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Bank erosion along the dam-regulated lower Roanoke River, North Carolina

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ABSTRACT

Dam construction and its impact on downstream fluvial processes may substantially alter ambient bank stability and erosion. Three high dams (completed between 1953 and 1963) were built 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, >700 bank-erosion pins were installed along 66 bank transects. Additionally, discrete measurements of channel bathymetry, turbidity, and presence or absence of mass wasting were documented along the entire study reach (153 km). A bank-erosion–floodplain-deposition sediment budget was estimated for the lower river. Bank toe erosion related to consistently high low-flow stages may play a large role in increased mid- and upper-bank erosion. Present bank-erosion rates are relatively high and are greatest along the middle reaches (mean 63 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 turbidity also peak along the middle reaches; floodplain sedimentation systematically increases downstream in the study reach. The lower Roanoke River is net depositional (on floodplain) with a surplus of ~2,800,000 m^3/yr. Results suggest that unmeasured erosion, particularly mass wasting, may partly explain this surplus and should be part of sediment budgets downstream of dams.

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INTRODUCTION

Over half of the world's largest river systems (172 of 292) have been moderately to strongly affected by dams (Nilsson et al., 2005). The downstream hydrogeomorphic effects of high dams have been documented for >80 yr (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). Flow regulation often dramatically alters the regime of alluvial rivers both 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; Grant et al., 2003). Channel narrowing downstream of dams is a common response along several streams in the western United States (Allred and Schmidt, 1999; Grant et al., 2003). However, along single threaded alluvial rivers without bedrock control or relatively coarse bed sediment, a 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. There are few models that allow for prediction of the downstream effects of dams and even less that include the geological setting as a central factor (Grant et al., 2003). A model of channel change following dam construction that includes geology, climate, sediment supply, topography, and hydrologic regime was developed by Grant et al. (2003) and quantitatively extended in the development of physical metrics (drivers) to predict sediment balances below dams by Schmidt and Wilcock (2008).

Few studies have documented, in detail, bank erosion along regulated Coastal Plain rivers (Ligon et al., 1995), and none to our knowledge have linked erosion with equally detailed floodplain sediment-deposition information. 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, which has operated as a power station since 1963, and farther downstream the smaller Roanoke Rapids Dam, which has operated as a power station since 1955; both of these dams are regulated by the Dominion Power Company. The ecological effects of these dams were investigated by Richter et al. (1996) for which they developed a series of biologically relevant hydrologic attributes that characterize intra-annual variation in flow conditions and used the lower Roanoke River as a case study. 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 high and particularly low flow pulses; this impact has been implicated in various forms of ecosystem degradation (Richter et al., 1996).

Evidence of bank erosion along the lower Roanoke River is common where bank heights (above mean water levels) are substantial (>2 m), particularly along middle reaches between the Fall Line and the Albemarle Sound (Figs. 1A, 1B). Evidence may take the form of particle-by-particle erosion along straight banks and cutbanks, with concave-upward profiles often leaving overhanging (undercut rootwads) trees and shrubs on the top of the 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 the present paper are, in general, to document, measure, and interpret bank erosion along the lower Roanoke River. Additional objectives include the quantitative description and interpretation of channel dynamics in relation to downstream trends in turbidity and floodplain trapping-storage of sediment. Specific research questions include: How do the current dam-flow releases affect bank-erosion patterns on the lower Roanoke River? Does sediment entrained from bank erosion affect downstream floodplain sediment deposition? Data used to complete these objectives and address these questions are derived, in part, from new specific analyses of bank erosion (the present study) and from previous studies by the U.S. Geological Survey (USGS) and others on floodplain sediment deposition.

