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# Using saline tracers to evaluate preferential recharge in fractured rocks, Floyd County, Virginia, USA

David F. Rugh · Thomas J. Burbey

**Abstract** Potassium chloride (KCl) and potassium bromide (KBr) tracers were used to explore the role of geologic structure on groundwater recharge and flow at the Fractured Rock Research Site in Floyd County, Virginia, USA. Tracer migration was monitored through soil, saprolite, and fractured crystalline bedrock for a period of 3 months with chemical, physical, and geophysical techniques. The tracers were applied at specific locations on the ground surface to directly test flow pathways in a shallow saprolite and deep fractured-rock aquifer. Tracer monitoring was accomplished with differential electrical resistivity, chemical sampling, and physical monitoring of water levels and spring discharge. KCl, applied at a concentration of 10,000 mg/L, traveled 160 m downgradient through the thrust fault aquifer to a spring outlet in 24 days. KBr, applied at a concentration of 5,000 mg/L, traveled 90 m downgradient through the saprolite aquifer in 19 days. Tracer breakthrough curves indicate diffuse flow through the saprolite aquifer and fracture flow through the crystalline thrust fault aquifer. Monitoring saline tracer migration through soil, saprolite, and fractured rock provided data on groundwater recharge that would not have been available using other traditional hydrologic methods. Travel times and flowpaths observed during this study support preferential groundwater recharge controlled by geologic structure.

**Résumé** Les traceurs de chlorure de potassium (KCl) et bromure de potassium (KBr) ont été utilisés pour explorer l'impact de la structure géologique sur la recharge et l'écoulement de l'eau souterraine au Site de Recherche sur les Roches Fracturées dans le comté de Floyd en Virginie

aux USA. La migration du traceur a été surveillée dans le sol, le saprolite et le socle cristallin fracturé sur une période de 3 mois au moyen de techniques chimiques, physiques et géophysiques. Les traceurs ont été injectés à la surface du sol, en des lieux spécifiquement choisis pour évaluer directement les lignes d'écoulement dans un saprolite peu profond et un aquifère de roche fracturée profond. La surveillance des traceurs a été réalisée au moyen de résistivité électrique différentielle, échantillonnage chimique et surveillance physique des niveaux d'eau et du débit des sources. Le KCl, injecté à une concentration de 10,000 mg/L, a parcouru en 24 jours 160 m en aval à travers l'aquifère affecté par la faille inverse jusqu'à l'exutoire d'une source. Le KBr, injecté à une concentration de 5,000 mg/L, a transité sur 90 m à travers l'aquifère de saprolite en 19 jours. Les courbes de restitution des traceurs indiquent un écoulement diffus à travers l'aquifère de saprolite et un écoulement de fracture à travers l'aquifère de socle cristallin affecté par la faille inverse. La surveillance de la migration du traceur salin à travers le sol, le saprolite et la roche fracturée a apporté des données sur la recharge de l'eau souterraine qui n'auraient pas été disponibles via d'autres méthodes hydrologiques. Les temps de transport et les directions d'écoulement observés durant cette étude étayaient l'idée d'une recharge préférentielle contrôlée par la structure géologique.

**Resumen** Mediante la utilización de cloruro potásico (KCl) y bromuro potásico (KBr), se ha investigado el papel de la estructura geológica en la recarga y flujo del agua subterránea en el punto de Investigación de rocas fracturadas en Floyd County, Virginia, USA. La migración de los trazadores se ha monitorizado a través del suelo, el saprolito y las rocas cristalinas fracturadas durante 3 meses mediante técnicas químicas, físicas y geofísicas. Los trazadores se aplicaron en sitios específicos de la superficie del suelo para testar directamente los flujos de agua en el saprolito superficial y el acuífero profundo en rocas fracturadas. La monitorización de los trazadores se acompañó de medidas de resistividad eléctrica diferencial, muestreo químico y monitorización física de los niveles de agua y la descarga en manantiales. KCl, aplicado en una concentración de 10,000 mg/L, viajó 160 m aguas abajo a través del acuífero hacia un manantial en 24 días. KBr, aplicado con una concentración de 5,000 mg/L, viajó

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aguas abajo 90 m a través de acuífero en el saprolito durante 19 días. Las curvas de la llegada de los trazadores indican la existencia de flujo difuso a través del saprolito y el flujo a través de fracturas del acuífero cristalino fallado. Monitorizando los trazadores salinos a través del suelo, el saprolito y la roca fracturada se consiguen datos de la recarga que no serían obtenidos usando otros métodos hidrológicos tradicionales. Los tiempos de residencia y los caminos del flujo observados durante este estudio apuntan a la existencia de recarga de agua subterránea por flujos preferenciales controlados por la estructura geológica.

**Keywords** Fractured rocks · Crystalline rocks · Tracer tests · Blue Ridge · Groundwater recharge

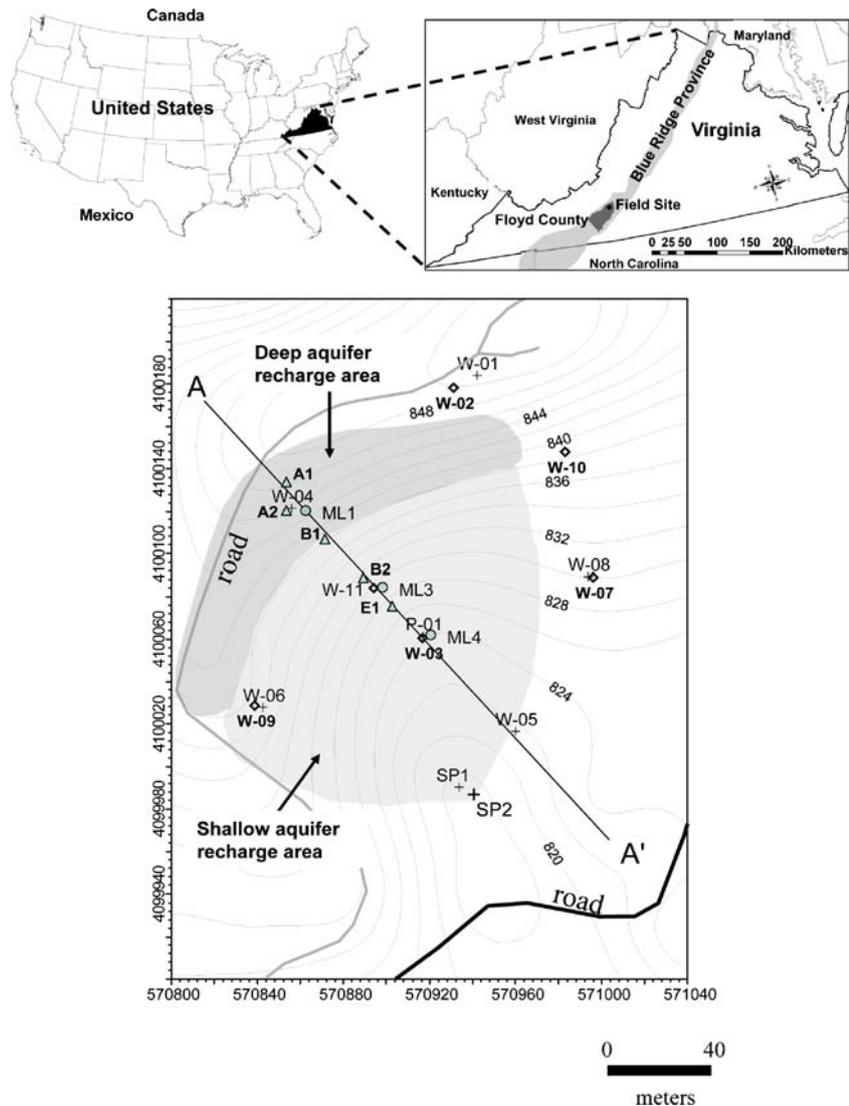
**Introduction**

Investigating possible preferential recharge pathways in heterogeneous fractured rock environments is an essential step in characterizing groundwater flow and recharge

