Determination of the location of the groundwater divide and nature of groundwater flow paths within a region of active stream capture; the New River watershed

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ABSTRACT

The relatively rapid stream capture of the New River basin by the Roanoke River basin provides a unique example of topographic change within a tectonically inactive environment. A previous investigation of abandoned river deposits has shown the capture of ~225 km^2 of New River basin area, which has caused approximately 250 m of incision by the Roanoke River (Prince et al., 2011). Difference in base level elevations between the lower Roanoke to the higher New River could be the source of potential energy driving rapid incision (Prince et al., 2011). Significant incongruities in base level elevations at the boundaries of an aquifer can steepen the gradient and shift the groundwater divide further toward the higher elevation boundary (Yechieli et al., 2009).

If a steep groundwater gradient and expanded groundwater basin exists beneath the Roanoke River tributaries, this would suggest a groundwater control on incision and capture. In this investigation we incorporate average total head, measured from 18 domestic wells, and constant-head river boundary conditions into numerical models to calculate water levels and gradients between the rivers. We also utilized thermal patterns and particle tracking of spring locations to better understand flow paths in the region. Our results show the groundwater divide is shifted toward the higher elevation boundary, indicating that the groundwater basin is captured prior to surface capture. Flow pathways utilized by groundwater capture can be either diffuse or conduits, however further work should be done to better understand travel times and flow depths.

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Introduction

Project Background

In 2002 the USGS submitted "Concepts for National Assessment of Water Availability and Use" in a report to Congress, in response to a directive from Congress regarding the future of water availability for the United States (USGS, 2002). The report addressed the lack of knowledge pertaining to groundwater levels across the nation and established that an inventory of the existing water-level networks for all major aquifer systems be made within the assessment (USGS, 2002). The Valley and Ridge aquifer system is a major aquifer system for the states of Deleware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia and West Virginia (USGS, 1997). Our study area in the New River Valley of Southwestern VA is located within the Valley and Ridge Provinces, between the Roanoke and New Rivers (Figure 1).

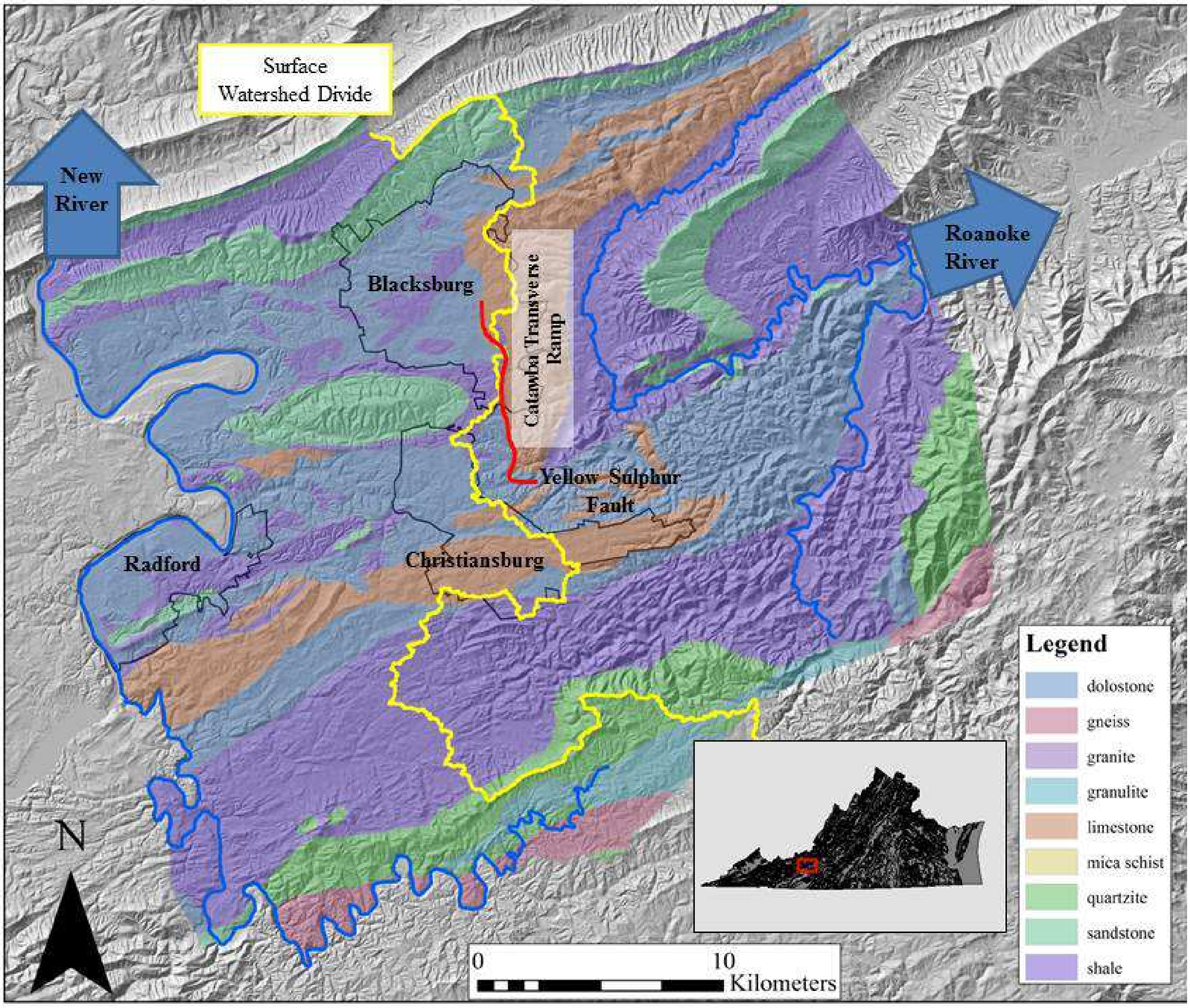


Figure 1: Map showing study area location in southwest VA. Elevation data (Gesch, 2002 and 2007) and geology shapefiles were both downloaded from the USGS (Dicken, 2005).

Blacksburg, VA in Montgomery County sits on the edge of a high plateau formed by the Catawba transverse ramp zone. The edge of the plateau is part of the ~500 km long Blue Ridge escarpment which separates the higher elevation Blue Ridge and Valley and Ridge provinces from the lower elevation Piedmont and Coastal Plain. Elevation differences across the escarpment result in 600-300 m of relief above the lower terrain (Spotila et al., 2004). In Virginia the Blue Ridge escarpment can have slopes typical of younger mountain ranges, on the order of 24° in some locations (Spotila et al., 2004).

Two major rivers flow through the Montgomery and Pulaski County region. The New River flows through Pulaski County and forms the majority of the border between it and Montgomery County (Figure 1). The headwaters of this river originate near the intersection of North Carolina, Tennessee and Virginia, and continue north-west until making a westward turn at Radford, VA as it nears the edge of the escarpment. From here the river continues toward the Ohio River and eventually will reach the Gulf of Mexico. The Roanoke River begins in Montgomery County as two small tributary branches which meet just at the north-eastern most portion of our study area (Figure 1). Average recharge to the aquifers in this region (8 in/yr) is about 20% of the annual precipitation rate. Aquifer transmissivities range several orders of magnitude due to varied lithology and deformation extent (Swain et al, 2004).

In 2011, using abandoned fluvial gravel deposits, Prince et al. (2011) were able to correlate rapid stream incision and knick-point migration within the upper Roanoke River basin to active stream capture, driven by potential energy resulting from the elevated Blue Ridge Plateau. Stream capture is the active erosion and incision of a river system a watershed divide, which leads to a watershed area increase and diversion of flow from the neighboring river system (Bishop, 1995). River capture can occur via two main processes; top-down or bottom-up (Bishop, 1995). Bottom-up refers to a river which actively intercepts and abstracts an abutting system, while top-down processes involve both rivers actively participating in capture, driven possibly by tectonics or channel migration (Bishop, 1995). During either form of capture, rearrangement of watershed divides can significantly affect the sediment budgets of each river, the biota living within the watersheds, and the overall landscape evolution of the region (Bishop, 1995). While the driver of river capture can be tectonic activity or catastrophic events, the requirements for capture are simple; significant differences in elevation between the two catchments as well as a low elevation divide between them (Bishop, 1995). These conditions are met by the higher elevation New River and lower elevation Roanoke, possibly driving the capture recorded in fluvial deposit records (Prince et al., 2011). Figure 2 demonstrates the processes of stream capture, specifically incision of the lower elevation Roanoke River system to the East into the higher elevation New River system to the west.

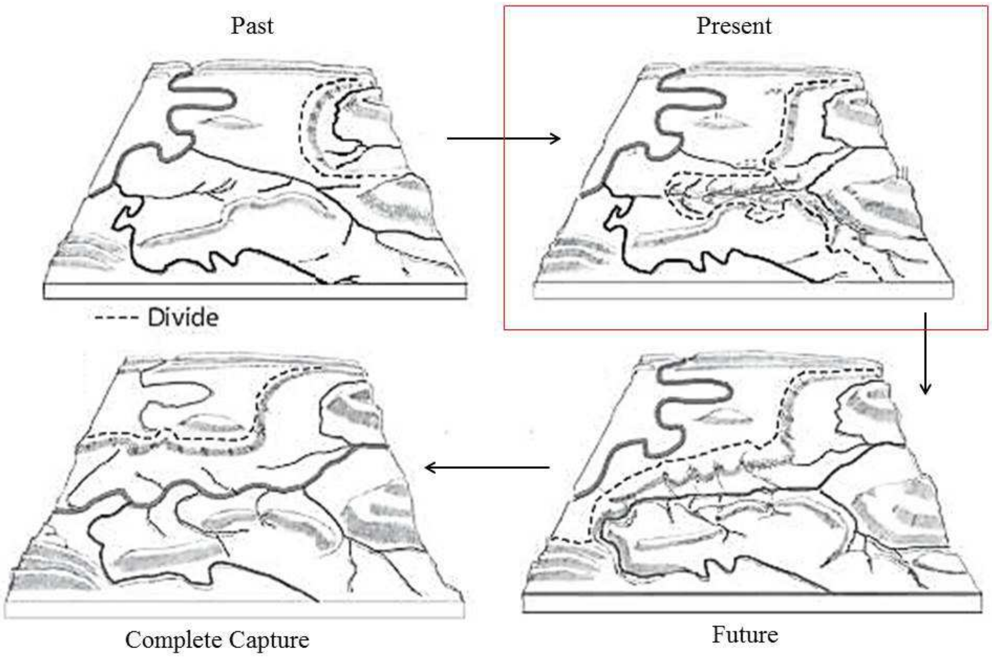


Figure 2: Conceptual model of New River stream capture. Figure shows the previous location of the divide, the current location of the divide, and the expected location in the future assuming incision continues most rapidly within weaker geologic units (modified from Prince et al, 2011).

Data from Prince et al. (2011) confirmed that capture was not only occurring between the Roanoke and New Rivers, but at a rate fast enough for fluvial deposits from previous New River tributaries to have remained on the upland basin (Prince et al., 2011). Furthermore, knick-point locations and gravel deposits were not correlated with lithologic changes or structures, again implying the system still remains in a dis-equilibrium and continues to adjust to regional base level elevations (Prince et al., 2011). As can be seen from Figures 1 and 2, the area experiencing most recent stream capture is located within the shale units of the Valley and Ridge. From this, Prince et al., (2011) present a conceptual model of divide retreat in which differential incision will continue to occur within more easily erodible geologic material until the New River is completely cut-off from its watershed (Figure 2).

Previous studies have shown that regional base levels which experience a tectonic shift, increasing the elevation difference, will result in a steepening of the gradient of groundwater flow near the lower elevation base level. Increasing the slope of the groundwater gradient will shift the location of the groundwater divide toward the base level of higher elevation (Kafri, 1970, Yechieli et al., 2009). Expansion of the groundwater basin by way of divide migration allows for transfer of groundwater flow from the higher elevation catchment into the other, a process that can increase sapping and drainage head retreat (Bishop, 1995; Dunne, 1980). Previous research sites with base level changes and groundwater divide shifts have shown evidence for river capture on the surface both morphologically and geologically (Kafri, 1970).

In order to satisfy the USGS request for better understanding of groundwater systems, we aim to identify the location of the groundwater divide between these two rivers, within the major Valley and Ridge aquifers. The capture of the New River by the Roanoke River would have direct downstream affects in Virginia and North Carolina (Roanoke River) as well as the Ohio and Mississippi River Watersheds (New River). If we hope to fully understand the future of water resources for these river systems, then we must first establish the relation of groundwater flow to active surface processes.

Purpose and Scope

This study incorporates a variety of tools to determine the location of the groundwater divide, the flow paths of water within the system, and the potential for basin expansion and groundwater interaction to increase or dictate headward stream retreat. We utilized analytical and numerical modeling, water level elevations, and spring temperature measurements during the course of this investigation. The study region includes numerous lithology changes as well as structural complexities, with the New and Roanoke Rivers representing the western and eastern margins, respectively, which will be considered constant-head boundaries associated with true base level. With the information collected during this investigation, we aim to evaluate the A) location of the groundwater divide between the Ronaoke and New Rivers, B) nature of groundwater flow paths, using spring temperature records, and C) relation of the groundwater divide location and flow pathways to surface stream capture.

Study Area Geology

Our study region is located in Southwestern VA in all of Montgomery County and small sections of Pulaski County. The study area is bounded to the east and west by the Roanoke and New Rivers respectively, and is split by the divide between them. This divide not only separates the rivers, but also forms a section of the Eastern Continental divide and coincides locally with the Blue Ridge Escarpment. The Blue Ridge escarpment lies along the border of the highland Valley and Ridge and Blue Ridge provinces and the lower Piedmont and Coastal Plain provinces (Figure 1).

The escarpment exists within thick Paleozoic sedimentary units which were deposited and also heavily deformed over several orogenies throughout the Paleozoic, ending with the Alleghanian Orogeny in the Pennsylvanian. The escarpment itself formed in the Mesozoic during Atlantic Rifting (~300 -200 myr ago) and continues to experience erosion and retreat from the shore today, although now in a tectonically inactive environment (Spotila, 2004). Although the mechanisms for this retreat are still being studied, researchers have identified fluvial disequilibrium in lowland areas with steep gradients and evidence of fluvial beheading (Hack, 1973; Prince et al., 2010). These studies have attributed differential erosive potential between the systems to this gradient disequilibrium.

In the Blacksburg area the escarpment falls along the western edge of the Catawba Transverse Ramp zone (Figure 1) (B. Henika, personal commun., 2013, VDMR). On either side of the ramp lithology is primarily represented by folded and thrusted Cambrian to Devonian carbonate rocks with interbedded mudstones that may act to confine flow in the region. However, few hydrogeologic studies have been done to determine how structure and lithology affect the direction and rates of groundwater flow within the study area. Also important, the Yellow Sulphur Springs fault (Figure 1), located to the west of the Catawba transverse ramp zone, truncates the southwest end of the Catawba syncline and the Price Mountain anticline to the west (Figure 1). The Yellow Sulphur spring located on the fault contains chemical constituents that are unique from other springs in the study area, implying that groundwater movement may occur across the divide and could possibly be influenced by the locations of large faults (Dave Nelms, personal commun., 2013, USGS).

Study Area Hydrogeology

The Valley and Ridge province is comprised of five hydrologic terrains: siliclastic rocks, argillaceous carbonates, limestone, dolomite, and alluvium (Swain et al., 2004). These terrains have been grouped based on well specific capacities and estimated transmissivities (Swain et al., 2004). Average transmissivity values range from a high of 8,000 ft^2/d in alluvium to a low of 250 ft^2/day in siliclastic rocks. However due to the heterogeneity of the region values are estimated to range from 90 to 90,000 ft^2/day (Swain et al., 2004). The Valley and Ridge Province is bordered by the Blue Ridge Province to the south and east. Small sections of the two Blue Ridge hydrogeologic terrains lie within our study region: gneiss-granite and shale-sandstone (Swain et al., 2004). These units have typical transmissivities of 3 ft^2/d to 35 ft^2/d, much lower than the Valley and Ridge units (Swain et al., 2004).

The Valley and Ridge hydrogeologic terrains are characterized by a significant amount of conduit or fracture flow. Little work has been done on the groundwater hydrogeology specifically within our study area; however studies have been done on Valley and Ridge units in other locations within VA. Groundwater within the Shenandoah Valley, located within the Valley and Ridge Province about 150 km NE of Blacksburg, flows primarily through interconnected fractures oriented orthogonal to bedding planes, leading to significant anisotropy within the units (as discussed in Yager et al., 2009). Additionally, these fractures are most likely widened due to dissolution of carbonate aquifer material, further increasing conductivity within the units as well as variability in aquifer transmissivities (Yager et al., 2009; Harlow et al., 2005). Yager et al. (2009) used the level of water hardness in spring discharge as an indicator of the time groundwater has spent within the system, as greater hardness can be expected in water which is able to slowly dissolve greater aquifer material. Their results show that the nature of flow is primarily diffuse as opposed to being dominated by conduits within the Shenandoah Valley area (Yager et al., 2009). However, recent studies using thermal patterns in springs have identified waters which are sourced from near-surface recharge (Doctor et al., 2014). This indicates that flow paths within the Valley and Ridge can vary greatly depending on both structures and recharge availability.

The Blue Ridge Province is comprised of crystalline rocks, however due to faults and fracturing, the region maintains similar hydrogeology to that of the Valley and Ridge units, varying greatly throughout the area. Seaton and Burbey (2005) found that portions of the Blue Ridge are typically dominated by an upper saprolite aquifer and an underlying low-storage fractured bedrock aquifer, except where ancient faults may influence the system. Fault planes have been shown to exhibit low permeability but adjacent areas can be dominated by a network of higher transmissivity fractures; however, storage of these systems remains low (Seaton and Burbey, 2005). Recharge in the region may be greater than or less than the average values determined by Swain et al. (2004) due to the mixing of young and old waters through slow leakage and rapid movement through fractures (Seaton and Burbey, 2005).

