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Bank Erosion, Mass Wasting, Water Clarity, Bathymetry and a Sediment Budget Along the Dam-Regulated Lower Roanoke River, North Carolina

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

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Conversion Factors

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 North American Vertical Datum 1988 (NAVD 88) or National Geodetic Vertical Datum (NGVD 29) depending on the data set.

Bank Erosion, Mass Wasting, Water Clarity, Bathymetry and a Sediment Budget Along the Dam-Regulated Lower Roanoke River, North Carolina

By Edward R. Schenk,[1] 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 153-kilometer-long study reach. Amounts of bank erosion in combination with prior estimates of floodplain deposition were used to develop a bank erosion and floodplain deposition sediment budget for the lower river. Present bank erosion rates are relatively high [mean 42 milimeters per year (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 migrated downstream. Mass wasting and water clarity also peak along the middle reaches.

Introduction

River regulation, through the development of dams, has affected more than one-half (172 of 292) of the world's largest river systems (Nilsson and others, 2005). The downstream hydrogeomorphic effects of high dams have been documented for more than 80 years (Lawson, 1925; Petts and Gurnell, 2005). More recently, the ecological effects of regulated flow below dams have been investigated (Ligon and others, 1995; Richter and others, 1996; Poff and others, 1997; Friedman and others, 1998). Flood-control operations on the Roanoke River have had a large hydrologic impact, including the elimination of high-magnitude flooding and a greater frequency of moderate and particularly low flow pulses; this impact has been implicated in various forms of ecosystem degradation (Richter and others, 1996). Flow regulation often dramatically alters the regime of alluvial rivers through 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, the most common effect along single threaded alluvial rivers is channel incision and subsequent widening through bank erosion (Williams and Wolman, 1984; Bravard and others, 1997; Friedman and others, 1998; Brandt, 2000). Williams and Wolman (1984) suggest that aspects of regulated flow that may increase bank erosion include decreased sediment loads that enhance entrainment of bed and bank material, leading to channel incision; a decrease of sediment delivered and stored on or near banks; consistent wetting of lower bank surfaces through diurnal flow fluctuations associated with upstream power generation, promoting greater erodibility; and 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 and others, 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 [of the Energy Policy Act of 2005 (Public Law 109–58)] study (authorized review of operations) conducted by the U.S. Army Corps of Engineers for flood control effects. One of the principal objectives of the Federal section 216 study is to assess environmental and economic impacts downstream. Two smaller hydroelectric dams located downstream of the Kerr Reservoir are the Gaston

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Dam, which has operated as a power station since 1963, and further downstream, the smaller Roanoke Rapids Dam, which has operated as a power station since 1955; both of these dams are regulated by Dominion Resources Inc.

Evidence of bank erosion along the lower Roanoke River is common where bank heights (above mean water levels) are substantial [more than 2 meters (m)], particularly along middle reaches between the Fall Line and the Albemarle Sound (fig. 1). Evidence may take the form of particle-by-particle erosion along straight and cut banks with concave upward profiles, often leaving overhanging (undercut root) 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 primary purpose of this report is to document and measure bank erosion along the lower Roanoke River. In addition, this report endeavors to quantitatively describe channel dynamics in relation to bank erosion and downstream trends in water clarity. The results cover a 4-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 701 erosion pins monitored in 124 transects, channel cross sections from surveys along transects, channel morphology, water clarity, and mass wasting measured from river bathymetry surveys.

Data used to create this report are also provided in the appendices. Bank erosion data are included in appendix 1 (bank erosion transect locations and summary data), and appendix 2 (bank erosion data for all 701 bank erosion pins). Channel morphology data are included in appendix 3 (channel cross-sectional data) and appendix 4 (bathymetric data cruise data including water clarity). Appendix 5 includes a summary of floodplain deposition rates determined from a previous study. Appendix 6 provides an approximate stage-discharge relationship for USGS streamgages that record only water stage. The information was used to determine the number of nearby bank erosion pins that were submerged or exposed based on mean, median, and mode water stages between measurement dates. An in-depth analysis of the results and data presented in this report was published by the Geological Society of America (GSA) (Hupp and others, 2009). 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 (FWS), and the National Research Program of the U.S. Geological Survey (USGS).

Study Area

The lower Roanoke River is located on the northern Coastal Plain of North Carolina (southern part of the Midatlantic 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 15.8°C (60.4°F) and average annual precipitation of 1,267 millimeters (mm) [49.9 inches (in.)] as measured at Williamston, N.C., elevation of 6.1 m [National Geodetic Vertical Datum (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 (m^3/s) as measured at Roanoke Rapids, N.C. (USGS