processes. Understanding the spatial distribution of groundwater recharge in geologically complex aquifer systems requires extensive long-term hydrologic and geophysical monitoring that includes periodic measuring of the physical, chemical, and electrical attributes of the subsurface. Accurate hydrogeologic models for the Blue Ridge Physiographic province are needed because of an increased demand for sustainable groundwater resources in the region.

The Blue Ridge physiographic province represents a relatively narrow band of complex geology and hydrogeology that stretches from Pennsylvania to Georgia states (Fig. 1). The Blue Ridge is comprised predominately of igneous and metamorphic rocks that are highly fractured and faulted due to several episodes of shortening and extension throughout the Paleozoic and Mesozoic eras (Dietrich 1970). Relatively few detailed hydrologic studies have been performed in the Blue Ridge despite the fact that numerous public water supplies exist. During a drought in 2002, existing public water supplies were so depleted that emergency water conservation legislation

**Fig. 1** Location map of Fractured Rock Research Site (FRRS) in Virginia State, USA, illustrating well (*W*, plus sign = shallow; *diamond* = deep), multi-level sampler (*ML*, circles), soil sample (*triangles*) and spring (*SP*) locations along the study transect, and land-surface contours (interval 2 m). Line *A-A'* represents the cross section of the conceptual model and differential resistivity electrode array. *Shaded regions* indicate interpreted recharge areas based on analyses from this investigation



was enacted and many communities received federal government disaster relief (Virginia Department of Environmental Quality 2003; Weaver 2005).

A better understanding of groundwater flow is needed for locating new reliable groundwater supplies in the heterogeneous fractured rock aquifers that are commonly found in the Blue Ridge. Investigating groundwater flow with tracer experiments allows in-situ observation and measurement of tracer migration. Many researchers have completed studies using saline tracers in different environments at a wide range of scales (Derby and Knighton 2001; Vanderborcht and Vereecken 2001; Dyck et al. 2005; Hu and Moran 2005; Levitt et al. 2005). Chloride and bromide tracers are widely used because they behave conservatively in a variety of geologic media, they often occur at low background levels, they are simple to quantify, and they are relatively benign when released into the environment (Levy and Chambers 1987; Käss 1998). Various saline tracers have also been extensively used in conjunction with electrical resistivity imaging (ER) to monitor fluid movement in a noninvasive nature at a high spatial and temporal resolution in unsaturated soils, saturated fractured rock aquifers, and saturated granular aquifers (Slater et al. 1997, 2000; Singha et al. 2003; Kim et al. 2005; Singha and Gorelick 2005). Applying tracers to evaluate recharge in the Blue Ridge province has not been previously attempted due to the considerable amount of site-specific knowledge that is necessary for successful monitoring in a highly complex heterogeneous setting.

This study aims to definitively assess the role of geologic structure on groundwater recharge at the Fractured Rock Research Site (later referred to as the FRRS) in the Blue Ridge province (Fig. 1). Previous investigations by Seaton and Burbey (2000, 2002, 2005), Gentry and Burbey (2004), and White and Burbey (2007) provide a wide variety of hydrologic, geologic, and geophysical data used to thoroughly describe this study site. These studies suggest that groundwater recharge in the Blue Ridge is highly correlated with geologic structure, which contradicts the accepted Blue Ridge conceptual model that portrays the regolith as a homogenous unit that transmits recharge in a spatially consistent manner to the underlying fractured bedrock aquifer (Legrand 2004). Evaluating suspected recharge pathways for this study required applying large volumes of saline tracers at the surface and monitoring plume migration through regolith and fractured rock. Multi-level samplers and deep wells were used for chemical sampling along the study transect.

Water chemistry was periodically analyzed at multi-level samplers, wells, and springs. ER profiles were gathered periodically along the plume transect to measure changes in the bulk electrical properties of the subsurface. Water levels were acquired from wells and multi-level samplers in the study area. Physical and electrical monitoring of springs was accomplished with a recording flow meter and specific conductance electrode. Data gathered during the course of this study are applicable to many sites throughout the Blue Ridge province where thrust faults are present in crystalline rock.

## Site geology and hydrogeology

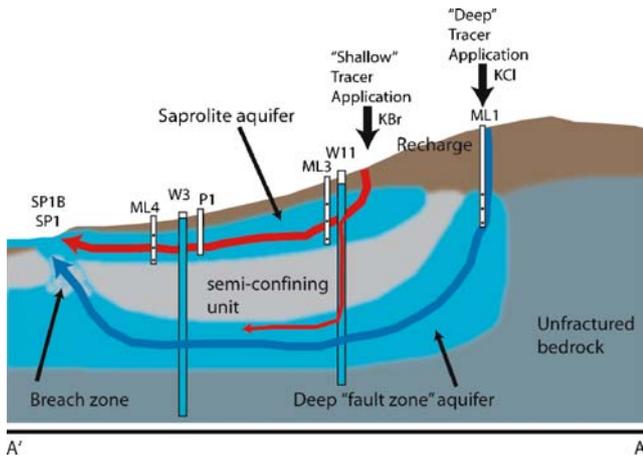
The Fractured Rock Research Site is located south of Roanoke, Virginia, near the western margin of the Blue Ridge Physiographic province (Fig. 1). This portion of the Blue Ridge is characterized by high relief topography and is underlain by highly metamorphosed sedimentary and igneous rocks. Episodes of compression and extension have resulted in a set of semi-regional NE–NW trending thrust faults that are topographically expressed as ridges in the vicinity of the study area (Dietrich 1970; Seaton and Burbey 2005).

The research site is underlain by the Ashe Formation which consists of gneisses, mica-schists, and granites. The bedrock at the FRRS is highly fractured and faulted at depth due to ancient reverse faulting (Seaton and Burbey 2005). Storage within the fractured bedrock is typically limited within the Blue Ridge but can increase significantly near localized fractures or faults (Daniel 1996; Seaton and Burbey 2005). Depth to bedrock at the site depends largely on topographic position and ranges from 10 to 25 m.

