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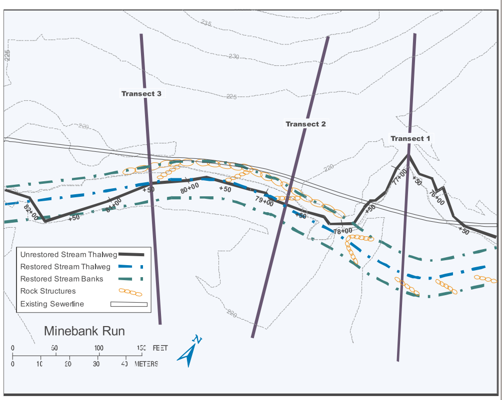
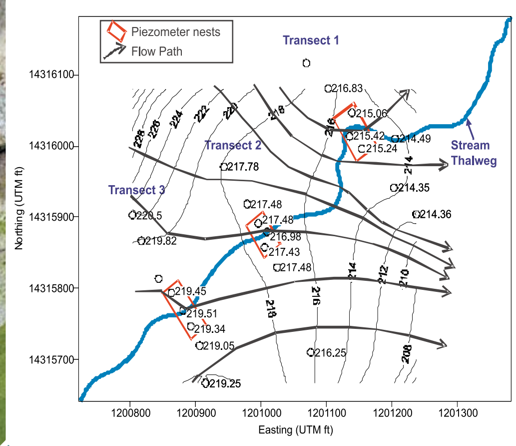
Assessment of Near-Stream Ground Water-Surface Water Interaction (GSI) of a Degraded Stream before Restoration





Office of Research and Development
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Assessment of Near-Stream Ground Water-Surface Water Interaction (GSI) of a Degraded Stream before Restoration

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Front Cover photos:

A view of Minebank Run looking upstream at Transect 3 in July 2002.

Aerial view of Minebank Run taken from low-level blimp platform (photo courtesy of Ken Jewell).

Regional ground water equipotentials on March 22, 2002.

Back Cover photos:

Composite topographic and aerial photograph of a portion of the heavily urbanized Minebank Run wtershed showing locations of piezometers (red dots) and the I-695 Beltway in the lower left (courtesy of Robert Shedlock).

Incision and infrastructure exposure at Minebank Run before restoration.

Location of monitoring well transects in relation to restoration design (Figure courtesy of Maryland Department of Environmental Protection and Resource Management).

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients. This report describes a case study of the influence of stream channel geomorphology on surface water and ground water hydrology. The objective of the study was to characterize ground water-surface water interaction (GSI) in Minebank Run (MBR), a degraded urban stream in Baltimore County, Maryland that was slated for restoration. This study represents the first phase in quantifying the effects of stream restoration on GSI at MBR and is intended to provide the basis for comparison of post-restoration GSI at MBR.

Stream restoration at MBR will utilize stream channel reconstruction methods designed to stabilize banks and reduce erosion, an approach intended to protect property and sewer and drinking water infrastructure. A clear understanding of GSI behavior under degraded conditions is necessary to quantify the effects of geomorphic methods of restoration on GSI. In turn, GSI is known to influence stream function such as nutrient uptake, stream metabolism, and primary production. Thus, the value of these baseline data extends to predicting the influence of geomorphic structure on GSI behavior and on subsequent biogeochemical and biotic response.

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Acknowledgments

We offer our sincere gratitude to the USGS researchers, Ed Doheny, Roger Starsonick, and Bob Shedlock for their tremendous work in collecting surface and ground water hydrology data and preparing the pre-restoration surface water hydrology analysis. We thank Baltimore County Department of Environmental Protection and Resource Management, especially Don Outen, Steve Stewart, Karen Ogle, and Candy Crowell for their assistance in site selection and continuing project support. We also thank Brad Scroggins, Ken Jewell, Steve Acree, Randall Ross, and Russell Neill for invaluable field and technical assistance. Finally, we thank the Cromwell Valley Park personnel, especially Leo Rebetsky, for supporting the project and providing unfettered access to the stream site at all times.

Abstract

In Fall 2001, EPA undertook an intensive collaborative research effort with the US Geological Survey (USGS) and the Cary Institute of Ecosystem Studies to evaluate the impact of restoration on water quality at a degraded stream in an urban watershed using a before/after stream restoration study design. One objective was to evaluate if particular stream restoration techniques improve ground water-surface water interaction (GSI) and if beneficial hydrologic exchanges between the stream and riparian/floodplain may be enhanced to improve water quality. An essential piece of this comprehensive study was to characterize, measure, and quantify near-stream (GSI) before and after stream restoration at specific stream features and assess how the geomorphology and geology at each feature impact GSI. This research report describes the pre-restoration study of GSI at specific stream features in a degraded urban stream in Towson, MD. The study employed a comprehensive evaluation of the surface water hydrology, ground water hydrology, geomorphology, and geology along a specific stream reach slated for restoration. Ground water level measurements in piezometer nests in the stream bed and banks over time were found to be sufficient to characterize the losing or gaining nature of near-stream GSI. Temperature measurements were used to verify these interactions. The GSI was simply and effectively quantified using gradients calculated from the piezometer nest ground water levels and Darcy's law in a simple compartment model. Flow was quantified and used to calculate residence times in the sediments. These residence times may be used to quantify the mass removal of nutrients and other contaminants if reaction kinetics are known. Results of the pre-restoration study reveal the highly variable nature of GSI on the temporal and spatial scales of interest. Results also reveal how specific stream features and settings influence GSI. Flow and residence time were found to be closely dependent on the stream feature geology and geomorphology. Consequently, any restoration that impacts these features likely will strongly influence GSI. Results of this study established the pre-restoration GSI. An identical study of the post-restoration GSI is underway. These results will be compared to the pre-restoration state in a second report to evaluate the impact of stream restoration on GSI to determine if improvements in water quality may be achieved.

Keywords: Baltimore, Maryland; geomorphology; ground water; ground water-surface water interaction; GSI; hydrology; hyporheic; Minebank Run; restoration; temperature; urban stream

1.0 Introduction

Stream restoration is comprised of a group of techniques that are intended to improve the physical, chemical and ecological functions of a degraded stream (Falk et al. 2006). Physical functions include the stream's ability to manage its flow and sediment load. Chemical functions include the stream's assimilative capacity to process nutrients and other contamination to maintain stream water quality. Ecological functions include providing aquatic and riparian habitats. All of these beneficial stream functions are intimately tied to the stream flow and the exchange of water in and out of the stream bed and banks known as ground water-surface water interaction (GSI).

GSI in streams is broadly defined as the exchange of ground water and surface water of a stream at several temporal or spatial scales. Watershed scale GSI is on the order of miles and involves ground water discharge over an entire watershed which supplies the stream base flow. Near-stream scale GSI, on the order of feet and days, captures the losing/gaining reaches of streams where transport and processing of nutrients that support aquatic and riparian habitats occurs. Sediment scale GSI refers to exchanges in the stream beds and banks that occur on the scale of inches and minutes. GSI in the near-stream and sediment scale is often called hyporheic flow and is critical for support of aquatic life.

One goal of stream restoration has been to improve GSI in the belief that enhanced exchange will improve the physical, chemical, and ecological functions of a stream. A critical key to unlock the impact of restoration on stream function is the ability to quantify GSI flow in and out of the stream and evaluate how restoration impacts this flow. In the case of water quality, GSI flow, magnitude, and direction may be used to calculate mass removal of nutrients and contaminants in the stream bed and banks using the measured reaction kinetics before and after restoration. Efforts to understand the physical factors which influence GSI and to develop practical methods to quantify it, however, have been hindered by the inherent complexity of the multiple temporal and spatial scales of the interaction. The challenges of evaluating near-stream GSI at various stream features, in particular, remain an impediment to assessing whether or not particular stream restoration actions have improved GSI and stream function.

In 2001, EPA/ORD/GWERD undertook an intensive collaborative effort with the US Geological Survey (USGS), Cary Institute of Ecosystem Studies and Baltimore County Department of Environmental Protection and Resource Management (DEPRM) to evaluate the impact of restoration on a degraded stream in an urban watershed using a before/after stream restoration study design. The main objective was to assess if stream restoration would improve the water quality of a degraded stream by improving its physical, chemical, and ecological functions. An essential piece of this comprehensive study was to evaluate the effects of particular stream restoration techniques on GSI. The hypothesis was that a degraded stream has poor GSI and if restoration could enhance GSI, water quality could be improved through beneficial hydrologic interactions between the stream and riparian/floodplain.

To assess the impact of restoration on GSI, it was essential to characterize, measure, and quantify near-stream GSI at specific stream features. Our study, therefore, had two phases, one before and one after restoration. The objectives of the pre-restoration study which took place from Fall 2001 to Summer of 2004 were to:

1. Evaluate the stream geomorphology and geology at specific stream features and assess how stream geomorphology and geology at specific stream features influences GSI.
2. Develop effective and simple methods to characterize, measure, quantify and verify GSI at specific stream features to establish baseline GSI in the unrestored stream for comparison to the restored state.

The objectives of the post-restoration phase, currently underway, are to employ methods developed during pre-restoration phase to evaluate water quality benefits of specific stream restoration techniques due to effects on GSI.

This research report describes the results of the pre-restoration assessment of GSI at specific stream features and methods to effectively and simply quantify it. The second research phase will describe the post-restoration GSI in relation to the pre-restoration state and quantify the mass removal of nutrients and contaminants which can be attributed to restoration impact on GSI. This comparison is intended to assess the impact of restoration on GSI and water quality due to specific stream restoration techniques. The results should provide restoration designers and stakeholders practical methods to measure GSI to determine mass removal of nutrients and contaminants in stream sediments and identify specific restoration techniques which improve GSI to enhance water quality and other beneficial stream functions.

2.0 Background

Numerous hydrologic, chemical, and ecological benefits to streams and riparian areas have been associated with near-stream GSI (Boulton et al., 1998; Cirmo and McDonnell, 1997; Hayashi and Rosenberry, 2002; Kasahara and Hill, 2006; Poole et al., 2006). Often a claim is made that stream restoration can enhance GSI and benefit stream function. For example, restoring incised streams in order to reconnect stream channels to floodplains, may improve near-stream GSI. Interaction may also be improved by incorporating permeable sediments in stream beds and banks in place of low conductivity strata. These changes may increase the transport of nutrient laden water into the organic rich soil profiles in the floodplain and riparian zones. These nutrients may be utilized by riparian plants or denitrified by microbial activity, thereby improving water quality by reducing excess nitrogen and other nutrients. There is also the potential for removal of contaminants through adsorption in the stream sediments. In addition, restoring stream channels may enhance a stream's ability to manage its flow and sediment load, reducing sediment transport. In this way, restoration which improves GSI is predicted to also improve water quality.

To date, few studies have assessed the effects of restoration on GSI (Kasahara and Hill, 2006). If an objective of stream restoration is to improve GSI, it is critical to characterize, measure, and quantify this exchange in the near-stream environment. However, GSI is notoriously difficult to evaluate because interactions are hidden and occur at spatially and temporally variable scales (Winter et al. 1998). In addition, the literature has employed inconsistent terminology to describe GSI.

Examples of GSI are demonstrated in Figure 1, which represents a general depiction of the sources of water to a stream in a watershed. Precipitation falling to the earth may become surface runoff to the stream or enter the subsurface ground water system. GSI includes the ground water and shallow subsurface flow that moves down gradient and discharges to the stream. GSI also encompasses stream water exiting and re-entering stream beds and banks through near-stream paths. The scales of these interactions are spatially and temporally variable and restoration will have a different impact on each.

To simplify the scale issue, this study employed a definition developed by Boulton et al. (1998) who separated GSI into three main scale categories; watershed, near-stream, and sediment scale GSI. Boulton et al. described watershed scale GSI as the regional perennial ground water flow to the stream shown in Figure 1. Watershed GSI occurs on the scale of miles and years and is typically defined as the base flow of a stream which is measured by stream gaging. At this scale, the ground water is assumed to discharge evenly to the stream with no variation along its length. As this discharge is a function of the watershed hydrologic setting, including ground water storage characteristics and climate, watershed GSI is typically not targeted and is unlikely to be modified in any significant fashion by stream restoration.

Near-stream GSI occurs on the scale of feet and days, as stream and ground water flows into and out of stream beds and banks (Figure 1). Near-stream GSI captures the spatial variability of the interaction along the length of a stream where reaches may be losing or gaining. In a losing reach, water moves from the stream into the bed and banks to ground water. In a gaining reach, ground water moves into the stream, thereby providing a portion of its flow. Stream restoration is highly likely to affect near-stream GSI, especially if it impacts the stream channel features, including stream depth, width, and bed and bank materials.

Sediment-scale GSI involves the small exchanges on the order of inches and minutes within the stream bed and banks. This interaction is a function of various factors including small changes in stream flow and stream bed structure (Castro and Hornberger, 1991; Savant et al., 1987). Stream restoration may greatly impact sediment-scale GSI but designing stream restorations to target these specific interactions may not be practical as they are difficult to maintain. Near-stream and sediment scale GSI are often referred to as hyporheic exchange, a lumped term that we will avoid using to prevent confusion.

For this study, near-stream GSI was of special interest because the exchange of surface and ground water in the stream bed and banks may be significantly impacted by stream restoration. Current methods available to characterize and measure near-stream GSI include stream and ground water level measurements, flow and temperature surveys, seepage measurements, numerical flow and heat modeling, and stream and subsurface tracer studies (Harvey and Wagner, 2000; Kalbus et al., 2006). These approaches have been used alone or in combination to measure and quantify GSI.

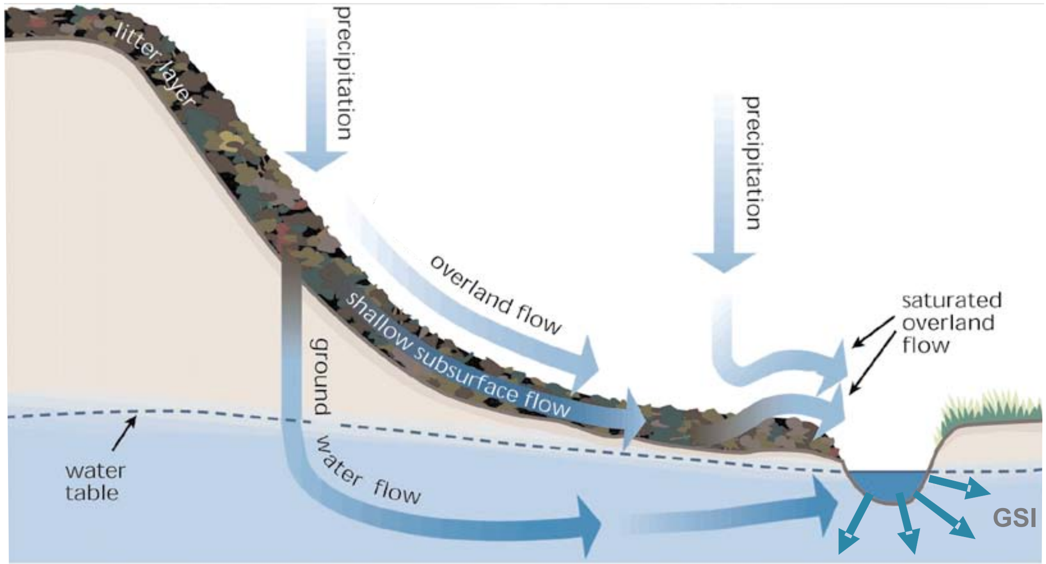

Figure 1. Scales of ground water surface water interaction (image adapted from Stream Corridor Restoration Handbook; FISWRG, 1998).

One set of techniques to quantify GSI employs ground water levels and stream flow measurements, usually coupled with ground water/stream tracer studies and analytical/numerical flow modeling. Bencala et al. (1984) and Bencala (1984) performed comprehensive tracer studies of streams to interpret the dynamic physical and chemical properties that control tracer transport in the stream and hyporheic zone. Harvey and Bencala (1993) were able to simulate and assess the impact of stream features on hyporheic GSI by measuring near-stream ground water levels and tracer studies. Wroblicky et al. (1998) also used water levels and tracer studies in transient numerical flow simulations to quantify the spatial and seasonal variation in reach scale GSI. Harvey et al. (1996) evaluated the reliability of tracer studies by testing their sensitivity to stream flow conditions. Choi and Harvey (2000) identified the need to address several storage zones in the stream to account for tracer behavior. Harvey and Wagner (2000) and Kalbus et al. (2006) described and summarized methods to quantify near-stream GSI.

Another set of techniques to quantify GSI uses stream and ground water temperature monitoring and heat modeling. Silliman and Booth (1993) and Constantz (1998) provided some of the first examples of the use of temperature measurements to identify losing and gaining portions of streams. Silliman et al. (1995) also provided mathematical formulations to quantify flux across the streambed for one-dimensional flow using measured temperatures. Conant (2004) used ground water levels and mapped streambed temperature to quantify stream bed GSI. Becker et al. (2004) quantified ground water discharge using stream flow measurements, stream temperature surveys and heat transport modeling of temperature gradients below the stream bed. Stonestrom and Constantz (2004) and Stonestrom and Constantz (2003) provide excellent descriptions of temperature measurement and modeling methods to quantify GSI.

Once GSI is measured and quantified, it may be possible to evaluate the factors that influence it and those that may be modified through stream restoration. Many studies have established the influence of stream geomorphology and geology on GSI along a stream reach (Savant et al., 1987; Castro and Hornberger, 1991; Eshelman et al., 1994; Fryar et al., 2000; Harvey and Bencala, 1993; Poole et al., 2006; Gooseff et al., 2006). For example, streams in high conductivity alluvial settings composed of cobbles and sands offer less resistance and therefore greater potential for GSI. Streams flowing through heavy clays would be expected to have less interaction. Highly incised streams in consolidated bed rock would likely experience less GSI than stream meandering through sandy point bars. Deep pools with low velocities will likely interact differently with the ground water system than swift flowing reaches. In addition, geomorphology and geology will affect the residence time in the stream sediments, thereby influencing biological interactions in the near stream environment. Longer residence times may allow sustained microbial activity such as denitrification. It is therefore, of interest to determine how geologic and geomorphologic characteristics of the stream influence hydrology and residence time.

3.0
Site Description

The stream selected for this study was Minebank Run (MBR), a second order stream located in a small watershed in the Piedmont physiographic region of Maryland in the south central section of Baltimore County (Figure 2). The headwaters of MBR are on the east side of Towson, MD and its outlet confluences with lower Gunpowder Falls, a major tributary of the Chesapeake Bay.

The choice of MBR was made after several reconnaissance trips with Baltimore Department of Environmental Protection and Resource Management (DEPRM) personnel to streams slated for restoration in Baltimore County. MBR had already undergone successful restoration of its headwaters in 1999 and its lower reaches were scheduled to be restored in 2004 and 2005. The unrestored reach possessed several characteristics that made it ideal for the before/after study, including a heavily degraded stream condition, a comprehensive geomorphic and riparian restoration design with significant manipulation of the stream channel and banks along the entire length of stream, a USGS stream gaging station, and convenient site access.