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 15.8 °C and an average annual precipitation of 1267 mm as measured at Williamston, North Carolina, elev. 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 m^3 per second (cms) as measured at Roanoke Rapids, North Carolina (USGS streamflow gauge 02080500) below the downstream-most dam; daily mean discharges range from 23 to 1008 cms over the period of record (43 yr). Prior to dam construction, annual peak flows regularly ranged from ~1400 cms to 2800 cms with extreme events >3400 cms (Fig. 2). Over the present gauging-station record (since 1964) the maximum peak flow was 1055 cms with normal peak-flow maxima ~980 cms. Conversely, low flows are sustained at higher discharges than before dam construction, annual flows rarely are <220 cms, and most peaks are held at ~560 cms (Fig. 2). Water-stage information is recorded at six streamflow gauges along the lower river from Roanoke Rapids (also the discharge-measurement station) near the dam, and in downstream order, at Halifax, Scotland Neck, Hamilton, Williamston, and Jamesville, North Carolina, nearest the Albemarle Sound (Figs. 1A, 1B).

The lower reach of the 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 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, 2006, written commun.), which thins downstream to near zero near the Albemarle Sound. The river is generally incised through the legacy sediment and other Coastal Plain sediments; although erosion on cutbanks 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

Techniques for monitoring bank erosion along the lower Roanoke River are described in detail in this section. However, this report uses some information gained from other, prior studies on floodplain deposition; pertinent techniques from these efforts are summarized here.

