SURFACE WATER/GROUND WATER INTERACTIONS ALONG THE TAR RIVER, NC

By
Michael A. O'Driscoll
David J. Mallinson
Patrick K. Johnson

Department of Geology
East Carolina University
Greenville, North Carolina

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Department of Geology
East Carolina University
Greenville, NC 27858-4353

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Abstract

The nature of river-groundwater interactions along coastal plain streams is not well-known. We used a two-fold approach to study groundwater inputs to the Tar River (Edgecombe and Pitt Counties, NC): using physical hydrograph separations and statistical analysis of long-term discharge (1931-2002) to look at the long-term and seasonal variability of groundwater inputs and a hydrogeophysical field study approach to evaluate geological controls on groundwater inputs to the Tar River.

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.

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.

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.
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Summary and Conclusions

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 ft³/s or a 20% increase relative to baseflow at Tarboro. This translates to groundwater inputs of approximately 9 ft³/s / mile. Seasonally there is significant variation in baseflow increases downstream ranging from 4 ft³/s / mile during summer to 17.5 ft³/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 $10^{-2.03}$ to $10^{-7.03}$ 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.

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.
**Recommendations**

1. 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.

2. 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.

3. 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.

4. 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.

5. 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.
INTRODUCTION

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 ground-penetrating 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.

METHODS

STUDY AREA

Geological setting

The Tar River drainage basin occurs predominantly in the coastal plain of North Carolina, with approximately 20% of the basin draining the piedmont. The central coastal plain is underlain by the unconfined surficial aquifer which is composed principally of Holocene to Pleistocene aged sediments. In the study region, within Pitt County, NC, the lower boundary of the unconfined surficial aquifer is always less than 15m below the land surface, but typically within 3-6m below the land surface (Sumison 1970). The regional surficial geology is mostly unconsolidated sands, silts and clays (Spruill et al. 2003). The Yorktown formation is also present in the near surface within the region (Figure 1). The Yorktown is a Pliocene fossiliferous clay with varying amounts of fine-grained sand (Winner and Coble 1996). Because of erosion the Yorktown may not be present in some locations underlying Pitt County. Along the study reach of the Tar River, from Falkland to Greenville, NC, the Yorktown or surficial aquifer is either directly underlain by the Black Creek formation to the west near Falkland, or the Pee Dee Formation, near Greenville (Figure 1). The Tar River has incised down through the Yorktown formation and Surficial aquifer along its banks in many locations may flow through the Black Creek Formation or the Pee Dee Formation along the study reach.

A notable occurrence along the Tar River is the valley asymmetry, with the river frequently located at the extreme southwestern side of its valley. This results in a common pattern of steep bluffs and very narrow floodplains to the southwest of the river, and extensive floodplains and gentle slopes on the northeast side of the river. This pattern is a common occurrence along Atlantic coastal plain rivers. Several researchers have indicated that tectonic uplift is a likely explanation for similar river asymmetry in South Carolina (Sexton 1999) and along the Cape Fear River in North Carolina (Soller 1988).

Other commonly observed features along the Tar River are paleo-braidplain deposits. Paleo-braidplain deposits are commonly found along terraces adjacent to major rivers in the Atlantic Coastal Plain and recent work indicates these may have been deposited between 17-70 thousand years ago during a different climate regime (Leigh et al. 2004). The transition from braiding to meandering rivers systems has been dated at approximately 15-16 thousand years ago and has been attributed to a climate shift to warmer and wetter conditions in the southeastern US which promoted vegetation growth and resulted in reduced sediment loads to rivers (Leigh
These deposits are often coarse grained and found along the north side of the Tar River. These deposits may have local influences on river-groundwater interactions because they are well drained and highly permeable.

The Black Creek Formation, which underlies the Tar along a large portion of Pitt County, consists of Late Cretaceous lagoonal to marine sediments. Typically Black Creek sediments are thinly laminated gray to black muds interlaminated to interbedded with tan sands that are very fine to fine (Winner and Coble 1996). The Black Creek aquifer is on average 60% sand and often is characterized by well-defined beds of clean sand and gray to black clay. A primary characteristic of the Black Creek Formation is that it has a high content of organic material, lignitized wood, shell material, and glauconite. The confining unit that overlies the Black Creek aquifer, is composed of clay, silty clay, and sandy clay and is an average of 13 m thick. Along the Tar River, the river may be directly connected with the Black Creek Aquifer System because it may cut through the Black Creek confining unit in some locations. The Black Creek may discharge into the Tar where the channel cuts into it or its overlying confining unit.

To the east, the Pee Dee Formation typically underlies the Tar River. The aquifer is mainly composed of Late Cretaceous fine to medium grained sand (almost 70% sand) interbedded with gray to black marine clays. The sand beds are often gray to greenish gray and contain varying amounts of glauconite. Thin beds of consolidated calcareous sandstone and impure limestone interlayered with sands and shells are commonly found throughout this formation. The Pee Dee confining unit on top of the Pee Dee aquifer is composed of clay, silty clay, and sandy clay and is on average 8 m thick. The clays of the Pee Dee confining unit typically have very low permeabilities in most areas (Winner and Coble 1996).
Figure 1. Generalized east-west cross-section through Pitt County study area illustrating the projected subsurface geology along the Tar River (modified from Maddry 1979).

**Hydrology and Meteorology**

The Tar–Pamlico River basin is the fourth largest river basin in North Carolina and its boundaries are located entirely within North Carolina. The basin drains an area of 14,000 km² (5,440 miles²). Land-use varies within the watershed with the major land-use being forest and wetlands (54%), 22% is cultivated cropland, 20% is open water area, 3% is pasture and other managed herbaceous areas, and 1% is urban (NC DENR 2003). Approximately 80% of the basin is located in the coastal plain and characterized by flat terrain, blackwater streams, low-lying swamps, and estuarine areas. Tributary streams are typically low-gradient, slow flowing with extensive swamps and bottomland hardwood forests in their floodplains (NCDENR 2003). The bulk of discharge to streams is from unconfined aquifers (Winner and Coble 1996).
A long-term record of streamflow has been collected for the Tar River at the U.S. Geological Survey stream gage in Tarboro, NC (Figure 2). Mean annual streamflow for the Tar River at Tarboro, NC is 2,286 ft³/s (65 m³/s), based on the period of 1931-2003. Typically streamflow is greatest during March and lowest during October along the Tar. A common occurrence is an increase in streamflow during September due to hurricane inputs (Figure 3).