The MBR watershed covers 3.24 square miles and the stream itself is three miles in length (Figure 3). Stream channel slopes are <1 percent in most locations (Doheny et al., 2006). Relief varies from 100 to 300 ft in the watershed. There is about a 340 ft drop in elevation from the headwaters of MBR to its outlet at Gunpowder Falls. The watershed geology is composed of a complex series of crystalline rocks including the Setters formation, the Cockeysville Marble and the Loch Raven Schist (Doheny et al., 2006). Underlying this group is the Baltimore Gneiss. Maps of surface geology show that the crystalline rocks are overlain by alluvial deposits composed of cobbles, gravels, and sands (Crowley et al., 1976). Some clay deposits were noted in the upper reaches of the watershed. The stream flows through exposed crystalline rocks in the upper reaches and unconsolidated deposits of colluvium and alluvium in lower reaches.

MBR is a classic example of stream that has undergone massive changes as a consequence of urban development in the watershed. When settled, the watershed was historically agricultural, but is now about 80% urbanized

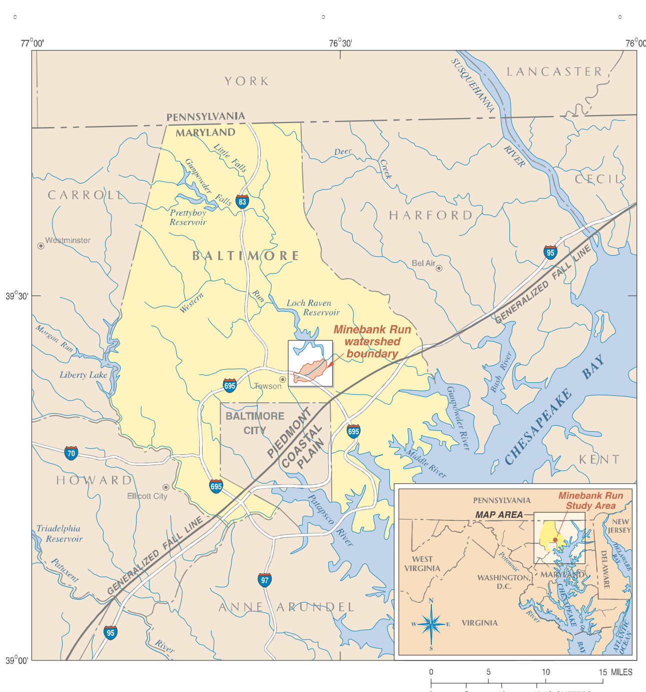

Figure 2. Minebank Run watershed geographic location (adapted from "Watershed Characteristics and Pre-Restoration Surface-Water Hydrology of Minebank Run, Baltimore County, Maryland, Water Years 2002–04," Doheny et al., 2006).

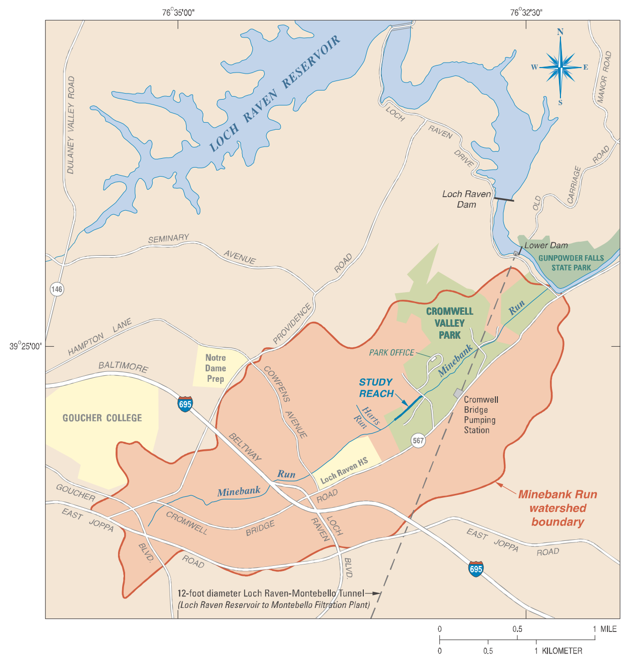

Figure 3. Minebank Run Watershed (adapted from “Watershed Characteristics and Pre-Restoration Surface-Water Hydrology of Minebank Run, Baltimore County, Maryland, Water Years 2002–04,” Doheny et al., 2006).

with over 25% impervious surfaces (Doheny et al, 2006). The stream has several runoff outfalls along its length including one from the I-95 corridor. The combination of fairly large stream slopes, significant relief and runoff from impervious surfaces causes the stream to experience pronounced flashy behavior during storm events (Doheny et al, 2006). MBR has experienced many of the geomorphic changes expected with flashy urban flows and is deeply incised with little to no riparian buffer. This incision has exposed infrastructure such as sewer lines and caused extensive bank failure, threatening personal property (Figure 4). In addition, this incision contributes to heavy sediment loads and diminished ecological condition.

As a consequence of its poor condition and threats to property and infrastructure, Minebank Run was one of the streams targeted by DEPRM for restoration. A detailed restoration study was made of the stream and comprehensive restoration designs for the entire stream were prepared. In 1999, about 1.5 miles of MBR from the headwaters downstream were restored. The remainder of the stream was scheduled to be restored in 2004. The headwater restoration included Natural Stream Channel Design (NSCD) techniques such as bank armoring with rip-rap, step pools, and meanders (Rosgen, 1996). Riparian restoration included geotextile bank stabilization and substantial riparian revegetation. Although these efforts were intended solely to achieve geomorphic stability to protect infrastructure and property, we speculated that restoration may influence GSI and water quality of MBR.

Figure 4. Incision and infrastructure exposure at Minebank Run before restoration.

4.0 Methods

Study design and site characterization

In the summer of 2001, a short section of the unrestored reach of MBR in Cromwell Valley Park, Towson, MD was selected for intensive study (Figure 5). A continuous stream gauge, 01583980 Minebank Run at Loch Raven, MD, had already been installed in the park by the USGS at MBR in 2000 (Figure 5). A new continuous stream gage, 0158397967 Minebank Run near Glen Arm, MD, was installed upstream of the study reach (Figure 5). A continuous rain gage, 392449076331100 Minebank Run Rain Gage, was also installed to provide a real time precipitation record (Figure 5).

In the Fall 2001, the locations of the three transects were chosen for intensive study of the stream before restoration (Figure 5). These locations were selected based on the unrestored condition of the reach and the restoration plans (Figure 6). The intent was to position transects in locations where degraded stream features would undergo a specific restoration technique. The study was designed to measure baseline conditions in the degraded stream condition and then measure the response to the restoration. To that end, the geomorphology of Minebank Run was evaluated by the USGS and published in a recent report (Doheny et al., 2007).

Transect 1, was located at a deeply incised pool where a new stream channel was to be created (Figure 5). Transect 2, was positioned 237 ft upstream of Transect 1 and placed across an incised narrow riffle and point bar which was to be armored and raised (Figure 5). Transect 3, was positioned 148 ft upstream of Transect 2 and located in a flat shallow terrace section which was to undergo little modification (Figure 5). An ancillary, 3-piezometer nest was placed in the stream channel approximately 100 ft downstream of Transect 1 was occasionally sampled for hydrology.

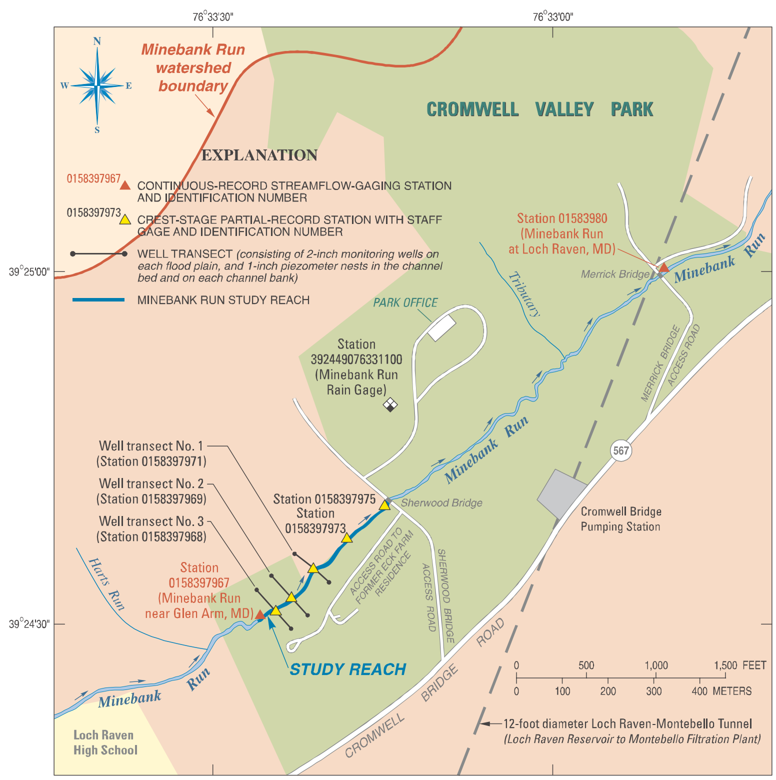

Figure 5. Location of the Minebank Run Study Reach in Cromwell Valley Park (adapted from "Watershed Characteristics and Pre-Restoration Surface-Water Hydrology of Minebank Run, Baltimore County, Maryland, Water Years 2002–04," Doheny et al., 2006).

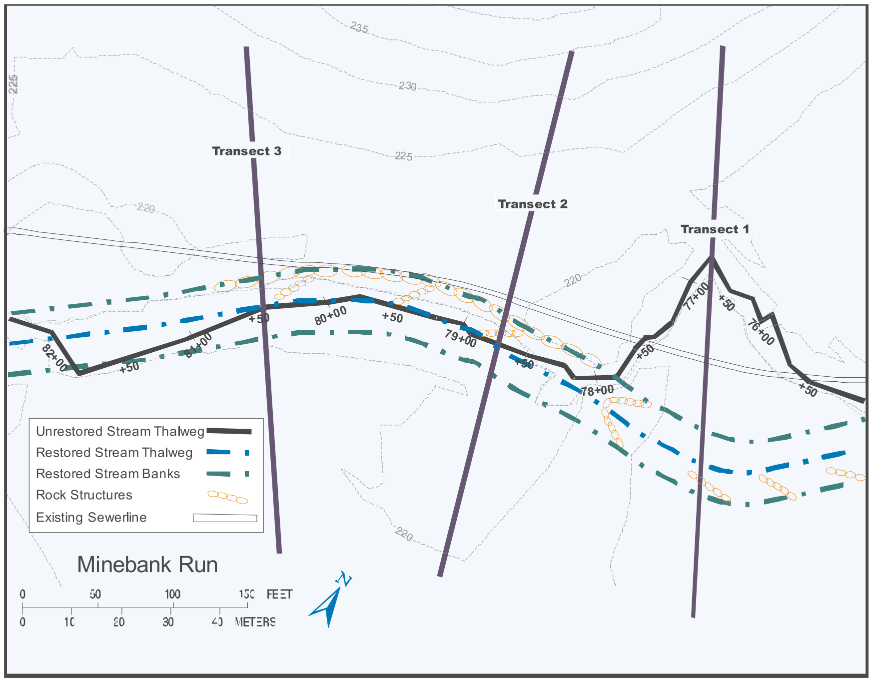

Figure 6. Location of monitoring well transects in relation to restoration design (Figure courtesy of Maryland Department of Environmental Protection and Resource Management).

In November 2001, an EPA field team installed the monitoring wells and piezometers at each transect at the site. The transect monitoring design (Figure 7) was composed of paired two-inch diameter monitoring wells in the floodplain and nests of three piezometers in the stream bed and banks. This design was intended to capture the spatial and temporal scales of near-stream GSI and the larger regional ground water flow system. For each transect, nests of three piezometers were installed in the stream bed and banks using a Simco™ direct push rig. The piezometers were one-inch diameter stainless steel with six inch long wire-wound screens with 0.01 inch mesh (Figure 8). Piezometer nests installed in the stream bed were driven to depths of approximately two, four, and six feet below ground surface in the thalweg. Next, piezometer nests were installed on each banks close to the stream edge. Bank piezometers were driven to depth to match the same mean sea level elevations of the piezometers in the stream. Throughout this report, the piezometers in the stream bed and banks will be identified as shallow, medium, and deep.

In addition to the piezometer nests, two-inch PVC cased monitoring wells with five-foot screens were installed in the floodplain near the stream. Pairs of wells were placed approximately fifty feet perpendicularly from the stream thalweg. One well of each pair was installed just below the water table and the second well of each pair was installed to the point of bedrock refusal. Single monitoring wells were placed approximately one hundred feet from the stream thalweg. After installation, all piezometers and monitoring wells were developed to ensure proper ground water sampling. The piezometer and monitoring well locations and elevations were surveyed using standard line of sight methods. The aerial map shows the georeferenced locations of the monitoring wells and piezometer nests (Figure 9).

As the monitoring wells were installed, 5 cm diameter (ID) continuous cores were collected to refusal using a Geoprobe™ direct drive system. The cores were characterized to describe the lithology. In July 2004, additional cores were collected at all of the stream bed and bank piezometer nests and characterized. Slug testing was done at all of the piezometers using falling and rising head tests to determine conductivity (Bouwer and Rice, 1976 and Bouwer, 1989).

Water levels were measured at all of the wells and piezometers approximately every two weeks starting in January 2002. To capture the continuous time scale, many of the piezometer nests and some of the floodplain wells were fitted with Solinst™ Model 3001 data loggers in March 2002 to measure temperature and ground water elevation every five minutes. These data loggers were downloaded every three months. Ground water data were collected until the wells were removed for the restoration in July 2004.

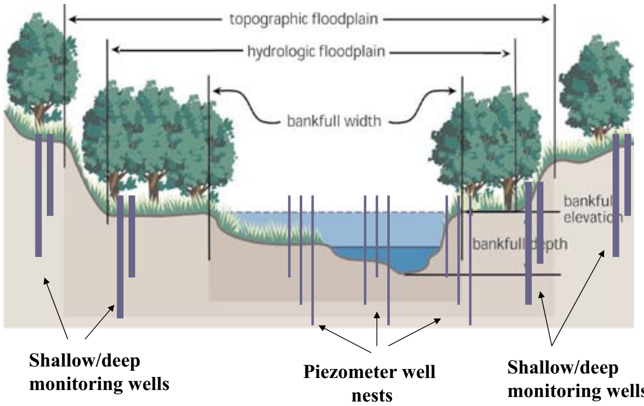

Figure 7. Transect monitoring well network design. Distances not to scale (image adapted from Stream Corridor Restoration Handbook, FISWRG, 1998).

Figure 8. Stainless steel piezometer used in piezometer nests.

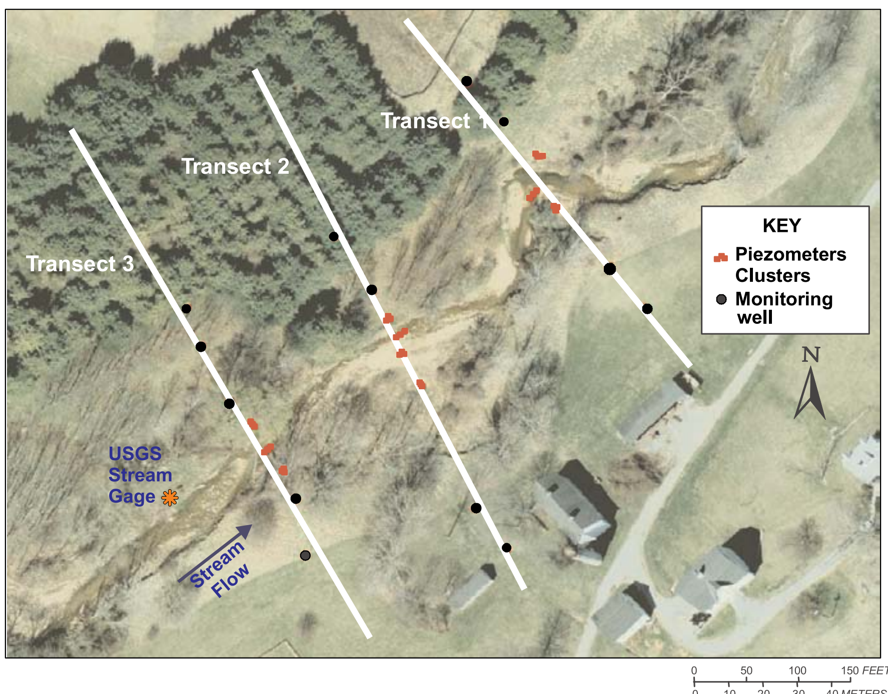

Figure 9. Location of monitoring wells and piezometer nests Minebank Run Study reach.

All of the site characterization and ground water level data were measured in English units of feet for increased resolution at the small scales involved in this study. All of the calculations were also done in units of feet to maintain consistency. Data and calculations were reviewed and stored in electronic form in databases or MS Excel spreadsheets according to the approved EPA Quality Assurance Project Plan. The USGS stream and rain gage data for MBR are available on line http://waterdata.usgs.gov/nwis/.

Ground water-surface water interaction analysis

One factor known to impact near-stream GSI is the geomorphological setting, the physical relationship between the stream and the ground surface. The stream geomorphological setting at each of the transects was evaluated using field observations, stream profiles, and stream velocity. The stream profile defines the cross sectional area at each transect which, in turn, determines the channel velocity for a given stream flow rate. The flow velocity through each transect was evaluated to determine if geomorphology created a stream hydrologic setting that influenced the GSI.

Another factor known to influence near-stream GSI is the geological setting. Geological setting is important because the lithology provides the stream bed location relative to the geologic layers. Geological setting also defines the conductivity of the sediments, a measure of the resistance to ground water-surface water exchange in the near steam sediments, with low conductivities limiting exchange and high conductivities enhancing exchange. If a stream is situated in highly conductive alluvial sediments such as sands and gravels, water will exchange easily in these zones. If fractures or other preferential flow features are present, GSI may be enhanced. If a stream is in silt, clays or incising into rock, near-stream GSI is limited by these non-conductive sediments. The geologic setting at MBR was defined using cores to develop lithologic cross sections and slug testing to assess hydraulic conductivity (Bouwer and Rice, 1976 and Bouwer, 1989).

To describe the watershed scale GSI at MBR, the regional stream and ground water hydrology were assessed. The USGS evaluated the MBR site pre-restoration stream hydrology data and published a comprehensive surface water hydrology report (Doheny, et al., 2006). The regional ground water flow system was defined using traditional horizontal ground water equipotential contours across the site developed from the biweekly ground water level data. These contours provided the ground water flow magnitude and direction across the site and gave some insight into the interaction of the regional ground water flow with the stream.

