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# Bank erosion, bathymetry, and water clarity along the dam regulated lower Roanoke River, North Carolina, USA

By Edward R. Schenk, Cliff R. Hupp, Jean M. Richter, and Daniel E. Kroes

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# Conversion Factors

## SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| Length | | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| meter (m) | 1.094 | yard (yd) |
| Area | | |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |
| hectare (ha) | 0.003861 | square mile ($mi^2$) |
| Volume | | |
| liter (L) | 1.057 | quart (qt) |
| liter (L) | 0.2642 | gallon (gal) |
| cubic meter ($m^3$) | 264.2 | gallon (gal) |
| cubic meter ($m^3$) | 0.0002642 | million gallons (Mgal) |
| cubic meter ($m^3$) | 0.0008107 | acre-foot (acre-ft) |
| Flow rate | | |
| meter per second (m/s) | 3.281 | foot per second (ft/s) |
| cubic meter per second ($m^3/s$) | 35.31 | cubic foot per second ($ft^3/s$) |
| cubic meter per second ($m^3/s$) | 22.83 | million gallons per day (Mgal/d) |
| Mass | | |
| gram (g) | 0.03527 | ounce, avoirdupois (oz) |
| kilogram (kg) | 2.205 | pound avoirdupois (lb) |
| megagram (Mg) | 0.9842 | ton, long (2,240 lb) |
| megagram per year (Mg/yr) | 1.102 | ton per year (ton/yr) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Vertical coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, “North American Vertical Datum of 1988 (NAVD 88)”
Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, “North American Datum of 1983 (NAD 83)”
Altitude, as used in this report, refers to distance above the vertical datum.

# Bank erosion, bathymetry, and water clarity along the dam regulated lower Roanoke River, North Carolina, USA

By Edward R. Schenk, Cliff R. Hupp[1], Jean M. Richter[2], and Daniel E. Kroes[3]

## Abstract

Dam construction and its impact on downstream fluvial processes may substantially alter ambient bank stability, floodplain inundation patterns, and channel morphology. Most of the world's largest rivers have been dammed, which has prompted management efforts to mitigate dam effects. Three high dams (completed between 1953 and 1963) occur along the Piedmont portion of the Roanoke River, North Carolina; just downstream the lower part of the river flows across largely unconsolidated Coastal Plain deposits. To document bank erosion rates along the lower Roanoke River, more than 700 bank erosion pins were installed along 124 bank transects. Additionally, discrete measurements of channel bathymetry, water clarity, and presence or absence of mass wasting were documented along the entire study reach (153 km). Amounts of bank erosion in combination with prior estimates of floodplain deposition were used to develop a bank erosion-floodplain deposition sediment budget for the lower river. Present bank erosion rates are relatively high (mean 42 mm/yr) and are greatest along the middle reaches (mean 60 mm/yr) and on lower parts of the bank on all reaches. Erosion rates were likely higher along upstream reaches than present erosion rates, such that erosion rate maxima have since migrated downstream. Mass wasting and water clarity also peak along the middle reaches. A reference to the discussion and interpretation of this report's results is provided.

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## Introduction

River regulation, through the development of dams, has affected over half of the world's largest river systems (172 of 292; Nilsson et al. 2005). The downstream hydrogeomorphic effects of high dams have been documented for over 80 years (Lawson 1925; Petts and Gurnell 2005). More recently, the ecological effects of regulated flow below dams have been investigated (Ligon et al. 1995; Richter et al. 1996; Poff et al. 1997; Friedman et al. 1998). Flood-control operations on the Roanoke River have had large hydrologic impacts including the elimination of high-magnitude flooding and a greater frequency of both moderate and particularly low flow pulses; this impact has been implicated in various forms of ecosystem degradation (Richter et al. 1996). Flow regulation often dramatically alters the regime of alluvial rivers through both confined water release scenarios and through substantial reductions in transported sediment below dams (Petts 1979; Williams and Wolman 1984; Church 1995; Brandt 2000). Channel beds and banks may undergo a wide range of adjustments to regulation (Williams and Wolman 1984), however along single threaded alluvial rivers the most common effect is channel incision and subsequent widening through bank erosion (Williams and Wolman; 1984; Bravard et al. 1997; Friedman et al. 1998; Brandt 2000). Williams and Wolman (1984) suggest that certain aspects of regulated flow may increase bank erosion including: (1) decreased sediment loads that enhance entrainment of bed and bank material leading to channel incision; (2) a decrease of sediment delivered and stored on or near banks; (3) consistent wetting of lower bank surfaces through diurnal flow fluctuations associated with upstream power generation that promotes greater erodibility; and (4) channel degradation, which allows for flow impingement low on the banks that may remove stabilizing toe slopes and woody vegetation.

