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Legacy Sediments and Stream Water Quality: Estimating Volume, Nutrient Content, and Stream Bank Erosion in 303(d)-Impaired Waterways of the North Carolina Piedmont

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ABSTRACT

Legacy Sediments and Stream Water Quality: Estimating Volume, Nutrient Content, and Stream Bank Erosion in 303(d)-Impaired Waterways of the North Carolina Piedmont

Objectives:
Physically and chemically, sediment is a pollutant of concern in many water bodies of the United States. Information on the nature and relative contribution of different watershed sediment sources is recognized as a key requirement in the design and implementation of targeted management strategies for sediment control. The goal of this project is to increase our understanding of the water quality impact of sediment (turbidity) and nutrients (N & C) derived from stream bank erosion of post-European legacy sediments formerly deposited along portions of the valley bottoms of Reedy, Richland, and Sycamore Creeks located in W.B. Umstead State Park, Wake County, North Carolina.

Methods:
The research was divided into three principal components: 1) Geomorphic mapping and stratigraphic characterization of sediments exposed along stream banks, 2) estimation of the decadal-to-hourly rates of stream bank erosion, and 3) characterization of the nutrient content stored in valley bottom deposits and the potential for nutrient release into stream waters following bank erosion. The geomorphic mapping and bank sedimentologic investigations were used to generate a composite late Holocene valley bottom stratigraphy for the study area. From this data we derive the extent, thicknesses and volumes of pre-European and legacy sediment deposits along with estimates of the volume of upland soil erosion that occurred following land clearing for agricultural purposes. The differentiation of stratigraphic units was aided by physical sedimentology, magnetic susceptibility, and radiocarbon geochronology. Estimates of stream bank erosion were determined on decadal-to-annual-to-hourly time scales via root dendrochronology, meander-bend planimetric surveys, and discharge event-specific total suspended solids and turbidity measurements from mill pond stream reaches, respectively. The total weight-% N and C of sedimentary intervals was determined from one former mill pond. From these values, we estimate the total storage of nutrients by stratigraphic interval for pre-European and legacy sediments within the study area. We performed laboratory-based leaching experiments to determine the amount of nutrient desorption following submersion of eroded stream bank sediments in pure and artificial river water.

Results:
We observe three distinct sedimentary units in stream bank exposures that are corroborated by radiocarbon dating. Pre-European sediments range from ca. 4400 – 250 yr B.P. and consist of quartz-rich stream gravels and off-channel organic rich clays. Two legacy sediment units are differentiable; pre and post-dam, and range in age from ca. 300 – 100 yr B.P. The pre-dam sediments consist primarily of fluvial sands, and are interpreted as channel aggradation in response to soil erosion from upland land clearing prior to dam construction. Post-dam sediments are distinguished by finer grain size and sedimentology consistent with slack water deposition. Stream bank magnetic susceptibility measurements exhibit large, mostly consistent increases at and above the pre-European – legacy sediment contact. Estimates of aggraded legacy sediment from two stream reaches indicate that the volume of eroded upland soils determined from geomorphic

mapping is approximately balanced by valley bottom aggradation, and that area-averaged depth of upland soil loss was equivalent to 3 – 15 cm across this part of the Piedmont. Stream banks along all three study streams show evidence for active erosion with linear rates of bank erosion varying between 0.05 to 4.5 $m^3 m^{-1} yr^{-1}$. These rates are dependent upon the length of observation across which they integrate. Stream water total suspended solid concentrations and turbidity levels generally increase during precipitation-driven higher discharge events following transit of the water through former mill pond reaches. In general, modern top soil had the highest wt % values for N and C compared to the legacy sediment and the pre-European settlement soil, while mill pond legacy sediment had roughly a fivefold more % N than did the pre-dam legacy sediment layers. Despite having fare lower wt% N than the modern top soil, the mill pond legacy sediment stores about five times more N owing to its much greater thickness and volume. Our 24-hour disaggregation experiments suggest that low amounts of N are released from legacy sediments in pure water or in artificial river water (salinity ~ 1).

Conclusions: Using the W.B. Umstead State Park as a proxy for a much larger region of the North Carolina Piedmont, it is evident that past agricultural practices resulted in extensive degradation of the pre-European landscape by the erosion of upland soils. Much of the eroded sediment aggraded in valley bottoms, including behind milldams, burying former per-European floodplains. Piedmont streams incised through these legacy sediments following the decrease in hillslope sediment delivery resulting from stabilization of upland soils by erosion control measures and reforestation. Stream incision has exposed these loosely consolidated primarily fine-grained sediments that are continuing to erode as channels migrate laterally. The volume of legacy sediments remaining in regional valley bottoms means that they will continue to contribute to stream turbidity into the foreseeable future. The absolute concentrations and the solubility in stream waters of nutrients stored in these sediments are low, yet their ubiquity across the landscape is high. Further research is needed to address the extent to which transport of the fine grained fraction from modern erosion of legacy sediment is contributing to the total nutrient budget and eutrophication of downstream estuaries.

Recommendations:

We recommend three main avenues of continued research to build upon the results of this project, beginning with investigating the coupled geochemical and desorption pathways that may exist between clay-bound nutrients derived from erosion of legacy sediments in the Piedmont upon their deposition in the upper oligohaline reaches of the Neuse River estuary. Second, applying geochemical fingerprinting techniques to storm water total suspended solids as a means for estimating the total catchment contribution from stream bank erosion of legacy sediments might be fruitful research at the smaller watershed scale when combined with total maximum daily load estimates and allocations. And third, paleoecology and geomorphology studies whose goal is to better characterize the biologic and physical state of Piedmont streams prior to European-American settlement and land use modifications. We know what is not a “natural” stream in the Piedmont of North Carolina, yet many questions remain as to what pre-European streams and valley bottom bio-geomorphic systems looked like and how best to direct stream restoration and water quality improvement efforts in the years and decades to come.

ACKNOWLEDGMENTS

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We are thankful to the staff of W.B. Umstead State Park who provided access to field sites through issuance of research permits, and specifically to Betty Anderson, the namesake for "Betty's Milldam", for sharing her knowledge and insight into the land use history and distribution of long-forgotten milldam sites. Doug Swords is gratefully acknowledged for sharing his time and insight into the history and distribution of grist mills in the greater Raleigh area, including within W.B. Umstead State Park. Mark Boone graciously provided repeated access to his property along Richland Creek.

1. INTRODUCTION

1.1. Environmental Perspective and Research Objective

The Neuse River basin (NRB) is one of a number of stream systems draining the Atlantic Piedmont physiographic province containing significant lengths of channel reaches that are impaired for both turbidity (total suspended sediment) and nutrients (Deamer, 2009). The third largest river basin in North Carolina, the Neuse includes 5,470 km of freshwater streams, 230 km of saltwater streams, and 150,000 hectares of saltwater estuary. A significant percentage of the freshwater and estuarine stream kilometers in the basin are impaired due to elevated turbidity, biological integrity, and low dissolved oxygen (Deamer, 2009). In 2007, American Rivers, a conservation organization, listed the Neuse River as among the top-ten most-endangered U.S. river systems. More broadly, the U.S. Environmental Protection Agency concluded that physically and chemically, sediment is a pollutant of concern in many water bodies of the United States (US Environmental Protection Agency, 2007). Information on the nature and relative contribution of different watershed sediment sources is recognized as a key requirement in the design and implementation of targeted management strategies for sediment control. Identification of sediment sources is particularly relevant in the sediment Total Maximum Daily Load (TMDL) process.

How did the Neuse River become so impaired? Is its impairment entirely a recent symptom of modern agricultural practices, urbanization, and land use change within the watershed, or might the current water-quality challenges facing the Neuse and other similar Piedmont streams result in part from significant and historic anthropogenic modifications of the watershed that continue to have a lasting environmental impact? There is little dispute that more recent human influences are culpable for a considerable amount of the impairment of fluvial systems; however, streams often remain impaired after the implementation of extensive soil conservation practices intended to reduce their effects (Meade, 1982; Knox, 2002; Schenk and Hupp, 2009). For example, a study conducted by the U. S. Geological Survey from 1983 to 1995 in the Research Triangle Area of North Carolina found no clear relationship linking water-quality trends to development and growth patterns (Childress and Neeti, 1997). The intent of this research is not to diminish the impact and societal responsibility for continuing poor stream-water quality conditions across much of the Atlantic Piedmont region, rather it is to highlight how centuries-to-decades old land use activities in and around Raleigh, NC have had a lasting impact on the morphology of local valley bottoms, stream form and function, and the persistent introduction of fine-grained sediments into streams during times of higher flow that contribute to diminished regional water quality levels.

Piedmont streams of the eastern United States have a long history of alteration by human activities, but earlier alterations are often forgotten. Modern land use practices such as the lack of riparian buffers along farm fields, streambank trampling by farm animals, increased stormwater runoff from suburbanization, point discharges of nutrient-laden waters from municipal wastewater treatment plants and agricultural manure ponds are typically blamed for various sorts of instability in river form, process, and water quality. Anecdotal evidence suggests that streams along the Atlantic Piedmont were not impaired with respect to turbidity and nutrient loads at the time of European settlement (e.g. Trimble, 1974), an indication that erosion of uplands and stream banks was minimal prior to the era of European land use modification.

Today, many streams in the low-relief mid-Atlantic Piedmont are incised, with steep eroding banks, and carry anomalously high amounts of suspended sediment (Fig. 1; Gellis et al., 2005). Many of these streams are bordered by fine-grained deposits that are thicker than would be expected from their recent flood deposits (Wolman and Leopold, 1957). These broad surfaces, adjacent to incised stream channels, referred to as the “valley flat”, are commonly interpreted as floodplains formed by a combination of migrating, meandering stream channels and overbank deposition of silts and clays (e.g., Wolman, 1955). However, Walter and Merritts (2008) demonstrated that in many cases, the elevation of the “valley flat” merges with the crests of breached, historic milldams, and that modern streams are incised deeply below this surface. In addition, Trimble (1974) documented that much of the sedimentation beneath the “valley flat” is post-colonial in age for Georgia piedmont streams. Walter and Merritts (2008) proposed that valley-bottom sedimentation resulted from not only accelerated hillslope erosion caused by deforestation and agricultural development (e.g. Costa, 1975), but also as a consequence of widespread Colonial to post-Reconstruction valley-bottom damming for water power. Damming was essential to the extensive trapping of sediment in broad valley flats that correspond to reservoir surfaces. Without the construction and maintenance of tens of thousands of milldams across the Atlantic Piedmont by the beginning of the 20th century, much of the soil eroded from the uplands would have been transported out of the river systems. Instead, a significant portion of this sediment continues to blanket the valley bottoms of Piedmont streams across the region, including specifically in the Neuse River watershed of North Carolina.

The goal of this one-year project, funded in 2010 by the Water Resources Research Institute of North Carolina (WRRI Grant # 70254) is to increase our understanding of the water quality impact of sediment (turbidity) and nutrients (primarily Nitrogen) derived from stream bank erosion of “legacy” sediments across the Piedmont physiographic province of North Carolina. Through our research we’ve made important headway towards our goal by studying the long-term environmental impact of post-colonial valley bottom sedimentation, including behind water-powered milldams in the Crabtree Creek sub-basin of the Neuse River watershed.

Legacy sediments are defined as sediment eroded from upland hill slopes after the arrival of European-American settlers and during the subsequent interval of intensive land uses; that was deposited on valley bottoms along stream corridors, burying the floodplains and wetlands of pre-settlement streams; and that altered and continues to impair the hydrologic, biologic, aquatic, riparian, estuarine, and chemical functions of pre-settlement and modern environments (Walter et al., 2007; Fig. 2). We identify two generations of legacy sediment that record valley bottom aggradation above the pre-European sediments (PES) both before (pre-dam legacy sediment – or PDLS) and following milldam construction (mill pond legacy sediment – or MPLS). Along portions of stream not impounded behind former milldams, yet where valley bottom aggradation is attributed to erosion from upland sources (based upon mapping), stream bank sediments are classified as either pre-European or post-settlement sediments (PSS; commensurate to pre-dam/milldam legacy sediments).

Figure 1. *Outside meander bend of Richland Creek as it cuts through sediments deposited in the slack water of Cook's mill pond, W.B. Umstead State Park. Note the near-vertical banks of mill pond legacy sediment, the sediment apron at the base of the face, and the high stream turbidity resulting from a moderate rain in early December, 2009.*

We hypothesized in our WRRI funding proposal that the erosion and transport of legacy sediments is a significant and persistent non-point source of sediment (total suspended solids – TSS) and nutrients delivered to regional waterways during periods of increased steam flow. In addition, we hypothesized that the incorporation of non-point source legacy sediments by stream bank erosion is a persistent detriment to regional water quality at temporal scales ranging from decades to individual storm events. The quantification of the physical and chemical processes, rates, and volumes of bank-eroded legacy sediments and associated nutrients will improve the understanding and modeling of nutrient pollution in piedmont streams and reservoirs, such as Falls Lake, as well as in coastal watersheds, which will be critical to reducing nutrient fluxes to North Carolina's eutrophying estuaries (e.g., Paerl, 2009; Paerl et al., 2010; Lebo et al., 2012). In addition, this research has important implications for interpretation of alluvial sedimentation, stream channel form and evolution, and the multi-million dollar stream restoration industry in North Carolina.

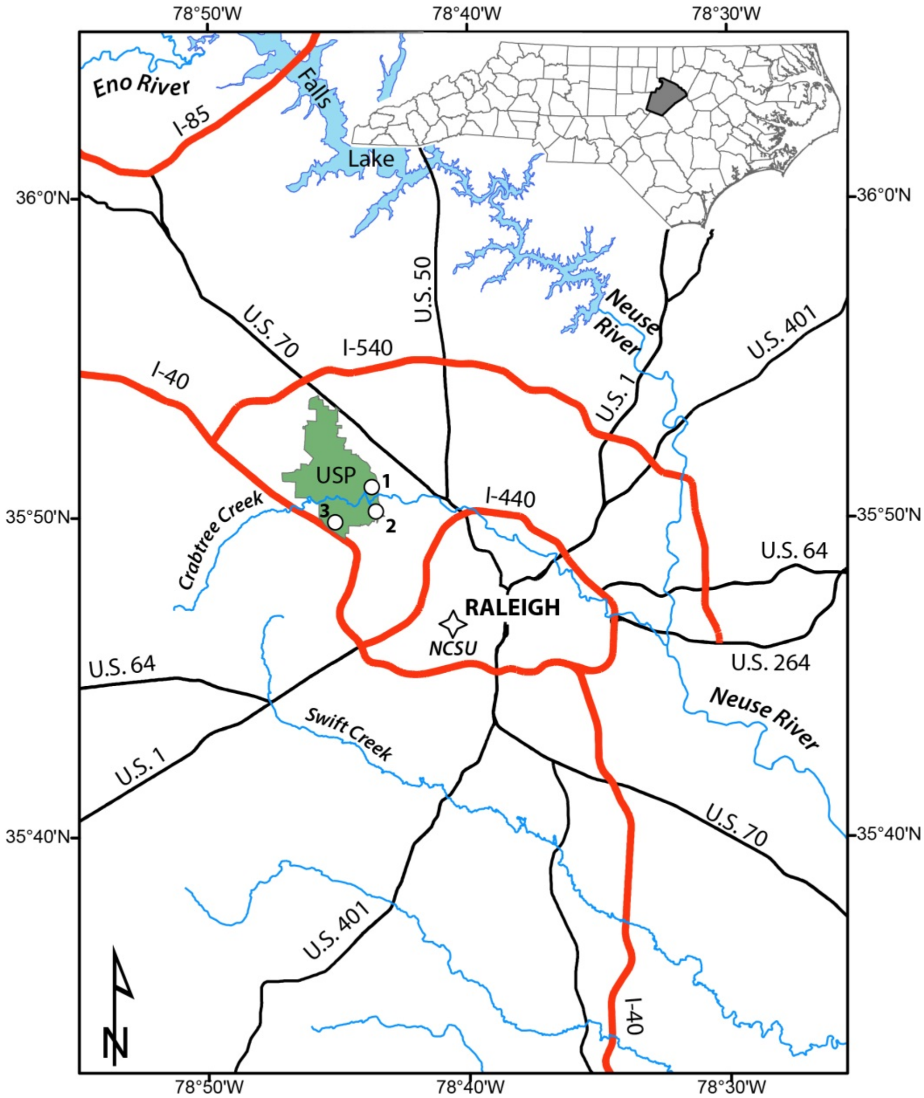


Figure 2. *Map of the greater Raleigh metro area, Wake County, North Carolina, showing major roads and streams. The location of Wake County within the state is shown in the on the map at the top of the page. W.B. Umstead State Park (USP) is located to the northwest of Raleigh and North Carolina State University (NCSU). The Sycamore (1), Richland (2) and Reedy Creek (3) field sites are identified. All three of these streams are tributaries to Crabtree Creek, and the Neuse River.*

The Neuse River Basin Water Quality Plan identifies nonpoint source runoff from a variety of land use practices as the primary cause (> 50%) of impacted surface waters in the NRB (Deamer, 2009). Although current land use practices and urbanization are anecdotally regarded as the sources of water quality impairment in the Neuse, post-European agricultural practices, which led to large volumes of impounded sediment behind milldams and more generally distributed along many of the regions valley bottoms, may be contributing significantly to current TSS and nutrient impairment. Modeling of the Total Maximum Daily Load (TMDL) allowances for a given pollutant typically relegates the collective importance of nonpoint sources to "background" concentrations. Reducing pollutant loads from known point sources is critically important for meeting 1972 Clean Water Act requirements; however, reductions from point-sources alone may not be significant enough to meet agreed-upon TMDL reductions. Recent studies in the Chesapeake Bay watershed have established that sediments impounded behind former milldams have nearly twice the concentration of certain nutrients (N and P) than pre-settlement soils (Walter and Merritts, 2008). Subsequent natural breaching and/or purposeful removal of many of the historic milldams, combined with modifications of the natural hydrologic regime from urbanization and climate change has led to anomalously high suspended sediment and nutrient loads in Piedmont streams in recent decades (Riggsbee et al, 2007; Walter and Merritts, 2008).

1.2. Study Area

Research was conducted in William B. Umstead State Park (USP), Raleigh, North Carolina, along portions of Reedy, Richland, and Sycamore creeks in the north-west portion of Wake County (Fig. 2). Before this area was declared a state park in 1943, it had been previously inhabited by Native Americans and later converted by settlers for agricultural use. In 1774, the Native American population was pushed out as land grants were offered to entice settlers to come to North Carolina (North Carolina State Parks, 2009). Forested areas were cleared and agriculture acreage quickly expanded. However, poor agricultural practices, such as one-crop production and farming on steep hillsides, led to depleted soil conditions and extensive hillslope erosion, evidenced by extensive gully formation, still visible across the park today (U.S. Dept. of Agriculture, 1935). The authors of the 1935 USDA report stated at the time that within the Umstead area:

> *People are obtaining income from stripping the last vestiges of timber from the land… the area is submarginal for agricultural purposes due to the steep and rocky slopes which have been ruined by a continual soil erosion.*

In an effort to restore severely damaged agricultural lands in the area that is now Umstead State Park, the federal government and state agencies united to buy 2,000 hectares (5,000 acres) in a recreation area demonstration project (North Carolina State Parks, 2009). After federal purchase of the Umstead acreage, the Civilian Conservation Corps (CCC) was contracted to mitigate and reduce upland erosion, for example, through the construction of small gully-crossing rock check dams. It is estimated that they built over 3,000 such dams across the streams and incised gullies of the demonstration area (North Carolina State Parks, 2009).

At least seven water-powered milldams were located along the streams in and adjacent to what is now USP. This study focuses upon the stream reaches adjacent to four of these historic milldams (Table 1). Several milldams not listed in historic archives have been located during the course of this research within the study area, including “Betty’s” milldam located in the Reedy Creek reach. Betty’s milldam is estimated to have been built prior to 1810 based upon construction techniques employed, and breached sometime before 1870 due to its lack of inclusion in the Hydrologic survey of Wake County (Bevers, 1871). Cooks Mill was built on Richland Creek around 1865 and breached possibly in 1910 due to a large discharge event (Bevers, 1871; Hunt, 2011). Sycamore Creek had two known milldams impacting the reach of stream studied; they were the Rhodes and G. Lynn Mills. The Rhodes milldam is named in a lawsuit (King, 1817) and the G. Lynn mill appears on the Bevers 1871 map, but dates of construction and beaching for both are unknown. The G. Lynn mill was located on Sycamore Creek, while the Rhodes mill was on Crabtree Creek, although its impoundment area included the lower portion of Sycamore Creek above its confluence with Crabtree Creek. All of the milldams in Umstead can be found in varying stages of disrepair, or are no longer extent. The research for this project was conducted along waterways once occupied by these dams and their ponds. Umstead State Park is an ideal location for this study since it has undergone widespread re-forestation, which slowed modern erosion and helped preserve historic erosional features, while adjacent upstream lands have undergone fairly rapid suburban-to-urban development since about 1970.