The near-stream GSI on the scale of tens of feet was demonstrated at each of the transects using vertical equipotential contours from piezometer water levels measured biweekly (Figure 10). These contours allowed the potential gradients under each of the stream transects to be visualized and the flow directions inferred. Although numerous methods were available to quantify GSI, it was immediately apparent from the data that most were not suited to the situation at MBR. Ground water equipotentials evaluated both seasonally and for the ground water high and low during the study at each of the transects demonstrated a complex flow system that was spatially and temporally variable. Traditional tracer and modeling techniques (Harvey and Bencala 1993) typically assume steady state conditions and were not suitable to capture the spatial and temporal variation observed in the near-stream GSI at Minebank Run. Tracer tests would need to be run each time the flow field varied to capture its unique signature. Flow and temperature modeling was also impractical as the models require many boundary and hydrologic condition assumptions and therefore, the true transient nature of the near-stream GSI would be nearly impossible to reproduce.

An objective of the study was to develop a transparent and effective method to quantify the GSI before and after restoration. We decided to employ a simple hydrologic flow analysis which used measured water levels from the piezometer nests. The vertical and horizontal gradients were calculated from these measured values at each of the transects. These gradients were used in Darcy's

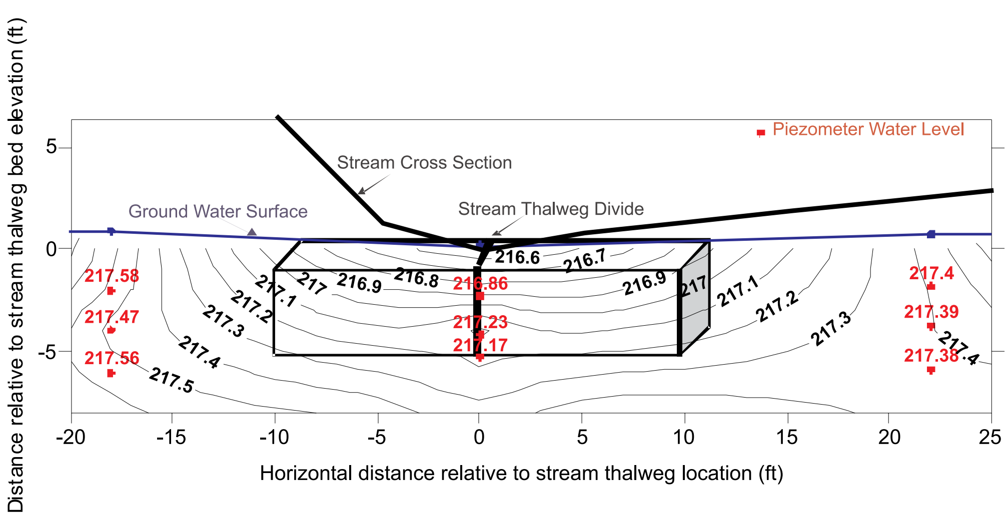

Figure 10. Example vertical equipotential stream cross section with left bank and right bank compartments on either side of the stream thalweg divide.

law to determine the flow at each of the transects over time by applying some simple assumptions. The first assumption was that the thalweg of the stream acts as a ground water divide at shallow depths near the stream bed such that flow on one side of the stream is not influenced by the flow on the other. In small headwater streams with partial penetration and perennial base flow such as MBR, this approach was strongly supported by near-stream piezometer temperature and ground water level measurements at the site. This allowed the flow system to be split into a left and a right bank compartment on either side of the stream thalweg divide as shown in Figure 10.

The second assumption was the ground water seepage, q, in each compartment can be represented by one constant linear vector. This vector was determined by calculating the vertical and horizontal gradients in each compartment separately based on the water levels measured in the stream bed and bank piezometers and applying Darcy's law:

$$q = -k\left(\frac{\partial h}{\partial x}\bar{i} + \frac{\partial h}{\partial z}\bar{k}\right) \qquad (1)$$

where k was the hydraulic conductivity measured by slug tests at the site. The horizontal gradient, $\partial h/\partial x$, was calculated for each bank using the difference between the piezometer water levels in the stream bank and stream beds. Concurrently, the vertical gradient, $\partial h/\partial z$, was determined using the water levels in stream bed piezometers. A negative horizontal or vertical gradient was defined as flow in toward the stream. The resultant seepage vector through the compartment on either side of the stream center line was then defined by determining its magnitude, $\partial h/\partial s$, , and its direction counterclockwise from horizontal, θ, using equations 2 and 3.

$$\left|\frac{\partial h}{\partial s}\right| = \sqrt{\left[\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial z}\right)^2\right]} \qquad (2)$$

$$\tan\theta = \left[\frac{\partial h}{\partial z}\Big/\frac{\partial h}{\partial x}\right] \qquad (3)$$

Once the magnitude of the seepage vector and its direction were known, it was possible to calculate the residence time, t, along a path line, s, through the compartment:

$$t = s/(q/n) \qquad (4)$$

where n is the porosity which was calculated from core measured bulk densities at each transect. A volumetric flow for the compartment was also determined:

$$Q = qA \qquad (5)$$

where A is the unit cross sectional area perpendicular to the flow vector.

The GSI flow rates for each transect were calculated on several dates to demonstrate the spatial and temporal variation in the near-stream GSI at MBR. To verify the results, the GSI rates were compared to the measured stream flow rates to assess if they supported the losing and gaining nature of the stream along the reach. In addition, the continuous record of temperature obtained from the Solinst™ Model 3001 data loggers installed in the shallow and medium depth piezometers in the stream beds was evaluated to verify the losing or gaining nature of the GSI at each stream transect using the methods of Stonestrom and Constantz (2003).

MBR experienced several storm surges during the study. The impact of these events was captured by the continuous data loggers which measured level and temperature every five minutes. The continuous temperature record during the storm surge in the piezometers was evaluated using the methods of Stonestrom and Constantz (2003) to help assess the residence time of the stream water as the surge drove water into the stream bed sediments. Water levels in the stream bed and bank piezometers were plotted to show how one particular storm surge event influenced GSI. Darcy's law was applied as a first approximation to make an estimate of the storm surge flow rates into the stream bed which varied continuously over time. The application of Darcy's law under these conditions was not rigorous. Typically one may use the gradients from these measurements and Darcy's law to assess the seepage velocity into the stream bed as was done for the vertical equipotentials for the bi-weekly water level data. However in the case of a storm surge, the hydraulic gradient in the stream bed and banks is continuously changing as a function of time so flow is not steady. The flow is also moving at high velocity, which means it is turbulent, with $Re>1$. Therefore Darcy's law is not truly applicable as it assumes steady laminar flow with a Reynolds number, $Re<1$. More research will be needed to develop the appropriate equations to truly evaluate this unsteady, turbulent flow system.

5.0
Results

Stream geomorphology

At MBR, transects were strategically placed so the unrestored stream physical features could be used to provide insights into the impact of stream geomorphology on stream flow behavior and the pre-restoration GSI. Transect 1 was located at a deep pool with severe incision on the left bank (top half of picture) and a depositional point bar on the right bank (lower half of picture) (Figure 11). Transect 2 was located at a shallow, narrow riffle with an incised left bank and a point bar on the right bank (Figure 12). Transect 3 was located at a shallow, wide terrace (Figure 13). The piezometer nests can be seen in the stream bed and banks (Figure 11). The stream bed piezometers were replaced flush with the stream after a storm event bent them (Figure 13).

Figure 11. Transect 1 at beginning of study in Fall 2001.

Figure 12. Transect 2 at beginning of study in Fall 2001.

Figure 13. Transect 3 at beginning of study in Fall 2001.

The mean sea level ground surface elevation of the stream profiles at Transects 1, 2, and 3 at the beginning of the study is shown in Figure 14. At Transect 1, stream velocity at base flow was measured as 0.19 ft/sec. This low velocity was a consequence of incision at this transect which had created a deep, wide pool with large cross sectional area. This low velocity created a relatively static setting for interaction with the ground water in the stream bed and banks. At Transect 2, the stream flowed through a narrow shallow cross section with a measured base flow stream velocity of 0.66 ft/sec. This high velocity created a dynamic setting for interaction with the underlying ground water. At Transect 3, flow moved through a large flat cross sectional area defined by the stream terrace. The measured base flow stream velocity was 0.29 ft/sec and created a static environment for GSI.

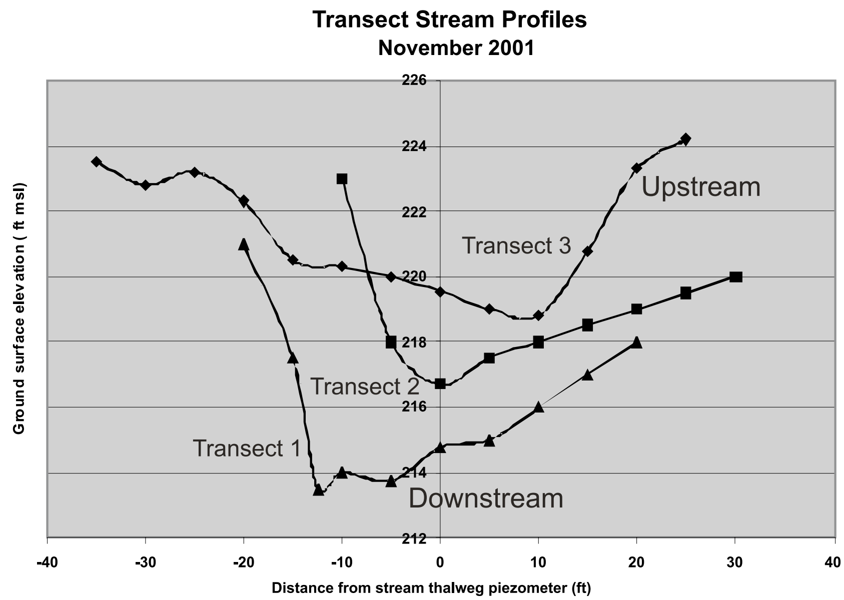

Figure 14. Ground surface elevation cross sections at Transects 1, 2, and 3 at beginning of study.

Stream geological setting

At MBR, cores were collected and characterized to create several cross sections to define the geological setting (Figure 15). Cross section A-A' was defined along the stream thalweg and shows the lithology described by the core holes near the deep stream bed piezometers, 146, 149 and 153 (Figure 16). The lithology directly under the stream was gravelly clay ranging from five to ten feet thick, underlain by a clay layer. A thick layer of poorly sorted sand was found under the clay. Sediment cores did not reach bed rock at these sites.

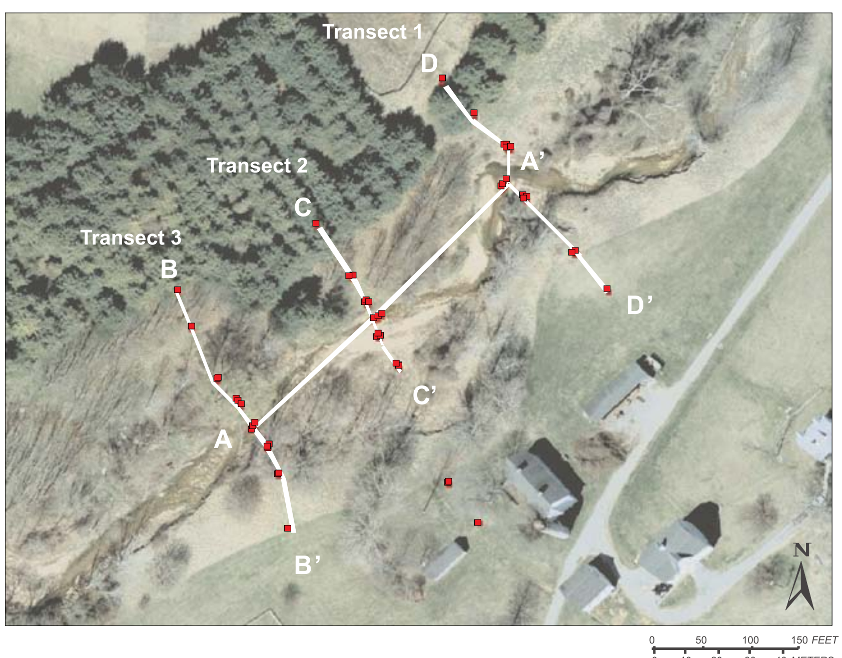

Figure 15. Geological cross section lines for Minebank Run study site.

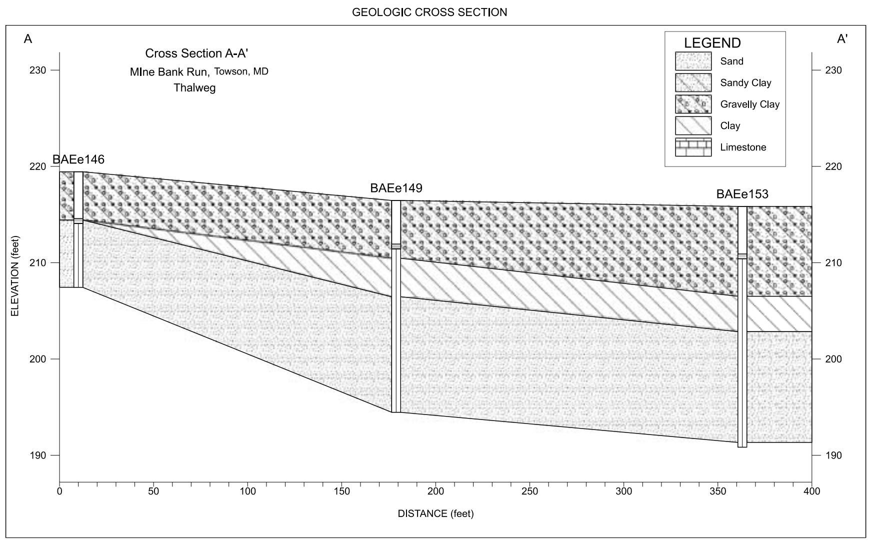

Figure 16. Minebank Run Thalweg Cross Section A-A'.

Cross section B-B' was constructed based on cores extracted along Transect 3 (Figure 17). Piezometer 146 was in the thalweg of the stream, 162 was in the left bank and 157 was in the right bank. The other cores were located at the floodplain monitoring wells. The lithology on the left side of the stream was a top layer of sandy clay underlain by a gravelly clay that varied from 3-6 feet thick. On the right side of the stream, the top layer was silty clay underlain by gravelly clay near the stream bed and sandy clay farther away from the stream. The clay layer was only found on the right side of the stream and was a few feet thick. A continuous layer of poorly sorted sand was encountered under both sides of the stream. Limestone bedrock was encountered on both sides of the stream but not reached directly under the stream.

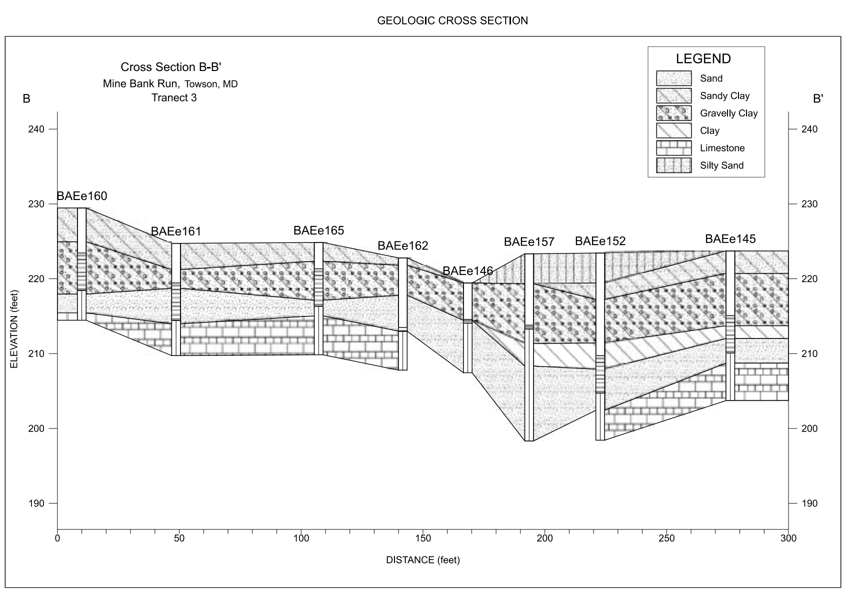

Figure 17. Transect 3 Cross Section B-B'.

Cross section C-C' was constructed from cores collected along Transect 2 (Figure 18). Piezometer 149 was in the thalweg of the stream, 167 was located in the left bank, and 171 was in the right bank. On the left side of the stream, the lithology was sandy clay underlain by the gravelly clay. On the right side of the stream, the top layer was part of a point bar composed of gravels and underlain by gravelly clay. The clay layer was only encountered under the right side of the stream. A thick continuous layer of poorly sorted sand was encountered under both sides of the stream. Limestone bedrock was encountered on the left side of the stream but was not reached directly under the stream or on the right side.

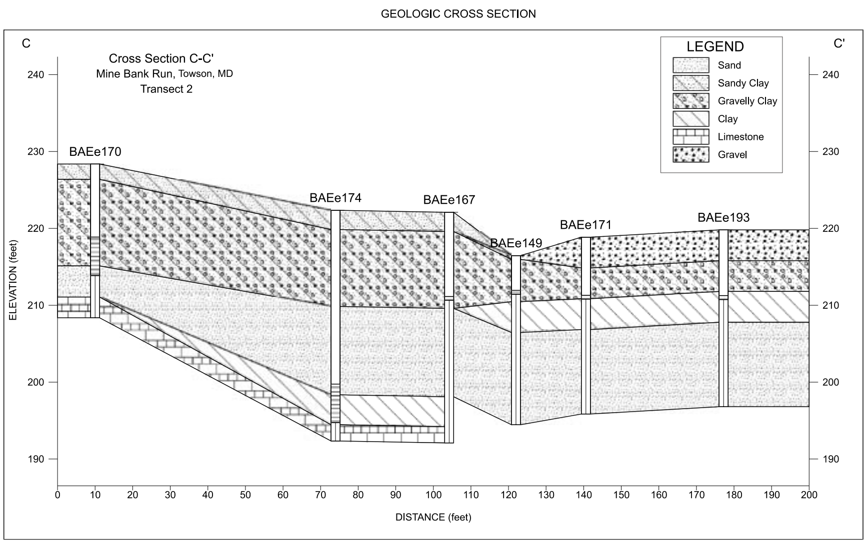

Figure 18. Transect 2 Cross Section C-C'.

Cross section D-D' was constructed from the cores collected along Transect 1 (Figure 19). Piezometer 153 was in the thalweg of the stream and piezometers 176 and 179 were located in the left and right bank, respectively. Both sides of the stream exhibited a top layer of sandy clay underlain by the gravelly clay. The gravelly clay was about twice as thick on the right side of the stream as on the left. The clay layer was evident under the right bank of the stream but disappeared on the left bank. A thick continuous layer of poorly sorted sand was encountered under both sides of the stream. The limestone bedrock, located at shallow depths under the left side dipped steeply before flattening out under the stream and right hand side.