Few studies have documented, in detail, bank erosion along regulated Coastal Plain rivers (Ligon et al. 1995). Three high dams were completed along the Roanoke River, North Carolina, between 1953 and 1963. The largest of these forms the John H. Kerr Dam and Reservoir, which controls major water discharges downstream and is currently under evaluation through a Federal Section 216 study (authorized review of operations) conducted by the U.S. Army Corps of Engineers for flood control effects. One of the principal objectives of this study is to assess environmental and economic impacts downstream. Two smaller hydroelectric dams located downstream of the Kerr Reservoir are the Gaston Dam that has operated as a power station since 1963 and further downstream the smaller Roanoke Rapids Dam that has operated as a power station since 1955; both of these dams are regulated by the Dominion Power Company.

Evidence of bank erosion along the lower Roanoke River is common where bank heights (above mean water levels) are substantial (> 2 meters), particularly along middle reaches between the Fall Line and the Albemarle Sound (Figs. 1A and 1B). Evidence may take the form of particle by particle erosion along straight and cut banks with concave upward profiles often leaving overhanging (undercut roots) trees and shrubs on the top of bank, or mass wasting through slab and rotational bank failures that may carry large amounts of soil and vegetation partly or completely down the bank slope (Hupp 1999). The purposes of this report are, in general, to document and measure bank erosion along the lower Roanoke River. Additional objectives include the quantitative description of channel dynamics in relation to bank erosion and downstream trends in water clarity. Data used to complete these objectives are funded, in part, by the U.S. Army Corps of Engineers (USACE), the U.S. Fish and Wildlife Service (USFWS), and the National Research Program of the U.S. Geological Survey (USGS).

## Site Description

The lower Roanoke River is located on the northern Coastal Plain of North Carolina (southern part of the Mid-Atlantic Region), an area of broad upland plains with low relief and broad sometimes underfit bottomlands (Hupp 2000). This region is characterized by humid temperate climatic conditions with a mean annual temperature of 15.8º C (60.4$^{o}$ F) and average annual precipitation of 1267 mm (49.9 in) as measured at Williamston, NC, elev. 6.1 m (NGVD 1929) above sea level (station 319440 Williamston 1E, 1971-2000 Climate Normals, State Climate office of North Carolina). The average water discharge (1964-2007) is 228 cubic meters per second (cms) as measured at Roanoke Rapids, NC (USGS streamflow gage 02080500) below the downstream-most dam; daily mean discharges range from 23 to 1008 cms over the period record (43 years). Prior to dam construction, annual peak flows regularly ranged from about 1400 cms to 2800 cms with extreme events in excess of 3400 cms (Fig. 2). Over the post-dam streamgaging record (since 1964) the maximum peak flow was 1055 cms with normal peak-flow maxima about 980 cms. Conversely, low flows are sustained at higher discharges than before dam construction; annual flows rarely are less than 220 cms and most peaks are held around 560 cms (Fig. 2). Water stage information is recorded at seven streamgages along the lower river from Roanoke Rapids, NC (also the discharge measurement station) near the dam, and in downstream order, at Halifax, Scotland Neck, Oak City, Hamilton, Williamston, and Jamesville, NC, nearest the Albemarle Sound (Figs. 1A and 1B)

The lower Roanoke River flows generally southeasterly from near the Fall Line to the Albemarle Sound as a largely single threaded meandering stream (Fig. 1) across Miocene sedimentary material overlain by Quaternary Alluvium (Brown et al. 1972). The material consists largely of unconsolidated fine sands, silt, and clay, although the clayey Miocene deposits may be indurated. Additionally, the floodplain along the lower river trapped a large volume of sediment associated with post-colonial agriculture (Hupp 1999). This legacy sediment may be between 4 and 6 meters in depth along upstream reaches of the lower river (P. Townsend, written communication, 2006), which thins downstream to near zero close to the Albemarle Sound. The river is generally incised through the legacy sediment and other Coastal Plain sediments; although erosion on cut banks and many straight reaches appears active, there is limited point-bar development. The floodplain along the lower river supports the largest contiguous Bottomland Hardwood forest on the Atlantic Coastal Plain (Hupp 2000).