Table 1. *Milldams of William B. Umstead State Park and surrounding area.*

Stream	Milldam Name	Latitude (°N)	Longitude (°W)	Pond Area (acres)	Constructed	Breached
Crabtree	Company	35.843534°	78.755516°	11	pre 1810	late 1930's
	Rhodes	35.844519°	78.718016°	108	pre 1816	?
Reedy	Betty's	35.829461°	78.753342°	6	pre 1810	pre 1865
	Allen	35.840112°	78.745327°	15	mid 1800	?
Sycamore	G. Lynn	35.854745°	78.742654°	11	mid 1800	?
Richland	Cook's	35.834146°	78.720228°	25	c. 1850	c. 1910
Pat's Branch	Pat's	35.875085°	78.757531°	3	mid 1800	intact

2. METHODS

2.1 GEOMORPHOLOGY

2.1.1 Geomorphic Mapping

Geomorphic field mapping was conducted within portions of the Sycamore and Reedy creek drainage basins of Umstead State Park in order to determine the upland sources and distribution of Holocene sediment types preserved along valley bottoms, and to estimate the volume of soils eroded from hillslopes and sediments aggraded above the pre-European settlement period horizon (Fig 3). Field mapping was performed at a scale of 1:12,000 on a base map derived from 6-m pixel resolution airborne lidar data (North Carolina Division of Emergency Management, 2009), and later transferred into a geographic information systems database using ESRI ArcMap software. Upland and hillslope erosional source areas were identified by the presence of gullies and erosional features, such as meter-scale slope parallel rills and undulating topography, caused by former agricultural practices and surface runoff of water. The location of small sediment-impoundment dams built by the Civilian Conservation Corps (CCC) across ephemeral streams and erosional gullies were also mapped. The known and possible locations of historic milldam sites in the park were identified (Table 1; Figs. 4, 5). Valley bottom mapping included the demarcation of aggraded late Holocene sediment.

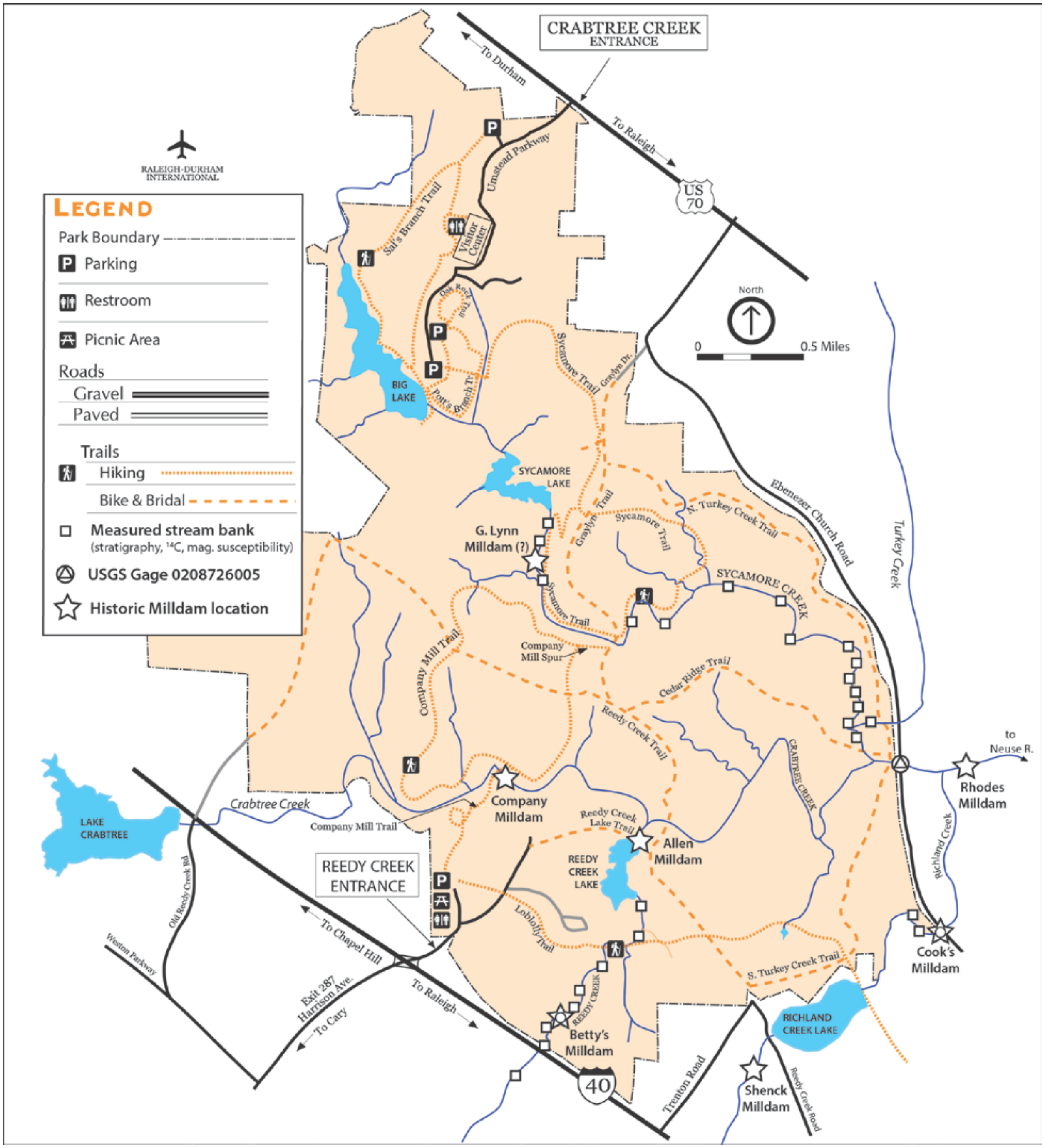


Figure 3. *Map of W.B. Umstead State Park indicating the locations of measured stream banks (stratigraphic sections, magnetic susceptibility, and radiocarbon sample locations), historic milldam sites, local roads, trails, and streams.*

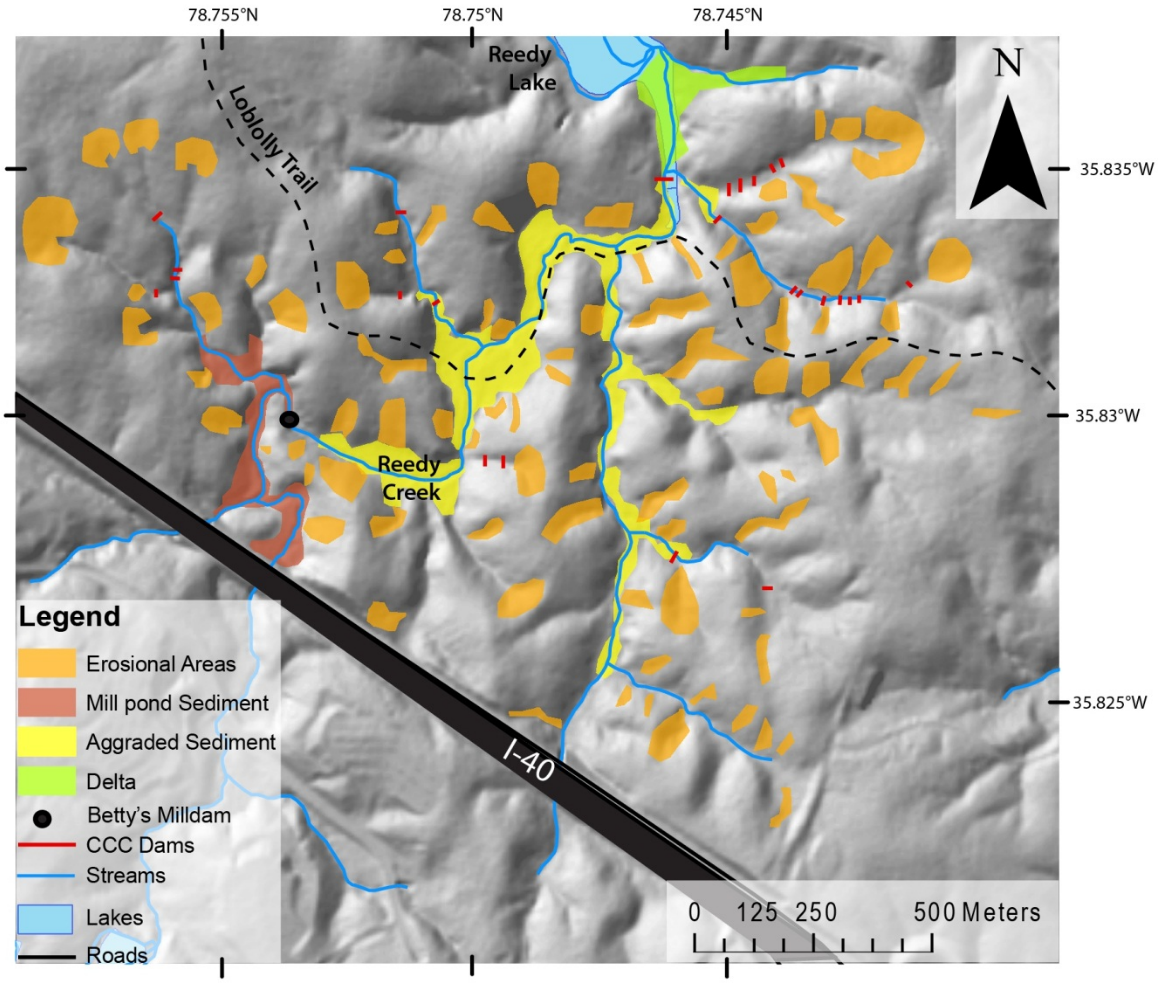


Figure 4. *Shaded relief map of the Reedy Creek study site within W.B. Umstead State Park, extending from Interstate 40 to Reedy Creek Lake. Post-European settlement deposits and landforms are mapped, including erosional gullies resulting from poor soil conservation practices. The modern delta at the head of Reedy Lake is also highlighted. This geomorphic map was used to estimate the area and volume of eroded upland soils and aggraded valley bottom deposits in the study area. CCC – Civilian Conservation Corps erosion control check dams on low-order channels.*

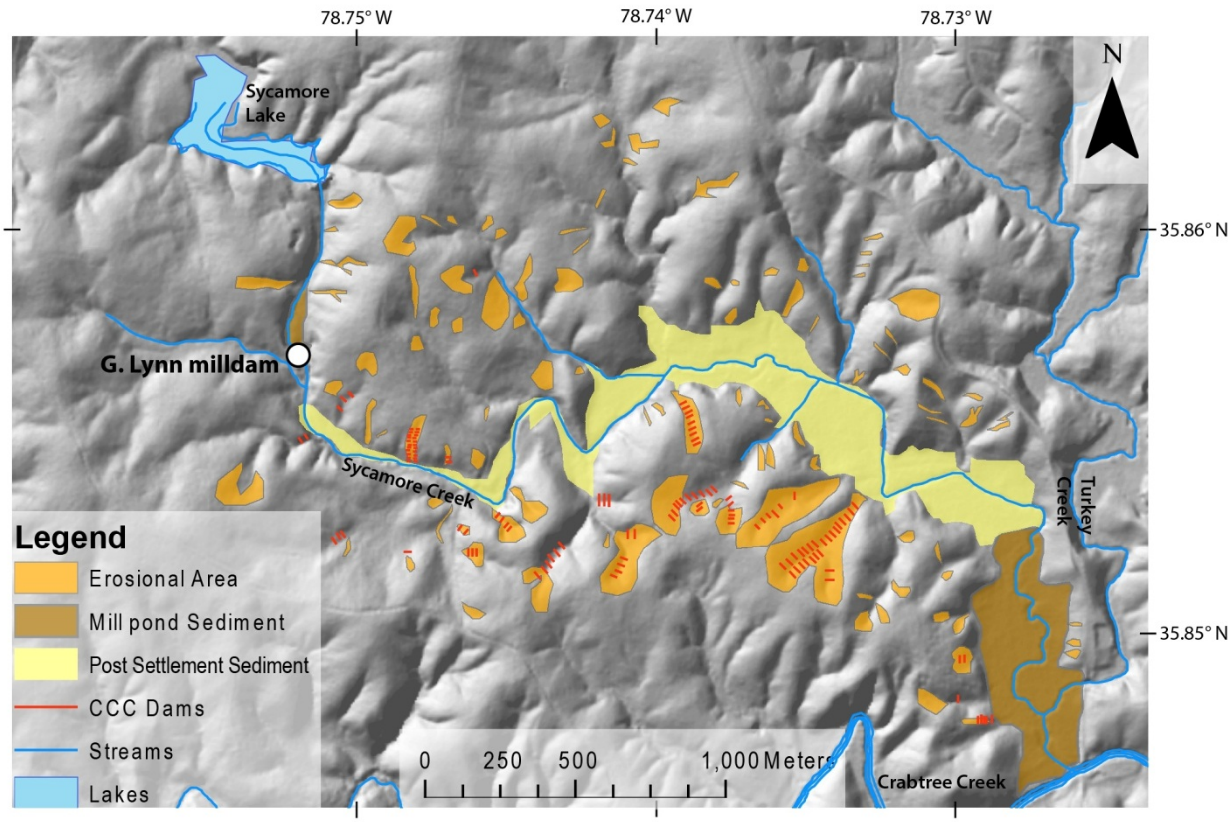


Figure 5. *Shaded relief map of the lower portion of the Sycamore Creek basin within W.B. Umstead State Park. Post-European settlement deposits and landforms are mapped, including erosion gullies resulting from poor soil conservation practices and Civilian Conservation Corps (CCC) check dams built to arrest gully formation. This geomorphic map was used to estimate the area and volume of eroded upland soils and aggraded valley bottom deposits in the Sycamore Creek study reach.*

2.1.2 Stream Bank Stratigraphy

We documented the stratigraphy of unconsolidated near-vertical stream bank exposures at 22 sites along Reedy, Richland, and Sycamore Creeks (Figs. 3, 6). Unconsolidated Holocene stratigraphic units were differentiated in the field based upon their physical composition and sedimentology, including the presence or absence of preserved macroscopic organic material (e.g., preserved leaves, seeds, and stems), evidence for deposition in either fluvial or slack-water settings based upon the continuity of preserved bedforms (cross bedding vs. laminar bedding), and grain size variations (e.g. silt-sand couplets). We differentiate four unique valley-bottom stratigraphic units: pre-European valley bottom sediment (PES), pre-dam legacy sediment (PDLS; sediment aggraded prior to dam construction), mill pond legacy sediment (MPLS; sediment deposited in the mill pond after the dam was in place), and the modern top soil (MTS; entisol-to-inceptisol soils developed in legacy sediment parent material that may include thin accumulations of more recent stream-deposited overbank clay, silt and sand). Along portions of stream not impounded behind former milldams, yet where valley bottom aggradation is attributed to erosion from upland sources (based upon mapping), stream bank sediments are classified as either pre-European or post-settlement sediments (PSS; commensurate in timing to the deposition of pre-dam/milldam legacy sediment units). Post-settlement deposits consist of eroded upland soils which have been transported and deposited along the stream channel, but were not impounded behind a milldam. The term "legacy sediment" refers to all valley bottom deposits attributed to the period subsequent to European settlement of the area. Field designations based upon stream bank stratigraphy were corroborated by magnetic susceptibility profiles and radiocarbon dating of bank exposures. We estimate the volume of maximum mill pond sediment impoundment behind Betty's and Cook's milldams on Reedy and Richland Creeks, respectively, based upon field mapping, stream bank stratigraphic relationships, and sediment bulk density (Table 1, Fig. 3).

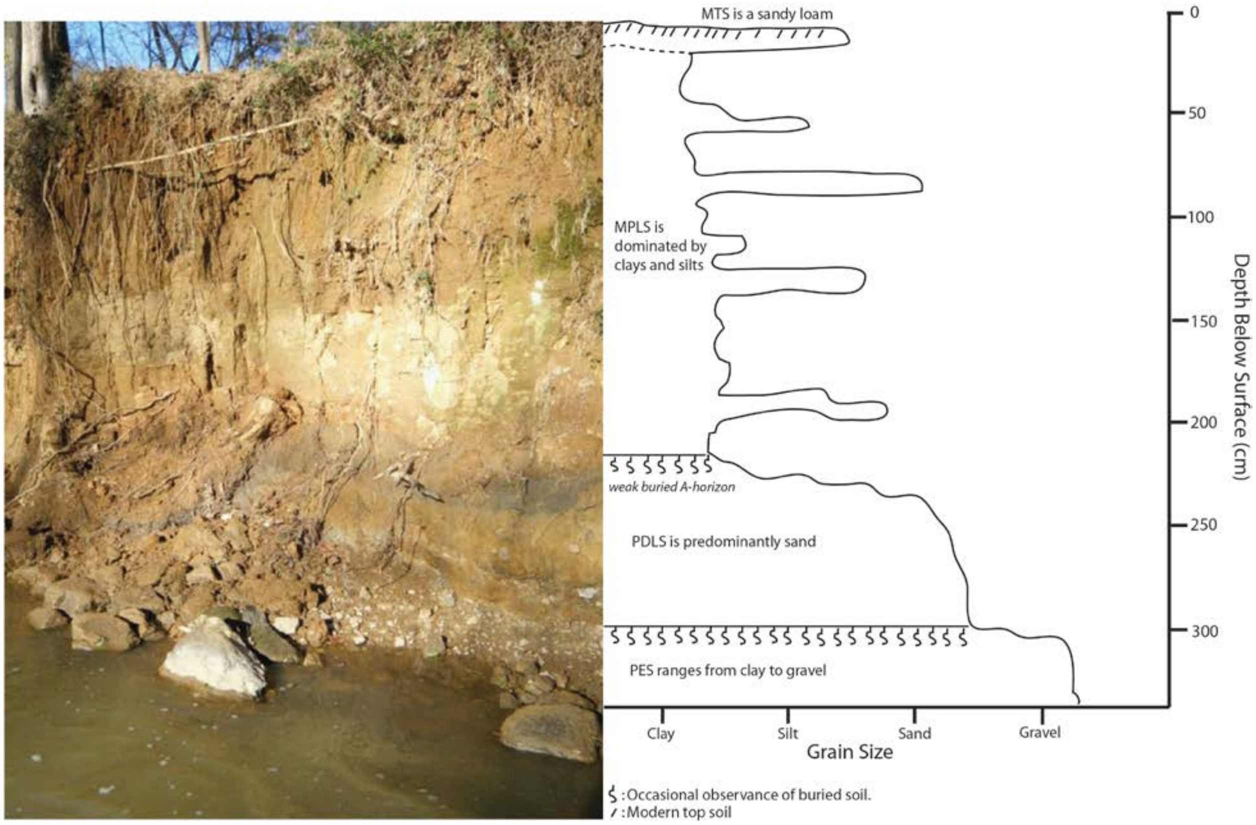


Figure 6. *Generalized composite stratigraphy (right) and corresponding photograph of stream bank exposure from the Richland Creek study reach (left). Distinct layers representing the Pre-European valley bottom sediments (PES), a relict stream bed in this instance, the pre-dam (PDLS) and milldam (MPLS) legacy sediments, and the modern top soil (MTS) are recognized. Stratigraphic interpretations are aided by relatively consistent grain size variations between the main stratigraphic units.*

2.1.3 Magnetic Susceptibility

Magnetic susceptibility values were obtained using a GF Instruments SM-20 magnetic susceptibility meter at 21 stream bank locations along reaches of Reedy and Sycamore Creeks (Figs. 7 and 8). Values of κ were collected every 15-cm along smooth, vertical transects extending from the top of the stream bank to the baseflow water surface. Bank surfaces were freshly exposed to a depth of 30 to 50 cm from the free face. Reported κ values are the average and standard deviation of three repeated measurements at each 15-cm increment.

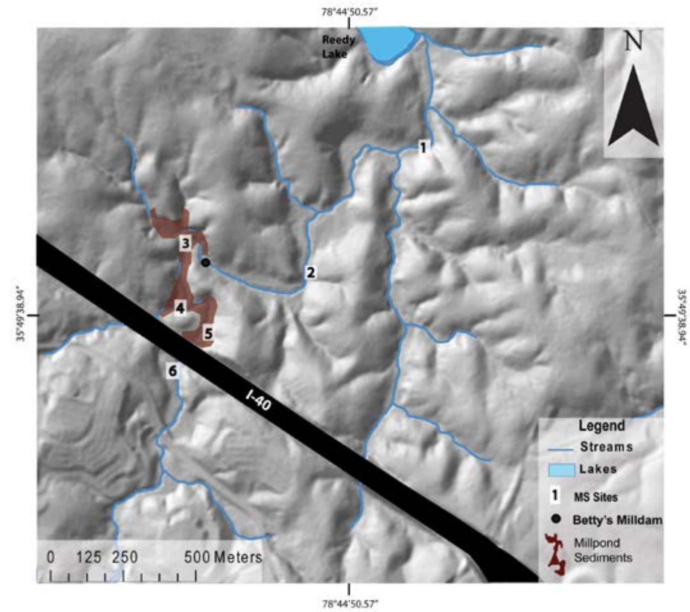


Figure 7. *Shaded relief map of the Reedy Creek study reach noting the location of the stream bank magnetic susceptibility profiles. See Other Appendices for access to the full magnetic susceptibility data set for this project. The aerial extent of the former Betty's mill pond is highlighted in brown.*

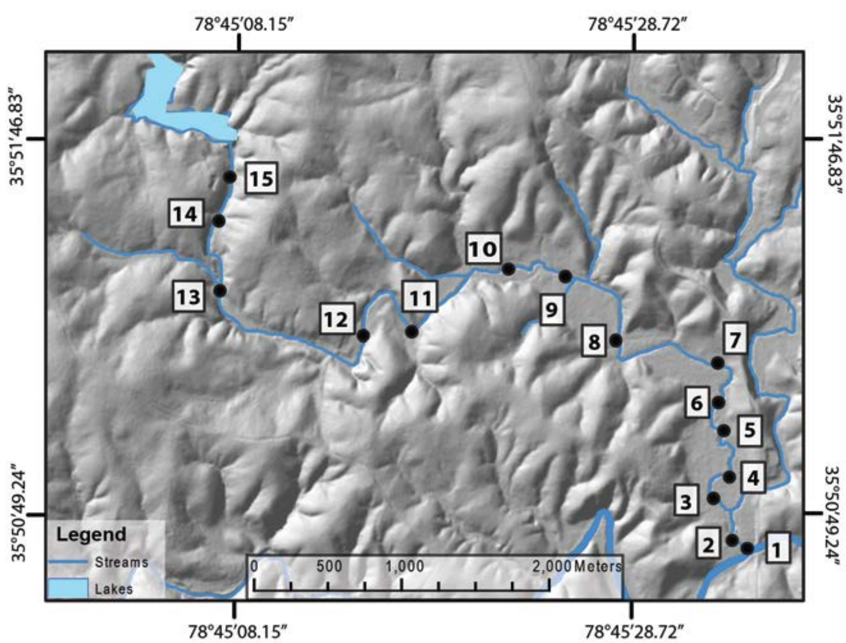


Figure 8. *Shaded relief map of the Sycamore Creek study reach noting the location of the stream bank magnetic suscepti-bility profiles. See Other Appendices for access to the full magnetic suscep-tibility data set from this project.*

2.1.4 Radiocarbon Geochronology

Samples of organic material for radiocarbon dating were recovered from stream bank exposures along Reedy, Richland, Sycamore, and Crabtree Creeks. Dated samples consisted of detrital charcoal and wood, leaves, seeds, and buried tree trunks preserved within stream bank deposits. With the exception of the rooted tree stumps, bulk sediment samples (~500 g) were collected from specific stratigraphic intervals at key localities. Each bulk sediment sample was immersed in deionized water in an ultrasonic bath for 60 minutes to loosen grain-to-grain adhesion. Following the ultrasonic bath, the sediments were wet-sieved to a grain size of ≥ 250 μm (fine sand), from which organic matter was identified and collected via binocular microscope. Radiocarbon analyses were performed at the Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California Irvine, at Beta Analytic in Miami Florida, at Aeon Laboratories in Tucson, Arizona, and at DirectAMS in Seattle, Washington. Samples received at the respective radiocarbon laboratories were first physically examined and cleaned of identifiable contamination before undergoing a standard acid-base-acid treatment to remove geological carbon accumulated on the sample from dust or soil (Olsson, 1986). The fraction of modern carbon in each sample was determined by accelerator mass spectrometry.

