Report for 2005NC47B: Characterization of Surface Water/Ground Water Interactions along the Tar River using Ground Penetrating Radar

Publications

- There are no reported publications resulting from this project.

Report Follows

Title

Characterization of Surface Water/Ground Water Interactions Along the Tar River Using Ground Penetrating Radar (70215)

Problem and Research Objectives

Groundwater inputs are important to streams for their influence on stream hydrology and ecology (Hayashi and Rosenberry 2002). Spatial variability of groundwater inputs to streams is common due to aquifer heterogeneity, slope, and variability in land cover. Groundwater withdrawals may also affect groundwater inputs to streams by pirating water from them (O'Driscoll 2004, Lautier 2001). The degree to which a stream interacts with the underlying ground water system is important for a variety of scientific, practical, and legal reasons, such as wellhead protection (Nnadi and Sharek 1999), bank filtration (Sheets et al. 2002), stream ecology (Brunke and Gonser 1997), and non-point source pollution from adjacent lands (Hill et al. 1998).

In the past, various methods have been used to study surface water-ground water interactions in diverse hydrogeological settings and at various scales (Edwards 1998, Harvey and Wagner 2000, and Woessner 2000). Common techniques include seepage runs (Zelwegger et al. 1989), seepage meters (Lee 1977, Isiorho and Meyer 1999), remote sensing (Atwell et al. 1971), radioactive and stable isotope tracers (Hoehn and Santschi 1987), water chemistry (Katz et al. 1997), dye tracers (Bencala et al. 1984, Triska et al. 1993), piezometery (Lee and Cherry 1978, Geist et al. 1998), biological investigations (Stanford and Ward 1993), numerical models (Nield et al. 1994), and water temperature (Silliman et al. 1995).

Stream channel sediment hydraulic properties are typically heterogeneous (Jones and Mullholland 2002). Numerous piezometers are required to adequately characterize hydraulic properties of an active river channel. Piezometer installation and monitoring in active river channels is difficult and expensive. In the Coastal Plain of North Carolina, it is difficult to maintain river channel piezometer installations for long periods because of flooding due to tropical storms and hurricanes. Practical techniques are needed to characterize the geological framework of the active river channel that controls the river's relationship with the ground water system.

Recently, ground penetrating radar has emerged as a tool to characterize complex heterogeneities in paleochannels and floodplain settings (Naegeli et al. 1996 and Beres et al. 1999). GPR has been used in river channels to characterize the sediments adjacent to gravel-bed river channels (Naegeli et al. 1996). In this study, they dug a trench to ground-truth the GPR profiles. In the Rhine valley of northeastern Switzerland GPR surveys were conducted in step mode to characterize the glaciofluvial sediment framework. The GPR data was ground-truthed against outcrop photographs (Beres et al.1999). These studies have shown that groundpenetrating radar has the potential to improve our understanding of the sedimentary framework of active river channels, and how rivers and groundwater systems interact.

An improved understanding of river-groundwater interactions along coastal plain rivers is important because water chemistry within these river systems is strongly influenced by the connections and fluxes between river and groundwater systems (Spruill 2004). These interactions are strongly controlled by the near-channel stratigraphic framework and the surficial aquifer. The surficial aquifer that extends across the Coastal Plain of North Carolina ranges from 1-68 meters thick (Lautier 2001). It consists of fine grained sand, silt, clay, and shell materials typically of Holocene to Pleistocene in age. The complex stratigraphy of floodplain settings, active channel sediments, the surficial aquifer, and other shallow aquifers influence the direction and magnitude of ground water flows and associated nutrients to rivers along the Coastal Plain. The nature of river-groundwater interactions along coastal plain rivers is not well known. We used a two-fold approach to study groundwater interactions with the Tar River: using physical hydrograph separations and field hydrogeophysical approaches to look at long-term and spatial variations of groundwater inputs to the Tar River and the geological controls on these inputs. Our study objective was to characterize river-groundwater interactions along the Tar River.

