Physical Investigation of Field Scale Groundwater Recharge Processes in the Virginia Blue Ridge Physiographic Province

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Abstract

Physical and geophysical data collected at the Fractured Rock Research Site in Floyd County, Virginia indicate that recharge rates to the subsurface are controlled by a small scale thrust fault associated with regional thrust faulting within the Blue Ridge Province. Recharge rates appear to be correlated to spatial variation in the hydraulic conductivity of the regolith, which has been influenced by weathering rates and the metamorphic and structural history of the underlying parent material. Previous studies conducted at the Fractured Rock Research Site suggest that recharge potential can be separated into two regions: one over a vertically oriented shear zone associated with the small scale thrust fault, and the other overlying a thrust fault hanging wall. The angle of dip of the thrust fault shear zone and the fracturing within the crystalline rock adjacent to the fault plane appear to serve as geologic controls that preferentially direct infiltrated meteoric water to a deeper confined aquifer. The structural competence of the granulite gneiss thrust fault hanging wall appears to act as a barrier to deeper groundwater recharge, causing the formation of a shallow semi-confined aquifer within the overlying regolith.

In-situ analysis of matric potential and moisture content shows two distinctly different recharge processes that are spatially correlated with the structure of the shallow subsurface (regolith overlying the vertically oriented shear zone and regolith overlying the thrust fault hanging wall), and have been shown to have strong temporal correlations with the dynamics of the underlying saturated conditions.

Recharge flux estimates within the regolith overlying the thrust fault hanging wall are uncharacteristically high, and appear to be offset within the monitored region by the upward hydraulic gradient associated with the potentiometric surface of the underlying semi-confined aquifer. Because of the influence exerted by the upward hydraulic gradient on matric potential within the unsaturated regolith overlying the semiconfined aquifer, accurate recharge estimates could not be obtained from the matric potential data recorded by the tensiometers along this portion of the transect. Recharge flux within the regolith overlying the vertically oriented shear zone is strongly controlled by the orientation and aerial extent of the thrust fault shear zone, and highlights the importance of accurate delineation of recharge areas in crystalline rock aquifer systems.

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Introduction

The Blue Ridge Physiographic Province represents a band of highly metamorphosed crystalline and sedimentary rock extending in a northeastern direction from western Georgia to south-central Pennsylvania and includes structurally complex assemblages of northeast-southwest striking thrust faults. The study site for this paper (the Floyd County Fractured Rock Research Site) is situated on the western margin of the Blue Ridge Physiographic province (Figure 1), and serves as an example of the regional metamorphism that gives the Blue Ridge Physiographic Province its distinct features. Hydrologic characterization of this site has revealed a geologically complex multi-aquifer system containing laterally separate water tables, a deep shear zone aquifer, and a semiconfined aquifer (Seaton and Burbey 2000; Seaton 2002; Gentry and Burbey 2004; Seaton and Burbey 2005). Although much of the saturated flow regime at the Fractured Rock Research Site has been delineated and quantified, the source locations and rates of groundwater recharge to the aquifers at the site were previously unknown. This thesis presents a description of the temporal and spatial occurrences of localized groundwater recharge and unsaturated flow at the Fractured Rock Research Site, and includes a discussion of the geologic controls on recharge.



Figure 1. Site location and topography; cross section A-A' delineates the study transect.

Background

The importance of groundwater recharge processes in the temperate Blue Ridge and Piedmont Physiographic Provinces has been accentuated by recent water shortages throughout the eastern United States. Current municipal and industrial demands on groundwater resources and rivers during base flow periods have shown that groundwater supplies are finite and subject to overuse in the absence of adequate precipitation. A period of below average precipitation from 1998 to Fall of 2002 prompted federal disaster relief of many drought stricken areas in the Blue Ridge and Piedmont. Hundreds of deeper wells were drilled with private and federal monies in these regions to replace springs and wells that have historically been of sufficient yield.

As populations in the Eastern U.S. continue to increase, many communities in the Blue Ridge Physiographic Province and the hydrogeologically similar Piedmont Physiographic Province will seek new sources of water to meet municipal and industrial demands. While some of this demand will be met with surface water impoundments, a significant portion of this demand will inevitably be met through groundwater extraction. A better understanding of the mechanisms controlling the occurrence and timing of groundwater recharge is essential for the purposes of regional planning and supply.

To date, hydrograph separation has been the only method used to quantify groundwater recharge within the Blue Ridge Physiographic Province (Daniel 1996; Daniel and Harned 1998). This technique permits a basin wide estimate of recharge through the analysis of long term stream flow hydrographs whereby the base flow portion of the hydrograph is assumed to equal the amount of recharge that occurred in the basin under study. Although this is a straightforward method for indirectly quantifying recharge, the assumptions inherent in this methodology constrain the use of hydrograph separation to the watershed scale, making it ineffective at correlating recharge rates with geologic structure or land use.

In order to correlate recharge rates with geologic controls, direct methods of recharge analysis must be used. Because controls on recharge rates in the Blue Ridge Physiographic Province are dominated by topography and geologic structure, an accurate description of recharge processes at a certain locale demands detailed geophysical and hydrogeologic site investigation and continuous in-situ monitoring of hydrologic conditions. From these observations, correlation of recharge rates with geologic structure can be made. There have been several classic studies that have directly quantified

groundwater recharge rates using in-situ approaches. Extensive work in the Chalk aquifer of England (Wellings 1984; Cooper, Gardner et al. 1990; Haria, Hodnett et al. 2003) has shown that the in-situ analysis of matric potential and volumetric water content is a viable approach for analyzing vertical drainage fluxes in response to precipitation, and for correlating the behavior of these fluxes with depth to water. Studies of matric potential in the unsaturated zone of fractured basalt aquifers in Idaho have shown that it is possible to correlate the timing of recharge with geologic structure (Hubbell and Sisson 1998), and additionally, have shown that is possible to quantify recharge rates in vertically extensive vadose zones with the use of tensiometers (Hubbell et al. 2004; McElroy and Hubbell 2004).

This study utilizes an assortment of geophysical and hydrogeologic characterization techniques for describing groundwater recharge processes occurring at the site and for correlating these processes with geologic structure. Geologic site characterization conducted by Bill Seaton (Seaton and Burbey 2000; Seaton 2002; Seaton and Burbey 2005) utilized two dimensional surface electrical resistivity surveys and geophysical borehole logs of multiple wells at the site, and serves as the basis for the geologic site conceptualization. In addition to providing a geologic representation of the site, these data and additional surface electrical resistivity data were used to guide the placement of access tubes and tensiometers at various depths in the unsaturated zone. Tensiometers were installed in selected portions of the unsaturated zone at depths ranging from 3 to 12 meters to monitor matric potential on an hourly basis. Access tubes installed at depths ranging from 3.5 to 7.5 meters were logged on a weekly basis and after significant rainfall events with a Trime T3 Tube Access Probe to characterize the

moisture profile as a function of depth. Borehole permeameter measurements provided valuable constraints on saturated hydraulic conductivity within the regolith overlying the shear zone. Continuous water-level measurements were recorded with dedicated pressure transducers in several of the site wells for the purpose of analyzing water-level fluctuations in response to precipitation. Evaluation of these data suggests that the rate and occurrence of recharge are highly controlled by the underlying structural geology, and that conceptualization of these recharge processes should include these geologic controls.

Site Description and Geologic Setting

The Blue Ridge Physiographic Province is composed of plutonic gneisses, intensely metamorphosed sedimentary and volcanic rocks, and a range of mineralogically diverse intrusions, and exhibits some of the most complex geology and hydrogeology in North America. Virtually all rocks within this province were subject to intense metamorphism and lateral and vertical displacement as a result of thrust faulting during the Paleozoic era. Subsequent rifting of basement rock and thinning of continental crust during the Triassic ended this period of intense crustal deformation that has resulted in a unique and extensive distribution of faults and fractures throughout the present day Blue Ridge (Dietrich 1990).

The Blue Ridge Physiographic Province is commonly divided into northern and southern sections: the northern section of the province is a narrow chain of mountains that extends north from Roanoke Gap in Virginia, to northeast Pennsylvania. The southern section is a roughly 100 kilometer wide plateau that extends southwest from

Virginia to Georgia (Clark, Ciolkosz et al. 1989; Dietrich 1990). The average maximum elevation of the Blue Ridge is approximately 900 meters AMSL although elevations above 1500 meters AMSL are common (Dietrich 1990).