Figure 2. Long-term Tar River discharge measured at the U.S. Geological Survey gage at Tarboro, NC (source: U.S. Geological Survey).
Average annual rainfall measured at the Upper Coastal Plain Research Center (Rocky Mount, NC) was 46.5 inches (118 cm) for the period of 1971-2000 (Boyles et al. 2004). Based on streamflow data for this period collected at Tarboro (14.7 inches or 37.3 cm of runoff per year), average annual evapotranspiration is 31.8 inches (80.7 cm) or approximately 68%. A longer term climate record (1931-2006) at Greenville, NC indicates that annual rainfall averages are greater downstream within the Tar watershed (49.3 inches or 125.2 cm) and average annual air temperature is 61.2º F (16.2ºC). In this record upward or downward trends in annual rainfall amount are not noticeable (Figure 4). However, Boyles (2000) has shown that although total annual precipitation amounts within North Carolina may not vary significantly over the last 50 years, there have been significant changes in precipitation distribution throughout the year across North Carolina. Rainfall data from 1949-1998 indicate an upward trend in rainfall amount during fall and winter seasons, along with decreased rainfall during summer months (Boyles 2000). Therefore, even though trends may not be obvious in average annual rainfall amount evidence suggests that rainfall distribution throughout the year is changing in North Carolina. A more noticeable change in climate (as observed at the Greenville, NC station) is the recent upward trend in annual average air temperatures (Figure 5). Although a recent upward trend exists, the recent average annual air temperatures at this location are similar to those observed at Greenville during the 1950s and earlier. Similar trends have been shown for other North Carolina locations (Boyles 2000).
Figure 4. Long-term annual rainfall amounts measured at Greenville, NC (1931-2006) (Source: North Carolina State Climate Office). The black line is the 10-year moving average.

Figure 5. Long-term average air temperature measured at Greenville, NC (1931-2006) (Source: North Carolina State Climate Office). The black line is the 10-year moving average.
STUDY SITES

Five sites along the Tar River were selected for study. The study reach extends from Falkland to Rainbow Banks, approximately 22 km long. Access permission was granted by the North Carolina Department of Transportation (Rte 264), North Carolina Wildlife Resources Commission (Falkland Boat Ramp), the City of Greenville (Elm Street and Port Terminal Road), and Dr. Stan Riggs, East Carolina University (Rainbow Banks) (Figure 6).

Figure 6. Study reach of the Tar River from Falkland to Greenville, NC. (F) Falkland, (2) 264, (E) Elm Street, (P) Port Terminal Rd, (R) Rainbow Banks.
The Falkland site is located approximately 13 km northwest of Greenville, NC upstream from the Falkland Boat Ramp, directly off of State Highway 222 (035° 41’ 43.78”N, 077° 29’25.34”W) (Figure 7). At this location the stream channel elevation is 3 m above mean sea level. Conetoe Creek discharges into the Tar River approximately 125 m downstream. Land-use surrounding the site consists of predominantly forested floodplain with some drained croplands. The floodplain is approximately 1 kilometer wide at this location. The elevation difference between the floodplain and the uplands varies significantly between the north and the south sides of the river, on the south side of the river steep bluffs exist and upland areas near the river can be as high as 24m, whereas on the north side of the river the greatest land surface elevations are typically less than 13 m. The predominant soil types at the site are Ch (Chipley sand, moderately well drained) and La B (Lakeland sand, excessively well-drained) along the channel and floodplain and AlB (Altavista sandy loam, moderately well drained soil) is present at greater distances from the river (Karnowski et al. 1974). The stream slope at the site is approximately 4.4 cm/km.
The 264 site is located approximately 5 km northwest of Greenville, NC downstream from the US 264 North Bridge (035° 38' 39.40"N, 077° 25' 1.91"W) (Figure 8). At this location the stream channel elevation is 1 m above mean sea level. Bryan Creek discharges into the Tar River upstream and to the west of the site and Johnsons Mill Run joins the Tar just east of the site. Land-use surrounding the site consists of predominantly forested floodplain with several gravel pits within the floodplain. There is some residential development on the north side of the river, whereas the south side is currently forested. The floodplain is approximately one kilometer wide at this location. The elevation difference between the floodplain and the uplands varies significantly between the north and the south sides of the river, on the south side of the river upland areas near the river can be as high as 25m, whereas on the north side of the river the greatest land surface elevations are typically less than 9 m. The predominant soil types at the site are Bb (Bibb fine sandy loam, poorly drained), Os (Osier loamy sand, poorly drained), and Sw (Swamp, poorly drained loamy organic mixed dark alluvium) which are typically located in floodplain areas adjacent to the river and La B (Lakeland sand, excessively well-drained) and AlB (Altavista sandy loam, moderately well drained soil) which are typically located at higher elevations and at a greater distance from the river (Karnowski et al. 1974). The stream slope at the site is approximately 13 cm/km.
Elm Street

Figure 9. Site map and location of the Elm Street (E) monitoring station.

The Elm Street site is located in Greenville, NC at the end of Elm Street, 1.5 km downstream of the Town Commons (035° 38’ 39.40”N, 077° 25’ 1.91”W) (Figure 9). At this location the stream channel elevation is 1 m above mean sea level. Parker Creek discharges into the Tar River upstream and to the west of the site. Land-use surrounding the site consists of predominantly forested floodplain on the north side of the river and urban development on the south side of the river. The floodplain is approximately 1.3 km wide at this location and most of the floodplain exists on the north side of the river. The elevation difference between the floodplain and the uplands varies significantly between the north and the south sides of the river, on the south side of the river upland areas near the river can be as high as 18 m, whereas on the north side of the river the greatest land surface elevations are typically less than 8 m. The predominant soil type at the site is Bb (Bibb fine sandy loam, poorly drained) near the river. This poorly drained soil is common in the floodplain (north side) and WaB (Wagram loamy sand, well drained), Os (Osier loamy sand, poorly drained), AgB (Alaga loamy sand, excessively well drained), and Pa (Pactolus loamy sand, moderately well drained) are more common at higher elevations and greater distances from the river (Karnowski et al. 1974). The stream slope at the site is approximately 3 cm/km.
Port Terminal Road

Figure 10. Site map and location of the Port Terminal Road (P) monitoring station.

The Port Terminal Road site is located in Greenville, NC at the end of Port Terminal Road, just downstream of the Boat Ramp, 6 km downstream of the Town Commons (035° 35’ 50.94”N, 077° 18’39.46”W) (Figure 10). At this location the stream channel elevation is 1 m above mean sea level. Hardee Creek and Meeting House Branch converge approximately 1 kilometer upstream and their waters discharge into the Tar just upstream of the Boat Ramp. Land-use surrounding the site consists of predominantly forested floodplain on the north side of the river and some residential development at higher elevations on the south side of the river. The floodplain is approximately 1.5 km wide at this location and most of the floodplain exists on the north side of the river, although several hundred feet border the south side of the river. The elevation difference between the floodplain and the uplands vary significantly between the north and the south sides of the river, on the south side of the river upland areas near the river can be as high as 20m, whereas on the north side of the river the greatest land surface elevations are typically less than 4 m. The predominant soil type at the site is Bb (Bibb fine sandy loam, poorly drained) near the river. This poorly drained soil is common in the low-lying floodplain areas (mostly on the north side of the river) and LaB (Lakeland sand, excessively well-drained), OcB (Ocilla loamy fine sand, somewhat poorly drained), and Os (Osier loamy sand, poorly drained) are more common at higher elevations and greater distances from the river (Karnowski et al. 1974). The stream slope at the site is approximately 3 cm/km.
Rainbow Banks

Figure 11. Site map and location of the Rainbow Banks (R) monitoring station.