Weathering of parent bedrock material has produced regolith of varying thickness and composition throughout the Blue Ridge. Regolith in the Blue Ridge consists of a relatively thin soil horizon and a relatively thicker underlying saprolite zone that typically retains the structure and foliation of the parent bedrock material (Buol et al. 2000). The type and amount of regolith is controlled by topographic elevation and bedrock weathering susceptibility. Regolith in the Blue Ridge upland can be a major storage reservoir for groundwater (Heath 1984; Daniel 1996; Swain et al. 2004). Unweathered resistant bedrock fragments are common in Blue Ridge regolith and their occurrence and size increase with depth.

Blue Ridge aquifer systems include varying amounts of bedrock and regolith. The heterogeneous distribution and anisotropic behavior of these materials results in complex hydrologic systems that are extremely variable on a local scale. The amount of groundwater available in Blue Ridge fractured rock aquifers is locally dependent on fractures, joints, and the hydraulic relationship between the saprolite and bedrock (Swain et al. 2004).

The heterogeneous multi-aquifer system at the FRRS has been extensively investigated by previous researchers who have used a wide variety of hydrogeologic tools to better define the conceptual model of Blue Ridge fractured rock aquifer systems. Initial site characterization was performed by Seaton and Burbey (2000, 2002, 2005) using ER profiling and geophysical borehole logging. These investigations revealed that recharge enters the regolith directly above the vertically oriented portion of the ancient thrust fault, travels through the unsaturated zone and enters the highly transmissive fractured fault-zone aquifer (Fig. 2). Recharge entering the regolith elsewhere infiltrates to the shallow saprolite aquifer (so-called because the soil horizon is not saturated at the site) located above a bedrock semi-confining unit and typically travels horizontally along the bedrock surface to local



**Fig. 2** Conceptual cross section of FRRS based on work completed by Seaton and Burbey (2000, 2002, 2005). Well (*W*) and multi-level sampler locations (*ML*-dots indicate positions of sampling ports) are illustrated along with interpreted tracer flowpaths. *Blue line* indicates path of KBr tracer and *red line* indicates path of KCl tracer

discharge zones such as streams and shallow springs. A localized breach zone at the site (Fig. 2) permits mixing of shallow and deep groundwater upgradient of a low flow spring, SP1, found near the southern boundary of the site (Fig. 1).

Evaluation of the hydrogeology and aquifer characteristics at the site was accomplished using 11 wells that were drilled to varying depths at different locations (Fig. 1; Table 1). Deep wells are those that penetrate and are open to a highly productive fracture zone (deep-fault-zone aquifer) at depths ranging from 36–44 m bgs (below ground surface). The wells open to the saprolite aquifer (Table 1) generally only penetrate a few meters into the underlying bedrock. The exception is W-04, but this well has no open fractures in the bedrock and is dominated by the hydraulics of the shallow saprolite aquifer. Hydraulic testing of installed wells, analysis of ER profiles, and chlorofluorocarbon age dating of shallow and deep aquifer waters were used to define the hydrogeology of the site, which was used as a framework for a new conceptual model for the Blue Ridge province (Seaton and Burbey 2005).

W-11 was installed specifically for this investigation and logging and flow-meter testing at this site indicates that a casing leak, resulting from a poor seal at the regolith/bedrock interface, occurs at a depth of ~21 m. While conducting heat-pulse flow-meter (HPFM) logging in W-11 during pumping conditions, a large head decline occurred near the casing leak allowing water to enter the borehole from shallow bedrock fractures. An inflatable packer was installed at a depth of 24.4 m to isolate the saprolite aquifer and casing leak from the deep aquifer. This packer remained inflated for the duration of the tracer study. W-11 was used to monitor tracer migration within the thrust fault (fault zone aquifer).

Solinst 3-channel CMT tubing was installed at ML1, ML3, and ML4 sites (Fig. 1; Table 1) by direct burial, and

sampling ports were isolated using bentonite chips, sand, and native materials. These multi-level samplers allow for direct observation of water levels to evaluate vertical hydraulic gradients and chemical sampling through minimal purge volumes at three depth zones within a single borehole.

A spring hydrograph study completed by Gentry and Burbey (2004) used hydraulic testing and springflow recording equipment to evaluate the source of shallow spring water. Long-term monitoring of water levels, precipitation, and springflow were used to study shallow and deep aquifer discharge to the springhead under different hydraulic conditions.

Since this earlier spring study, the springhead has been modified by the landowner to distribute the spring discharge through two separate outlets. SP1, the main outlet, contains approximately three-fourths of the discharge and was instrumented with the springflow recording system for this study. SP1B, located several meters downgradient from SP1, contains approximately one-fourth of the spring discharge. For this investigation, SP1 (Fig. 1) was monitored between January 2006 and October 2006 to correlate water chemistry with springflow. Flow and specific conductance were recorded using a modified version of the low-flow recording system developed by Gentry and Burbey (2004).

Physical monitoring of the unsaturated zone was performed at the FRRS by White and Burbey (2007) using time domain reflectometry logging and tensiometers to evaluate recharge mechanisms at the site. Soil moisture and matric potential readings were used to calculate quantitative recharge estimates for several locations along the A-A' transect (Figs. 1 and 2). The results of this study suggest that the shallow saprolite aquifer and the deep-

**Table 1** Wells and multi-level samplers at FRRS

Well (W or P) or multi-level sampler (ML)	Unit of open interval	Total depth of well or multi-level sampling port, in meters
P-01	Saprolite	20.0
W-01	Saprolite	61.0
W-02	Fault-zone aquifer	189.2
W-03	Fault-zone aquifer	152.4
W-04	Saprolite	97.5
W-05	Saprolite	15.2
W-06	Saprolite	30.5
W-07	Fault-zone aquifer	91.4
W-08	Saprolite	16.8
W-09	Fault-zone aquifer	91.4
W-10	Fault-zone aquifer	304.8
W-11	Fault-zone aquifer	58.0
ML1	Fault subcrop	16 p1 <sup>a</sup> 17.5 p2 18.5 p3
ML3	Saprolite	11.2 p1 14.3 p2 17.3 p3
ML4	Saprolite	10.8 p1 9.5 p2 7.6 p3

<sup>a</sup>p1, p2, and p3 are suffix indicators for ML1, ML2, and ML3 to identify specific port opening

fault-zone-aquifer exhibit distinct and different recharge processes that reflect the underlying geology.