Significant physical and chemical weathering within the province has resulted in the dynamic accumulation of regolith of variable thickness over almost all of the geologic structure. Due to the vastly different hydrogeologic properties of the regolith and the underlying bedrock, there are two distinct but interconnected hydrogeologic flow regimes within the province: unconfined and semiconfined flow in the porous and permeable regolith, and fracture flow in the underlying crystalline rock (Trapp and Horn 1997; Daniel and Dahlen 2002).

Comprised of saprolite, alluvium, and soil of varying proportions, the structure of regolith in the Blue Ridge Physiographic Province is often highly correlated to the structure and mineralogy of the underlying geology, and topographic position. Saprolite is usually the dominant component of the regolith (Daniel 1996; Daniel and Harned 1998; Daniel and Dahlen 2002), and because it is the weathering product of mineral rich crystalline bedrock, exhibits high clay content and often contains sand to boulder sized fragments of more weathering resistant minerals (Daniel 1996; Daniel and Harned 1998; Daniel and Dahlen 2002). The size and occurrence of these unweathered fragments generally increases with depth toward unweathered bedrock.

A transition zone from saprolite to unweathered bedrock within the regolith of the Piedmont and Blue Ridge Physiographic Provinces has been reported by Daniel (1996) and Stewart et al. (1964), and is characterized by an increase in permeability near the regolith/ bedrock interface. It is thought that the transition zone from regolith to bedrock

in crystalline rock environments acts both as a reservoir and a conduit for flow along the surface of the competent bedrock. This plane is often called 'first water' by well drillers, but does not appear to be correlated with high well yield in crystalline bedrock aquifers.

Fracture trends within the crystalline aquifers of the Blue Ridge Physiographic province are directly related to the orientation and magnitude of local and regional faulting. Among the most common types of fractures are zones of disturbed and highly fractured bedrock adjacent to nearly vertical to sub-horizontal thrust fault planes on both local and regional scales, and stress related fractures created by the compressional and extensional forces associated with regional tectonics in otherwise competent bedrock. Due to the metamorphism occurring from multiple tectonic episodes, the orientation of these compressionally and extensionally derived fractures is highly variable and difficult to generalize on a regional scale.

Figure 2 presents a conceptual model of the hydrogeology of the study site. Geologic mapping and geophysical site characterization have shown that study area is underlain by a variably fractured granulite gneiss thrust fault sheet (Seaton and Burbey 2000; Seaton 2002; Gentry and Burbey 2004; Seaton and Burbey 2005). The underlying thrust fault plane assumes a horizontal orientation at the southeastern corner of the study site, and rises steeply to a nearly vertical orientation in the northeastern portion of the study area.

Two distinctly separate confined flow systems have been delineated at the research site (Seaton and Burbey 2000; Seaton 2002; Seaton and Burbey 2005). The upper confined system resides within the regolith/ bedrock transition zone, and is partially confined by clay-rich saprolite. The lower confined system occurs within highly

fractured rock directly above a low permeability fault plane approximately 60 meters below ground surface, and has been confirmed by pump tests and geophysical borehole logging (Seaton and Burbey 2000; Seaton 2002; Seaton and Burbey 2005).

Recent work at the Fractured Rock Research Site has shown that the highly fractured rock above this thrust fault plane stores and transmits significant quantities of groundwater, and suggests that similar fault planes could be the primary reservoirs for groundwater storage in many crystalline aquifer systems of the Blue Ridge Physiographic Province (Seaton and Burbey 2000; Seaton 2002; Seaton and Burbey 2005). The angle of dip of the thrust fault shear zone and the fracturing within the crystalline rock adjacent to the fault plane appear to serve as geologic controls that preferentially direct infiltrated meteoric water to deeper confined aquifer systems (Fig. 2).





Site Conceptual Model

Based on previous work conducted by Seaton (2002), and Seaton and Burbey (2000, 2005), an overall conceptual recharge model has been developed for the study site. Figure 3 illustrates the recharge processes thought to be occurring along the study transect.



Figure 3. Conceptual recharge model- based on work conducted by Seaton (2002), and Seaton and Burbey (2005).

According to the model, a large portion of infiltrated water migrates through the regolith adjacent to the shear zone and collects in a localized water table underlain by impermeable granulite gneiss bedrock. Much of the water within this local aquifer is eventually discharged through a nearby spring. A portion of the water stored in the local water table may eventually recharge the underlying bedrock aquifer by traveling through

localized quartz breach zones that occasionally contact the otherwise impermeable granulite gneiss bedrock (Seaton and Burbey, 2005).

Water that does not collect in this topographically low water table migrates through the regolith above the phyllonitic shear zone, and eventually seeps into the highly fractured damage zones adjacent to the low conductivity fault plane and impermeable bedrock. Water in this portion of the shear zone is eventually stored within the deep, fractured bedrock aquifer. The quantity of meteoric water that is eventually recharged to the deep fractured aquifer is thought to be limited by the near surface orientation of the thrust fault shear zone, and the unsaturated hydraulic conductivity of the materials within the shear zone.

Physical, Geophysical, and Optimization Techniques Utilized to Test the Proposed Conceptual Recharge Model

In an effort to test the conceptual site model, a variety of field and computer modeling techniques were utilized to estimate the distribution of moisture content throughout the study transect and the depth and rate of recharge flux at multiple points along the study transect. The following sections describe the methodology employed for this effort.

Surface Electrical Resistivity Profiling

Surface electrical resistivity was utilized to study the distribution of moisture content within the unsaturated zone, and to further characterize the site geology. Resitivity data obtained from the site before the start of this project were used to constrain the extent of the study area, and to assist with the hydrogeologic conceptualization. Because pre-existing profiles were conducted on 10 meter wide electrode spacings, additional resistivity profiles were performed along transect A-A' (Figure 1) on 2 and 4 meter wide electrode spacing to obtain higher resolution data on the distribution of moisture content in the shallow subsurface. A Campus Geopulse 25 electrode system was used for the resistivity work. Files were combined and inverted with the RES2DINV inversion software (Loke 2002).

Data acquired from surface electrical resistivity profiles along transect A-A' were used to guide the placement of access tubes within the study transect so that records of moisture content from both inside and outside of the shear zone could be obtained. The

cross section and plan views of the study transect and access tube locations are shown in Figures 4 and 5, respectively.

Moisture Content Profiling

A total of 6 access tubes were installed in the unsaturated zone, ranging in depths from 3.5 to 7.5 meters. Because direct push methods proved to be ineffective at the site, a tractor mounted Giddings solid stem 3" auger was used to drill the holes for the access tubes. The 2" sch. 40 PVC access tubes were then assembled on site, emplaced in each borehole, and backfilled with native materials. Bentonite chips were placed in the top foot of each access tube annulus to discourage the preferential flow of water along the PVC/soil interface. For access tubes 2-6, drilling commenced until either saturated conditions within the regolith were encountered, or all of the auger flights were used. A quartz vein was encountered at a depth of 5.5 meters at the location of access tube #1, and drilling was terminated at this depth.

A Trime T3 tube probe was used to measure the volumetric moisture content adjacent to each access tube on a weekly basis, and after most significant rainfall events. This device uses TDR (time domain reflectometry) technology to measure the transit time required for an electrical pulse to travel down and reflect back along a cable connected to a series of waveguides in communication with surrounding regolith. Travel time (velocity) of the pulse is dictated by the soil bulk dielectric constant of the material near the wave guides, which is governed chiefly by the presence of water. Due to the overwhelming effect of water on the soil bulk dielectric constant, travel times can be







Figure 5. Plan view of site instrumentation along study transect - well, access tube, and tensiometer location

calibrated to the dielectric constants, and ultimately yield measurements of volumetric moisture content.

Although the driest of the cuttings were selected for backfilling the annulus between the access tube and the auger hole during emplacement of the access tubes, some of the cuttings caused materials to bridge between the exterior of the access tube and the surrounding regolith and the subsequent creation of unwanted void space adjacent to the access tube. Because no standardized procedure was employed to insure that the direction of the TDR pulse was oriented to a fixed reference point on the access tube during each measurement, even small heterogeneities within the backfill were a source of repeatable error. Additionally, the TDR probe contains an inherent repeatability error of ± 0.5 %. Despite these sources of error, TDR measurements remain accurate enough to be used for conceptualizing moisture content distributions along the study transect.