# Methods

## Transect Bank Erosion

Bank transects were established along a 153 kilometer reach of the lower river, from upstream near the Fall Line to near the Albemarle Sound, ultimately the banks are non-existent nearest the Sound (Fig. 1). Site selection for transects was stratified to capture proportionate amounts of inside bends, outside bends, and straight reaches. We (USGS in cooperation with the USFWS) instrumented 66 transects 32 of which are in pairs on opposite sides of the river. Further, 58 additional transects (in 12 pairs with triplicate transects), originally established by the USFWS, were incorporated into the present study for a total of 124 transects. These transects begin near the water surface (low water stages) and extend 3 meters to 10 meters past the top of bank onto the generally flat natural levee surface, oriented normal to the channel. Transects vary in length according to bank height, angle, and profile. Each transect is referenced by the establishment of a steel spike driven into the base of a mature nearby tree, which also serves as a temporary vertical benchmark and monument for current and future studies; monuments were assigned an arbitrary elevation for relative measurements and later corrected to the NAVD 88 datum. Transect locations were recorded on maps documented using Global Positioning System (GPS, Garmin GPSmap 60CSx) technology (horizontal accuracy about 3.5 m).

Erosion pins (approximately 1 meter long) were placed along transects (Fig. 3) beginning at or near the low water surface and ending on the levee adjacent to the top of bank, during the fall of 2005. Pins were spaced to capture prominent breaks in the bank slope and erosion along long straight bank sections. Long transects (>25 m, high banks) typically had 7 -10 pins established, while short transects, a few meters, had at least three pins. The pins were driven into the soil normal to the local bank slope, flush to the ground surface. In total, 701 pins were established for monitoring. The pins were re-visited annually during the summers of 2006, 2007, and 2008; in selected cases pins were revisited more frequently. During each visit the pins were measured for the amount of erosion (pin exposure) or amount of deposition (pin burial); buried pins were located using a metal detector. Measurements were taken along an axis normal to the local bank slope, parallel to the pin.

Each transect was differentially leveled in detail using a survey rod and optical level. Surveys were tied to the temporary benchmark, which had been assigned an arbitrary elevation. Elevations were later corrected using Light Detection and Ranging (LIDAR) 0.61 m (2 ft.) contour data generated in April 2007 and provided by the North Carolina Dept. of Transportation. Cross-sectional survey data was vertically corrected to the NAVD 88 datum using LIDAR elevations from the approximate top of each transect bank. Every pin was specifically documented in the survey and in addition to the temporary benchmark served to preserve horizontal stationing. All USGS transects were leveled at the time of establishment (2005) and again during 2007 to document erosion/deposition over the intervening period. Erosion pins are highly accurate and allow for detailed measurement at specific locations. A comparison of differences between first and final surveys and mean pin measurements was used to infer erosion/deposition rates along the entire transect.

Paired transects, on opposite sides of the river, were tied to each other using bathymetric surveys (Fig. 3). Toe slopes were surveyed (from boat) using a tag line attached to the bank at the water surface for horizontal station. A survey rod was used to determine elevation relative to the water surface (depth). This procedure was used for about 10 meters of transect (cross section) length from the water's edge. The channel bed, along transect, was surveyed to capture the entire channel cross section between paired bank transects using a laser rangefinder for horizontal station and a narrow-beam depth finder (200khz) to determine depth (elevation). Toe-slope and channel cross section measurements were tied to the monumented bank surveys using a series of duplicate measurements including rod and level, tag line and rod, and depth finder and rangefinder (Fig. 4).