Methodology

The distribution of floodplain and river channel sediments adjacent to coastal plain rivers is complex and requires numerous sediment cores to characterize, yet is very important to understanding river-ground water interactions and contaminant transport. Eighteen piezometers and 39 meters of split spoon cores and hand auger samples were used to characterize the subsurface and groundwater inputs along a 22 kilometer stretch of the Tar River, eastern North Carolina, USA. Additionally, 2-D and 3-D GPR data were collected using a GSSI SIR-2000 system with a 200 MHz antenna, to define the shallow stratigraphic framework. The ultimate goal was to use GPR to assess the hydraulic characteristics of floodplain and channel deposits.

Hydrograph separations and discharge analysis

Daily discharge data was obtained from the U.S. Geological Survey stream gage at Tarboro, NC (USGS Gage 02083500 Latitude 35°53'40", Longitude 77°31'59", Drainage Area - 2,183 miles^2 or 5653 km^2). This record spans the period of 1931-2002 and was used to determine long-term variations in baseflow contributions to the Tar River. In addition, the daily discharge data from the U.S. Geological Survey stream gage at Tarboro, NC was statistically analyzed for the period from 1931-2002 to determine long-term trends in discharge and discharge variability over time. U.S. Geological Survey stream flow records from Tarboro and Greenville were used to quantify seasonal downstream increases in stream flow over the period of record (1997-2005).
The Greenville gage has a record from 1997-present (USGS Gage 02084000 Latitude 35°37'00", Longitude 77°22'22", Drainage Area-2,660 miles^2 or 6890 km^2). To determine large-scale ground water inputs to the Tar River, differences in baseflow were compared between Tarboro and Greenville.

Mechanical hydrograph separation was performed on the discharge data using a hydrograph analysis model (W.H.A.T.- Web-based Hydrograph Analysis Tool) developed by Lim et al. 2005. The local minimum method was chosen to separate the stream hydrograph into baseflow and stormflow components. This method analyzes each daily measurement of streamflow. A discharge point is considered the local minimum if it is the lowest discharge in one half the interval minus 1 day (0.5(2N-1) before and after the date being considered (Sloto and Crouse 1996). The baseflow values for each day between local minimums are estimated by linear interpolations, the lowest points on the hydrograph are connected by straight lines, anything above this line is considered stormflow and anything below is considered baseflow. The line for the entire data series of daily streamflow from 1931-2003 was estimated using the model and the associated stormflow and baseflow components were estimated.

Geophysical surveys

Ground penetrating radar (Geophysical Survey Systems Inc., Subsurface Interface Radar System-2000 with 200 MHz antenna) was used to characterize heterogeneity in the underlying active river channel sediments. The stratigraphy beneath the river bottom was imaged to depths up to approximately 5 meters. GPR transect data was collected in continuous mode, and at higher spatial resolution at targeted sites to characterize subsurface stratigraphy along 18 segments of the 22 km study reach. To reference GPR data we used sediment logs and hydraulic conductivity information from borings within and adjacent to the river channel. The GPR antenna was floated in a rubber raft and data were collected in continuous mode (Figure 12). Navigation was acquired using a Trimble GPS, and differentially corrected position data were linked to the GPR data by waypoint and scan number. Twenty-one surveys included cross-sections perpendicular to the river channel.

GPR data was processed using Radan v.7 (copyright Geophysical Survey Systems, Inc.). Raw data were filtered to remove background noise and gain was adjusted to bring out horizons and other reflectors. Processed GPR data was then uploaded into Canvas v.8, where color interpretations, scale and direction were added.

Sediment Sampling and Ground Water/Surface Water Monitoring

Eighteen piezometers and 39 m of split spoon cores and hand auger samples were used to characterize the subsurface near the Tar River. Split-spoon samples of floodplain and active channel sediments were obtained during piezometer installation to reference GPR transects. Slug tests were performed at all piezometers to characterize the hydraulic properties of the surrounding sediments. The Bouwer and Rice Slug Test Method was used (Fetter 1994). Water level changes during slug tests in each piezometer were recorded using Hobo water level recorders.