Data Collection

Water Level Data and the Role of Social Media:

Hydrogeologic research is often limited by available access points to the groundwater system. This project required access to numerous wells and springs throughout the study region for water level sampling and temperature monitoring. Past researchers have begun by visiting the health department for well records within the appropriate location for the study. However, health departments in Virginia do not maintain electronic well records. Furthermore, paper well records are filed in several ways; either by land owner name, tax parcel ID, address, or permit date. This made it extremely difficult to locate potential wells for the study.

In order to reach local homeowners in a more efficient manner, we used social media to post information regarding our research and ask for homeowners to volunteer their wells. An undergraduate researcher created a post for the Virginia Tech News website page, (http://www.vtnews.vt.edu/) which included the following information: a simple explanation of the nature of the project, an assurance that no harm would be done to the wells, my contact information and connection to the university, and a broad description of the geographical range of our project area. This website is openly available to the public, but also sends highlights directly to university faculty and students. Additionally, the local Roanoke, VA news station, WSLS 10 posted the text from our VT News post on their Facebook page. Lastly, the same information was published onto a physical flyer (Appendix A). This flyer was posted throughout the study area on bulletin boards, in stores and community buildings. Within one week of the postings we had received >30 emails and phone calls with volunteers for the study.

Several difficulties arose in processing the volunteer emails. First, our postings had not given specific instructions to volunteers on information to include in their email. This resulted in 3 emails per volunteer before we could determine whether or not their well would even be useful to the study. Second, I chose to use my personal school email for the contact information. This further complicated processing the large in-flux of emails, as they were interspersed with my own personal and professional communications. We highly recommend that future users of social media in research create a new email address or profile accounts for each project. Lastly, we received several inquiries which were outside of our physical study area due to the lack of detail in our study description. Therefore, although we attempted to keep the posting simple to attract attention, we also recommend giving specific details which would eliminate volunteers who cannot actually participate in the project.

From the wells that were volunteered, and located within the study region, 18 were selected for the project. Selection was based on several factors which were determined during the first visit to each well. Because Blacksburg town water supply has expanded over the past 50 years, leaving many private wells have been abandoned. Unfortunately, many of these wells were unable to be opened or had blockage in the borehole, preventing a measurement from being taken. Also, several wells seemed to have natural mud or rock blockages within the borehole where our water level meter would become stuck. The final wells selected were all able to be opened, clear for measurement, and located in an area useful for our modeling goals.

Water Elevations

Bimonthly water-level measurements were taken in each of the 18 study wells using a Solinst Water Level Meter, Model 101, providing water level readings with an accuracy of 1mm (Well locations can be seen in Figure 3, numbers correspond to values in Table 5 in Water Elevations Results section). Surface elevation values were estimated using a Trimble GPS unit with an accuracy of… overall. Additionally, accuracies can be read from the unit for each elevation point taken. Water elevations were then calculated by subtracting the depth to water (minus the height of the well) from the best land surface elevation value taken by the GPS unit. Water elevations were incorporated into the regional 2D numerical model, discussed later in this section. Images of each well used in this study can be seen in Appendix B.

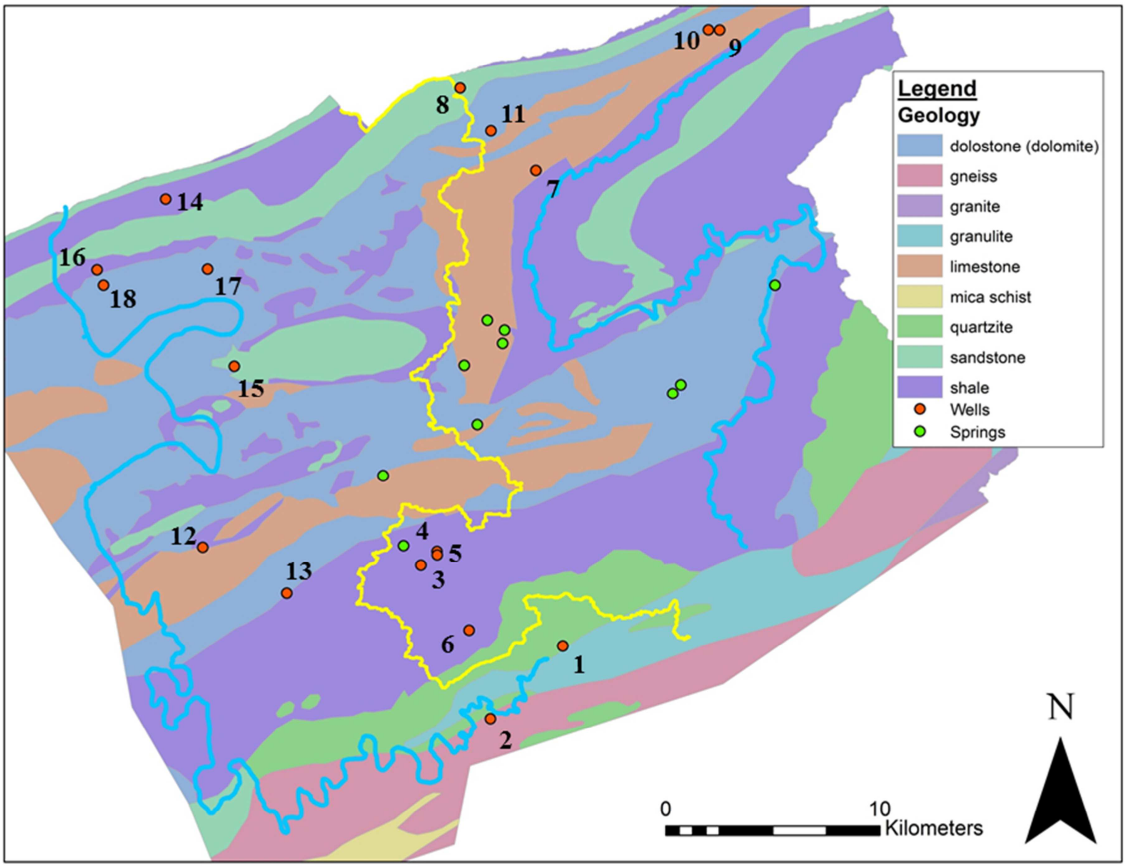


Figure 3: Map of well locations used for water elevations. Numbers can be used with Table 5 in results section. Both rivers are shown in blue and the surface divide is shown by the thick yellow line. Green points are spring locations as shown in Figure 4.

Spring Temperature Measurements

As described above, our aquifer system is comprised of highly soluble rocks, such as dolostone and limestone, and also less soluble rocks with high density fractures and faulting. Due to these factors, all units are expected to be heterogeneous and anisotropic, with locations of relatively fast conductivities along conduits and fracture openings. These conduits, along with rapid surface elevation changes, have led to numerous springs throughout the region, primarily in the Roanoke watershed. To better evaluate the influence the divide location has on energy transfer between watersheds, we utilized water temperatures and backward particle modeling in MODFLOW to determine variations in groundwater flow pathways and travel times as well as and source recharge areas for each spring.

Identifying flow pathways, travel times, and sources areas is important in supplementing our regional model, as MODLFOW assumes flow through a porous medium (using Darcy's law within a finite difference formulation of the groundwater flow equation) (Reilly, 2001). The applicability of using MODFLOW to simulate flow in fractured rock systems and particularly karstic rock environments has been a topic of discussion in the literature (White, 2002). Scanlon, et al., (2003) showed that regional flow patterns in the highly karstic Edwards aquifer system in Texas could be accurately simulated with a distributed parameter model like MODFLOW. However, local flow directions and flow rates could not be simulated where conduit flow (turbulent flow) dominated.

Spring water temperatures have been previously used as a tracer in groundwater systems (Anderson, 2005) as they can be useful in identifying integrated travel time and flow pathway signals for the entire watershed, not just point locations as with a well (Manga, 2002). Luhmann et al. (2011) logged water temperatures in 25 springs throughout southeastern Minnesota for just over a year long period using HOBO and Their data revealed four distinct patterns under which a spring thermal record can fall; 1) Event scale fluctuations over hour or day timescales, 2) seasonal fluxes in temperature, in phase with surface, 3) seasonal fluxes which are out of phase with surface, and 4) long-term stable temperatures with timescales of weeks to years (Luhmann et al., 2011). We utilized spring temperature records in a similar manner, identifying groundwater flow paths using these known patterns, which have also been identified in springs throughout the Valley and Ridge region (Doctor et al., 2014).

Seven springs were selected for the current project throughout the Blacksburg and Christiansburg areas (Figure 4). Springs were selected based on their location to each other, their distance from the divide, ease of access for sensor deployment, security of the sensor from the public and from surface temperature influence, and the surrounding geology. We also attempted to record values from varying lithologies and distances from the divide to better understand spring temperature relation to surface processes (see Table 1).

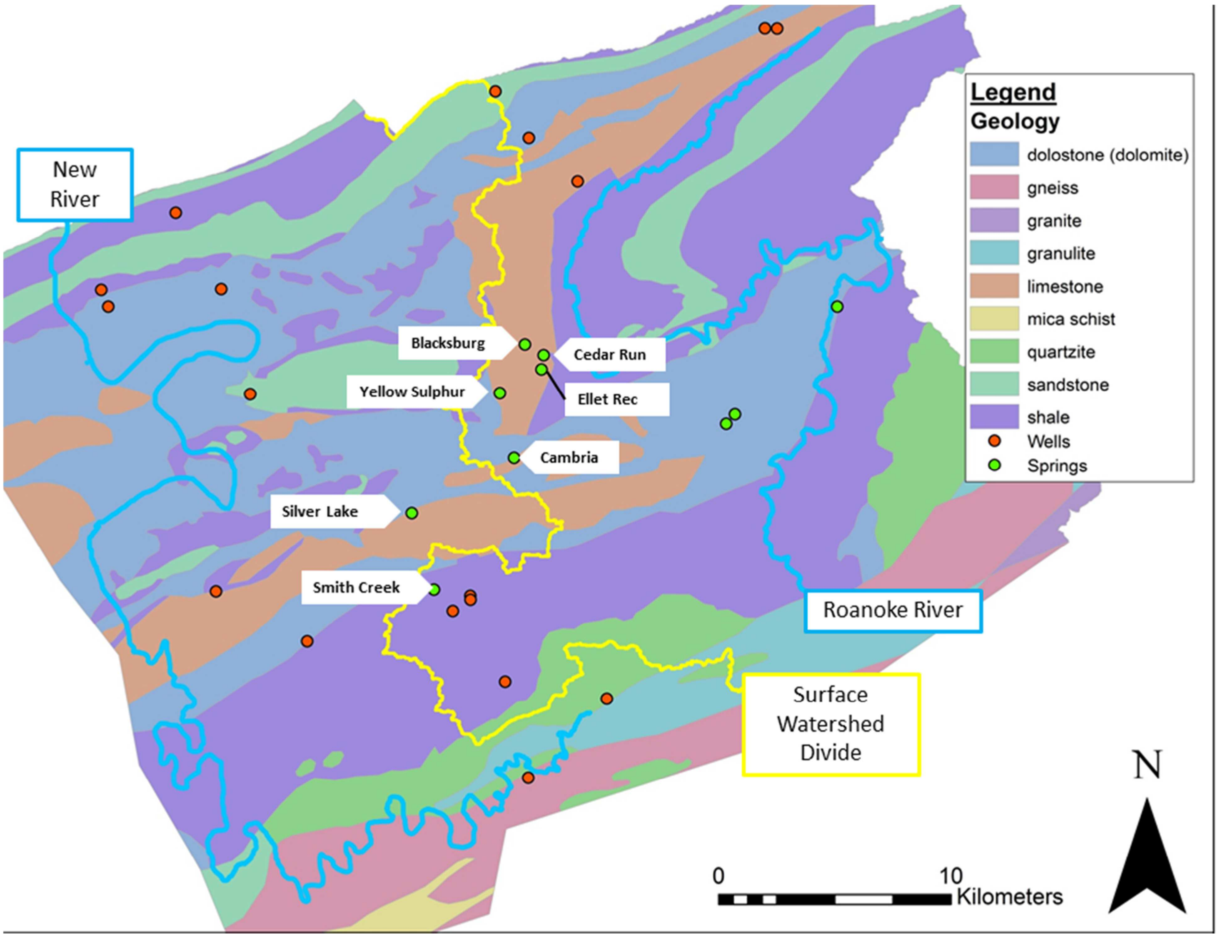


Figure 4: Map of monitored spring locations. Both rivers are shown in blue and the surface divide is shown by the thick yellow line. Red points are well locations as shown in Figure 3.

Three of the springs are owned by the town of Blacksburg, two by the town of Christiansburg, and two are private. We deployed 4 Pendant and 2 TidBit HOBO temperature loggers in each spring. The HOBO Pendant loggers have an accuracy of ±0.53°C from 0° to 50° and resolution of 0.14°C at 25°C. These loggers have lower memory and battery life than the TidbiT loggers and were therefore set to log water temperature every 30 minutes. Three springs were monitored using the HOBO TidbiT loggers with accuracy of ±0.21°C from 0° to 50°C and resolution of 0.02°C at 25°C. Measurements with the TidbiT loggers were taken every 15 min (Details of temperature measurements are shown in Table 1). Total sample time is not equal among springs due to complications with sensor deployment and therefore sections of time were not logged in select springs.

Spring	Owner	Sensor Type Sample interval	Surficial Geology from GIS	Distance from divide (m)	Elevation (m amsl)
Ellet Rec Path	Blacksburg, VA	HOBO Pendant 15 min	Limestone	2302	551
Blacksburg Town Spring	Blacksburg, VA	HOBO TidbiT 30 min	Limestone	1569	561
Cambria Town Spring	Christiansburg, VA	HOBO TidbiT 30 min	Dolostone	1006	582
Silver Lake Rd	Christiansburg, VA	HOBO TidbiT 30 min	Dolostone	1657	613
Smith Creek Rd	Private	HOBO Pendant 15 min	Shale	619	610
Yellow Sulphur Resort	Private	HOBO Pendant 15 min	Limestone	128	580
Cedar Run	Blacksburg, VA	HOBO Pendant 15 min	Limestone	2376	513

Table 1: Monitored springs information. Includes owner, sensor details, geology, elevation, and distance from divide (location of each can be seen in Figure 3).

Each sensor was deployed using a different set-up than the rest, due to the variation in spring outlets and spring boxes at the discharge point. The main goal of deployment was to ensure the sensor was as close to the discharge point as possible and that the sensor was in a location which would minimize effects of surface climate (at the spring box) on readings. As can be seen in the photos; Cambria, Yellow Sulphur and Silver Lake springs were each completely surrounded by a concrete spring box which was closed using locked or sealed covers (Figure 5). Here, sensors were suspended on a cable from the spring cover to just above the ground surface, well into the water column. A similar set-up was achieved for the Blacksburg Town spring, however the concrete spring box was exposed to the outside with no cover (Figure 5). Very similar in construction, the Cedar Run spring also consists of an open concrete box, however the sensor could not be suspended and was instead attached to a heavy rock and placed in the back corner of the spring (Figure 5).The Silver Lake Rd spring was also covered by a large concrete box, however it was entirely sealed shut. We deployed the sensor by attaching it to the pipe outlet and ensuring that it was hidden from any sunlight to minimize change in temperature following discharge (Figure 5). Lastly, the Ellet Rec Path spring had not been covered by concrete, but discharged into a man-made rock damn. Here, were drove a metal rod into the soft bottom and attached the sensor mid-way down the rod, well below the water surface (Figure 5).

Figure 5: Images of monitored spring locations and set-up. Descriptions of each spring and device deployment info can be found in text.

Data from sensors were offloaded onto the HOBO waterproof shuttle at various time intervals during the research (Figure 5: Cambria). The HOBO shuttle allows for data to be offloaded in the field, without removal of the sensor. Sensors began logging again immediately following each offload. Data from the offloads were downloaded into HOBOware and then analyzed in Excel as time series data. Small data corrections had to be made to remove temperature measurements logged before the sensor was placed in the water, and for shuttle-computer time differences.

Methods

Analytical Transect Modeling

Using a regional approach for a constant porous media we can estimate the location of the groundwater divide by first employing simple analytical solutions using two constant head boundary conditions that represent base flow conditions of the upland New River and the lowland Roanoke River. Although base flow conditions of these two river systems can fluctuate seasonally or over years of prolonged drought or excess precipitation, these types of fluctuations tend to be small relative to the head change between the base flow levels of these river systems (typical boundary condition elevation differences for the region can be seen in analytical model results figures, where here the elevation difference is ~400 ft). Thus, any fluctuations are likely to show negligible effects on the location of the groundwater divide.