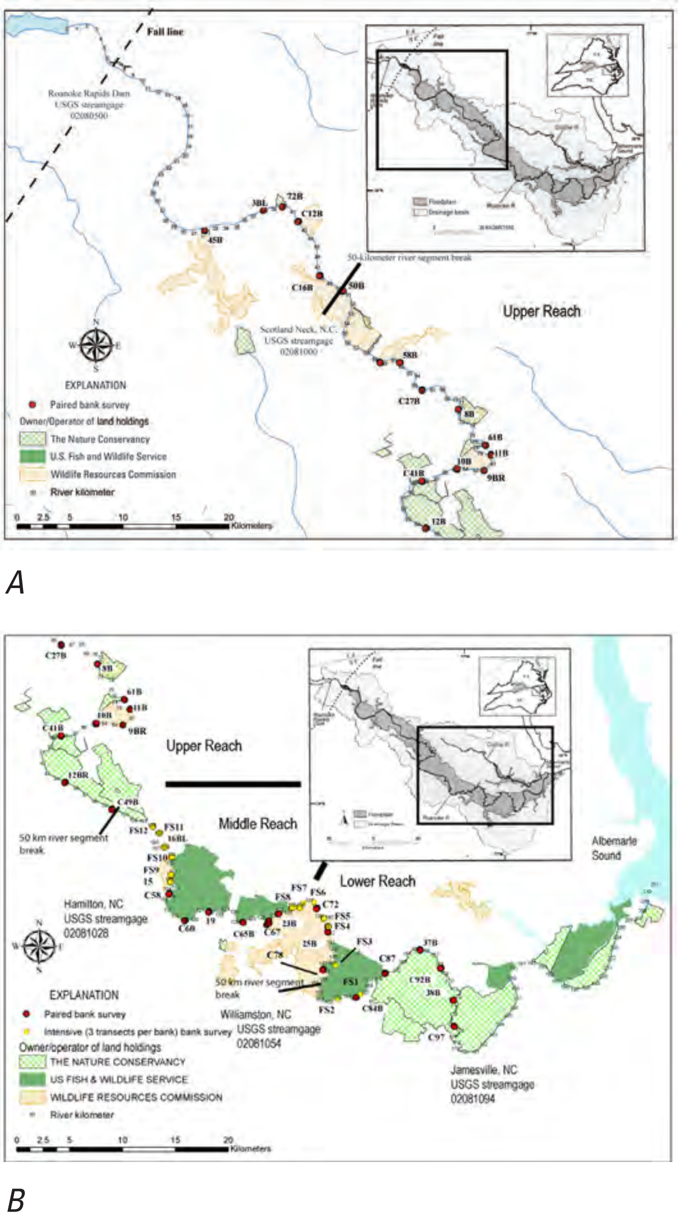

Figure 1. Maps of the lower Roanoke River, N.C. Inset maps of the entire lower Roanoke River reaches and the watershed in Virginia/North Carolina indicate the section being detailed. Locations of paired transects, river kilometer below dam, and land holdings are indicated. *A*. Upstream part of the lower Roanoke River, N.C. *B*. Downstream part of the lower Roanoke River, N.C. km, kilometers.

streamflow gaging station 02080500) below the downstream-most dam; daily mean discharges range from 23 m^3/s to 1,008 m^3/s over the period of record (43 years). Prior to dam construction, annual peak flows regularly ranged from 1,400 m^3/s to 2,800 m^3/s, with extreme events in excess of 3,400 m^3/s (fig. 2). Over the course of the postdam streamgaging record (since 1964) the maximum peak flow has been 1,055 m^3/s, with normal peak-flow maxima about 980 m^3/s. Conversely, low flows are sustained at higher discharges than before dam construction; annual flows rarely are less than 220 m^3/s, and most peaks are held around 560 m^3/s. Water stage information is recorded at seven streamgages along the lower river from Roanoke Rapids (also the discharge measurement station) near the dam and, in downstream order, at Halifax, Scotland Neck, Oak City, Hamilton, Williamston, and Jamesville, N.C., nearest the Albemarle Sound (fig. 1).

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 and others, 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 postcolonial agriculture (Hupp, 1999). This legacy sediment may be between 4 and 6 m in depth along upstream reaches of the lower river (P. Townsend, written commun., 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

Bank Erosion

Bank transects were established along a 153km reach of the lower river, from upstream near the Fall Line to near the Albemarle Sound; ultimately the banks are nonexistent nearest the sound (fig. 1). Site selection for transects was stratified to capture proportionate amounts of inside bends, outside bends, and straight reaches. The USGS in cooperation with the FWS 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 FWS, were incorporated into the current study for a total of 124