Piezometers were used to characterize the interaction of ground water and surface waters of the study reach consisting of a 22 km stretch along the Tar River, Pitt County, North Carolina, USA. We selected five locations for ground water and surface water monitoring, as indicated in Figure 6. At four of the five locations along the Tar River nested piezometers were installed adjacent to the river at shallow and deeper depths of 4 and 7m (respectively) below the channel sediment-water interface. These installations were performed with a hollow-stem auger drill rig and sediment cores were collected using a split-spoon sampler. The fifth location at US Route 264 was not instrumented with nested piezometers , but was instrumented with channel piezometers. Channel piezometers were installed at all sites within the river channel. Channel piezometers had screens that were 0.76 m long and the bottom of the screens were typically installed approximately 1.83 m below the sediment-water interface. Piezometers were typically secured to large trees located along the stream banks (Figure 13). Casing elevations for all piezometers were surveyed using a laser theodolite.

Hydraulic conductivity was estimated for 18 piezometers. River-ground water head gradients were measured in each piezometer every two weeks since September 2005. In addition, on the south side of the river the surface water and ground water levels and temperatures were recorded with HOBO pressure transducers at 30 minute intervals and downloaded monthly using a laptop computer. Measured hydraulic conductivity values were used to calculate ground water flux to and from the river channel (Darcy's Law), using head gradients based on those measured in the river.

Water temperature recorders and pressure transducers were installed in stream channel piezometers adjacent to the river. Surface water temperature and stream stage were also recorded at these locations. Ground water temperature and water level measurements were recorded at all five sites to quantify temporal variations in ground water flux to the river channel. Water temperature and hydraulic head data were downloaded on a monthly basis.

Principal Findings

Long-term (1931-2003) baseflow analysis for the Tar River at Tarboro indicated that baseflow is the major component of river discharge along the Tar (60% on average). There have been slight changes in baseflow discharge along the Tar over this time period. In general, baseflow has become more variable over time, with an increase in the occurrence of high and low flow events. These changes may be due to changes in climate and/or land-use over time.

Urbanization, stormwater runoff, wastewater discharge, water supply withdrawals, and interbasin transfers may all affect the frequency, timing, and magnitude of baseflow discharge over time in the Tar River basin. In addition, subtle changes in climate that have occurred over the last 50 years may also influence baseflow discharge. Work done by Boyles (2000) indicates that the climate in North Carolina has been slowly changing since the 1950s with a common pattern of increased rainfall during fall and winter and decreased rainfall in summer months. This change in rainfall patterns may explain trends in Tar River baseflow since increased precipitation during high baseflow periods in the winter could cause the occurrence of high baseflows to increase, whereas lesser rainfall in summer months could result in a decrease in occurrence of low baseflows. If this rainfall trend continues the summer low baseflows along the Tar may be susceptible to further decreases in the future.

Seasonal variations in baseflow are common along the Tar and the extreme low baseflows are typical occurrences in the summer months due to increased solar radiation, warmer temperatures, increased evaporation, and plant uptake of surface water and ground water. During summer months the Tar River is vulnerable to low baseflows that are related to recent weather patterns and this time period is likely to be the most sensitive to future climate change in the region. A comparison of annual baseflow and rainfall grouped by season (dormant vs. growing) showed dormant season rainfall to be most important to annual groundwater recharge and baseflow generation within the Tar Basin. The amount of dormant season rainfall that occurs annually has a greater influence on the baseflow discharge to the Tar than rainfall during the growing season. If rainfall amounts change in the region as a result of climate change, the modifications of rainfall distribution throughout the year will be important to determining the effects on baseflow to this and other coastal plain rivers. Typically, the greatest variability in baseflow occurred during the months of September and October, due to hurricane effects on baseflow. Baseflow magnitudes can be extremely low or high during these months depending on recent storm activity. If the frequency and magnitude of hurricane and tropical storm landfalls change in the future this will have an effect on baseflow discharge to the Tar, particularly during the fall.

Baseflow inputs along the Tar typically increase downstream from Tarboro to Greenville. However, there are several time periods where baseflow decreases downstream, indicating channel losses or large amounts of evapotranspiration between the gauges. During our study, stream losses were also indicated in several piezometers along the Tar. For the period of April 1997-Feb 2006 the average baseflow increase downstream was 199 ft^3/s or a 20% increase relative to baseflow at Tarboro. This translates to groundwater inputs of approximately 9 ft^3/s/mile. Seasonally there is significant variation in baseflow increases downstream ranging from 4 ft^3/s/mile during summer to 17.5 ft^3/s/mile during winter.