We initially choose a one dimensional, unconfined model for horizontal flow in which the water levels measured in wells within the rock formations of the study area are assumed to represent water table values that extend deeply enough, and are continuous laterally enough, to drive the hydrologic system. We assume that the Dupuit equation is valid (horizontal flow) and that recharge to the aquifer does not vary laterally across the system, hydraulic gradients are not influenced by local topological changes, and flow (long term) is steady. We also initially assume that the rocks have a constant hydraulic conductivity distribution. Under these conditions the one dimensional groundwater flow equation can be stated as

$$\frac{d^2h^2}{dx^2} = \frac{-2R}{K} \quad (1)$$

where h is the hydraulic head, R is the areal recharge rate and K is the hydraulic conductivity in units of meters per day. The solution of the hydraulic head, h(x) at any point along the entire system with the two constant head river boundaries can be determined by

$$h(x) = \left[\frac{Rx}{K}(L-x) + \frac{(h_{RR}^2 - h_{NR}^2)x}{L} + h_{NR}^2 \right]^{1/2} \quad (2)$$

where h_{RR} is the head in the Roanoke River, h_{NR} is the head in the New River and L is the distance between them. Based on annual recharge estimates of Swain et al. (2004) approximately 20% of the annual precipitation rate (8 in/yr) enters the groundwater system as recharge. With only the hydraulic conductivity as the unknown parameter, an overall approximation of the hydraulic conductivity can be made by plotting the results with the topography along any transect from the New River boundary to the Roanoke River boundary and then adjusting water levels based on intersection with topography (four selected transects can be seen in Figure 6). This was accomplished using ArcMap and a digital elevation model (Gesch, 2002 and 2007) for boundary elevations and the distance tool for the total distance between the boundaries (L). The final equation, with K, L, h_{RR}, and h_{NR} was calculated for any x along each transect in Excel. The location of the calculated groundwater divide was determined by fitting an equation to water elevations and solving for the maximum head and then mapping in ArcMap its location relative to the surface divide. The starting K values were set to be 25 ft/d and the final "calibrated" values are shown in Table 2.

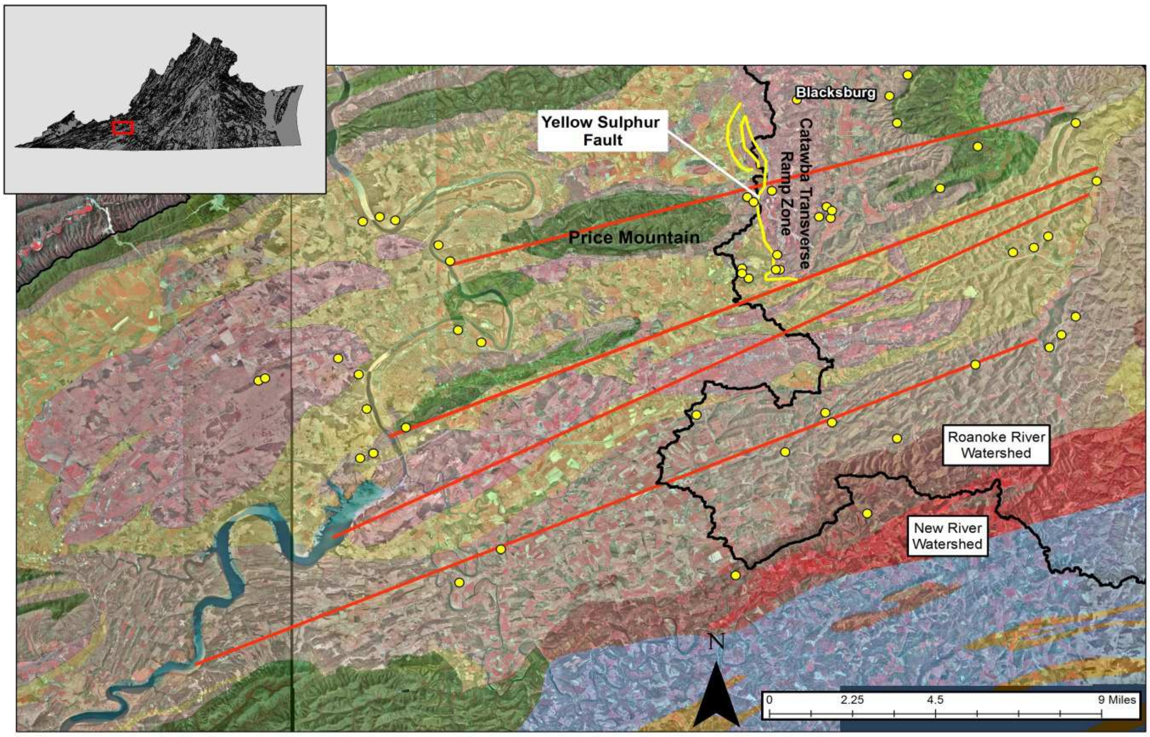


Figure 6: Map showing location of analytical modeling transects. Each transect begins at the New River boundary condition and extends to the Roanoke River boundary (Small tributaries are difficult to see here, but images of river boundaries are clear in Figures 3 & 4) Yellow points show previously identified springs provided by the DEQ, used to determine transect locations (J. Maynard, personal commun., 2013, DEQ)

Numerical Transect Modeling

Recognizing the limitations of the 1D analytical model, we developed numerical models along the same transects using Modelmuse, a GUI for the MODFLOW-2005 finite-difference code (Harbaugh, 2005). Each model was given surface elevations using the elevation data extracted from GIS sources, uniform K values along the transect, average recharge over the entire transect, and constant-head boundary conditions at each river. The model grid was constructed to be spaced equal to the elevation points extracted in ArcMap and oriented parallel to the transect. The Groundwater Flow Process used was the Layer Property Flow package in MODFLOW, along with the CHD Time Varient Specified Head package for the river boundary, and the Recharge Package allowed for the specification of constant flux across the water table from precipitation. The construction of this model as a 1D, one-layer system assumes that all flow is horizontal and we have no vertical flow or changes in conductivity vertically. Figure 7 shows the top and front view of the model for transect 1, including model grid and boundary condition locations. The grids were identical for the remaining 3 transects, only surface elevations and boundary condition elevations were changed. The bottom boundary was set to be just below the boundary condition elevations since water elevations cannot be calculated to be below this level.

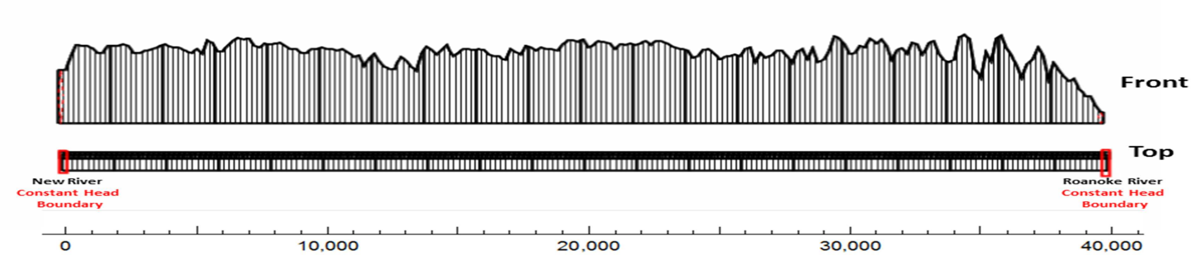


Figure 7: Numerical model domain for transect 1. Show is the top and front view of the model created using the USGS GUI Modelmuse.

2D Regional Numerical Modeling

The two-dimensional transect models were expanded to an aerial two-dimensional model covering the entire study area because few wells and springs actually fell within a reasonable distance to the transects in the previous modeling effort. This areal modeling effort was also conducted to perform particle tracking for the identification of recharge source areas that feed the spring locations and to provide a better estimation of the groundwater divide's true location within the study region. Our conceptual model (Figure 8) consists of our two constant-head river boundary condition along the eastern and western study boundaries, a no-flow boundary along the north, which represents a high topographic divide (Brush Mountain), and a general-head boundary to the south, which reflects the likely head-dependent nature of this region. The model has one layer of constant thickness (100m), which is assumed to represent the active depth of weathered high-permeable fractures. Again, the creation of a one-layer system assumes no changes in hydraulic conductivities with depth. This was done for simplicity of the first regional model of the area and the assumption should be addressed with a multi-layer model in the future. The hydraulic conductivities given to each zone were based on the simplified lithology (6 different units described further later in this section) (geology shapefiles from Dicken, 2005) discussed previously.

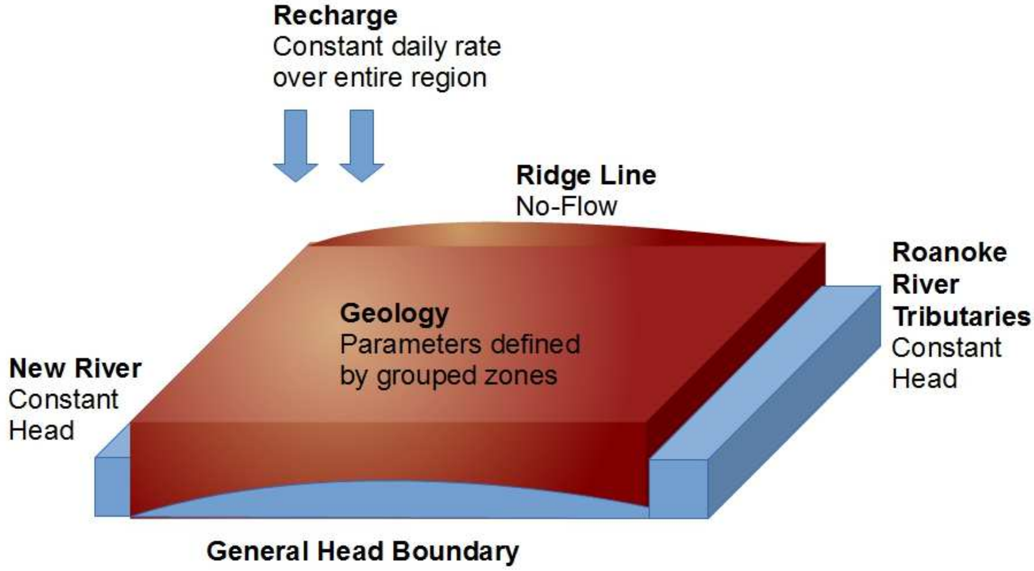


Figure 8: Conceptual model of 2D regional numerical model. The general-head boundary is dependent on the average depth to water taken in a well near the boundary.

Numerical modeling was performed using the MODFLOW-2005 (Harbaugh, 2005) finite-difference code developed by the USGS. MODFLOW was initially created in 1984 to facilitate the addition of "packages" that simulate specific processes into a unified code. A main part of the MODFLOW structure combines algorithms describing volumetric groundwater flow across model cells with boundary conditions, and defined parameters values into the "Groundwater Flow Process" (Polluck, 2012). Since its original release, additional versions of MODFLOW have been developed to better represent situations such as stream-aquifer interactions and land subsidence (as discussed in Pollock, 2012). With time the code has expanded to allow for additional capabilities such as parameter estimation through the implementation of UCODE_2005 (Poeter et al., 2005), which uses known observations of hydraulic head or flow velocities to inversely calibrate key aquifer parameters. The increased sophistication of the code has not compromised its ease of use. The current version of

MODFLOW still readily allows for the incorporation of boundary conditions, observations, and recharge within the Groundwater Flow Process only with better management of the code's internal data (Pollock, 2012).

The model domain was created by utilizing GIS resources and known boundary conditions (Figure 9). The top of the model was created by resampling a 30 m DEM to 250 m resolution (Gesch, 2002 and 2007) and then importing elevation point files into ModelMuse. The grid was then created from this point file, with each grid cell given one surface elevation value. The bottom elevation of the model is assumed to be 100 m below the surface elevation. This assumption is based on the average typical depth of an interconnected hydraulic fracture network based on bedrock weathering. Starting head values were set to be equal to the surface elevation minus the average depth to water recorded in our study wells.

The model domain was bounded by three different boundary condition types: no-flow, constant-head, and general head. The no-flow boundary to the north of the region was created using a watershed boundary with the outlet at the furthest downstream location in both rivers, within the study region. The watershed boundaries were created in ArcMap by summing the areas of cells that contribute flow to the pour point cell. The constant head boundary conditions were created by extracting the section of river segments which comprised the New River and Roanoke River in our study area, from the national hydrography dataset downloaded from the USGS Seamless server (USGS, 2010). The general head boundary line connects the farthest upstream point of either river system in the southern portion of the region. Head values assigned to this boundary line segment are a function of surface elevation and an average depth to water measured in a nearest study well.

We have simplified the geology of the study area by grouping the geologic rock types exhibiting similar hydrogeologic characteristics into hydrogeologic units similar to, but slightly more detailed, than those described by Swain et al. (2004) in the USGS study of the Valley and Ridge, Blue Ridge and Piedmont provinces. Units within our study region include: dolostone, limestone, shale, sandstone, quartzite, granulite, and gneiss (Dicken, 2005). This allowed us to simplify model parameters by grouping geologic rock types in ArcMap prior to importation into Modelmuse. Resulting geology shape files were then used to define parameter zones in the model. Spring and well locations were imported as point shapefiles directly from ArcMap with attribute fields given name and average head values. Actual head observations were set within the MODFLOW Packages tab for each point. Figure 9 shows the entire model domain with boundary conditions and parameter zones.

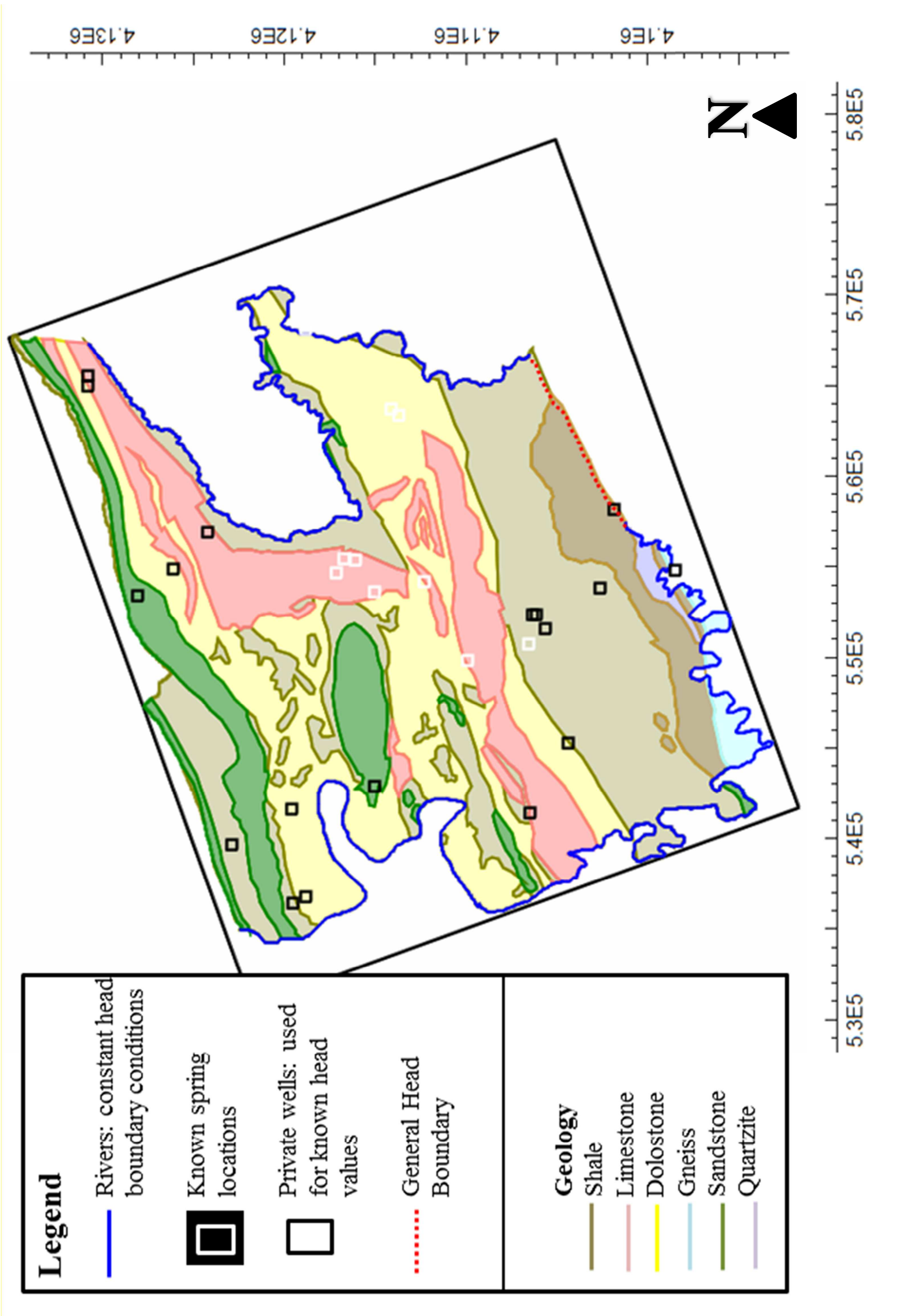


Figure 9: Numerical model domain as created in ModelMuse (MODFLOW GUI). Boundary conditions, well and spring locations, and parameter zones (simplified geologic rock types) are shown.

Our numerical model was calibrated using UCODE_2005 (Poeter et al., 2005), which is a parameter estimation code that inversely estimates parameters by minimizing the sum of squares of residuals (difference between simulated and measured values of heads at well locations).This process involved using the original model HK (hydraulic conductivity) parameters taken from the literature (Swain et al., 2004). Values were set to allow for log-transforming due to the many orders of magnitude in which the HK values can potentially range within the study region. The HK values representing granulite and gneiss were held constant due to their low composite scaled sensitivities when compared to other parameters, which is likely associated with the fact that no observations exist in these units, since composite sensitivities are based on the difference between the simulated values and observed. UCODE converged after 11 iterations and final values are shown in Table 2. Simulated heads were compared to surface elevations as an additional check on model accuracy (differences can be seen in 2D Model Results section). Perhaps the most important aspect of numerical modeling is that pathlines and approximate travel times can be computed using the MODPATH particle tracker (Pollock, 2012). MODPATH pathlines were computed for each spring location, identifying the source recharge location and total travel time from the recharge source area to the discharge point at each spring. Pathlines were computed using a group of 9 particles which were originated internally within the model cell representing the spring and were allowed to track backwards (toward the source area) until termination at the surface.