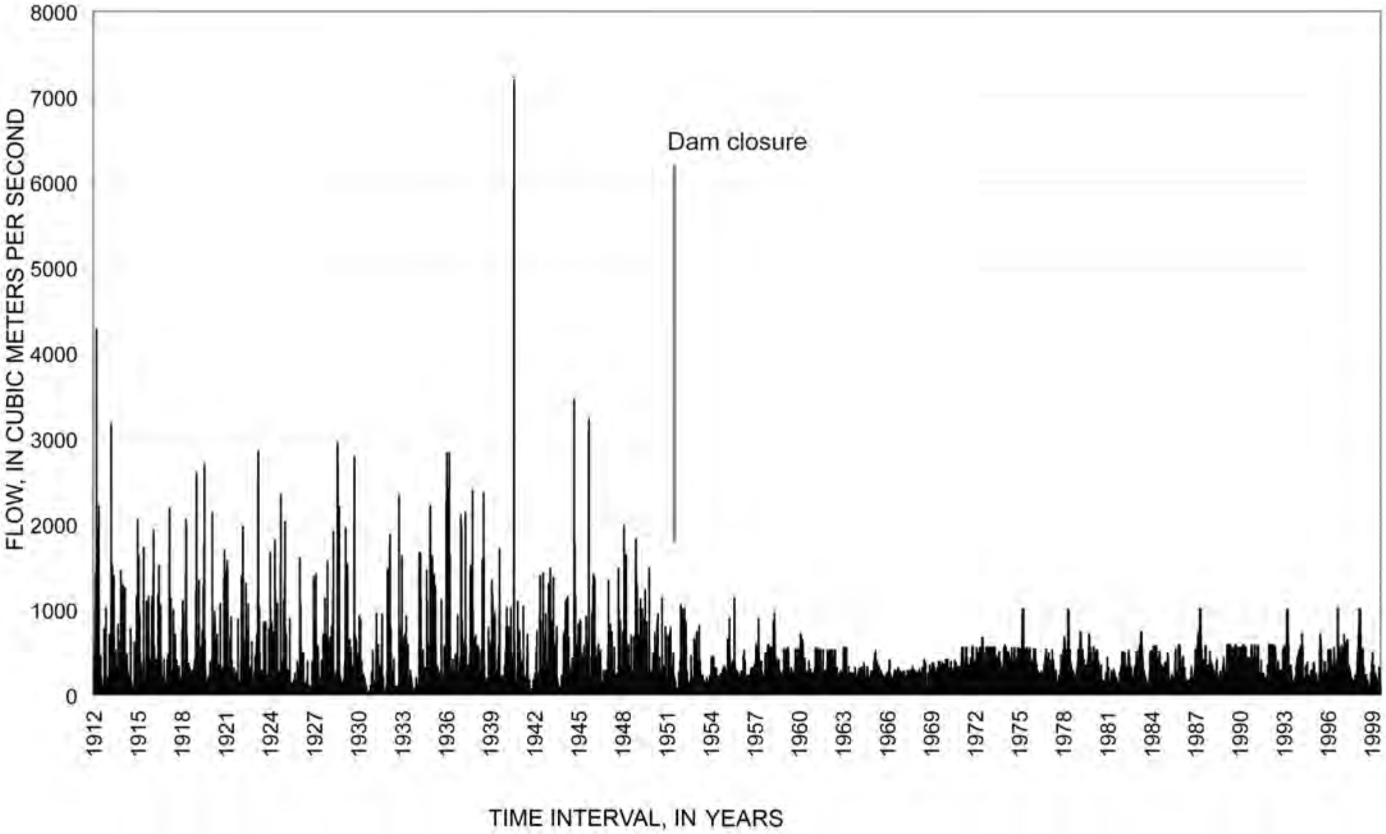

Figure 2. Daily flows on the lower Roanoke River from 1912 through 1999, as measured at Roanoke Rapids, N.C., covering both predam and postdam operations. Date and effect of initial dam completion is shown.

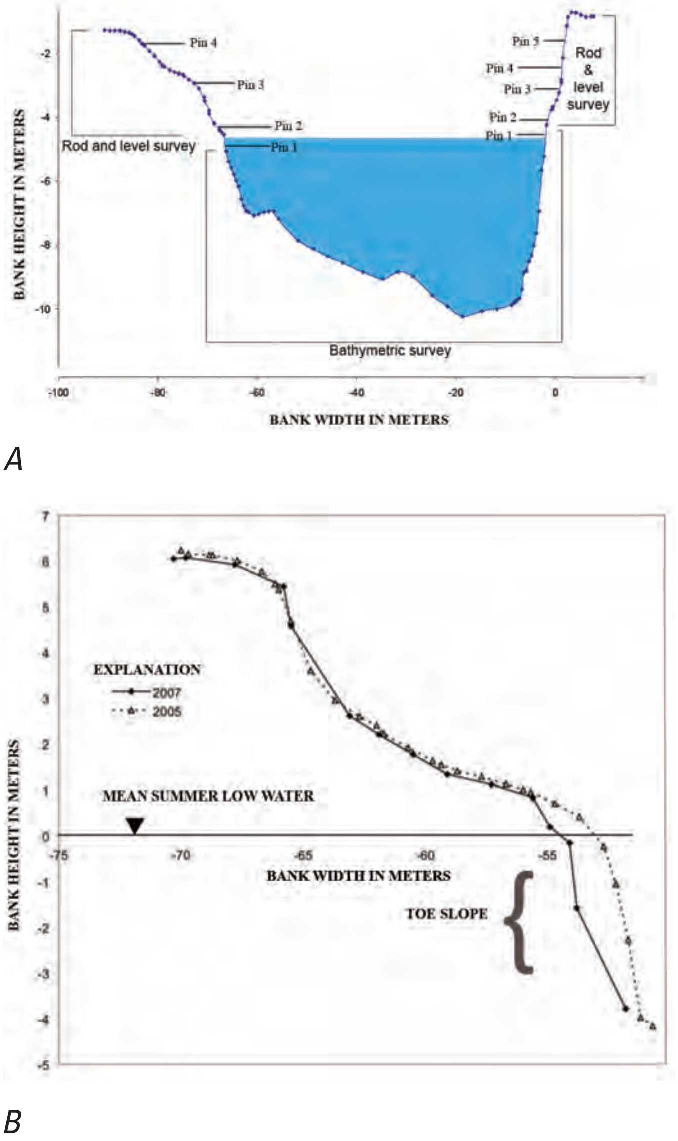

Figure 3. Cross sections of banks at transects *A*, 23 (entire), and *B*, C60 (left bank). Pin locations and survey methods are shown along transect 23; pins are driven into bank, flush to surface, typically at an oblique angle, normal to bank slope. Shaded part of cross section was surveyed below water 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.

transects. These transects begin near the water surface (low water stages) and extend 3 to 10 m 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 North American Vertical Datum 1988 (NAVD 88). Transect locations were recorded on maps documented using Global Positioning System (GPS, Garmin GPSmap 60CSx) technology (horizontal accuracy about 3.5 m).

During the fall of 2005, approximately 1-m-long erosion pins 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. Pins were spaced to capture prominent breaks in the bank slope and erosion along long straight bank sections. Long transects (larger than 25-m-high banks) typically had 7 to 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 at the ground surface. In total, 701 pins were established for monitoring. The pins were revisited annually, in 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-foot (ft)] contour data generated in April 2007 and provided by the North Carolina Department of Transportation. Cross-sectional survey data were 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 when established in 2005 and again in 2007 to document erosion and deposition over the intervening period. Erosion pins are highly accurate and allow for detailed measurement at specific locations. A comparison of differences between the first and final surveys and mean pin measurements was used to infer erosion and 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 m 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 [200 kilohertz (kHz)] 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).

Figure 4. Surveying and bathymetric methods used to create cross-sections. *A*, bank pin installation along a transect; *B* and *C*, optical level surveying along the transect; *D*, the beginning of a bathymetric survey from an optically surveyed fixed point.

Channel Bathymetry, Water Clarity, and Mass Wasting

River surveys for channel bathymetry and bank feature measurements were conducted as part of the current study. Using geospatial information systems (GIS), a series of observation points on the lower Roanoke River were established in 1998, midchannel, 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 km (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 midchannel 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 provided in this report.