Because the production of ^{14}C in Earth's atmosphere has been non-linear through time, calibration is needed to convert lab-reported ages from the radiocarbon time scale to the Gregorian, or Western Calendar. We converted lab-reported radiocarbon ages to calendar years BC / AD, including the 2-σ errors for each, with the OxCal Online Radiocarbon Calibration program, v. 4.1 of Ramsay (2009), using the INTCAL09 calibration curve of Reimer et al. (2009), and the year 1950 as "modern" following standard procedures established by Stuiver and Polach (1977). The calibrated radiocarbon ages were rounded to the nearest 5 years (Table 3).

A reported radiocarbon age may result in multiple age-intercepts upon conversion because of uncertainties associated with both the actual measurement of ^{14}C in a sample and in converting from the radiocarbon to the Gregorian time scale. Multiple age intercepts occur when the radiocarbon age and its standard deviation intersect more than one interval (peak) on the INTCAL09 radiocarbon vs. Gregorian timescale curve. Therefore a laboratory reported radiocarbon age, say of 350 ± 15 ybp will, upon calibration result in two possible ranges, for example 1465 to 1525 AD and 1555 to 1635 AD. A probability of occurrence value is associated with each of these age ranges, for example 43.5 and 51.9%, respectively for the above example ages at the 2-σ (95%) confidence level. Following with the above example, there is then a ≦5% chance that the radiocarbon age of 350 $\pm$ 15 ybp is from the interval 1526 to 1554 AD. In Table 3 we report laboratory-derived radiocarbon ages, sample ages converted to the Gregorian calendar, and the probabilities that the calibrated sample age is bracketed by a given age range at the 95% confidence level.

2.1.5 Root Dendrochronology

Tree root dendrochronology was used to estimate horizontal bank erosion rates over a 5 to 10 year interval along sections of Reedy Creek above and below Betty's milldam (Fig. 9). When the roots of some tree species are exposed directly to the atmosphere and are no longer gravitationally supported by the surrounding soil they may undergo anatomical changes at the cellular level. These microscopic variations allow for determination of the timing of root exposure to the first year of ring growth subsequent to the event (Gärtner, 2007). When roots are exposed suddenly, for example by rapid lateral migration of a stream bank, the tree responds by increasing the number of cells and cell-wall thickness in the exposed root and decreasing the inner cell volume (Gärtner et al., 2001). In the first growth ring following exposure, coniferous trees such as *Pinus taeda* (Loblolly pine) tend to exhibit a reduction in cell size and an increase in the number of cells in the root's earlywood (Gärtner et al., 2001). Deciduous trees display a decrease in the number of cells and their size and an increase in fibrous material, which the tree grows in order to support the suddenly exposed root (Hitz et al., 2008). Both coniferous and deciduous tree types exhibit changes in the anatomical structure of their roots towards those more closely resembling the limb (trunk) structure of the tree.

Exposed roots were selected along a 1.25 km stretch of Reedy Creek from sections of mill pond and post-settlement sediments (Fig. 9). Roots were taken from living trees that were in a stable growing position on top of the bank, and for which the tip of the protruding root was still buried in the soil (Fig 10). A total of 9 mature (> 50 year old) trees were sampled. Three 2.5-cm wide discs were cut with a hand saw from the still-buried, transitional boundary (buried-to-exposed), and exposed sections of each root (Fig 10). The root disks were dissected into blocks along one or two radii, depending on the size of the root, in the Wood Anatomy Laboratory at North Carolina State University. A sledge microtome was used to cut 15 to 20 µm thick slices from each block. The thin sections were stained with safranin and were mounted on glass slides and analyzed with a Nikon SMZ 800 microscope. Oriented photographs of each thin section were taken with a Nikon Coolpix 4500 digital camera mounted to the microscope (Fig. 11).

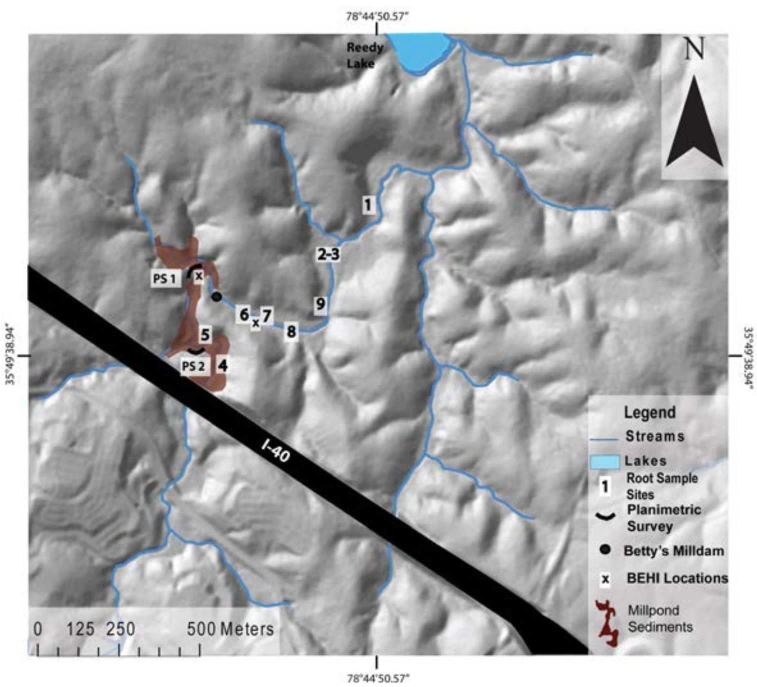


Figure 9. *Shaded relief map of the Reedy Creek study reach noting the locations of root dendrochronology samples, planimetric surveys, and the Bank Erosion Height Index (BEHI), which are reported by Lewis (2011), but not included in this report. The aerial extent of the former Betty's mill pond is highlighted in brown.*

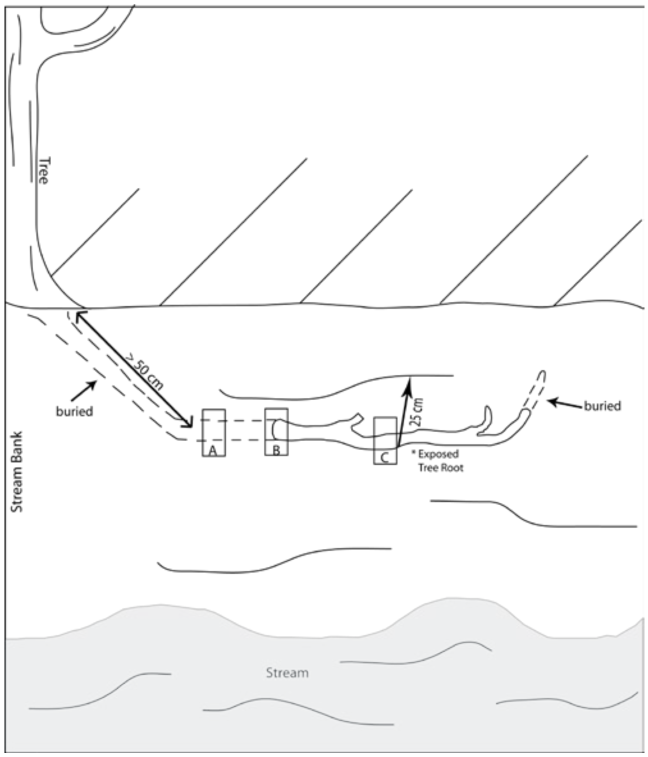


Figure 10. *Schematic drawing illustrating the type of root, location, and sections of roots sampled in this study. Root disks were collected from the buried (A), transitional (B), and exposed (C) sections of the root. Minimum rates of bank erosion were determined by measuring the distance from the exposed root to the bank edge perpendicular to the root and equidistant from the stream surface at the point furthest from the bank, as this is assumed to be the first area exposed (C).*

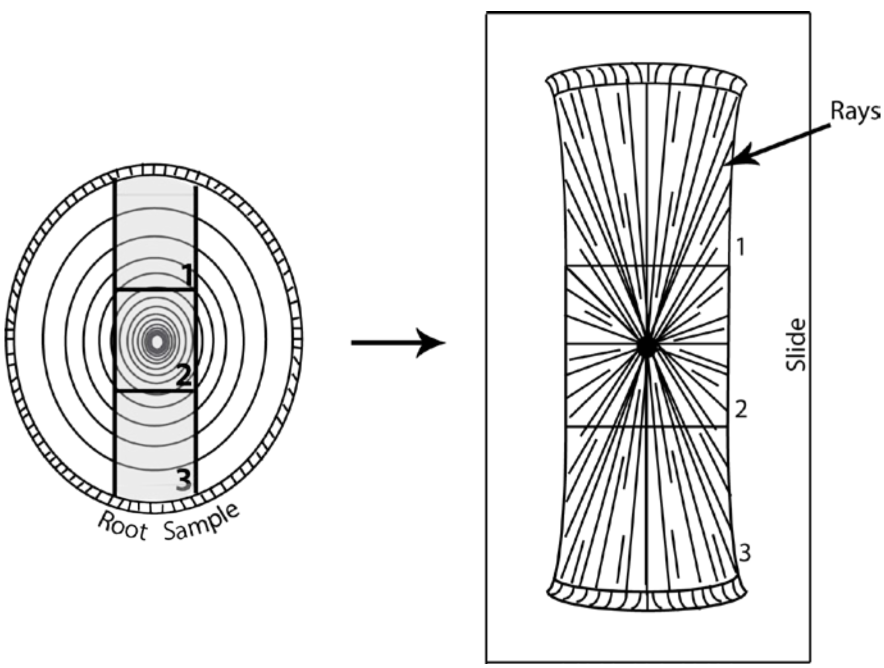


Figure 11. Cartoon detailing the location of blocks to be cut from the root disks and proper alignment of thin sections on the slide (Lewis, 2011). Blocks are cut along the radii and numbered sequentially from the top of the root down. Rays can be used to ensure that the thin sections are placed in the proper "stratigraphic" alignment in the root sample.

2.1.6 Meander Bend Planimetric Survey

Planimetric surveys were conducted along two 30-m long Reedy Creek cut banks formed in mill pond legacy sediments located 50 (site 1) and 150 (site 2) m upstream from Betty's milldam (Fig. 9). Monument stakes were placed back from the bank edge approximately 4 and 2 m for

Sites 1 and 2, respectfully. A taught line was extended between the monument stakes. The horizontal distance from the transect line to the cut bank face was measured every 25 cm along the length of the transect (Fig. 12). The cut bank face was presumed to be vertical; this assumption introduces potential error (perhaps ± 10-25%) into the rate of bank erosion and entrained sediment volume. Repeat surveys were recorded over 18 and 7 month intervals for Sites 1 and 2, respectively. The first survey period at Site 1 was conducted for the period November 21, 2009 to December 30, 2009, upon which the transect datum had to be reestablished following vandalism. The second study period for Site 1 lasted from April 1, 2010 to April 2, 2011. Site 2 was installed on September 11, 2010 and was resurveyed once on April 17, 2011. Spatially-averaged along channel bank erosion rates for each site were calculated by dividing the total volume of eroded sediment over the measurement interval spread equally across the 30-meter survey length. The erosion rate was calculated in this manner to enable comparison with along-bank erosion rates from the root dendrochronology and repeat terrestrial lidar survey components of the project.

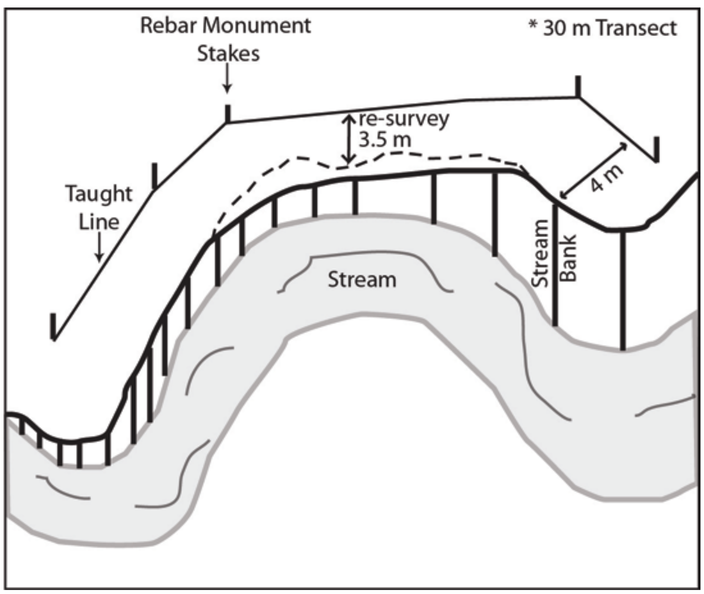


Figure 12. *Cartoon illustrating the setup of the planimetric stream bank erosion surveys.*

2.1.7 Stream Total Suspended Solids and Turbidity

In order to quantify the amount and levels of total suspended solids (TSS) and turbidity being contributed to Reedy and Richland creeks from bank erosion of legacy sediments, stream water samples were collected using automated ISCO 3700 samplers. The samplers were deployed along the Betty's Mill and Cook's Mill reaches of Reedy and Richland Creeks, respectively (Fig. 13). Three ISCO samplers were installed along Reedy Creek, the upstream most where the stream exits the main-stem reservoir south of Interstate 40, an intermediate one where the stream enters the mill pond sediment field immediately downstream (north) of Interstate 40 and a third approximately 150 m downstream from the site of Betty's milldam (Fig. 13). At the Richland Creek study site, mill pond legacy sediment extends upstream from Cook's milldam to the base of the modern reservoir; therefore, only two ISCO samplers were placed along the Cook's mill pond reach (Fig. 14). The first Richland Creek sampler was located directly below the reservoir, and represents the baseline water quality location. The second Richland Creek site was located on private property immediately downstream from Cook's milldam, where Ebenezer Church Road now crosses the creek (Fig. 14). Sampler locations were positioned such that a TSS baseline was established during each precipitation event at the upstream location. At Reedy Creek, TSS measurements were also taken at the point where the stream enters the reach containing legacy sediments (intermediate site) to determine the amount of TSS attributed to sources other than the mill pond sediments. The downstream monitoring location was used to evaluate suspended sediment levels after the stream has passed though the reach containing mill pond deposits.

For each collection site, 48 samples (2 per 500 ml ISCO bottle) were captured over a 24 hour period at a sampling rate of 250 ml every 30 minutes, providing twenty-four 500 ml samples per precipitation – stream discharge event (Fig. 15). This sampling interval was chosen in an attempt to record the representative TSS and turbidity levels during a discharge event and to both minimize potential pulses of sediment that if sampled could result in an overestimation of the amount of bank erosion from study reaches, as well as so that those same pulses would not be missed if the interval between sample collection was great.

Sampled stream water was processed for TSS at the Geomorphology and Surface Processes lab at North Carolina State University using a modified version of the ASTM standard D 3977-B filtration method (ASTM, 2007). Stream water samples were filtered using oven-baked preweighed 47mm diameter, 0.7 µm thick GF/F filters, Nalgene filtration towers, and a Barnant Company vacuum pump. The volume of the post-filtered water was recorded. Filter papers were then oven dried at 105° C for 24 hours, following which samples were re-weighed and the TSS concentration (mg/l) was calculated by subtracting the final from initial filter weight and dividing by the volume of filtered water. Replicate samples indicate that TSS measurements are reproducible to within 5% of reported values.

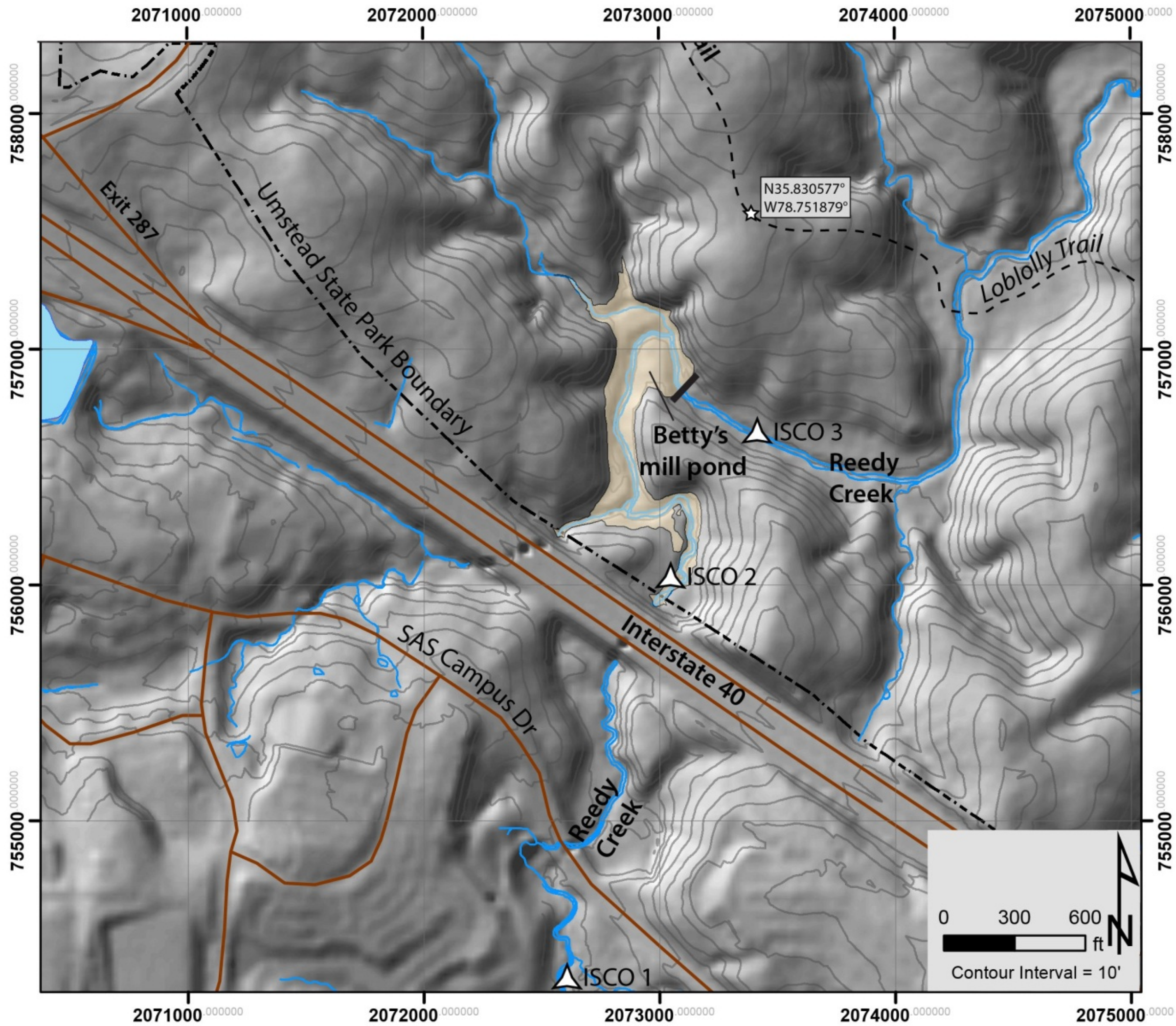


Figure 13. *Shaded relief contour map for the Betty's Mill – Reedy Creek field site. The area formerly flooded by Betty's Milldam extends from the dam upstream to where Interstate 40 crosses Reedy Creek. Three automated water samplers (ISCO 1–3) were used to measure variations in total suspended solids above and below the mill pond reach.*