Borehole Permeametry

In order to better understand the hydraulic properties of the shear zone, a Guelph Permeameter was utilized to provide vertical point measurements of saturated hydraulic conductivity at selected locations within the regolith overlying the shear zone. The Guelph Permeameter is an apparatus designed to provide a measurement of saturated hydraulic conductivity in the vadose zone by introuducing and maintaining water at a specified head within a borehole of known dimensions. As water is ponded at a known height within the borehole, a bulb of saturation forms and equilibrates within the underlying media. The dimensions of the bulb are dictated by the height of ponding within the borehole, and the structure of the media being tested. After the dimensions of the bulb equilibrate, the rate of infiltration becomes constant. At this point, accurate measurements of hydraulic conductivity can be made.

Point measurement profiles of field saturated hydraulic conductivity were taken at half meter increments adjacent to access tubes #2 and #3 to depths of 4, and 3.5 meters, respectively.

Tensiometry

Tensiometers were used in this investigation to measure the matric potential of water in the unsaturated zone. Matric potential values in unsaturated media are typically negative, owing to the non-linear relationship between capillary suction and volumetric moisture content. As the volume of water within a volume of porous media decreases from saturation to a level below saturation, the ability of the media to retain the remaining water increases. Because this is a quantifiable relationship, matric potential measurements can be used to describe the movement of water in the unsaturated zone if the relationship between volumetric moisture content and matric potential is known.

Tensiometers measure matric potential (negative pore water pressure) by sensing pressure changes within a fluid filled porous ceramic cup in equilibrium with the surrounding porous matrix. Pressure changes detected by the tensiometer originate within the surrounding matrix and instantaneously propagate through the ceramic cup via a pressure gradient between the surrounding matrix and the interior of the cup. When matric potential in the surrounding matrix is higher than the interior of the cup, water is drawn from the matrix through the porous cup- when the potentials are higher inside of the cup, water is drawn through the cup and into the matrix. Electronic pressure

transducers housed above a vaccum seal interfacing with the ceramic cup translate pressures into millivolt output signals that are then stored by dedicated dataloggers.

During the summer of 2004, digitally automated tensiometers were built and installed to continuously monitor and log measurements of matric potential at the Fractured Rock Research Site. In addition to providing a necessary parameter for quantifying recharge fluxes in the deep vadose zone, the record of continuous data provides information regarding the dynamics of the unsaturated flow regime in selected portions of the study site.

Five nests of tensiometers were installed at the Fractured Rock Research Site in late July of 2004. Figure 4 illustrates the approximate location of each nest; Figure 5 shows these locations in plan view. Two nests of three tensiometers (nests A and B) were installed in the shear zone at 3.05, 6.10, and 12.2 meters below land surface. Three nests of two tensiometers (nests C, D, E) were installed in the regolith outside of the shear zone at average depths of 1.5 and 3.0 meters. Because saturated conditions occur at shallower depths outside of the shear zone, C, D and E series tensiometers were not as deeply placed.

Due to the extreme sensitivity of the pressure transducers housed at the base of the tensiometers, it took several months to test, re-build, and establish reliably operating tensiometer sets. The design of the tensiometers used in this investigation was based largely on the Advanced Tensiometer Design (Hubbell and Sisson 1998; Hubbell 2004). Appendix A illustrates the final design and dimensions of the tensiometers used in this investigation.

Particle Size Analysis

In an effort to describe the relationship between unsaturated hydraulic conductivity and in-situ matric potential, particle size analysis was conducted on core samples obtained adjacent to tensiometers A3 (core C1) and D1 (core C2). Based on field analysis of solid stem and bucket auger cuttings, analysis of tensiometric data at several locations within the transect, and analysis of field borehole permeameter data, it was determined that cores C1 and C2 were valid representations of the unsaturated saprolitic materials inside the mylonitized shear zone (C1), and above the massive, non-fractured bedrock hanging wall (C2).

A hammer driven Mini Core TM sampler manufactured by AMS Inc. was used in a pre-augered hole to obtain undisturbed cores at a depths of 3 and 2.5 meters for cores C1 and C2, respectively. After the samples were oven dried, the bulk density and volumetric moisture content of each core were calculated. The materials in each core were passed through a #10 sieve to remove coarse fragments (> 2 mm). Once the coarse fragments were removed, nested sieves were used to remove the sand fraction of each sample. The pipette method was used to obtain percent (by weight) silt and clay.

The pipette method was used to separate the clay and silt fractions of a given sample, and relies on gravitational sedimentation to quantify silt and clay percentages. Once the sand fraction is sieved from the sample and weighed, a portion of the silt and clay fractions are weighed, treated with a dispersing agent, placed in a solution of known viscosity and density, and allowed to settle after agitation. Terminal velocity of the particles in the suspension is related to particle diameter by the following equation:

$$v = [g(\rho_s - \rho_1)X^2]/18h$$
 [Eq.1]

Where ρ_s is the particle density, ρ_1 is the liquid density, X is the particle diameter, *h* is the height relative to a known datum, and *g*, the gravitational constant.

A pipette is periodically placed into the agitated solution at a pre-determined depth and time (determined by using Eq.1) to withdraw sediment with a diameter less than or equal to a diameter of interest. In this case, the pipette method was used to determine gradations of silt (0.04-0.02mm, 0.02-0.005mm, and 0.005-0.002mm diameters), and the percentage of clay in suspension (< 0.002mm diameter).

The size fraction percentage of suspended sediment drawn into the pipette is determined by oven drying and weighing the volume of sediment captured by the pipette to obtain a concentration (grams per liter). The concentration is then compared to the total oven dry weight of the sample- the result is the percent of total sample weight composed of particles with a diameter less than or equal to 'x'.

Neural Network Analysis of Soil Hydraulic Properties, and Modeling of Unsaturated Hydraulic Conductivity

One dimensional recharge flux in the vertical (z) direction can be expressed mathematically in terms of matric potential by a form of the Richards equation (Richards 1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\Psi) \frac{\partial \Psi}{\partial z} \right] - \frac{\partial K(\Psi)}{\partial z} \qquad [Eq.2]$$

Where (θ) is the volumetric moisture content, (ψ) is the matric potential, K(ψ) is the unsaturated hydraulic conductivity at a known matric potential, *z* is the vertical direction in the unsaturated profile, and t is time.

Equation 2 states that the change in the mass of water at a specific depth over time is directly proportional to gravity drainage at a rate controlled by hydraulic conductivity at a given matric potential, and the capillary suction gradient. In this form, the Richards equation relies on the quantifiable relationship between (θ) and (ψ) (the soil water characteristic curve) to calculate the mathematical expression of recharge in the unsaturated zone in terms of matric potential.

Darcy's Law [Eq.3] can be used to further illustrate vertical flow in the unsaturated zone, and is expressed as:

$$q = -K\left(\Psi\right)\left(\frac{dh}{dz}\right)$$
 [Eq.3]

where *q* represents the flux of water through a given point in the unsaturated profile, $K(\Psi)$ is the unsaturated hydraulic conductivity at a known matric potential, and dh/dz is the hydraulic gradient. The hydraulic gradient dh/dz can be expanded to illustrate the contribution of matric potential within the unsaturated flow regime:

$$\frac{dh}{dz} = \frac{d\Psi}{dz} + \frac{dz}{dz}$$
[Eq.4]

where dh/dz is the total hydraulic gradient, $d\Psi/dz$ is the matric potential gradient, and dz/dz is the gradient driven by gravitational force.

When matric potential gradients can be directly and continuously quantified through field measurement (*i.e.* tensiometry), it is useful to utilize either Richards Equation or Darcy's Law for calculation of the recharge flux estimate. Because these equations rely on the unsaturated hydraulic conductivity at known matric potentials, reasonable estimates of $K(\psi)$ must be obtained. This is often accomplished through the construction of a soil water characteristic curve that plots the values of capillary pressure over a wide range of moisture content. These data can either be directly measured in the laboratory or the field through drainage and infiltration experiments, or they can be predicted with a number of different computer codes that rely on various types of input data ranging from limited capillary pressure/moisture content data to particle size distribution analyses.

Due to the difficulty associated with conducting in-situ infiltration and drainage experiments deep within the vadose zone, data obtained for the soil water characteristic curves associated with this investigation were generated in part by the artificial neural network computer code ROSETTA (Schapp 2000).

Artificial neural networks are systems of data processing elements that operate simultaneously until convergence upon a global solution. The behavior of a neural network is controlled by the relative weight associated with each parameter, calculated by the neural network processing elements. These computational systems are adept at constructing models from input data (in this case, the basic soil properties of bulk density and particle size distribution) that are not directly associated with the convergent model solution (predictions of unsaturated hydraulic parameters).