The Rainbow Banks site is located in Greenville, NC at the Riggs’ Property along Rte 33, 6 km downstream of the Greenville Town Commons (035° 35’ 50.94”N, 077° 18’ 39.46”W) (Figure 11). At this location the stream channel elevation is 1 m above mean sea level. Mill Branch discharges into the Tar approximately 200 meters upstream. Land-use surrounding the site consists of predominantly forested floodplain on the North side of the river, croplands are more common at greater distances and higher elevations from the river. Some residential development is present at higher elevations on the south side of the river. The floodplain is approximately 1.5 km wide at this location and most of the floodplain exists on the north side of the river. The elevation difference between the floodplain and the uplands varies significantly between the north and the south sides of the river, on the south side of the river upland areas near the river can be as high as 19 m, whereas on the north side of the river the greatest land surface elevations are typically less than 6 m. The predominant soil type at the site is WaC (Wagram loamy sand, well drained, steep slope), at higher elevations and Bb (Bibb fine sandy loam, poorly drained) at lower elevations near the river on the south side and Ch (Chipley sand, moderately well drained) adjacent to the river and OcB (Ocilla loamy fine sand, somewhat poorly drained), at greater distances from the river on the north side of the river (Karnowski et al. 1974). The stream slope at the site is approximately 3 cm/km.
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 miles² or 5653 km²). 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 miles² or 6890 km²). 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.

SUBSURFACE INVESTIGATION

Geophysical Surveys

Ground penetrating radar (Geophysical Survey Systems Inc., Subsurface Interface Radar System-2000 with a 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. We used sediment logs and hydraulic conductivity information from borings within and adjacent to the river channel to reference horizons in the GPR data. The GPR antenna was floated in a rubber raft; 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, longitudinal transects, and 3-D grids. Data was processed using Radan v.6 software (copyright GSSI), which allowed for 2-D visualization of data.
Figure 12. Ground penetrating radar was floated in a raft to image the underlying river channel sediments at the Falkland site along the Tar River.

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.
Figure 13.a. Typical stream-ground water level monitoring station

Figure 13.b. Water level recorders along the Tar River at Falkland, NC.
RESULTS

Hydrograph Separation and Discharge Analysis

The hydrograph separation (local minimum method) performed on the daily Tar River discharge data (Tarboro gage) from 1931-2003 revealed that on average baseflow makes up 60% of total discharge (Figure 14). The extreme values of baseflow and total discharge in 1999 were related to runoff from Hurricane Floyd. In general, there is a strong seasonality in baseflow related to annual variations in rainfall and evapotranspiration.

![Figure 14. Long-term total hydrograph separation (1931-2003) for total discharge at Tarboro, NC USGS gage. Total discharge is in blue and the baseflow component is in red.](image)

Based on the long-term record, baseflow is typically at a maximum during March and at a minimum during October (Figure 15). There is a small upward trend in total discharge during the summer that peaks in September, this is likely due to the type of rainfall events common in summer months, convective thunderstorms that quickly saturate the ground and allow runoff to occur. The large water demand by vegetation during these months would also result in lower baseflows. In September the increase in total discharge is related to the occurrence of tropical storms and hurricanes. A time series of the baseflow composition of the total runoff (as a percentage) reveals a large difference in composition of total discharge during the growing season (May-October) with a minimum during September (Figure 16).
Figure 15. Long-term variations in monthly total discharge and baseflow, at Tarboro, NC USGS gage (1931-2003).

Figure 16. Long-term variations in monthly baseflow percentage of total discharge, at Tarboro, NC USGS gage (1931-2003).

The importance of non-growing season rainfall to annual baseflow can be illustrated by comparing the total annual rainfall and the dormant season annual rainfall with the annual baseflow at Tarboro. A comparison of mean annual baseflow versus total annual rainfall and a comparison of mean annual baseflow versus total annual dormant season rainfall (1932-2002) indicate that rainfall during the non-growing season is more important in determining the amount of annual baseflow in the Tar (Figure 17). The regression equations indicate that dormant season precipitation for a given year predicts the mean annual baseflow better than the total annual precipitation for a given year. Based on $R^2$ values from the regression equations the dormant
season precipitation predicts 11% more of the variance in baseflow when compared to total annual precipitation, indicating that lesser recharge occurs during the summer/growing season.

![Graph showing comparison of mean annual baseflow versus total annual rainfall and a comparison of mean annual baseflow versus total annual dormant season rainfall (1931-2003).](image)

**Figure 17.** Long-term comparison of mean annual baseflow versus total annual rainfall and a comparison of mean annual baseflow versus total annual dormant season rainfall (1931-2003).

To evaluate the variability of baseflow and total discharge during a given month the coefficient of variability (standard deviation/mean*100%) was calculated for each month using daily baseflow and total daily discharge values (Figure 18). The analysis revealed that the greatest variability in daily baseflow and total discharge occurred during the growing season. The extreme amounts of variation observed during September and October are likely related to tropical storm and hurricane runoff. These data reveal that predictions of baseflow based on past statistical data would be most reliable for the non-growing season and least reliable for the hurricane season.
Figure 18. Long-term variability in monthly total discharge and baseflow at Tarboro, NC USGS gage (1931-2003), as expressed by the coefficient of variation (standard deviation/mean × 100%).

The long-term variation of total discharge, runoff, and baseflow was evaluated using 10-year moving averages of the daily data (Figure 19). There is a notable decline in average total discharge, baseflow, and runoff during the 1970s which may be related to a drop in rainfall amounts in the late 1960s and early 1970s. After this period there is a slight decrease in average baseflow. A comparison of 10-year average baseflows from 1941-1971 versus those from 1972-2002 revealed that a slight decrease (88 cfs or 2.5 cms) in median baseflow has occurred based on a Mann-Whitney test (significant at 0.0027). Similarly a slight decrease in median total discharge of 204 cfs (5.8 cms) has occurred since the 1970s (significant at 0.0034).