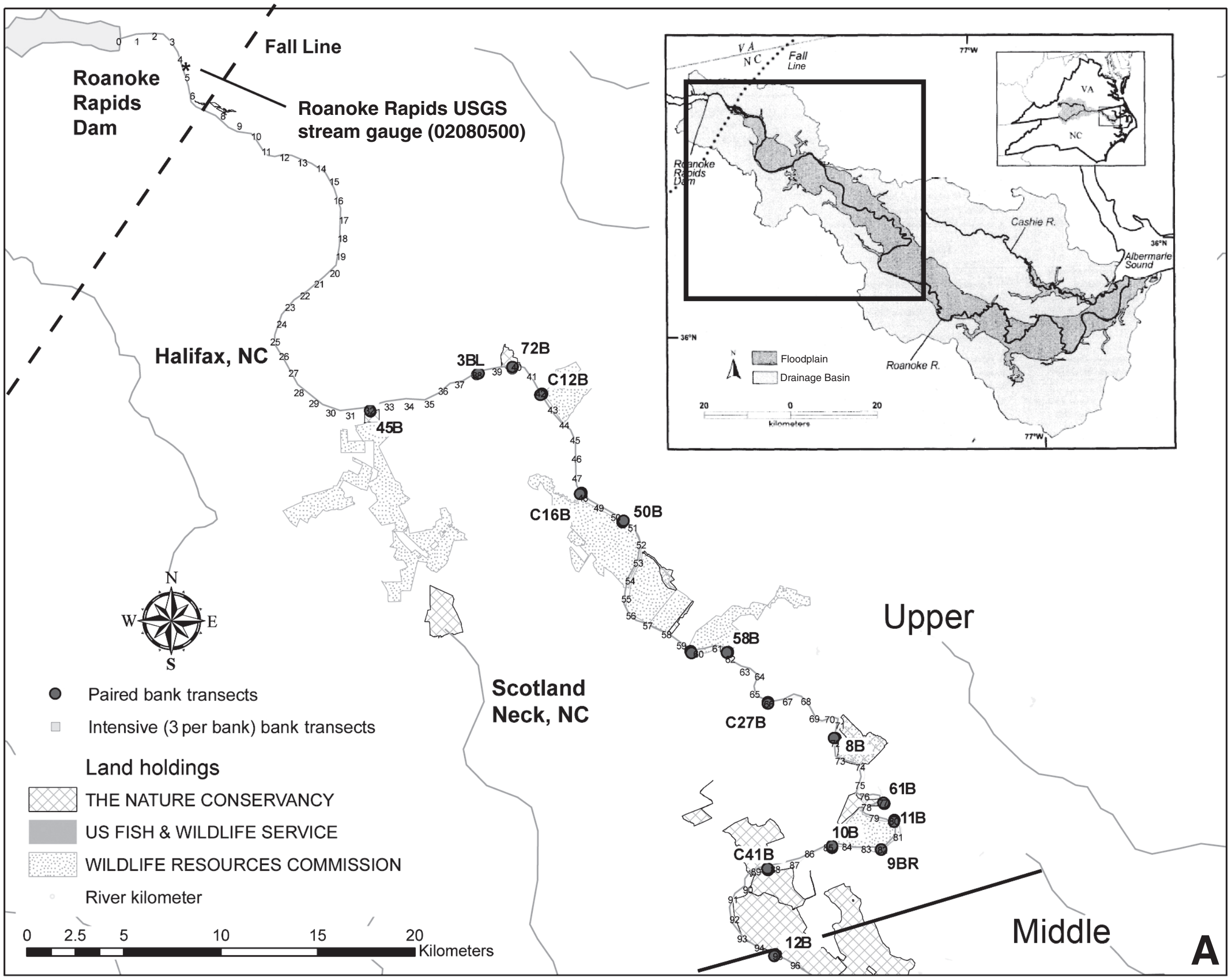

Figure 1 (*continued on following page*). (A) Map of the upstream part of the lower Roanoke River, North Carolina. Locations of paired transects, river kilometers below dam, and land holdings are indicated. Inset: maps of the entire lower Roanoke River reaches and the watershed in Virginia–North Carolina.

Transect Bank Erosion

Bank transects were established along a 153 km reach of the lower river, from upstream near the Fall Line to near the Albemarle Sound, where banks become <1 m high; 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. Whenever possible, transects were located near existing floodplain sedimentation transects to facilitate interpretation of process linkage between bank erosion and downstream floodplain deposition. We (USGS in cooperation with the U.S. Fish and Wildlife Service, USFWS) instrumented 66 transects 32 of which are in pairs on opposite sides of the river. Further, 36 additional transects (in 6 pairs with triplicate transects), originally established by the USFWS, were incorporated into the present study for a total of 102 transects. These transects begin near the water surface (low-water stages) and extend 3–10 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 NGVD 1929 datum. Transect locations were recorded on maps documented using global positioning system (GPS) technology (horizontal accuracy ~3.5 m).

Erosion pins (~1 m 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 or erosion along long, straight bank sections. Long transects (>25 m, high banks) typically had 7–10 pins established, whereas short transects, a few meters, had at least three pins. The pins were driven into the soil normal to