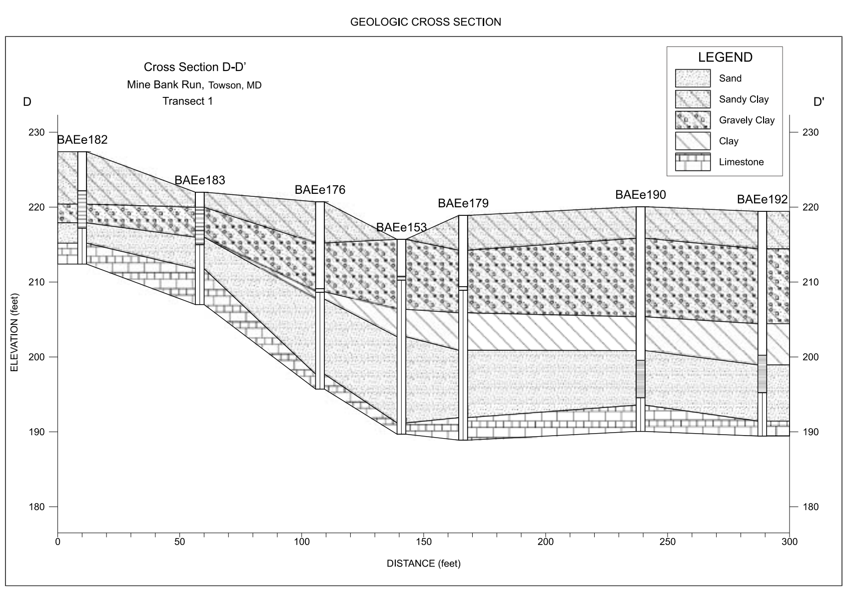

Figure 19. Transect 1 Cross Section D-D'.

These cross sections demonstrate that the stream and floodplain were composed of thick sections of gravelly clay, clay, and sand underlain by limestone bedrock. The gravelly clay and sands were found on both sides of the stream and the clay was located on the right side in the floodplain. The limestone bedrock was encountered at depth and cores indicated it was weathered and fractured. However, as the limestone was so removed from the stream bed, that the possibility of preferential flow from the bedrock fractures to the stream was dismissed.

Before this geological characterization, the MBR watershed was described as being composed of strictly heterogeneous alluvial deposits ranging from cobbles, gravels and sands which were underlain by limestone bedrock. A search was made to determine if a manmade dam was used in the watershed to account for the clay layers (Walter and Merritts 2008), but no historical evidence for such a structure could be located. However, historical records, including maps and photographs, were discovered of extensive iron mining operations active until the 1800s that stripped topsoil throughout the watershed (Dorothy Merritts, personal communication). This type of mining involved digging shallow pits along the watershed, excavating a shipping canal parallel to the current stream thalweg, and constructing limestone kilns along the stream channel. Slag from historic smelting operations can be seen in the stream channel today and some unusual sediment layers observed in incised banks of Minebank Run are probably derived from the intensive mining activity of this era (Dorothy Merritts, personal communication). Based on this information, the geological setting for Minebank Run has clearly been very disturbed.

To complete the description of the geological setting and interpret its impact on GSI, conductivity, k, was measured using slug tests at each of the transect piezometers at MBR. The results are shown in Tables 1, 2 and 3, respectively. The measured values were in general agreement with the geological characterizations of the cores in the stream bed and banks. At Transect 1, the piezometers were screened in a heterogeneous gravelly clay and the conductivity ranged from 0.01 to 310.0 ft/day. The low values in the deeper piezometers indicate they were in a clay layer whereas the medium depth stream bed and right bank piezometers were most likely screened in cobble layer, perhaps part of an abandoned channel not clearly identifiable from the cores. At Transect 2, the conductivities were also representative of a heterogeneous gravelly clay but had less of a range from 0.07- 9.2 ft/day. At Transect 3, the conductivities were consistent and higher because the piezometers were screened in the sand, with the exception of one deep piezometer in the clay. The range was 10.0-58.0 ft/day.

Table 1. Transect 1 Piezometer Conductivity

Name	**Location**	**Estimated K (ft/day)**
BAEe176	T1 LB deep	0.01
BAEe177	T1 LB medium	6.90
BAEe178	T1 LB shallow	3.70
BAEe153	T1 Stream deep	0.14
BAEe154	T1 Stream medium	310.00
BAEe155	T1 Stream shallow	ND
BAEe179	T1 RB deep	0.89
BAEe180	T1 RB medium	170.00
BAEe181	T1 RB shallow	19.00

Table 2. Transect 2 Piezometer Conductivity

Name	**Location**	**Estimated K (ft/day)**
BAEe167	T2 LB deep	8.00
BAEe168	T2 LB medium	9.20
BAEe169	T2 LB shallow	0.07
BAEe149	T2 Stream deep	2.70
BAEe150	T2 Stream medium	5.10
BAEe151	T2 Stream shallow	ND
BAEe171	T2 RB deep	1.80
BAEe172	T2 RB medium	0.41
BAEe173	T2 RB shallow	2.30

Table 3. Transect 3 Piezometer Conductivity

Name	**Location**	**Estimated K (ft/day)**
BAEe162	T3 LB deep	46.00
BAEe163	T3 LB medium	38.00
BAEe164	T3 LB shallow	49.00
BAEe146	T3 Stream deep	0.14
BAEe147	T3 Stream medium	14.00
BAEe148	T3 Stream shallow	47.00
BAEe157	T3 RB deep	58.00
BAEe158	T3 RB medium	10.00
BAEe159	T3 RB shallow	32.00

The conductivity of the sediments in the stream bed and banks have significant implications for GSI. The magnitude of ground water flow in the bed and banks, q, is directly proportional to the magnitude of the conductivity, k, and the hydraulic gradient, h, as defined in Darcy's law for flow in saturated sediments, $q=kh$. For example, Transect 1 has high conductivities in the shallow- and medium-depth stream bed and in the right bank piezometers suggesting higher exchange of ground water and surface water in response to the hydraulic gradient created by the stream and regional ground water elevations.

The left bank at Transect 1 had lower conductivity, suggesting lower exchange rates under similar stream flow rates. All of the deep piezometers at Transect 1 had low conductivity, which suggested sediments at this depth would limit ground water and surface water exchange. Conductivity at Transect 2 was homogeneous throughout all locations and depths, suggesting homogeneous ground water exchange throughout all depths across the channel. Transect 3, situated in sands with conductivity an order of magnitude higher than the other transects, would be expected to have greater ground water-surface water exchange in response to changes in the stream or regional ground water levels.

Regional surface water and ground water hydrology

The regional surface water hydrology of Minebank Run was evaluated by the USGS and published in a recent report (Doheny et al., 2006). According to the report, the average annual precipitation for the Baltimore region is 42 inches. Water year 2002 was considered a drought with an annual precipitation of 32.95 inches. Water year 2003 was a wet year with a total precipitation of 64.19 inches. In water year 2002, the low mean annual discharge for MBR at the Glen Arm, MD, stream gage just above Transect 3 was measured as 1.15 ft^3/sec. In water year 2003, the high mean annual discharge of 4.34 ft^3/sec was reported at this same gage.

Using these values, it was possible to estimate a range of the mean amount of ground water discharged to the stream on a regional scale each day during years 2002 and 2003 of this study. Assuming that stream flow is entirely base flow, a mean discharge of 1.15 ft^3/sec in 2002 translates into about 99,360 ft^3/day of ground water entering the stream above the gage. For 2003, the annual mean discharge of 4.34 ft^3/sec translates into 374,976 ft^3/day of ground water entering the stream which represents a small portion of the ground water storage in the 2.1 square miles drained above the gage. At the watershed scale, assuming that this discharge is equally distributed along the length of the stream (ca. two miles for this gage), discharge ranges from 0.0036 ft^3/day/ft in 2002 to 0.0135 ft^3/day/ft in 2003.

These data demonstrate that little of the total ground water enters the stream as base flow. Because MBR only partially penetrates the thick sediments under the thalweg as demonstrated in the geological cross sections, the stream intercepts little ground water. The majority of ground water moves slowly at depth down the valley under the stream with very little interaction with the stream because the ground water and surface water are not defined by the same boundary.

This minimal interaction between the ground water and stream system revealed by the stream hydrology at the watershed scale can also be seen in the ground water hydrology at MBR. Figure 20 displays the horizontal equipotentials derived from the ground water level measurements for each of the transects at the beginning of the study on March 22, 2002 for a 400 x 400 ft region around the stream reach. These equipotentials show that ground water flow moves from roughly west to east across the study site. The gradient ranges from 2.0 - 4.0 ft/100 ft. With an estimated average hydraulic conductivity of 20 ft/day, this translates into a ground water seepage velocity of 0.4 - 0.8 ft/day. The equipotentials on March 22, 2002 are not clearly perturbed by the stream, which means that minimal ground water was moving into the stream. These data are corroborated by the stream gage flow of only 0.87 ft^3/sec on this date.

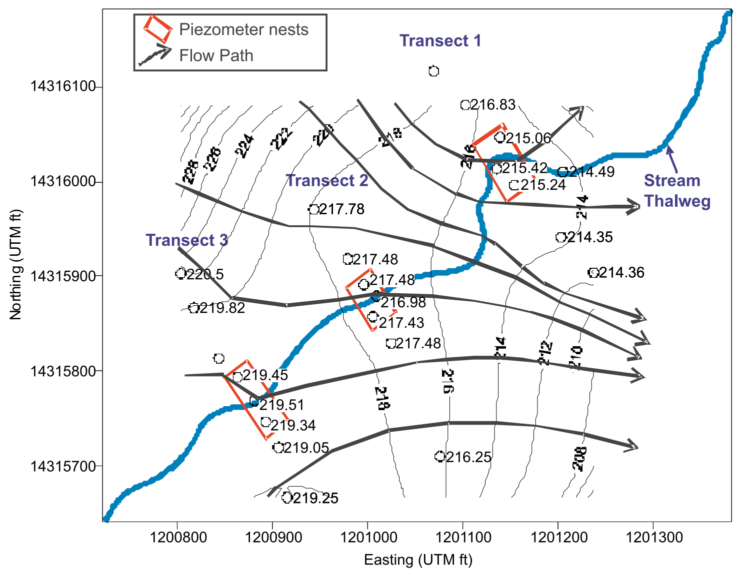

Figure 20. Regional ground water equipotentials on March 22, 2002.

In the summer of 2002, MBR experienced a severe drought. Figure 21 displays the equipotentials on August 22, 2002 for the ground water low created by the drought. The flow was still from west to east. The gaged stream flow for this date was 0.04 ft^3/sec. During this time, the stream ceased to flow at Transects 1 and 2 and stream water began entering the ground water system as recharge due to dropping ground water levels. As a consequence, equipotentials show the complete lack of interaction of the ground water with the stream.

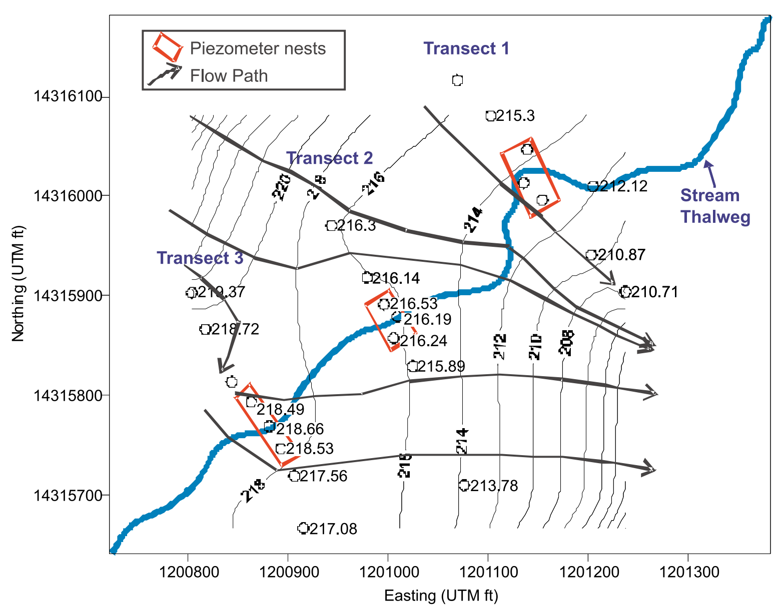

Figure 21. Regional ground water equipotentials on August 22, 2002.

In 2003, the MBR watershed received high rainfall amounts. In response to this recharge, a ground water level high was recorded on September 23, 2003 (Figure 22). The stream gage reflected this event with a recorded flow of 7.7 ft^3/sec. The regional ground water equipotentials, which clearly show the influence of the stream, are strongly distorted by stream interaction at both Transect 1 and Transect 3. The stream was acting as the drain for the additional recharge.

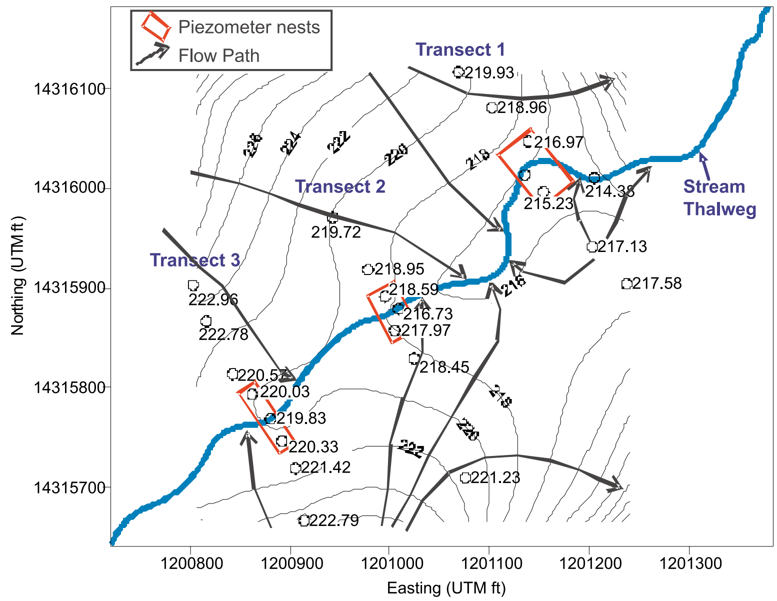

Figure 22. Regional ground water equipotentials on September 23, 2003.

These equipotentials demonstrate the temporal variability of the ground water levels and stream flow. The ground water levels varied greatly over time at the site, with water levels at some of the monitoring wells differing by more than seven feet from the low to the high (Table 4). The equipotentials also capture the spatial variability in the ground water levels. The water level variation in specific wells increases with increasing distance from the stream; wells farthest from the stream showed the greatest variation in water level while wells close to the stream maintained a smaller range.

Table 4. Comparison of ground water levels on dates of March 22, 2002, August 22, 2002, and September 23, 2003

Name	Location	3/22/2002 msl (ft)	8/22/2002 msl (ft)	9/23/2003 msl (ft)	High vs. Low msl (ft)
BAEe182	T1 MW 100 ft Left bank	NA	NA	219.93	NA
BAEe183	T1 MW 50 ft Left bank	216.83	215.30	218.96	3.66
BAEe178	T1 Left bank shallow	215.06	NA	216.97	NA
BAEe155	T1 Stream shallow	215.42	NA	NA	NA
BAEe186	T1 Riffle shallow	214.49	212.12	214.38	2.26
BAEe181	T1 Right bank shallow	215.24	NA	215.23	NA
BAEe191	T1 MW 50 ft Right bank	214.35	210.87	217.13	6.26
BAEe192	T1 MW 100 ft Right bank	214.36	210.71	217.58	6.87
BAEe170	T2 MW 100 ft Left bank	217.78	216.30	219.72	3.42
BAEe175	T2 MW 50 ft Left bank	217.48	216.14	218.95	2.81
BAEe169	T2 Leftbank shallow	217.48	216.53	218.59	2.06
BAEe151	T2 Stream shallow	216.98	216.19	216.73	0.54
BAEe173	T2 Right bank shallow	217.43	216.24	217.97	1.73
BAEe195	T2 Point bar shallow	217.48	215.89	218.45	2.56
BAEe188	T2 MW 180 ft Right bank	216.25	213.78	221.23	7.45
BAEe161	T3 MW 110 ft Left bank	219.82	218.72	222.78	4.06
BAEe160	T3 MW 150 ft Left bank	220.50	219.37	222.96	3.59
BAEe 166	T3 MW 50 ft Left bank	NA	NA	220.57	NA
BAEe164	T3 Left bank shallow	219.45	218.49	220.03	1.54
BAEe148	T3 Stream shallow	219.51	218.66	219.83	1.17
BAEe159	T3 Right bank shallow	219.34	218.53	220.33	1.80
BAEe156	T3 MW 50 ft Right bank	219.05	217.56	221.42	3.86
BAEe145	T3 MW 100 ft Right bank	219.25	217.08	222.79	5.71

Characterization of Near-Stream Ground Water-Surface Water Interaction

Once the geomorphology, geology, stream and ground water hydrology for MBR were described, the near-stream GSI was characterized. Vertical equipotential contours were created at each of the transects using measured piezometer-nest water levels for several dates to show the gradients under each of the stream transects at a scale in tens of feet. The equipotentials were drawn using an automatic contouring program for the dates of March 22, 2002, June 24, 2002, August 22, 2002, September 30, 2002, December 17, 2002 and September 23, 2003. These dates were selected to show seasonal variation and capture the GSI on the ground water low observed on August 22, 2002 and the ground water high on September 23, 2003. The gaged stream flow on these dates was 0.87, 0.35, 0.04, 0.12, 1.7, and 7.7 ft^3/sec, respectively. For all vertical equipotential figures, the black, solid line represents the stream bed profile at the transects in Fall 2001. The blue line represents the ground water level surface based on the shallow piezometer measurements (e.g. Figure 23). Ground water level is drawn across the stream for reference, but it does not represent actual stream water level which is a function of other factors besides ground water level. Note that the automatic contouring can create artifacts from edge effects outside the data points which should be ignored. Flow is from high to low equipotential.

Transect 1 was a deep incised pool with a slow base flow velocity and high conductivity. These features would suggest it would experience good exchange with the ground water system. Figures 23 to 28 show vertical ground water equipotentials under Transect 1 for select dates. The March 22, 2002 equipotentials indicate flow was moving from the stream into the bed and banks, demonstrating that the stream was losing water. The situation was the same for June 24, 2002 but the gradients were greater. These data suggest that water level in the pool was sufficient relative to the ground water to allow stream water to move continuously into the stream bed and banks. Near the height of the drought on August 22, 2002, the pool dried up and the water levels in the piezometers dropped below the shallow stream bed and bank piezometers. Flow then moved under the bed, down gradient, and parallel to the stream as part of the larger regional ground water flow system. Therefore, ground water was not interacting with surface water at this time. On September 30, 2002, ground water levels had risen above the stream and there was once more interaction between ground and surface water. Consequently, stream flow moved downward and outward to the left bank. During the ground water high on September 23, 2003, Transect 1 flowed from the left bank under the stream to the right bank. The stream bed shallow piezometer was lost in a storm and could not be used to create these contours. Although the ground water levels had risen, the stream depth in the pool was apparently sufficient to prevent ground water from discharging upward into the stream. Overall, Transect 1 was a consistently losing reach.