Figure 19. Long-term variations in total discharge, baseflow, and runoff, at Tarboro, NC USGS gage (10-year moving average).
Discharge-frequency distribution curves were constructed for total daily discharge and baseflow using the data record from 1931-2003 (Figures 20 and 21) to evaluate the observed changes in streamflow and baseflow over time along the Tar River. The data were split into two categories—before 1971 and after 1971. The total discharge and baseflow curves reveal a common pattern indicating that stream discharge and baseflow variation has slightly changed over time along the Tar River. The portion of the discharge-frequency curves where this is most notable is for the discharges that occur between 50-90% chance of exceedance. The flows that occur with this frequency have decreased in magnitude over time. For example, the baseflow that should be equaled or exceeded 75% of the time was 470 cfs (13.3 cms) for the period of 1931-1971 however for the period of 1972-2003 the baseflow for this 75% probability dropped to 383 cfs (10.8 cms). These curves indicate that lower streamflows and baseflows have become more common over time along the Tar River. However at the extreme high probabilities (>98%) or extreme low flows, the baseflow and streamflows have slightly increased. This may be a consequence of the changing amounts of wastewater discharge to the stream over time or interbasin transfers. At the other extreme, for extreme low probability discharges, (<10%) baseflow and total discharge has shown a slight increase, possibly related to increased storm activity. The discharge frequency distributions indicate that slight changes in the magnitude of total discharge and baseflow discharge have occurred over time along the Tar River when comparing the time period of 1931-1971 versus 1972-2003, most notably a decrease in the magnitude of discharge for higher probability discharges (>50% likelihood of occurrence). These data indicate that streamflow and baseflow have become more variable over time along the Tar River. Recent work has indicated that these types of changes are common and there is evidence to support the occurrence of an intensification of the global hydrologic cycle, with many regions throughout the world showing trends of increased rainfall, runoff, and drought during the last century (Huntington 2006).

![Figure 20. Total discharge-frequency distribution curves at Tarboro, NC USGS gage (split into two groups: 1931-1971 and 1972-2003).](image_url)
The minimum daily baseflow in a given year was used to evaluate long-term trends in low discharge events (Figure 22). The data indicate that recent baseflow minimums are significantly lower than those observed before 1972. A Mann-Whitney test compared the 1941-1971 data with the 1972-2002 data and indicated that baseflow minimums for the most recent period have dropped by 33 cfs (0.93 cms) when compared to the earlier period (significant at < 0.0001). These trends are evident when comparing the 10-year average minimum values and their variation over time (Figure 23). A similar comparison for maximum baseflows indicated no significant difference between these two time periods.

The annual coefficient of variation of baseflow (annual standard deviation/annual mean*100%) was analyzed to determine trends in the variability of baseflow over time (Figure 24). The 10-year moving average reveals an upward trend in variation in baseflow within the year over the time period of 1941-2002. A Mann-Whitney test compared the 1941-1971 data with the 1972-2002 data and indicated that baseflow coefficients of variation for the most recent period have increased from 84.5% to 92.7% when compared to the early period (significant at 0.0000). These trends are evident when comparing the 10-year average coefficient of variation values over time (Figure 25) and indicate that over time baseflow has become more variable along the Tar River.
Figure 22. Annual minimum daily baseflow at Tarboro, NC USGS gage (1931-2003). Black line is 10-year moving average.

Figure 23. Comparison of 10-year moving average annual minimum daily baseflow at Tarboro, NC USGS gage for the period of 1941-1971 versus the period of 1972-2002.
Figure 24. Annual coefficient of variation (standard deviation/mean*100%) of baseflow at Tarboro, NC USGS gage (1931-2003). Black line is 10-year moving average.

Figure 25. Comparison of 10-year moving average annual coefficient of variation of baseflow (standard deviation/mean*100%) at Tarboro, NC USGS gage for the period of 1941-1971 versus the period of 1972-2002.
The magnitude of baseflow contributions along the Tar River were evaluated by comparing the baseflow contributions estimated at Tarboro to those estimated at Greenville USGS gages. The Tarboro gage is approximately 35 km upstream of the Greenville gage, a long enough distance for baseflow contributions to be measurable downstream. The USGS Greenville gage has a limited record compared to Tarboro, therefore upstream-downstream comparisons could only be conducted during the time period when both discharge records overlapped (April 1997-Feb 2006). Due to Hurricanes Dennis and Floyd (September 1999), the data between September 5 and October 10 1999 were outliers affected by extreme flooding during these periods. These data were excluded from baseflow analyses. Baseflow contributions at each gage were estimated using the local minimum hydrograph separation method. For the period of April 1997-Feb 2006 the average baseflow increase downstream was 199 cfs (5.6 cms) or a 20% increase relative to baseflow at Tarboro. Average baseflow increases along the Tar for April 1997-Feb 2006 were 9 cfs/mile (0.16 cms/km). The variability in baseflow inputs over time along this stretch is illustrated in Figure 26.

![Figure 26. The percent change in baseflow between Tarboro and Greenville, NC USGS gages for the period of 1997-2006.](image-url)
Along this stretch of the Tar River baseflow typically increases downstream for most of the year. During the time period of 1997-2006 it is apparent that numerous periods existed when baseflow losses between Tarboro and Greenville occurred, these may be due to downward seepage through channel sediments or from evapotranspiration losses (Figure 26). The City of Greenville obtains water supplies from the Tar between gages but these amounts are less than 1.5 cfs (0.04 cms) and should not represent a large difference when compared to total baseflow. Seasonal comparisons of baseflow differences downstream reveal that on average baseflow increases downstream for every month of the year. However, there is significant variability in the magnitude and percentage of baseflow increase downstream. June is the month when baseflow increases downstream are typically the lowest, approximately 87 cfs (2.46 cms) or 13% increase from baseflow at Tarboro (Figure 27). January typically exhibited the largest baseflow increases downstream with average baseflow at Greenville during January being 385 cfs (10.9 cms) larger than that estimated at Tarboro (26.4% of Tarboro baseflow). With respect to baseflow magnitude, the greatest flows typically occur during the non-growing season. These analyses help to bracket average baseflow inputs along this stretch of the Tar between 4 cfs/mile (0.07 cms/km) and 17.5 cfs/mile (0.31 cms/km) in a given year, based on the past 9 years of data. These estimates do not isolate ground water that only discharged along the main channel of the Tar, they include groundwater discharged to tributaries along this stretch of the Tar.

![Baseflow Differences Between Tarboro and Greenville](image_url)

**Figure 27.** The monthly average change in baseflow between Tarboro and Greenville, NC USGS gages for the period of 1997-2006.
Hydraulic Conductivity

River channel sediment hydraulic properties are typically very heterogeneous (Jones and Mullholland 2002). Hydraulic conductivity values of the sediments in and adjacent to the Tar River ranged from $10^{-2.03}$ to $10^{-7.03}$ cm/s (Figure 28) based on data from 19 slug tests. The median hydraulic conductivity for all sediments was $10^{-3.38}$ cm/s. These values are in agreement with other published values (p.98 Fetter 1994). The majority of samples fall within the categories of fine sands or well-sorted sands ranging in hydraulic conductivity from $10^{-5}$ to $10^{-1}$ cm/s. This indicates that most sediments within or adjacent to the Tar tend to be relatively permeable. At four locations the hydraulic conductivity values were extremely low (<$10^{-6}$ cm/s) indicating the presence of clay sediments in the subsurface. With the exception of the Route 264 site, the hydraulic conductivity values typically were lower on the south side of the river (Figure 29). The median hydraulic conductivity for the north side of the river was $10^{-2.82}$ cm/s, whereas along the south side the median hydraulic conductivity was $10^{-3.38}$ cm/s. This may be related to the differences in sediment type related to depositional processes, sediments on the north side of the river are likely reworked river deposits, which tend to be very permeable. On the south side of the river the Tar is typically incising into Pliocene or older Cretaceous sediments, which may be clay-rich because they were deposited in estuarine or marine environments. Along our study reach and for most of the length of the Tar River a similar asymmetrical pattern exists with steep bluffs and very narrow floodplains to the southwest of the river, and extensive floodplains and gentle slopes on the northeast side of the river.