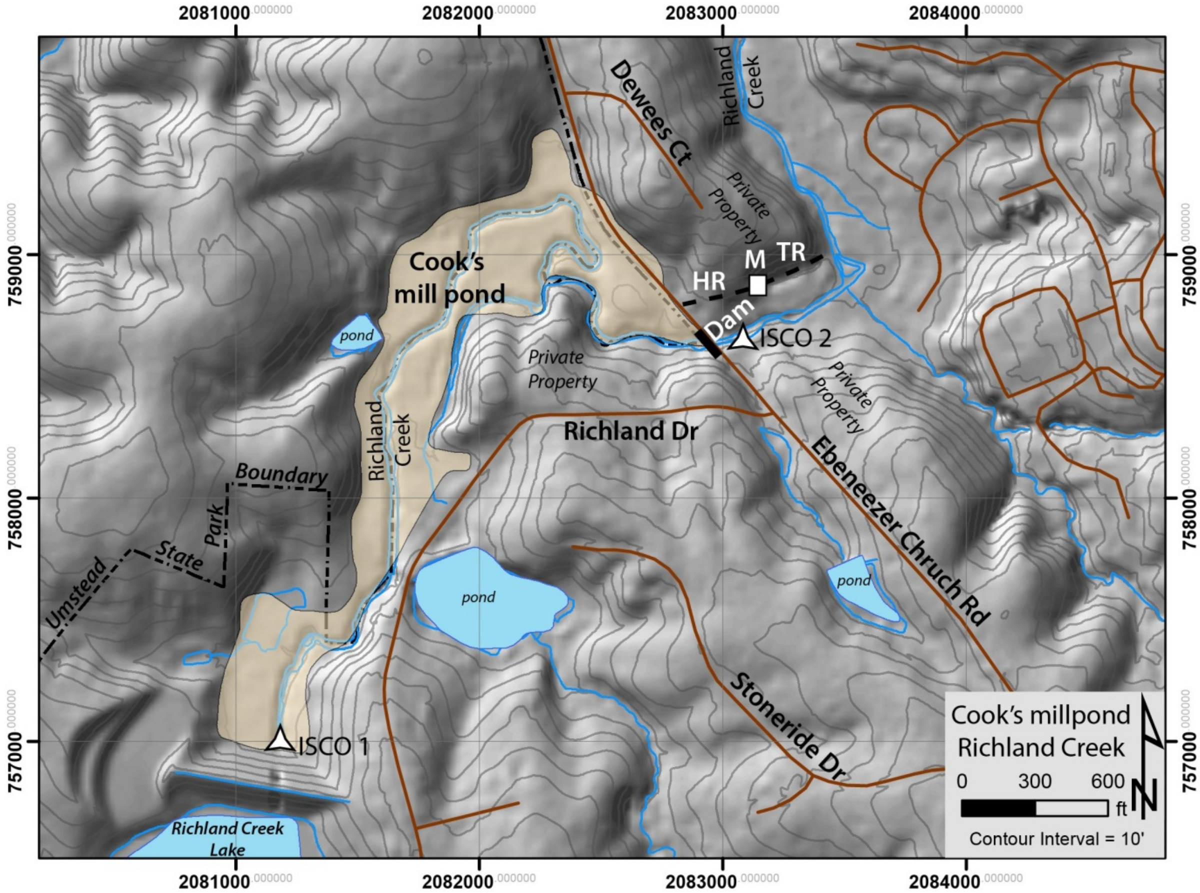


Figure 14. *Shaded relief map for the Richland Creek study site. The area formerly flooded by Cook's Milldam extends from the bridge upstream to the base of the Richland Creek Lake impoundment structure. A headrace (HR) and tailrace (TR) connected the mill pond, Cook's Mill (M) and Richland Creek. Two automated water samplers (ISCO 1 and 2) were used to measure variations in total suspended solids above and below the mill pond reach.*

Stream water turbidity, an optical measurement of the amount of light scattering that occurs as a light source is passed through the water sample, was measured in Nephelometric Turbidity Units (NTU) in the lab on 10 ml subsamples from each 500 ml ISCO sample via a LaMotte 2020e turbidity meter. The Accuracy of this meter is ± 0.05 or 2% of the reading for values below 100 NTU, and 3% of the reading for values above 100 NTU. Each reported NTU measurement is the average of three replicates.

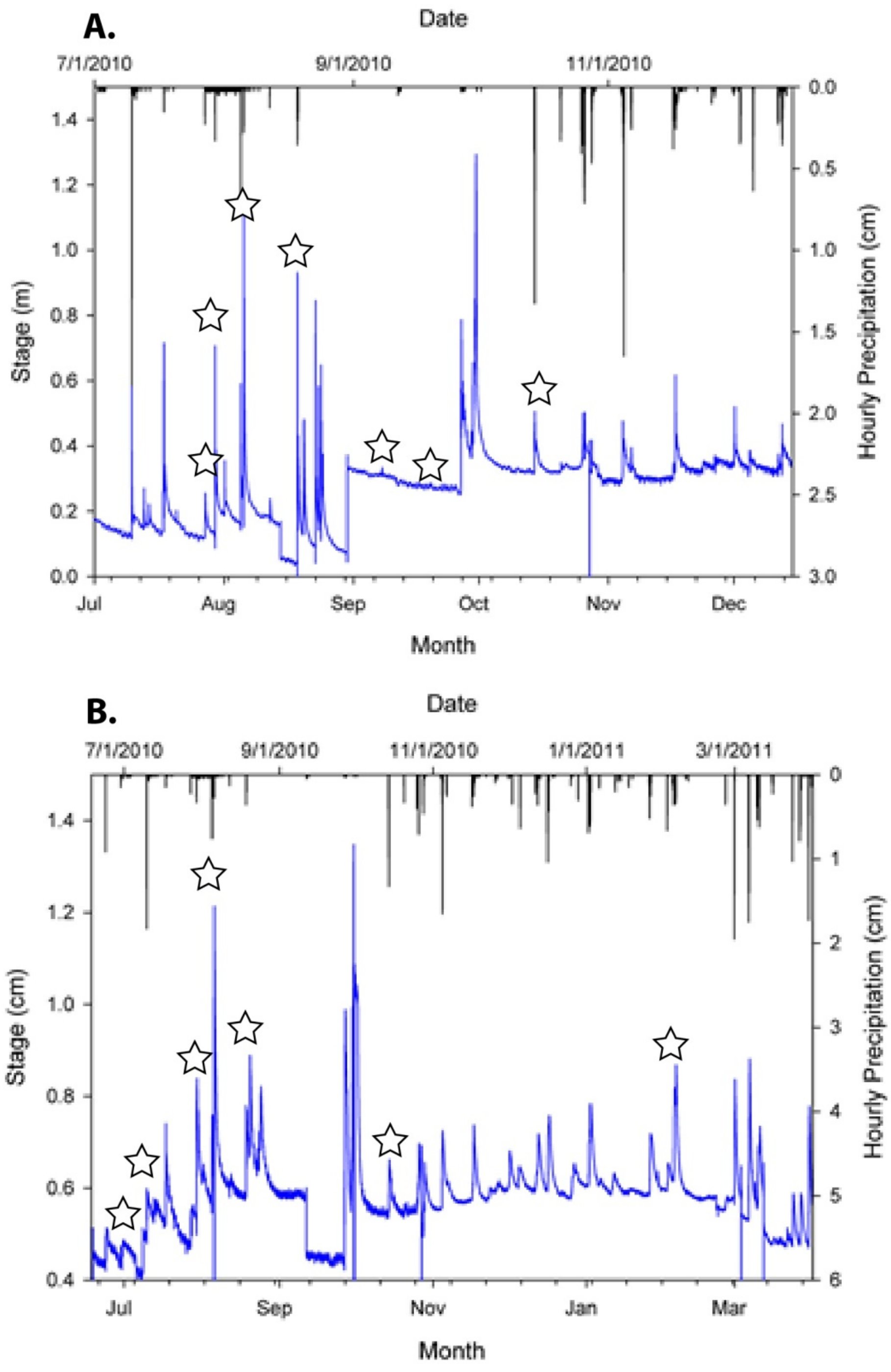


Figure 15. *Plots of stream stage and hourly precipitation for Richland (A) and Reedy (B) Creek study sites. Precipitation was sampled hourly at the State Climate Office of North Carolina's Reedy Creek Field Laboratory (REED) site, located at 35.80712° N, 78.74412°W. Stream Stage was recorded every 15 minutes with Solinst leveloggers deployed in each stream near the former milldams. Stars indicate the individual precipitation – discharge events that were sampled. Note the low flows resulting from drought-like conditions beginning in the fall of 2010.*

2.2 NUTRIENTS FROM STREAM BANK SEDIMENTS

2.2.1 Weight Percent Nitrogen of Bank Sediments

One kilogram samples of sediment from the MTS, MPLS, LSPD, and PSS were collected from the upstream and downstream sections of the Betty's mill pond and a downstream section of the Cook's mill pond at Richland Creek. Samples were stored frozen in plastic bags prior to determination of the wt. % N and C, and each was mechanically homogenized prior to analysis.

Weight percent of N and C were measured by elemental analysis. An amount of thawed wet sediment was oven-dried (50°C overnight) and ground to a powder with mortar and pestle. Using cleaned labware, dried samples were weighed into pre-cleaned tin capsules on a microbalance and then sealed. The weighed samples were placed into a carousel of a Thermo Flash EA 1112 CHN analyzer. Samples were flash combusted at 950 °C in an oxygen atmosphere converting organic N and C to NO_x and CO_2, respectively. The gasses were then swept over a packed copper reactor held at 650 °C which reduced NO_x to N_2 and then the gasses were separated on a packed chromatographic column prior to detection. A calibration curve was calculated using combustion of a pure compound standard (acetanilide) that has a known wt % N and C.

2.2.2 Nitrogen Release from Stream Bank Sediments Following Suspension

2.2.2.1 Leaching Experiments

Leaching of dissolved N species was conducted by disaggregating sediment into both pure lab water (salinity = 0) and into an artificial river water (ARW) solution with a salinity =1. This represented a close approximation of the lower Neuse River at the head of its estuary. A salinity of 1 was chosen to create a solution near Neuse River water, but also to mitigate any artificial effects of using pure lab water, which had been deionized, polished, and passed across an ultraviolet lamp to destroy organics. The aim here was to determine the maximum potential of N release from disaggregated sediments against the lowest N background possible.

Approximately 1 g of sediment was placed into cleaned 250 mL Erlenmeyer flasks and 100 mL of water (pure water or ARW) was added to create a concentrated solution. Triplicate solutions and blanks (pure water or ARW without sediment) were placed on a shaker table and agitated for up to 24 hours. After agitation, samples were filtered through Whatman GF/F filters (nominal pore size of 0.7 µm) which had been pre-combusted to remove organics and the filtered solutions were frozen until nutrient analyses were performed.

2.2.2.2 Measurement of DON and DIN

Dissolved organic nitrogen (DON) was calculated as the difference between total dissolved N (TDN) and total dissolved inorganic N (DIN: sum of nitrite, nitrate, and ammonium). TDN was measured on a Shimadzu TOC-V carbon analyzer using a total N (TN) module, while DIN was measured on a Lachat Quick-chem 8000 auto analyzer (Lachat, Milwaukee,WI, USA)—both sets of analyses were conducted by the Paerl Laboratory at UNC-Institute of Marine Sciences. Standard EPA protocols were used for all analyses (H. Paerl, pers. comm.).

3. RESULTS
3.1 GEOMORPHOLOGY

3.1.1 Geomorphic Mapping
Seven historic milldams and their associated ponds have been identified within Umstead State Park (Table 1). We estimate that approximately 73 hectares (180 acres) of valley bottom within the park were flooded at various times between ca. 1800 to 1950. The typical milldam height was about 4 m above stream level. Legacy sediments accumulated behind milldams to an average thickness of 1.5 m, resulting in a potential stored sediment volume of 1.1 x 10^6 m^3, or the equivalent of 3.3 cm of surface erosion spread evenly across the 54 km^2 area of the Park; however, the depth of upland soil erosion was certainly not uniform. Geomorphic mapping has revealed the presence of hundreds of erosional gullies, resulting from upland soil erosion during the period of intensive agriculture prior to the establishment (and reforestation) of the state park (Figs. 4, 5, and 16). These gullies represent a direct link between sediment being eroded from uplands and transported to and deposited on top of pre-settlement valley bottoms. The age of living trees rooted in the floors of these erosional features suggest that gully expansion slowed significantly following land acquisition and reforestation efforts by federal and state government beginning in 1933. In addition to sediments accumulated in the slack water environments upstream from milldams, we also recognize a substantial volume of historic-aged sediment that was deposited along valley bottoms in the absence of milldams.

Figure 16. *Erosional gully feeding into the former Betty's mill pond off Reedy Creek. The pre-erosion ground surface slope is approximated by the red line. Living trees now growing in the floor and sides of the gully are ± 75 years old, indicating that erosion from this gully has been relatively minor since ca. 1935-1940. Erosional features similar to this one are common across the Umstead landscape, and speak to the severe erosion that occurred in the wake of land clearing and agricultural activities. Note the person for scale.*

Mapping reveals that 13% of the Reedy Creek study site surface area (c. 260,000 m^2) exists as erosional areas of historic age (Fig. 4). In 1975, Trimble estimated an average upland soil loss across Wake County of 0.1 m resulting from post-colonial agriculture. Applying Trimble's estimate to the 2 km^2 Reedy Creek study area results in a projected volume of 200,000 m^3 of soil loss due to erosion (Table 2). The maximum volume of eroded upland soils deposited along the 1.3 km-long alluvial valley bottom between Betty's milldam and Reedy Creek Lake is estimated at 204,000 ± 34,000 m^3; a similar amount of erosion to that calculated when applying Trimble's Wake County average upland soil loss to the study area. The amount of valley-bottom post-settlement sediment storage between Betty's milldam and Reedy Lake equates to 157 ± 27 m^3 (20 dump truck loads) of aggradation per linear meter of valley bottom. The volume of sediment estimated to have been trapped within the 450 m long mill pond behind Betty's dam on Reedy Creek is 91,000 ± 9,000 m^3, or 202 ± 20 m^3 per linear meter of mill pond. Combining the sediment accumulated along valley bottoms and behind milldams results in a maximum total of 295,000 ± 43,000 m^3 (c. 18,000 standard dump truck loads; if parked end to end they would stretch for 190 km). Not all of this sediment remains within the Reedy Creek study site, as some of it has been eroded and transported downstream following stream incision into these legacy sediments. If the entire volume of aggraded mill pond and post-settlement sediments were derived from upland sources within the 2 km^2 Reedy Creek study site than an average upland soil loss of 0.15 ± 0.02 m would be required. If most of the erosion was concentrated into the erosional gullies that we identified during the geomorphic mapping, the average depth of gully erosion would have been 1.15 ± 0.15 m. This result is likely an upper limit of upland soil loss, as it does not allow for the introduction of sediment to the study reach from upstream source areas.

Similar results were observed for the 5 km^2 Sycamore Creek study site, also located within Umstead State Park (Fig. 5). Geomorphic mapping confirmed that upland gully erosion resulting from post-colonial agriculture accounts for a minimum of 4.2% of the surface area (211,000 m^2) of the Sycamore study site. Application of Trimble's estimate of 0.1 m of vertical upland soil loss to the Sycamore Creek area results in 500,000 m^3 of erosion. Collectively, the two mill ponds located on this reach of stream impounded approximately 500,000 ± 50,000 m^3 of eroded sediment, while c. 613,000 ± 104,000 m^3 of post-settlement soils aggraded along the non-mill pond reaches of the alluvial channels.

3.1.2 Stream Bank Stratigraphy

We have constructed a composite stratigraphic profile for first to third order streams within the study area based upon field observations of numerous natural exposures along Reedy, Richland, Crabtree, and Sycamore Creeks (Figures 6 and 17). We observe intact-to-weathered bedrock at the elevation of the modern channel bottom that is overlain by (i) a thin (<0.5 m) bed of angular to subrounded quartz-rich gravel and (ii) a thin (0.25 to 0.5 m), dark black (black, 10YR 2/1) to dark bluish-gray, (GLEY2 4/5B) organic-rich clay-to-silt loam, which we've designated as pre-European sediments (PES), consistent with what is typically identified in the field as a buried wetland or waterlogged soil layer overlying coarser axial channel gravels. Exposures of the buried and gleyed pre-European soil contain yellowish brown, brown, and black mottles, suggesting preservation of organic material in mostly anaerobic reduced-iron conditions (Buol et al., 1989). This soil layer locally contains well-preserved woody debris, seeds, nuts, roots, and even leaves. At several sites we observe tree stumps rooted in this stratum (Fig. 17). Radiocarbon dating of this buried soil confirms that it pre-dates European settlement of North America (Figure 18; Table 3) as we have consistently obtained dates between 350 and 3,880 ^{14}C ybp from this stratigraphic interval (Table 3). We interpret the underlying quartz-rich gravels as a valley bottom fluvial lag deposit representing concentration of recalcitrant clasts in a landscape characterized primarily by chemical rather than physical weathering processes. The stratigraphic order of units (i) and (ii) may be reversed.

Table 2. *Estimates of the volume of aggraded legacy sediments in the Sycamore and Reedy Creek study reaches of W.B. Umstead State Park*

Study Site	Geomorphic Unit	Unit Thickness (m)	Surface Area (m^2)	Volume (m^3)	Error (m^3)
Reedy Creek					
	Uplands[1]	-0.1	2×10^6	2×10^5	5×10^4
	Erosional Gullies[2]	-1.15	2.6×10^5	2.95×10^5	7.5×10^4
	MPLS	2.5	3.64×10^4	9.1×10^4	9×10^3
	PSS	1.5	1.36×10^5	2.04×10^5	3.4×10^4
Sycamore Creek					
	Uplands[1]	-0.1	$5 X 10^6$	$5 X 10^5$	$1.25 X 10^5$
	Erosional Gullies[2]	-5.3	2.1×10^5	1.1×10^6	2.8×10^5
	MPLS	2.5	$2 X 10^5$	$5 X 10^5$	$5 X 10^4$
	PSS	1.5	$4.1 X 10^5$	$6.13 X 10^5$	$1.04 X 10^5$

[1] Average historic agricultural upland soil loss for Wake County, NC (Trimble, 1975)

[2] Averge depth of gully erosion needed to balance aggraded sediment volume from the valley bottom. This estimate does not account for delivery of sediment from upstream sources, and thus is an overestimation. The impact of this overestimation is likely greater for the larger Sycamore Creek watershed compared to Reedy Creek.

Above the pre-European sediments we observe (iii) a pale-to-yellowish brown sequence of sandy silt with fluvial bedforms indicating deposition in a meandering to braided sand-bed channel, identified as either post-settlement (PSS) or pre-dam legacy sediments (PDLS), depending upon whether or not a particular site was flooded behind a milldam. Pre-dam legacy sediments exhibit signs of weak soil formation, with little pedogenic development, as most material is weakly-bedded to massive silty sands. Field and geochronologic evidence indicates that the contact between the PES and PDLS deposits is most often disconformable. Where mill pond flooding occurred, we recognize (iv) massive-to-thinly laminated pale yellow-to-brown silt-to-sandy silts deposited in slack water environments (MPLS) underlying (v) a thin weakly-developed modern soil (MTS) (Figs. 6 and 17). Mill pond sediments are unconsolidated and exhibit little signs of soil development. Stream reaches not formerly impounded behind milldams do not contain the mill pond legacy sediments; however, equivalent fluvial sediments suggestive of valley bottom aggradation are preserved (PSS).

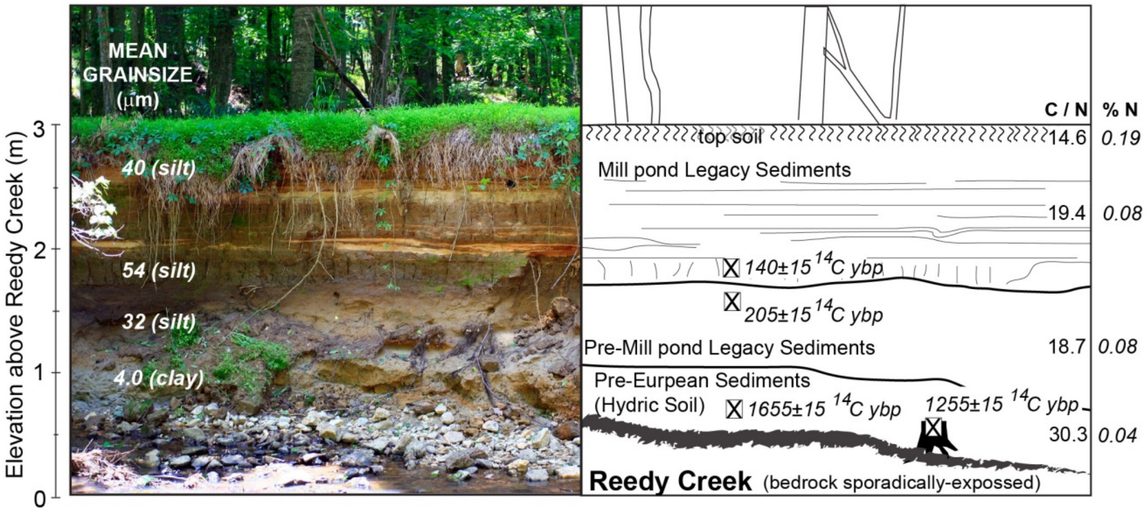


Figure 17. *Mean grain size, radiocarbon, and stable isotope analyses from the upper end of Betty's mill pond, ~250 m upstream from the milldam. Note the near-vertical bank and lower grain sizes of the 1600-year old, pre-European hydric bottomlands deposit. Also note the decrease in carbon-nitrogen (C/N) ratio values and the doubling of wt % N of the legacy sediments with respect to pre-European deposits.*

3.1.3 Differentiation of Stream Bank Sediments with Magnetic Susceptibility Mapping

We collected magnetic susceptibility (MS) profiles of stream bank sediments at 21 sites along the Sycamore and Reedy Creek study reaches (Figs. 7, 8). Mean MS (κ) values observed for the pre-European sediment, corroborated by radiocarbon dating (see section 3.1.4), fall within the narrow range of 10–20 κ. We observe consistent up-section increases in MS from pre-European levels to those in the pre-dam, mill pond, and post-settlement soils, with values typically decreasing near the modern top soil (Fig. 19). Mean MS values for the post- European sediments range between 20 to 120 κ, with most between 20 to 60 κ. Overall, the six sites from Reedy Creek PDLS, MPLS, and PSS deposits contained less variability and lower overall mean MS values, typically between 25 to 45 κ. One of the six Reedy Creek sites displayed an up-section decrease in MS within the PSS layer before returning to levels equal to the PES. Two additional Reedy Creek locations preserved a sharp increase at the modern top soil, while the sediments beneath remained relatively unchanged from the values obtained from the PES (Lewis, 2011).