## Channel Bathymetry, Water clarity, Mass Wasting

River surveys for channel bathymetry and bank feature measurements were conducted as part of the present study. A series of observation points on the lower Roanoke River were established using GIS in 1998, mid-channel, from near the Fall Line downstream to and into the Albemarle Sound covering a distance of about 200 river kilometers (125 miles). Channel observation points are generally about 1.6 kilometers (1 mile) apart. Depth, channel width, bank height, and bank angle were measured at each observation point using a laser rangefinder and sonic depth finder (200 Khz beam); a GPS unit was used to locate channel observation points. Each river survey was completed over a contiguous 2-day period. Water stage information was recorded for the observation period from the series of gages on the lower river. Variation in water-surface elevation along the study reach was corrected by using the sum of the vertical distance from top of bank to mid-channel bed depth to estimate overall channel depth. This survey was conducted most recently in the summer of 2007, during this recent survey water clarity, as measured by Secchi depth, and an index of bank erosion was recorded in addition to the aforementioned parameters. Elements of the 2007 bathymetric survey are reported in the present report.

A Secchi disk is a simple device that is commonly used to quantitatively measure water clarity. It is a 20 cm (8 inch wide) disk with alternating black and white quadrants. It is lowered into the water until it can be no longer seen by the observer. The depth of disappearance is called the Secchi depth and may be affected by the color of the water, algae, and suspended sediments. Because the Roanoke River is a large alluvial (rather than blackwater) system with substantial velocity, even at low flow, an assumption was made that the preponderance of water clarity information results from suspended sediment.

A bank-erosion index was developed to approximate the degree of primary mass wasting on both banks at the stations where bathymetric data were collected. The index ranges between zero and six, zero representing stable or depositional banks and six representing active mass wasting on both banks. Field evaluations were performed independently by two USGS scientists, positioned in a boat mid-stream with at least 100 m of visible banks. The scientists' judgments were nearly always in consensus; this index is presented in Table 1.

# Results

The results cover a four-year period of bank erosion monitoring. Nevertheless, considerable point, transect, reach, and ancillary information provide for a potentially wide array of analyses. The scope of this report includes the presentation of bank erosion as determined by erosion pins monitored in transects, channel cross sections from surveys along transects, channel morphology, water clarity, and mass wasting measured from river bathymetry surveys. In-depth analysis of these results, compared to previous studies on floodplain deposition rates, can be found in the Geological Society of America's Special Papers (Hupp et al., in press).

## Bank Erosion

Net bank erosion (channel widening), by transect, was observed on 110 transects, while net deposition occurred on only 14 transects (Fig. 5). In general, erosion rates increased from the upstream transects (mean 41 mm/yr) to those along the middle study reaches (mean 60 mm/yr), peaking in the vicinity of Hamilton (Fig. 1B), and then diminished (mean 27 mm/yr) toward the downstream transects (Table 2). Mean erosion by transect ranged from 380 mm/yr along a transect near Hamilton (Fig. 5) to nearly zero at many transects. To date, only 4 transects have captured a mass wasting event (15BR, T23BR, and FS8LM and LU at river kms 112, 131.5, and 133.5 respectively). Many more mass wasting events have been observed during the study outside of the bank transects, erosion results are likely quite conservative. Where there was net deposition, the transect was typically located on a point bar; the greatest mean deposition amount (55 mm/yr) occurred along the point bar directly opposite the cut bank with highest erosion (Fig. 5; near Hamilton). Total bank erosion tends to be greatest nearest the dam and attenuates downstream (Williams and Wolman, 1984). Bank erosion rates on the Roanoke River (0.38 m/yr maximum) are similar to other published erosion rates (relatively rare in the literature) where human activities have affected natural channel processes (Simon and Hupp 1992, Madej et al. 1994, Merritt and Cooper 2000, Simon and Rinaldi 2000, Kendall et al. 2002).

Variation in lower Roanoke River erosion rates occurs among straight and curved (inside and outside banks) reaches. Mean erosion rates were greatest on the outside and inside banks of curved reaches (50 to 60 mm/yr) while straight banks average about 40 mm/yr. Considerable secondary bank failures of accreted material on inside bends (usually point bars) keep erosion rates relatively high. These rates do not reflect the impact associated with observed mass wasting.