![Hydraulic conductivity](image)

Figure 28. Hydraulic conductivity values measured in stream channel and bank piezometers along the study reach of the Tar River.
Figure 29. A comparison of hydraulic conductivity values measured in stream channel and piezometers along the North vs. South sides of the Tar River.

Groundwater Flux

Vertical groundwater fluxes to the Tar River varied over time and ranged from +0.0033 and -0.0036 m³/day/m² in piezometer nests from September 2005-March 2006. Since 264 did not have a piezometer nest installed, the channel piezometer data on the south side was used as a substitute. The piezometer nests at Falkland and the Riggs property tended to show a vertical downward flux of groundwater during the period of study indicating that sections of the river may lose water at certain times of the year. The other sites tended to show gaining conditions, typically vertical groundwater flux was upwards to the river. A net comparison over this time period indicates that conditions are typically gaining along the Tar (Figure 30). A comparison between the north and south sides of the river indicates that the north side typically has greater groundwater inputs than the south side, at least for the time of year when these data were collected (Figure 31). The median vertical groundwater flux on the north side was $3.99 \times 10^{-4}$ m³/day/m² whereas the south side median groundwater flux was $-1.7348 \times 10^{-6}$ m³/day/m². These differences are related to the common presence of lower hydraulic conductivity materials on the south side of the river. A continuation of the monitoring along the Tar will reveal if this pattern holds for the entire year.
Figure 30. A comparison of average vertical groundwater fluxes at five study sites along the Tar River (September 2005-March 2006).
Figure 31. A comparison of vertical groundwater fluxes at the north versus the south side of the river, along the Tar River over the study period.

Water Temperature

Water temperature data were collected during site visits in all piezometers and at a 30-minute interval by Hobo water level/temperature recorders at channel piezometers on the south side of the river. The temperatures were found to vary in deep groundwater piezometers at each site, with lowest average groundwater temperatures observed at the Rainbow Banks site at 17.27 ºC and the highest groundwater temperatures measured at Elm Street (19.63 ºC) for the period of September 2005-March 2006 (Figure 32). Groundwater temperatures measured in stream channel piezometers related well to surface water temperature measurements (Figure 33). This indicates that large magnitude groundwater inputs were not common at the study sites and a mixture of surface water and groundwater is typically present in the river channel sediments. A continuation of water temperature monitoring along the Tar will reveal patterns for at least one annual cycle.
Figure 32. A comparison of groundwater temperatures (°C) measured in deep piezometers at four site along the Tar River over the study period.

Figure 33. A comparison of groundwater temperatures measured in stream channel piezometers and surface water temperatures measured in the Tar River over the study period.
Specific Conductance

Specific conductance of surface water and ground water varied at each site. Typically the ground water specific conductance was greater than the surface water specific conductance at each site (Figures 34-38). The 264 monitoring site was an exception, where the ground water on the south side consistently had specific conductance values less than the surface water. These ground waters have specific conductance values that are more similar to rainwater values for the region. The average specific conductance values at 10 channel settings (north and south sides) along the Tar River were calculated from piezometer specific conductance data collected from 10/27/05 – 2/22/06. A comparison of the specific conductance of groundwater in the river channel and the hydraulic conductivity of river channel sediments indicates that an inverse relationship exists between river channel sediment hydraulic conductivity and specific conductance of ground water (Figure 39). These data indicate that specific conductance may be a useful tracer of river-ground water interactions in this and other coastal plain stream settings.

Figure 34. Specific conductance data measured in channel piezometers on the north (GW(N)) and south side (GW(S)) of the river and of surface water at Route 264 site. Figure
Figure 35. Specific conductance data measured in channel piezometers on the north (GW(N)) and south side (GW(S)) of the river and of surface water at Rainbow Banks site.

Figure 36. Specific conductance data measured in channel piezometers on the north (GW(N)) and south side (GW(S)) of the river and of surface water at Port Terminal Road site.
Figure 37. Specific conductance data measured in channel piezometers on the north (GW(N)) and south side (GW(S)) of the river and of surface water at Elm Street site.

Figure 38. Specific conductance data measured in channel piezometers on the north (GW(N)) and south side (GW(S)) of the river and of surface water at Falkland site.
Figure 39. Average groundwater specific conductance data measured in channel piezometers along the Tar River compared to hydraulic conductivity values measured in the same piezometers.

**Sediment Distribution**

Falkland (Figures 40-42)

In the south bank split spoon cores, the uppermost meter of sediment is a sandy clay loam which grades to a very fine sand at 50 to 70cm. Color grades from brown to a yellow orange. This material appears to be reworked material and fill from the construction of the Hwy 222 bridge at Falkland. At 1.77 meters, there is a contact with medium sand and gravel. This gravel unit grades to fine sand from 2.08 to 2.18m and at 2.96 to 3.10m. The gravel unit extends to at least 3.45m. Color ranges from tan to reddish brown. Hollow stem auger cuttings at 6.7 meters are also fine to medium sands.

Hand auger samples from the north bank at Falkland indicate the upper 50 to 60 centimeters of sediment is a tan to orange sandy loam. From 0.6 meters to 2.1 meters, a very fine to fine-grained sand grades into a medium to coarse, tan colored sand.

With the exception of the shallow material near the bridge, the sediments at Falkland appear to be reworked river sands.
Figure 40. Split spoon core at Falkland south – 0-1.15 m.

Split Spoon Core Section:
Falkland South: 0.00m to 1.15m

0.00m to 0.25m: no recovery

0.25m to 1.15m: sandy clay loam, heavy organic matter in upper 25cm, grades to very fine sand from 50cm to 70cm
Figure 41. Split spoon core at Falkland south –1.15 -2.30 m.

Split Spoon Core Section:
Falkland South: 1.15m to 2.30m

1.15m to 1.73m: no recovery

1.73m to 1.77m: sandy clay loam

1.77m to 2.18m: medium sand and gravel, grades to fine and medium sands in last 10cm

2.18m to 2.30m: medium sand and gravel
Figure 42. Split spoon core at Falkland south –2.30-3.45 m.