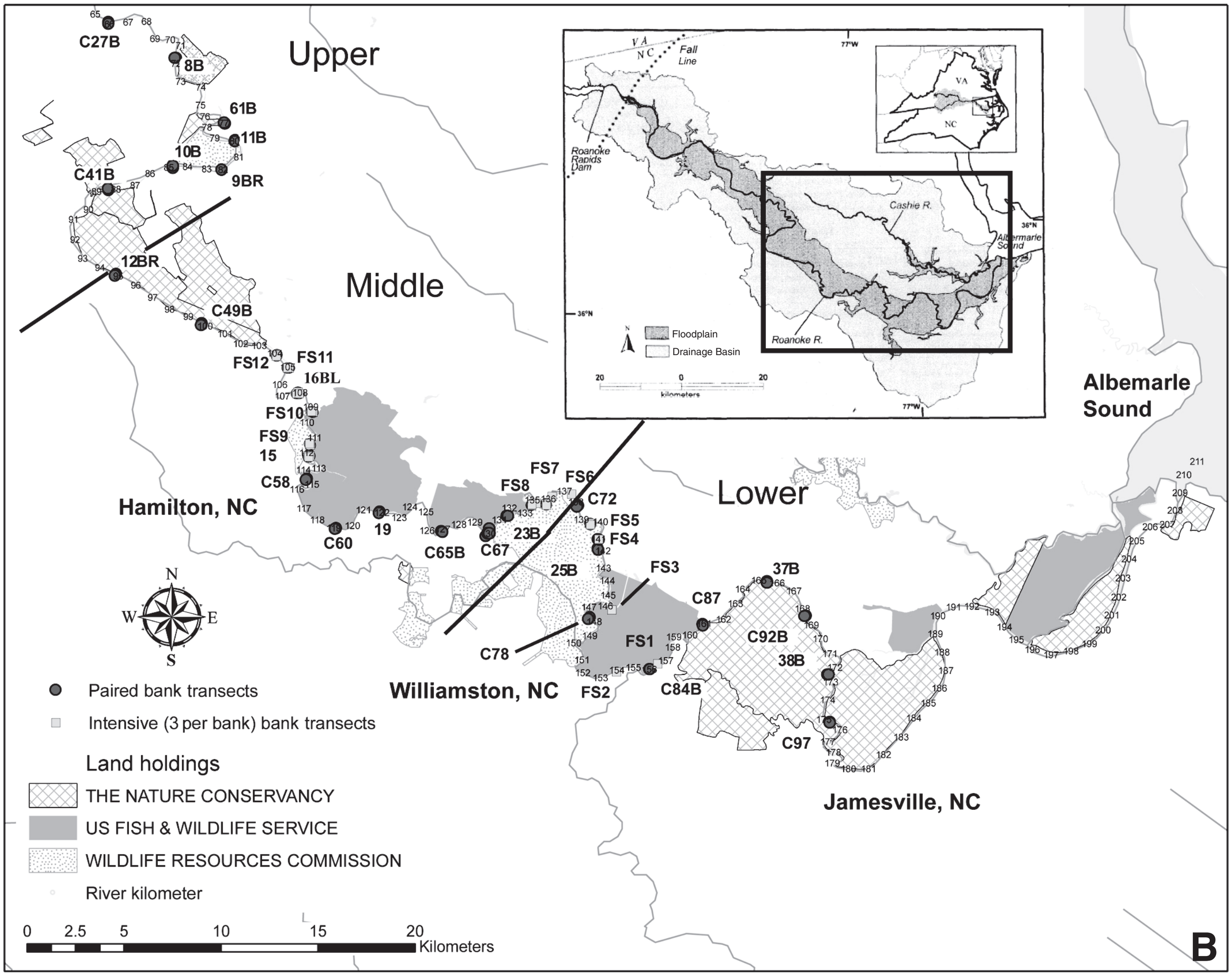

Figure 1 (*continued*). (B) Map of the downstream part of the lower Roanoke River, North Carolina. Features shown in Figure 1A are the same here, and the identification and delineation of upper, middle, and lower reaches/transects are shown.

the local bank slope, flush to the ground surface. In total, 706 pins were established for monitoring. The pins were revisited annually during the summers of 2006 and 2007; 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) that had taken place; 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. Every pin was specifically documented in the survey, and in addition to the temporary benchmark served to preserve horizontal stationing. All 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 ~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 range finder for horizontal station and a narrow-beam depth finder 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 range finder.

Channel Bathymetry, Turbidity, Mass Wasting

River surveys for channel bathymetry and bank-feature measurements were conducted as part of both the present study and the previous floodplain study. A series of observation points on the lower Roanoke River were established using GPS in 1998, mid-channel, from near the Fall Line downstream to and into the Albemarle Sound, covering a distance of ~200 river km (125 mi). Channel observation points are generally ~1.6 km (1 mi) apart. Depth, channel width, bank height, and bank angle were measured at each observation point using a laser range finder and a