Substantial variation in bank erosion may occur between upper and lower bank segments. Bank erosion, when divided into upper and lower parts (roughly half the pins in a given transect) of the bank followed the same general trend of peaking in the middle reaches near Hamilton. Along all reaches erosion tends to be greatest on the lower bank (Table 2). Further, erosion on the upper banks along the upper reaches is nearly an order of magnitude less than that of the lower banks (Table 2). A subset of transect sites by the USFWS (FS transects, n=10, FS 5 and 7 not included, Fig. 1B) was composed of three parallel transects spaced by 25 meters; and located so that the actively eroding middle reaches and part of the adjacent lower reaches were sampled. Along the unstable, actively eroding reach, the lower banks erode more rapidly than upper banks, while along the lower reaches this trend is reversed, albeit less pronounced (Fig. 6). Transect erosion rate variation (at these intensely monitored sites, FS transects) is distinctly higher on the unstable middle reach than at sites located on the lower more stable reach (Fig. 6). Pronounced erosion on the toe of banks occurs along the lower Roanoke River, documented partially in the pin measurements presented above and in rod and level surveys. An example of the predominant lower bank and toe erosion is illustrated in Figure 3.

## Mass Wasting and Water clarity

Mass wasting (Fig. 7) as measured by our bank-erosion index (Table 1) increased from the upper reaches to the middle reaches where it peaked at 3.5 (Table 2) and decreased downstream to the lower reaches. Index values were estimated during the 2007 river survey and when averaged over 8 km (approximate) river segments from about 30 to 175 km below the dam also show the distinct trend of peaking along the middle reaches (Fig. 8). This trend is generally mirrored by mean transect/pin data plotted at actual transect locations (Fig. 8). Mean maximum bank-erosion index values range between 4 and 5 (Fig. 9), over about a 24 km reach beginning just below Hamilton (river km 115, Fig. 1B). Channel width measurements, taken during river cruises, demonstrate that channel width decreases from upstream (near the dam) to the relatively narrow middle reaches then increases toward the Albemarle Sound (Table 2).

Entrainment of bank sediments may substantially affect stream water clarity. Water clarity as measured by Secchi depths decreased (low Secchi depth) from near the dam toward the actively eroding middle reaches (Fig. 8). The water released from high dams is notoriously clear; suspended sediment is normally low or nonexistent as the reservoir is typically an effective sediment trap

(Williams and Wolman 1984). Thus, suspended sediment in the Roanoke River downstream of the dams must come from tributary inputs or from erosion and entrainment of bed and bank sediments. There are no substantial tributaries entering the Roanoke River between the dam and the downstream-most bank erosion sites. Thus, it is reasonable to assume that there is a direct relation between increased turbidity and active channel erosion (Figure 6), most of which may be derived from the banks as noted in analogous situations by Simon and Hupp (1992) where relative bank heights increased as a result of channel incision. Additionally, variation in flow velocity associated with power generation (peaking) may facilitate bank erosion (Williams and Wolman 1984), especially particle-by-particle entrainment, which also may lead to bank-toe removal and subsequent bank failure (Thorne and Abt 1993). Water clarity increased slightly in the lowest reaches near brackish tidal water (Fig. 8) as is typical along Coastal Plain rivers (Hupp 2000).

## Channel Morphology

Between 1998 and 2007 we completed 4 bathymetric data cruises from near Halifax, NC to the Albemarle Sound. Data from the most recent cruise (2007) is provided in Appendix __. Cruises were completed at or near summer mean low water depth. Summer mean low water depth was relatively consistent from near the dam to river km 75 and then increased until approximately river km 150 when the water surface approached mean sea level (Fig. 9). Water depth decreased from approximately river km 150 to the Albemarle Sound as the river width increased proportionally. Width/depth ratios mirror the mean low water depth trend, with greater channel incision in the downstream direction from river km 75 to river km 150 (Fig 10).

## Bank and Floodplain based Sediment Budget

Bank erosion rates were converted to masses by assigning each transect a width of 1 m and multiplying the surveyed bank height by the erosion rate; 9, 23, 68, and 12 bank transects were used in each segment, respectively downstream. Bank heights decrease from nearly 7 meters near the upstream transects to less than 1 meter in the vicinity of the downstream most transects. Thus, the effective volume of eroded material decreases from upstream to downstream for any given erosion rate. Volumes of sediment removed from the bank was converted to mass using a bulk density of 0.94 $g/cm^3$ determined from bank measurements taken upstream of Williamston, NC on Oct. 23 2008.