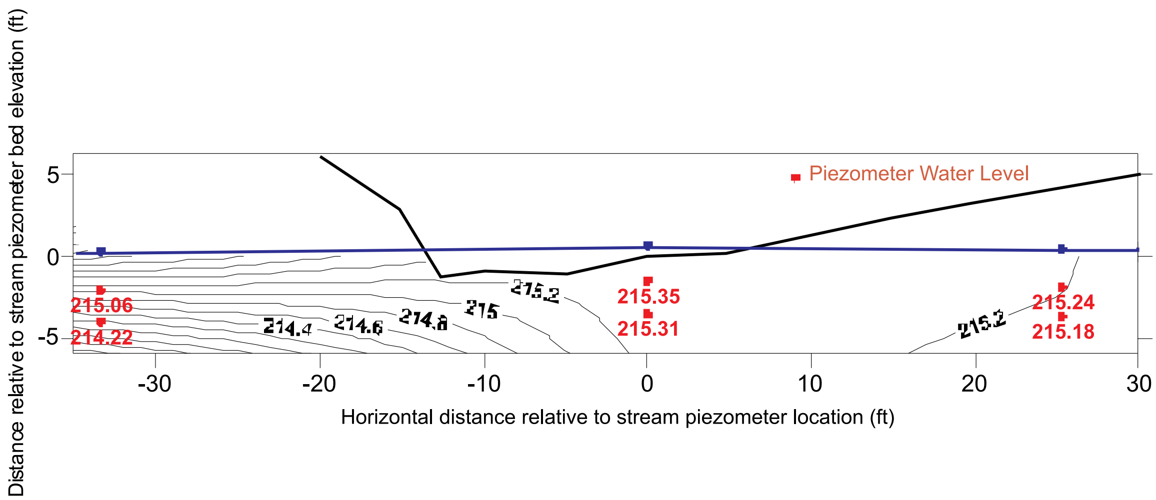

Figure 23. Transect 1 vetical cross section equipotentials on March 22, 2002.

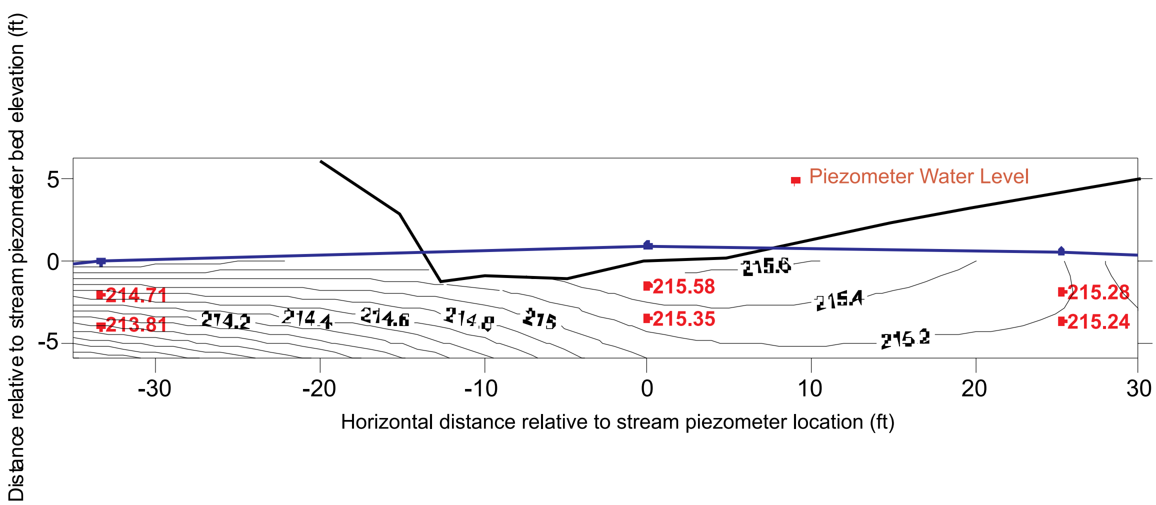

Figure 24. Transect 1 vertical cross section equipotentials on June 24, 2002.

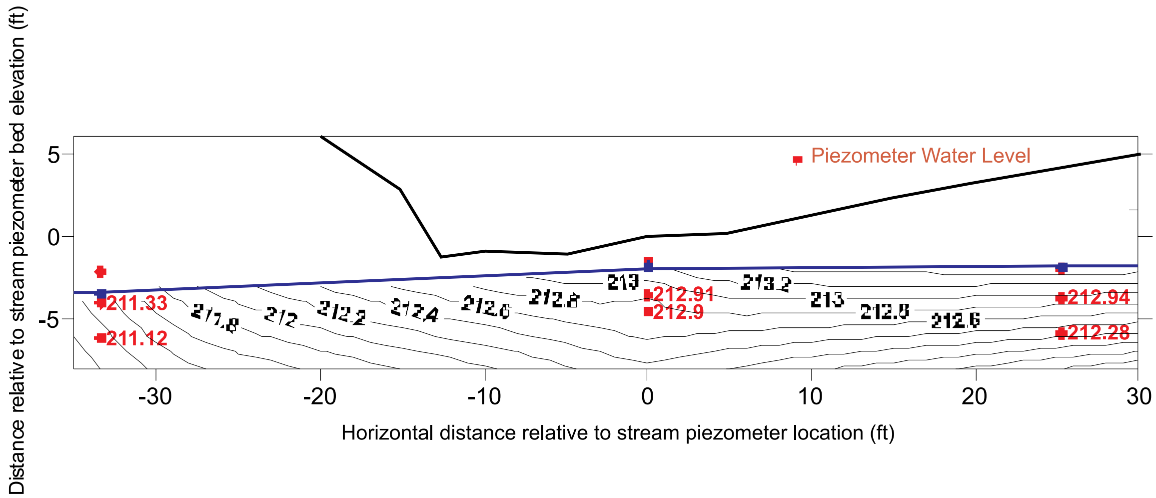

Figure 25. Transect 1 vertical cross section equipotentials on August 22, 2002 (study low).

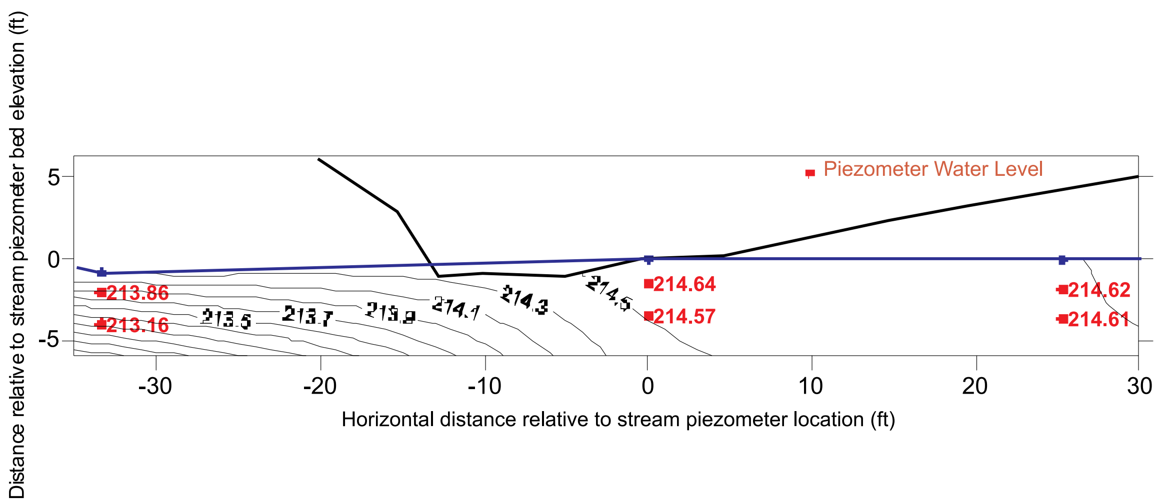

Figure 26. Transect 1 vertical cross section equipotentials on September 30, 2002.

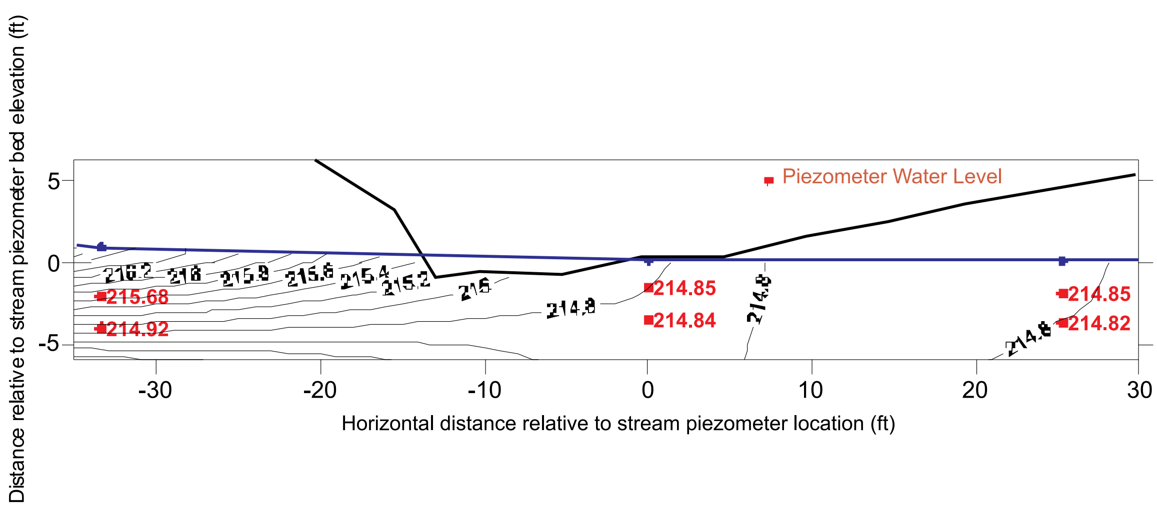

Figure 27. Transect 1 vertical cross section equipotentials on December 17, 2002.

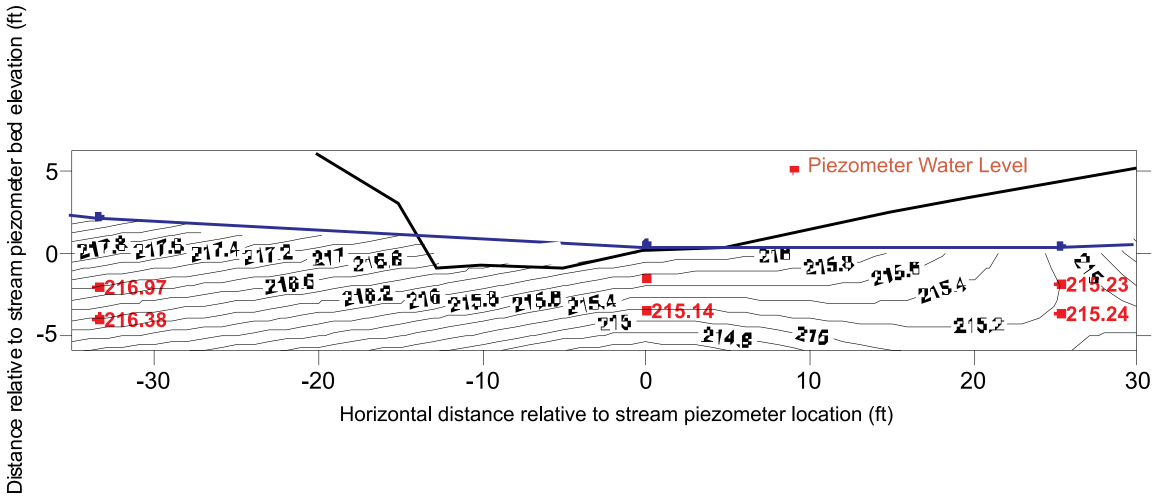

Figure 28. Transect 1 vertical cross section equipotentials on September 23, 2003 (study high).

Transect 2 was a shallow narrow riffle with a steep incised left bank and a point bar on the right bank with a high base flow velocity. Piezometers in Transect 2 were situated in low conductivity sediments with slow hydrologic exchange. Figures 29-34 show the ground water equipotentials under Transect 2 for select dates. Ground water flow was consistently from the stream banks into the bed, indicating that Transect 2 was a gaining reach.

The vertical gradient ranged from a low of 0.02 ft/ft during the drought to a high of 0.1 ft/ft on Sept. 23, 2003. Stream width was narrow and surface flow was swift so the area for GSI was small. This geomorphology was likely the cause of a focused upwelling of ground water discharge at this point. Rapid flow at this reach may also have allowed for more discharge to the stream.

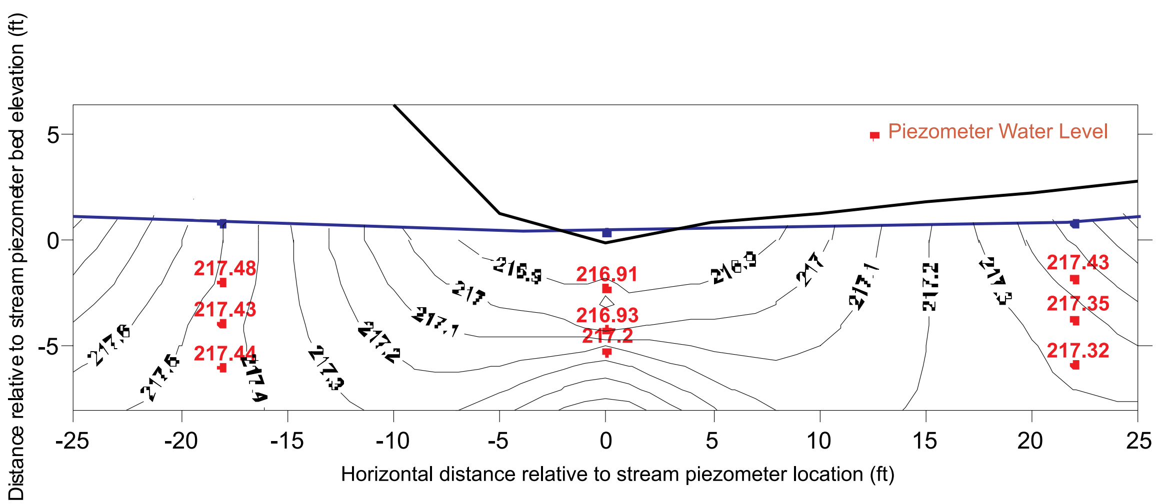

Figure 29. Transect 2 vertical cross section of equipotentials on March 22, 2002.

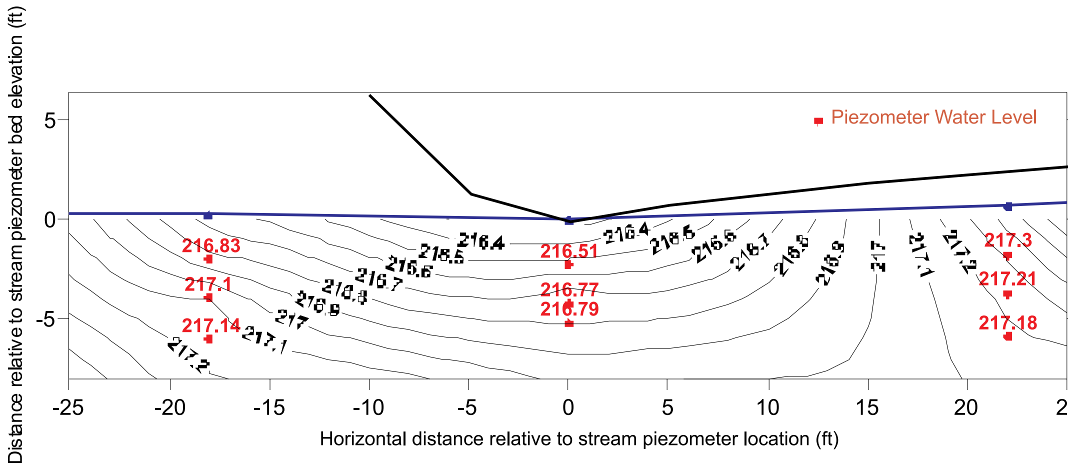

Figure 30. Transect 2 vertical cross section of equipotentials on June 24, 2002.

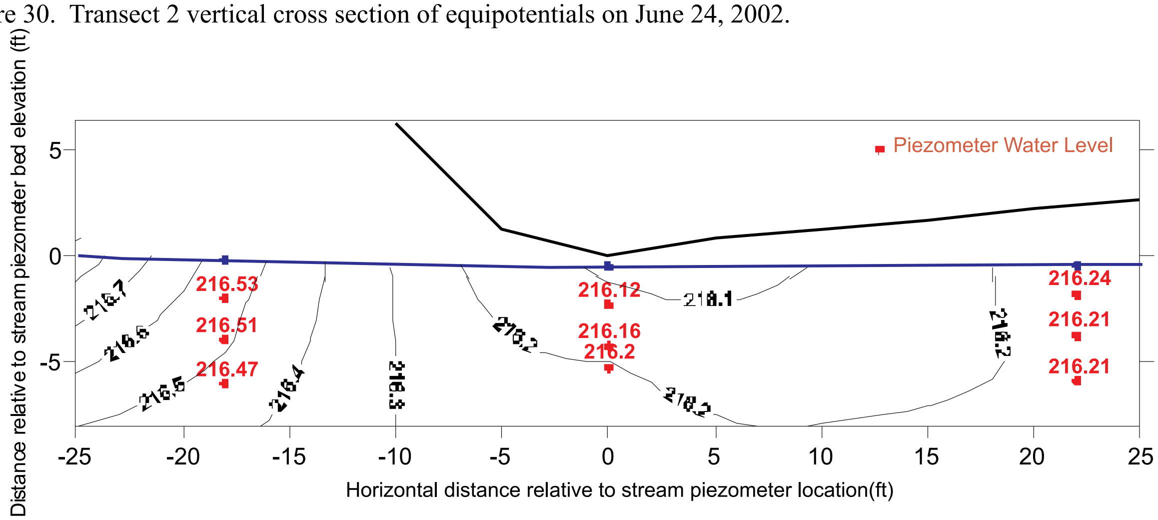

Figure 31. Transect 2 vertical cross section of equipotentials on August 22, 2002 (study low).