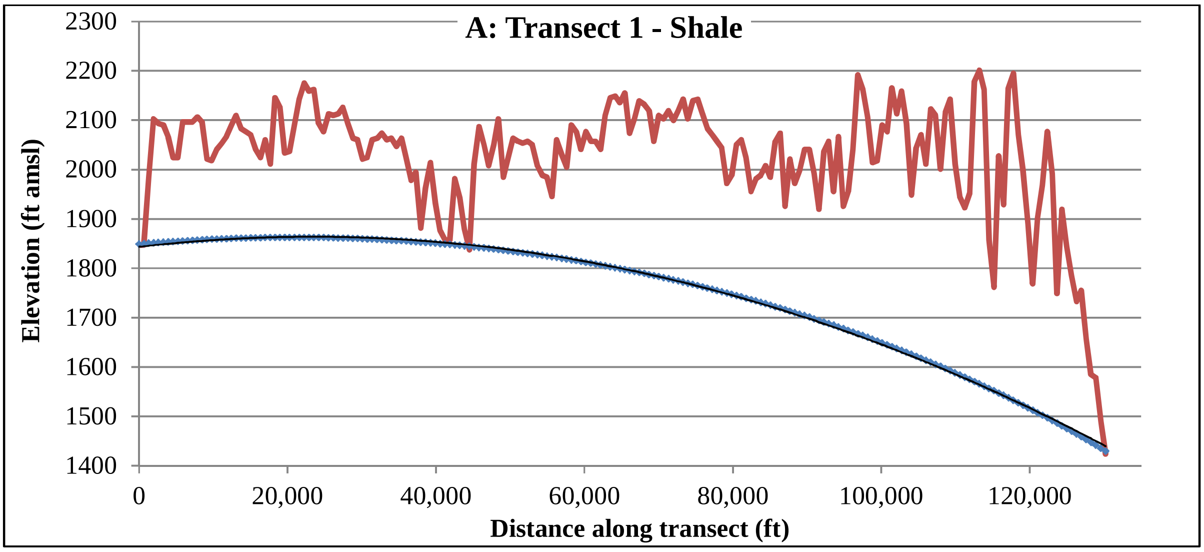
Lithology	Transmissivity (m^2/d)	Hydraulic Conductivity (m/d)	Calibrated HK parameter (m/d)
Limestone	279	2.79	0.2831
Dolostone	511	5.11	4.650
Shale	33	0.33	8.105
Sandstone	33	0.33	0.0557
Quartzite	7	0.07	0.1684
Granulite	3	0.03	Not variable
Gneiss	3	0.03	Not variable

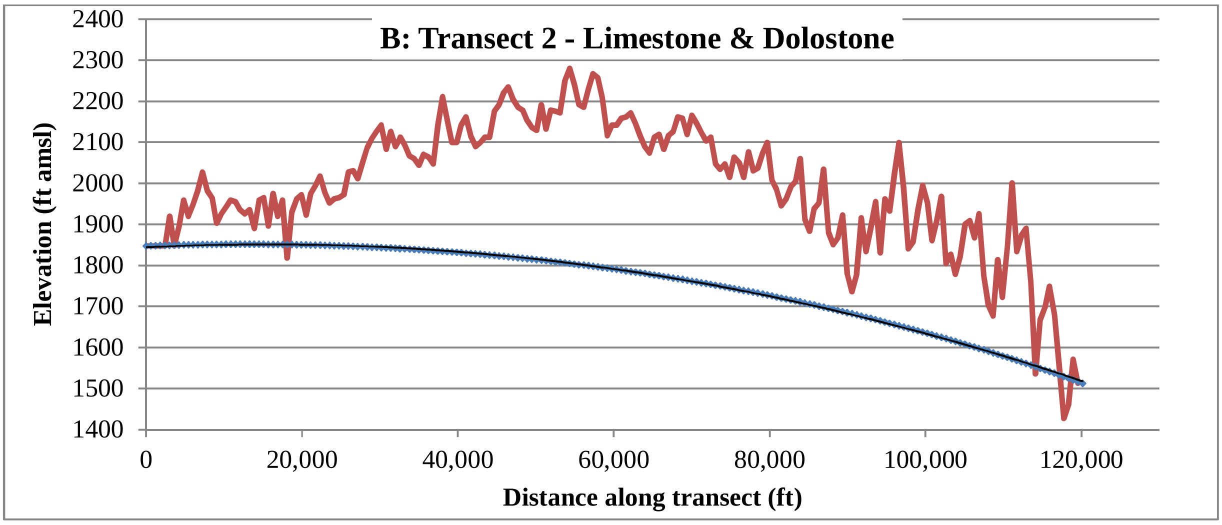
Table 2: Geologic parameters for regional model. Starting transmissivity values are average values taken from Swain et al. 2004. Hydraulic conductivity (HK) was calculated by dividing T by thickness (100m). Estimated values were determined using inverse modeling in UCODE.

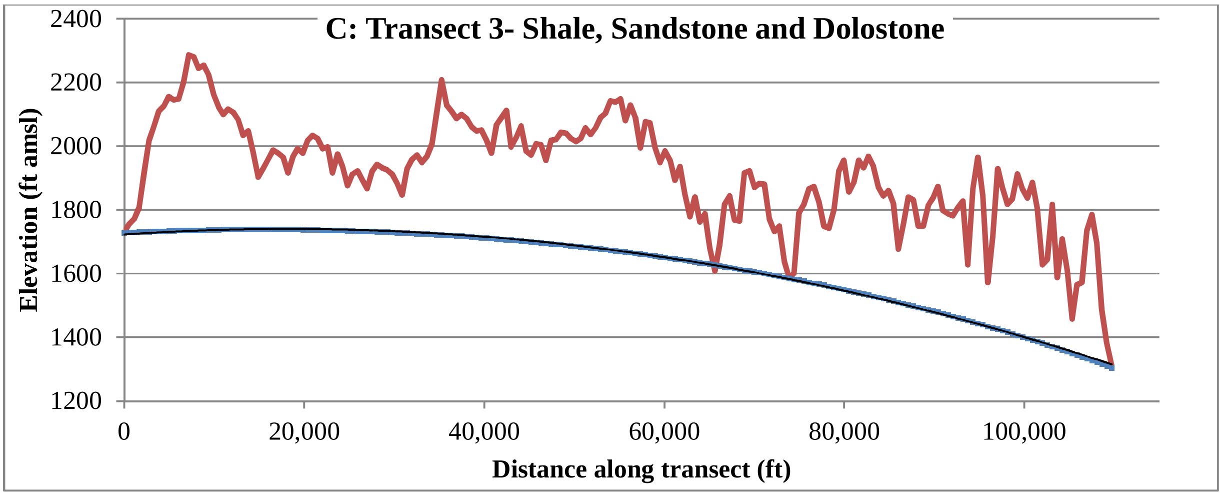
Results

Analytical modeling

As can be seen in Figure 10 A-D, resulting water elevations from analytical modeling can potentially fit two curve types: 1) a parabolic-shaped water table profile, with the apex representing the groundwater divide being closer to the New River than the Roanoke River or 2) a sloping water-table with very little mounding, resulting in essentially no groundwater divide with New River water flowing toward the Roanoke River (New River is 0 dist. location). Result #2 implies the New River watershed is not only being captured by the Roanoke in its upper tributaries, but that the river itself is losing water (transects 2 & 4 below). As described in the methods, hydraulic conductivities were constant for the entire transect, but adjusted based on water elevations and their relation to the surface topography. Adjusted final values can be seen in Table 3 below.


A: Transect 1 - Shale
Elevation (ft amsl)
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
0
20,000
40,000
60,000
80,000
100,000
120,000
Distance along transect (ft)


B: Transect 2 - Limestone & Dolostone
Elevation (ft amsl)
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
0
20,000
40,000
60,000
80,000
100,000
120,000
Distance along transect (ft)


C: Transect 3- Shale, Sandstone and Dolostone
Elevation (ft amsl)
2400
2200
2000
1800
1600
1400
1200
0
20,000
40,000
60,000
80,000
100,000
Distance along transect (ft)

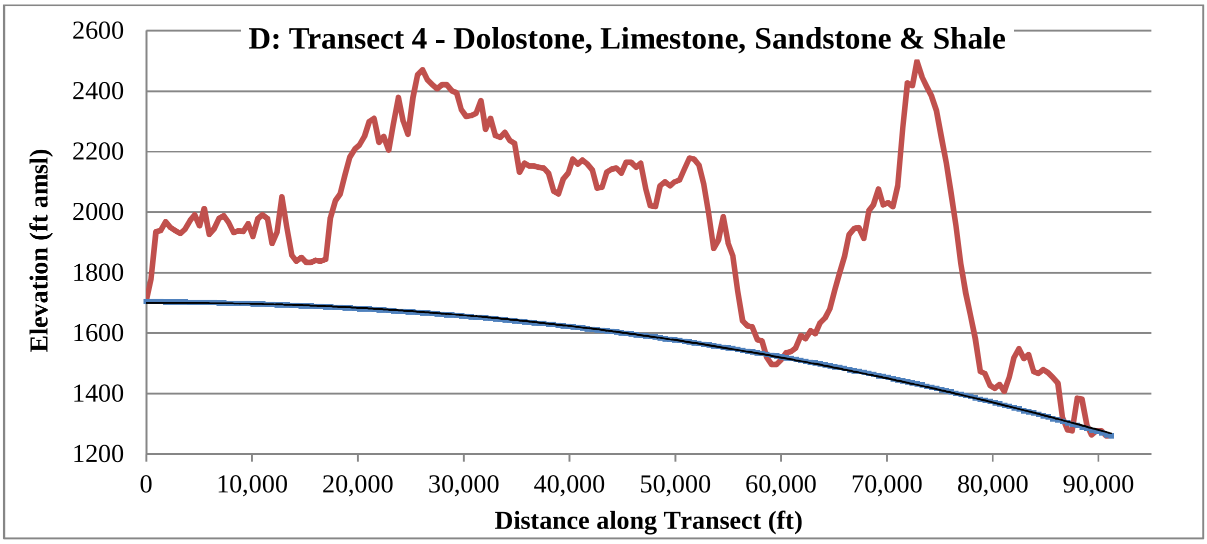


Figure 10 (A-D): Results from analytical modeling along the four selected transects. Transect extends from New River (0 dist.) to Roanoke. Lithology along the transect is listed on each plot. Surface elevations are shown in red and calculated water elevations in blue.

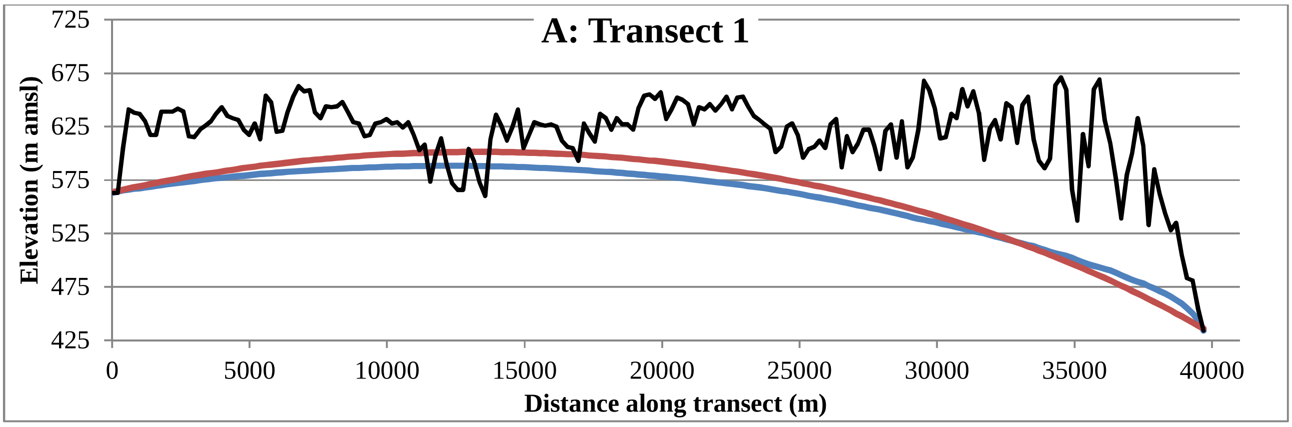
Distances between the calculated groundwater divide and surface watershed divide, along with the final hydraulic conductivity values following calibration is shown in Table 3. Distances range over 1 mile and the maximum map distance difference is over 6 miles. Since this is unlikely and also not evident in New River discharge records from USGS gauging stations (Table 4) we switched from analytical models with semi-calibrated hydraulic conductivity values to numerical models in order to better represent the system.

Transect	Map Distance (miles)	Final Hydraulic Conductivity (ft/d)	Geology
1	5.5	25	Shale
2	5.8	30	Limestone, Dolostone
3	4.5	20	Shale, Sandstone, Dolostone
4	6.3	20	Shale, Sandstone, Limestone, Dolostone

Table 3: Map distance between surface divide and calculated groundwater divide location. Geology along each transect is also shown as well as hydraulic conductivity values calibrated using topography and water levels. Hydraulic conductivities were constant along each transect but varied between transects.

Numerical Transect Modeling

Results from initial transect numerical modeling show similar water level elevations to the analytical results. Slight variations in computed head can be seen along the water elevation lines, however the overall groundwater shape and gradients remained the same and the same two resulting profiles are produced. Below are plots showing both the numerical results and the analytical results. Surface topography is shown by the black line (Figure 11).



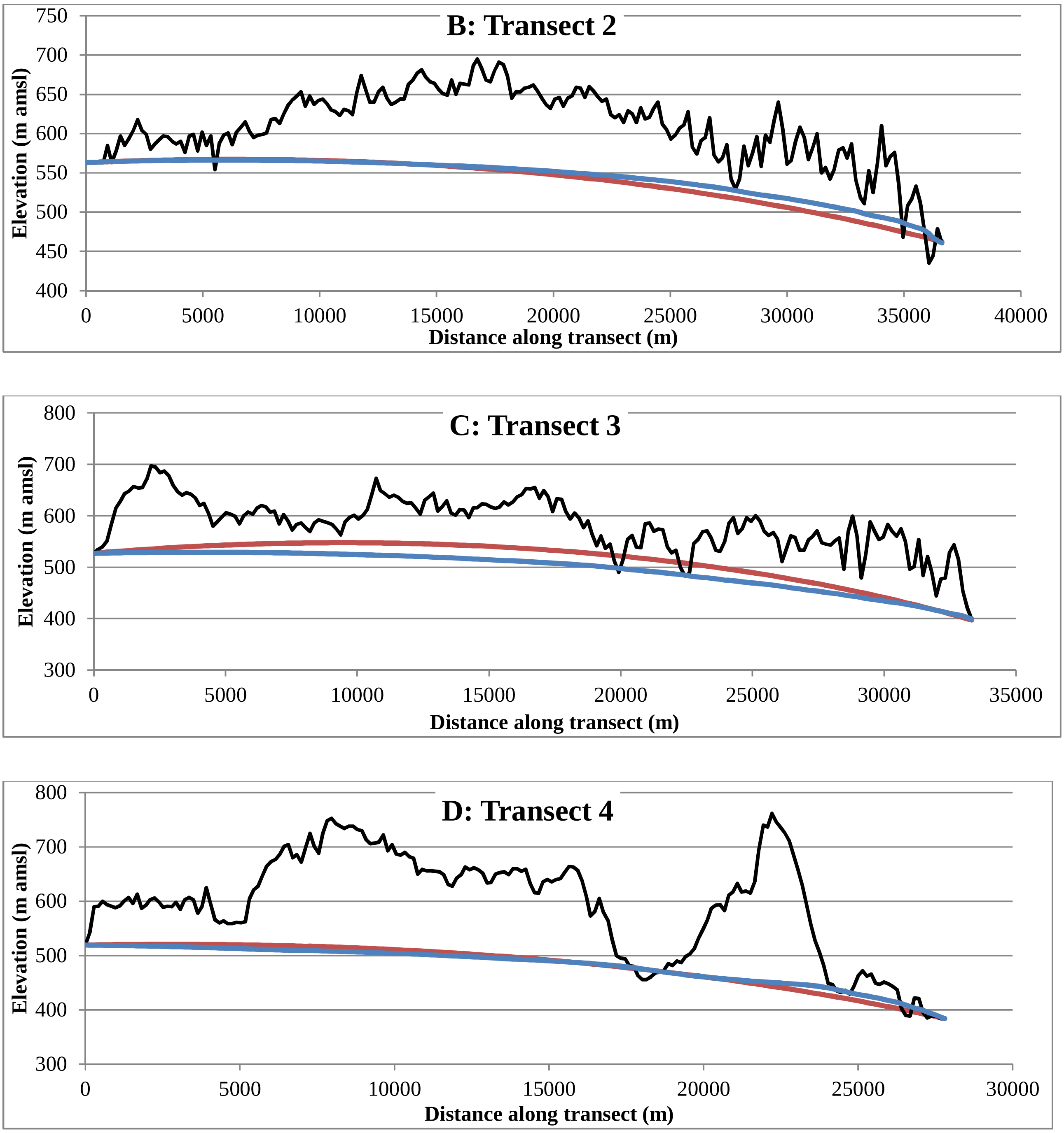


Figure 11 (A-D): Profiles of simulated head from numerical modeling for each transect. Blue line indicates numerical model results, red line is analytical results, and black line shows surface topography. Transect numbers correlate to the same transects from analytical modeling, however units have changed.