Variations in river-groundwater interactions were noticeable with time and distance along the Tar and were observed in channel and nested piezometers. The river was typically gaining groundwater, however several instances of losing segments were observed. Hydraulic conductivity variations were large between sites, with the range of hydraulic conductivity measured in piezometers of $10^{-2.03}$-$10^{-7.03}$ cm/s, with a median value of $10^{-3.38}$ cm/s, representative of sandy channel sediments. A pattern was evident in the hydraulic conductivity data, the channel sediments on the north side of the river typically had greater hydraulic conductivity values when compared to those on the south side of the river. Sediment cores and GPR data indicate that there are differences in sediment type that are related to the channel asymmetry commonly observed along the Tar. Generally the south side of the river has steep banks, and is underlain by Pliocene to Cretaceous sediments that often contain marine or estuarine clays that tend to have low hydraulic conductivities. On the north side of the river the floodplain is extensive, the topography is gentle, and the underlying sediments tend to be sandy deposits that are likely reworked alluvial sediments. These sediments tend to be more permeable, hence groundwater inputs on the north side of the river tend to be greater than those on the south side of the river. Clay sediments on the south side of the river may also cause groundwater inputs to occur as springs or seeps which were not inventoried in this study. The general presence of sandy sediments along the north side of the river is one reason for the high concentration of sand and gravel pits on the north side of the river when compared to the south side.

Cross-sections of the river channel were typically asymmetrical, with the steeper banks almost always located on the southern side of the river. The channel asymmetry that occurs along the Tar is noticeable for the entire study reach and this pattern is also common along other Coastal Plain Rivers in Virginia, North Carolina, and South Carolina, indicating that these differences in hydraulic conductivity and the groundwater fluxes may also occur at a regional scale. Several studies have indicated that this floodplain asymmetry may be related to uplift in the region, causing rivers to incise to the south and preserving reworked fluvial deposits to the north (Sexton 1999 and Soller 1988).

Another pattern related to channel asymmetry was observed in the groundwater specific conductance data. Typically the specific conductance of groundwater underlying the Tar varied depending on what side of the river it was sampled along. This is likely related to differences in residence time and groundwater flowpaths adjacent to and underlying the river. Greater hydraulic conductivity sediments were found to typically have lower groundwater specific conductance values. This relationship between hydraulic conductivity and specific conductance in channel groundwaters may be useful in future studies to quantify river groundwater interactions and channel hydraulics of this and other coastal plain rivers. Ground penetrating radar was found to be a useful tool in determining the bathymetry of the river channel and the nature of the sediments underlying the river channel. The stratigraphy beneath the river bottom was imaged to depths up to approximately 4 to 5 meters using GPR transect data collected in continuous mode. Data collected along the Tar River indicated that GPR appears to be well-suited to characterize the variability of active channel sediment properties along and perpendicular to the river channel at depths of several meters below the channel.

Two notable limitations to the use of GPR in these coastal plain systems exist, first the signal is attenuated in clay sediments so the GPR data may only indicate the depth to the first clay layer. Second, as salinity increases in coastal plain rivers towards the coast, the GPR signal becomes attenuated in the water column.

The hydrograph separation analysis indicated that baseflow (groundwater) comprises 60% of the Tar River streamflow over time. Hydrograph separations and discharge analysis revealed that baseflow contributions to the Tar River have changed since the 1930s. The magnitude and variability of baseflow feeding the Tar River have changed slightly, daily mean baseflow has decreased by 49 cubic feet per second (cfs) (1.34 m^3/s) and daily minimum baseflows have dropped 33 cfs (0.93 m^3/s). The variability of baseflow within a given year as measured by the coefficient of variation has increased by 8% when comparing data before 1971 and after 1971.

Ground water head data indicated that the shallow water table aquifer had a high degree of complexity on a local scale. Sediment samples and slug tests conducted in stream-channel piezometers indicated that the geology between the north and south sides of the river varied significantly, with a direct effect on the movement of ground water through the river channel.