3.1.4 Radiocarbon Geochronology

Sixteen organic samples were collected and dated via AMS radiocarbon analysis in order to bracket the depositional timing of valley bottom sedimentary units now exposed along stream banks within the study area. Dating revealed that valley bottom sediments belong to one of two distinct intervals (Figure 18; Table 3) that are distinguished either as sediment deposited prior to, or after European settlement in the region, whether that be pre-dam, mill pond, or post-settlement legacy sediments. Pre-European sediments are confined to the lower 50 cm or less as measured up from the base-flow stream level at all investigated stream bank exposures; yet these deposits account for a minimum of 4,250 (cal ybp) of alluvial valley bottom history within the study area. In contrast, the 1 to 3 m thick legacy sediment deposits that disconformably bury the pre-European valley bottom sediments range between 205 to 85 ^{14}C ybp, representing a maximum of only 300 years of deposition after radiocarbon calibration (Table 3). The radiocarbon ages from legacy sediments are consistent with what is known about the timing of local settlement, agricultural expansion, and the damming of streams for water power applications. These numeric ages corroborate the designation of stratigraphic layers based upon sedimentology, stratigraphy, and the stream bank magnetic susceptibility profile results.

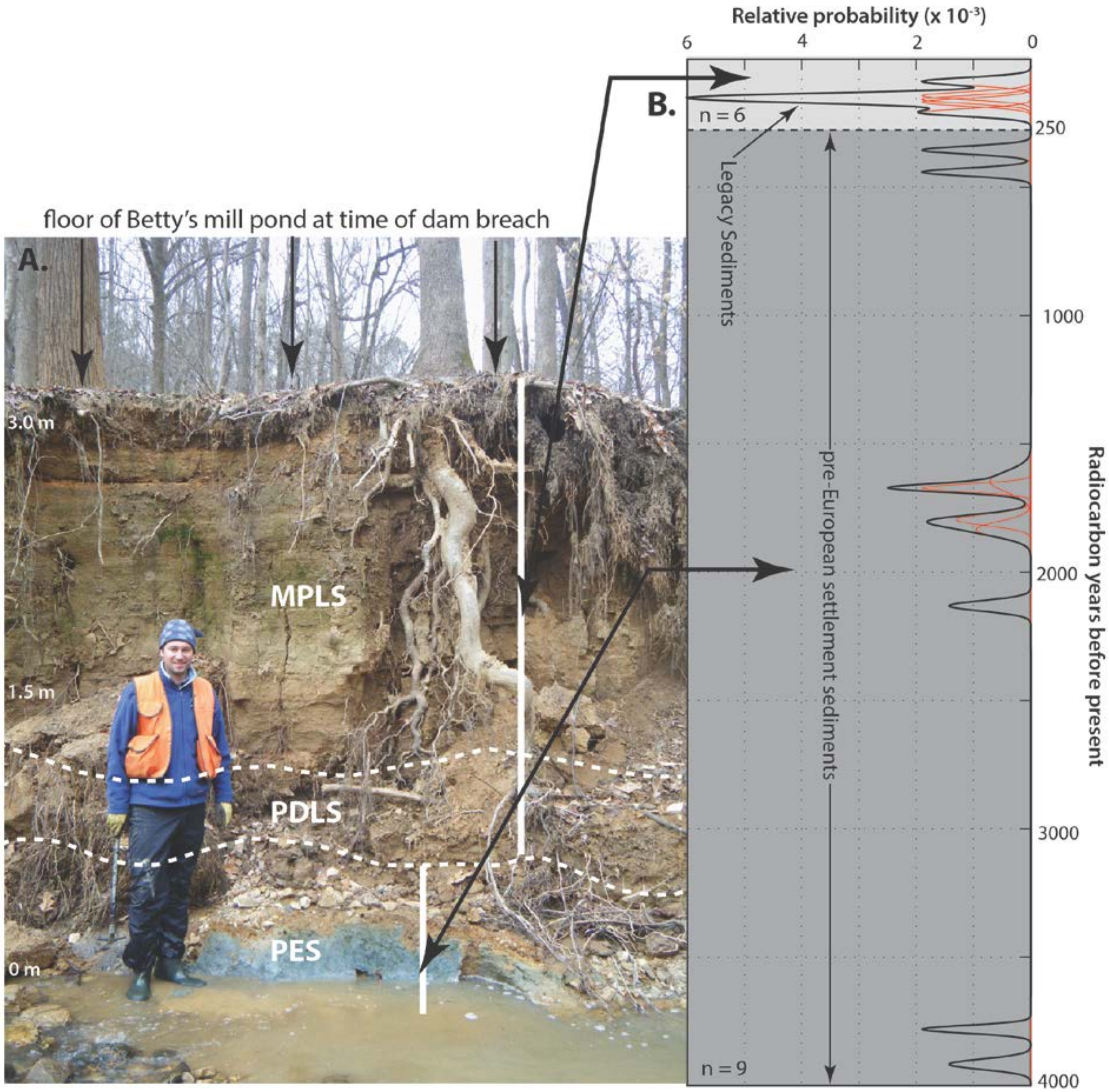


Figure 18. (A) Stream bank exposure along Reedy Creek showing thick legacy sediments (PDLS and MPLS) overlying pre-European sediment (PES). (B) A cumulative radiocarbon probability distribution for 16 samples collected in W.B. Umstead State Park plotted next to the photograph to demonstrate that much of the legacy sediment was deposited in a short interval compared to the ca. 3,700 years of deposition recorded in dated pre-European sediments. See Table 3 for the radiocarbon details. MPLS – mill pond legacy sediment; PDLS – pre-dam legacy sediment; PES – pre-European sediments.

Table 3. *Radiocarbon geochronology for stream bank deposits found within W.B. Umstead State Park*

Location	Lab ID [1]	Lat (°N)	Long (°W)	Dated Material	d^{13}C [2, 3] (‰)	Fraction [4, 5] modern	^{14}C age (BP)	±	2σ calendar ages in yrs. [6] BC/AD (probability)
Sycamore creek - Rhodes Millpond									
millpond legacy sediments									
	UCI-68067	35.84862	78.72596	charcoal	-26.75 ± 0.1	0.982 ± 0.002	140	15	1670–1710 AD (0.155) 1720–1780 AD (0.268) 1795–1820 AD (0.117) 1830–1885 AD (0.222) 1915-1945 AD (0.193)
	UCI-68063	35.84862	78.72596	leaves & seeds	-28.8 ± 0.1	0.981 ± 0.001	155	15	1665–1695 AD (0.157) 1725–1785 AD (0.476) 1795–1815 AD (0.123) 1915-1945 AD (0.197)
pre-dam legacy sediments									
	UCI-68065	35.84769	78.72713	charcoal	-26.1 ± 0.1	0.979 ± 0.001	165	15	1665–1690 AD (0.165) 1725–1785 AD (0.513) 1795–1810 AD (0.104) 1925–1950 AD (0.172)
pre-European sediments									
	UCI-68066	35.84862	78.72596	charcoal	-27.6 ± 0.1	0.957 ± 0.001	350	15	1465–1525 AD (0.435) 1555–1635 AD (0.519)
	D-AMS	35.8476	78.72537	charcoal	-15.1 ± 0.1	0.8014 ± 0.22	1778	22	135–195 AD (0.107) 205–265 AD (0.469) 270–335 AD (0.378)
Sycamore creek - upstream of Rhodes Millpond									
post-settlement sediments									
	UCI-86060	35.85482	78.74284	charcoal	–	0.989 ± 0.002	85	15	1690–-1730 AD (0.271) 1810–1855 AD (0.236) 1865–1920 AD (0.447)
pre-European sediments									
	UCI-86059	35.85482	78.74284	charcoal	–	0.627 ± 0.001	3745	15	2205-2125 BC (0.820) 2090–2045 BC (0.134)
	UCI-86058	35.85482	78.74284	charcoal	–	0.617 ± 0.001	3880	20	2465–2295 BC (0.954)

(continued)

Reedy Creek - Betty's Mill Pond									
pre-dam legacy sediments									
	UCI-68071	35.82791	78.75427	charcoal	-26.2 ± 0.1	0.983 ± 0.001	140	15	1670–1710 AD (0.155) 1720–1780 AD (0.268) 1795–1820 AD (0.117) 1830–1885 AD (0.222) 1915-1945 AD (0.193)
	UCI-68068	35.82993	78.75385	charcoal	-27.1 ± 0.1	0.975 ± 0.001	205	15	1650–1685 AD (0.256) 1760–1805 AD (0.472) 1935–1955 AD (0.227)
pre-European sediments									
	UCI-86062	35.82791	78.75427	charcoal	–	0.947 ± 0.002	435	15	1430–1465 AD (0.954)
	UCI-68062	35.82993	78.75385	rooted stump	-26 ± 0.1	0.856 ± 0.001	1255	15	680–780 AD (0.954)
	UCI-68070	35.82791	78.75427	charcoal	-26.1 ± 0.1	0.814 ± 0.001	1655	15	345–430 AD (0.954)
Reedy Creek - Downstream of Betty's Millpond									
pre-European sediments									
	Aeon-758	35.83268	78.74734	charcoal	-25.1 ± 0.1	0.769 ± 0.002	2110	20	200–85 BC (0.857) 80–55 BC (0.097)
Richland Creek - Cook's Mill Pond									
pre-European sediments									
	BETA - 276073	35.83516	78.72234	charcoal	-24.5 ± 0.1	–	1630	40	265–275 AD (0.006) 335–540 AD (0.948)
Crabtree Creek									
pre-European sediments									
	Aeon-759	35.84150	78.72983	charcoal	-26.2 ± 0.1	0.798 ± 0.003	1815	30	90–100 (0.004) 125–260 AD (0.909) 295–325 AD (0.041)

Notes: [1] Radiocarbon laboratory codes: AEON – Aeon Laboratories; BETA – Beta Analytic, Inc.; D-AMS – DirectAMS; UCI – University of California – Irvine keck Carbon Cycle AMS Facility. [2] Reported $\delta^{13}C$ values were measured to a precision of <0.1‰ relative to standards traceable to Peedee belemnite, using a Thermo Finnigan Delta Plus stable isotope ratio mass spectrometer (IRMS) with Gas Bench input. [3] All results have been corrected for isotopic fractionation according to the conventions of Stuiver and Polach (1977), with $\delta^{13}C$ values measured on prepared graphite using accelerator mass spectrometry (AMS). These can differ from $\delta^{13}C$ of the original material, if fractionation occurred during sample graphitization or the AMS measurement, and are not shown. [4] Sample preparation backgrounds have been subtracted, based on measurements of ^{14}C-free coal. [5] Radiocarbon concentrations are given as fractions of the modern standard, $\Delta^{14}C$, and conventional radiocarbon age, following the conventions of Stuiver and Polach (1977). [6] Radiocarbon ages were converted to unmodeled 2σ calibrated calendar years BC/AD and rounded to the nearest 5 years with OxCal Online Radiocarbon Calibration program v. 4.1 (Ramsay, 2009) using the INTCAL09 calibration curve (Reimer et al., 2009) and the year 1950 as "modern".

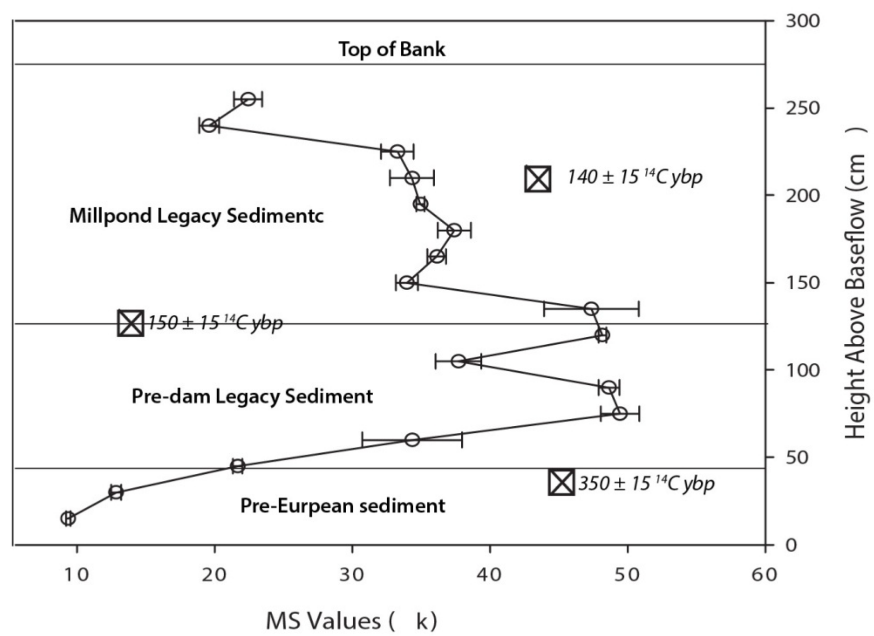


Figure 19. *Magnetic susceptibility (MS) profile for stream bank exposure through the Rhodes mill pond along Sycamore Creek located at 35.848616°N, 78.725956°W. The spike in MS is apparent in the pre-dam legacy sediments and begins to taper off at about 150 cm above baseflow, just prior the impoundment of sediments behind the milldam. The full MS data set is available in the Other Appendices section and from Lewis (2011).*

3.2. STREAM BANK EROSION

3.2.1 Root Dendrochronology and Stream Bank Retreat

Nine roots were selected from five tree species (coniferous and deciduous) along straight channel reaches within the 1.8 km Reedy Creek study area (Fig. 9). Sampled trees included *Fagus grandifolia* (American Beech), Q*uercus alba* (White Oak), *Pinus taeda* (Loblolly Pine), C*arya glabra* (Pignut Hickory), and *Liriodendron tulipifera* (Tulip Poplar; Table 4). Microscopic analysis was performed on 150 root sections. Four of the nine species exhibited visible anatomic evidence at the microscopic level for rapid (within one growth ring) exposure of the protruding root due to bank retreat (Lewis, 2011).

Table 4. *Stream bank erosion rates determined from anatomical changes in exposed tree roots along the Reedy Creek study reach.*

Root ID	Latitude (° N)	Longitude (° W)	Species	Anatomical Change (Yes / No)			First Exposure (Year)	Total Exposure (Year)	Distance to bank (m)	Local Erosion Rate (m/yr)
				Buried	Transitional	Exposed				
1	35.83164	78.74785	*Fagus grandifolia*	N	N	N	—	—	0.19	—
2	35.74956	78.74956	*Carya galbra*	Y	Y	N	2008	2010	0.27	0.27
3	35.74956	78.74956	*Carya galbra*	Y	N	Y	2009	2009	0.15	0.075
4	35.82758	78.75317	*Pinus taeda*	N	N	Y	—	—	0.2	—
5	35.82817	78.75406	*Carya galbra*	Y	Y	Y	2010	2010	0.9	0.9
6	35.82896	78.75304	*Quercus alba*	N	N	Y	2006	2009	0.33	0.16
7	35.82896	78.75187	*Liriodendron tulipifera*	N	N	Y	1998	1998	0.3	0.025
8	35.82826	78.75110	*Pinus taeda*	N	N	Y	—	—	0.3	—
9	35.82893	78.74962	*Fagus grandifolia*	N	N	N	—	—	0.29	—

All genera, with the exception of *Fagus*, exhibited anatomical change following root exposure. *Carya* and *Quercus* showed the most dramatic cellular-level variations (Fig. 20). The anatomical-level alterations of the roots of these two species undergo a transformation from a diffuse porous cell structure (typical of buried roots) to a ring to semi-ring porous structure (typical of subaerial stems). Fibrous woody material was observed to increase in the exposed root sections, as it is necessary for structural support following root exposure, concomitant with a decrease in the number of vessels.

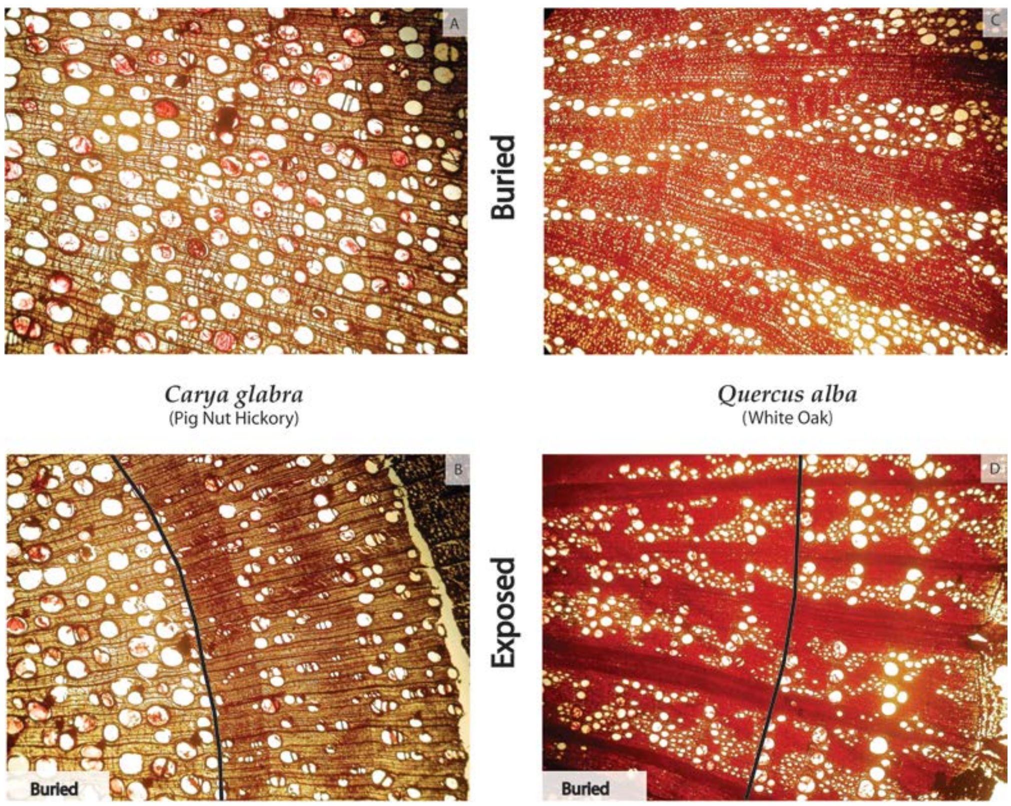


Figure 20. *Examples of photomicrographs of thin sections from roots that were buried and exposed at the time of collection. Following exposure, the roots of some tree species undergo alterations in their anatomical structure resulting in a more limb-like alignment of the vessels along the growth ring. This is observed as a change from a diffuse-porous to ring-porous structure where the number of vessels is reduced and an increase in the fibrous material occurs. Photos A & C show a diffuse porous configuration , which also exists in photos B & D left of the black lines. Growth to the right of the black lines in photos B & D occurred after the roots were exposed by bank erosion, as they exhibit a more limb-like organization of vesicles and a darkening of the growth rings due to the increase in fibrous material after exposure. The field of view in each photomicrograph is 3cm horizontal x 2 cm vertical.*

The *Liriodendron* and *Pinus* samples also exhibited anatomical changes in root cellular structure. In thin sections of *Liriodendron,* the size of vessels decreased and the amount of fibrous woody material increased at the time of exposure. *Liriodendron* specimens maintained diffuse porous structure throughout the root following exposure. *Pinus* samples exhibited decreased lumen size and an increase in cell wall thickness upon exposure; however, growth ring boundaries are difficult to identify at the microscopic level, rendering them less useful for the determination of stream bank erosion rates.

Carya and *Quercus* showed the most promise of the nine genera evaluated for their applicability to record the year of root exposure, and thus the rate of stream bank erosion. Exposed *Quercus* and *Carya* root specimens result in single-point horizontal bank erosion rates of between 0.16 to 0.9 m yr^{-1} (Lewis, 2011), and the mean bank retreat calculated from five exposed roots is 0.3 ± 0.3 m yr^{-1} (Table 4). Using these at-a-point horizontal bank retreat rates, a bank that is on average 2 m high, and an 1800-m long study reach, we estimate that the 12-year spatially averaged volume of eroded sediment is 1080 m^3, with the majority being legacy sediment. The linear rate of bank erosion for the exposed root study reach is then estimated at 0.05 m^3 m^{-1} yr^{-1}.This estimate assumes erosion on only one side of the channel, and does not account for higher rates or bank retreat along the outside, or sediment accretion on the inside of meander bends. Because the bank are comprised of predominately fine-grained legacy sediments (see Section 2.1.2), much of the eroded material is transported downstream as suspended load (see Section 3.2.3), rather than being redeposited along the study reach during waning flows following periods of increased discharge.