Water Elevations

Depth to water measurements ranged from -0.26 to 88.267 meters below the surface throughout the study region. After subtracting from surface elevations, water elevations ranged from 527.779 to 747.699 meters above mean sea level. The largest temporal changes in depth to water occurred in wells 8 and 9, both high on the no-flow boundary ridge to the north of the study region. Outside of these two measurements, very little seasonal change can be seen in water level elevations. Table 4 provides depth to water measurements at each well along with surface elevations and the average water elevation using the average depth to water.

Spring	Surface elevation (m)	Depth to water (meters below the surface)				Average water elevation (m)
		August	October	January	March	
1	701.232	1.9	0.082	-0.405	-0.26	700.903
2	702.03	43.14	38.5	38.439	39.605	662.109
3	684.69	82.825	83.431	83.769	83.29	601.359
4	691.55	73.08	72.707	71.636	73.12	618.919
5	627.205	25.76	27.075	26.550	24.813	601.156
6	603.741	2.475	2.913	2.621	2.051	601.226
7	598.96	88.267	66.774	65.301	64.382	527.779
8	798.1505	42.165	41.49	79.840	38.31	747.699
9	654.4795	22.985	23.585	22.871	22.46	631.504
10	682.7665	26.03	27.795	27.511	25.055	656.169
11	665.65	DNV	32.955	33.055	32.633	632.769
12	614.067	9.295	8.856	9.491	22.63	601.499
13	596.047	13.159	12.36	10.367	10.619	584.421
14	644.955	3.679	4.144	2.516	3.191	641.573
15	619.5835	21.1	21.046	23.355	21.168	597.916
16	601.965	19.42	19.826	19.405	19.204	582.501
17	562.308	14.719	15.397	15.400	14.895	547.205
18	578.4445	-0.725	0	-0.815	-0.808	579.032
Average depth to water		28.78	27.72	29.5	27.58	

Table 4: Depth to water measurements for each well visit. Average water table elevation was calculated using the average depth to water subtracted from the surface elevation. These average water table values were used in the model as known head observations. DNV means we “Did Not Visit” that well for measurement.

Spring Temperatures Measurements

Average spring water temperatures range from 9.86 C° (Ellet Rec) to 14.05 C° (Silver Lake), with the greatest range of 6.4 C° occurring at Ellet Rec spring. Figure 10 shows the water temperature versus time for all monitored springs. Three distinct temperature patterns can be observed from these plots; (1) event-scale temperature influences (using events which can be seen in air temperature records), (2) seasonal temperature influence, and (3) seasonal and event temperature influences (Figure 12). Cedar Run, Blacksburg, and Smith Creek fall into pattern (1). Only Cambria falls into pattern (2), with almost no event influence on temperature. The remaining springs, Silver Lake, Ellet Rec, and Yellow Sulphur all fall into pattern (3) with seasonal changes as well as event fluctuations. Figure 12 also shows the range in daily air temperature with time, including the average value in red. The minimum, maximum, range, and average temperature values for each spring are listed in Table 5. Correlation coefficients between air temperature and water temperature as well as between precipitation and water temperature support these visually identifiable patterns (Table 5).

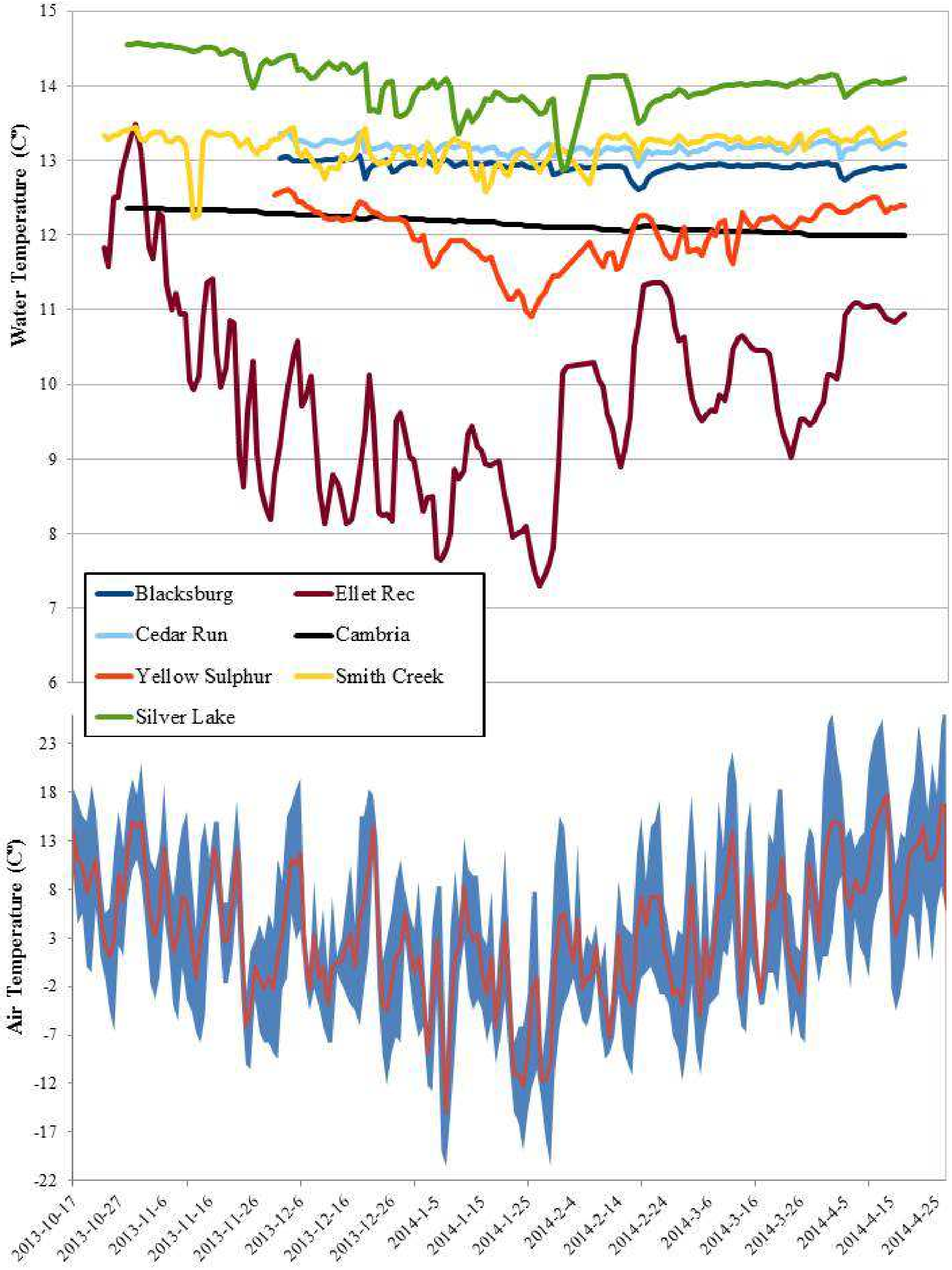


Figure 12: Plot of daily average water temperature vs time for monitored springs (top). Springs fall into one of three patterns: event-scale fluctuations, seasonal fluctuations, and both (discussed further in discussion section). Bottom: Range of min-max air temperature vs time. Average daily temperature is shown in red (weather data from weatherunderground.com)

Spring	Min	Max	Range	Average	Corr. with Air	Corr. with Precip.
Cambria	11.997	12.389	0.412	12.163	-0.12	0.02
Blacksburg	12.485	13.112	0.627	12.9219	-0.14	-0.19
Cedar Run	12.594	13.365	0.771	13.174	0.37	-0.09
Ellet Rec	7.179	13.558	6.379	9.864	0.55	-0.0005
Silver Lake	12.703	14.577	1.874	14.047	0.27	-0.11
Yellow Sulphur	10.846	12.69	1.844	12.018	0.66	0.08
Smith Creek	11.014	13.75	2.709	13.180	0.58	0.075

Table 5: Spring water temperature summary. Min, max, range, and average water temperatures are shown for each spring. Additionally, the correlation coefficients between water temperature and air temperature as well as water temperature and precipitation are shown.

2D Regional Numerical Modeling

Calibrated steady-state water table elevations for the 2D areal model are shown in Figure 13. Simulated heads range from elevations of 363 meters above mean sea level to 864 meters above mean sea level. There are steep groundwater gradients along the northern and southern ridges as well as beneath Price Mountain. Overall, gradients appear to be steeper beneath the Roanoke River basin than beneath the New River basin. The groundwater divide according to the simulated head values exists in the region of the surface divide, yet is slightly shifted towards the New River in most locations (red dashed line in Figure 13). It appears to cross through Price Mountain, bringing groundwater from this location into the Roanoke River catchment.

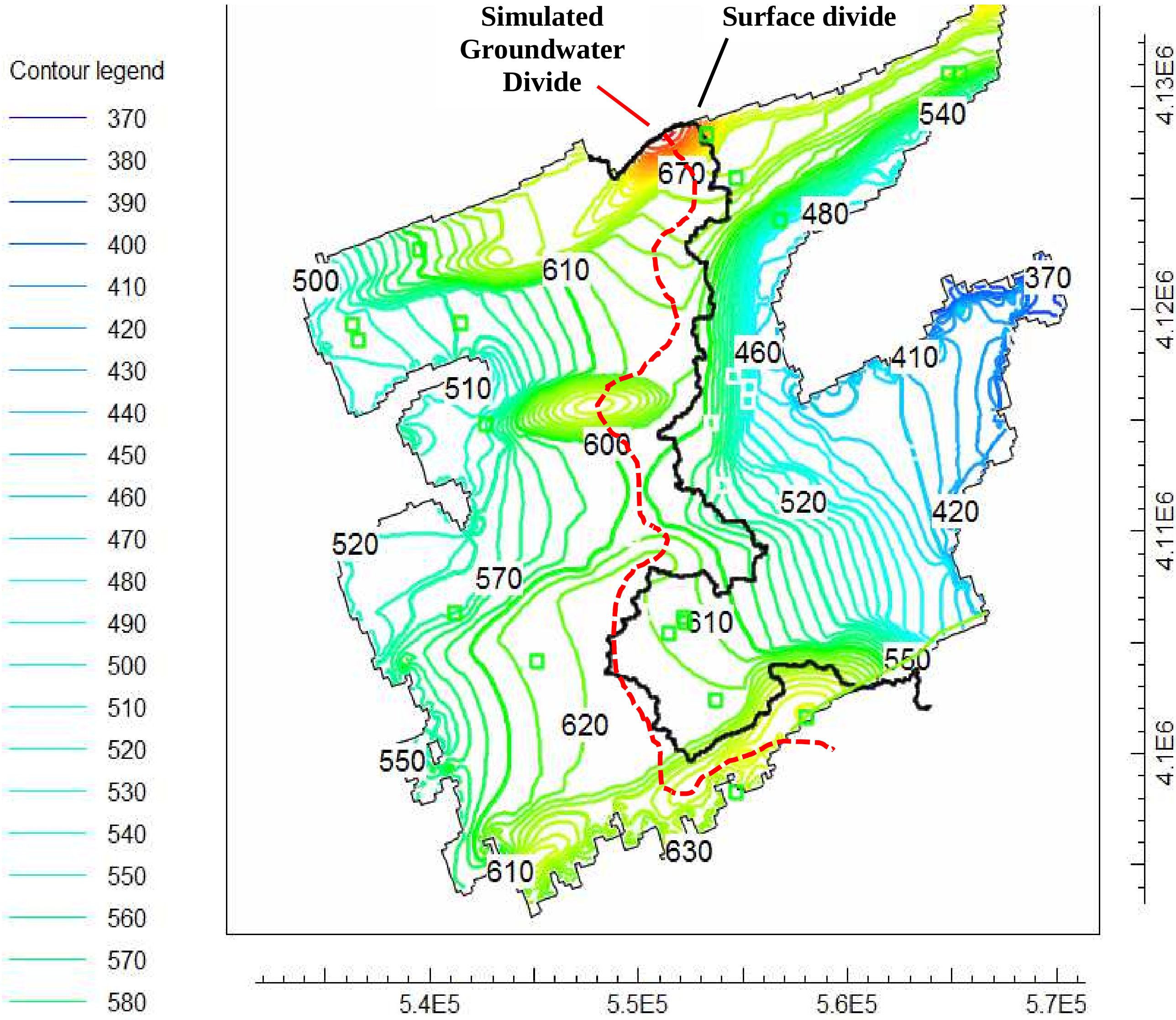


Figure 13: Contours of simulated total head from the 2D regional model. Head gradients vary significantly throughout the region due to changes in lithology and conductivity. The groundwater divide as given by these contours is shown by the red dashed line, the surface divide is shown by the thick black line.

Differences between the simulated heads and the surface elevations are provided in Figure 14 (calculated surface elevation – simulated head elevation). As can be seen from the contours, simulated water elevations are often higher than the surface topography. The greatest differences are found in the region of steep gradients in the southern and northern portions of our study region. Potential reasons for this large over-simulation of head are discussed further in the discussion section. However, it is important to note that the shallower, lower elevation locations were able to more accurately simulate head values close to measured depths below land surface. Additionally, Table 6 shows the differences between the observed head values (for well and spring locations) as well as the simulated values from the final model. Several large difference values show a need for bettering of the model, with the greatest difference being just over 58 meters (Table 6). A map showing the residuals, positive values as blue circles and negative values as red circles, can be seen in Figure 15. The size of the circle shows the magnitude of the residual.

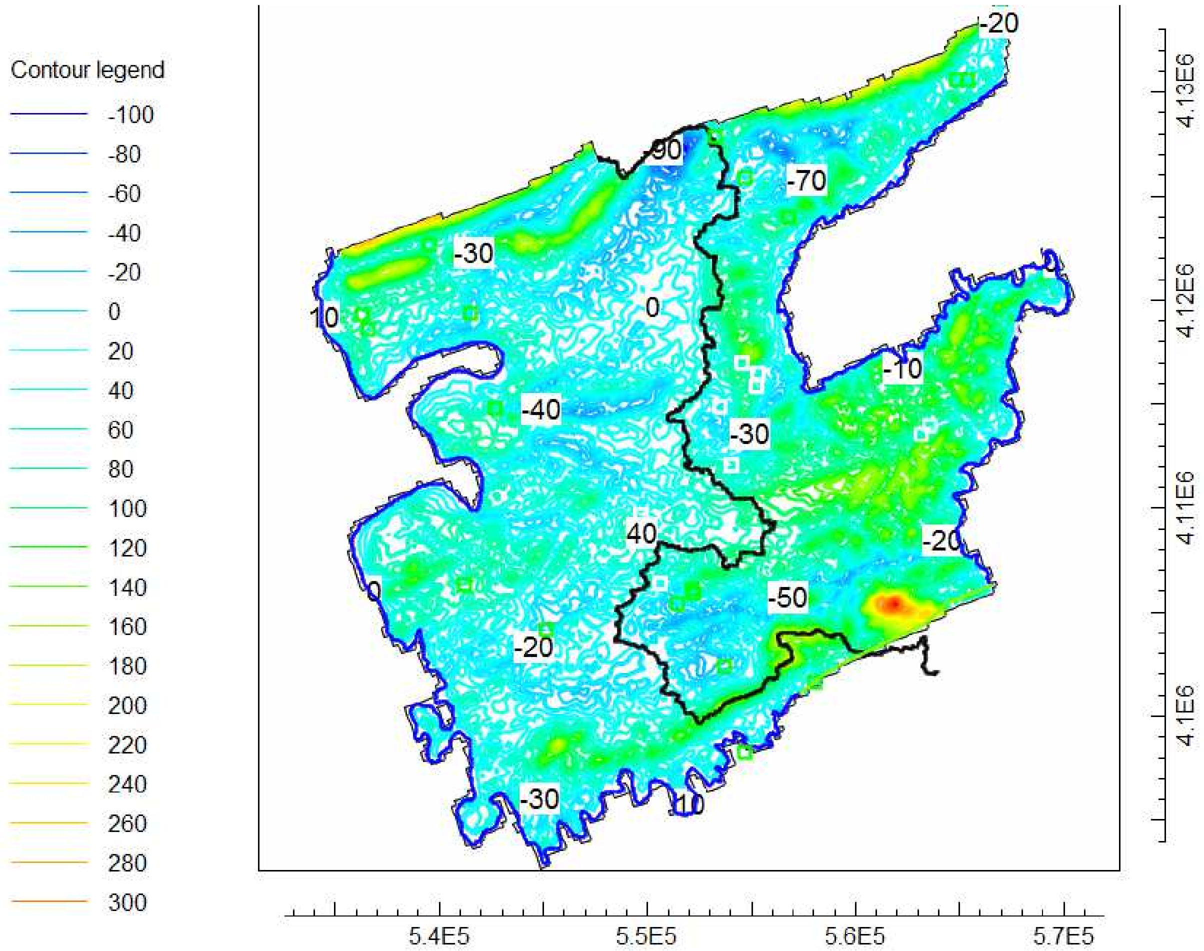


Figure 14: Contour map of differences between simulated water elevations and surface elevations. Negative values indicated areas where head was modeled to be above the land surface (discussed further in text).

Spring/Well	Observed Value	Simulated Value	Difference
Yellow Sulphur	580.17	591.845	-11.675
Cedar Run	513.03	497.9753	15.05472
Blacksburg	561.09	547.1245	13.96558
Cambria	582.32	568.0889	14.23114
Smith Creek	609.66	619.6338	-9.97382
Ellet Rec	550.55	505.6031	44.94684
Silver Lake	612.6	604.837	7.762939
Well 1	700.9028	703.4806	-2.57782
Well 3	601.3588	615.4836	-14.1248
Well 4	618.9193	615.1962	3.723022
Well 5	601.1555	618.6724	-17.5168
Well 6	601.226	622.3809	-21.1549
Well 7	527.779	508.3005	19.47852
Well 8	747.6993	757.9255	-10.2263
Well 9	631.5043	623.9412	7.563049
Well 10	656.1688	632.8454	23.32336
Well 11	632.769	659.2449	-26.476
Well 12	601.499	561.3888	40.11023
Well 13	584.4208	614.7585	-30.3377
Well 14	641.5725	597.8347	43.73779
Well 15	597.9163	539.2708	58.64551
Well 16	582.5012	527.7106	54.79065
Well 17	47.20526	551.5991	-4.39386
Well 18	579.0315	525.7213	53.31018

Table 6: Observed versus simulated head values from 2D regional model.

