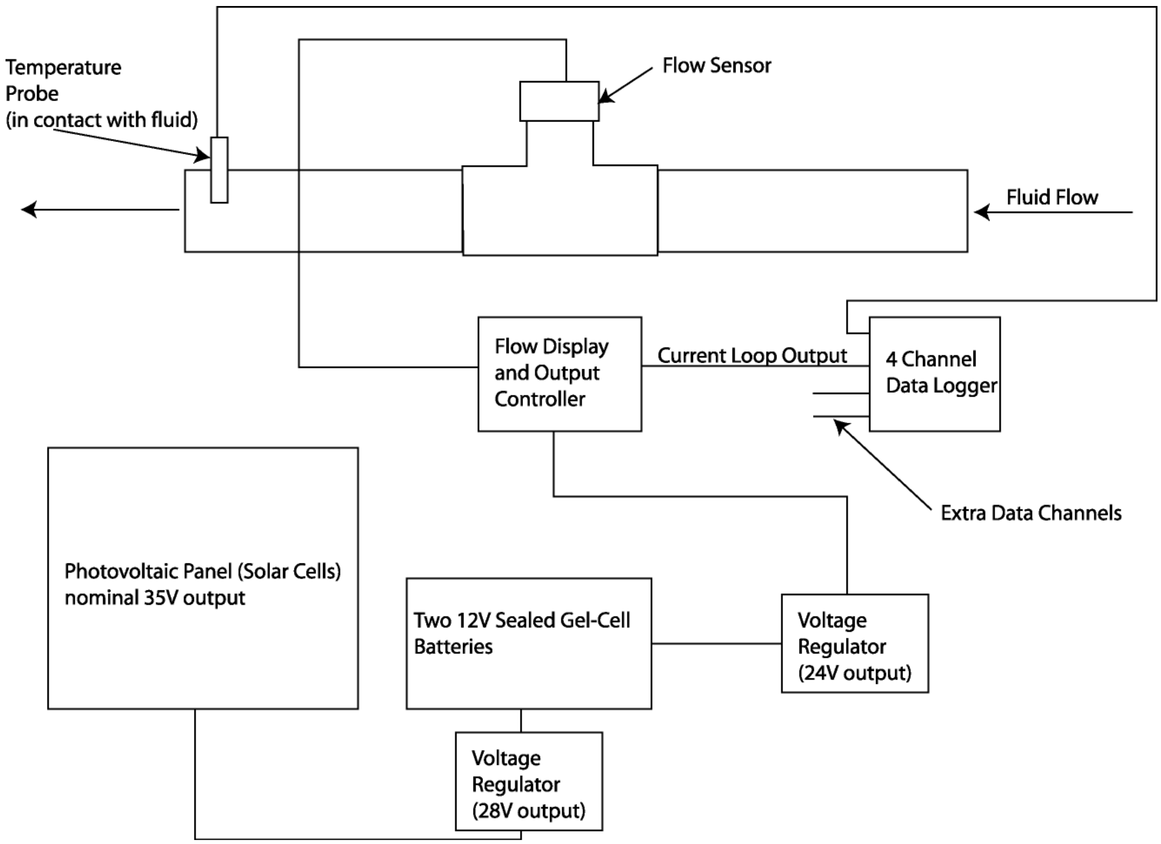
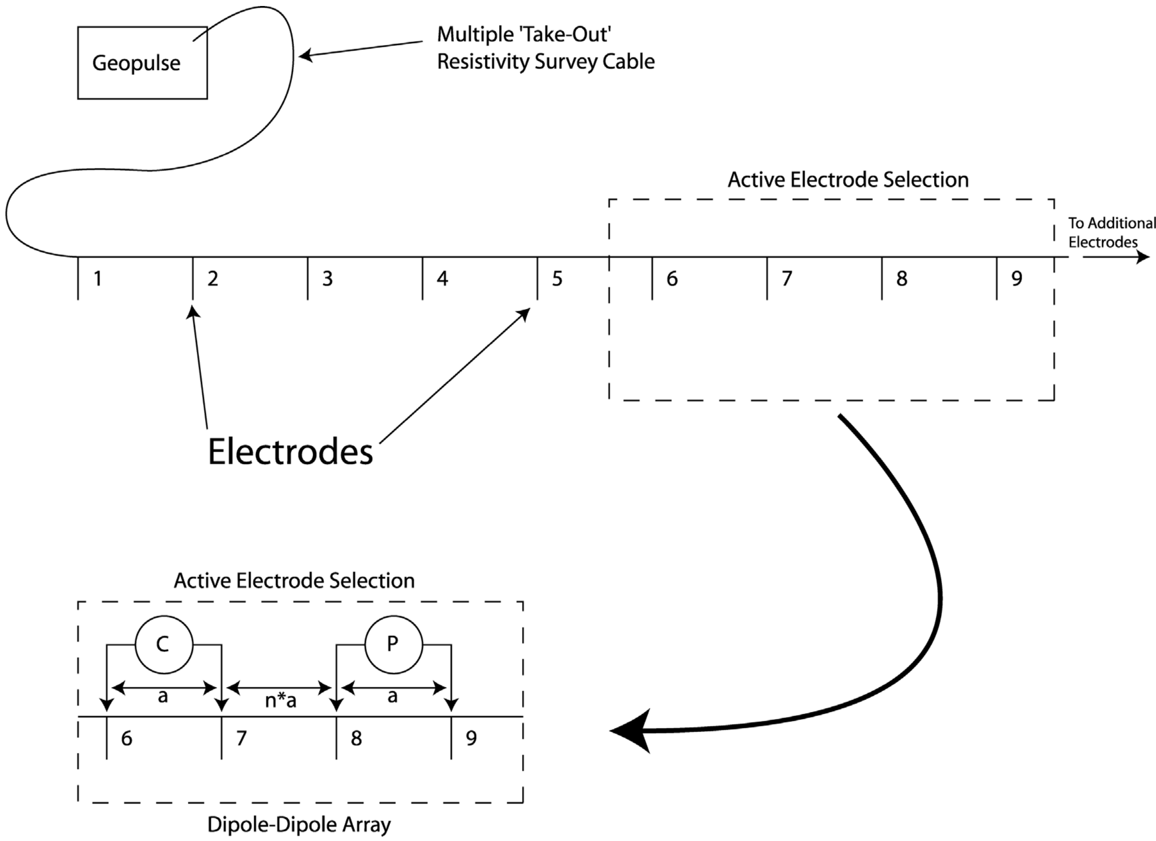
Appendix I – Schematic Diagram of Discharge Measurement System