Instead of predicting properties directly from physically measured input data such as soil hydraulic properties from direct measurements of moisture content and matric potential, neural network predictions are the product of calibration and optimization of the neural network to a known data set. During the optimization process, the artificial

neural network is calibrated by a procedure that optimally relates the input data to the output data- forcing the network of processing elements to transition from randomly weighted and inaccurate, to a network that is capable of accurately predicting the properties of each sample within the data set. Once the network is properly calibrated, it may then be exposed to external input data to make predictions about samples outside of the data set.

The computer code ROSETTA is described as a feed-forward back propagation neural network consisting of an input layer, a hidden layer, and an output layer- each with a specified number of nodes. (Schapp, 2000) The nodes in the input and output layers correspond with the number of input and output variables respectively- the nodes in the hidden layer are connected to both the input and output layers by weights that are optimized through the calibration process (Figure 6). Data are fed from the input nodes to the hidden layer nodes where the weighting process occurs. At each of the hidden nodes, all of the input values are multiplied by weights and summed according to the following equation:

$$S_{k} = \sum_{j=1}^{J=J} \left(w_{jk} x_{j} + w_{jb} \right)$$
 [Eq.5]

Where S_k represents the sum, *j* represents any input node, *J* represents the total number of input nodes, w_{jk} represents the weight matrix, x_j represents the input variable, and w_{jb} represents a bias value added to help maintain numerical stability (a constant input value of 1).

 S_k is then utilized in the following transform equation for the hidden node output:

$$H_k = 1/(1 + e^{-S_k})$$
 [Eq.6]



Figure 6. Overview of a feed forward back propagation neural network (after Schapp and Leij, 1998).

Output from the hidden nodes are then fed to the output nodes where an identical weighting and transform process occurs.

The weight values w_{jk} and w_{jl} are obtained through an iteratively applied objective function that minimizes the sum of the squared residuals:

$$O(\mathbf{b}) = \sum_{i=1}^{i=N} \sum_{j=1}^{j=M} (t_{i,j} - t_{i,j})^2$$
 [Eq.7]

Where N denotes the number of samples, M represents the number of parameters, $t_{i,j}$ and

 $\hat{t}_{i,j}$ are observed and predicted variables, respectively.

The objective function illustrated in equation 5 compares the predicted value to the actual value in the database, and quantifies the difference between them. The output from this function is then fed back through the network. Weights are adjusted slightly to further reduce the value of the objective function. This process is repeated until the output from the objective function is minimized to within an acceptable margin of error. Once this process is completed for each sample, the neural network is considered to be calibrated to the data set.

The database to which the artificial neural network program ROSETTA is calibrated consists of 2085 samples- each with known physical (bulk density, particle size distribution) and hydraulic properties (laboratory and field derived soil water retention data). Retention data for each sample were optimized to obtain the hydraulic properties $\theta_r, \theta_s, K_0, K_s, n, L, \alpha$ that are required to model unsaturated hydraulic conductivity/soil water retention relationships. Neural network processing elements were then calibrated to the optimized data, using particle size distribution and bulk density as input variables.

In addition to providing the variables necessary to construct an unsaturated hydraulic conductivity curve, ROSETTA utilizes a random re-sampling procedure to generate multiple data subsets (60 subsets) for optimizing the input data. Overall prediction accuracy can then be evaluated through statistical analysis of the hydraulic parameter predictions from each database subset. The generation of confidence intervals from the parameter uncertainty estimates (expressed as standard deviations) allows for the inclusion of uncertainty in subsequent unsaturated flux estimates.

Once the variables θ_r , θ_s , K_0 , K_s , n, L, α and associated uncertainty estimates have been obtained from the calibrated neural network predictions, they can be used in any number of simulation models. In this study, the curve fitting/ parameter optimization code RETC (van Genuchten, Simunek et al. 1991) was used to construct an unsaturated hydraulic conductivity/pressure head curve from the variables obtained through the neural network analysis.

The model of van Genuchten and Mualem (van Genuchten 1980) is utilized by RETC to relate the optimized soil water retention variables to unsaturated hydraulic conductivity, expressed by the following equations:

$$S_e(h_m) = \frac{\theta(h_m) - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h_m|^n)^m}$$
 [Eq.8]

$$K(S_e) = K_0 S_e^L \{1 - [1 - S_e^{n/(n-1)}]^{(1-1/n)}\}^2$$
 [Eq.9]

where (h_m) is the soil water matric head, $S_e(h_m)$ is a measure of relative saturation at a specific matric head, $\theta(h_m)$ is the volumetric water content at a specific matric head, θ_r and θ_s represent the residual and saturated volumetric water content respectively, and α, m, n are curve shape parameters. In [Eq.9], $K(S_e)$ denotes the predicted hydraulic conductivity at a given relative saturation, K_0 is the unsaturated hydraulic conductivity match point, and L is a parameter that accounts for pore tortuosity and pore connectivity.

Water Level Information

Pressure transducers were installed in well 4 (w-04) and piezometer 1 (p-01) (shown on Figures 4 and 5) to continuously log water levels in the saturated portion of the thrust fault shear zone (w-04) and the saturated portion of the semi-confined aquifer overlying the thrust fault hanging wall (p-01). Data from these transducers were periodically downloaded and barometrically compensated to correct for the barometric influence on water-level fluctuations.

Results and Discussion

Initial sections of the results and discussion present the surface electrical resistivity and TDR data along transect A-A', and illustrate the geologic controls on the distribution of moisture content throughout the study site. Subsequent sections within the results and discussion are based on the analysis of recharge processes as they pertain to two distinctly separate flow mechanisms identified within the study transect: recharge processes within the regolith overlying the vertically oriented shear zone, and recharge processes within the regolith overlying the thrust fault hanging wall (Figure 2).

Transect Overview: Surface Electrical Resistivity Profiling

Results of the high resolution surface electrical resistivity profile indicate a nonuniform distribution of moisture throughout the subsurface that appears to be controlled by the underlying geologic structure (Fig.7).



Figure 7. Interpreted surface electrical resistivity section from the study site (4m spacing). Access tube locations superimposed on the profile for spatial reference (axes in meters). Line of section A-A' shown on Figure 1.

The resistivity values on the modeled cross section (fig. 7) range over 3 orders of magnitude and illustrate the high degree of heterogeneity at the study site. Low resistivity values correlate with saturated and nearly saturated porous earth materials (sands, clays, highly weathered saprolite) while high resistivity values correlate with drier earth materials (typically non-porous bedrock and unsaturated porous materials).

The location and dimensions of the low resistivity zone in the bottom center of the modeled cross section (fig. 7) are coincident with the orientation and dimensions of the vertically oriented thrust fault shear zone described by Seaton and Burbey (Seaton and Burbey 2000; Seaton 2002; Seaton and Burbey 2005). Much of the material within the shear zone is saturated and nearly saturated fault gouge. The zones immediately adjacent to the low resistivity interval are interpreted as highly fractured bedrock damage zones with higher hydraulic conductivity. Because these zones are drier than the adjacent fault

gouge, it is possible that these are regions of through flow and that these zones may be serving as preferential pathways for deeper groundwater recharge.

The zone of high resistivity on the bottom right portion of Figure 7 is interpreted as highly competent granulite gneiss, and has been confirmed by borehole geophysical logging (Seaton and Burbey 2000). Due to the lack of fracturing within this portion of the bedrock, it appears that the downward movement of water and eventual recharge to an underlying aquifer is highly restricted. Instead, infiltrated water collects in the overlying regolith, forming a localized water table in a topographically low portion of the study site. This localized water table has been modeled as a zone of low resistivity above the bedrock on Figure 7.

The left portion of the resistivity profile exhibits resistivity values ranging between 1100 and 3500 ohm meters, and are within the range of resistivity values reported by Seaton and Burbey (2005) shown to be unsaturated regolith along a nearby transect at the site. The absence of water table conditions indicate that this is likely a region of through flow to topographically low areas, but the presence of the thrust fault footwall (modeled on 10 meter resistivity sections) not far below the unsaturated regolith may act as a barrier for deep infiltration and recharge.
Transect Overview: Moisture Content Profiles

Directly measured values of volumetric moisture content support the interpretation of the surface electrical resistivity data recorded along the study transect A-A' and indicate a non-uniform distribution of moisture within the shallow subsurface. Figures 8, 9, and 10 illustrate the variations in volumetric moisture content at selected depths along the study transect from mid-August, 2003 to September 2004. Because volumetric moisture content was measured periodically (usually once a week), the resolution representing increases in volumetric moisture content due to precipitation inputs is poor, and in some cases the change in moisture content went unrecorded.