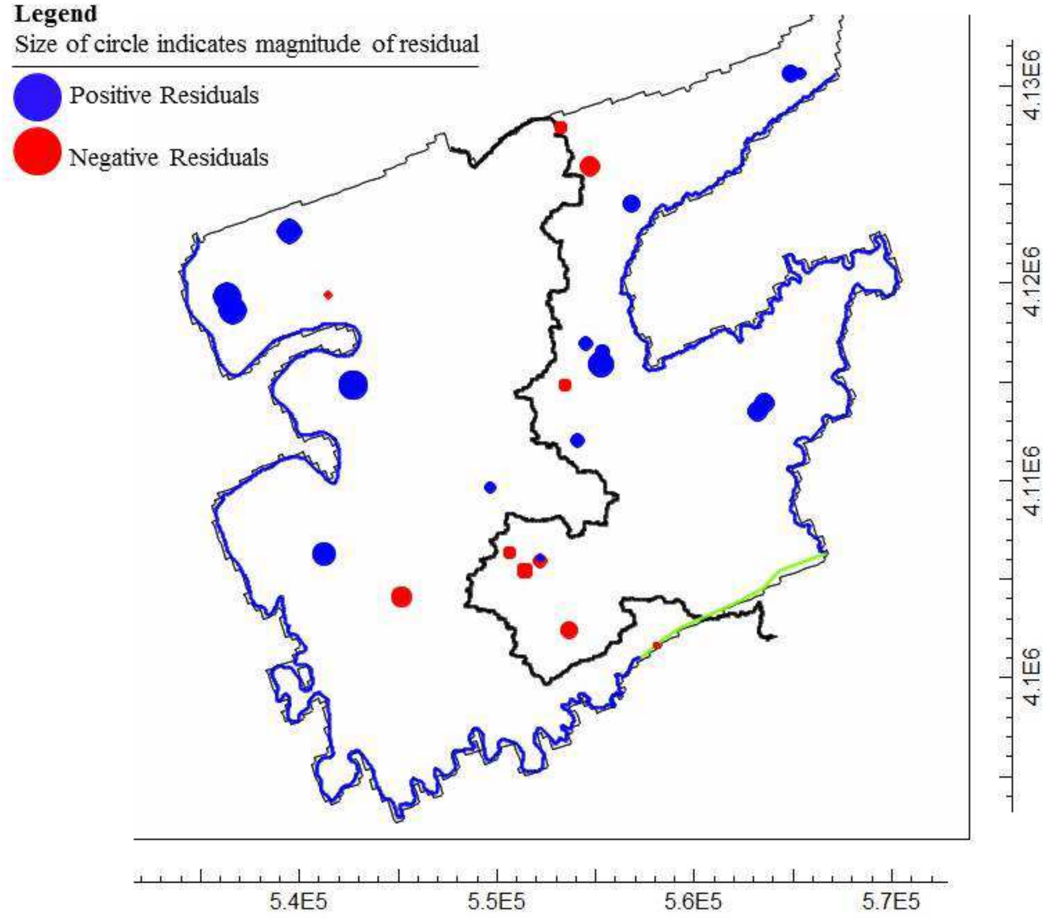


Figure 15: Map showing residuals between observed and simulated heads from 2D regional model. The size of the circle denotes the magnitude of the residual and the color represents negative and positive values, red being negative and blue being positive.

Pathlines computed using backwards tracking in MODPATH can be seen in Figure 16. Pathlines show travel distance and flow path for recharge to each spring and are color coded by travel time, blue being shorter travel times and red being longer times. Pathlines for Blacksburg, Ellet Rec, Cedar Run, and Yellow Sulphur spring appear to originate in a similar location east of Price Mountain within the New River watershed. Cambria spring pathlines indicate a source area west of the spring, also well within the New River watershed. However, the total travel distance and times appear to be slightly less. Both Silver Lake spring and Smith Creek spring have much shorter travel distances. Silver Lake spring is the only spring with flow originating and discharging entirely from within the same watershed, although the source area for Smith Creek does not extend as far into the New River watershed as the other springs. This could present a situation in which the spring has had a truncated watershed or was even created by the rapid incision process occurring high within the Roanoke watershed, where the spring is located. Interestingly, although structure was not added to this simple model, MODPATH results do show a clear directional change in the northern four springs once they cross the divide.

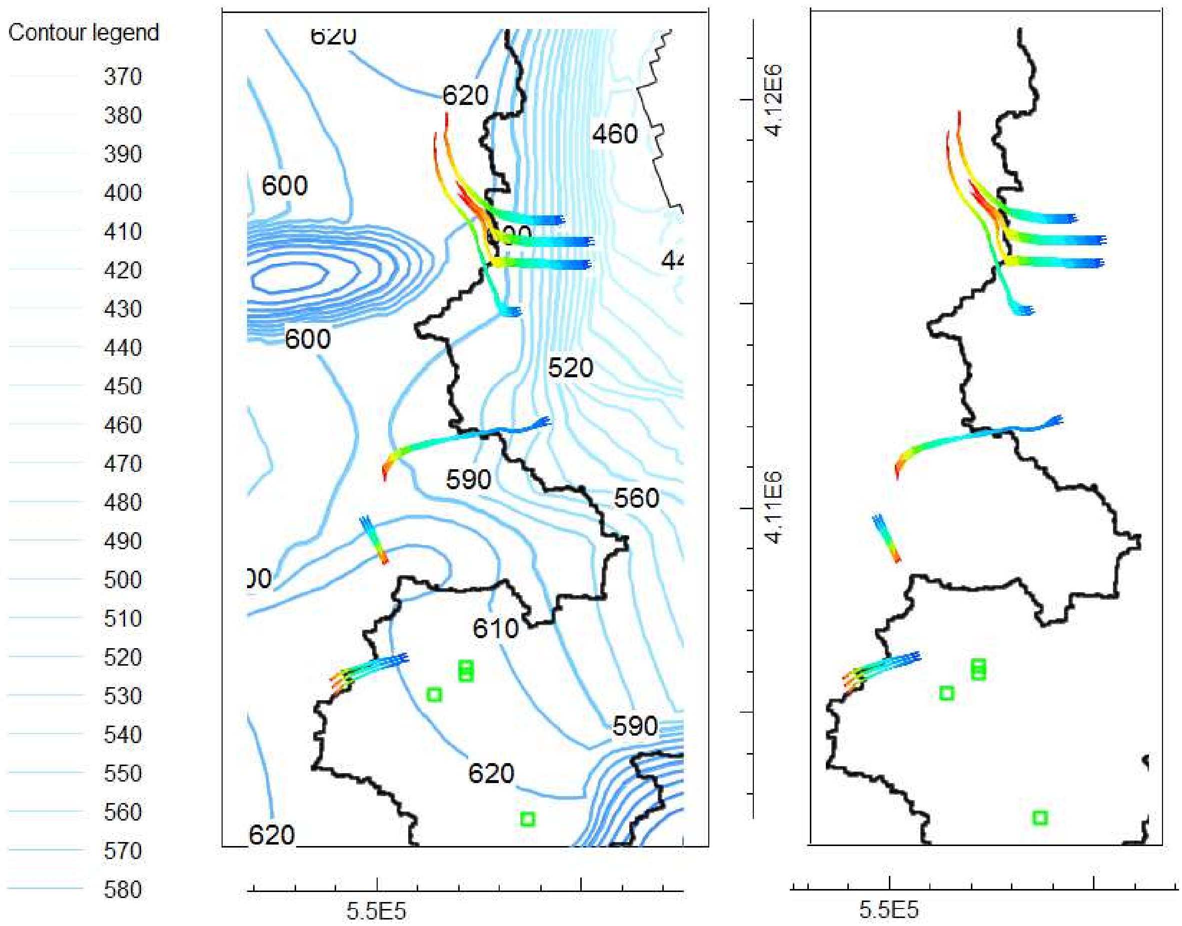


Figure 16: Pathlines computed using MODPATH and the steady-state model, with updated parameters from parameter estimation. On the left, simulated head contours are shown and on the right are only the backwards modeled pathlines.

Discussion

Analytical Model and Transect Models

Analytical model results imply the New River is not only being captured by the Roanoke River, but is actually losing water directly with no groundwater divide between the two boundary conditions. This illusion is most likely due to the simplicity of our model conductivities between the two boundary conditions. Yechieli et al. (2009) showed that incorporating non-uniform transmissivity values into an analytical groundwater model can alter the location of the groundwater divide, even with varying base levels. Simply stated, analytical models are not complex enough to represent the head conditions of this system due to varying geology and aquifer material conductivities.

Differences in head calculations between the analytical solutions and numerical transect models could result from the additional volume added to groundwater as recharge when taking surface relief into account. Analytical solutions a linear total map distance for L (actual total distance between boundary conditions) and therefore do not include the added distances associated with hills and valleys that are included in the numerical model. Similarities arose between the analytical models and the transect numerical models due to the simplicity in aquifer parameterization. The transect models are assumed to have constant conductivities along the entire transect and the same boundary conditions are applied in the transect models as for the analytical models. However, it is clear from these models that the location of the groundwater divide in this region is not likely to coincide with the surface divide and the simplistic simulated heads suggest that a more complex model is needed to more accurately represent the position of the divide.

Water Elevations

Groundwater elevations do not exhibit significant seasonal change (<2 m of change in the average depth to water – see Table 5). This could be attributed to the significant water storage and rapid response pathways available for well recharge within this karst and fractured-rock dominated area. Furthermore, the construction of domestic wells typically consists of an extensive open wellbore with significant borehole storage. Thus, the well would tend to dampen water level changes that may occur in the aquifer, allowing the well to maintain a fairly constant water level regardless of season.

However, two wells did have a few observed head measurements that were noticeably different from other readings (shown in red in Table 4). These outliers are likely attributed to their location on hillslopes in steep terrain, and also high within the watershed, where small changes in hydraulic gradient could result in a large local change in hydraulic head. Furthermore, homeowners were home when these outlier measurements were made, which could simply point to drawdown due to pumping. This is particularly plausible again due to the small source area for each well. With a small catchment we would expect a quick drawdown response when the well is pumped.

2D Regional Numerical Modeling

Numerical modeling and particle tracking results show an average total head distribution that generally mimics the surface topography; however, a westward shift of the groundwater divide toward the New River has occurred relative to the surface divide. This implies that groundwater capture occurs prior to stream capture, allowing for a larger groundwater basin than expected. This is not only more realistic than the results from analytical modeling, but it also appears to confirm the idea that the boundary condition elevations may be influencing groundwater flow in a manner that increases energy for the Roanoke River tributaries. Incision during stream capture occurs high within the watershed, where streams have naturally very little stream power due to their small catchment. The addition of groundwater due to subsurface basin capture could explain the over-energized erosion potential we see in small streams at the surface. Not only would this divide shift allow for more energy, but would also increase the transport of water across the surface boundary (escarpment face), which would allow for greater seepage at the escarpment, a process which could potentially decrease hill slope stability and thereby increase hill slope creep.

The 2D conceptual flow model was developed with some fairly large, yet reasonable assumptions. First, without the addition of dual-porosity modeling, MODFLOW assumes porous (Darcian) horizontal flow according to the Dupuit equation. Even with spring measurements, the conduit geometry of the study area is still unknown and is expected to be quite complex. In order to utilize MODFLOW we must assume that the intensity of fracture influence and the degree of dissolution in conduits is low enough to assume a single porosity model. This assumption should be valid due to the large scale of our model, however studies have been done which show regional conductivity to be similar and different to localized values such as those taken from Swain et al. (2004) for our study (as discussed in Hseih, 1998).

Second, vertical flow was not simulated in our one-layer model. The structural orientations of the geologic units that may influence the direction of groundwater flow were not simulated. These preferred orientations could influence recharge and depth of groundwater circulation by introducing significant vertical flow components. Additionally, the water elevations used for this model were taken from domestic wells several times over an 8 month period. Using domestic wells for this model also removes our ability to model more than one layer within the system, since domestic wells are typically open over their entire depth, thus yielding an average hydraulic head over the depth of the borehole. Thus, we assume that measured heads represent an average head over the entire thickness of the aquifer system. With the goal of creating essentially a broad conceptual model of the groundwater system, this is a valid assumption. However, we cannot determine how gradients or the divide location would change with depth or evaluate confined versus unconfined conditions. Additionally, as can be seen in Table 6, the result of a one-layer model with heads taken from multiple aquifer units can lead to large residuals in the model. The addition of multiple layers would be expected to aid in the decrease these residuals and bettering of the model as a whole.

Third, we assume the river boundaries represent constant head boundary conditions. This can only be true if the rivers represent groundwater base level with fairly constant stage, instead of perched features above the water table. Although, we did not collect data to determine whether or not the rivers are true base flow, the scale of the model minimizes the effect of this assumption. With distances of ~100,000 feet and elevation differences of several hundred feet, any seasonal fluctuations of stream stage can be considered negligible.

The groundwater flow model readily converged using parameter estimation following the removal of low sensitivity parameters from the estimation process. As discussed in the methods, we expect these parameters were not sensitive to changes due to the lack of observation wells within these units. To better estimate parameters for these units we would need to obtain additional prior information and/or head observations within them. Additionally, we were forced to keep a constant conductivity beneath the river boundary conditions due to the requirements of the Layer Property Flow package in ModelMuse. This did not affect our results since we are modeling a steady-state system and the river is represented as a constant head condition; however, this condition would need to be addressed for a potential future transient model. Also, our starting values were taken from average values provided by one literature source (Swain et al., 2004). Parameter estimation in this case could be improved by running the simulated additional times with a range of starting values.

Even with a calibrated model using inverse modeling and parameter estimation, difference contours between surface elevation and simulated head yield a number of heads that are above the ground surface. These differences imply that the water elevations may not be as high as simulated, nor the gradients as steep. However, observed head elevations used in the model were calculated using GPS acquired elevations and topographic data were from DEMs available online (in low resolution from older sources). Also, the DEMs were sampled for a lower resolution due to the large size of our model. This means that in steeply sloping areas we may be under-representing or over representing surface elevations in relation to water levels. This could be addressed by developing a higher resolution model in the future with more accurate surface elevations at each grid cell.

Particle Tracking and Spring Water Temperatures

Results from particle tracking in MODPATH also suggest that groundwater movement occurs across the divide. In particular, Blacksburg spring, Ellet Rec spring, Cedar Run spring, and the Yellow Sulphur spring have their recharge source areas considerably west of the topographic divide, into the New River basin near Price Mountain. Our results correlate nicely with the drainage retreat conceptual model proposed by Prince et al. in 2011 which was discussed in the introduction (Figure 15 is taken from Prince et al., 2011). This model proposes that divide retreat will continue to occur most quickly within the weak shale units (see Figures 1 & 2) until the New River has been cut off entirely. These four springs all fall within the stretch of escarpment which has not begun to incise as rapidly into the New River basin, allowing them to source water from further distances into the New River watershed (Figure 17). Again, this evidence suggests that the groundwater basin may begin the capture process by expanding into the higher elevation plateau before surface incision begins.

Interestingly, these springs revealed two of the three identified thermal patterns (event scale fluctuations and event & seasonal scale fluctuations). Since temperature records within springs can be used as a proxy for the amount of time water has spent within an aquifer, (Luhmann et al., 2011) we can assume that the discharge from these springs is relatively young groundwater, even though the source area is well outside of the surface basin. Additionally, this variation in temperature patterns between the springs can be an indication of the variations in flow pathways and travel times within the groundwater system.

The Cambria spring also has a recharge source area from across the divide; however temperature records of the Cambria spring show only slight seasonal changes in temperature with no response to small scale event fluctuations (from rain events or surface temperature changes, as seen in surface temperature records), indicating longer travel times for groundwater. Again, this correlates nicely with the conceptual model proposed by Prince et al., (2011); however it implies that there are locations within the system which allow for deeper flow and therefore older groundwater discharging from springs. Unfortunately, particle tracking in this simple one-layer horizontal flow model is not able to provide differences in travel times, however it is clear from temperature data that flow pathways can vary greatly and are not dependent upon geology at the spring or the size of the source basin. This outcome is representative of the heterogeneity and possibly anisotropy of the system and will require further investigation to better understand the nature of flow pathways utilized by the groundwater capture process.

The remaining two springs, Smith Creek and Silver Lake both have much shorter travel paths. This correlates well with the drainage retreat conceptual model. These springs are located within the region of capture which has been occurring most rapidly thus far (Figure 17). Divide migration appears to have truncated the catchment for the Silver Lake spring and potentially even created the Smith Creek discharge location, or captured its upper watershed. Just as with an overall energy increase from an expanded groundwater basin, spring discharge into the Roanoke watershed will increase available water for tributaries further increasing energy available for erosive processes.

The comparison between the northern 5 springs (1-5 in Figure 17) and the southern 2 springs (6 & 7 in Figure 17) allow us to infer that groundwater capture occurs in addition to surface capture, however in regions experiencing active surface capture the groundwater becomes slightly less predictable. Here surface divide and groundwater divide locations are coincident. It is possible that the region of rapid capture once looked similar to the slower capture region, but that the addition of groundwater from an expanded basin, as seen currently in the northern springs, allowed for a kick-started rapid incision. If this is true, we would expect the region with slower capture to also pick-up erosive speed and begin to resemble the rapidly incising region. Then we could also predict a possible slowing of capture in the previously rapidly migrating region, due to the removal of an expanded groundwater basin now that the surface basin has been able to "catch-up" to the groundwater divide location.