Split Spoon Core Section:
Falkland South: 2.30m to 3.45m

- 2.30m to 2.96m: no recovery
- 2.96m to 3.10m: medium sand, grades to sandy loam
- 3.10m to 3.45m: medium sand and gravel
Hand auger samples show that the upper 30cm of the south bank at US 264 is loamy sand, underlain by at least 3 meters of tan colored fine sand with intermittent sandy loam lenses. The upper 2.75 meters at the north bank of US 264 is a silty clay loam with abundant organic material in the top 40 cm and from 1.5 to 2.1 meters. At approximately 3 meters, there is a contact with a dark grey silty clay with abundant wood fragments. From 4.5 meters to at least 6.4 meters, wood fragments make up 50 to 70% of each hand auger sample. The south bank at US 264 appears to be composed of reworked river sands, while the northern bank appears to be an older clay deposit.

Figure 43. Hand auger core at 264 south –0-3.05 m.
Elm Street (Figures 44-48)

Split spoon cores from the south bank at Elm Street show that the upper meter is a sandy clay loam with a sharp contact with a fine sand at 1.05 meters. The fine sand extends to 3.12 meters, with a sand and gravel lens at 2.88 to 2.91 meters. The fine sand at 2.91 meters grades to a sandy clay loam with a sharp basal contact with a coarse sand at 3.25 meters. The coarse sand has a sharp contact with a sandy loam at 3.52 meters. The sandy loam has a sharp contact with coarse sand and gravel at 3.625 meters. The coarse sand and gravel extends to 4.19 meters where it has a sharp contact with a sandy clay loam, extending to 4.6 meters. Coarse sand and gravel extend from 4.6 to 5.75 meters.

Hand auger samples from the north bank at Elm Street indicate the upper 50 to 60 centimeters of sediment is a tan sandy loam. From 0.6 meters to approximately 2.5 meters, a very fine to fine-grained sand grades into a medium to coarse, tan colored sand. The sediments on the south bank appear to be a complex series of Cretaceous material, while the sediments on the north bank appear to be reworked river deposits.

**Figure 44. Split spoon core at Elm St. south –0.00-1.15 m.**
Figure 45. Split spoon core at Elm St. south –1.15-2.30 m.

Split Spoon Core Section:
Elm St. South: 1.15m to 2.30m

1.15m to 1.57m: no recovery

1.57m to 1.63m: loose loam and pine straw

1.63m to 1.82m: loam, gradational basal contact

1.82m to 1.93m: sandy clay loam, gradational basal contact

1.93m to 2.00m: loamy sand, gradational basal contact

2.00m to 2.30m: fine to very fine sand
Figure 46. Split spoon core at Elm St. south –2.30-3.45 m.

Split Spoon Core Section:
Elm St. South: 2.3m to 3.45m

- 2.3m to 2.75m: no recovery
- 2.75m to 2.88m: very fine to medium sand
- 2.88m to 2.91m: sand and gravel lens
- 2.91m to 2.975m: very fine sand
- 2.975m to 3.12m: very fine sand to loamy sand
- 3.12m to 3.25m: sandy clay loam, sharp contact with underlying unit
- 3.25m to 3.45m: coarse sand
Figure 47. Split spoon core at Elm St. south –3.45-4.60 m.

Split Spoon Core Section:
Elm St. South: 3.45 to 4.60m

<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.45m to 3.52m</td>
<td>coarse sand, sharp basal contact</td>
</tr>
<tr>
<td>3.52m to 3.625m</td>
<td>sandy loam, sharp basal contact</td>
</tr>
<tr>
<td>3.625m to 4.19m</td>
<td>coarse sand and gravel up to 1.5cm, sharp basal contact</td>
</tr>
<tr>
<td>4.19m to 4.60m</td>
<td>sandy clay loam</td>
</tr>
</tbody>
</table>

scale: 0.5’ = 10cm
Figure 48. Split spoon core at Elm St. south –4.60-5.75 m.

Split Spoon Core Section:
Elm St. South: 4.60m to 5.75m

4.60m to 5.75m: coarse sand and gravel

scale: 0.5" = 10 cm
Port Terminal (Figures 49-52)

Split spoon cores from the south bank at Port Terminal show a tan colored sandy clay loam at the surface, grading to fine sand at 1.75 meters. The fine sand then grades to a tan colored medium to coarse sand at 2.3 meters with a medium sand and gravel lens at 2.05 to 2.1 meters. Medium to coarse sand and gravel from 2.3 to 3.1 meters has a sharp contact with a grey sandy clay unit with abundant white shell fragments, to a depth of 3.45 meters. The last core was predominantly sand and gravel from 3.45 to 4.5 meters. The final 0.1 meters of the core is a grey sandy clay unit with white shell fragments.

Hand auger samples from the north bank at Port Terminal show the uppermost 25 cm of sediment is very fine to loamy sands, underlain by sandy loam, grading to a sandy clay loam from 2.13 to 3.35 meters. Abundant organic material exists between 3.04 to 3.35 meters. At 3.35 meters, the sandy clay loam grades to a tan colored, fine to medium-grained sand.

The fossiliferous clays present on the south bank at Port Terminal indicate a Cretaceous or more recent marine unit, most likely the Yorktown Formation (Pliocene). The predominantly loamy sediments on the northern bank appear to be reworked river and floodplain deposits.
Figure 49. Split spoon core at Port Terminal south –0-1.15 m.

Split Spoon Core Section:
Port Terminal South: 0.00m to 1.15m

0.00m to 0.60m: loamy sand (hand auger)

0.67m to 1.15m: sandy clay loam, grades to fine sand at 1.15m
Figure 50. Split spoon core at Port Terminal south –1.15-2.30 m.

Split Spoon Core Section:
Port Terminal South: 1.15m to 2.30m

1.15m to 1.58m: no recovery

1.58m to 1.75m: sandy clay loam, grades to fine sand at 1.75m

1.75m to 2.05m: fine sand, gradational basal contact

2.05m to 2.10m: medium sand and gravel, gradational basal contact

2.10m to 2.30m: medium to coarse sand
Figure 51. Split spoon core at Port Terminal south –2.30-3.45 m.

Split Spoon Core Section:
Port Terminal South: 2.30m to 3.45m

2.30m to 3.10m: medium to coarse sand and gravel, sharp basal contact

3.10m to 3.45m: sandy clay, abundant (30-50%) shell fragments
Figure 52. Split spoon core at Port Terminal south –3.45-4.60 m.

Split Spoon Core Section:
Port Terminal South: 3.45m to 4.60m

3.45m to 4.50m: fine to coarse sand and gravel, sorting grades gently

4.50m to 4.60m: sandy clay, shell fragments ~15%
Rainbow Banks (Figures 53-58)

In split spoon cores from the south bank at Rainbow Banks, the upper 2.13 meters is very fine to fine sand with some loamy material. The fine sand grades to a loam from 2.13 to 2.3 meters. Below the loam is a very fine-grained sand with a sharp contact with a grey silty clay at 2.63 meters. The silty clay extends to 3.45 meters. Below the silty clay is a fine to very fine sand that has a sharp contact with a fossiliferous silty clay at 3.75 meters, which extends to 4.6 meters. From 4.6 to 4.78 meters, there is a sandy clay loam with a sharp contact with a fossiliferous sandy loam, grading to a sandy clay loam, which extends to 5.75 meters.