Figure 8. Volumetric moisture content fluctuations at 1 meter b.g.s. for access tubes 1-4 and 6 (see Figure 4 for locations).

At a depth of one meter (fig 8), the volumetric moisture content (given as a percentage) of the materials surrounding the access tubes typically ranges between 10 and 20. The relatively low volumetric moisture content values for the regolith surrounding all access tubes at a depth of one meter suggest that infiltration extends beyond the indicated depth.



Figure 9. Volumetric moisture content fluctuations at 3.5 meters b.g.s. for access tubes 1-3, 5 and 6 (see Figure 4 for locations).

Figure 9 illustrates the trends in volumetric moisture content at a depth of 3.5 meters. Access tubes 1-3 exhibit low values, but the materials surrounding access tubes 5 and 6 remain near or at saturation (access tube 5). Both of these access tubes were installed in a topographically low portion of the study transect in the regolith overlying

the non-fractured granulite gneiss bedrock. These data are in good agreement with the surface electrical resistivity data for this portion of the section, and suggest that recharge is not occurring in the underlying bedrock in the topographically low portions of the study area.



Figure 10. Volumetric moisture content fluctuations at 7.5 meters b.g.s. for access tubes 2-4 (see Figure 4 for locations).

Volumetric moisture content fluctuations for access tubes 2-4 are displayed in Figure 10. At a depth of 7.5 meters, the volumetric moisture content of the materials adjacent to access tubes 3 and 4 is approaching saturation. Access tube 4 was installed in the regolith above the northern terminus of the thrust fault hanging wall, and is in contact with the moist, clay rich materials overlying the granulite gneiss. Access tube 3 was installed directly above the mylinotized portion of the thrust fault shear zone, and is likely intersecting the low conductivity, nearly saturated fault gouge.

Access tube 2 was installed in the regolith overlying the fractured portion of the thrust fault shear zone. In spite of its proximity to the saturated fault gouge within the shear zone, Figure 10 shows that access tube 2 remains dry at the 7.5 meter depth. These data, coupled with the resistivity data, suggest an absence of water table conditions in this portion of the cross section, and the possible occurrence of deep recharge within highly fractured thrust fault damage zones.

Factory calibration of the T3 probe yielded uncharacteristically high volumetric moisture content readings (between .5 and $.9 cm^3/cm^3$) in the nearly saturated and saturated regolith adjacent to access tubes 5 and 6, the bottom half of access tube 4, and the very bottom of access tube 3. When used in clay rich materials possessing high moisture content values, the probe typically yields inaccurate measurements. Although these measurements are artificially elevated, they can still be used as an indicator of high moisture content within these zones.

Borehole Permeametry

Figure 11 illustrates the measured ranges in field saturated hydraulic conductivity with respect to depth within the regolith overlying the vertically oriented shear zone.



Figure 11. Field saturated hydraulic conductivity measurements above the vertically oriented shear zone adjacent to access tubes 2 and 3.

In both cases, relatively low hydraulic conductivity values (between 1×10^{-5} and 3×10^{-6} cm/s) occur within the top meter of regolith. Below a depth of 1 meter, the soil grades to a saprolite possessing higher saturated hydraulic conductivity values. Field

saturated hydraulic conductivities within the saprolite are generally one to nearly two orders of magnitude higher, ranging between 1×10^{-4} and 2×10^{-3} cm/s.

Based on the hydraulic conductivity measurements illustrated in Figure 11, the saturated hydraulic conductivity within the upper 4 meters of the shear zone follows a uniform distribution of hydraulic conductivity within the shear zone regolith. The weathered saprolite within the regolith overlying the shear zone occurs as a result of the preferential chemical and physical weathering of highly mylonitized bedrock associated with the thrust fault shear zone, and is thought to serve as a conduit for recharge to the fractured bedrock aquifer.

Particle Size Analysis and Unsaturated Hydraulic Conductivity Estimates

Based on borehole permeametry, analysis of TDR and matic potential data, and the analysis of multiple auger cuttings above the regolith overlying the shear zone, materials retrieved from core C1 are considered to be representative of the regolith adjacent to the 1 and 2 series tensiometers. Approximately half (by volume) of the core C1 solids fraction (obtained from the 3 meter interval adjacent to tensiometer A3) contained fragments of mica-schist, a strong indication of the presence of the underlying fault plane subcrop.

A #10 sieve was used to separate coarse fragments from the <2mm portion of the sample (Figure 12). The pipette method was utilized to obtain the particle size distribution of the < 2mm fraction. Sample analysis results are displayed in Table 1.



Figure 12. Contents of core C1- mica schist shown on left; screened fraction shown on right.

Particle Size Distribution		
and Bulk Density		
Core C1		
% very coarse sand	6.3	
% coarse sand	7.5	
% medium sand	11.8	
% fine sand	17.0	
% very fine sand	22.9	
TOTAL % SAND	65.4	
% coarse silt	6.5	
% medium silt	14.2	
% fine silt	2.8	
TOTAL % SILT	23.5	
TOTAL % CLAY	11.1	
BULK DENSITY		
g/cm^3	1.49	

Table 1. Particle size analysis and bulk density, core C1 (see Figure 4 for location).

Under fully saturated conditions, use of a particle size analysis (PSA) to indirectly determine hydraulic conductivity would be complicated by the occurrence of secondary porosity characteristics associated with the mica schist. The stable matric potential data recorded by the shear zone tensiometers indicate that in unsaturated conditions, secondary porosity has little to no role in the movement of vadose zone water. These results suggest that flow occurs within the porous granular matrix surrounding the mica-schist fragments, indicating that the PSA based estimation of hydraulic conductivity is a viable approach for constructing hydraulic conductivity curves.

Results from the physical analysis of core C1 (percent sand, silt, clay, and bulk density) were imported into ROSETTA to generate hydraulic parameter estimates. Results of the parameter estimation process are displayed in table 2, along with uncertainty estimates associated with each parameter (standard deviation from the mean estimate). A higher degree of uncertainty is associated with the hydraulic parameters L and K_0 due to a weak correlation with particle size distribution (Schapp and Leij 2000).

Estimated Hydraulic Parameters			
Core C1			
Parameter	value	std.dev.	
$\theta_r \left(\frac{cm^3}{cm^3} \right)$	0.0440	0.0059	
$\theta_s \left(\frac{cm^3}{cm^3} \right)$	0.3842	0.0065	
$\log_{10} \alpha(m/c_m)$	-1.5329	0.0675	
$\log_{10} N$	0.1611	0.0147	
$\log_{10} K_s \left(\frac{cm}{d} \right)$	1.6174	0.0702	
$\log_{10} K_0 \left({}^{cm}_{d} \right)$	1.2053	0.2207	
L	-0.9929	0.7668	

Table 2. Values of hydraulic parameters and standard deviation for Core C1estimated from ROSETTA .

Uncertainty ranges for θ_r , θ_s , α , N, and K_s are one to two orders of magnitude smaller than the associated parameter estimate, and thus have a negligible influence on the parameter optimization process used to generate the unsaturated hydraulic conductivity curve from the C1 core materials. For this reason, uncertainty estimates associated with θ r, θ s, α , N, and Ks were disregarded, and the mean parameter estimate associated with each variable was used as input for the optimization process.

In an effort to include the range of uncertainty associated with the L and Ko hydraulic parameters, the L and Ko uncertainty values were used to generate 99% mean confidence intervals. The upper and lower bounds of the Ko and L confidence intervals were then used along with the mean input variables of θ r, θ s, α , and N for the unsaturated hydraulic conductivity optimization process. Use of the upper and lower bound data resulted in the creation of four hydraulic parameter data sets for introduction into the optimization program RETC. At the end of each optimization simulation (one for each data set), the unsaturated hydraulic conductivity/ pressure head output data were saved and plotted on a log/log scale graph. Figure 13 presents the estimated hydraulic conductivity/ pressure head relationship for the C1 core materials generated from RETC simulations. The range of hydraulic conductivity values generated with the 99% confidence intervals is bounded by the upper and lower curves.



Figure 13. Unsaturated hydraulic conductivity/pressure head relationship for the C1 core materials. The possible range of hydraulic conductivity values generated with the 99% hydraulic conductivity intervals are bounded by the upper and lower curves.

Interpretation and Analysis of Matric Potential Data



Figure 14 presents matric potential data from late December, 2004 to early June 2005 for five tensiometers installed in shear zone tensiometer nests A and B.

Figure 14. Matric potential fluctuations for tensiometer nests A and B.