A Secchi disk is a simple device that is commonly used to quantitatively measure water clarity. It is a 20-centimeter (cm)- (8-in.-) 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 resulted 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 ranged between zero and six (table 1), 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 midstream with at least 100 m of visible banks. The scientists' judgments were nearly always in consensus.

Bank- and Floodplain-Based Sediment Budget

A bank- and floodplain-based sediment budget was prepared by dividing the lower Roanoke River into 50 km reaches. Mean bank erosion and floodplain deposition data along 153 km of the river were used to populate the 50 km reaches. 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 50-km river segment, respectively downstream. The median transect erosion area (observed rate multiplied by surveyed bank height) for each segment was multiplied by 50 km to produce a river segment bank erosion rate. 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 1.24 grams per cubic centimeter (g/cm^3) determined from bank measurements taken between river kilometers 68 and 86 on April 16, 2009.

Studies of floodplain sediment deposition on the lower Roanoke River between 2002 and 2005 and suspended sediment loads measured at the Roanoke Rapids Dam between 1980 and 1995 were included for development of a bank and floodplain based sediment budget. Measurements at the Roanoke Rapids Dam (USGS site 02080500, n = 96) between 1980 and 1995 provide a mean of 84,000 million grams per year (Mg/yr) of suspended sediment passing through the dam. The floodplain along the lower Roanoke River annually traps more than 2.5 million cubic meters of sediment (Hupp and others, 2009). The annual deposition rate was calculated using the median deposition rate for each 50-km river segment. Deposition rates were measured over 335 clay feldspar pads spread out in transects perpendicular from the channel extending from the levee into the backswamp. The floodplain area for each river segment was delineated using LiDAR. Sediment deposition on floodplains increases dramatically and systematically from near the dam to the downstream reaches.

Results

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 millimeters per year (mm/yr)] to those along the middle study reaches (mean 60 mm/yr), peaking in the vicinity of Hamilton (fig. 1*B*), 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 four transects have captured a mass wasting event (15BR, T23BR, and FS8LM and LU at river kilometers 112, 131.5, and 133.5 respectively). Because 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 bank 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 bank with highest erosion (fig. 5) near Hamilton. Total bank erosion tends to be greatest nearest

Table 1. Bank erosion index used to determine bank erosion for approximately 100-meter 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 unweathered 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, for example, 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 (less than 1 year) primary mass wasting, vegetation within slump block is stressed or not exhibiting preferential growth or slump scar appears fresh with an unweathered surface.
6	Recent primary mass wasting on both banks.

the dam and attenuates downstream (Williams and Wolman, 1984). Bank erosion rates on the Roanoke River (380 mm/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 and others, 1994; Merritt and Cooper, 2000; Simon and Rinaldi, 2000; Kondolf and others, 2002).

Variation in lower Roanoke River erosion rates occured 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 averaged about 40 mm/yr. Considerable secondary bank failures of accreted material on inside bends (usually point bars) kept 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 one-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 tended to be greatest on the lower bank (table 2). Further, erosion on the upper banks along the upper reaches was nearly an order of magnitude less than that of the lower banks. A subset of transect sites by the FWS (FS transects, n=10, FS 5 and 7 not included) (fig. 1*B*) comprised three parallel transects spaced by 25 m 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 eroded more rapidly than upper banks, while along the lower reaches this trend was reversed, albeit less pronounced (fig. 6). Transect erosion rate variation (at these intensely monitored sites, FS transects) was distinctly higher on the unstable middle reach than at sites located on the lower, more stable reach. Pronounced erosion on the toe of banks occured 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.

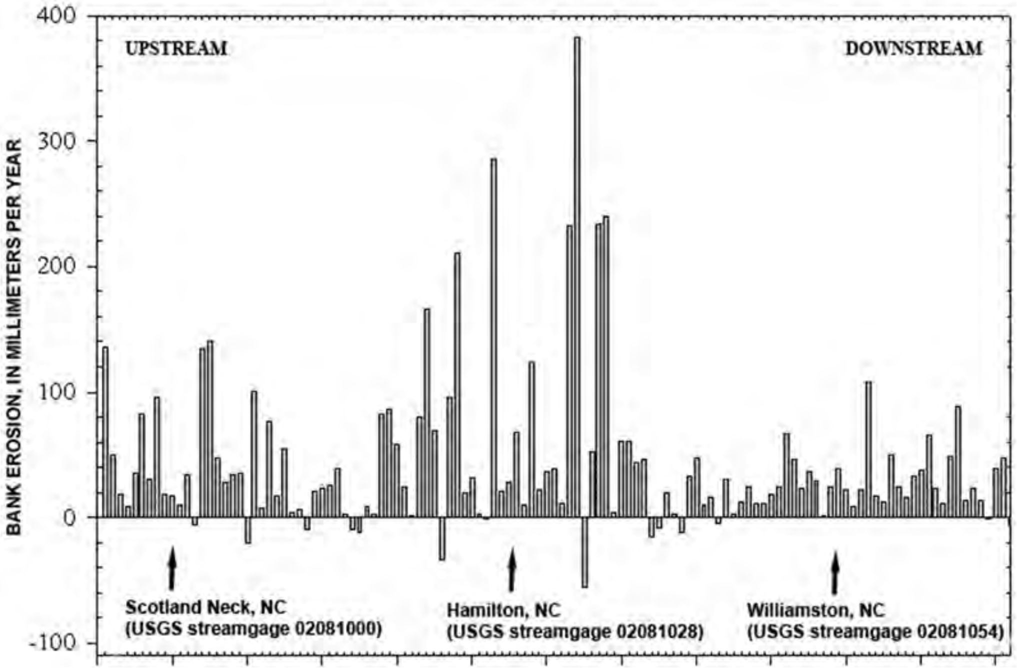

Figure 5. Mean bank erosion rate on the lower Roanoke River from erosion pin data from upstream (left) to downstream (right); left and right banks of each transect are shown separately. Observations and transects that are less than zero are net depositional. Approximate locations of stream gages near Scotland Neck, Hamilton, and Williamston, N.C., are shown.