Ground water flux into and out of the channel varied between the north and south sides of the river by as much as four orders of magnitude. The differences appear to be related to stratigraphic differences between the north and south sides of the river. GPR transects successfully located key hydrogeologic elements such as clay layers (confining beds), sand lenses, and active channel bedforms, which had a direct impact on the movement of ground water. GPR is a useful tool for the characterization of subsurface sediments underlying river channels and can provide information on the interactions between the shallow water table aquifer and surface waters along coastal plain rivers.

Future work will include various field tasks to improve the understanding of the relationship between GPR transects and sediment hydraulic properties. A sediment sampling program is being developed to obtain deeper sediment samples underneath the river channel (drill /vibracore ~ 5-10m depth) to develop an improved understanding of GPR profiles and their relationships with groundwater inputs. Future groundwater monitoring at the sites will help to develop relationships between groundwater flux and specific conductance of ground water along the Tar and we will seek to monitor specific conductance during storm events to determine how groundwater fluxes vary during runoff episodes. In addition more hydraulic conductivity data will be collected along the river in temporary wells to better determine the spatial variability of hydraulic conductivity in the river channel sediments and their relationships to groundwater flux and ground penetrating radar data.

Significance

Future work will include various field tasks to improve the understanding of the relationship between GPR transects and sediment hydraulic properties. A sediment sampling program is being developed to obtain deeper sediment samples underneath the river channel (drill /vibracore ~ 5-10m depth) to develop an improved understanding of GPR profiles and their relationships with groundwater inputs. Future groundwater monitoring at the sites will help to develop relationships between groundwater flux and specific conductance of ground water along the Tar and we will seek to monitor specific conductance during storm events to determine how groundwater fluxes vary during runoff episodes. In addition more hydraulic conductivity data will be collected along the river in temporary wells to better determine the spatial variability of hydraulic conductivity in the river channel sediments and their relationships to groundwater flux and ground penetrating radar data.

Ground penetrating radar surveys should be run along all major coastal plain rivers in North Carolina and correlated with the geology. These data would help indicate locations where the rivers are in connection with important aquifers or are separated by aquicludes. A map of these features would be very useful in determining areas where groundwater management may affect rivers or vice versa.

Ground penetrating radar surveys should be run along piedmont and mountain rivers in North Carolina. Future work should evaluate the effectiveness of ground penetrating radar as a subsurface investigation tool in these settings.

In this study groundwater fluxes were typically several orders of magnitude larger on the north side of the river when compared to the south side. Hydraulic characteristics of sediment along the Tar River were dependent on the side of the river they were measured along. The river is in contact with Pliocene or older marine or estuarine sediments that tend to have clays and silts on the south side of the river. On the north side, the river is frequently in contact with reworked fluvial sediments which tend to be better sorted and coarser, typically fine to coarse sands. From observations made by other researchers this pattern is quite common along other coastal plain rivers in Virginia, North Carolina, South Carolina and Georgia. If similar behavior exists in other coastal plain rivers it is likely that the effects of land-use will vary based on the side of the river. Contaminants from septic systems, leaking underground storage tanks, and other anthropogenic sources on the north side of the river will be more likely to migrate to the river when compared to similar land-use on the south side of the river. Future work should address the variability in contaminant transport due to floodplain asymmetry along coastal plain rivers.

The degree of asymmetry of the Tar floodplain is notable. The Tar has been migrating to the south for at least thousands of years. The incision of the river and the presence of terraces to the north has allowed for the preservation of Holocene and Pleistocene sediments on terraces to the north. These sediments may hold important information with regards to past climate, hurricane occurrence, and flood frequency along the Tar. With new age dating technologies, such as optically stimulated luminescence (OSL), dating of these terraces and the various sediments underlying them may help unravel the past climate of the region.

Measurement of hydraulic conductivity in channel sediments is necessary to determine the hydraulic properties of river channels and their interactions with groundwater systems. However, this requires installing numerous piezometers or wells throughout a river basin which can be very labor intensive and expensive. Based on our hydraulic conductivity data obtained from channel piezometers along the Tar and their relationship with specific conductance data obtained from the same piezometers it may be possible to develop a relationship between hydraulic conductivity and specific conductance of groundwater as a means to estimate hydraulic conductivity in the channel. Future work will aim to evaluate the effectiveness of this approach.

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