Matric potential values for four of the tensiometers installed in the shear zone nests (A2, A3, B2, B3; Figures 4 and 5) remain negative throughout the period of observation, ranging between -315 cm and -175 cm water. TDR and resistivity values recorded within this region agree well with the tensiometric data, indicating relatively dry, unsaturated conditions. Overall trends for tensiometers A2 and B2 (installed 6.1 meters b.g.s.) and tensiometers A3 and B3 (installed 3.05 meters b.g.s.) are notably similar with respect to depth, suggesting that overall recharge processes within the

instrumented portion of the regolith overlying the shear zone are relatively uniform with depth, regardless of lateral position within the shear zone.

The overall stability of the matric potential values measured by tensiometers A2 and B2 (6.1m bgs) is an indicator of dampened response to infiltrated water from transient precipitation events. These results suggest that the downward movement of infiltrated water approaches near steady state conditions with depth despite the dynamics of the near-surface wetting and drying processes that are driven by precipitation. The occurrence of attenuated response to recharge with depth in the unsaturated zone has been observed and documented in the 1960s by Gardner (1964) and Childs (1969), and later by a number of field investigators in a variety of climactic conditions (Stephens and Knowlton 1986; Kengni et al. 1994; Normand et al. 1997; Hubbell et al. 2004).

Gradual fluctuations in matric potential for tensiometers A3 and B3 (3.05 meters b.g.s.) throughout the recorded period indicate that although dampened, deeper response to recharge is evident. The early spring increase in matric potential of approximately 100 cm water for tensiometer A3, and approximately 50 cm water for tensiometer B3 indicates a contribution of meteoric water above the stable conditions recorded from late December through March. The gradual increase in matric potential is likely associated with an important seasonal contribution to groundwater storage associated with late winter precipitation, and the thawing and mobilization of frozen water accumulated in the upper portions of the vadose zone throughout the previous winter.

During late April and early May, tensiometers A2 and B2 (6.1 meters b.g.s.) registered an increase in matric potential of approximately 30 and 20 cm water, respectively. This slight increase in matric potential is associated with the same early

spring contribution recorded by tensiometers A3 and B3, but the matric potential response within tensiometers A2 and B2 is attenuated. The later response of tensiometers A2 and B2 to the same recharge event suggests that infiltration is occurring downward through the vadose zone in the regolith above the vertically oriented thrust fault shear zone.

By examining the time delay associated with the vertical response from the spring recharge event within the A series and B series shear zone tensiometer nests, an approximation of flux velocity associated with the early spring recharge event is attainable. Figures 15 and 16 present travel time estimates between the A series and B series tensiometers based on the spacing of peak matric potential values within each shear zone nest. A travel time of 28 days (to travel 3 meters) between tensiometers A2 and A3 and 34 days (to travel 3 meters) between B2 and B3 indicate that recharge within the regolith above the shear zone occurs within a porous media possessing similar soil water retention characteristics. Conceptually, the regolith above the shear zone appears to accommodate the storage and flow of meteoric water, eventually recharging to the underlying saturated fault gouge and adjacent fractures parallel to the vertically oriented fault plane.

The gradual increase in matric potential associated with the early spring recharge event for the A and B series tensiometers is indicative of infiltration through a porous media matrix and suggests that secondary porosity within the regolith above the shear zone plays little to no role in the vertical transport of infiltrated water for the period of observation.

Tensiometer B1 was installed approximately 12 meters b.g.s. in the saturated, mylonitic shear zone fault gouge associated with the vertically oriented thrust fault plane. Matric potential data from tensiometer B1 (fig.14) reveal that saturated conditions within the fault gouge are closely related to the matric potential fluctuations recorded by tensiometers A2 and B2. Flow within this portion of the saturated fault gouge is speculated to move either down gradient through the low permeability fault plane, or through the adjacent fracture zone at the base of the vertically oriented thrust fault hanging wall at rates that are comparable to matric potential fluctuations in the lower portions of the unsaturated regolith.



Figure 15. Travel time associated with Spring 2005 recharge event for A series tensiometers.



Figure 16. Travel time associated with Spring 2005 recharge event for B series tensiometers.

Water Retention Characteristics

Below a depth of approximately 3 meters, moisture content and matric potential within the unsaturated regolith overlying the vertically oriented shear zone become increasingly stable with depth. Figure 17 displays the mean hydraulic head $(z + \Psi)$ for the period of observation plotted with a 1:1 elevation head gradient for the shear zone tensiometers. Because average matric potential values within this portion of the unsaturated zone do not change significantly with depth, the average unsaturated hydraulic gradients between tensiometers A3/A2 and B3/B2 are close to unity, indicating stable matric potential conditions within the deeper portions of the unsaturated zone. The steeper slope associated with the B series tensiometers suggests that the dynamics of precipitation inputs propagate to deeper regions of the unsaturated zone within this portion of the study transect.



Figure 17. Total head for 2 and 3 series tensiometers in tensiometer nests A and B plotted against a 1:1 elevation head gradient.

Additional evidence of stable conditions within the regolith surrounding the shear zone access tubes is yielded by the seasonal trend in volumetric moisture content recorded using the TDR methodology. Figures 18-20 present TDR profile and point measurement data for access tubes 2 (adjacent to tensiometer nest A) and 3b (adjacent to tensiometer nest B) for ten months prior to tensiometer placement.

Figure 18 illustrates the fluctuations in volumetric moisture content at the 6 meter interval for access tubes 2 and 3b (same depth as tensiometer A2/B2). The mean volumetric moisture content of 18.3% for both observation points indicates that the unsaturated flow processes within this interval of the study transect are governed by uniformly distributed water retention characteristics. A standard deviation of 0.89% from

the mean volumetric moisture content recorded at the 6 meter interval adjacent to access tube 2 indicates stable moisture content conditions throughout the study period. Moisture content data for the 6 meter interval for access tube 3b substantiates this observation.



Figure 18. Volumetric moisture content fluctuations at 6 meters b.g.s : access tubes 2 and 3b (see Figure 4 for location).

Figures 19 and 20 present seasonal volumetric moisture content depth profiles recorded within the regolith adjacent to access tubes 2 and 3b. The profiles indicate that the upper 1-5 meters of the regolith overlying the shear zone is subject to the transient influence of infiltrated meteoric water, and is governed by a dynamic unsaturated flow regime. Volumetric moisture content within the deeper portions of the profiles exhibits significantly less variation, and suggests predominately gravity driven unsaturated flow that is only marginally affected by the wetting and drying of the overlying regolith.



Figure 19. Seasonal volumetric moisture content profiles: access tube 2 (see Figure 4 for location).



Figure 20. Seasonal volumetric moisture content profiles: access tube 3b (see Figure 4 for location).

Recharge Flux Estimates

Estimates of recharge flux within the shear zone regolith were generated by referencing the hydraulic conductivity/pressure head relationship (Figure 13) against recorded matric potential data from tensiometers A2 and B2. Matric potential values were used along with the hydraulic parameters generated with ROSETTA to obtain values of relative saturation (S_e ; equation 8) for use with Mualem's equation (equation 9) to calculate unsaturated hydraulic conductivity adjacent to each tensiometer for discrete time intervals. Because matric potential values were stored once every 15 minutes in the data-logger memory, the hydraulic conductivity of the materials adjacent to tensiometers A2 and B2 was assumed to be stable throughout each 15 minute interval. Hydraulic gradients between tensiometers A3/A2 and B3/B2 were calculated for each 15 minute interval by subtracting the difference in total head associated with each tensiometer for the 15 minute period and dividing through by the vertical distance separating the points of measurement. Once the hydraulic conductivities and hydraulic gradients associated with each 15 minute period were obtained, total flux adjacent to each tensiometer for each 15 minute period was calculated. Finally, an estimate of total recharge flux for the period of observation was obtained by summing all of the flux estimates for each 15 minute period.

Recharge calculations associated with matric potential measurements adjacent to tensiometers A2 and B2 were calculated to reflect the uncertainty associated with hydraulic conductivity generated by ROSETTA. Figures 21 and 22 illustrate the total recharge estimates adjacent to tensiometers A2 and B2 for the period of observation, as well as the observed variations in recharge flux and hydraulic gradient between the

A3/A2 and B3/B2 tensiometers. Two estimates of total recharge associated with each tensiometer for the period of observation are given to illustrate the influence of uncertainty in the hydraulic conductivity estimates generated by ROSETTA. The minimum and maximum cumulative recharge estimates were generated by using the hydraulic conductivity/pressure head curves that bound the possible range of hydraulic conductivity values depicted in Figure 13.