Table 2. Mean bank erosion rates by upper, middle, and lower study reaches.

[Mean bank erosion rates of the lower and upper mean low summer stage are also presented. Upper reach is 32 to 95 kilometers (km), middle reach is 96 to 137 km, and lower reach is 138 to 175 km. Abbreviations used: km, kilometers; m, meters; mm/yr, millimeters per year]

River reach	River kilometer	Mean bank erosion rate (mm/yr)			Bank height (m)	Mass wasting index	Mean channel width (m)
		Lower	Upper	Entire transect			
Upper	32–95	68.5	10.2	41.0	5.3	1.4	92.2
Middle	96–137	68.9	50.6	59.6	4.1	3.5	79.8
Lower	138–175	25.2	24.8	27.3	1.7	2.6	82.0

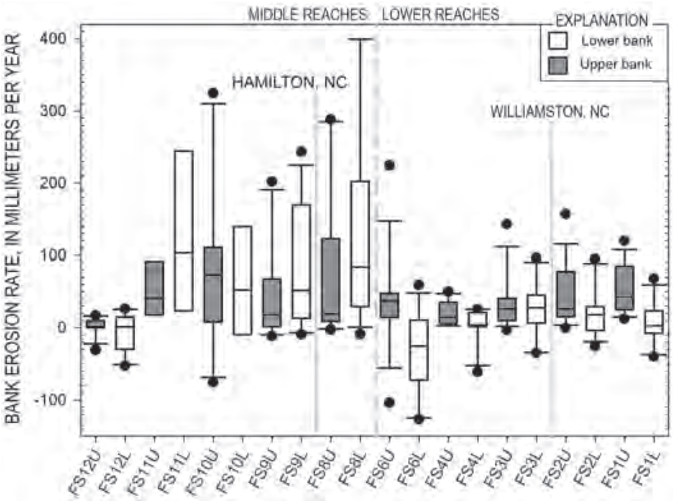

Figure 6. Mean bank erosion rate and variation at selected (triplicate) transect locations along middle and lower reaches of the lower Roanoke River. Location of separation between middle and lower reaches is shown in figure 1*B*.

Mass Wasting and Water Clarity

Mass wasting (fig. 7) as measured by the 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 about 8 km, river segments from about 30 to 175 km below the dam also showed the distinct trend of peaking along the middle reaches (fig. 8). This trend was generally mirrored by mean transect and pin data plotted at actual transect locations. Mean maximum bank-erosion index values ranged between 4 and 5 (fig. 9), over about a 24-km reach, beginning just below Hamilton (river kilometer 115, fig. 1*B*). Channel width measurements, taken during river cruises, demonstrated that channel width decreased from upstream (near the dam) to the relatively narrow middle reaches then increased 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 (fig. 6); most of the erosion 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).

Figure 7. A recent (summer 2005) bank failure near Hamilton, N.C.

Bathymetry

Between 1998 and 2007, four bathymetric data cruises were completed from near Halifax, NC to the Albemarle Sound. Data from the most recent cruise (2007) are provided in appendix 4. Cruises were completed at or near summer mean low water depth. Data from three of the data cruises were aggregated to provide a longer term analysis of longitudinal trends. Summer mean low water depth was relatively consistent from near the dam to river kilometer 75 and then increased until approximately river kilometer 150 when the water surface approached mean sea level (fig. 9). Water depth decreased from approximately river kilometer 150 to the Albemarle Sound as the river width increased proportionally. Width-to-depth ratios mirror the mean low-water-depth trend, with greater channel incision in the downstream direction from river kilometer 75 to river kilometer 150 (fig. 10).

Bank- and Floodplain-Based Sediment Budget

Eighty nine percent of transects (110) experienced net erosion. Erosion by both largely particle-by-particle removal and mass wasting peaked 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 demonstrated