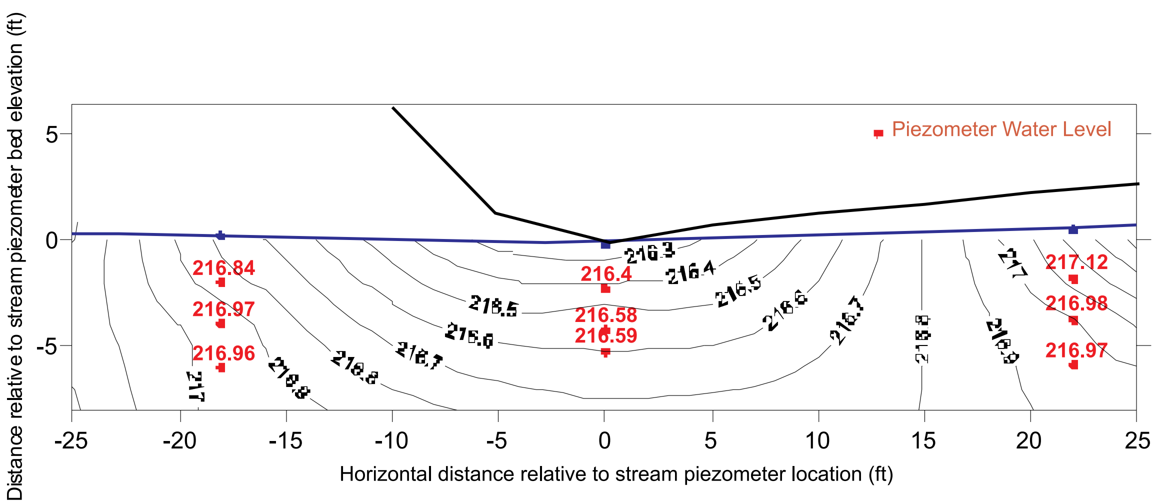

Figure 32. Transect 2 vertical cross section of equipotentials on September 30, 2002.

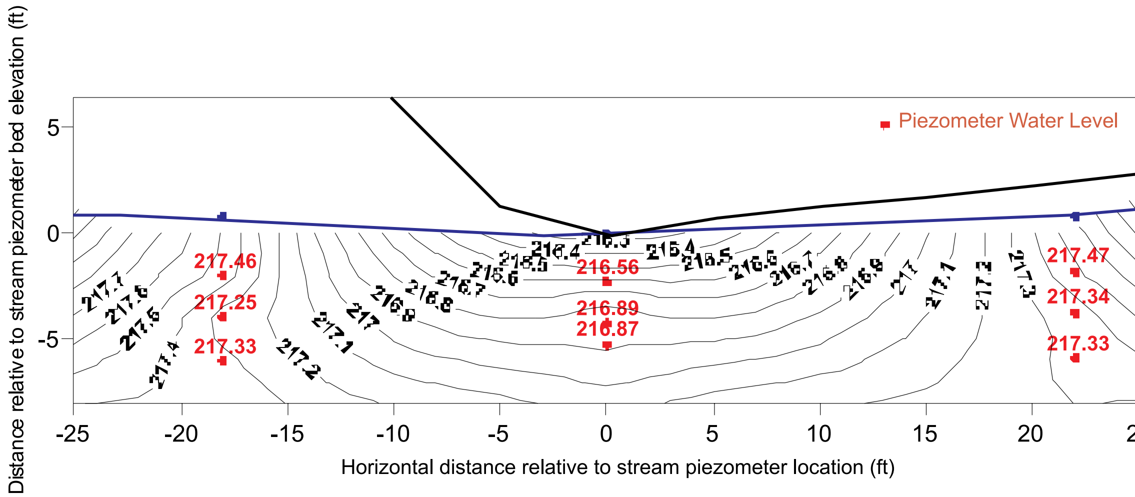

Figure 33. Transect 2 vertical cross section of equipotentials on December 17, 2002.

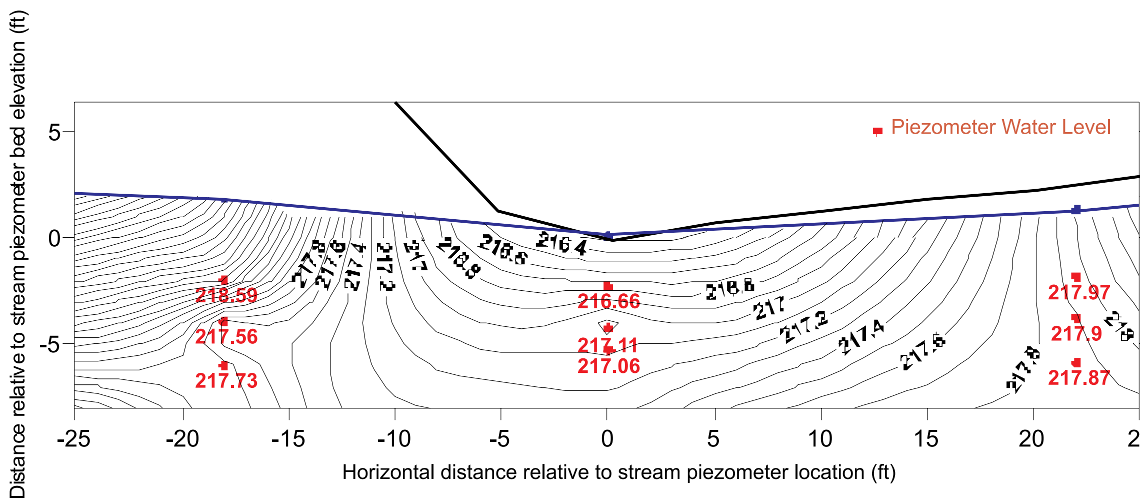

Figure 34. Transect 2 vertical cross section of equipotentials on September 23, 2003 (study high).

Transect 3 was a wide shallow stream terrace with low stream velocity and high conductivity bed sediments. Figures 35-40 show the ground water equipotentials under Transect 3 for the chosen dates. Stream water consistently moved from the stream into the beds and banks at low gradients ranging from 0.005 to 0.02 ft/ft, indicating that Transect 3 was a losing reach. On December 17, 2002, however, the direction of flow reversed and began moving into the stream. During the ground water high level on September 23, 2003, this reversal was complete, and the transect became a gaining reach with a gradient of 0.022 ft/ft. The vertical gradients in Transects 1 and 2 were of similar magnitude, but gradients at Transect 3 were about an order of magnitude less, likely a consequence of the conductive stream bed lithology. The bed and banks at Transects 1 and 2 were composed of the same gravelly clay. Transect 3, however, had more sandy sediments and a higher conductivity as shown in Table 1, indicating that gradients may be lower. This high conductivity may have allowed the flow direction to be more easily reversed over a short time frame.

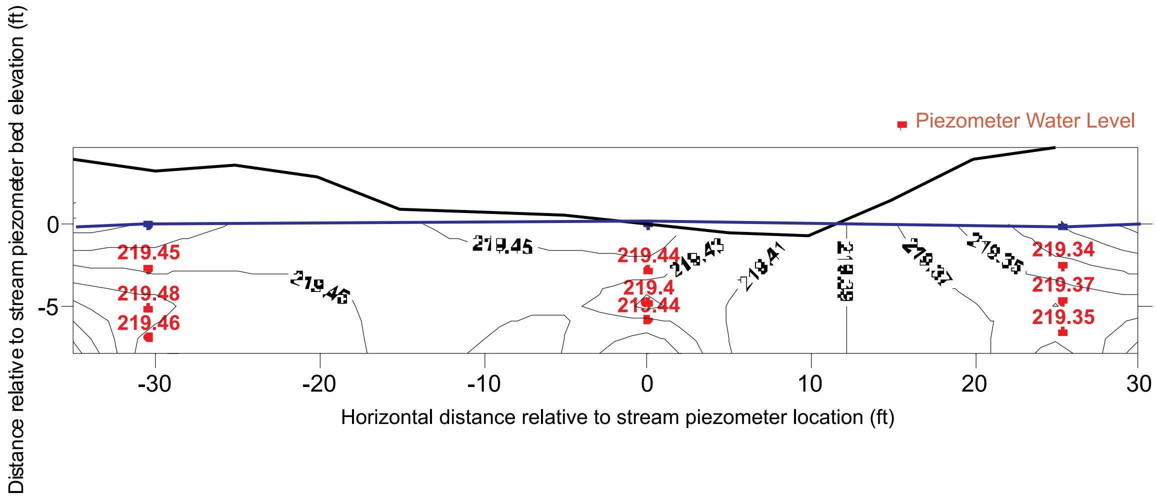

Figure 35. Transect 3 vertical cross section of equipotentials on March 22, 2002.

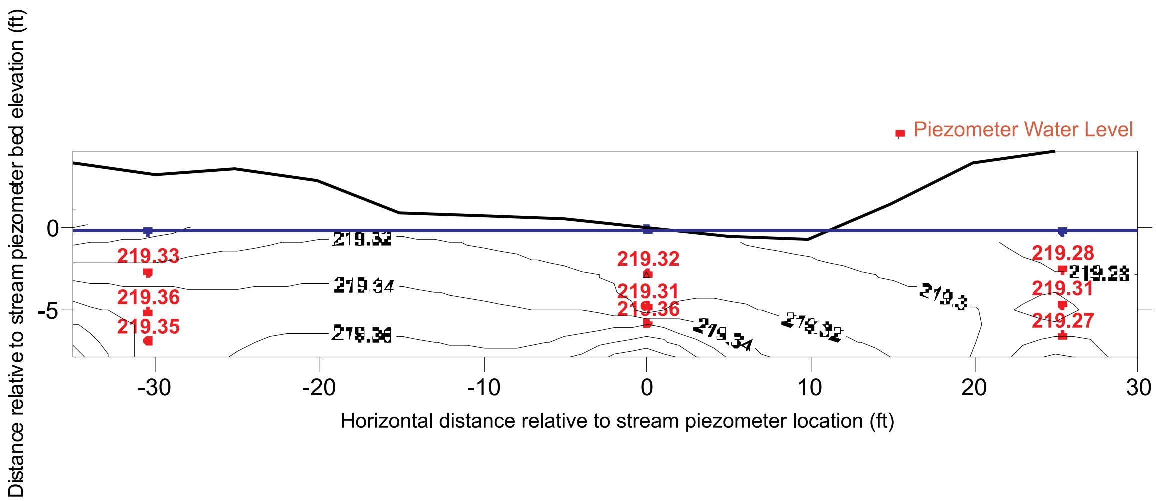

Figure 36. Transect 3 vertical cross section of equipotentials on June 24, 2002.

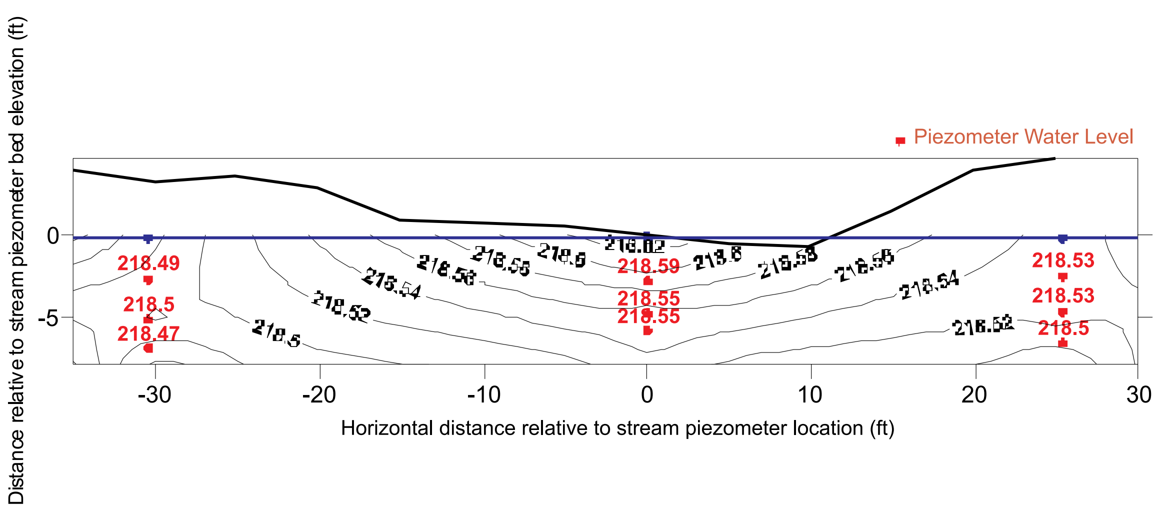

Figure 37. Transect 3 vertical cross section of equipotentials on August 22, 2002 (study low).

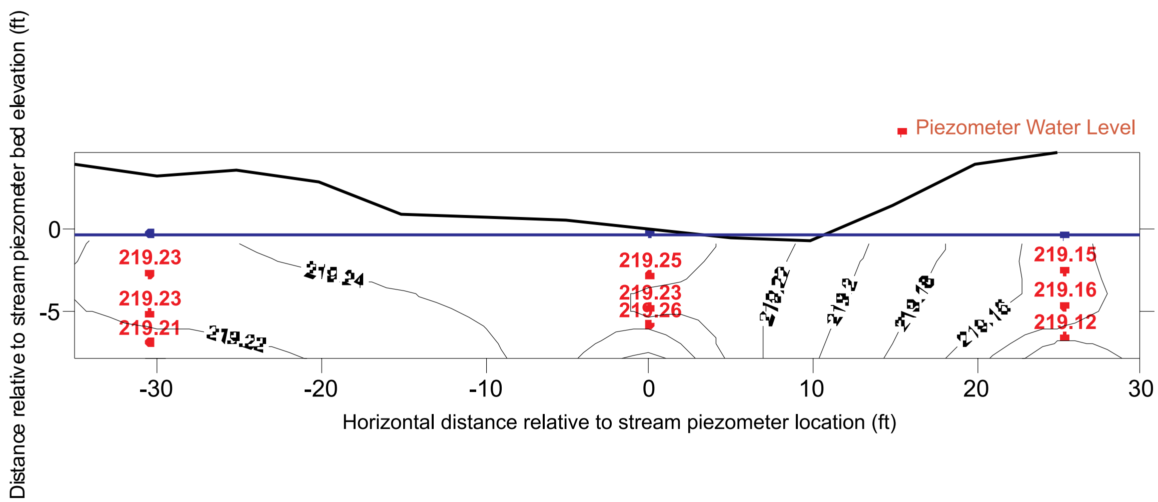

Figure 38. Transect 3 vertical cross section of equipotentials on September 30, 2002.

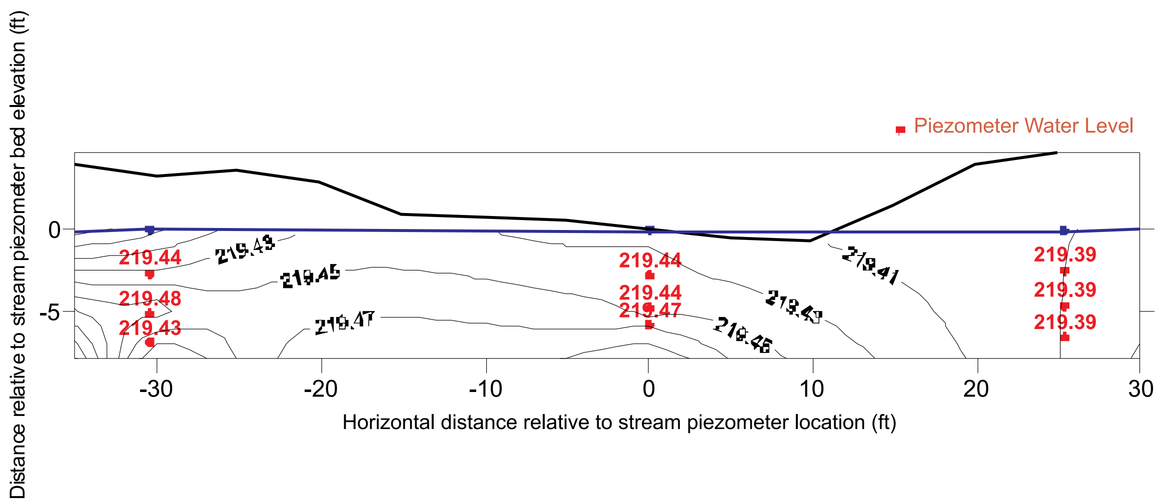

Figure 39. Transect 3 vertical cross section of equipotentials on December 17, 2002.

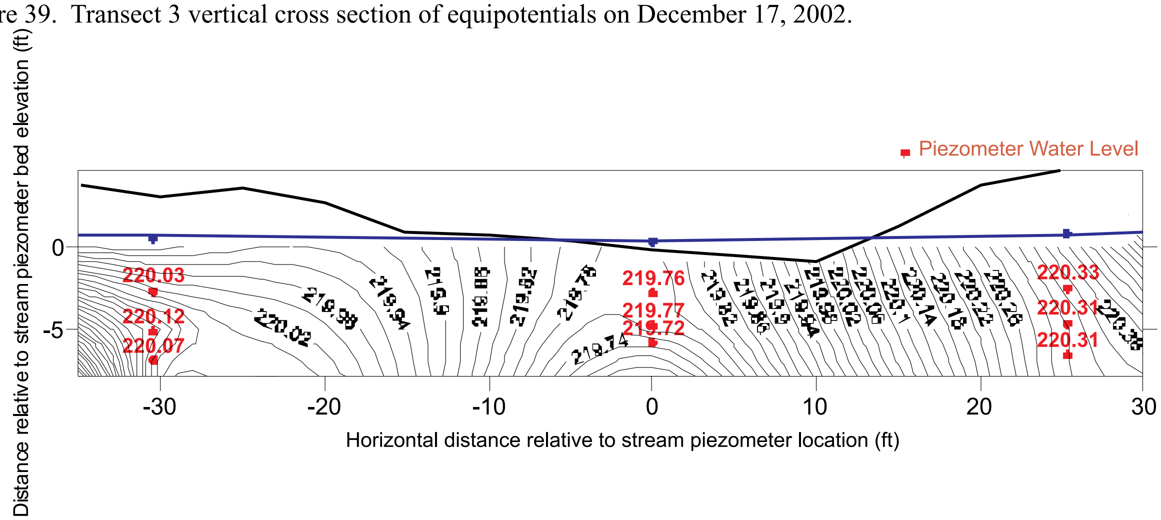

Figure 40. Transect 3 vertical cross section of equipotentials on September 23, 2003 (study high).

Using the gradients and Darcy's law as described in Methods, near-stream GSI flow was calculated for all transects on the selected dates. Flow results for Transect 1 are calculated based on a five-foot wide by five-foot deep compartment (Table 5). In the incised pool on Transect 1, water consistently moved into the ground water system at a high rate due to conductive sediments and high vertical gradients, indicating that this reach was a losing section of the stream. On March 22, 2002, a volumetric flow rate, Q, of 6.32 and 8.06 $ft^3/day/ft^2$ moved into the ground water system on the right and left banks, respectively. At this rate, the ground water residence time, to cover a five foot path, *s*, was 0.32 and 0.25 days, respectively. On June 24, 2002, the rate was substantially higher with 35.56 $ft^3/day/ft^2$ entering the ground water system on the right bank and 37.17 $ft^3/day/ft^2$ entering the left bank. Higher rates were a consequence of the encroaching drought which lowered ground water levels below the stream bed. By August 22, 2002, the drought was so severe that no stream flow was present at Transect 1 and therefore no interaction occurred between ground and surface water. All surface water was moving into ground water just upstream of Transect 2. The GSI returned to a rate of 1.55 and 4.46 $ft^3/day/ft^2$ to the ground water for the right and left banks by December 2002. GSI at Transect 1 could not be calculated on September 23, 2003, the ground water high because the shallow stream piezometer was lost in a storm in June 2003. Overall, the data demonstrated Transect 1 was in a losing reach with high and variable volumetric flow rates and low residence times in the stream bed sediments.