Eighty nine percent of transects (110) experienced net erosion. Both erosion by largely particle-by-particle removal and mass wasting presently peak in the middle reaches (95 to 137 river kilometers below the dam) in the vicinity of Hamilton, NC. This middle part of the study area also demonstrates higher flow elevations and durations for low-flow conditions than most non-regulated streams. Accordingly, bank erosion along the entire study reach is greatest on the lower half of the bank slopes. The upstream reach (32 to 95 river kilometers below the dam) experiences less bank erosion than the middle reach. However, this reach has a wider channel and higher banks than downstream.

In 4 years of monitoring only 4 transects of 124 captured a primary mass wasting event (15BR, FS8LM, FS8LU, 23BR) although many events were observed outside of our transects. A visual survey of mass wasting events at 1.6 km intervals found 19 recent mass wasting events, two each in river segments two and four (51-100 and 151-200 river km respectively) and 15 in river segment three (101-150 km, the active middle reach).

We incorporated previous studies of floodplain sediment deposition on the Lower Roanoke River and suspended sediment loads measured at the Roanoke Rapids Dam between 1980 and 1995 to develop a bank and floodplain based sediment budget. The floodplain along the lower Roanoke annually traps more than 2.5 million cubic meters of sediment (Hupp et al. in press). Sediment deposition on floodplains increases dramatically and systematically from near the dam to the downstream reaches. A comparison of deposition and erosion rates and loads provides two distinct views of the sediment processes on the lower river (Fig. 11). The total observed deposition and erosion shows a several orders of magnitude difference between sediment storage and removal (Fig. 12). The total budget, minus suspended sediment loads, also shows the large surplus of sediment that is not accounted by the particle-by-particle erosion measured by the bank erosion pins (Fig. 13). Future work on the sediment budget should include measurements of toe slope erosion (below the water line), quantification of sediment mobilized by mass wasting events, and detailed analysis of spatial patterns of floodplain sediment deposition. Further interpretation of this data, minus the 2008 measurements, can be found in a peer-reviewed article published in the GSA Special Papers (Hupp et al. in press).

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**Figure 1.** A. Map of the upstream part of the lower Roanoke River, North Carolina. Locations of paired transects, river kilometer below dam, and land holdings are indicated. Inset, maps of the entire lower Roanoke River reaches and the watershed in Virginia/North Carolina. B. Map of the downstream part of the lower Roanoke River, North Carolina. Features shown in Fig. 1 A are the same, and the identification and delineation of upper, middle, and lower reaches/transects is shown.

**Figure 2.** Daily flows (1912 – 1999) on the lower Roanoke River as measured at Roanoke Rapids, North Carolina covering both pre- and post-dam operations. Date and effect of initial dam completion is shown.

**Figure 3.** Cross sections of banks at transects 23 (entire) and C60 (left bank). Pin locations and survey methods are shown along transect 23; pins are driven into bank, flush to surface, typically at an oblique angle, normal to bank slope. Shaded part of cross section was surveyed below water surface using bathymetric techniques. Detail of differences in bank profile from 2005 to 2007 on C60 left bank; mean summer low flow elevation is shown. Note the >1 meter difference between surveys is largely on the lowermost part of the bank and toe slope.

**Figure 4.** Surveying and bathymetric methods used to create cross-sections. The top left photo shows bank pin installation along a transect. The top right and bottom left photos shows optical level surveying along the transect while the bottom right photo shows the beginning of a bathymetric survey from an optically surveyed fixed point.

**Figure 5.** Mean bank erosion rate on the lower Roanoke River from erosion pin data from upstream (left) to downstream (right); left and right banks of each transect are shown

separately.  Observations/transects < 0 are net depositional. Approximate locations of stream gages near Scotland Neck, Hamilton, and Williamston, NC are shown.

**Figure 6.** Mean bank erosion rate and variation at selected (triplicate) transect locations along middle and lower reaches of the lower Roanoke River. Location of separation between middle and lower reaches is shown in Figure 1 B.