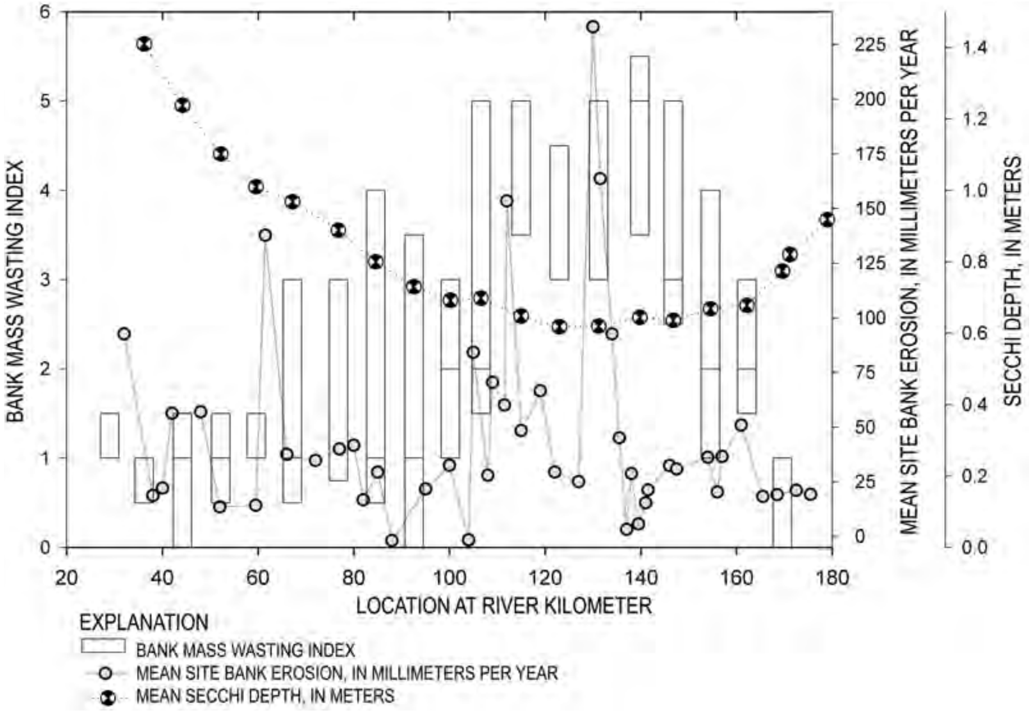

Figure 8. Trends in mean bank erosion, bank erosion index, and water clarity (Secchi depth) from upstream to downstream by river kilometer. Mean bank erosion data are from transect pins; bank erosion index and water clarity are averages over sequential river segments, approximately 8 kilometers each.

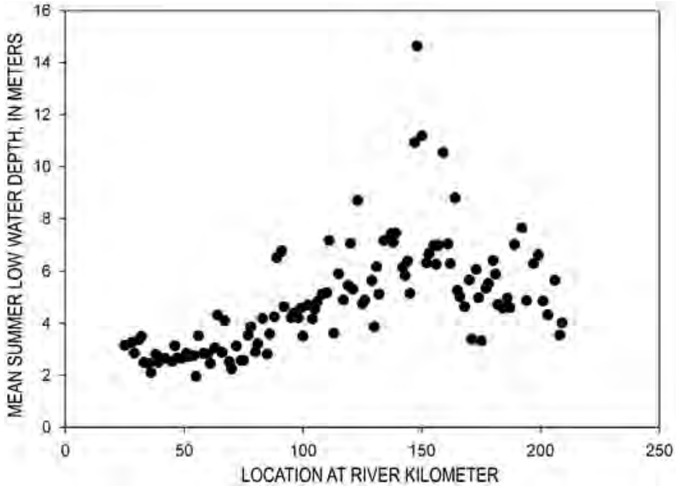

Figure 9. Mean summer low water depth; measured in meters. Data were compiled from 1999, 2005, and 2007 bathymetric river surveys.

higher flow elevations and durations for low-flow conditions than most nonregulated 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 (15BR, FS8LM, FS8LU, 23BR) transects of 124 captured a primary mass wasting event although many events were observed outside of the studied transects. A visual survey of mass wasting events at 1.6-km intervals found 19 recent mass wasting events, two each in river segments 2 and 4 (51–100 and 151–200 river kilometers, respectively) and 15 in river segment 3 (101–150 river kilometers, the active middle reach).

A comparison of floodplain deposition and bank erosion rates and loads provides two distinct views of the sediment processes on the lower river (fig. 11). The total observed deposition and erosion showed 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.

Summary

The lower Roanoke River has experienced dramatic alterations in hydrologic conditions since dam completion. The highly regulated dam release patterns concentrate flow on middle and lower bank surfaces and facilitate bank erosion. Bank erosion along the lower Roanoke River is apparent in both particle-by-particle removal and mass wasting along most reaches including cut banks, straight and inside bend reaches; where 77 percent of transects (90) experienced erosion. Bank erosion rates increased from the upstream transects to those along the middle study reaches, and then

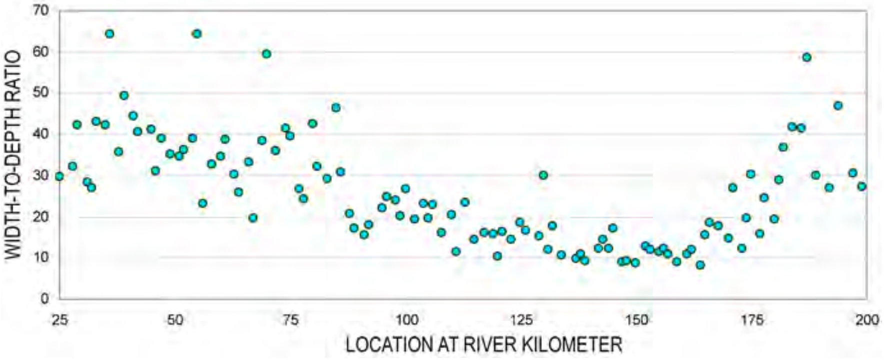

Figure 10. Mean width-to-depth ratio by river kilometer. Data were compiled from 1999, 2005, and 2007 bathymetric river surveys.