Hand auger samples from the north bank at Rainbow Banks show a tan colored sandy loam at the surface which grades to a tan colored fine to medium sand at 1.5 to 2.4 meters.

As with Port Terminal the fossiliferous sediments are most likely Pliocene or older deposits, while the sandy sediments on the north bank appear to be reworked river and floodplain deposits.
Figure 53. Split spoon core at Rainbow Banks south –0.00-1.15 m.

Split Spoon Core Section:
0.00m to 1.15m

0.00m to 0.50m: no recovery

0.50m to 1.15m: very fine to fine sand grading to loamy sand at base
Figure 54. Split spoon core at Rainbow Banks south –1.15-2.30 m.

Split Spoon Core Section:
- 1.15m to 2.30m

1.15m to 1.25m: no recovery

1.25m to 1.85m: very fine sand to loamy sand, gradational basal contact

1.85m to 2.13m: fine sand, gradational basal contact

2.13m to 2.30m: loam
Figure 55. Split spoon core at Rainbow Banks south –2.30-3.45 m.

Split Spoon Core Section:
2.30m to 3.45m

2.30m to 2.63m: very fine sand, sharp basal contact

2.63m to 3.45m: silty clay

Scale: 0.5" = 10cm
Figure 56. Split spoon core at Rainbow Banks south –3.45-4.60 m.

Split Spoon Core Section:
3.45m to 4.60m

- 3.45m to 3.75m: fine to very fine sand, sharp basal contact
- 3.75m to 4.60m: silty clay, shell fragments from 4.05m to 4.60m

scale: 0.5" = 10cm
Figure 57. Split spoon core at Rainbow Banks south –4.60-5.75 m.

Split Spoon Core Section:
4.60m to 5.75m

4.60m to 4.78m: sandy clay loam, sharp basal contact

4.78m to 5.48m: sandy loam, shell fragments, diffuse basal contact

5.48m to 5.75m: sandy clay loam grading to silty clay, shell fragments

scale: 0.5" = 10cm
Figure 58. Split spoon core at Rainbow Banks south –5.75-6.90 m.

Split Spoon Core Section:
5.75m to 6.90m

5.75m to 6.70m: clay loam, gradational basal contact, shell fragments

6.70m to 6.90m: loam, shell fragments
Ground Penetrating Radar Surveys

General Methodology

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. 21 surveys included cross-sections perpendicular to the river channel.

Interpretation of Geophysical Surveys

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.

Falkland

Site-Specific Methodology

GPR surveys were conducted along the Falkland section of the Tar River. Four cross-channel profiles were collected (Lines 884, 885, 886, and 887) and two along-channel profiles were collected on a channel bar (Lines 882 and 883; see Figure 59). The cross-channel profiles were collected in monostatic continuous mode, with a 200 MHz antenna, with a sampling window of 300 ns, 1024 samples per scan, and a scan rate of 32 scans/second. Along-channel profiles were collected with the same antenna, but using a survey wheel and scanning at 5 scans/meter.

A 3-d subsurface survey was additionally performed on the channel bar by surveying along 17, 1 m-spaced lines (Figures 59 and 62). Dimensions of the grid were 50 m by 16 m.

All gpr data were processed using Radan v. 7 software. Processing consisted of applying high and low bandpass filters (125 and 225 MHz, respectively), and increasing the gain. Data were then exported as bitmap files and digitized using Canvas, or gridded using Radan.

For vertical scale purposes (Figures 60 and 61), a dielectric constant of 80 is assumed for the water column, and a dielectric constant of 25 is assumed for saturated channel sands. These estimates are used for all of the study areas.
Figure 59. Map showing the location of transects and the 3-d survey grid in the Falkland area.
Results and Interpretations

The channel geomorphology in this area consisted of a channel bar approximately 30 m wide by 200 m long. Shallow (<1 m depth) channels existed on either side of the bar, with the widest occurring on the east side of the river.

Subsurface data reveal a high-amplitude continuous, horizontal to gently westward dipping reflection with approximately 0.25 m of surface relief. The reflection occurs at a subsurface depth (relative to river level) of approximately 3 to 3.5 m. Data are attenuated below the horizon, indicating relatively impermeable (clayey) materials. Split spoon core penetration stopped approximately 3m short of the horizon.

This surface is interpreted as the erosional base of the river channel, and is likely to be the top of the Cretaceous Black Creek Formation or possibly the Pliocene Yorktown Formation. The Black Creek occurs regionally in the shallow subsurface, and is readily exposed in cut banks. Typically Black Creek sediments are thinly laminated gray to black muds interlaminated to interbedded with tan sands that are very fine to fine (Winner and Coble 1996).

Channel sediments overlying this formation are 2 to 3 m thick, and consist of poorly sorted medium to very coarse quartz sand and gravel based upon sub-soil probe samples. Centimeter to meter-scale bedform structures can be seen in the lower half of the sand sequence, while the upper 1 to 1.5 meters show little structure.
Figure 60. Processed data from N-S transects 882 and 883, potentially showing the top of the Black Creek or Yorktown Formation deepening toward the south.
Figure 61. Processed data with interpretations potentially showing the top of the Black Creek or Yorktown Formation deepening toward the west (generally).
Figure 62. 3-d survey box looking NW, and illustrating a slice at 3.13 m subsurface. The red surface seen is the erosional base of the channel which corresponds to the top of the Black Creek Formation. The surface dips toward the west.
Elm Street

Site-Specific Methodology

GPR surveys were conducted along an East-West oriented section of the Tar River in Greenville, near the northern end of Elm Street. Four cross-river profiles were collected, (Lines 928, 929, 930, and 931) (Figure 63). The cross-channel profiles were collected in monostatic continuous mode, with a 200 MHz antenna, with a sampling window of 300 ns, 512 samples per scan, and a scan rate of 32 scans/second. A 3-d survey was also performed using a line spacing of 1 m. Grid size is 30 m by 50 m. The 3-d survey was performed along the second floodplain terrace. Data for the 3-d survey were collected with the same settings as the channel surveys, with the exception that a survey wheel was used and data were collected at 20 scans/meter.

Results and Interpretation

The Elm Street study area occurs in Greenville, along a section of the river oriented east-west. In the Elm Street region the Tar River is approximately 50 m wide. The channel consists of a thalweg that is 2.5 to 4 m in depth, deepening towards the east. The thalweg occurs on the south side of the channel. A bar occurs along the north side of the channel, with depths ranging from ca. 1.4 to 2.0 m. The channel banks rise steeply adjacent to the thalweg and the bar.

The upper 0.5 to 1 meters at Elm Street have little structure, while data 1.5 to 3 meters below the river channel show abundant bedforms. Large woody debris (LWD) shows up as point-source reflectors, and is abundant in the water column and shallow sediments. A multiple image of the water/sediment interface is located at twice the water depth on all four Elm Street transects. In most cases, data are attenuated below the bottom multiple. Line 930 shows a horizon at 2.5 meters below the river channel below which data is lost. This is likely the top of a low-permeability material, possibly clay. Split spoon cores stop approximately 1 meter above this horizon.