This low flow monitoring and logging system was developed to compliment the research performed in this study. The system is capable of monitoring flows down to ¼ of a gallon per minute and has virtually no upper limit to its measurement capability. Additional probes have been developed for measurment of numerous environmental parameters. Currently in use at the Brinton Arsenic Mine Site (BAMS) are pressure transducers for monitoring of water levels in wells or impoundments and temperature probes. Any industry standard probe with 4-20mA current loop output can be readily connected to the system for monitoring and logging. The system provides power through two solar panels that are capable of supporting current loads in excess of 50mA if the solar panels receive direct light for a majority of daylight hours. More current capacity is available by upgrading the solar cells to 10watt or larger capacity panels.

Appendix II – Dipole-Dipole Array Details



The Campus Geopulse is an automated resistivity profiling system, capable of making resistivity measurements that may be converted into resistivity pseudosections. The system consists of a laptop controlled resistivity meter (labeled Geopulse), which is connected to a twenty five electrode resistivity cable. Electrodes are planted in the soil at even spacings (in most cases either 5 or 10m) and a series of measurements are taken. For this study, the dipole-dipole array was selected. The dipole-dipole array supplies a current to two electrodes while taking a potential (voltage) reading between another pair of electrodes. The spacing between the two dipoles (n*a) is widened with each successive pass down the resistivity cable, resulting in imaging of deeper subsurface features. The a spacing remains constant throughout the survey. Potential measurements are converted to resistances and ultimately resisitivities by software contained on the laptop controlling the Geopulse.