3.2.2 Meander Bend Migration

We established two 30-m long erosion pin monitoring networks along the outside of meander bends where Reedy Creek migrates laterally into and is actively eroding legacy sediments that were impounded behind Betty's milldam (Figs. 9, 21). An eroded volume of 129 m^3 of predominantly legacy sediment was recorded from Site 1, located 50 m upstream from Betty's milldam during an initial 51 day survey (Nov. 21, 2009 to Dec. 30, 2009). The majority of the erosion during this period occurred when a tree was undercut and felled from atop the stream bank. After resetting the Site 1 survey following vandalism of the monument stakes, the stream bank lost an additional 24 m^3 of sediment during the second study period (April 1, 2010 to April 2, 2011). At the second upstream measurement site, 4 m^3 of sediment was removed by bank retreat during a 7-month interval (Sept. 11, 2010 to April 17, 2011). Time-integrated rates of bank erosion range from 0.2 m^3 m^{-1} yr^{-1} for 7 months of observation at Site 2, to 4.5 m^3 m^{-1} yr^{-1} for 13.5 months of observation at Site 1, and illustrate the variability expected with data collected across short spatial and temporal observation intervals (e.g. Gardner et al., 1987; Table 5).

3.2.3 Discharge Event Specific Total Suspended Solids and Turbidity

Our sampling protocol was designed to establish a baseline for TSS and turbidity at the upstream location above a mill pond reach during precipitation – storm runoff events. At the same time, we collected water samples immediately downstream from the mill pond reach in order to determine if a substantial increase in TSS levels is observed as the stream flows through the former mill pond. Our ISCO water sampling results from the Reedy and Richland Creek study reaches indicate that the erosion of legacy sediment is a contributor to TSS, and thus to stream water turbidity during periods of increased discharge.

The North Carolina Department of the Environment and Natural Resources has placed the threshold for TMDL for class B Nutrient Sensitive Waters, which both Reedy and Richland Creeks are, at 50 NTUs (Deamer, 2009). We performed a categorical analysis of how many times each site met or exceeded the allowable turbidity TMDL threshold for impairment out of the total number of water samples collected during 24-hour sampling campaigns. From upstream to downstream, Reedy Creek Site 1(upstream control location) had a 0% exceedance during the entire study interval, while Sites 2 (upstream end of the mill pond) and Site 3 (immediately downstream of the mill pond) surpassed the allowable TMDL by 4% and11%, respectively (Table 6). Slight downstream increases across the mill pond section of stream were also found at Richland Creek, with Sites 1 (upstream mill pond) and 2 (downstream mill pond) meeting or exceeding the TMDL for 9% and 10% of water samples, respectively.

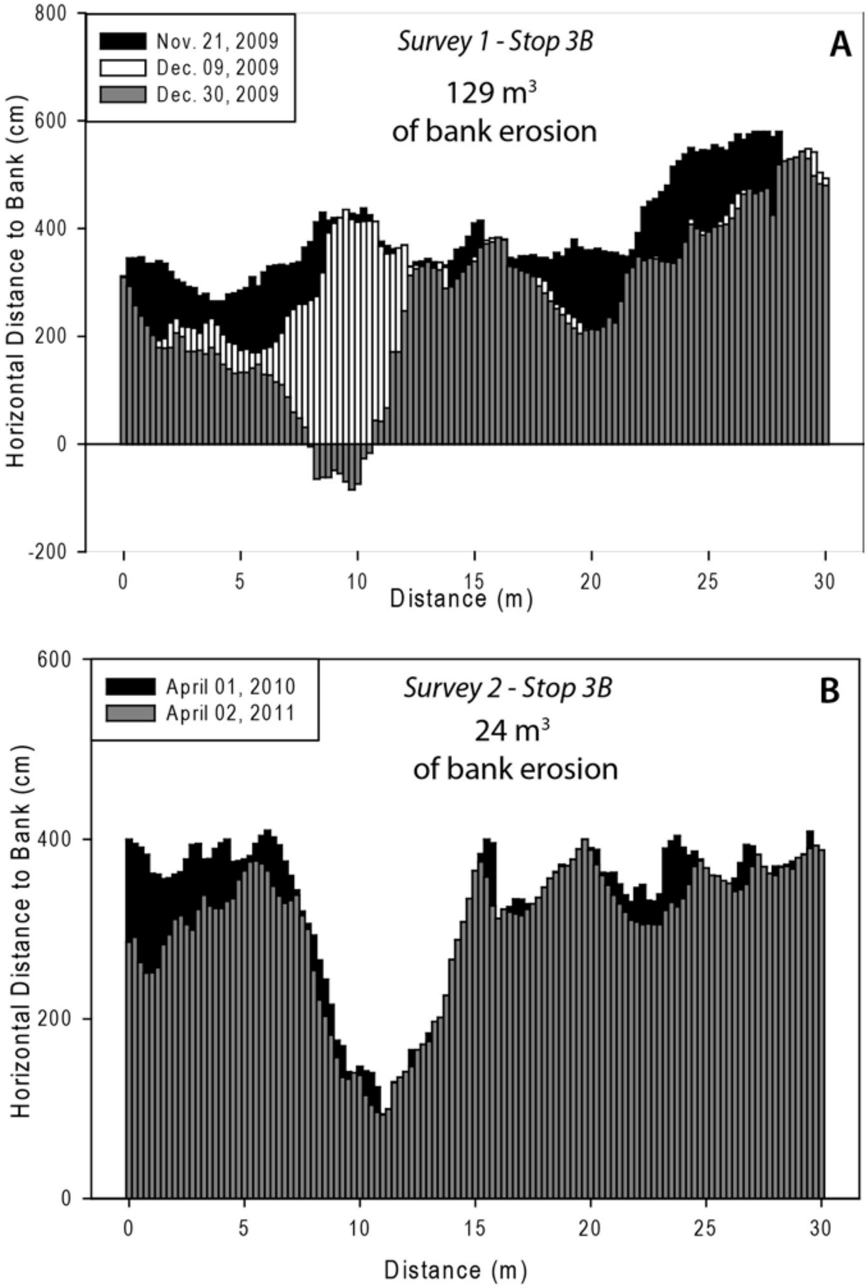


Figure 21. *Planimetric bank erosion surveys conducted along meander bends within the Betty's mill pond reach of Reedy Creek. (A) the initial monitoring periof was from 21 November 2009 to 30 December 2009, when 129 m^3 of bank erosion occurred along this 30 m section of bank. (B) The transect datum had to be reestablished following vandalism. The second study period lasted from 1 April 2010 to 2 April 2011, during which time an additional 24 m^3 of bank erosion was recorded.*

Table 5. *Comparison of stream bank erosion rates by measurement technique.*

Method	Observation Period (yr)	Stream Bank Length (m)	Stream Bank Height (m)	Estimated Total Eroded Volume (m^3)	Along Channel Erosion Rate (m^3 m^{-1} yr^{-1})
Root Dendrochronology	12	1800	2	1080	0.05
Meander Bend Planimetric Survey 1	1.125	30	3	153	4.5
Meander Bend Planimetric Survey 2	0.5	30	2.5	4	0.3
Repeat Terrestrial Lidar Survey	1.375	11	3.2	9	0.6

*Reported in Starek et al., 2013 for the Richmond Creek - Cooks Millpond Site.

The Reedy Creek TSS and NTU results exhibit consistent increases from Site 1 downstream to Site 3 (Fig. 22). TSS and NTU levels for Site 1 were typically at low levels, between 10 to 20 mg/L, and remained relatively consistent for all 24 hours of sampling during individual discharge events. In contrast, both Reedy Creek Sites 2 and 3 exhibited increases in TSS and NTU values concomitant with corresponding hydrograph peaks, with site 3 resulting in larger peaks than site 2, for most precipitation-discharge events (Fig. 15). Collectively, most samples (95%) were below the TMDL for Reedy Creek for all sites during the study period. Data from Richland Creek (Fig. 22) demonstrates the same trends in TSS and NTU as observed from Reedy Creek, with TSS and turbidity levels increasing downstream as the stream traverses the former Cook's mill pond reach (Fig. 22). Steep increases in both water-quality impairment metrics for Richland Creek also corresponded to hydrograph peaks; although the timing is not always one-to-one (Lewis, 2011).

3.3 Stream Bank Nutrients

3.3.1 *In-situ* Measurements and Mass Storage

3.3.1.1 Nitrogen

Elemental analysis of sediment samples from stratigraphic sections from the Reedy Creek and Richland Creek mill pond sites revealed a substantial storage of both N and C. The sections assayed included MTS, MPLS, PDLS, and PES. The average and standard deviation of wt % N and C are presented in Table 7 (N=3).

In general, modern top soil had the highest wt % values for N and C compared to the legacy sediment and the pre-European settlement soil (Table 7). An exception was in the Richland Creek sediments where wt % N was similar between the MTS and PES layers. This is not surprising given that modern top soil is a biogeochemically-active substrate with extant growing plants. However, this sequence also was typically the thinnest (0.25 m). The MPLS layer had roughly a fivefold more % N than did the PDLS layer. Between the two sites, Reedy Creek sediments had more N per mass, even for the MTS layer, than did Richland Creek.

Table 6. *Percent exceedance of total maximum daily loads for turbidity for the Reedy (A) and Richland Creek (B) study reaches.*

A.

Sampling Campaign	Date	Start Time	End Time	Site 1 (above millpond) Samples Collected	Site 1 (above millpond) Exceeded TMDL (>50 NTUs)	Site 2 (head of millpond) Samples Collected	Site 2 (head of millpond) Exceeded TMDL (>50 NTUs)	Site 3 (below millpond) Samples Collected	Site 3 (below millpond) Exceeded TMDL (>50 NTUs)
1	6/17/2010	0:00	23:00	24	0	24	0	24	2
2	07/10 to 07/11/2010	17:00	16:00	24	0	24	0	24	0
3	07/31 to 08/01/2010	14:45	14:15	24	0	24	0	24	0
4	08/05 to 08/06/2010	13:00	12:30	24	0	24	3	24	14
5	08/18 to 08/19/2010	19:00	18:00	24	0	24	2	24	0
6	09/27 to 09/28/2010	9:15	8:45	24	0	24	3	24	2
7	09/29 to 09/30/2010	9:45	9:15	18	0	24	0	24	0
8	10/27 to 10/28/2010	15:00	14:45	24	0	24	0	0	0
Total				186	0	192	8	168	18
TMDL Exceedance					0%		4%		11%

B.

Sampling Campaign	Date	Start Time	End Time	Site 1 (head of millpond) Samples Collected	Site 1 (head of millpond) Exceeded TMDL (>50 NTUs)	Site 2 (below millpond) Samples Collected	Site 2 (below millpond) Exceeded TMDL (>50 NTUs)
1	6/17/2010	0:00	23:00	24	0	24	1
2	07/10 to 07/11/2010	17:00	16:00	24	0	24	0
3	07/31 to 08/01/2010	13:10	12:40	24	0	24	0
4	08/05 to 08/06/2010	13:00	12:30	24	15	24	16
5	08/18 to 08/19/2010	15:45	15:15	24	0	24	2
6	09/27 to 09/28/2010	9:55	9:25	24	0	24	3
8	10/27 to 10/28/2010	15:00	14:45	24	0	24	0
Total				168	15	168	19
TMDL Exceedance					9%		11%

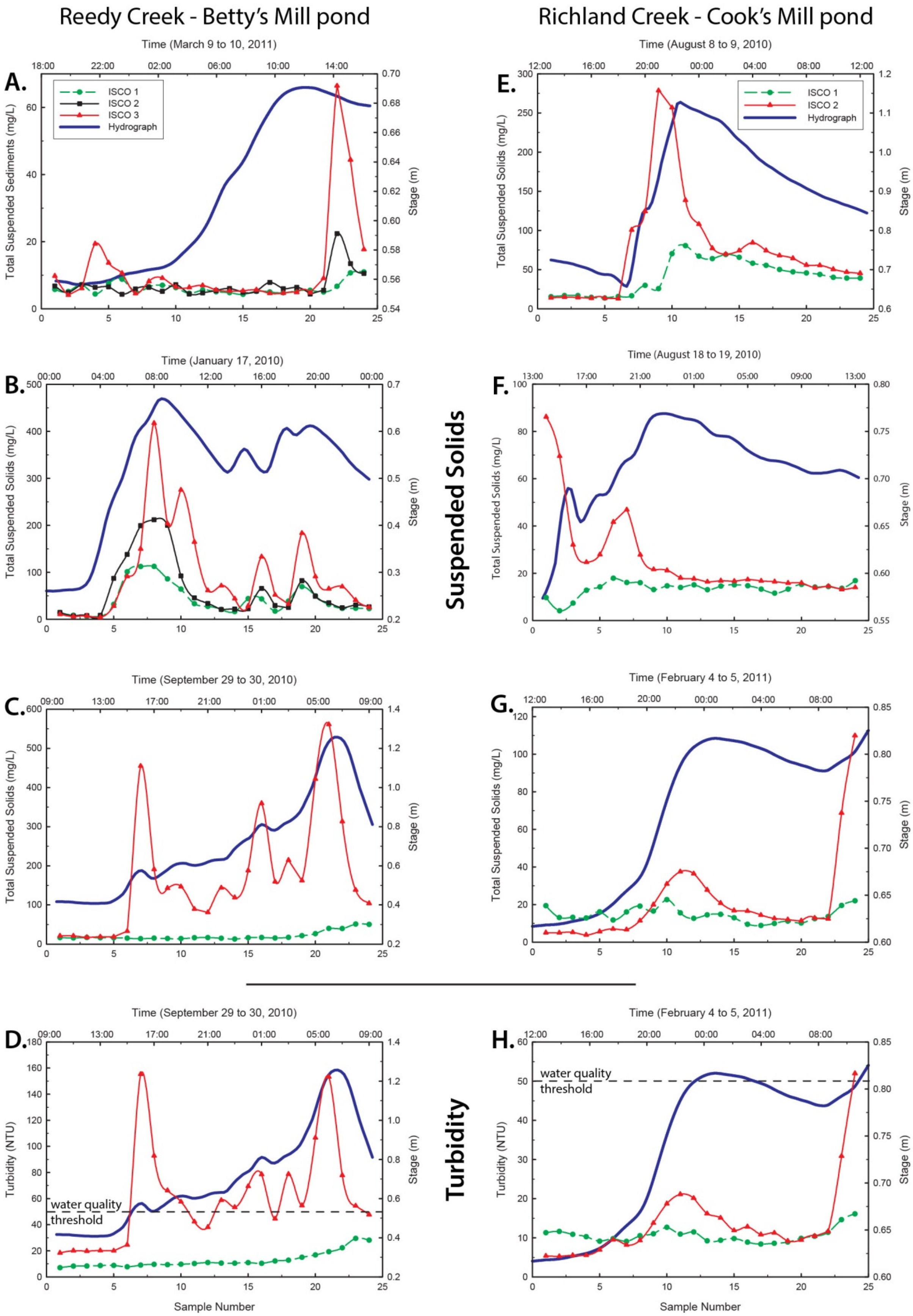

Reedy Creek - Betty's Mill pond
Richland Creek - Cook's Mill pond
A.
Time (March 9 to 10, 2011)
ISCO 1
ISCO 2
ISCO 3
Hydrograph
Total Suspended Sediments (mg/L)
Stage (m)
E.
Time (August 8 to 9, 2010)
Total Suspended Solids (mg/L)
B.
Time (January 17, 2010)
F.
Time (August 18 to 19, 2010)
Suspended Solids
C.
Time (September 29 to 30, 2010)
G.
Time (February 4 to 5, 2011)
D.
Time (September 29 to 30, 2010)
Turbidity (NTU)
water quality
threshold
Turbidity
H.
Time (February 4 to 5, 2011)
Sample Number

Figure 22 (previous page). *Mill pond legacy sediment contributions to total suspended solids levels in Reedy and Richland Creeks for six precipitation-increased discharge events. Plots show total suspended sediment (mg/L) and turbidity (NTU) versus stream stage (m) as measured during 1 h increments for six 24 h periods from the Reedy Creek – Betty's mill pond (A–D) and the Richland Creek – Cook's mill pond (E–H) sites (Figs. 9 & 13). Stream water samples were collected at the same times from upstream sites (circles), at the immediate upstream end of the mill pond (squares), and the downstream end of the mill pond (triangles). Stream stage (blue line) was measured immediately downstream from each milldam site with a Solinst Levelogger pressure meter. The stream stage time series were corrected for local atmospheric pressure variations as recorded by a Solinst Baralogger located ~ 8 km away from the two sites.*

Table 7. Averages and standard deviations for wt. % N and C measured on stratigraphic sections from Richland Creek Cook's mill pond (RCCM) and Reedy Creek Betty's mill pond (RCBM). modern top soil (MTS), pre-European settlement soils (PES), pre-dam legacy sediment (PDLS), and millpond legacy sediment (MPLS) were the sections assayed.

Sample	avg wt % N	stdev wt % N	avg wt % C	stdev wt % C
RCCM MTS	0.124	0.002	1.588	0.002
RCCM MPLS	0.068	0.001	1.069	0.006
RCCM PDLS	0.012	0.001	0.18	0.015
RCCM PES	0.021	0.001	0.258	0.009
RCBM MTS	0.168	0.003	2.668	0.313
RCBM MPLS	0.073	0.001	1.394	0.027
RCBM PDLS	0.022	0.002	0.392	0.032
RCBM PES	0.17	0.009	3.127	0.174

3.3.1.2 Carbon

Trends in average carbon wt % values in the mill pond sediment sequences mirrored N values at both sites. However, the sediments had 10 to 30-fold greater amounts of C than of N. Unlike the N values, the PES layer, rather than the MTS layer, from Reedy Creek had the highest wt % C (3.13). For both sites, the MPLS layer had higher average wt % C values than did the PDLS layer. Thus, both sites exhibited higher amounts of C and N in the MPLS layer compared to the PDLS layer.

3.3.1.3 C:N Ratio

Atomic ratios of C to N inform on the source and to a lesser extent the transformation of organic matter in soils and sediments. Typically, C:N ratios for terrestrial soils range from 15 to 50 resulting from the relative abundance of N-poor molecules comprising terrestrial organic matter (Meyer, 1997). C:N ratios were highly variable between sites and among stratigraphic layers (Table 8). Richland creek had lower overall C:N values than did Reedy Creek, but both sites exhibited C:N ratios (14.7 to 22.3) consistent with temperate soils. At Richland Creek, the MTS and PES C:N values were much lower than the pre-dam and mill pond legacy sediment layer values. At Reedy Creek, the MTS layer had the lowest C:N value and PES was not substantially different from the legacy sediment layers.

Table 8. *Atomic C:N ratios calculated on legacy sediments from the North Carolina Piedmont.*

Sequence	Richland Creek	Reedy Creek
MTS	15	18.5
MPLS	18.4	22.3
PDLS	17.5	20.6
PES	14.7	21.4

3.3.1.4. Mass Storage of N

The mass of N stored in the sediments was calculated as:

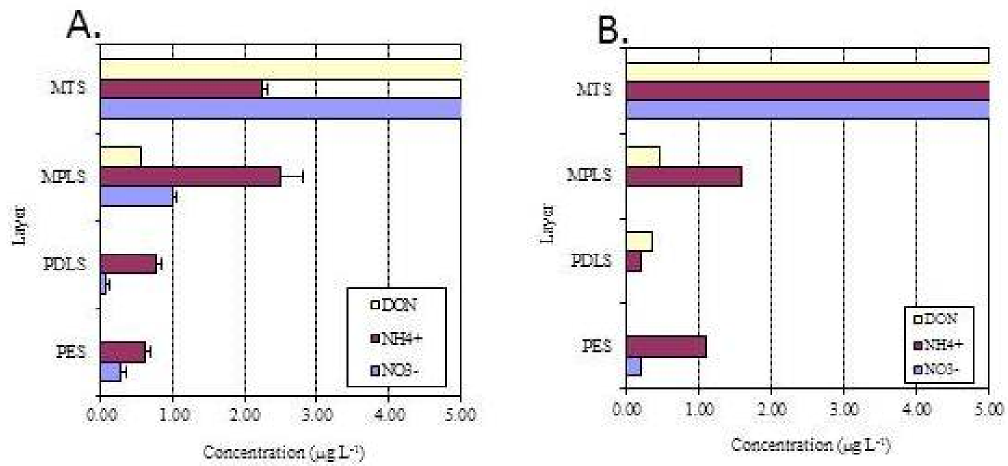
$$\text{Tonnes N ha}^{-1} = \text{wt \% N} \times \text{Pond Area} \times \rho_{bulk} \times \text{Thickness} \qquad (1),$$

where Pond Area is in m; ρ_{bulk} is the sediment bulk density in kg m^{-3}; and Thickness is in m. The standard deviations for these average N measurements from Table 7 were low enough that averages represent significant ($P<0.05$) differences between stratigraphic layers and between sites. Owing to their thickness, the MPLS layers, despite having far lower wt % N than the MTS layers, stored about five times more N.

It should be noted that the form of N or C stored in soils and sediments is important. In the solid sediment and top soil, the form of N and C is predominantly organic. Inorganic nitrogen species, NH_4^+ and NO_3^-, are highly soluble in aqueous solution and therefore are unstable in any solid phase. The exception is NH_4^+ bound to particles or humic substances, and thus N released from legacy sediments is expected to be primarily dissolved organic nitrogen (DON) and possibly ammonium ion (NH_4^+). Therefore, we also measured the capacity of legacy sediments to release DON and DIN (as ammonium and nitrate).