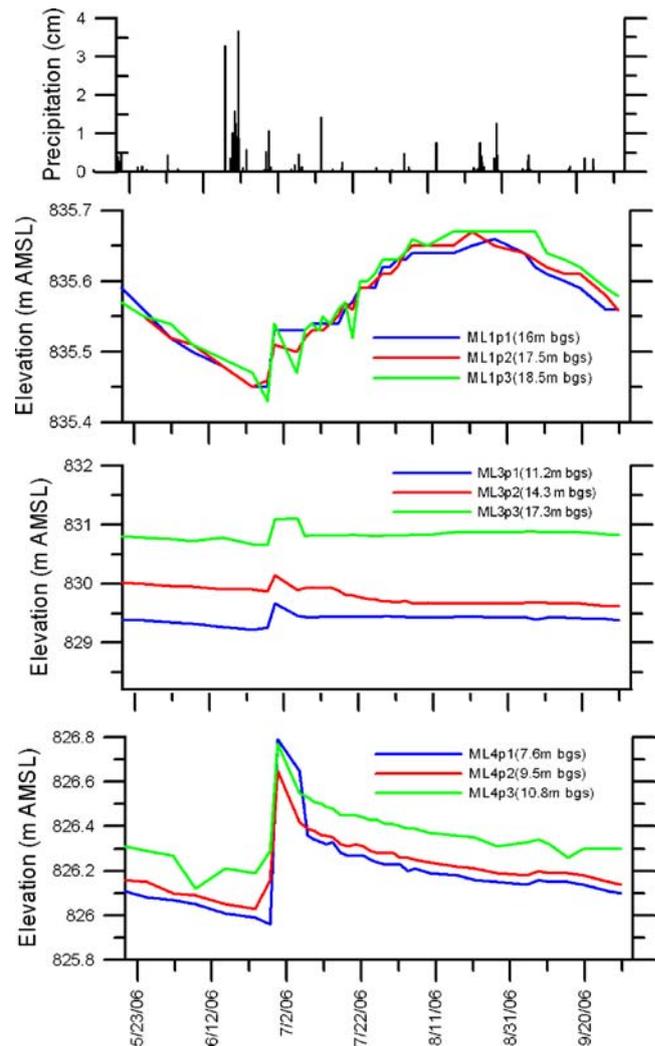
### Water level, precipitation and springflow data

Prior to releasing the tracers in this natural gradient tracer experiment for this study, water levels were monitored to evaluate hydraulic gradients (particularly in response to precipitation events) in both the saprolite and fault-zone aquifers because gradients will greatly influence both the horizontal and vertical migration patterns of the tracers. Water levels were monitored on an hourly basis throughout this investigation using pressure transducers at both shallow and deep well sites (Fig. 1; Table 1). The data from all transducers were barometrically corrected with an onsite barometric pressure logger. Water levels were measured manually at all multi-level sampling ports during the study during each site visit, which was at a minimum of twice per week with increased measurement frequency immediately after precipitation events. Precipitation was continuously recorded using a self-contained battery operated tipping bucket style rain gauge that records the time and date of every 0.25 mm of precipitation.

ML1, situated near W-04 (Fig. 1), exhibits a damped response to meteoric recharge due to the depth of the sampling ports below the land surface. Head values monitored from each sampling port consistently differ by less than several centimeters over a vertical distance of 2.5 m (Fig. 3). This small apparent hydraulic gradient is the result of several factors including locally homogenous high hydraulic conductivity saprolite, sample port arrangement, and systematic errors from the water-level meter.

Water levels from ML3 (Fig. 1) reveal a consistent upward hydraulic gradient that supports the matric potential measurements reported by White and Burbey (2007). The amplitude of precipitation response from each port is dependent on the depth of the sampling port (Fig. 3). The highest port in multi-level sampler ML3, i.e., ML3p1 responds quickly to a large precipitation event (17 cm) between 25 June 2006 and 27 June 2006 and decreases to a new equilibrium water level in a period of 8 days. ML3p2 responds to the 25 June 2006 precipitation event as well as a subsequent (4 cm) event on 5 July 2006. The second precipitation event only affects water levels at ML3p2.

The hydraulic response of each sampling port can be at least partially attributed to saprolite heterogeneity observed during multi-level sampler installation. ML3p3 was completed near the saprolite/bedrock interface where large quartz bedrock fragments were encountered. The saprolite/bedrock interface at this location acts as a barrier to vertically infiltrating groundwater and horizontal flow occurs along this boundary. This increased flow explains the large water-level response to precipitation observed at ML3p3. Visual analysis of water levels also indicates that the peak water level—831.40 m above mean sea level



**Fig. 3** Precipitation and water levels from multi-level sampling ports (ML1, ML3, ML4) measured between 19 May 2006 and 29 September 2006

(AMSL)—from the 25 June 2006 precipitation event could have occurred between water-level measurements. As observed during this study, water-level response to precipitation in the saprolite aquifer greatly affects tracer movement.

ML4 (Fig. 1) was completed in a sandy interval up-gradient of the breach zone (Fig. 2) where the shallow and deep aquifers mix and eventually discharge to the ground surface at SP1. ML4 exhibits an upward vertical hydraulic gradient that is consistent with breach zone aquifer mixing (Fig. 2). After a precipitation event on 25 June 2006, the previously upward hydraulic gradient between ML4p1 and ML4p2 reversed for several days (Fig. 3). The gradient between ML4p2 and ML4p3 did not change directions during this time. Precipitation loading inputs temporarily reversed the vertical gradient at depths of up to 9.5 m below ground surface, allowing surface infiltration to enter the regolith aquifer. Upward gradients consistently measured at ML3 and ML4 suggest that any tracer present in the thrust fault aquifer could migrate upward into the saprolite aquifer.

Springflow (SP1) monitoring results indicate that during baseflow conditions (evaluated by hydrograph separation), spring discharge (Fig. 1) consists of 75% deep aquifer water (fault zone) and 25% shallow aquifer water (regolith) (Gentry and Burbey 2004). During significant precipitation events (>5 cm), elevated springflow is attributed to increased shallow aquifer discharge to the springhead. SP1 flow and specific conductance varied little during the monitoring period except during significant precipitation events. For the 2006 recording period, the arithmetic mean discharge was 5.51 L/min with a standard deviation of 1.09 L/min and the average specific conductance was 46.94  $\mu\text{S}/\text{cm}$  with a standard deviation of 3.02  $\mu\text{S}/\text{cm}$ . The specific conductance was found to decrease with increased discharge. Chemical variability at the spring is the result of breach zone groundwater mixing from the shallow and deep aquifers (Fig. 2). Deep aquifer groundwater at the FRRS has a significantly higher specific conductance than shallow aquifer water. Prior to the tracer experiment, W-03 (deep) had an average specific conductance of 88.9  $\mu\text{S}/\text{cm}$  and W-05 (shallow) had an average conductance of 43.2  $\mu\text{S}/\text{cm}$ . Deep groundwater discharge to the spring remains consistent through precipitation events while shallow groundwater discharge is heavily influenced by precipitation (Gentry and Burbey 2004). During elevated springflow conditions, the specific conductance of the springflow decreases as discharge increases.

## Tracer experiment

Prior to releasing the saline tracers, simple bulk sorption experiments were conducted using different soils from the FRRS to evaluate whether chloride (as KCl) and bromide (as KBr) behave conservatively in the geologic environment encountered at the FRRS. Soil was sampled at three depths (0.1, 0.5, and 1.0 m) at three different locations representing different positions along the study transect (labeled as A1, B1, and E1 on Fig. 1).

Saline tracers were chosen because: (1) they are not harmful to the environment, (2) they create an electrical signature which allows qualitative monitoring with specific conductance probes and ER surveys, (3) they are present at low background concentrations at the FRRS, and (4) they are easy to quantify in a laboratory setting using ion chromatography. Results of the adsorption experiments showed only small amounts of Cl or Br were adsorbed to the soils. Averaging all depths and sample locations,  $-0.26\%$  of the applied Cl was lost to sorption (the negative number indicates Cl release from soils) and 4.63% of applied Br adsorbed to soil particles.