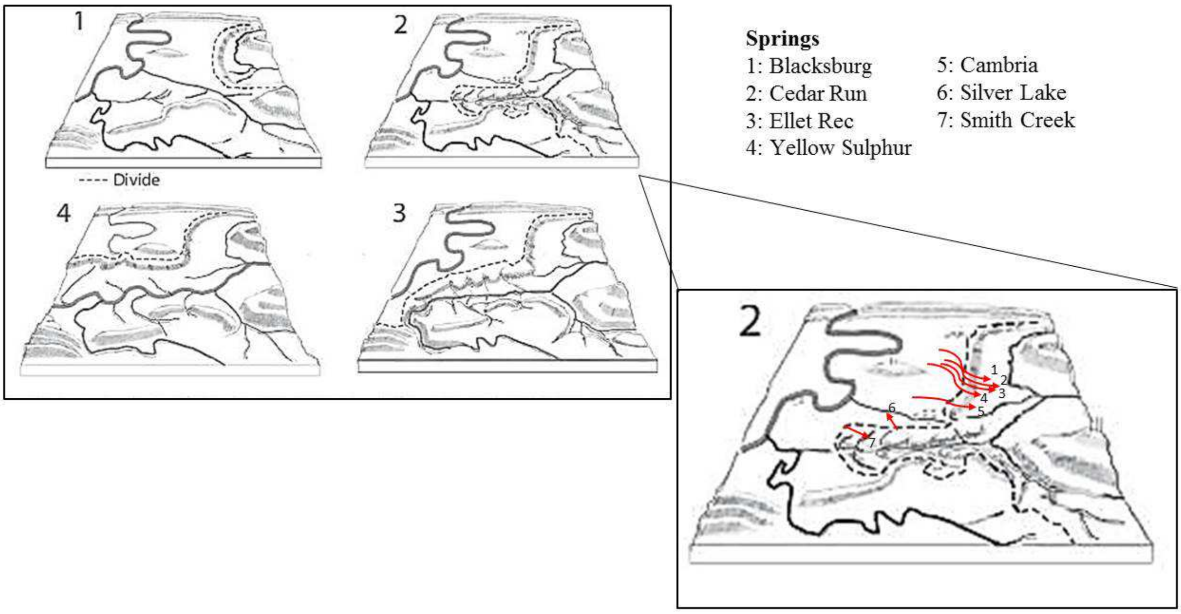


Figure 17: Conceptual model of stream capture process at the surface. 1-4 show the progressive incision of the Roanoke River through time, 2 being the current position of the divide (dashed line) and 3 & 4 showing predicted divide location. Expanded box: Current location of the divide with spring particle tracking results shown in red. Spring source areas are further into the New River divide in the northern portion of the region where capture has not yet occurred, implying a pre-captured groundwater basin. Springs in the southern region have experienced full capture, removing groundwater basin (modified from Prince et al., 2011).

Conclusions and Future Work

Stream capture between the New River and Roanoke River in southwestern VA provides a unique example of non-tectonically driven drainage rearrangement. Using simple field measurements and numerical models, we were able to create a generalized groundwater potential map for this region in an attempt to determine groundwater influence, or response, in regard to stream capture. Our results suggest that the groundwater divide has shifted west relative to the surface divide and groundwater flow occurs across the surface divide toward the Roanoke River, potentially capturing the groundwater basin prior to actual divide retreat. The addition of groundwater to the Roanoke River basin, in addition to what its surface basin provides, could lead to an over-energizing of upper Roanoke tributaries, theoretically increasing stream power and further driving incision and headward retreat.

Spring temperature records and particle tracking results further support the occurrence of groundwater basin capture; however clearly show the variation in the flow pathways and groundwater travel times within the system. In the four streams that source water from outside of their surface basin, we observed all of the three identified thermal patterns; 1) event-scale fluctuation, 2) seasonal fluctuation, and 3) a combination of both. This implies that groundwater capture is not strictly a diffuse or conduit process, but a mixture of both depending upon the individual spring location and flow pathways available. This variation in flow pathways can lead to a variation in added energy to the Roanoke system. Both slow seepage and rapid, concentrated discharge locations will need to be incorporated into models of surface processes differently. One would simply add water to the basin, possibly driving hillslope creep (seepage) and the other could create a new stream location entirely (direct spring discharge).

Future work in the region will need to focus on similar data collection, but at a higher resolution and for longer time periods. Our current steady-state model has only 18 well observations, none of which provided information about lithologic changes and/or fracture locations and orientations. The addition of more wells, sampled at higher temporal resolution over longer time scales, would provide the basis to build a transient groundwater model and allow for seasonal changes in recharge to be taken into account. Also, logging of a number of wells could provide information on hydraulically active fracture locations and orientations and identification of the hydrologic units containing the fracture pathways. This could allow for modeling of more than a one-layer system which could also yield more accurate simulated hydraulic heads. The use of the newly developed MODFLOW-USG (Panday et al., 2013) would make it far easier to incorporate geologic structure and anisotropy into the model, which could provide far more detailed information about recharge pathways into the subsurface and vertical flow components and depth of circulation. Additionally, spring temperature records, although informative in a relative sense, cannot give actual recharge ages which would be useful in determining pathways of flow used in the basin capture process. Dating of the spring water using dissolved gases would provide actual ages and allow for a clearer picture of groundwater capture and depth of circulation.

In addition, future work should attempt to not only better characterize the groundwater system, but also evaluate the connection between groundwater and surface capture with the use of evidence from the land surface. If we aim to understand the role groundwater capture has on erosion and headward incision, we need to assess the effect an expanded groundwater basin has on surface processes. This could be done by comparing the actual discharge in upper tributaries to the expected discharge, according to the surface catchment size. If discharge is greater than expected then groundwater capture could have the potential to increase stream power, adding incision-driving energy to the system. Additionally, if an expanded groundwater basin exists we would expect increased seepage and sapping along the divide. Studies in the future could focus along the divide, utilizing surface features and seepage determination tools (such as electrical resistivity) to better understand the role groundwater may play in disperse hillslope erosion along the escarpment.

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Appendix A: Research Informational Flyer

Do you have a well?

Do you live in the New River Valley?

Help with graduate research!

Your well would be used only to measure the depth to the water table. This information will be essential to expanding our knowledge of groundwater in the region!

No chemicals or dyes would be placed in your water and the measurement takes only minutes.

Contact: Lyndsey Funkhouser
Graduate Student, Virginia Tech Geosciences
lyndsey8@vt.edu
540-335-5857

geosciences AT VIRGINIA TECH

Appendix B: Images of Wells Used For Observed Head Values

Below are shown two images for each of 16 of the 18 wells. First image shows well location and second shows a closer view of the well. Two of the research wells were not able to be photographed.

Well 1

Well 2

Well 3

Well 4 - Not Pictured

Well 5

Well 6

7 - Not Pictured

Well 8

Well 9

Well 10

Well 11

Well 12

Well 13

Well 14

Well 15


Well 16


Well 17


Well 18

Appendix C: Daily Spring Temperature Data

Table shows the average daily spring temperature measurement calculated from the original 15 min or 30 min sample interval data. Original tables could not be provided due to the large size. The remaining 3 springs are continued on page 79.

Yellow Sulphur		Smith Creek		Silver Lake		Ellet Rec	
Date	Temp (C°)	Date	Temp (C°)	Date	Temp (C°)	Date	Temp (C°)
12/02/13	12.541	10/25/2013	13.333	10/30/13	14.554	10/25/13	11.829
12/03/13	12.576	10/26/2013	13.283	10/31/13	14.556	10/26/13	11.572
12/04/13	12.594	10/27/2013	13.331	11/01/13	14.569	10/27/13	12.507
12/05/13	12.618	10/28/2013	13.327	11/02/13	14.56	10/28/13	12.503
12/06/13	12.55	10/29/2013	13.397	11/03/13	14.553	10/29/13	12.867
12/07/13	12.443	10/30/2013	13.409	11/04/13	14.541	10/30/13	13.127
12/08/13	12.441	10/31/2013	13.431	11/05/13	14.538	10/31/13	13.331
12/09/13	12.399	11/1/2013	13.443	11/06/13	14.55	11/01/13	13.481
12/10/13	12.352	11/2/2013	13.287	11/07/13	14.549	11/02/13	13.14
12/11/13	12.294	11/3/2013	13.263	11/08/13	14.531	11/03/13	12.543
12/12/13	12.304	11/4/2013	13.327	11/09/13	14.524	11/04/13	11.827
12/13/13	12.233	11/5/2013	13.365	11/10/13	14.517	11/05/13	11.694
12/14/13	12.209	11/6/2013	13.373	11/11/13	14.516	11/06/13	12.308
12/15/13	12.211	11/7/2013	13.365	11/12/13	14.503	11/07/13	12.251
12/16/13	12.235	11/8/2013	13.255	11/13/13	14.482	11/08/13	11.35
12/17/13	12.189	11/9/2013	13.253	11/14/13	14.46	11/09/13	11.007
12/18/13	12.207	11/10/2013	13.307	11/15/13	14.482	11/10/13	11.208
12/19/13	12.221	11/11/2013	13.291	11/16/13	14.504	11/11/13	10.948
12/20/13	12.355	11/12/2013	13.217	11/17/13	14.518	11/12/13	10.952
12/21/13	12.439	11/13/2013	12.805	11/18/13	14.521	11/13/13	10.059
12/22/13	12.417	11/14/2013	12.239	11/19/13	14.5	11/14/13	9.936
12/23/13	12.34	11/15/2013	12.272	11/20/13	14.43	11/15/13	10.114
12/24/13	12.304	11/16/2013	13.263	11/21/13	14.442	11/16/13	10.897
12/25/13	12.282	11/17/2013	13.365	11/22/13	14.47	11/17/13	11.354
12/26/13	12.229	11/18/2013	13.367	11/23/13	14.471	11/18/13	11.408
12/27/13	12.207	11/19/2013	13.343	11/24/13	14.431	11/19/13	10.432
12/28/13	12.209	11/20/2013	13.337	11/25/13	14.414	11/20/13	9.959
12/29/13	12.207	11/21/2013	13.347	11/26/13	14.172	11/21/13	10.214
12/30/13	12.207	11/22/2013	13.359	11/27/13	13.97	11/22/13	10.856
12/31/13	12.175	11/23/2013	13.313	11/28/13	14.1	11/23/13	10.811
01/01/14	12.072	11/24/2013	13.187	11/29/13	14.276	11/24/13	9.037
01/02/14	11.942	11/25/2013	13.233	11/30/13	14.346	11/25/13	8.62
01/03/14	11.918	11/26/2013	13.279	12/01/13	14.292	11/26/13	9.635
01/04/14	11.991	11/27/2013	13.134	12/02/13	14.313	11/27/13	10.316
01/05/14	11.74	11/28/2013	13.09	12/03/13	14.376	11/28/13	9.083
01/06/14	11.585	11/29/2013	13.167	12/04/13	14.392	11/29/13	8.597

01/07/14	11.633	11/30/2013	13.181	12/05/13	14.412	11/30/13	8.323
01/08/14	11.754	12/1/2013	13.267	12/06/13	14.396	12/01/13	8.194
01/09/14	11.833	12/2/2013	13.285	12/07/13	14.201	12/02/13	8.792
01/10/14	11.916	12/3/2013	13.307	12/08/13	14.214	12/03/13	9.188
01/11/14	11.916	12/4/2013	13.357	12/09/13	14.191	12/04/13	9.645
01/12/14	11.928	12/5/2013	13.403	12/10/13	14.1	12/05/13	9.977
01/13/14	11.93	12/6/2013	13.447	12/11/13	14.106	12/06/13	10.377
01/14/14	11.867	12/7/2013	13.124	12/12/13	14.188	12/07/13	10.577
01/15/14	11.819	12/8/2013	13.05	12/13/13	14.265	12/08/13	9.716
01/16/14	11.781	12/9/2013	13.136	12/14/13	14.311	12/09/13	9.818
01/17/14	11.698	12/10/2013	13.022	12/15/13	14.256	12/10/13	10.114
01/18/14	11.673	12/11/2013	12.927	12/16/13	14.221	12/11/13	9.367
01/19/14	11.714	12/12/2013	12.929	12/17/13	14.299	12/12/13	8.605
01/20/14	11.548	12/13/2013	12.757	12/18/13	14.271	12/13/13	8.128
01/21/14	11.397	12/14/2013	12.903	12/19/13	14.177	12/14/13	8.44
01/22/14	11.251	12/15/2013	12.903	12/20/13	14.187	12/15/13	8.796
01/23/14	11.139	12/16/2013	12.889	12/21/13	14.244	12/16/13	8.666
01/24/14	11.139	12/17/2013	13.08	12/22/13	14.289	12/17/13	8.423
01/25/14	11.254	12/18/2013	13.004	12/23/13	13.664	12/18/13	8.134
01/26/14	11.181	12/19/2013	13.024	12/24/13	13.686	12/19/13	8.197
01/27/14	10.988	12/20/2013	13.092	12/25/13	13.64	12/20/13	8.477
01/28/14	10.907	12/21/2013	13.311	12/26/13	13.951	12/21/13	8.852
01/29/14	11.037	12/22/2013	13.425	12/27/13	14.048	12/22/13	9.398
01/30/14	11.145	12/23/2013	13.094	12/28/13	14.066	12/23/13	10.122
01/31/14	11.236	12/24/2013	13.016	12/29/13	13.605	12/24/13	9.552
02/01/14	11.354	12/25/2013	12.946	12/30/13	13.596	12/25/13	8.273
02/02/14	11.443	12/26/2013	12.992	12/31/13	13.634	12/26/13	8.24
02/03/14	11.458	12/27/2013	12.946	01/01/14	13.703	12/27/13	8.255
02/10/14	11.902	12/28/2013	13.026	01/02/14	13.856	12/28/13	8.174
02/11/14	11.785	12/29/2013	13.175	01/03/14	13.97	12/29/13	9.506
02/12/14	11.643	12/30/2013	13.147	01/04/14	13.969	12/30/13	9.628
02/13/14	11.587	12/31/2013	13.074	01/05/14	13.995	12/31/13	9.299
02/14/14	11.74	1/1/2014	13.04	01/06/14	14.072	01/01/14	9.023
02/15/14	11.762	1/2/2014	13.169	01/07/14	13.976	01/02/14	8.988
02/16/14	11.548	1/3/2014	12.972	01/08/14	14.019	01/03/14	8.591
02/17/14	11.587	1/4/2014	12.944	01/09/14	14.098	01/04/14	8.295
02/18/14	11.75	1/5/2014	13.253	01/10/14	13.986	01/05/14	8.477
02/19/14	11.964	1/6/2014	13.123	01/11/14	13.575	01/06/14	8.491
02/20/14	12.148	1/7/2014	12.843	01/12/14	13.361	01/07/14	7.686
02/21/14	12.241	1/8/2014	12.968	01/13/14	13.534	01/08/14	7.651
02/22/14	12.258	1/9/2014	13.147	01/14/14	13.662	01/09/14	7.792
02/23/14	12.253	1/10/2014	13.251	01/15/14	13.517	01/10/14	8.013
02/24/14	12.197	1/11/2014	13.301	01/16/14	13.612	01/11/14	8.863
02/25/14	12.013	1/12/2014	13.255	01/17/14	13.697	01/12/14	8.736
02/26/14	11.906	1/13/2014	13.199	01/18/14	13.817	01/13/14	8.843
02/27/14	11.766	1/14/2014	13.229	01/19/14	13.809	01/14/14	9.324
02/28/14	11.678	1/15/2014	12.873	01/20/14	13.91	01/15/14	9.433
03/01/14	11.706	1/16/2014	12.73	01/21/14	13.895	01/16/14	9.166