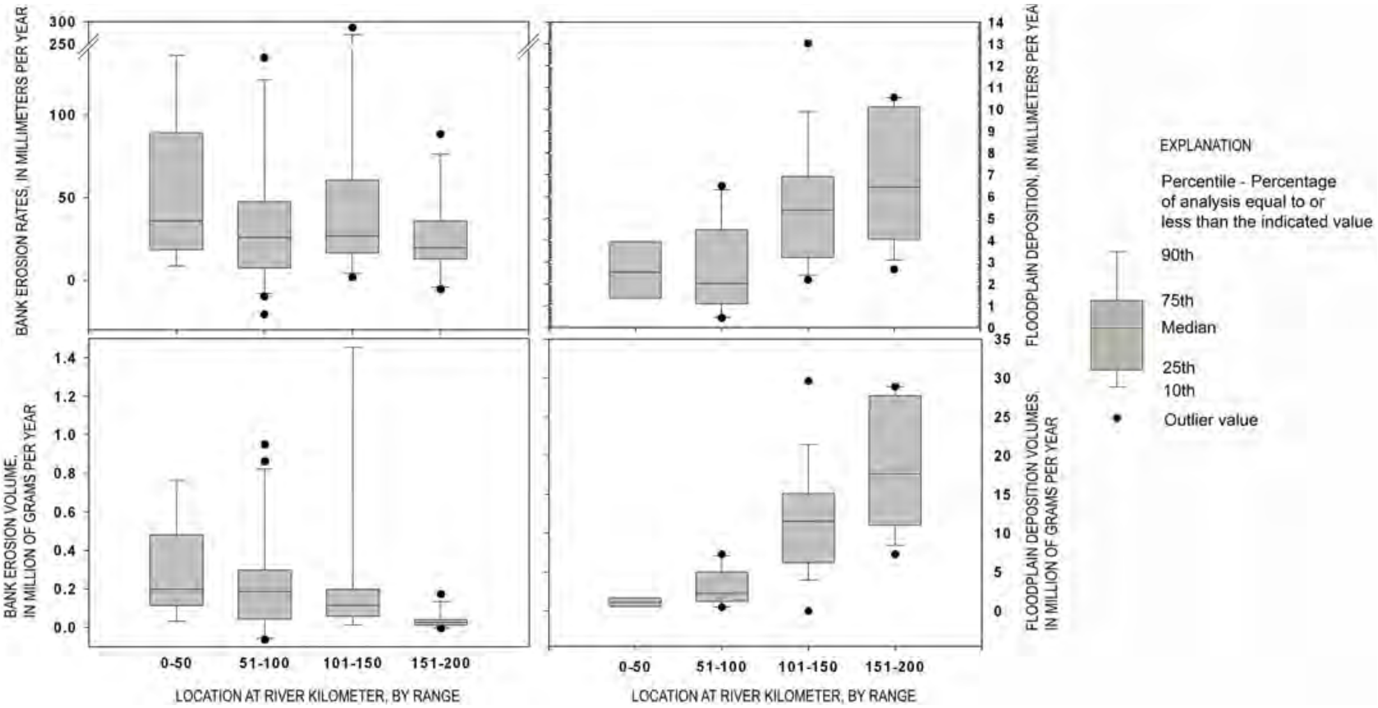

Figure 11. Trends in bank erosion and floodplain deposition rates and masses divided into 50-kilometer river reach segments from upstream to downstream. Note the inverse relation between bank erosion and floodplain deposition, particularly as revealed in mass estimates.

diminish toward the downstream transects. Mean erosion by transect ranged from near 0 to 383 mm/yr in the middle reaches. 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). This middle part of the study area also demonstrates higher flow elevations and durations for low-flow conditions than most non-regulated streams. These hydrologic conditions may, in part, affect the actively eroding nature of the middle reach. The upper reach has a wider channel (not the typical trend on alluvial rivers) and higher banks than downstream. The upper reach presumably began eroding soon after dam completion and presently the impetus for erosion has lessened locally and migrated downstream to the middle reaches; old though relatively stable remnants of slump blocks are still evident on upper reach banks.

Water released from high dams is typically nearly devoid of suspended sediment. This sediment "starved" nature of dam releases is conducive to entrainment of sediment from channel beds and banks. The mid channel water in the lower Roanoke River increases in turbidity from near the dam toward the Albemarle Sound downstream; there are no significant tributaries that join the river along the study reach. Thus, this suspended sediment must come from the channel bed and banks; previous studies and our results indicate that bank erosion may provide the greatest share of the suspended sediment load on the lower Roanoke River. The estimated sediment budget for the lower Roanoke River is net depositional. Much

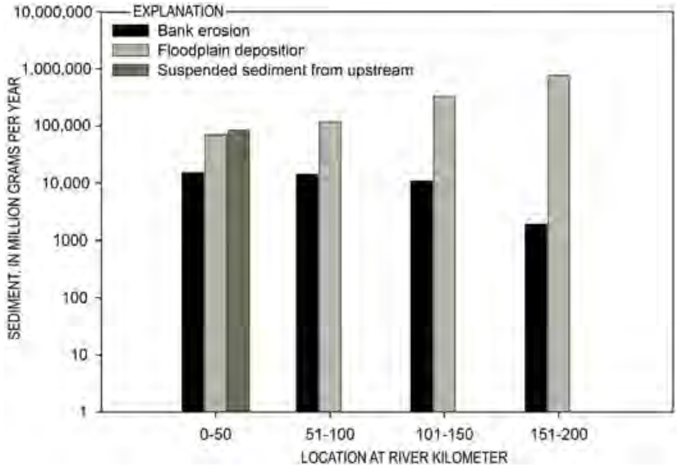

Figure 12. Total observed bank erosion and floodplain deposition by 50-kilometer river segment. Included in the figure is an annual suspended sediment yield estimate derived from mean suspended sediment loads measured by the U.S. Geological Survey North Carolina Water Science Center between 1980 and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

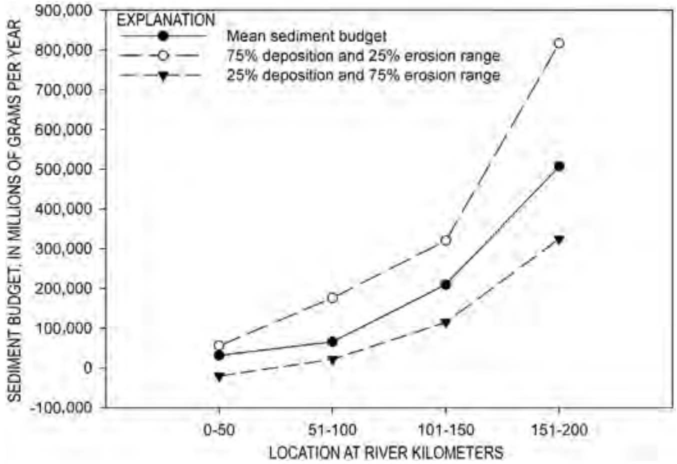

Figure 13. Bank erosion and floodplain deposition sediment budget by sequential 50-kilometer river reach segments, upstream to downstream. Where the line plots below zero, more material is eroded from banks than is deposited on floodplains. The 25 and 75 percentile ranges for erosion and deposition are 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.

of this surplus may be explained by the amount of sediment contributed by mass wasting on the banks, which, to date, is substantially under represented in the present transect monitoring effort. This suggests that mass wasting may play an important role here and elsewhere in sediment budgets below dams. Further interpretation of these data, minus the 2008 measurements, can be found in GSA Special Paper 451 (Hupp and others, 2009).