Table 5. Ground water (GW) and surface water (SW) flow calculations for Transect 1

Date	Compartment	dh/dz*	dh/dx**	dh/ds	K (ft/day)	q (ft/day)	A (ft^2)	Q(ft^3/d)	s (ft)	n***	t (days)	Direction
3/22/2002	Transect 1 Right Bank	0.020	0.005	0.020	310.00	6.32	1.00	6.32	5.00	0.41	0.32	SW to GW
6/24/2002	Transect 1 Right Bank	0.114	0.008	0.115	310.00	35.56	1.00	35.56	5.00	0.41	0.06	SW to GW
8/22/2002	Transect 1 Right Bank	NO CONNECTION										
9/30/2002	Transect 1 Right Bank	0.035	0.000	0.035	310.00	10.79	1.00	10.79	5.00	0.41	0.19	SW to GW
12/17/2002	Transect 1 Right Bank	0.005	0.000	0.005	310.00	1.55	1.00	1.55	5.00	0.41	1.32	SW to GW
9/23/2003	Transect 1 Right Bank		SHALLOW PIEZOMETER DESTROYED									
3/22/2002	Transect 1 Left Bank	0.020	0.021	0.026	310.00	8.06	1.00	8.06	5.00	0.41	0.25	SW to GW
6/24/2002	Transect 1 Left Bank	0.114	0.036	0.120	310.00	37.17	1.00	37.17	5.00	0.41	0.06	SW to GW
8/22/2002	Transect 1 Left Bank			NO CONNECTION								
9/30/2002	Transect 1 Left Bank	0.035	0.033	0.048	310.00	14.82	1.00	14.82	5.00	0.41	0.14	SW to GW
12/17/2002	Transect 1 Left Bank	0.005	0.014	0.014	310.00	4.46	1.00	4.46	5.00	0.41	0.46	SW to GW
9/23/2003	Transect 1 Left Bank		SHALLOW PIEZOMETER DESTROYED									

*Positive flow from stream: Negative flow to stream **Positive flow out from stream: Negative flow in toward stream ***Calculated from soil core bulk density

The GSI flow results for Transect 2 were calculated based on a five-foot wide by five-foot deep compartment (Table 6). In this high velocity riffle with an incised left bank and a point bar on the right bank, flow moved consistently from the ground water into the stream. The low rates were a consequence of the less conductive sediments and lower vertical gradients. On March 22, 2002, a volumetric flow rate, Q, of 0.07 and 0.10 $ft^3/day/ft^2$ moved into the stream from the ground water on the right and left banks, respectively. At this rate, residence time to cover a five foot path was 21.03 and 15.17 days for the right and left banks, respectively. On June 24, 2002 when flow rates were substantially higher, 0.52 $ft^3/day/ft^2$ entered the ground water system on the right bank and 0.51 $ft^3/day/ft^2$ entered the left bank. By August 22, 2002, the drought was so severe that no stream flow was present at Transect 2 and therefore no GSI. All surface water moved into ground water just upstream of Transect 2. The GSI remained in this range through the rest of 2002 but returned to 0.90 and 0.91 $ft^3/day/ft^2$ on September 23, 2003, the date of the ground water level high. Overall, the data indicated that Transect 2 was a consistently gaining reach with low and relatively consistent volumetric flow rates and high residence times in the stream bed sediments.

Table 6. Ground water (GW) and surface water (SW) flow calculations for Transect 2

Date	Compartment	dh/dz*	dh/dx**	dh/ds	K (ft/day)	q (ft/day)	A (ft^2)	Q (ft^3/d)	s (ft)	n***	t (days)	Direction
3/22/2002	Transect 2 Right Bank	-0.010	-0.016	0.019	3.90	0.07	1.00	0.07	5.00	0.31	21.03	GW to SW
6/24/2002	Transect 2 Right Bank	-0.131	-0.025	0.133	3.90	0.52	1.00	0.52	5.00	0.31	2.99	GW to SW
8/22/2002	Transect 2 Right Bank				NO CONNECTION							
9/30/2002	Transect 2 Right Bank	-0.091	-0.023	0.094	3.90	0.37	1.00	0.37	5.00	0.31	4.25	GW to SW
12/17/2002	Transect 2 Right Bank	-0.167	-0.028	0.169	3.90	0.66	1.00	0.66	5.00	0.31	2.35	GW to SW
9/23/2003	Transect 2 Right Bank	-0.227	-0.044	0.231	3.90	0.90	2.00	1.80	5.00	0.31	1.72	GW to SW
3/22/2002	Transect 2 Left Bank	-0.010	-0.024	0.026	3.90	0.10	1.00	0.10	5.00	0.31	15.17	GW to SW
6/24/2002	Transect 2 Left Bank	-0.131	-0.019	0.132	3.90	0.51	1.00	0.51	5.00	0.31	3.01	GW to SW
8/22/2002	Transect 2 Left Bank				NO CONNECTION							
9/30/2002	Transect 2 Left Bank	-0.091	-0.0222	0.0935	3.90	0.36	1.00	0.36	5.00	0.31	4.25	GW to SW
12/17/2002	Transect 2 Left Bank	-0.167	-0.0318	0.169	3.90	0.66	1.00	0.66	5.00	0.31	2.35	GW to SW
9/23/2003	Transect 2 Left Bank	-0.227	-0.0564	0.234	3.90	0.91	1.00	0.91	5.00	0.31	1.70	GW to SW

*Positive flow from stream. Negative flow to stream **Positive flow out from stream, Negative flow in toward stream ***Calculated from soil core bulk density

The GSI flow results for Transect 3 were calculated based on a five-foot wide by five-foot deep compartment (Table 7). Results indicated a generally losing reach at this wide, shallow terrace where water moved slowly from the stream into the ground water system despite sediments that were conductive. On March 22, 2002, a volumetric flow rate, Q, of around 0.61 ft^3/day/ft^2 passed to the stream from the ground water on the right and left banks, respectively. At this rate, the residence time, to cover a five-foot path was about 2.4 days. On June 24, 2002, the rate was substantially lower; 0.15 ft^3/day/ft^2 entered the ground water system on the right bank and 0.02 ft^3/day/ft^2 entered the left bank. On August 22, 2002, the drought was severe and the stream lost more surface water to the ground water system. The stream started to recover and, by December 2002, ground water and surface water flowed slowly downstream parallel to the stream bed with little interaction. During the ground water high on September 23, 2003, the GSI had reversed direction and Transect 3 became a gaining reach, receiving 1.34 ft^3/day/ft^2 from the left bank and 0.71 ft^3/day/ft^2 from the right bank. Overall, Transect 3 was a consistently losing reach with long residence times which experienced a flow reversal to a gaining reach in the wet year of 2003.

Table 7. Ground water (GW) and surface water (SW) flow calculations for Transect 3

Date	Compartment	dh/dz*	dh/dx**	dh/ds	K (ft/day)	q (ft/day)	A (ft^2)	Q (ft^3/d)	s (ft)	n***	t (days)	Direction
3/22/2002	Transect 3 Right Bank	0.020	0.003	0.020	30.50	0.61	1.00	0.61	5.00	0.29	2.37	SW to GW
6/24/2002	Transect 3 Right Bank	0.005	0.002	0.005	30.50	0.15	1.00	0.15	5.00	0.29	9.51	SW to GW
8/22/2002	Transect 3 Right Bank	0.020	0.002	0.019	30.50	0.58	1.00	0.58	5.00	0.29	2.50	SW to GW
9/30/2002	Transect 3 Right Bank	0.010	0.004	0.010	30.50	0.31	1.00	0.31	5.00	0.29	4.75	SW to GW
12/17/2002	Transect 3 Right Bank	0.000	0.002	0.002	30.50	0.06	1.00	0.06	5.00	0.29	23.77	parallel to bed
9/23/2003	Transect 3 Right Bank	-0.005	-0.022	0.022	30.50	0.67	2.00	1.34	5.00	0.29	2.16	GW to SW
3/22/2002	Transect 3 Left Bank	0.020	-0.001	0.020	30.50	0.61	1.00	0.61	5.00	0.29	2.39	SW to GW
6/24/2002	Transect 3 Left Bank	0.005	-0.001	0.001	30.50	0.02	1.00	0.02	5.00	0.29	95.08	SW to GW
8/22/2002	Transect 3 Left Bank	0.020	0.003	0.020	30.50	0.61	1.00	0.61	5.00	0.29	2.38	SW to GW
9/30/2002	Transect 3 Left Bank	0.010	0.0008	0.0099	30.50	0.30	1.00	0.30	5.00	0.29	4.80	SW to GW
12/17/2002	Transect 3 Left Bank	0.000	0.000	0.000	30.50	0.00	1.00	0.00	5.00	0.29	NA	parallel to bed
9/23/2003	Transect 3 Left Bank	-0.005	-0.011	0.012	30.50	0.36	2.00	0.71	5.00	0.29	4.06	GW to SW

*Positive flow from stream; Negative flow to stream **Positive flow out from stream; Negative flow in toward stream ***Calculated from soil core bulk density

Temperature verification of ground water-surface water interaction

Transect 1 exhibited strongly losing behavior. This movement of surface water to the ground water was corroborated by the continuous stream bed ground water temperatures measured in the data loggers around March 22, 2002 at both the shallow and medium depths (Figure 41). These temperatures clearly exhibited the expected diurnal temperature variation of the stream surface water as it moved relatively quickly into the highly conductive bed sediments at Transect 1. This diurnal temperature swing in the stream bed piezometers, which varied by several degrees Celsius, strongly supported the conclusion that this deeply incised pool in conductive sediments was consistently losing.

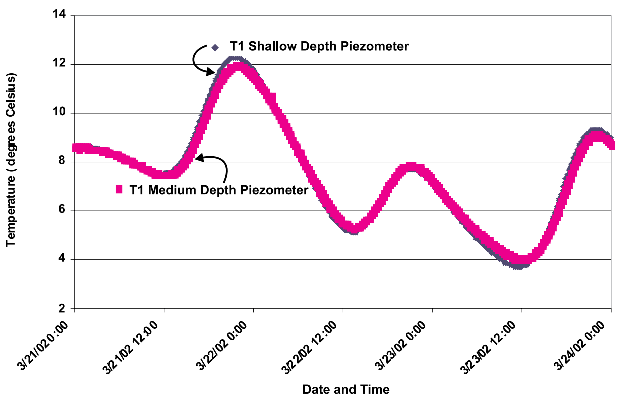

Figure 41. Transect 1 continuous stream bed piezometer temperatures.

Vertical equipotentials mapped over time showed Transect 2 to be a consistently gaining reach. Data from the stream bed piezometer in Transect 2 on the days around March 22, 2002 demonstrated relatively consistent temperatures at the medium depth as ground water discharged to the stream (Figure 42). The temperature in the stream bed piezometers displayed steady ground water temperature unaffected by the diurnal variation in the stream water temperature. The mild variation in the shallow piezometer temperature over 0.5 degree Celsius range was most likely a function of the sediment temperature and not stream water movement. If stream water was moving into the bed, as it did at Transect 1, the temperature would likely show a diurnal variation of several degrees.

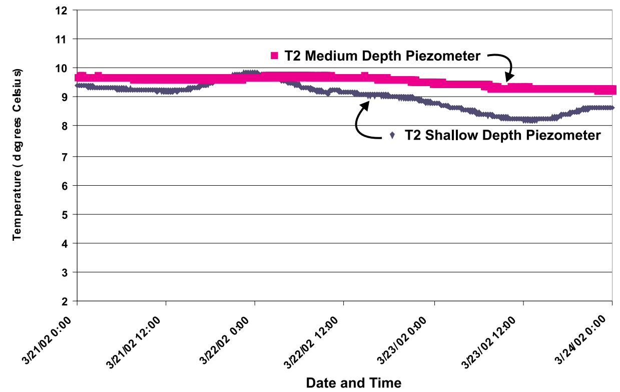

Figure 42. Transect 2 continuous stream bed piezometer temperatures.

Vertical equipotentials showed Transect 3 to be a slowly losing reach with parallel flow under the bed. Consequently, temperature in the stream bed piezometers would be expected to display the diurnal variation of the stream surface temperature. However, continuous stream bed temperatures for Transect 3 for the days around March 22, 2002 indicated that temperature in the shallow piezometer varied diurnally but that the medium-depth piezometer did not (Figure 43). This temperature signature was closer to that of Transect 2, a gaining reach, than that of the losing reach at Transect 1. This may have been a consequence of the very slow flow into the bed which was too small to strongly reflect the diurnal variation of the stream surface temperature.

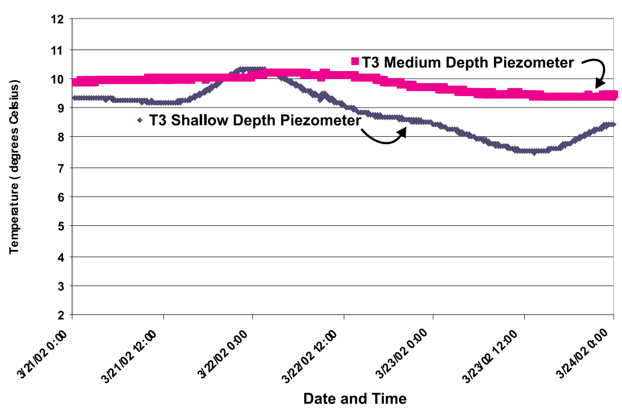

Figure 43. Transect 3 continuous stream bed piezometer temperatures.

Stream flow verification of ground water-surface water interaction

The classification of the specific transects as losing or gaining from the above near-stream GSI flow calculations and temperature analysis were also verified by examining the stream flow measurements at each transect. By comparing these values, the flow loss and gain between transects can be roughly assessed. However, this approach may only be used if no tributaries or springs are along the study reach which was the case.

Table 8 shows measurements of surface stream flow that were made at the USGS stream flow gage above Transect 3, Transect 3, Transect 2, Transect 1, and just below Transect 1 over time. Nearly all measurements indicated loss of stream flow between the stream gage and just below Transect 1, a finding supported by the equipotential analysis. Table 8 shows little difference in stream flow between Transects 3 and 2, corresponding to the low GSI calculated at these transects. However, a consistent loss of flow between Transects 2 and Transect 1 and between Transect 1 and below corresponds to the GSI calculations which show Transect 1 to be strongly losing.

Table 8. Stream flow at each of the transects on specific dates

Date	Q--Gage (cfs)	Q-Transect 3 (cfs)	Q-Transect 2 (cfs)	Q-Transect 1 (cfs)	Q-Below Transect 1 (cfs)
1/15/2002	0.385	0.396*	0.396*	0.357	0.226
3/05/2002	0.489	0.489*	0.489*	0.499	0.397
5/20/2002	0.726	0.711*	0.711*	0.626	0.478
7/15/2002	0.220	0.208*	0.208*	0.133	0.073
9/03/2002	0.166	0.179	0.172	0.141	0.014
11/07/2002	0.691	0.643*	0.643*	0.622	0.579
1/13/2003	-----	1.45*	1.45*	1.44	1.38
3/10/2003	3.40	3.15*	3.15*	3.89	3.59
5/12/2003	1.62	1.37*	1.37*	1.39	1.34
7/07/2003	2.68	2.53	2.61	2.59	2.29
9/02/2003	1.16	1.04*	1.04*	0.95	0.83
11/09/2004	0.802*	0.802*	-----	-----	-----

*--One discharge measurement was made that approximately represents both locations.

Storm surge ground water-surface water interaction

From November 2001 to July 2004, Minebank Run stream experienced eighteen large storm discharges in response to major precipitation events (Doheny et al., 2006). Instantaneous peak discharges during these events ranged from 247- 1390 ft^3/sec compared to a mean annual discharge of 1.15 ft^3/s-4.34 ft^3/s (Doheny et al., 2006). All of these events were captured in real time by the continuous data loggers installed in the piezometer nests and monitoring wells.

A storm on August 3, 2002 with a duration of 1.0 hour produced 1.18 inches of rainfall (Doheny et al., 2006). The peak gage height measured 7.58 feet and discharge in the stream increased from 0.05 ft^3/sec (drought conditions) to an instantaneous peak discharge of 725 ft^3/sec (Doheny et al., 2006). The stream gage response is shown in Figure 44. Remarkably, the storm surge peaked and disappeared within about two hours.

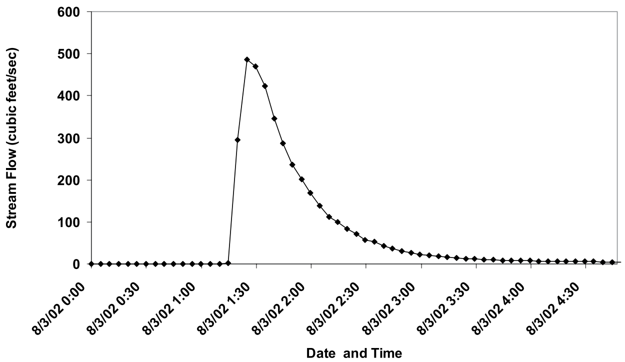

Figure 44. Stream discharge hydrograph in response to storm event on August 3, 2002.

The shallow and medium depth piezometers in the stream bed exhibited the expected rise in water level with the storm surge (Figure 45). Strikingly, the rise and fall of the hydrograph matched the timing of the stream discharge almost exactly and covered some six feet of water level fluctuation. The stream bed at Transect 1 had a high conductivity of 310 ft/day, which enabled this almost instantaneous interaction. The right bank piezometer had a high conductivity of 170 ft/day and also reflected a similar but reduced and delayed rise and fall in water level as a consequence of the head loss and time lag as water moved through the sediments. The piezometer in the left bank, positioned in sediments with much lower hydraulic conductivity (7 ft/day), responded with a lower and delayed peak.

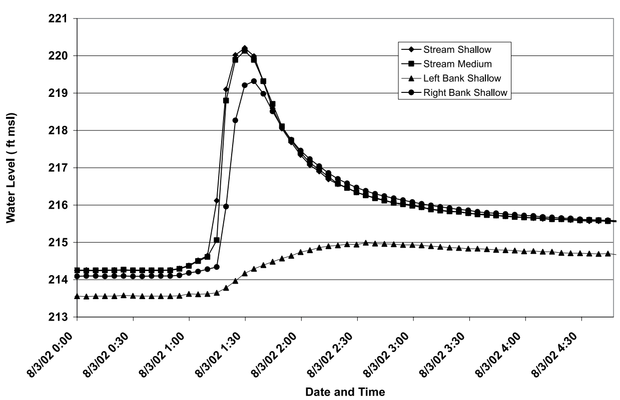

Figure 45. Transect 1 piezometer hydrograph response to storm event on August 3, 2002.