03/02/14	11.916	1/17/2014	12.929	01/22/14	13.839	01/17/14	9.106
03/03/14	12.108	1/18/2014	12.57	01/23/14	13.811	01/18/14	8.941
03/04/14	11.773	1/19/2014	12.696	01/24/14	13.805	01/19/14	8.92
03/05/14	11.787	1/20/2014	12.917	01/25/14	13.799	01/20/14	8.957
03/06/14	11.811	1/21/2014	12.954	01/26/14	13.852	01/21/14	8.961
03/07/14	11.732	1/22/2014	12.831	01/27/14	13.807	01/22/14	8.514
03/08/14	11.892	1/23/2014	12.789	01/28/14	13.748	01/23/14	8.265
03/09/14	12.041	1/24/2014	12.972	01/29/14	13.687	01/24/14	7.962
03/10/14	12.001	1/25/2014	13.086	01/30/14	13.63	01/25/14	8.001
03/11/14	12.15	1/26/2014	13.098	01/31/14	13.635	01/26/14	8.022
03/12/14	12.185	1/27/2014	13.092	02/01/14	13.787	01/27/14	8.095
03/13/14	11.736	1/28/2014	12.992	02/02/14	13.825	01/28/14	7.69
03/14/14	11.613	1/29/2014	12.942	02/03/14	13.116	01/29/14	7.448
03/15/14	12.001	1/30/2014	12.847	02/04/14	12.863	01/30/14	7.307
03/16/14	12.296	1/31/2014	12.966	02/05/14	12.9	01/31/14	7.456
03/17/14	12.191	2/1/2014	13.052	02/10/14	14.115	02/01/14	7.596
03/18/14	12.11	2/2/2014	13.213	02/11/14	14.122	02/02/14	7.818
03/19/14	12.13	2/3/2014	13.112	02/12/14	14.113	02/03/14	8.931
03/20/14	12.207	2/4/2014	13.129	02/13/14	14.118	02/04/14	10.141
03/21/14	12.207	2/5/2014	13.1	02/14/14	14.123	02/05/14	10.238
03/22/14	12.237	2/10/2014	12.677	02/15/14	14.125	02/11/14	10.297
03/23/14	12.253	2/11/2014	12.897	02/16/14	14.134	02/12/14	10.053
03/24/14	12.201	2/12/2014	13.269	02/17/14	14.137	02/13/14	9.975
03/25/14	12.122	2/13/2014	13.311	02/18/14	14.133	02/14/14	9.595
03/26/14	12.106	2/14/2014	13.337	02/19/14	13.939	02/15/14	9.4
03/27/14	12.08	2/15/2014	13.299	02/20/14	13.73	02/16/14	9.104
03/28/14	12.15	2/16/2014	13.303	02/21/14	13.503	02/17/14	8.906
03/29/14	12.223	2/17/2014	13.295	02/22/14	13.545	02/18/14	9.124
03/30/14	12.217	2/18/2014	13.351	02/23/14	13.701	02/19/14	9.562
03/31/14	12.189	2/19/2014	13.255	02/24/14	13.769	02/20/14	10.518
04/01/14	12.231	2/20/2014	13.213	02/25/14	13.813	02/21/14	10.803
04/02/14	12.322	2/21/2014	13.036	02/26/14	13.831	02/22/14	11.316
04/03/14	12.401	2/22/2014	13.237	02/27/14	13.854	02/23/14	11.334
04/04/14	12.401	2/23/2014	13.277	02/28/14	13.869	02/24/14	11.366
04/05/14	12.401	2/24/2014	13.281	03/01/14	13.902	02/25/14	11.368
04/06/14	12.326	2/25/2014	13.269	03/02/14	13.945	02/26/14	11.358
04/07/14	12.304	2/26/2014	13.269	03/03/14	13.906	02/27/14	11.301
04/08/14	12.304	2/27/2014	13.249	03/04/14	13.837	02/28/14	11.135
04/09/14	12.342	2/28/2014	13.231	03/05/14	13.884	03/01/14	10.777
04/10/14	12.387	3/1/2014	13.257	03/06/14	13.892	03/02/14	10.585
04/11/14	12.401	3/2/2014	13.327	03/07/14	13.895	03/03/14	10.642
04/12/14	12.441	3/3/2014	13.265	03/08/14	13.916	03/04/14	10.128
04/13/14	12.491	3/4/2014	13.217	03/09/14	13.948	03/05/14	9.805
04/14/14	12.497	3/5/2014	13.253	03/10/14	13.972	03/06/14	9.61
04/15/14	12.497	3/6/2014	13.249	03/11/14	13.986	03/07/14	9.505
04/16/14	12.385	3/7/2014	13.271	03/12/14	14	03/08/14	9.585
04/17/14	12.306	3/8/2014	13.311	03/13/14	14.01	03/09/14	9.663
04/18/14	12.371	3/9/2014	13.309	03/14/14	14.003	03/10/14	9.649

04/19/14	12.357	3/10/2014	13.329	03/15/14	14.021	03/11/14	9.854
04/20/14	12.401	3/11/2014	13.337	03/16/14	14.018	03/12/14	9.786
04/21/14	12.401	3/12/2014	13.319	03/17/14	14.008	03/13/14	10.033
		3/13/2014	13.259	03/18/14	14.015	03/14/14	10.477
		3/14/2014	13.267	03/19/14	14.027	03/15/14	10.612
		3/15/2014	13.321	03/20/14	14.023	03/16/14	10.651
		3/16/2014	13.259	03/21/14	14.033	03/17/14	10.582
		3/17/2014	13.231	03/22/14	14.038	03/18/14	10.492
		3/18/2014	13.251	03/23/14	14.02	03/19/14	10.455
		3/19/2014	13.279	03/24/14	14.02	03/20/14	10.455
		3/20/2014	13.295	03/25/14	14.002	03/21/14	10.455
		3/21/2014	13.239	03/26/14	13.993	03/22/14	10.402
		3/22/2014	13.305	03/27/14	14.016	03/23/14	10.1
		3/23/2014	13.243	03/28/14	14.048	03/24/14	9.673
		3/24/2014	13.235	03/29/14	14.076	03/25/14	9.357
		3/25/2014	13.221	03/30/14	14.047	03/26/14	9.207
		3/26/2014	13.151	03/31/14	14.059	03/27/14	9.025
		3/27/2014	13.171	04/01/14	14.085	03/28/14	9.318
		3/28/2014	13.303	04/02/14	14.109	03/29/14	9.536
		3/29/2014	13.355	04/03/14	14.118	03/30/14	9.525
		3/30/2014	13.139	04/04/14	14.134	03/31/14	9.452
		3/31/2014	13.277	04/05/14	14.143	04/01/14	9.517
		4/1/2014	13.319	04/06/14	14.131	04/02/14	9.644
		4/2/2014	13.373	04/07/14	13.981	04/03/14	9.766
		4/3/2014	13.381	04/08/14	13.848	04/04/14	10.136
		4/4/2014	13.399	04/09/14	13.906	04/05/14	10.128
		4/5/2014	13.311	04/10/14	13.948	04/06/14	10.083
		4/6/2014	13.291	04/11/14	13.994	04/07/14	10.361
		4/7/2014	13.243	04/12/14	14.018	04/08/14	10.919
		4/8/2014	13.273	04/13/14	14.04	04/09/14	11.041
		4/9/2014	13.259	04/14/14	14.059	04/10/14	11.086
		4/10/2014	13.269	04/15/14	14.06	04/11/14	11.094
		4/11/2014	13.355	04/16/14	14.028	04/12/14	11.041
		4/12/2014	13.395	04/17/14	14.036	04/13/14	11.041
		4/13/2014	13.445	04/18/14	14.04	04/14/14	11.053
		4/14/2014	13.401	04/19/14	14.063	04/15/14	11.045
		4/15/2014	13.263	04/20/14	14.083	04/16/14	10.984
		4/16/2014	13.209	04/21/14	14.092	04/17/14	10.891
		4/17/2014	13.243			04/18/14	10.846
		4/18/2014	13.279			04/19/14	10.84
		4/19/2014	13.323			04/20/14	10.885
		4/20/2014	13.335			04/21/14	10.944
		4/21/2014	13.368				

Cedar Run		Cambria		Blacksburg	
Date	Temp (C°)	Date	Temp (C°)	Date	Time (C°)
12/03/13	13.345	10/30/13	12.364	12/03/13	13.034
12/04/13	13.357	10/31/13	12.364	12/04/13	13.039
12/05/13	13.365	11/01/13	12.364	12/05/13	13.049
12/06/13	13.275	11/02/13	12.364	12/06/13	12.995
12/07/13	13.269	11/03/13	12.364	12/07/13	12.989
12/08/13	13.267	11/04/13	12.364	12/08/13	12.995
12/09/13	13.243	11/05/13	12.363	12/09/13	12.983
12/10/13	13.211	11/06/13	12.363	12/10/13	12.984
12/11/13	13.195	11/07/13	12.358	12/11/13	12.983
12/12/13	13.215	11/08/13	12.347	12/12/13	12.993
12/13/13	13.267	11/09/13	12.34	12/13/13	13.012
12/14/13	13.265	11/10/13	12.34	12/14/13	13.011
12/15/13	13.259	11/11/13	12.34	12/15/13	13.01
12/16/13	13.251	11/12/13	12.34	12/16/13	13.02
12/17/13	13.223	11/13/13	12.34	12/17/13	12.998
12/18/13	13.241	11/14/13	12.34	12/18/13	13.005
12/19/13	13.265	11/15/13	12.34	12/19/13	13.017
12/20/13	13.307	11/16/13	12.34	12/20/13	13.042
12/21/13	13.365	11/17/13	12.34	12/21/13	13.064
12/22/13	13.118	11/18/13	12.34	12/22/13	12.763
12/23/13	13.169	11/19/13	12.34	12/23/13	12.887
12/24/13	13.145	11/20/13	12.34	12/24/13	12.939
12/25/13	13.179	11/21/13	12.333	12/25/13	12.963
12/26/13	13.191	11/22/13	12.322	12/26/13	12.984
12/27/13	13.221	11/23/13	12.316	12/27/13	13.003
12/28/13	13.148	11/24/13	12.316	12/28/13	12.844
12/29/13	13.173	11/25/13	12.316	12/29/13	12.859
12/30/13	13.173	11/26/13	12.316	12/30/13	12.916
12/31/13	13.181	11/27/13	12.316	12/31/13	12.958
01/01/14	13.193	11/28/13	12.316	01/01/14	12.978
01/02/14	13.147	11/29/13	12.306	01/02/14	12.958
01/03/14	13.133	11/30/13	12.292	01/03/14	12.969
01/04/14	13.193	12/01/13	12.292	01/04/14	13.001
01/05/14	13.181	12/02/13	12.292	01/05/14	12.983
01/06/14	13.082	12/03/13	12.292	01/06/14	12.932
01/07/14	13.129	12/04/13	12.292	01/07/14	12.965
01/08/14	13.183	12/05/13	12.292	01/08/14	12.991
01/09/14	13.227	12/06/13	12.288	01/09/14	13.009
01/10/14	13.199	12/07/13	12.275	01/10/14	12.965
01/11/14	13.171	12/08/13	12.268	01/11/14	12.91
01/12/14	13.197	12/09/13	12.268	01/12/14	12.945

01/13/14	13.229	12/10/13	12.268	01/13/14	12.968
01/14/14	13.173	12/11/13	12.268	01/14/14	12.952
01/15/14	13.161	12/12/13	12.268	01/15/14	12.946
01/16/14	13.173	12/13/13	12.267	01/16/14	12.957
01/17/14	13.122	12/14/13	12.247	01/17/14	12.935
01/18/14	13.159	12/15/13	12.243	01/18/14	12.956
01/19/14	13.171	12/16/13	12.243	01/19/14	12.968
01/20/14	13.165	12/17/13	12.243	01/20/14	12.963
01/21/14	13.078	12/18/13	12.243	01/21/14	12.924
01/22/14	13.074	12/19/13	12.242	01/22/14	12.925
01/23/14	13.046	12/20/13	12.224	01/23/14	12.908
01/24/14	13.116	12/21/13	12.219	01/24/14	12.929
01/25/14	13.127	12/22/13	12.219	01/25/14	12.943
01/26/14	13.163	12/23/13	12.238	01/26/14	12.955
01/27/14	13.078	12/24/13	12.243	01/27/14	12.913
01/28/14	13.07	12/25/13	12.243	01/28/14	12.892
01/29/14	13.044	12/26/13	12.226	01/29/14	12.898
01/30/14	13.129	12/27/13	12.219	01/30/14	12.935
01/31/14	13.185	12/28/13	12.219	01/31/14	12.952
02/01/14	13.229	12/29/13	12.219	02/01/14	12.968
02/02/14	13.066	12/30/13	12.239	02/02/14	12.81
02/03/14	13.09	12/31/13	12.222	02/03/14	12.823
02/04/14	13.133	01/01/14	12.219	02/04/14	12.867
02/05/14	13.11	01/02/14	12.219	02/05/14	12.873
02/06/14	13.112	01/03/14	12.219	02/06/14	12.883
02/07/14	13.155	01/04/14	12.207	02/07/14	12.9
02/08/14	13.173	01/05/14	12.195	02/08/14	12.916
02/09/14	13.161	01/06/14	12.195	02/09/14	12.903
02/10/14	13.076	01/07/14	12.195	02/10/14	12.897
02/11/14	13.142	01/08/14	12.195	02/11/14	12.917
02/12/14	13.086	01/09/14	12.195	02/12/14	12.908
02/13/14	13.131	01/10/14	12.188	02/13/14	12.918
02/14/14	13.169	01/11/14	12.172	02/14/14	12.926
02/15/14	13.163	01/12/14	12.188	02/15/14	12.913
02/16/14	13.139	01/13/14	12.191	02/16/14	12.91
02/17/14	13.151	01/14/14	12.179	02/17/14	12.924
02/18/14	13.177	01/15/14	12.171	02/18/14	12.904
02/19/14	13.157	01/16/14	12.171	02/19/14	12.743
02/20/14	13.07	01/17/14	12.171	02/20/14	12.674
02/21/14	12.915	01/18/14	12.171	02/21/14	12.619
02/22/14	13.042	01/19/14	12.171	02/22/14	12.649
02/23/14	13.127	01/20/14	12.167	02/23/14	12.755
02/24/14	13.088	01/21/14	12.149	02/24/14	12.813
02/25/14	13.11	01/22/14	12.147	02/25/14	12.85
02/26/14	13.102	01/23/14	12.147	02/26/14	12.871
02/27/14	13.092	01/24/14	12.147	02/27/14	12.883
02/28/14	13.102	01/25/14	12.147	02/28/14	12.904
03/01/14	13.124	01/26/14	12.145	03/01/14	12.916

03/02/14	13.205	01/27/14	12.125	03/02/14	12.936
03/03/14	13.139	01/28/14	12.122	03/03/14	12.92
03/04/14	13.074	01/29/14	12.122	03/04/14	12.894
03/05/14	13.112	01/30/14	12.122	03/05/14	12.907
03/06/14	13.122	01/31/14	12.112	03/06/14	12.911
03/07/14	13.153	02/01/14	12.098	03/07/14	12.919
03/08/14	13.163	02/02/14	12.098	03/08/14	12.928
03/09/14	13.205	02/03/14	12.098	03/09/14	12.94
03/10/14	13.223	02/04/14	12.099	03/10/14	12.94
03/11/14	13.225	02/05/14	12.1	03/11/14	12.947
03/12/14	13.211	02/10/14	12.098	03/12/14	12.938
03/13/14	13.145	02/11/14	12.098	03/13/14	12.917
03/14/14	13.171	02/12/14	12.079	03/14/14	12.922
03/15/14	13.209	02/13/14	12.074	03/15/14	12.935
03/16/14	13.181	02/14/14	12.074	03/16/14	12.926
03/17/14	13.171	02/15/14	12.074	03/17/14	12.92
03/18/14	13.171	02/16/14	12.073	03/18/14	12.923
03/19/14	13.183	02/17/14	12.06	03/19/14	12.937
03/20/14	13.197	02/18/14	12.05	03/20/14	12.944
03/21/14	13.195	02/19/14	12.058	03/21/14	12.936
03/22/14	13.221	02/20/14	12.096	03/22/14	12.938
03/23/14	13.173	02/21/14	12.102	03/23/14	12.921
03/24/14	13.135	02/22/14	12.122	03/24/14	12.914
03/25/14	13.161	02/23/14	12.122	03/25/14	12.908
03/26/14	13.106	02/24/14	12.117	03/26/14	12.894
03/27/14	13.139	02/25/14	12.098	03/27/14	12.909
03/28/14	13.231	02/26/14	12.098	03/28/14	12.933
03/29/14	13.255	02/27/14	12.098	03/29/14	12.942
03/30/14	13.173	02/28/14	12.09	03/30/14	12.92
03/31/14	13.193	03/01/14	12.074	03/31/14	12.928
04/01/14	13.231	03/02/14	12.074	04/01/14	12.936
04/02/14	13.239	03/03/14	12.074	04/02/14	12.946
04/03/14	13.269	03/04/14	12.074	04/03/14	12.954
04/04/14	13.269	03/05/14	12.074	04/04/14	12.964
04/05/14	13.233	03/06/14	12.074	04/05/14	12.944
04/06/14	13.229	03/07/14	12.074	04/06/14	12.936
04/07/14	13.01	03/08/14	12.074	04/07/14	12.769
04/08/14	13.127	03/09/14	12.066	04/08/14	12.741
04/09/14	13.145	03/10/14	12.052	04/09/14	12.791
04/10/14	13.145	03/11/14	12.05	04/10/14	12.824
04/11/14	13.223	03/12/14	12.05	04/11/14	12.846
04/12/14	13.239	03/13/14	12.05	04/12/14	12.869
04/13/14	13.263	03/14/14	12.05	04/13/14	12.887
04/14/14	13.269	03/15/14	12.05	04/14/14	12.896
04/15/14	13.221	03/16/14	12.05	04/15/14	12.896
04/16/14	13.153	03/17/14	12.05	04/16/14	12.887
04/17/14	13.173	03/18/14	12.05	04/17/14	12.902
04/18/14	13.213	03/19/14	12.05	04/18/14	12.909

04/19/14	13.239	03/20/14	12.046	04/19/14	12.92
04/20/14	13.229	03/21/14	12.029	04/20/14	12.92
04/21/14	13.204	03/22/14	12.025	04/21/14	12.92
		03/23/14	12.025		
		03/24/14	12.025		
		03/25/14	12.025		
		03/26/14	12.025		
		03/27/14	12.025		
		03/28/14	12.025		
		03/29/14	12.023		
		03/30/14	12.008		
		03/31/14	12.001		
		04/01/14	12.001		
		04/02/14	12.001		
		04/03/14	12.001		
		04/04/14	12.001		
		04/05/14	12.001		
		04/06/14	12.001		
		04/07/14	11.998		
		04/08/14	12.001		
		04/09/14	12.001		
		04/10/14	12.001		
		04/11/14	12.001		
		04/12/14	12.001		
		04/13/14	12.001		
		04/14/14	12.001		
		04/15/14	12.001		
		04/16/14	12.001		
		04/17/14	12.001		
		04/18/14	12.001		
		04/19/14	12.001		
		04/20/14	12.001		
		04/21/14	12.001		