Appendix III – Resistivity Inversion Parameters

Initial damping factor
0.3000
Minimum damping factor
0.0300
Line search option
2
Convergence limit
1.0000
Minimum change in RMS error
0.4000
Number of iterations
10
Vertical to horizontal flatness filter ratio
1.0000
Model for increase in thickness of layers(0=default 10, 1=default 25, 2=user defined)
1
Number of nodes between adjacent electrodes
4
Flatness filter type
1
Reduce number of topographical datum points?
0
Carry out topography modeling?
1
Type of topography trend removal
1
Type of Jacobian matrix calculation
2
Increase of damping factor with depth
1.0500
Type of topographical modeling
4
Robust data constrain?
1
Cutoff factor for data constrain
0.0500
Robust model constrain?
1
Cutoff factor for model constrain
0.0050
Allow number of model parameters to exceed datum points?
1
Use extended model?
0

Reduce effect of side blocks?
2
Type of mesh
2
Optimise damping factor?
1
Time-lapse inversion constrain
0
Type of time-lapse inversion method
0
Thickness of first layer
0.3418
Factor to increase thickness layer with depth
1.2500
USE FINITE ELEMENT METHOD (YES=1,NO=0)
1
WIDTH OF BLOCKS (1=NORMAL WIDTH, 2=DOUBLE, 3=TRIPLE,
4=QUADRAPLE, 5=QUINTIPLE)
1
MAKE SURE BLOCKS HAVE THE SAME WIDTH (YES=1,NO=0)
1
RMS CONVERGENCE LIMIT (IN PERCENT)
1.000
USE LOGARITHM OF APPARENT RESISTIVITY (0=USE LOG OF APPARENT
RESISTIVITY, 1=USE RESISTANCE VALUES, 2=USE APPARENT RESISTIVITY)
0
TYPE OF IP INVERSION METHOD (0=CONCURRENT,1=SEQUENTIAL)
0
PROCEED AUTOMATICALLY FOR SEQUENTIAL METHOD (1=YES,0=NO)
0
IP DAMPING FACTOR
0.150
USE AUTOMATIC IP DAMPING FACTOR (YES=1,NO=0)
0
CUTOFF FACTOR FOR BOREHOLE DATA (0.0005 to 0.02)
0.00100
TYPE OF CROSS-BOREHOLE MODEL (0=normal,1=halfsize)
0
LIMIT RESISTIVITY VALUES(0=No,1=Yes)
1
Upper limit factor (10-50)
20.000
Lower limit factor (0.02 to 0.1)
0.050
Type of reference resistivity (0=average,1=first iteration)
0

Vita

W. Miles Gentry

Education
B.S., Geological Sciences, 2000, Virginia Tech
M.S., Geological Sciences, Virginia Tech

Work Summary
Mr. Gentry has two years experience in evaluation of aquifer properties using traditional field methods, and using custom manufactured equipment for measuring low discharge spring flow. The investigation involved measurement of spring discharge and resulting hydrographs to evaluate aquifer properties and use of traditional aquifer evaluation techniques including geophysical surface and borehole techniques to confirm the results obtained using the hydrograph method. Mr. Gentry also has experience with numerical modeling of groundwater transport and flow, geophysical inversion modeling, and laboratory analysis of water samples using Dionex DX-120 Ion Chromatograph.
Professional Experience
January 2001 to Present, Graduate Research/Teaching Assistant, Virginia Tech. As a Master's student at Virginia Tech, Mr. Gentry designed field equipment to measure and record low spring discharge. Equipment was used in the production of a master's thesis and is currently used at the Brinton Arsenic Mine Site for environmental monitoring. Other research included analysis of water samples using a Dionex DX-120 Ion Chromatograph to analyze concentration of basic anions. Mr. Gentry also conducted surface geophysical resistivity surveys at four sites and processed the resulting datasets into resistivity pseudosections. These datasets were used to evaluated the springflow hydrograph method as a useful tool for characterization of groundwater resources in the Blue Ridge Province of Virginia.

Computer Proficiency
Mr. Gentry has experience with document production using Word, Adobe Photoshop, Adobe Illustrator, ArcView 3.2 and ArcMap 8.1. Mr. Gentry also has extensive modeling experience including use of RES2dINV for inversion modeling of resistivity data, ArgusOne/MODFLOW 2000 and GMS for modeling of groundwater flow and transport.

Publications
Gentry, W. M., and T. J. Burbey, 2002, Analysis of Spring Discharge for Characterization of Groundwater Flow in the Blue Ridge Province, Virginia: Geological Society of America Annual Meeting.
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