Figure 21. Total recharge flux estimates for tensiometer A2 for the period of observation. Dashed lines indicate cumulative recharge calculated for the upper and lower 99% confidence intervals associated with the hydraulic conductivity/pressure head relationship. A2 flux a and A2 flux b are graphical representations of the variations in recharge flux associated with the upper and lower bounds of hydraulic conductivity depicted in figure 13, respectively.



Figure 22. Total recharge flux estimates adjacent to tensiometer B2 for the period of observation. Dashed lines indicate cumulative recharge calculated for the upper and lower 99% confidence intervals associated with the hydraulic conductivity/pressure head relationship. B2 flux a and B2 flux b are graphical representations of the variations in recharge flux associated with the upper and lower bounds of hydraulic conductivity depicted in figure 13, respectively.

Recharge flux estimates for flux adjacent to tensiometer A2 range between 0.34 cm and 3.88 cm for the period of observation (120 days), comprising 1% to 15% of total precipitation (26.53 cm) recorded throughout this period of observation. Recharge flux estimates for flux adjacent to tensiometer B2 range between 0.85 cm and 8.03 cm for the period of observation (162 days), comprising 3% to 24% of total precipitation (33.24 cm) recorded throughout the period of observation.

Comparison of Matric Potential and Water Level Data

Figure 23 displays water-level data from well W-04 installed directly in the vertically oriented shear zone and with the matric potential data recorded by tensiometer B2 installed in the regolith overlying the shear zone for the period of observation. The similar response of shear zone matric potential and water level suggest that recharge to the shear zone aquifer occurs as advective flow from the lower portions of the unit and flows downward at a rate consistent with the unsaturated hydraulic conductivity.



Figure 23. Water level and tensiometric data within regolith overlying vertically oriented shear zone.

The data displayed in Figure 23 show that the maximum peak in matric potential occurs shortly after the water-level elevation has attained maximum elevation for the period of observation. This lag indicates that the shear zone water table is likely recharged from regions of saprolite within and above the shear zone, and meteoric water

is transmitted at rates that are slightly higher than the rates occurring within the saprolite surrounding the monitored regions of the shear zone regolith. Nevertheless, the correlation between matric potential and water-level indicate a high degree of communication between the unsaturated regions of saprolitic shear zone materials adjacent to tensiometers 1B and 2B, and the water table within the shear zone.

Analysis of Data Associated with the Thrust Fault Hanging Wall

Particle Size Analysis and Unsaturated Hydraulic Conductivity Estimates

The particle size analysis and hydraulic conductivity optimization procedures employed for the characterization of core C1 in the shear zone were also utilized for the characterization of the C2 core extracted from the regolith overlying the thrust fault hanging wall at a depth of 2.5 meters. The C2 core contained notably fewer coarse grained fragments, comprising a small fraction of the total volume. Coarse fragments within core C2 were composed primarily of granite gneiss, and contained little mica. Results from the C2 particle size distribution analysis are displayed in table 3. Hydraulic parameter estimation results from ROSETTA are displayed in table 4.

Particle Size Distribution		
and Bulk Density		
Core C2		
% very coarse sand	2.6	
% coarse sand	3.4	
% medium sand	8.0	
% fine sand	20.7	
% very fine sand	13.2	
TOTAL % SAND	47.9	
% coarse silt	4.5	
% medium silt	9.8	
% fine silt	8.1	
TOTAL % SILT	22.3	
TOTAL % CLAY	29.8	
BULK DENSITY		
g/cm^3	1.23	

Table 3. Particle size analysis and bulk density, core C2.

Estimated Hydraulic Parameters			
Core C2			
Parameter	value	std.dev.	
$\theta_r \left(\frac{cm^3}{cm^3} \right)$	0.0815	0.0105	
$\theta_s \left(\frac{cm^3}{cm^3} \right)$	0.4817	0.0112	
$\log_{10} \alpha(\gamma_{cm})$	-1.7947	0.0943	
$\log_{10} N$	0.1519	0.0195	
$\log_{10} K_s \left(\frac{cm}{d} \right)$	1.5236	0.2297	
$\log_{10} K_0 \left(\frac{cm}{d} \right)$	0.7549	0.2539	
L	-0.6492	0.9299	

Table 4. Estimated hydraulic parameters for Core C2.

Standard deviation ranges for core C2 are slightly wider than those for C1, due to a paucity of fine grained samples within the ROSETTA database. Exposure of the neural network to fewer fine grained samples during the initial calibration resulted in diminished accuracy for clay rich compositions (Leij et al. 2002). Although the C2 core contains a significant amount of sand, the 30 % clay content likely decreased the accuracy of the C2 predictions.

Figure 24 illustrates the core C2 hydraulic conductivity/ pressure head relationship generated using RETC. As with Figure 13, the bounded region was generated by the introduction of uncertainty (related to the Ko and L hydraulic parameters) into the parameter optimization process.



Figure 24. Unsaturated hydraulic conductivity/pressure head relationship for the C2 core materials generated using RETC. The possible range of hydraulic conductivity values generated with the 99% hydraulic conductivity intervals are bounded by the upper and lower curves.

Interpretation and Analysis of Matric Potential Data



Figure 25 displays the fluctuations in matric potential for tensiometers in nests C,D,and E for the period of observation.

Figure 25. Matric potential fluctuations for tensiometer nests C,D, and E (installed above the thrust fault hanging wall).

Tensiometers within nests C,D, and E were installed 1.5 to 3 meters below ground surface within the clay-rich semi-confining unit overlying the non-fractured granulite gneiss hanging wall (see Figure 4 for locations and depths). Tensiometers C1, D1, and E1 were installed 3 meters bgs; tensiometers D2, and E2 were installed 1.5 meters bgs. The high moisture content within the clay rich regolith and the near proximity of the tensiometers to the semi-confined aquifer in this region of the study transect resulted in

considerably higher matric potential values, compared with matric potential values from similar depths within the shear zone.

The temporal trends of matric potential values for the D and E series tensiometers are quite similar (Figure 25), and indicate that the portions of the study transect monitored by the D and E series tensiometers are governed by similar soil water retention characteristics.

The stable matric potential trend for tensiometer C1 is similar to the D and E series tensiometers, but matric potential values are notably lower. Matric potential values within the upper portions of the regolith mantle in the vicinity of tensiometer C1 are thought to be lower as a result of deeper drainage, and the higher position of the tensiometer above saturated conditions associated with the semi-confined aquifer. Malfunctions with the ceramic cup assembly for tensiometer C2 prohibited the measurement of matric potential adjacent to this tensiometer.

Water Retention Characteristics

Figure 26 illustrates the variations in volumetric soil moisture content associated with the regolith adjacent to the 1.5 meter interval of access tube 6. Standard deviations from the mean volumetric moisture content value of 14.42% are \pm 1.43%, and corroborate the stable matric potential behavior observed at this depth.



Figure 26. Volumetric moisture content fluctuations obtained with TDR at 1.5 meters b.g.s : access tube 6 (see Figure 4 for location).

Seasonal profiles of volumetric moisture content adjacent to access tube 6 (Figure 27) illustrate a fairly dynamic response to precipitation within the upper meter of the regolith. A variation in volumetric moisture content of approximately 10% in the near surface portion of the profile illustrates the dynamic influence of shallow subsurface flow, infiltration, and runoff within this region. Below the depth of 1 meter, the

influences of the shallow subsurface and surface flow diminish. Relatively stable volumetric moisture content measurements within the 1-2 meter interval are in good agreement with the stability exhibited by the tensiometric data associated with tensiometers D2 and E2 (Figure 25). Due to the inability of the TDR probe to accurately and consistently measure volumetric moisture content under saturated and near saturated conditions, the dynamics of the volumetric moisture content within the region below 2.5 meters remain unclear. Tensiometric data for the 3 meter depth interval (tensiometers D1 and E1) indicate a nearly saturated/ saturated region of relatively stable matric potential.



Figure 27. Seasonal volumetric moisture content profiles obtained with TDR: access tube 6.

An additional source of uncertainty associated with the TDR measurements utilized in this study stems from access tube installation, particularly in the clay rich regolith surrounding access tubes 4,5, and 6. Auger cuttings used to backfill these access tube holes consisted predominately of sandy clays of variable moisture content.