Sample location A2 (near W-04, Fig. 1) exhibited the most Cl sorption, with 1.77% of the total applied amount adsorbed at the end of the 48-h experiment. Locations B2 (near W-11) and E1 (near ML3) released Cl throughout the experiment, 1.81 and 0.77% of the total applied mass, respectively.

The largest amount of Br sorption was observed at sample location E1 (near ML3, Fig. 1), with 7.24% of the

total applied Br adsorbed. Sorption was highest at this location most likely because soils contain a high proportion of clay (Levy and Chambers 1987; White and Burbey 2007), which provide more possible sorption sites than sand or silt-sized particles. Sample location A2 resulted in 4.88% of total applied Br adsorbed to soil particles. Sample location B2 showed very little sorption over the experiments; 1.88% of the total applied Br was adsorbed. During the field experiment, the KBr tracer was applied several meters from soil sample B2 because of the minimal sorption observed for this location.

After the sorption experiments were completed, the KCl and KBr tracers were applied at separate locations to evaluate preferential recharge at the FRRS. The KCl tracer was applied to the soil directly above the suspected thrust-fault-recharge-zone upgradient of W-04 and the KBr tracer was applied at ground surface above the saprolite aquifer over the hanging wall of the thrust fault upgradient of W-11 (Fig. 2).

The tracer concentrations were chosen to minimize density driven flow while still achieving a detectable chemical signature. KCl was applied at a concentration of 10,000 mg/L and KBr was applied at a concentration of 5,000 mg/L. Both tracers were applied using 1.8 cm PVC irrigation piping and a 900 L polyethylene water tank. The application of the freshwater and tracer did not have a measurable effect on multi-level sampler water levels.

The tracers were applied at ground surface into 2 m  $\times$  1 m  $\times$  2 m (length  $\times$  width  $\times$  height) pits that were dug with a shovel. Prior to tracer application, a  $\sim$ 900-L pulse of freshwater was applied over several days to saturate a small area of the unsaturated zone (A. Shapiro, US Geological Survey, personal communication, 2005). After this slug of freshwater was applied, the tracer (900 L) was continuously released into the pit over the course of several days. The KCl and KBr tracers were applied on 5 July 2006 and 11 July 2006, respectively. An additional  $\sim$ 900-L pulse of freshwater was applied after infiltration of the saline pulse had completed. The purpose of this additional freshwater pulse was to advance the tracer through the unsaturated zone. Application of freshwater and tracer solution was limited by the hydraulic conductivity of the soil. Flow rates of  $\sim$ 3 L/min were used to prevent overflowing of the application pits.

During the tracer investigation, water samples were periodically collected along the study transect at samplers, wells, and at the spring. Samples were taken every other day for the first 5 weeks of the study, every third day for weeks five to seven, and twice weekly for the remainder of the study which ended 14 weeks after tracer injection. Specific conductance was monitored during sample collection with a handheld field electrode.

Samples obtained from multi-level samplers were gathered with a Solinst mini inertial pump. Each multi-level sampling port was evacuated prior to conductance measurement and sample collection. Wells were sampled with a bailer after pumping with a submersible pump. Wells were not completely evacuated during each sampling event because withdrawing the recommended three

wellbore volumes of water could remove significant volumes of Br or Cl tracer from the system. W-03, W-05, and W-11 were sampled weekly during the study to minimize the effects of pumping on the deep aquifer. Wells were pumped according to their casing diameter and depth: ~250 L was removed from W-03, ~100 L was removed from W-05, and ~100 L was removed from W-11. Wells were allowed to recover to pre-pumping levels before conductance measurements were taken and samples were gathered. All water samples were collected in a 50-ml centrifuge tube and taken to the laboratory for ion chromatography analysis.

Interpretation of quantitative Cl and Br chemical data after ion chromatography analysis reveals that groundwater flowpaths are consistent with the conceptual model proposed by Seaton and Burbey (2000). The KCl tracer moved from the surface application site through the fault zone aquifer to the springhead in approximately 1 month. Elevated Cl levels were present at SP1 for a period of 3 weeks (Fig. 4). The KBr tracer moved from the surface application site to the spring outlet in 3 weeks and was present there for another 6 weeks.

Chemical data from ML1 do not show a statistically significant Cl or Br breakthrough (Fig. 4). ML1 was located several meters off the study transect from the KCl application site. Hill slope limitations on the air rotary

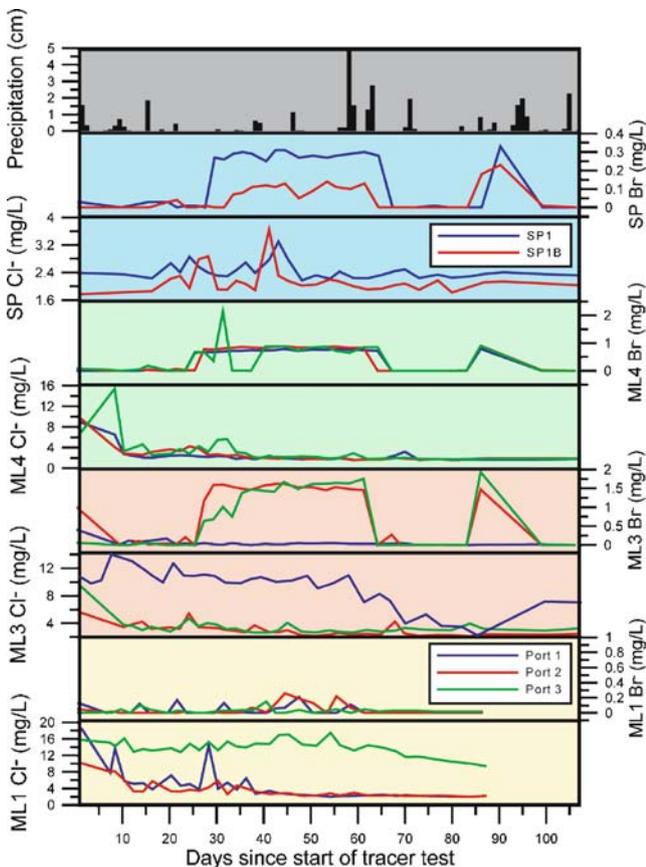
drill rig during sampler installation caused the sampler to be installed 2 m from its planned location. No KCl tracer breakthrough was observed at ML1 because of the lateral distance between the sampler and the study transect, which is in alignment with the hydraulic gradient from the tracer application.

Chemical data from ML3 indicated Br breakthrough at ports 2 and 3 that began 18 days after tracer application (Fig. 4). Elevated levels of Cl were not observed at any ML3 ports during the tracer study indicating that the KCl tracer was present only in the thrust fault aquifer. Br was detected at ports ML3p2 and ML3p3 simultaneously, but the concentration at port 2 was higher for the first 10 days then observed at port 3. Ten days after the initial Br arrival at ML3p2 and ML3p3, Br concentrations at both ports remained steady at ~1.5 mg/L for 23 days. After 3 weeks of relatively consistent tracer movement, a precipitation event during day 58 flushed the Br downgradient and no Br was measured after 4 September 2006 at ML3 for the next 22 days. A very short second Br breakthrough occurred at ports 2 and 3 after the 22 day Br non-detect period. Several samples gathered at ML3 after the second breakthrough did not contain Br.