3.3.2 Transfer of N from Legacy Sediments to Stream Waters

Our disaggregation experiments suggest that low amounts of N are released from legacy sediments in pure water or in ARW (Figure 23). Results are reported as concentrations in micrograms N per L and reflect the release of dissolved N after 24 hours, which should simulate the potential release of N from legacy sediments after streambank erosion of and disaggregation of sediment in stream water. Only Richland Creek was investigated for dissolved N production in pure water (salinity = 0, deionized ultrapure lab water; Fig. 24a), while both Richland Creek and Reedy Creek were investigated for dissolved N production in ARW (salinity ~ 1; Figs. 23b, c). In all experiments, MTS layers produced far greater amounts of NH_4^+, NO_3^-, and DON than did any sedimentary layer from either mill pond location. For example, after 24 hours in ARW, disaggregated MTS produced dissolve N concentrations of 32.0, 43.6, and 95.5 µg-N L^{-1} for NO_3^-, NH_4^+, and DON, respectively. The concentrations for NO_3^- and NH_4^+ are similar to averages measured for other Neuse River Basin streams during 2001-2002 (Stowe et al. 2005). However, DON concentrations were far lower than those estimated from the results presented in that report. This indicates that ON may be more tightly bound by sediments than the more soluble NO_3^-, which is sensible, but also that desorption of NH_4^+ is greater than DON.



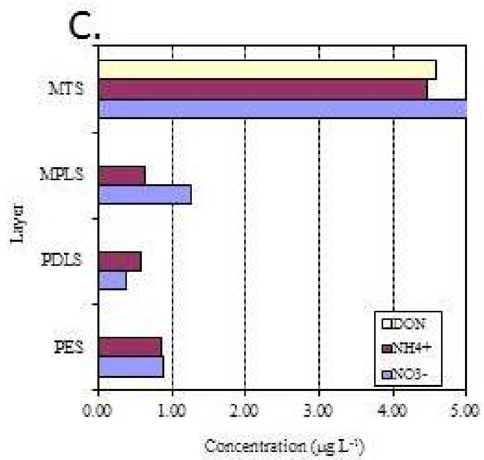


Figure 23. *Production of dissolved N species from disaggregation experiments, measured as a concentration of N species in solution after 24 hours of disaggregation of 1 g (wet weight) of A) legacy sediment from Reedy Creek – Betty's mill pond into 100 ml of pure lab water; B) legacy sediment from Richland Creek – Cook's mill pond into 100 ml of ARW (salinity ~1); and C) legacy sediment from Reedy Creek – Betty's mill pond into 100 ml of ARW (salinity ~1).*

Desorption of NH4+ dominated dissolved N production in pure water by legacy sediments from Richland Creek and by sediments from the PES layer, while the nitrate production was often not different from method blanks. It is expected that little nitrate would be bound in legacy sediments. Between the two legacy sediment layers at the Richland Creek site, the mill pond (MPLS) layer desorbed nearly twice as much NH_4^+ as did the pre-dam layer (PDLS).

In ARW, different amounts of N desorption were measured for Richland Creek (Fig. 23b) compared to Reedy Creek (Fig. 23c). However, much like for the experiment conducted in pure water, the MTS layer produced the highest dissolved N concentrations. First, salts used to prepare ARW had substantial ammonium and nitrate. These values were subtracted from the concentrations measured for each solution produced by desorbing N from sediments. Second, and similar to the results for pure water, more ammonium was produced than was nitrate, except for the MPLS layer in Reedy Creek. In fact, Reedy Creek sediments in general produced substantially more nitrate than did Richland Creek sediments in ARW and the amount produced in Reedy Creek was similar to that produced in Reedy Creek in pure water. Third, both Richland Creek and Reedy Creek sediments produced ammonium at concentrations between 0.5 and 1.0 µg-N L^{-1}. In Richland Creek, most ammonium was produced in the MPLS layer whereas in Reedy Creek, similar amounts of ammonium were produced in the MPLS, PDLS, and PES layers.

4. DISCUSSION

4.1 UPLAND EROSION AND VALLEY BOTTOM SEDIMENTATION

Geomorphic mapping of portions of Reedy, Richland, and Sycamore Creeks within Umstead State Park reveal land surface and soil degradation directly related to the agricultural practices in use by early settlers up until the time of federal takeover of the land in the 1930s (Figs. 4, 5). We estimate that at a minimum, 13% of upland areas of the Reedy Creek study area, for example, were directly affected by erosion in the form of gullies incised into hillslopes. These gullies provided a routing mechanism for the transfer of eroded upland sediment to the valley bottom – channel network (Fig 16). This eroded hillslope material was the source of aggraded sediments that buried pre-settlement valley bottoms with up to several meters of fluvial and colluvial deposits (Figs. 17, 18; Table 3). A significant amount of upland soil loss likely occurred as sheet erosion and would not be as apparent in the landscape today as are the incised gullies, but such erosion could be identified if truncated upland soil profiles are observed in existing or future pedologic investigations. Based upon Trimble's 1975 account of soil loss for Wake County, it is probably safe to assume that most of the sloping upland areas now within the boundaries of USP experienced at least some amount of soil loss via downslope transport processes.

Radiocarbon dating of sediments exposed along regional stream banks is consistent with the interpretation that the lowest exposed stratigraphic unit represents the pre-European valley bottom, and that these sediments are in places at least as old as 3,880 ^{14}C ybp (BC 2,465 to 2,295; Fig. 18, Table 3). Burial of the pre-European valley bottom began as early as 205 ^{14}C ybp (250 ± 75 ybp, or between AD 1650 to 1800), when stream sediment load exceeded the transport capacity (Table 2). Stream bank exposures along Sycamore, Reedy, and Richland Creeks consistently exhibit 2 to 6-time increases in the magnetic susceptibility of the sediments above the pre-European valley bottom and legacy sediment contact (Lewis, 2011; Fig. 19). This result further supports the hypothesis that the sediments that we have identified as "legacy" within Umstead State Park resulted from the erosion, transportation, and deposition of upland soils that were modified by early Colonial land use practices such as clearing land by burning and tilling the soil in order to grow crops.

Both indigenous peoples and European-American settlers employed slash-and-burn practices in order to quickly clear land and provide needed soil nutrients for farming along with forage for wild game and livestock (Van der Donck, 1841; Otto and Anderson, 1982; Helms, 2000; Fesenmyer and Christensen, 2010; Stinchcomb et al., 2011). Variability in MS profiles likely reflects the complex interactions between local timing and extent of land clearing, upland soil erosion, transport, and deposition within the fluvial network. In general, post-European legacy sediments maintain MS values that are higher than the background levels of MS as observed in pre-European valley bottom deposits. We suggest that the high MS values associated with the legacy sediments have resulted from human-induced magnetic enhancement of soil properties, such as by widespread burning (for charcoal or land clearing) and tilling of the landscape (Oldfield et al., 1989; Ketterings et al., 2000). Both clearing and burning occurred extensively across the study area as early settlers cleared forests to create new agricultural land. Microscopic analysis of regional stream bank deposits reveals an upward increase in charcoal particulates, possibly fly ash from land clearing and forest burning that mirror the pre- to post-European settlement increase in magnetic susceptibility (Hunt, 2011). We interpret this relationship between charcoal and magnetic susceptibility increases in stream bank deposits as evidence of enhanced upland burning that resulted in the modification of soil magnetic properties and increased charcoal in stream sediments.

Valley bottom sediments derived from eroded upland soils should, to a first order, retain the magnetic susceptibility signature of the parent material. For example, sediments derived from the upper portion of the soil profile (A-horizon), which would likely experience the highest temperatures during the burning of the forest floor and canopy, are expected to have higher k values than sediments derived from deeper in the soil profile (C-horizon). This is due, in part, to the poor thermal conductivity of earth materials in general and the frequency and duration of fire at a particular location. We utilize both stratigraphic observables and MS properties to differentiate the stream bank sediment samples and insure that the nutrient and bioassay results derived from these samples are appropriately distinguished as PES, PSS (PDLS & MPLS), and MTS, based upon the relative age of the sediments. Based upon our MS survey results, we propose that it is a suitable proxy for approximately identifying the pre-European – Post-European unconformity in valley bottoms in the greater Raleigh metro area. Additional assessments are needed before adoption of the MS-proxy to late Holocene stream bank sediments elsewhere, but preliminary results from the streams flowing in the Durham Triassic basin northeast of the city of Durham suggest that the technique is able to differentiate between pre-and-post European sediments there as well (Voli, 2012; Voli et al., in press).

Estimates of the volume of sediment impounded behind milldams and aggraded along the waterways and hillslopes in both the Reedy and Sycamore study areas accounts for more than can be attributed to upland soil loss using the estimated Wake County average of 10.2 cm (Trimble, 1975). Trimble's mean post-colonial Wake County soil loss estimate is for a large area with variable geology, soil, and topographic properties, land use history, and vegetation dynamics. It is likely safe to assume that some areas exceeded 10 cm of total vertical soil profile loss to erosion, while others experienced less. In addition to the likelihood of local variability in historic soil erosion rates, legacy sediment could also be contributed from eroding areas upstream of our Reedy and Richland Creek study areas. The volumes reported in Table 4 are also based on an average legacy sediment thickness, as revealed from stream bank exposures along each investigated stream. Currently, the sub-legacy sediment valley bottom topography is unknown, and topographic variability of the pre-European valley bottom could also be a reason for the difference between lower estimates for the eroded upland soils than that for the aggraded valley bottom legacy sediments.

The fact that much of the legacy sediment is still present, along the lower hillslopes and alluvial valleys underscores the significance of the upland erosion that occurred prior to the mid 1930's. These deposited sediments are loosely consolidated and are now rapidly eroding as these channels migrate across their valley bottoms in an effort to reestablish pre-European steady state conditions. Our geomorphic mapping of the Umstead State Park area demonstrates that large volumes of legacy sediment are deposited along stream channels and alluvial bottomlands; this result from the North Carolina Piedmont region is consistent with previous studies conducted to both the north along the outer Piedmont of Maryland and Pennsylvania (e.g., Happ, 1945; Trimble, 1975; Costa, 1975; Trimble, 1985; Walter and Merritts, 2008, Schenk and Hupp, 2009; Merritts et al., 2011) and to the south in South Carolina and Georgia (e.g., Trimble, 1975; Magilligan et al., 1997; Hyatt and Gilbert, 2000; Jackson et al., 2005; Galang et al., 2007; Munkundan et al., 2010).

Recent research along the Delaware River in the Piedmont of Pennsylvania and New Jersey by Stinchomb et al. (2011) has recognized that maize-based agriculture employed by Native Americans was responsible for increased sedimentation in valley bottoms prior to the arrival of Europeans. From their findings, it can be surmised that pre-European so-called “natural” floodplains have a history of prehistoric indigenous land use, and thus colonial-era Europeans were not the first people to have an impact on the hydrologic systems of eastern North America. It is beyond the scope of this project to attempt to assess the impacts that prehistoric small-scale agricultural societies might have had on increasing upland erosion and valley bottom sedimentation in the piedmont of Wake County; however, this is an exciting avenue for future research.

4.2 STREAM BANK EROSION AND THE CONTRIBUTION OF LEGACY SEDIMENTS TO TSS LOADS

Throughout this research project we have attempted to test they hypothesis that stream bank erosion of exposed legacy sediments in the USP area contributes to modern water quality impairment. The use of root dendrochronology, planimetric surveys and the measurement of TSS and Turbidity shed light on how post-colonial agriculture and mill pond deposits are currently affecting stream water quality. From our results, we conclude that erosion of legacy sediments is a persistent problem that is occurring on multiple time scales, from decadal to individual rain-discharge events (Figs 20 – 23; Table 5).

4.2.1 Stream Bank Erosion measured by Root Dendrochronology and Planimetric Surveys

Root dendrochronology has proven to be a viable tool for monitoring stream bank erosion on 5 to 10 year times scales along the Reedy Creek study reach. Changes in the anatomical structure of tree roots support the idea that bankfull or larger discharges are responsible for most of the erosion on the straight reaches of Reedy Creek, as the roots we analyzed exhibit evidence for rapid exposure. If stream bank erosion occurred slowly and continuously, root anatomical changes would only be seen as portions of the root were exposed starting from the outer-most edge and expanding through the growth ring over one or more annual cycles until the entire root was exposed.

Although the physical evidence suggests that individual roots were exposed relatively rapidly during effective discharge events, the fact that the anatomical changes occur in different years for trees at widely-spread locations supports the inference that bank erosion along Reedy Creek is spatially and did not occur during a single event (Table 4). Although the anatomical changes suggesting exposure occur during different years for each tree they are all grouped within a couple of years, and none of the sampled roots suggested significant (i.e. > 10 years) duration since exposure, further demonstrating the erodibility of the banks composed of predominantly legacy sediment. This suggests that the lateral migration of the channel is removing trees, and as such limits the usefulness of root dendrochronology for erosion studies of this stream to a 1 to 10 year interval. Pizzuto and O'Neal (2010) discuss the process of tree-removal due to lateral migration of the stream bank in the context of legacy sediments. Aggraded legacy sediments are more susceptible to stream bank erosion due to their lack of cohesive structure and weak soil development. Lateral migration of the stream channel leads to bank destabilization and material being removed from the stream bank. Bank destabilization is one of the primary contributors of suspended sediment to a stream (U.S. Environmental Protection Agency, 2007). The lateral migration of the stream channel by means of erosive processes is contributing to the water quality degradation of Reedy Creek through increased TSS levels and temporary sedimentation within the stream channel.

The planimetric bank erosion surveys installed on Reedy Creek provide additional support for the idea that larger flows are responsible for extensive erosion to the stream banks. This is apparent in Meander Bend 1 of the Reedy Creek – Betty's mill pond, where the largest volume of sediment eroded occurred over a five week period between November 21 and December 30, 2009, during which time the largest three discharge events of the 18 month study occurred (Fig. 21). The volume of sediment (129 m^3) transferred from temporary storage in the stream bank to the active channel during these 5 weeks was equivalent to 4.3 m^3 of sediment delivered per linear meter of stream bank, or 11 tandem axle dump trucks (11.5 m^3 per load) depositing their loads into the stream from this single 30m long cut bank. During the April 1 2010 to April 2, 2011 interval, an additional 24 m^3 of sediment was made available for transport from Reedy Creek Meander Bend 1. This is less than 0.8 m^3 per linear meter of bank for an entire year. It is expected that some additional bank erosion occurred during the gap in data from December, 2010 through April, 2011. At our Reedy Creek Meander Bend 2 survey, which was installed in September, 2010, no large precipitation – discharge events occurred during the study period; therefore, only minor amounts of bank erosion (4 m^3) occurred along this portion of stream reach incised into the upstream portion of the former mill pond. The lack of large erosion events during 2010 through early 2011 is attributed to drier-than normal conditions that resulted in mostly low-flow conditions beginning in June 2010 (Fig. 15). During near-normal (30-year moving average) climate patterns it is expected that larger volumes of legacy sediments will be transferred from temporary storage to the active channel on a more frequent basis. The planimetric survey results also highlight the temporal variability in geomorphic processes, such that the measurements of erosion rates are typically greater during shorter observational intervals, decreasing as the period for observation increases (e.g. Gardner et al., 1987; Wegmann and Pazzaglia, 2002; Table 5).

Although rates of stream bank mass wasting slowed at Reedy Creek Meander Bend 1 during the study period other factors continued to impact the bank, contributing to the chronic introduction of fine-grained legacy sediment to the channel. Because the stream banks incised into legacy sediments are nearly vertical, the interaction of gravitational forces coupled with hydraulic forces combine to consistently erode the banks (e.g., Simon et al., 2000). In addition, subaerial processes such as freeze-thaw during winter months (Wynn et al., 2008), and ground water seepage (Simon et al., 1999; Lindow et al., 2009) were observed to contribute to chronic bank erosion. These processes assure that there is a frequent transfer of sediment from the upper elevations of the bank to the bank toe slope. Undercutting provides an effective means for channel migration as sediment is removed from the base of the stream bank by fluvial erosion, leading to the collapse of the material situated above as gravitational forces overcome the bank shear strength. The eroded bank material can then be entrained by the steam and transported downstream or disseminated across the bed during moderate flows that are well below bankfull discharge levels.

4.2.2 Discharge Event Specific Total Suspended Solids and Turbidity

Evidence for the contributions from stream bank erosion to modern water quality impairment at short time-scales is provided by event-level measurements of total suspended solids and turbidity. Our sampling protocol was designed to establish a baseline for TSS and turbidity via automated water sampling upstream of a mill pond reach during precipitation – discharge events utilizing ISCO samplers. At the same time, we collected water samples immediately downstream from the mill pond reach in order to determine if a substantial increase in TSS levels is observed as the stream flows through a former mill pond. Our ISCO water sampling results from both the Richland and Reedy Creek study reaches indicate that erosion of legacy sediment is a contributor to TSS and turbidity during periods of increased discharge (Lewis, 2011).

TSS and turbidity levels consistently increased downstream across mill pond reaches for both Reedy and Richland Creeks. Both stream reaches had multiple data sets where TSS and turbidity values at the downstream end of the former mill ponds attained levels more than double the upstream control sites. The Reedy Creek location was used to differentiate between sediments attributable to runoff from impervious cover and recent construction sites as compared to TSS derived from legacy sediments eroded from the Betty's mill pond site.

Typical base flow TSS values for both stream reaches are ~10 mg/L. During high stream discharge events, we observe significant increases in TSS at the downstream end of a mill pond reach. We provide six examples of increasing TSS and turbidity at the downstream exit point of a milldam reach from both Reedy and Richland Creeks in Figure 22. For example, on 29 September 2010, the downstream TSS load for Reedy Creek was occasionally greater than 500 mg/L, a 1000% increase when compared to the TSS load of ~50 mg/L collected synchronously at the upstream end of the mill pond.

The single most important factor in determining downstream TSS and turbidity values was found to be stream stage. At low discharges, below the elevation at which the stream surface reaches the toe of the accumulated legacy sediment apron, TSS and turbidity values are attributable to either background levels (determined at ISCO site 1), as runoff from impervious cover and storm drains from a nearby business park, or from in-situ stream bank material. Once the stream stage raises enough to initiate removal of material from the base of the bank, TSS input from legacy sediment begins to outpace upstream locations (Fig. 22). Another contributing factor to site measurements of TSS input is how "primed" the system is, or how much material has been transferred to the toe of the bank during intervening low-flow intervals as well as bank aggregates, coherent blocks of mill pond silt and clay, deposited directly into the stream following gravitational collapse of a segment of the bank (Fig. 24). During precipitation – discharge events where the stream water level increase may not have been significant enough to remove sediments at the toe of the bank, we propose that these primed materials are the main cause for increased TSS and turbidity levels. Previously eroded sediments, situated at the base of the stream bank, were the primary contributors during the study period since drier-than-normal conditions persisted and large flows were infrequent.

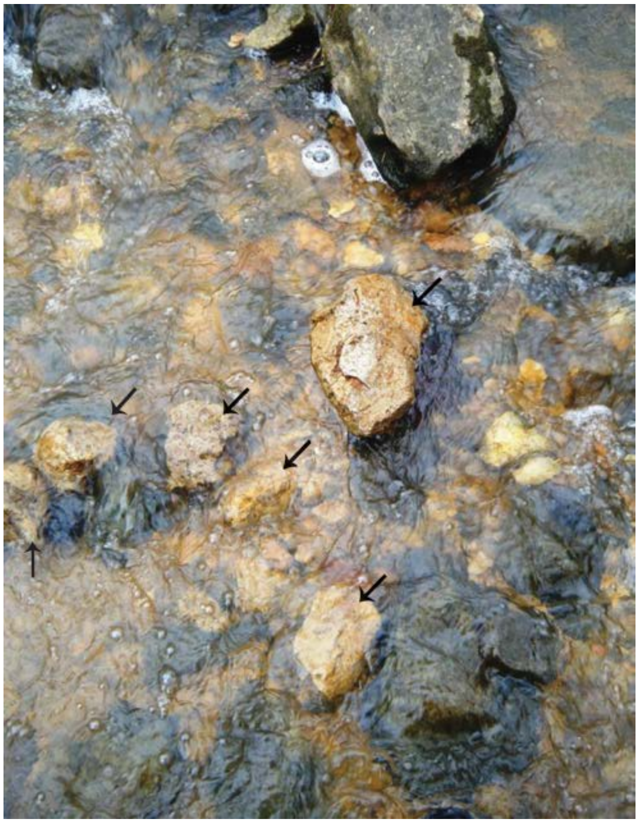


Figure 24. Along former mill pond reaches, failure of near-vertical banks often deposits intact blocks or smaller aggregates of mill pond legacy sediment on the toe slope and in the stream. These smaller aggregates pictured here (identified by arrows) will remain in the stream until they are abraded by bedload transport processes or the silts and clays slake and become part of the suspended load. These blocks comprise an important component of the bedload where streams traverse former mill pond reaches, and thus supply fine-grained sediment to the stream even during low-flow conditions.

The March 9 to10, 2011 sampling event from Reedy Creek is highlighted as a demonstration of downstream increasing TSS and turbidity concentrations corresponding to rising stream stage (Fig. 22). During the fifth hour of sampling there is a slight increase in stream TSS content (~10 mg/L), however, turbidity is unchanged. This increase in TSS is more of an aberration due to the fact that stream stage only rose 2 cm at this time. Other than this slight increase, TSS and turbidity levels at site 3 track the incoming levels observed from Site 1. Stream stage begins to rise in earnest after the 10th hour of sampling and stage increase peaks at about 15 cm above the initial base-flow level. All three sampling locations show an increase in the 22nd hour of sampling. However, the increase at Site 1 is negligible, with only a 2 mg/L increase above background levels, rising to only 4 mg/L at the end of 24-hour sampling period. Over the same period, Site 2 TSS levels go up by 17 mg/L, whereas for Site 3 they increase by 60 mg/L, three times greater than the Site 2 measurements at the same time. Lab measurements of turbidity from the ISCO-collected water samples exhibit the same downstream increasing trend as exhibited by the TSS concentration data (Fig. 22). Since stream stage only rose 15 cm during the sampling interval it can be assumed that flow conditions were not high enough to erode the stream banks. It is inferred that increases in TSS and turbidity were due to previously primed legacy sediments that had accumulated at the toe of the bank prior to the increase in discharge brought on by this precipitation event.