References Cited

Brandt, S.A., 2000, Classification of geomorphological effects downstream of dams: Catena, v. 40, no. 4, August, p. 375–401.

Bravard, J.-P., Amoros, Claude, Pautou, Guy, Bornette, Gudrun, Bournaud, Michel, Creuzé des Châtelliers, Michel, Gibert, Jeanine, Piery, J.-L., Perrin J.-F., and Tachet, Henri, 1997, River incision in south-east France—Morphological phenomena and ecological effects: Regulated Rivers—Research and Management, v. 13, no. 1, p. 75–90.

Brown, P.M., Miller, J.A., and Swain, F.M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic coastal plain, North Carolina to New York: U.S. Geological Survey Professional Paper 796, 79 p.

Church, Michael, 1995, Geomorphic response to river flow regulation—Case studies and time-scale: Regulated Rivers—Research and Management, v. 11, no. 1, p. 3–22.

Friedman, J.M., Osterkamp, W.R., Scott, M.L., and Auble, G.T., 1998, Downstream effects of dams on channel geometry and bottomland vegetation: regional patterns in the Great Plains: Wetlands, v. 18, p. 619–633.

Hupp, C.R., 1999, Incised channels and riparian vegetation, form and process, *in* Darby, S.E., and Simon, Andrew, eds., Incised river channels—Processes, forms, engineering, and management: Chichester, United Kingdom, Wiley, p. 219–245.

Hupp, C.R., 2000, Hydrology, geomorphology, and vegetation of coastal plain rivers in the southeastern United States: Hydrological Processes, v. 14, nos. 16–17, p. 2991–3010.

Hupp, C.R., Schenk, E.R., Richter, J.M, Peet, R.K, and Townsend, P.A., 2009, Bank erosion along the dam-regulated lower Roanoke River, North Carolina, *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., Management and restoration of fluvial systems with broad historical changes and human impacts: Geological Society of America Special Paper 451, p. 97–108.

Kleiss, B.A., 1996, Sediment retention in a bottomland hardwood wetland in eastern Arkansas: Wetlands, v. 16, no. 3, p. 321–333.

Kondolf, G.M., Piégay, H., and Landon, N., 2002, Channel response to increased and decreased bedload supply from land use change—Contrasts between two catchments: Geomorphology, v. 45, nos. 1–2, June, p. 35–51.

Lawson, J.M., 1925, Effect of Rio Grande storage on river erosion and deposition: Engineering News-Record, September, v. 95, p. 327–334.

Ligon, F.K., Dietrich, W.E., and Trush, W.J., 1995, Downstream ecological effects of dams: Bioscience, v. 45, no. 3, March, p. 183–192.

Madej, M.A., Weaver, W.E., and Hagans, D.K., 1994, Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA: Environmental Management, v. 18, no. 2, March, p. 235–250.

Merritt, D.M., and Cooper, D.J., 2000, Riparian vegetation and channel change in response to river regulation—A comparative study of regulated and unregulated streams in the Green River Basin, USA: Regulated Rivers—Research and Management, v. 16, no. 6, p. 543–564.

Nilsson, Christer, Reidy, C.A., Dynesius, Mats, and Revenga, Carmen, 2005, Fragmentation and flow regulation of the world's large river systems: Science, v. 308, April 15, p. 405–408.

Petts, G.E., 1979, Complex response of river channel morphology subsequent to reservoir construction: Progress in Physical Geography, v. 3, p. 329–362.

Petts, G.E., and Gurnell, A.M., 2005, Dams and geomorphology—Research progress and future directions: Geomorphology, v. 71, nos. 1–2, October, p. 27–47.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C., 1997, The natural flow regime: Bioscience, v. 47, no. 11, December, p. 769–784.

Richter, B.D., Baumgartner, J.V., Powell, Jennifer, and Braun, D.P., 1996, A method for assessing hydrologic alteration within ecosystems: Conservation Biology, v. 10, no. 4, August, p. 1163–1174.

Simon, Andrew, and Hupp, C.R., 1992 , Geomorphic and vegetative recovery processes along modified stream channels of west Tennessee: U.S. Geological Survey Open-File Report 91–502, 142 p.

Simon, Andrew, and Rinaldi, Massimo, 2000, Channel instability in the loess area of the midwestern United States: Journal of the American Water Resources Association, v. 36, no. 1, p. 133–150.

Thorne, C.R., and Abt, S.R., 1993, Analysis of riverbank instability due to toe scour and lateral erosion: Earth Surface Processes and Landforms, v. 18, no. 9, p. 835–844.

Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p.

Appendix 1.—Summary of Bank Transect Locations, Number of Erosion Pins per Transect, Bank Erosion Index Values, Mean Bank Height, and Erosion Rates

Appendix 2.—Erosion Pin Measurements for Each of the 701 Bank Erosion Pins

Appendix 3.—Cross-Sectional Survey Data by Transect, Including Bathymetry

Appendix 4.—Bathymetric, Water Clarity, and Mass Wasting Data Collected on an Approximately 200-Kilometer River Survey from Near Halifax, N.C., to the Alblemarle Sound

Appendix 5.—Mean Floodplain Sedimentation from 2002 to 2005 Measured Using Feldspar Clay Pads on Transects Perpendicular to Channel

Appendix 6.—Stage-Discharge Relationships at Selected USGS Streamgages, River Stage Information Between Pin Measurement Dates, and Pin Bank Erosion Rates Related to River Stage and Date