Chromatography data from ML4 indicated Br breakthrough at all three ports and one elevated Cl peak measured at ML4 p3 (Fig. 4). Br was measured at ML4p1 and ML4p3 16 days after KBr application on the surface. Br arrived at ML4p2 2 days after arrival at ports 1 and 3. Br concentrations remained consistent at ports 1 and 2 for 37 days after their respective arrivals. Br concentrations at port 3 exhibited a large amount of variability throughout the breakthrough period when compared to all other ports observed during the study. After the initial Br arrival at port 3, concentrations ranged from 0 to 2.15 mg/L over the next 14 days. Br concentrations at ML4p3 were constant at ~0.9 mg/L for 23 days after the initial period of variability. Br was not detected at any ML4 ports after day 65 until day 87 (Fig. 4). A sharp Br peak appears on day 87 that is coincident with the secondary Br breakthroughs observed at ML3. This bromide peak consisted of only a single sample from each ML4 sampling port that was sampled near the end of the study when sampling was conducted once per week.

Chemical data from SP1 and SP1B indicated a Br arrival time 19 days after application and increased Cl concentrations 24 days after application (Fig. 4). Br was detected at SP1 4 days before detection at SP1B. Elevated Br concentrations were observed at SP1 and SP1B for 33 and 27 days, respectively. A second Br peak was observed at both spring outlets 23 days after the initial bromide breakthrough ended. This secondary breakthrough is consistent with chemical data measured at ML3 and ML4. Elevated Cl concentrations were observed for 30 days at both spring outlets. Two distinct Cl peaks were measured on day 24 and day 41. No secondary Cl breakthrough was observed throughout the sample collection period.

Chemical analysis of samples gathered from wells indicated elevated levels of Br in the fault zone aquifer



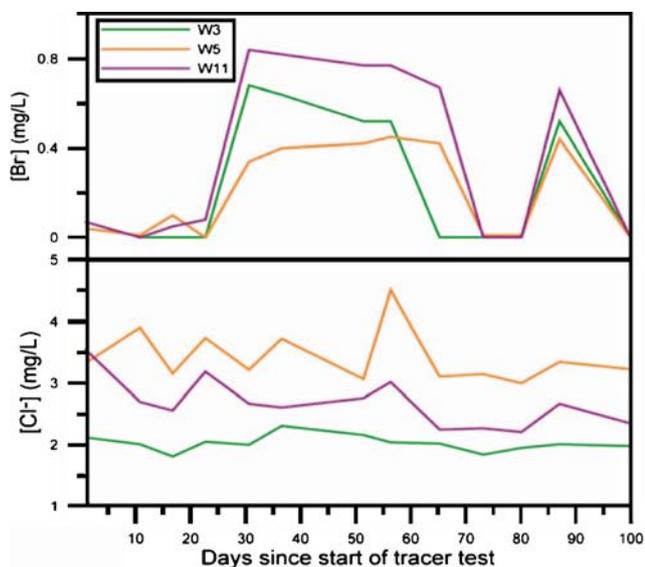
**Fig. 4** Chloride and Bromide concentrations for all multi-level samplers (ML) and spring outlets (SP) during the study period. The KCl tracer was applied on day 1 and the KBr tracer was applied on day 9

(Fig. 5). Br is found at W-03, W-05, and W-11 from day 30 to day 56. A secondary Br peak consisting of one sample was measured on day 87. W-11 consistently had the highest Br concentrations and W-05 consistently had the lowest Br concentrations. The decline in Br concentration downgradient suggests a single zone of Br inflow into the fault zone aquifer; Br concentrations increased downgradient when the semi-confining unit was leaking in multiple locations. This secondary Br peak at day 87 coincided with other secondary Br peaks measured at multi-level samplers and springs.

### Differential electrical resistivity surveys

ER surveys using a dipole-dipole array configuration were performed periodically throughout the tracer investigation in order to monitor bulk electrical changes in the subsurface due to saline tracer migration. Twenty-five permanent graphite electrodes were installed at 10 m increments along the study transect (Fig. 1). Permanent electrodes are preferred for differential surveys because systematic errors due to electrode placement are minimized. Graphite electrodes were chosen over standard steel electrodes because: (1) they exhibit lower contact resistance values than steel, (2) they do not oxidize during long-term burial, and (3) voltage potentials do not accumulate at the electrodes.

Resistivity data were inverted using Advanced Geosciences Incorporated Earthimager 2D (AGI 2006). The smooth model inversion algorithm was used for all data in this study because it is stable, fast, and robust for all types of resistivity data (AGI 2006). Differential resistivity data collected are consistent with chemical data from multi-level samplers, wells, and springs. The KCl tracer



**Fig. 5** Bromide and chloride concentrations at wells W3, W5, and W11 during the study period. W11 is located 5 m downgradient from the KBr application area, W5 is 96 m downgradient from the KBr application area, and W3 is 36 m downgradient from the KBr application area

produced a larger resistivity contrast for a longer period of time due to the higher concentration of the Cl tracer solution. The KBr tracer produces a detectable resistivity anomaly of smaller magnitude for a shorter period of time. The KCl tracer was consistently visible in differential images gathered between the application and the exit from the system at the spring (Fig. 2). The high concentration of the Cl tracer allowed the plume to be detected visually with a percent difference scale of  $\pm 50\%$ . This difference scale was chosen because the KCl plume is easily visible and small-scale variations that are not related to the applied tracer are not considered.

The differential profile collected 6 days after KCl infiltration revealed rapid vertical movement through unsaturated soil (Fig. 6). A very coarse homogeneous sandy soil was noted in this location during drilling. Between day 6 and day 14, the KCl tracer entered the fault zone aquifer and moved rapidly through the fractured metamorphic bedrock into the deep-fault-zone-aquifer system. The 14-day difference image was gathered when chemical samples from SP1 began to show statistically significant elevated Cl levels. Between day 14 and day 31, the resistivity difference in the fault zone aquifer increased both in magnitude and physical size. The 31-day resistivity difference image corresponds with the sharp Cl peak visible at SP1 (Fig. 6). No plume locations were interpreted in the 71-day difference image because the majority of the KCl had flushed through the system by this time.