Recharge Flux Estimates Within Regolith Overlying the Thrust Fault Hanging Wall

Representative estimates of recharge rates through the regolith (semi-confining unit) overlying the thrust fault hanging wall could not be obtained from the matric potential measurements recorded throughout the period of observation. Matric potential measurements associated with the tensiometers above the thrust fault hanging wall indicate that the lower portion of the monitored region remains near saturation as a result of the occurrence of the semi-confined aquifer. Because the lower tensiometers within the D and E series tensiometer nests registered persistent matric potential values near zero, recharge flux calculations utilizing the hydraulic gradients between tensiometers D2/D1 and E2/E1 and hydraulic conductivity values adjacent to the D1 and E1 tensiometers yield recharge flux estimates that are orders of magnitude greater than the total recorded precipitation throughout the period of observation (33.24 cm).

Persistently high matric potential values within the unsaturated regolith overlying the thrust fault hanging wall appear to be associated with an upward hydraulic gradient originating in the semi-confined aquifer. High-resolution surface electrical resistivity illustrates the structure of the semi-confined aquifer and associated confining unit (Figure 28). Variations in resistivity between the surface, the unsaturated portion of the semiconfining unit, and transition zone aquifer emphasize the discontinuous nature of the flow system within the regolith.

Figure 29 is a graphical interpretation of the matric potential distribution within the regolith overlying the thrust fault hanging wall. The flow system depicted in Figure 29 is restricted to flow in the vertical direction, and is bounded on the bottom by the impermeable thrust fault hanging wall (a no flow boundary). Matric potential values associated with the hydraulic gradient in the semi-confined aquifer are highest (most positive) below the semi-confining unit. Matric potential values associated with the saturated hydraulic gradient decrease upward from the semi-confined aquifer, and become zero above the base of the semi-confining unit. Conversely, matric potential data recorded with the D and E series tensiometers indicate that matric potentials associated with the unsaturated hydraulic gradient within the regolith above the thrust fault hanging wall are most negative near the top of the unsaturated profile, and become increasingly positive with depth.





Figure 29. Conceptual model describing flow processes within the regolith overlying the semi-confined transition zone aquifer.

Comparison of Matric Potential and Water-Level Data

Figure 30 shows water level data from piezometer P-01 installed within the saturated regolith in conjunction with the matric potential data recorded by tensiometer D2 for the period of observation.



Figure 30. Piezometric and tensiometric data within regolith overlying thrust fault hanging wall.

Piezometric response to precipitation is readily recorded by the tensiometers installed within the semi-confining unit. Persistently high matric potential values suggest that the upward moving hydraulic gradient associated with the semi-confined aquifer masks the actual contribution of gravity driven infiltration through the regolith overlying the thrust fault hanging wall for the depths in which the D and E series tensiometerd are installed. Due to the persistence of saturated conditions within the semi-confined aquifer as well as the persistence of high matric potential values recorded with the tensiometers in the unsaturated portion of the semi-confining unit, it is evident that the fractured rock aquifer overlying the horizontally oriented thrust fault plane is not being recharged from this portion of the transect, and that the thrust fault hanging wall is acting as a no-flow boundary for water within the semi-confined aquifer.

Uncertainty Associated With Recharge Flux Estimates

It is important to note that the reported recharge fluxes ranging between 0.34 and 8.03 centimeters within the shear zone are based solely on the period of observation. This observation period does not include the potentially substantial precipitation inputs that occur in late summer and early fall. Because the effects of substantial precipitation events have not yet been successfully recorded with tensiometers at the field site, the contribution of such events to total recharge is not yet understood.

Inaccuracies associated with recharge flux estimates within the regolith overlying the thrust fault hanging wall stem from the persistently high matric potentials within the regolith as a result of a vertical hydraulic gradient within the shear zone aquifer. Consequently, matric potential data used for the estimation of recharge flux in this portion of the transect must be representative of conditions where only downward flux is occurring. It may be possible to quantify recharge flux through the semi-confining unit with the use of matric potential measurements taken from higher elevations in the unsaturated profile, outside of the influence of the upward hydraulic gradient in the semi-
confined aquifer. Because this study did not focus on flux within the shallower portions of the study transect, it is unknown if such an approach is feasible at this location.

The unsaturated hydraulic conductivity/ matric potential curves used in this study are based on the generation of water-retention parameters from a neural network system and not by in-situ water retention measurements. For this reason, it is not possible to test the validity of the water-retention parameters assigned by the neural network program ROSETTA with retention data measured in-situ. Uncertainty estimates (right hand column on tables 2 and 4) assigned to each retention parameter by ROSETTA provide the only way to validate the accuracy of the water retention parameters used in the construction of the hydraulic conductivity/matric potential curves. Although these uncertainty estimates indicate the effectiveness of the optimization processes inherent to ROSETTA, they provide no means of comparing the optimized data to the actual retention data. No methodology for directly and continuously measuring in-situ recharge flux in undisturbed materials over a range of known matric potentials has been presented in the literature to date. However, such a technique would be invaluable for characterizing and modeling unsaturated flow systems such as described here.

Conclusions

Two distinctly different groundwater recharge processes have been shown to occur along the study transect A-A' as the result of the occurrence of a thrust fault. Infiltrated meteoric water above the vertically oriented thrust fault shear zone appears to be driven by a gravity-dominated hydraulic gradient below a depth of approximately 3 meters. Relatively slow recharge rates in the shear zone (approximately 4-10 centimeters per year based on the period of observation) result from persistently low matric potentials within the loosely structured saprolite. Infiltrated water within the unsaturated portion of the shear zone is eventually directed to saturated fault gouge where it is thought to migrate laterally to adjacent damage zones in communication with the underlying fault plane aquifer.

Matric potential values recorded within the regolith overlying the thrust fault hanging wall are higher (by nearly 300 cm) than recorded matric potential values within the vertically oriented shear zone. The matric potential values within this portion of the transect indicate erroneously high recharge rates in excess of the annual precipitation average of 119 cm. Additionally, persistently high matric potential values indicate that the use of matric potential data from the monitored portion of the semi-confining unit are not useful for quantifying recharge, and that an alternative approach for quantifying recharge in this region should be taken. Matric potential measurements from higher elevations within the unsaturated profile outside of the influence of the vertical hydraulic gradient associated with the semi-confined aquifer may be more effective at quantifying recharge through this region of the transect.

The correlation between matric potential and potentiometric surface fluctuations within the regolith overlying the thrust fault hanging wall indicates a high degree of communication between the unsaturated semi-confining unit and the semi-confined transition zone aquifer overlying the thrust fault hanging wall. This correlation illustrates the influence that changes in the upward hydraulic gradient associated with the semiconfined aquifer have on matric potential in the lower portions of the semi-confining unit. Additionally, the persistence of saturated conditions within the semi-confined aquifer as well as the persistence of high matric potential values in the monitored portion of the semi-confining unit indicate that the fractured rock aquifer overlying the horizontally oriented thrust fault plane is not being recharged from this portion of the transect, and that the thrust fault hanging wall is a vertical no-flow boundary for water within the semiconfined aquifer.

The occurrence of two different recharge processes along the study transect A-A' indicate that groundwater recharge to the crystalline aquifers within the Blue Ridge Physiographic Province is strongly controlled by the underlying geologic structure. Although recharge rates within the vertically oriented thrust fault shear zone have been shown to be relatively slow, the ubiquity of small scale thrust faults within the Province (Seaton and Burbey 2000; Seaton 2002; Seaton and Burbey 2005) suggests that infiltration and recharge along vertically oriented thrust fault planes is an important mechanism contributing to groundwater storage within deeper crystalline bedrock aquifers of the Province.

The variability in the size and distribution of localized thrust fault aquifers and associated recharge zones within the Blue Ridge Province indicate that the issues of

groundwater quality protection and sustainable yield within the region will need to be addressed on a geographically localized basis. More demands on these largely untapped resources will be made with increasing growth, and a better understanding of the occurrence and timing of groundwater recharge will help to minimize potential contaminant and utilization impacts on groundwater resources.

Although outside of the scope of this paper, additional mechanisms of groundwater recharge within the Province likely include the infiltration of meteoric water along vertically oriented brittle fracture sets such as joints and fractured quartz veins, and the recharge of surface waters at springs sourced at least partially by waters originating from deep crystalline aquifers. Additional research into these more localized mechanisms of groundwater recharge could yield valuable information regarding quantity and occurrence.

Tracer tests within the unsaturated and saturated regions of the thrust fault shear zone are planned, and will yield vital information pertaining to the timing and final source destination of infiltrated meteoric water within the shear zone. Additionally, future research regarding recharge rates within the more localized geologic features such as vertically oriented brittle fracture sets and springs could be a final and important step in understanding recharge processes within the Province.

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Appendix A-Schematic for Tensiometers Used in Recharge Investigation



Appendix B- Historical Water Level Data: w-04