The response of the stream bed and bank piezometers at Transect 2 to the August 2002 event is shown in Figure 46. The conductivity in the stream bed at Transect 2 was 3.9 ft/day, about two orders of magnitude less than at Transect 1. Though the stream was gaining at Transect 2, the response of the stream bed piezometers was similar to Transect 1. The height of the storm surge at this transect was unknown but was likely less than the stream gage peak height because this transect was situated at a point bar which would have allowed over bank flow, thus reducing the height of the storm surge. The shallow depth stream bed piezometer data logger failed so no data were collected. The right bank piezometer located in the point bar near the stream reflected about the same rise as the stream bed piezometer. The left bank piezometer was located about thirty feet from the stream bed piezometer and showed a much smaller increase in water level because of the large head loss through the gravelly clay sediments.

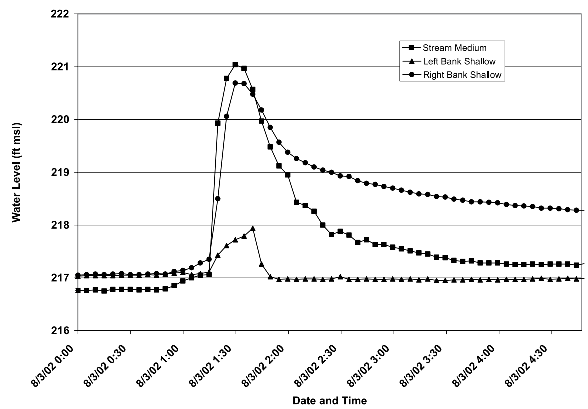

Figure 46. Transect 2 piezometer hydrograph response to storm event on August 3, 2002.

The response of the stream bed and bank piezometers at Transect 3 to the August 2002 event is shown in Figure 47. This transect was a shallow wide terrace with an average stream bed conductivity of 30.5 ft/day. The near-stream GSI equipotential analysis showed that Transect 3 was a slowly losing reach. As the storm surge passed through, water level in the stream bed piezometers rose almost four feet. The medium depth piezometer exhibited less of a rise, reflecting the head loss as the water was pushed into the bed sediments. The left bank stream piezometer was in conductive sands and thus, showed a similar rise, muted by the distance from the stream bed. The right bank piezometer, although in similarly conductivity sediments, showed an unexpected muted response.

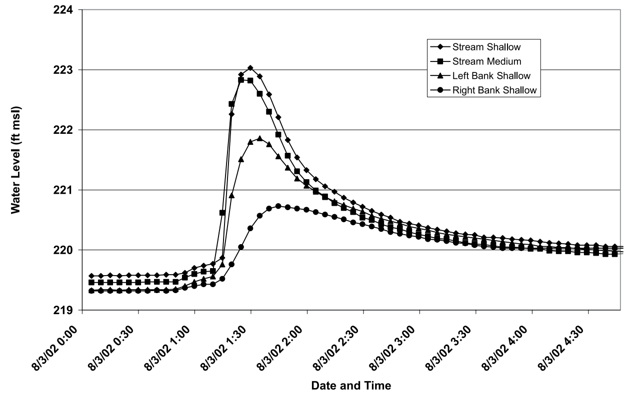

Figure 47. Transect 3 piezometer hydrograph response to storm event on August 3, 2002.

The August 3, 2002 storm surge clearly drove water rapidly into the stream beds and banks as shown by the water levels. Despite its limitations for this unsteady, turbulent flow system discussed in the methods section, Darcy's law was used as a first estimate of the temporal variation in GSI in the stream bed at Transect 1 on the August 3, 2002 storm event. Figure 48 displays the flow rates calculated using Darcy's law and the gradient in the stream bed as a function of time during the storm surge. The results reveal a flow that was strongly driven down into the stream bed (positive), peaking at the height of the storm surge, falling off, and finally reversing back into in the stream (negative). This event demonstrates how rapidly the storm surge affects the GSI in the stream bed. Such events may significantly influence stream function but have not typically been quantified in GSI evaluations.

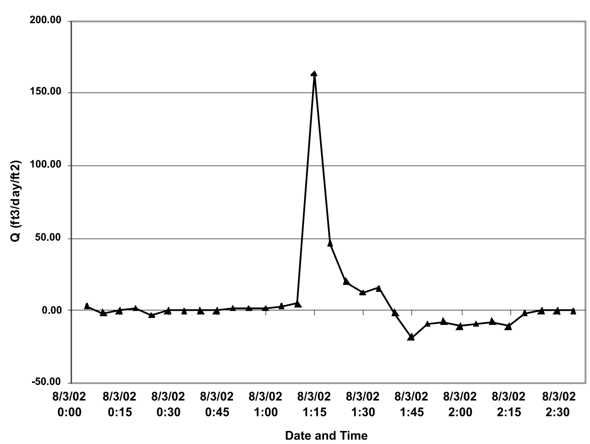

Figure 48. GSI flow rates at Transect 1 during storm surge on August 3, 2002.

In addition to the change in water level, data loggers also recorded changes in water temperature in the stream bed piezometers during and after the storm event. Figure 49 shows the temperature response at Transect 1 from midnight August 2 to midnight August 12. Just before the storm event, Transect 1 was a strongly losing reach and the stream bed piezometers reflected a diurnal variation in both the shallow and medium depth piezometers. As the storm surge moved through, stream water was driven into the bed. The temperature response showed a cooling of almost 8 degrees Celsius in the medium depth piezometer. In the days following the storm surge, the shallow depth piezometer showed a muted diurnal temperature response. The medium depth stream bed piezometer reflected a constant temperature indicating that the water driven deeper into the bed by the storm surge was cooling to match the ground water temperature and no new water was moving down into the bed. At this time, the losing nature of Transect 1 was changed to gaining as stream water driven into the bed water was flowing back into the stream. This reversal lasted almost 8 days after which the flow was reestablished as losing at Transect 1 when the diurnal pattern resumed on August 11.

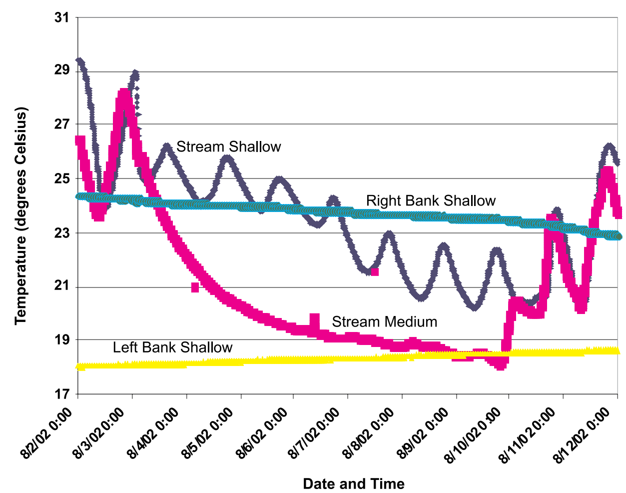

Figure 49. Transect 1 piezometer temperature response to storm event on August 3, 2002.

Figure 50 shows the temperature response at Transect 2 from midnight August 2 to midnight August 12. The shallow stream bed piezometer data logger failed, so no data were available at this depth. Just before the storm event, Transect 2 was a consistently gaining reach. The stream bed and the nearby right bank piezometer in the point bar reflected a corresponding ground water temperature pattern. As the storm passed, a surge of cool stream water was driven into the bed. Unlike the response at Transect 1, the medium depth stream bed piezometer showed a short dip in temperature at the time of the storm surge and then quickly returned to the steady ground water temperature signature expected for a gaining reach. The right bank piezometer did not reflect this dip and the left bank piezometer showed no response with the stream temperature during the entire period. This limited response was likely a function of low hydraulic conductivity at this transect (3.9 ft/day) which precluded a large amount of water from moving into the stream bed and banks.

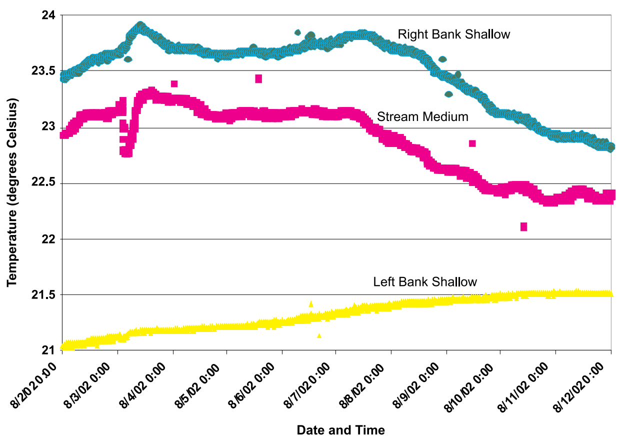

Figure 50. Transect 2 piezometer temperature response to storm event on August 3, 2002.

Figure 51 shows the temperature response at Transect 3 from midnight August 2 to midnight August 12. Just before the storm event, Transect 3 was a weakly losing reach. The shallow piezometer showed the diurnal variation of the stream temperature, while the medium-depth piezometer reflected the steady ground water temperature. As the storm passed, stream water was driven into the bed and the temperature response showed a cooling of about three degrees Celsius in the shallow piezometer and one degree in the medium-depth piezometer, a pattern similar to Transect 1, but reflecting the lower conductivity of transect 3. The temperature also did not return to a pre-storm temperature as did Transect 1. The right bank and left bank piezometers showed no discernable response to the event.

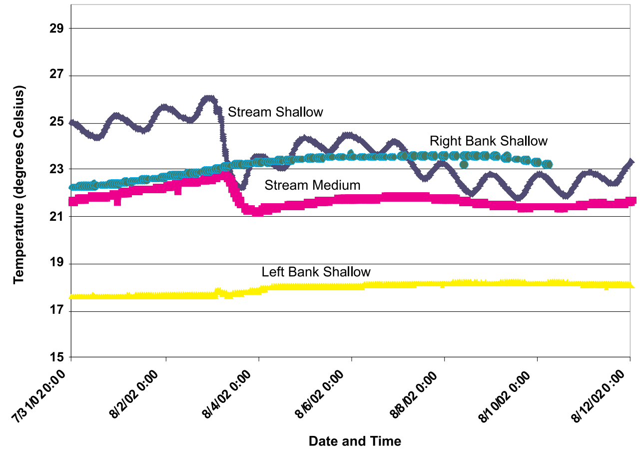

Figure 51. Transect 3 piezometer temperature response to storm event on August 3, 2002.

6.0 Discussion

The first objective of this pre-restoration study was to assess the stream geomorphology and geology at specific stream features and determine their influence on GSI at MBR. Our results strongly demonstrated the impact of geology and geomorphology on GSI. For example, Transect 1 was located at a deep incised pool in highly conductive sediments, creating a setting of low velocity flow and high hydrostatic gradient between the stream and the surrounding ground water. Consequently, the stream was consistently losing. Transect 2 was located at a narrow riffle with high velocity in low conductivity sediments where the reach was consistently gaining at a low rate due to the swift flow in a low conductivity stream bed, creating a hydraulic gradient conducive to flow into the stream. Transect 3 was located in a shallow, wide terrace with slow velocity in conductive sediments, a feature creating a mildly losing reach that reversed to gaining when the ground water levels were high. The tremendous variation in GSI at each stream feature clearly demonstrated the impact of geomorphology and geology.

The second objective of the pre-restoration study was to develop effective and simple methods to characterize, measure, and quantify near-stream GSI at specific stream features. Our results demonstrated that using a network of monitoring wells and piezometer nests to measure water levels at defined time intervals was sufficient to characterize and quantify the GSI at MBR at both the regional and near-stream scale.

Ground water equipotentials defined by the bi-weekly water levels at all of the site wells were used to assess the ground water gradients at the regional watershed scale at MBR. Our results demonstrated that ground water flow varied greatly over space and time at the regional scale at MBR. Given this variability, it was important to be aware that numerous factors influence ground water gradients and the interaction of the ground water with the stream on a regional scale. The system was never in a steady state and frequent sampling of ground water levels and stream flow were necessary to characterize hydrology.

The regional ground water horizontal equipotentials were not very useful for interpreting the near-stream GSI because they did not reveal the impact of the stream on the ground water flow system. This was not unexpected, as the majority of groundwater discharges at depth from the MBR watershed and only a small amount is intercepted by the stream as base flow. For MBR, the regional scale should not be used to describe near-stream GSI as it can not capture the spatial and temporal scale at which this interaction occurs. The regional scale horizontal equipotentials also do not address the vertical gradients which define the exchange in and out of the stream beds and banks at the near-stream scale.

The near-stream GSI at MBR was easily characterized and quantified using the vertical equipotentials developed from the stream bed and bank piezometer water levels. On the near- stream scale, the losing or gaining nature of the stream features at each transect could be seen on these equipotentials. Equipotentials also showed the near-stream GSI to be highly spatially and temporally variable at each feature. Consequently, many of the typical methods used to quantify GSI at this scale, such as tracer tests or numerical heat and flow modeling would be impractical or fail to capture this variation.

Our results showed that a simple model which split the stream into two compartments at the thalweg was sufficient to quantify the GSI flow at each stream feature. The horizontal and vertical gradients for each compartment were calculated using the water levels in the stream bed piezometers and banks at each sampling time. These gradients were then substituted into the 2-D vector form of Darcy's law to determine the magnitude and direction of the seepage vector along the resultant flow path through the compartment on either side of the stream at each transect. The residence time of the water to pass through a five foot deep compartment was then determined. This simple approach allowed the spatial and temporal variation in the near-stream GSI to be quantified biweekly using easily obtained ground water level measurements. The results showed Transect 1 was consistently losing but the magnitude of GSI was highly variable, ranging from 1.55 to 37.17 $ft^3/day/ft^2$ with a residence time of 1.32 to 0.06 days over the two year study period. Transect 2 was in a weakly gaining reach with GSI flow ranging from 0.07 to 1.80 $ft^3/day/ft^2$. The residence time through a five foot depth was from 1.70 to 21.03 days. Transect 3 was in a losing reach that reversed to gaining during a period of high ground water levels. As a losing reach, GSI flow at Transect 3 reached a maximum of 0.61 $ft^3/day/ft^2$ with a residence time of 2.37 days. As a gaining reach, GSI flow at Transect 3 reached a maximum gain of 1.34 $ft^3/day/ft^2$ with a residence time of 2.16 days to pass through five feet. The alternating losing and gaining behavior was verified by stream flow measurements and continuous temperature data at each transect.

The impact of a storm surge on GSI was also evaluated at the transects using water level and temperature readings collected at 5 minute intervals in the stream bed and bank piezometers using continuous data loggers. Our results showed that the storm surge drove water into the stream bed at each feature to various degrees depending on geomorphology and geology. GSI at Transect 1 during the storm surge was estimated using Darcy's law and showed flow entering the bed and then reversing rapidly. Temperature data also confirmed the impact of the storm surge on GSI at each transect and helped assess the residence time of the surge in the bed.

The direction of the near-stream GSI at each of the features is critical to the issue of water quality. If the flow direction is consistently from the ground water to the stream, as found at Transect 2, the water quality in the stream is being impacted by ground water quality. When no stream water enters the bed or banks, little processing of stream contaminants in the sediments to improve stream water quality occurs. If flow is consistently from the stream into the stream bed and banks, as at Transect 1 and Transect 3, beneficial processing such as denitrification and adsorption may occur (Kaushal et al. 2008). The magnitude of the near-stream GSI flow at each feature is also critical. High flows in high conductivity settings move more fluid through the system as seen at Transect 1. Slower flows, like at Transect 2 and 3, move less fluid but increase residence time. Increasing residence time is critical for increasing the mass removal of nutrients and contaminants via biological processes and can only be determined by knowing the GSI flow direction and magnitude (Kaushal et al. 2008).

From the assessment of near-stream GSI, it is clear that geomorphology and geological setting are major factors that impact the magnitude and direction of near-steam GSI. These factors will be greatly impacted by restoration efforts which can change both the geomorphology of the stream channel and the underlying sediments. Restoration that changes geology and geomorphology will alter GSI. GSI, in turn, influences biological processes like nitrification and denitrification which control the flux of nitrogen in water and, therefore, dictate water quality. Therefore, the potential exists to identify and select restoration techniques that enhance GSI and improve water quality.

7.0 Conclusions

1. Stream channel geomorphology and geologic setting, especially stream channel width, depth, and sediment lithology strongly influenced near-stream GSI at MBR.
2. The regional ground water horizontal equipotentials developed from bi-weekly ground water level measurements at MBR varied substantially spatially and temporally and did not provide the required resolution for interpreting the near-stream GSI.
3. The characterization of near-stream GSI at MBR stream features as losing or gaining was easily demonstrated using cross-sections of vertical equipotentials developed from water levels measured in piezometer well nests in the stream bed and banks.
4. Near-stream GSI flow rates were simply and effectively quantified at MBR stream features using a simple hydrologic analysis of stream bed and bank piezometer nest water levels measured bi-weekly.
5. The direction and magnitude of near stream GSI at MBR varied spatially and temporally among and within stream features. Some features changed from losing to gaining during the study.
6. Residence times derived from a stream bed compartment model at each stream feature at MBR were highly variable given their dependency on GSI flow rate. Mass removal of nutrients and contaminants in stream bed sediments is dependent upon residence times.
7. The spatial and temporal variability of GSI at MBR precluded the use of traditional stream tracer tests and modeling to characterize and quantify GSI as they are not suited to capture the highly variable nature of the exchange.
8. Near-stream GSI losing and gaining behavior was verified by stream flow measurements and continuous data logger temperature data at each of the stream features at MBR.
9. Continuous data loggers that measure water level and temperature were successfully employed at MBR to evaluate the impact of a storm surge on GSI at stream features.
10. Given the dependency of GSI at MBR on stream features and their geomorpholigical settings, any restoration activity impacting these features would likely also impact the GSI. The magnitude and direction of GSI change could be easily characterized using water levels in piezometer nest in the stream bed and banks measured at regular time intervals.

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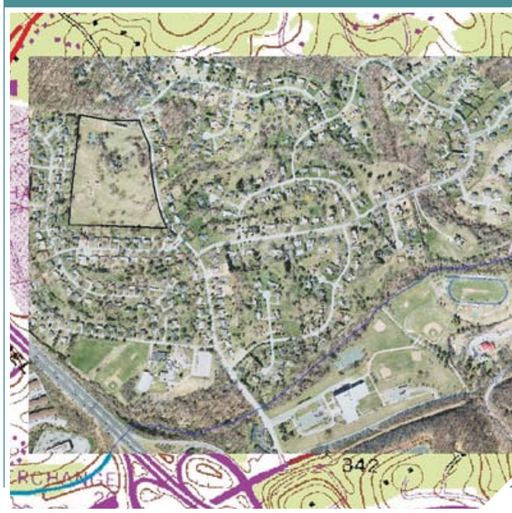

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