The subsurface data reveal a high-amplitude semi-continuous reflection occurring at ca. 2.8 to 3 m below the river level in the western two lines (L928, L929), and 3.5 to 4 m in the eastern two lines (L930, L931) (Figures. 64-68). The reflection appears to be nearly exposed within the thalweg. Based on the regional understanding of the stratigraphy, this surface is likely to be the top of the Pliocene Yorktown Formation, a muddy unit that should serve as a confining bed. If the Yorktown has been eroded away at this location, the material is likely the confining unit of the Black Creek or PeeDee Formation. The stiff, cohesive mud is forming the erosional base of the Tar River channel in this area.

Sediment overlying the basal erosion surface (top of the Yorktown) varies in thickness from ca. 0 m in the thalweg to ca. 3 m beneath the bar on the north side of the river. Three-dimensional views of the data also show that attenuation occurs at approximately 3 to 3.5 m subsurface due to the presence of clays (Figure 69). These data also indicate that there may be some breaks in the clay layer underlying this site.
Figure 63. Map showing the locations of cross-channel gpr transects in the Elm Street area.
Figure 64. Transect line 928 across the Tar River in the Elm Street area.
Figure 65. Transect line 929 across the Tar River in the Elm Street area.
Figure 66. Transect line 930 across the Tar River in the Elm Street area.
Figure 67. Transect line 931 across the Tar River in the Elm Street area.
Figure 68. Transect lines 928-931 across the Tar River in the Elm Street area.
Figure 69. 3-d perspectives of the grid data from the floodplain terrace adjacent to the Tar River in the Elm Street study area. Top image is looking southeast. Bottom image is looking northeast. Note the horizontal bedding characteristic of overbank deposits. Data become attenuated at approximately 3 to 3.5 m subsurface due to the presence of clays.
Port Terminal

Site-Specific Methodology

GPR data at the Port Terminal site were collected and processed using the same settings as previous sites. Seven cross-river profiles were collected (Lines 932 through 938) (Fig. 70). No 3-d survey was performed in this area.

Results and Interpretations

The channel geomorphology in this area consists of a large channel bar approximately 80 m wide with approximately 2 to 2.5 m of relief, formed by the confluence of the Tar River and a tributary creek. Two channels exist on either side of the bar, with the deepest (3.5 to 4 m) corresponding with the Tar River thalweg on the north side of the river (Figs 71-76). The tributary thalweg narrows and shoals eastward.

Cross-channel, subsurface data reveal a high-amplitude semi-continuous, reflection at approximately 3 to 4 m below the river water level. Data are attenuated below the horizon, indicating relatively impermeable (clayey) materials. The reflection appears to be exposed within the Tar River thalweg, and nearly so in the tributary thalweg. The Tar River thalweg appears to have incised into this surface. Based on the regional understanding of the stratigraphy, this surface is likely to be the top of the Pliocene Yorktown Formation, a muddy unit that should serve as a confining bed. Split spoon cores stop approximately 2m short of this horizon.

The channel sediments exhibit a complex stratigraphy, with mainly aggradational characteristics in the cross-channel direction. Some bedding appears to dip toward the tributary thalweg, indicating greater sediment transport across the bar from the Tar River. Centimeter to meter-scale bedforms are evident on the surface of the channel bar and into the thalweg. LWD is present along both banks, in the water column and in shallow sediments. Data are completely attenuated at approximately 3.5 meters below the sediment-water interface.
Figure 70. Map showing the locations of cross-channel GPR transects in the Port Terminal area.
Figure 71. Transect lines 932 and 933 across the Tar River in the Port Terminal area.
Figure 72. Transect line 934 across the Tar River in the Port Terminal area.
Figure 73. Transect line 935 across the Tar River in the Port Terminal area.
Figure 74. Transect line 936 across the Tar River in the Port Terminal area.
Figure 75. Transect line 937 across the Tar River in the Port Terminal area.
Figure 76. Transect line 938 across the Tar River in the Port Terminal area.
Rainbow Banks

*Site-Specific Methodology*

GPR data at the Rainbow Banks site were collected and processed using the same settings as previous sites. Three cross-channel profiles were collected (Lines 965, 967, 968) (Figure 77).

![Rainbow Banks Map](image)

**Figure 77.** Map showing the locations of cross-channel gpr transects in the Rainbow Banks area.
Results and Interpretations

Data were attenuated within the water column in this area, possibly due to minor salinity. Due to this attenuation, subbottom penetration was typically <1.5 m. The channel morphology in this area consists of a steep cut bank on the south side, dropping to a thalweg depth of 4 to 5 meters below river level. The channel beyond the thalweg is relatively horizontal at a depth of 3 m in the west (line 965; Figure 78), and shoals to the east as a point bar develops on the north side of the river (lines 967 and 968) (Figures 79-80).

Cross-channel, subsurface data reveal a high-amplitude semi-continuous, reflection at approximately 3.5 to 4 m below the river water level (approximately 1 m below the sediment-water interface). Clays of the Yorktown Formation occur at water level, forming a terrace at the base of the cut bank in this area. The reflection below the river channel sediments marks the erosional base, and may be within the Yorktown Formation, or could be the top of the Pee Dee Formation.

The point bar sediments exhibit aggradational and minor progradational characteristics, with centimeter scale bedforms at the sediment-water interface.

Figure 78. Transect line 965 across the Tar River in the Rainbow Banks area.
Figure 79. Transect line 967 across the Tar River in the Port Terminal area.
Figure 80. Transect line 968 across the Tar River in the Port Terminal area.
DISCUSSION

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 the baseflow has become more variable over time, with the difference most notable during periods of extreme high or low flows. 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 pattern may in part explain trends in Tar River baseflow because increased rains during high baseflow periods in the winter cause high baseflows to increase, whereas lesser rainfall in summer months result in a decrease in low baseflows. If this trend persists 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 warm temperatures, increased solar radiation 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. The amount of dormant season rainfall that occurs annually has a greater influence on the baseflow discharge to the Tar than the 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 baseflows. Baseflow magnitudes can be extremely low or high during these months depending on 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 amounts typically increase downstream from Tarboro. However, there are several time periods where baseflow decreases downstream, indicating channel losses or large amounts of evapotranspiration between the gauges. 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 along the Tar were observed in channel and nested peiezometers. 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 $10^{-3.38}$, representative of sandy channel sediments. A noticeable pattern emerged in the
hydraulic conductivity data, with the channel sediments on the north side of the river typically having greater hydraulic conductivity values when compared to 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 fluxes through channel sediments 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 the difference in specific conductance depending on the side of river. Typically the specific conductance of groundwater underlying the Tar varied depending on what side of the river it was sampled at. 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 groundwater 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.
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 aimed at obtaining 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.
REFERENCES