**Figure 7.** A recent bank failure near Hamilton, NC.

**Figure 8.** Trends in mean bank erosion, bank erosion index, and water clarity (Secchi depth) from upstream to downstream by river kilometer.  Mean bank erosion data from transect pins; bank erosion index and water clarity are averages over sequential river segments, approximately 8 km each.

**Figure 9.** Mean summer low water depth (m).  Data was compiled from 1999, 2005, and 2007 bathymetric river surveys.

**Figure 10.** Mean width depth ratio by river km.  Data was compiled from 1999, 2005, and 2007 bathymetric river surveys.

**Figure 11.** Trends in bank erosion and floodplain deposition rates, left panel, and masses, right panel divided by 50-km river reach segments from upstream to downstream. Note the inverse relation between bank erosion and floodplain deposition, particularly as revealed in mass estimates.

**Figure 12.** Total observed bank erosion and floodplain deposition by 50 km river segment.  Included in the figure is an annual suspended sediment yield estimate derived from suspended sediment loads measured by the USGS North Carolina Water Science Center between 1980 and 1995 at the Roanoke Rapids Dam.

**Figure 13.** Bank erosion – floodplain deposition sediment budget by sequential 50-km river reach segments, upstream to downstream.  Where the line plots below 0 more material is eroded from banks than is deposited on floodplains.   The 25 and 75% ranges for erosion and deposition are included.  Sediment budget does not include toe erosion not documented by bank erosion pins, mass wasting events, or suspended sediment from upstream and other sources.

**Table 1.** Bank erosion index, used to determine bank erosion for approximately 100 m reaches of the Roanoke River during the 2007 Roanoke River bathymetric river survey.

| Index | Description |
|---|---|
| 0 | No bank failure, banks are vegetated or composed of bedrock, and/or appear depositional. |
| 1 | Particle-by-particle erosion on one bank, evidence of erosion may include exposed tree roots, gully erosion, or un-weathered soil surfaces. Erosion near the water surface caused by boat wakes is not included in the determination. |
| 2 | Particle-by-particle erosion on both banks. |
| 3 | Historical primary mass wasting (slump block includes top of bank, e.g. bank retreat) apparent on one bank, weathered mass wasting scars evident extending to the top of bank. Slump blocks may contain vegetation exhibiting preferential growth (adapted to new aspect). |
| 4 | Historical primary mass wasting apparent on both banks. |
| 5 | Recent (< 1 yr.) primary mass wasting, vegetation within slump block is stressed or not exhibiting preferential growth or slump scar appears fresh with an un-weathered surface. |
| 6 | Recent primary mass wasting on both banks. |

**Table 2.** Mean bank erosion rates by upper (32-95 km), middle (96-137 km) and lower (138-175 km) reach. Mean bank erosion rates of the lower and upper mean low summer stage are also presented.

| River km | ---- Mean (mm/yr) ---- Lower | Upper | Entire transect | Bank height (m) | Mass Wasting index | Mean channel Width (m) |
|---|---|---|---|---|---|---|
| 32-95 | 68.5 | 10.2 | 41.0 | 5.3 | 1.4 | 92.2 |
| 96-137 | 68.9 | 50.6 | 59.6 | 4.1 | 3.5 | 79.8 |
| 138-175 | 25.2 | 24.8 | 27.3 | 1.7 | 2.6 | 82.0 |

# Appendix

**Appendix 1. Summary of bank transect locations, number of erosion pins per transect, bank erosion index values, mean bank height, and erosion rates. Appendix available as an .xls file here or on the internet at: http://**

**Appendix 2. Erosion pin measurements for each of the 701 bank erosion pins. Appendix available as an .xls file here or on the internet at: http://**

**Appendix 3. Cross-sectional survey data by transect including bathymetry. Appendix available as an .xls file here or on the internet at: http://**

**Appendix 4. Bathymetric, water clarity, and mass wasting data collected on an approximately 200 km river survey from near Halifax, N.C. to the Alblemarle Sound. Appendix available as an .xls file here or on the internet at: http://**

**Appendix 5. Mean floodplain sedimentation from 2002 to 2005 measured using feldspar clay pads on transects perpendicular to channel. Appendix available as an .xls file here or on the internet at: http://**