Water quality sampling along Richland Creek focused on measuring TSS levels as the stream flowed through milldam deposits. Data from this study site also confirmed the significance of primed lower-bank sediments and their impacts on water quality (Fig. 22). Sampling that occurred between February 4-5, 2011 show increasing TSS and turbidity levels in the downstream direction. Site 2 TSS and turbidity concentrations are below background levels as established by the upstream Site 1, until the 9^{th} hour of sampling. The observed increase in TSS and NTUs is again correlated to rising stream stage. Stream stage increases 20 cm before falling 5 cm between the 12^{th} and 22^{nd} hour of sampling, and then continues to increase past the final sampling hour. A return to base level TSS and turbidity values is observed during this lull in the stream stage upturn. The final two hours of sampling exhibit dramatic increases in TSS and turbidity concentrations for Site 2, with final concentrations in excess of 100 mg/L and 52 NTUs, which exceeds the allowable TMDL for Richland Creek (Deamer, 2009). These measurements are 5 times those found at Site 1 at the same time. Again, stream stage only increased 20 cm, making erosion of higher bank material unlikely. Increases in TSS and turbidity are most probably attributable to fluvial transport of previously eroded sediment deposited at the base of the stream bank (Starek et al., 2013). This is important since the stream attained NTU concentrations above the allowable TMDL, even though it is unlikely that any new intact bank material was eroded. It can be expected that TSS and NTU levels would have continued to increase if the sampling interval would have captured the peak in stream stage. Despite the fact that increased discharge events did not occur during the sampling period, these data demonstrate that even slight increases in stream stage, on the order of 20 cm, can impair stream conditions due to the accumulation and transport of legacy sediment accumulated by gravitational mass-wasting processes at the base of the stream bank between precipitation-driven increases in discharge (Lyons et al., 2013).

Richland Creek samples demonstrated greater increases in TSS and turbidity levels when compared to Reedy Creek over the study period, and this might be attributable to channel geometry. The Cook's milldam was breached in 1910**,** while Betty's mill on Reedy Creek is assumed to have been removed prior to 1870, since it was not included in the first hydrologic survey of Wake County (Bevers, 1871). Richland Creek is still significantly channelized with steep vertical banks on both sides of the stream and a narrow channel, while Reedy Creek has a wider channel, numerous depositional bars, and has begun to re-establish a lower floodplain inset into the legacy sediment surface. Changes in Reedy Creek's geometry are believed to be due to a longer time since breaching of the dam, allowing for the channel to adjust to stream inputs. The morphological changes encountered along Reedy Creek could be responsible for relatively lower TSS and turbidity fluxes. These changes allow the stream to accommodate higher flows, since water is diffused across a wider channel and the establishment of bars and lower floodplains leads to more active deposition than along Richland Creek with its more channelized stream banks.

In this study we primarily have measures of stream stage, but not discharge. An area for future research is to generate local stage-discharge rating curves for the study reaches that will allow for the determination of total suspended sediment flux loads resulting from both base flow and high-discharge events. The high-discharge event flux loads represent the combination of resuspension of fine-grained sediment from within the channel as well as from bank erosion. As an example, we did measure the discharge for a high flow event at the downstream end of the Cook's mill pond on 17 January, 2010 when the Raleigh-Durham International Airport recorded 3.7 cm of precipitation and the mean Richland Creek discharge was 0.67 $m^3 s^{-1}$. This produced a calculated ~1370 kg downstream increase in suspended sediment integrated over the 1 km study reach during the 24-hour monitoring period. This is equivalent to 0.8 m^3 of bank erosion across the mill pond reach for this one precipitation-discharge event.

4.3 Stream Bank Nutrients and Transfer to Stream Waters

A striking feature of the mill pond sediments is both their spatial and stratigraphic heterogeneity with respect to stored N. Our calculations show the importance of the mass storage of legacy sediments in terms of stored (sequestered) N (Table 9). Although the MTS layers had higher mass fractions of N, organic-rich soil horizons in the Piedmont tend to be thin, less than 0.5 m in thickness. The damming of streams to build mill ponds created a wide range of effective sediment traps that sequestered not only sand but also silts and clays. This was important because clays can be very effective at binding N (Meyers 1997; Murphy et al. 2000). Damming served to create slack water in which clays were deposited. Further, it is reasonable to suspect that the creation of ponds in regions of agricultural activity led to the formation of eutrophic water bodies.

Table 9. *Weight-percent nitrogen from bank sediments along Reedy and Richland Creeks.*

Site	*Stratigraphy*	*N* (*wt %*)	*Pond Area* (m^2)	*Sediment Bulk Density* (kg/m^3)	*Average Thickness* (*m*)	*Tonnes* *nitrogen / hectare*
Reedy Creek Betty's Mill	Post-Settlement *(minimum nitrogen)*	0.08	25,095	1700	3	40.8
Upstream Site	Post-Settlement *(maximum nitrogen)*	0.08	25,095	1900	3	45.6
	Pre-Settlement	0.04	25,095	1600	0.3	1.9
Reedy Creek	MTS	0.168	25,095	1000	0.25	4.2
Betty's Mill	MPLS	0.073	25,095	1800	2	26.3
Downstream	PDLS	0.022	25,095	1800	1	4
Site	PES	0.17	25,095	1600	0.3	8.2
Richland Creek	MTS	0.124	101,697	1000	0.25	3.1
Cooks Mill	MPLS	0.068	101,697	1800	2	24.5
Downstream	PDLS	0.012	101,697	1800	1	2.2
Site	PES	0.021	101,697	1600	0.3	1

Brugam (1978) did a paleolimnological study of Linsley Pond, a 9 ha lake in Connecticut to determine the effects of land use change on small water bodies. Linsley Pond can be thought of as a medium-sized mill pond, intermediate in size to the Betty and Cook’s mill ponds investigated in this study. Although Linsley Pond was not used for water power, a smaller tributary to it was dammed and used to power a mill. The Linsley family used the land for dairy farming in addition to operating a grist mill. Brugam's examination of the sedimentary record in Linsley Pond revealed large increases in stored organic matter in the top 80 cm of the lake, corresponding to post-settlement by the Linsley family. Immediately post settlement, the percent mineral matter in the core increased, which Brugam interpreted as resulting from increased erosion in the pond's catchment. This would be analogous to the PDLS layers in our mill pond sites. Diatom reconstructions indicated an increase in trophic status resulting from eutrophication. It is well known that small lakes and ponds situated in agricultural regions often are eutrophic and such high primary production can sequester N into organic matter deposited to sediments (Downing et al. 2010). Despite ammonifcation of organic N in sedimentary pore waters, the presence of clays in the MPLS layer to which small, eutrophying ponds have added organic matter likely leads to the sequestration of ammonium. Thus, when the mass of sequestered N is calculated, it is clear that mill pond sediments represent enormous stores of N (and C) which are potentially available for re-mobilization during the disaggregation of sediment into water, resulting from stream bank erosion. Table 10 shows our calculations of tonnes N per ha, which represents the stored N available for release. The stored N primarily is $NH4+$ and organic N and to a lesser degree, nitrate.

Despite large stores of N in legacy sediments, we conclude that the majority of this N is not released as a result of their erosion and disaggregation into stream water during precipitation-high discharge events. The nutrient concentrations measured on the solutions we prepared by disaggregating legacy sediments into pure water and into ARW provided concrete evidence that this material remains largely bound to sediment in freshwater, producing N concentrations that only are a fraction of those reported for streams in the Neuse River Basin. We contend that this is due to the presence of clay particles, many perhaps in the colloidal size range, and humic substances, which keep ammonium and organic N bound. This results suggests that the overall contribution of N from legacy sediment disaggregation (and hence eutrophication) is minor in North Carolina piedmont streams. However, photochemical-driven desorption of ammonium from sediments and humic substances also could be important and should be investigated (e.g., Estapa et al. 2012).

5. SUMMARY & CONCLUSIONS

We conclude by restating that past land use and agricultural practices resulted in extensive degradation of the pre-European landscape by the erosion of upland soils. Much of the eroded sediment aggraded in valley bottoms, including behind milldams, burying the former per-European floodplains within W.B. Umstead State Park, and by inference along most lower Piedmont Streams in east-central North Carolina. Valley bottom aggradation resulting from upland erosion produced by settlers in the late eighteenth through early twentieth centuries is is detectable based upon stream bank stratigraphy, magnetic susceptibility profiles, and radiocarbon geochronology. These loosely consolidated, primarily fine-grained sediments are continuing to erode today, as channels migrate laterally. Channel migration into these legacy sediments has likely increased in recent decades due to changes in upstream surface water hydrology resulting from increased runoff and faster surface water transit times from hillslope to channel following municipal development in the headwaters of the study streams. Our preliminary results indicate that erosion of these legacy sediments is contributing as a distributed and nearly ubiquitous non-point source of pollution to the current impairment of water quality along headwater streams of the Neuse River basin by increasing turbidity and TSS. Furthermore, erosion of these sediments is detectable across daily-to-decadal time scales.

With respect to the introduction of N into streams our preliminary data suggests that as a source, legacy sediments are not a significant contributor to stream and reservoir eutrophication. However, we also strongly suggest that legacy sediments do have an important effect on N dynamics in estuaries and that regulators should be concerned because this effect is not quantified. The scope of the present project limited our focus to mill pond sediments and immediate effects on water directly receiving legacy sediments after disaggregation. While we saw little difference between N released from pure lab water and artificial river water (nominal salinity of 1), Rysgaard et al. (1999) showed the importance of salinity on controlling release of ammonium from estuarine sediments and most importantly that the desorption effect was maximal at salinity ~ 10. Thus, we propose that the erosion of legacy sediments potentially exacerbates estuarine eutrophication if these sediments are eroded, transported into the Neuse River and deposited in the upper oligohaline reaches of its estuary. We recommend further studies to couple sediment geochemistry, nutrient desorption assays, and ecological studies to de-convolve this potentially very complex relationship.

This study highlights the interconnections between past land use activities and modern stream form, function, nutrient transfer, and water quality, but many important research questions remain. In particular, how do we best move forward with stream restoration and water quality improvement efforts in light of the fact that there are literally millions of tons of legacy sediment still sequestered along regional valley bottoms?

6. RECOMMENDATIONS

- Mapping at the regional scale in order to determine the distribution, thickness, and volume of stored legacy sediment.

- Incorporate stream bank erosion of legacy sediment into Total Maximum Daily Load estimates for total suspended solids and turbidity.

- Investigate the ecological impacts of stream bank erosion of mill pond legacy sediments on reach-scale benthic communities.

- Utilize geochemical fingerprinting of storm water total suspended solids as a means for estimating the total catchment contribution from stream bank erosion of legacy sediments versus other potential contributing sources (e.g., construction sites, road cuts, forested uplands, and agricultural fields).

- Determine the discharge-event flux rates for total suspended solids from mill pond reaches by establishing site-specific stage-discharge rating curves.

- Perform paleoecology studies on pre-European sediments preserved beneath legacy sediment to ascertain the composition structure of valley bottom vegetation and geomorphology prior to the time of European arrival as a guide for regional stream restoration efforts.

- Experiment with photochemical-driven desorption of ammonium from inorganic and humic substances derived from stream bank erosion of legacy sediments.

- Investigate the coupled geochemical and desorption pathways that may exist between clay-bound nutrients derived from erosion of legacy sediment upon deposition in the upper oligohaline reaches of the Neuse River estuary.

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APPENDIX 1: ABBREVIATIONS AND SYMBOLS WITH DEFINITIONS

ARW	Artificial River Water
BC / AD	Before Christian Era / After Christian Era
B.P.	Before Present
C	Carbon
CCC	Civilian Conservation Corps
CO_2	Carbon Dioxide
CHN	Carbon – Hydrogen - Nitrogen
DIN	Dissolved Inorganic Nitrogen
DON	Dissolved Organic Nitrogen
EA	Elemental Analyzer
EPA	U.S. Environmental Protection Agency
GF/F	Glass Fiber Filters
κ	Kappa – Unit of Magnetic Susceptibility
MPLS	Mill Pond Legacy Sediments
MS	Magnetic Susceptibility
MTS	Modern Top Soil
N	Nitrogen
N_2	Nitrogen Gas
NH_{4+}	Ammonium
NOx	Generic Term for Nitrogen Oxides NO and NO_2
NO_{3-}	Nitrate
NTU	Nephelometric Turbidity Units
NRB	Neuse River Basin
P	Phosphorus
PDLS	Pre-dam Legacy Sediments
PES	Pre-European valley bottom Sediment
PSS	Post-Settlement Sediments
TDN	total Dissolved Nitrogen
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
USP	William B. Umstead State Park
WRRI	Water Resources Research Institute of North Carolina
wt %	Weight-percent of a particular element

APPENDIX 2: PROJECT RESULTS

PRESENTATIONS AND PUBLICATIONS

Presentations:

1. Durham Technical Institute, October 20, 2010, “The Modern Environmental Impact of Historic Water-Powered Mills on North Carolina Piedmont Streams” by Karl W. Wegmann.

2. Appalachian State University, February 4, 2011, “Legacy Sediments and Modern Stream Water Quality: A North Carolina Piedmont Perspective” by Karl W. Wegmann.

3. Water Resources Research Institute of North Carolina Annual Conference, March 22, 2011, “How much Nitrogen do Legacy Sediments Contribute to Streams?” by Christopher L. Osburn.

4. Water Resources Research Institute of North Carolina Annual Conference, March 22, 2011, “Legacy Sediments and Stream Water Quality: Estimating Volume and Stream Band Erosion in 303(d)-impaired waterways of the north Carolina Piedmont” by Karl W. Wegmann

5. Water Resources Research Institute of North Carolina Annual Conference, March 22, 2011, “Living Erosion Pins: Exposed Root Dendrochronology and Multi-year Rates of Stream Bank Erosion” by Robert Q. Lewis

6. Geological Society of America Southeastern Section Meeting, March 25, 2011, “NC mill ponds: A new archive for post-colonial storm events?: by M. Cody Hunt

7. Geological Society of America Southeastern Section Meeting, March 25, 2011, “The Lasting Impacts of Post-Colonial Agriculture and Water-Powered Milldams on Current Stream Water Quality”, by Robert Q. Lewis

8. North Carolina State University, College of Physical and Mathematical Sciences’ Scope Academy, April 9, 2011, “What is our Legacy? The Impact of Historic Land Use Activities on Modern Water Quality” by Karl W. Wegmann

9. North Carolina State University Encore Program of Life Long Enrichment, May 3, 2012, “What is Our Legacy? The History of Land Use Change and Modern Stream Water Quality in North Carolina” by Karl W. Wegmann

10. Geological Society of America Annual Meeting, November 4, 2012, “The Lasting Impact of Human-Induced Soil Erosion on Piedmont Stream Morphology and Water Quality near Raleigh, North Carolina” by Karl W. Wegmann

11. Water Resources Research Institute of North Carolina Annual Conference, March 20, 2013, “Identifying Suspended Sediment Source from Streams near Raleigh, NC: Water Quality and Land Use Management Implications” by Karl W. Wegmann

Publications:

<u>Graduate Theses</u>:

1. Hunt, M., 2011, Millponds: An Archive for Post-Colonial Storm Histories [M.S. thesis]: North Carolina State University, 87 p.

2. Lewis, R. Q., 2011, The Lasting Impacts of Post-Colonial Agriculture and Water-Powered Milldams on Current Water Quality, Umstead State Park, Wake County, North Carolina [M.S. thesis]: North Carolina State University, 178 p.

<u>Peer-Reviewed Articles and Field Guides:</u>

1. Wegmann, K. W., Lewis, R. Q., and Hunt, M. C., 2012, Historic mill ponds and piedmont stream water quality: Making the connection near Raleigh, North Carolina, *in* Eppes, M. C., and Bartholomew, M. J., eds., From the Blue Ridge to the Coastal Plain: Field Excursions in the Southeastern United States: Geological Society of America Field Guide 29: Boulder, Geological Society of America, p. 93-121.

2. Starek, M. J., Mitasova, H., Wegmann, K. W., and Lyons, N., 2013, Space-Time Cube Representation of Stream Bank Evolution Mapped by Terrestrial Laser Scanning: Geoscience and Remote Sensing Letters, IEEE, doi:10.1109/lgrs.2013.2241730.

<u>Meeting Abstracts</u>:

1. [^] Hunt, M. C., Leithold, E. L., and Wegmann, K., 2011, NC mill ponds: A new archive for post-colonial storm events?: Geological Society of America Abstracts with Programs, v. 43, no. 2.
2. [*] Johnson, K. G., and Wegmann, K. W., 2010, Quantifying stream water quality impacts from the spatial distribution of historic "legacy sediments" by analyzing discharge and suspended solids above Cook's Mill, Richland Creek, Wake County, North Carolina: North Carolina State University Spring Undergraduate Research Symposium.
3. [*] Johnston, J. A., and Wegmann, K. W., 2011, Comparison of Anthropologic effects on bedload particle sizes transported by piedmont streams of central North Carolina: Geological Society of America Abstracts with Programs, v. 43, no. 2.
4. [^] Lewis, R. Q., and Wegmann, K. W., 2011, The lasting impacts of post-colonial agriculture and water-powered milldams on current stream water quality: Geological Society of America Abstracts with Programs, v. 43, no. 2.
5. [^] Lewis, R. Q., Wegmann, K. W., and Peszlen, I. M., 2011, Living erosion pins: Exposed root dendrochronology and multi-year rates of stream bank erosion: Water Resources Research Institute of the University of North Carolina Annual Conference, v. 13, no. Abstract 1A-4.
6. [*] Mass, J., Wegmann, K., Osburn, C., 2010, Legacy sediments and stream water quality: Estimating available nutrient content in Richland Creek, a tributary to Crabtree Creek and the Neuse River: North Carolina State University Spring Undergraduate Research Symposium.
7. Osburn, C. L., and Wegmann, K. W., 2011, How much nitrogen do legacy sediments contribute to streams?: Water Resources Research Institute of the University of North Carolina Annual Conference, v. 13, Abstract 1A-2.

8. Starek, M. J., Mitasova, H., and Wegmann, K. W., 2011, Terrestrial Laser Scanning for Measuring Stream Bank Erosion within Legacy Sediments: Data Processing and Analysis Methods: Eos Trans. AGU, Fall Meet. Suppl., Abstract EP41A-0581.
9. Wegmann, K. W., [^]Lewis, R. Q., Osburn, C. L., Peszlen, I., Starek, M. J., and Mitasova, H., 2011, Legacy sediments and stream water quality: Estimating volume and stream bank erosion in 303(d)-impaired waterways of the North Carolina Piedmont: Water Resources Research Institute of the University of North Carolina Annual Conference, v. 13, Abstract 1A-1.
10. Lyons, N., Mitasova, H., Starek, M. J., and Wegmann, K., 2012, Terrestrial laser scanning of a stream bank during naturally and experimentally induced failure by groundwater seepage: Eos Trans. AGU, EP53A-1014.
11. Wegmann, K. W., [^]Voli, M. T., and [^]Lewis, R. Q., 2012, The lasting impact of human-induced soil erosion on Piedmont stream morphology and water quality near Raleigh, North Carolina: Geological Society of America Abstracts with Programs, v. 44, no. 7, p. 104.
13. Lyons, N. J., Wegmann, K. W., Mitasova, H., and Starek, M. J., 2013, The contribution of legacy sediment to stream turbidity characterized with a terrestrial laser scanner along Richland Creek, North Carolina: 15th Annual Conference of the Water Resources Research Institute, v. 15, no. 1; [accessed March 21, 2013: http://www.ncsu.edu/wrri/pdfs/events/Concurrent%20Session%202%20Abstracts.pdf].
12. Wegmann, K. W., [^]Voli, M. T., and [^]Lewis, R. Q., 2013, Identifying suspended sediment source from streams near Raleigh, NC: Water quality and land use management implications: 15th Annual Conference of the Water Resources Research Institute v. 15, no. 1; [accessed March 21, 2013: http://www.ncsu.edu/wrri/pdfs/events/Concurrent%20Session%202%20Abstracts.pdf].

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PATENTS, DATA SETS, OR WEB SITES

None.

EFFORTS AT TECHNOLOGY TRANSFER OR COMMUNICATION OF RESULTS TO END USERS, POLICY MAKERS, OR OTHERS

Informational Meetings:

1. Meeting with staff from the 319 Grant Program, North Carolina Department of the Environment and Natural Resources, Division of Water Quality, February 18, 2010.

2. Meeting with staff members from the North Carolina Department of Natural Resources, Division of Water Quality, Wetlands Program and Policy Development Unit, May 7, 2010.

3. Meeting with Nutrient Cycle Program Scientists, Environmental Protection Agency, Research Triangle Park.

Popular Press Articles:

1. The Greenville Daily Reflector, February 7, 2010, “Relics of our industrial past are hiding in plain sight”.

2. The Charlotte Observer, March 21, 2010, “Mystery lies in old millponds”.

3. The Raleigh News & Observer, March 22, 2010, “Mystery lies in old millponds”; http://www.newsobserver.com/2010/03/22/401126/mystery-lies-in-old-millponds.html.

OTHER APPENDICES

Archived appendix data generated during the course of this project is available in electronic form as part of the Masters of Science thesis submitted to North Carolina State University by Robert Lewis (2011). This document may be accessed from the North Carolina State University Library system at: http://www.lib.ncsu.edu/resolver/1840.16/7040.

Available datasets include:

1. Stream bank magnetic susceptibility results for the Sycamore and Reedy Creek study sites.
2. Plots of total suspended solids and turbidity for sampled storm events from the Reedy and Richland Creek study sites.
3. Total suspended solids and turbidity results for each sampled storm-discharge event for Reedy and Richland Creeks.