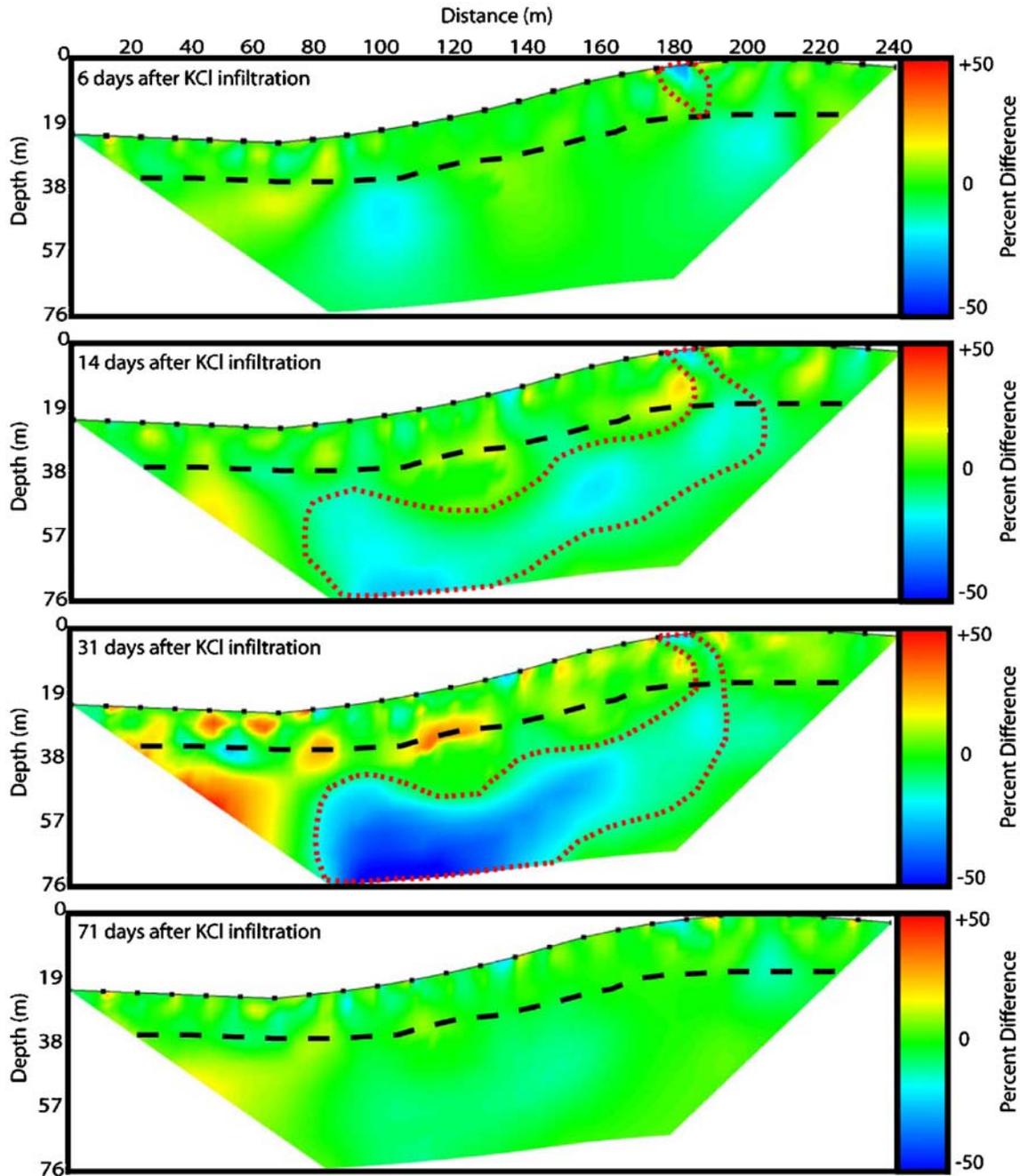
No resistivity anomalies have been attributed to KCl presence in the saprolite aquifer. The tracer plume migrated through the thrust fault aquifer beneath the saprolite aquifer. Chemical data from multi-level samplers are consistent with this interpretation. The slight resistivity difference visible in the 14-day difference image, located near the ground surface at  $x=140$  m (as shown on Fig. 6), is interpreted to be the downward migration of the KBr tracer in the shallow saprolite likely resulting from the casing leak at W-11 (Fig. 2).

### Discussion

Measurements of water levels, springflows, precipitation, tracer concentrations, and electrical resistivity yielded data that can be used to further constrain the Blue Ridge conceptual model and evaluate the effect of geologic structure on groundwater recharge and flow processes.

Water levels from multi-level samplers measured throughout this study illustrate the effect of regolith heterogeneity on groundwater flow during infiltration events. Water-level response to major precipitation events ( $>5$  cm) varied over a vertical distance of 2 m. Quantifying recharge processes in the Blue Ridge must occur on a local scale and must consider the highly variable hydraulic properties of the regolith.

The upward hydraulic gradient that was consistently measured at ML3 and ML4 was sufficient to cause the KCl tracer from the deep thrust fault aquifer to appear in



**Fig. 6** Differential resistivity images showing the movement of the KCl tracer through the fault zone aquifer. The *dotted red line* indicates the interpreted location of the KCl plume. The *dashed black line* indicates the bedrock/regolith interface. KCl was applied on the resistivity profile at an x-location of 180 m. Springs SP1 and SP1b are located laterally off the resistivity section at an x-location of 55 m

measurable concentrations at the springhead. The hydraulic gradient would suggest that deep aquifer groundwater flows upward through the semi-confining unit into the saprolite aquifer; no upward fluid migration through the semi-confining unit was observed during this study. Upward Cl migration from the deep aquifer to the spring occurred through the fractured breach zone (Fig. 2). Cl concentrations measured at ML4 could indicate that the breach zone is located near ML4p3, as indicated by a single elevated Cl concentration on day 32 of the study (Fig. 4).

The spring recording system did not provide statistically significant data pertaining to tracer breakthrough as it was intended. Tracer dilution in the groundwater system resulted in low breakthrough concentrations of KCl and KBr that did not affect the specific conductance of the spring discharge. However, all spring data recorded during this study were consistent with the current Floyd conceptual model and data gathered by Gentry and Burbey (2004). Increased springflows are a result of elevated shallow aquifer groundwater discharge to the springhead.

KBr, which was applied to the shallow saprolite aquifer, entered the deep aquifer as a result of leakage through the W-11 wellbore. Br concentrations measured at W-03, W-05, and W-11 were relatively consistent throughout the study period, suggesting that Br was continuously leaking through the W-11 casing seal at the regolith/bedrock interface (Fig. 2). Br was first measured in W-11 only 2 days after it was first measured at ML3p3, suggesting that the Br tracer must have migrated through W-11. Because the Br solution was applied to the ground surface only 10 m upgradient of W-11, the tracer solution appears to have leaked through W-11 around the packer seal or through fractures intersecting the W-11 borehole that bypass the packer.

Cl levels measured at ML1, ML3, and ML4 declined throughout the study period due to incomplete screen development after sampler installation (Fig. 4). Background concentrations of Cl measured at all multi-level sampling ports were equal to or higher than the Cl concentrations measured after KCl application. Cl is naturally present at the FRRS due to weathering of micas present in the saprolite; mica was visible in many of the early water samples gathered from the samplers. The amount of mica present in the water samples decreased during the course of the study causing the Cl levels to also decline.

Monitoring KCl infiltration and transport with differential electrical resistivity provided qualitative estimates of tracer concentration at a high spatial resolution. Subsurface locations exhibiting a “negative percent difference” in a time-lapse ER cross section were consistent with the timing of tracer breakthrough and the pre-existing site conceptual model defining the location of the thrust fault aquifer. Delineating the KBr plume with resistivity did not provide definitive results due to the lower concentration of the applied tracer and the large natural resistivity variations in the shallow saprolite that are not related to tracer movement. Resistivity data proved to be extremely beneficial for monitoring KCl migration in conjunction with chemical sampling. These data proved to be especially important when the KCl plume was located between sampling points.

Average linear velocity estimates calculated from tracer breakthroughs along the study transect can be used to approximate hydraulic parameters for the saprolite aquifer (Fig. 4). Heterogeneity in the saprolite aquifer limits the calculation of travel-time data but several breakthrough correlations can be made to extract average linear velocity data. The last positive Br sample from the first breakthrough at ML3p2 and ML4p1 was used to calculate an average linear velocity of 30 m/day. Also, correlation of the late time breakthrough peak between ML3p2 and SP1 yields an average linear velocity of 22.5 m/day. These velocity estimates represent the highest hydraulic conductivity pathways and could vary somewhat based on the accuracy of travel-time estimations resulting from the sampling frequency.

The Cl peaks measured at ML4p3 and SP1B (Fig. 4) were used to calculate an average linear velocity of 6 m/

day. This velocity differs from those calculated for the saprolite aquifer because groundwater flow in this portion of the groundwater system is dominated by aquifer mixing and preferential flow pathways through breach zone fracturing of the semi-confining unit (Fig. 2).

Br concentrations measured at the spring were much lower than the actual concentration present in the shallow aquifer before mixing with water from the fault zone aquifer. Assuming that the spring discharge represents 25% shallow groundwater and 75% deep groundwater, all shallow aquifer tracer concentrations are diluted by a factor of four when they exit the springhead.

Analysis of tracer concentrations measured at the spring outlets suggests that outlets SP1 and SP1B contain slightly different proportions of deep and shallow groundwater. SP1 exhibits a higher breakthrough for Br and a less significant Br peak. SP1B contains higher concentrations of Cl and lower concentrations of Br. Br and Cl breakthroughs are present at each springhead; however, SP1 contains a larger proportion of shallow groundwater compared to SP1B. Differing spring chemistry over a distance of several meters further illustrates the effect of aquifer heterogeneity in the shallow subsurface.

Br breakthrough concentrations suggest rapid flow in the saprolite aquifer where tracer migration due to dispersion is minimal when compared to advective transport. Dispersion could extend breakthrough times as the tracer migrates downgradient. However, this was not observed during the study as Br was present at ML3, ML4, and SP1 for approximately 30 days. The lack of dispersion suggests that fractures could play a significant role in fluid migration in the saprolite aquifer. Precipitation influences on tracer migration also suggest rapid infiltration and groundwater flow in the saprolite aquifer.

The secondary Br breakthrough observed throughout the site on day 87 is the product of KBr tracer being released from a low hydraulic conductivity portion of the regolith. A single source of Br release could result in nonzero Br concentrations at several locations along the study transect due to the high average linear velocities in the saprolite aquifer and highly transmissive fractures in the semi-confining unit. Because the secondary Br breakthrough was also observed in the deep aquifer; the zone of secondary Br release must have been located between the KBr application zone and W-11. It is highly likely that primary and secondary Br breakthroughs in the deep aquifer are the result of the same fractures or packer leakage. It is also likely that precipitation events could have influenced the timing and magnitude of the second breakthrough peak (Fig. 4).

The diffuse nature of groundwater flow observed in the saprolite aquifer is a product of several factors: (1) tracer application over a period of 53 h, (2) flowpaths of varying length and hydraulic conductivity due to heterogeneous saprolite material, and (3) sampling frequency. Tracer application over several days was necessary due to infiltration rates in the application pits. KBr was applied at the maximum flow rate that would not cause the pit to overflow and distribute the tracer solution along the

ground surface. The influence of heterogeneous saprolite materials was observed during the study as the KBr tracer migrated through a variety of weathered bedrock in the shallow aquifer. Breakthrough times measured at ML4 imply lower hydraulic conductivity material in the vicinity of port 2 because Br arrived at ML4p2 2 days after it arrived at ports 1 and 3 and disappeared at ML4p2 3 days before it disappeared at ports 1 and 3.

## Conclusions

Tracer data gathered during this study suggest that groundwater recharge in the Blue Ridge province is strongly controlled by local or semi-regional geologic structure. SE-NW trending ancient thrust faults present in crystalline bedrock can serve as highly productive fractured rock aquifers with a limited recharge area (Fig. 1). The application of a saline tracer above a vertically oriented thrust fault zone verified preferential recharge to a fractured thrust fault aquifer along the fault subcrop. A second tracer application above a saprolite aquifer demonstrated high hydraulic conductivity preferential flow pathways in the regolith near the bedrock surface. Springflow at the FRRS is comprised of shallow and deep groundwater that is not fully mixed upgradient of the spring outlet. Tracer flowpaths and travel times were verified with chemical and geophysical methods that produced consistent tracer concentration results.

Saline tracers can be applied to the ground surface under a natural hydraulic gradient to gain information about flow pathways and groundwater velocities. Tracer methods used during this study are applicable for testing flowpaths in a variety of geologic media. As with any tracer investigation, previous knowledge of groundwater flowpaths is required in the planning phases of the experiment. The natural gradient tracer method utilized for this study requires a significant amount of hydrogeologic background information because precipitation-influenced changing hydraulic gradients make plume delineation difficult. The monitoring of plume migration was successful because of the abundance of previously collected hydrogeologic data that helped constrain this aquifer system.

Though this was a local scale experiment, the findings of this study can be applied to other areas in the Blue Ridge where complex geologic structure creates preferential flow pathways. Lineament analysis of the Check topographic map, (VA1:24,000 USGS quadrangle) which includes the study area, reveals a large number of regional scale lineaments with similar orientations to the thrust fault complex investigated in this study (Seaton and Burbey 2005). The regional geology suggests that complex aquifer systems comparable to the FRRS are common throughout the Blue Ridge; though few detailed hydrologic studies have been completed in the region to validate the presence of fault zone aquifer systems.

Data from this study and previous studies at the FRRS have shown that geologic structure has a significant effect

on groundwater recharge. Geologic structure is not considered an important factor in currently accepted conceptual model for the Blue Ridge physiographic province (Legrand 2004), despite the extensive faulting that is present throughout the province. Recent studies at the FRRS have resulted in several observations that are not consistent with the current conceptual model: (1) the primary source of groundwater is the fractured thrust fault aquifer and not shallow bedrock fractures associated with weathering, (2) heterogeneity in the saprolite results in preferential flow pathways, (3) distinct aquifer systems in the saprolite and underlying fractured bedrock are separated by a relatively unfractured crystalline rock confining unit, and (4) preferential recharge occurs along vertically oriented thrust fault zones.

The need for accurate groundwater information in the Blue Ridge province is an ever growing concern as the population increases and metropolitan areas continue to spread into the surrounding rural areas. Locating sustainable groundwater resources in the Blue Ridge has historically been a difficult task, and it will become increasingly complex as demand increases. Scientists and regulators should consider geologic structures, especially faults, in future groundwater investigations as possible conduits and even groundwater reservoirs.

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