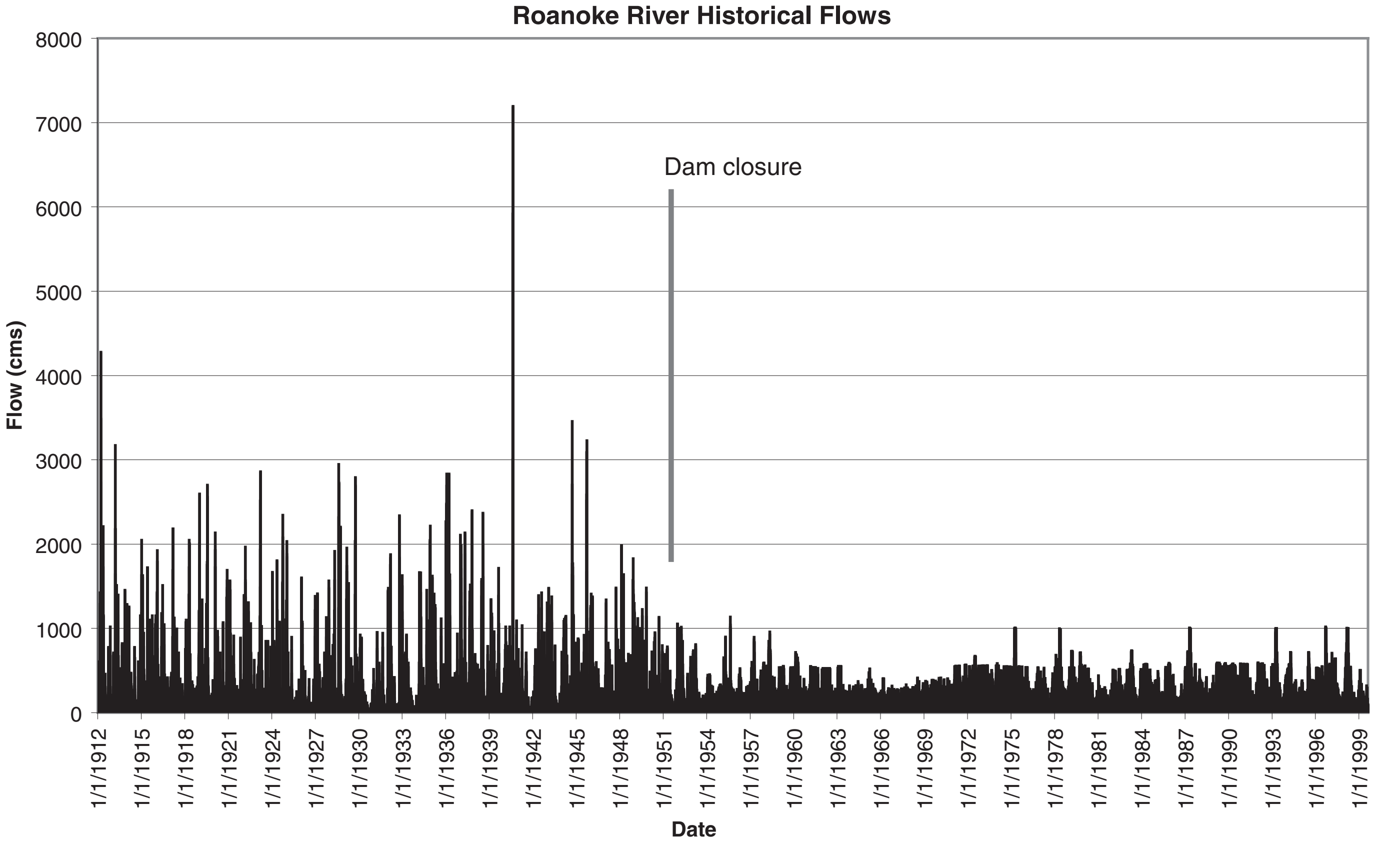

Figure 2. Daily flows in cubic meters per second (cms) (1912–1999) on the lower Roanoke River as measured at Roanoke Rapids, North Carolina, covering both pre- and post-dam operations. Date and effect of initial dam closure is shown.

sonic depth finder; a GPS unit was used to locate channel observation points. Each river survey was completed over a consecutive 2-day period. Water stage information was recorded for the observation period from the series of gauges 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. The most recent survey was conducted in the summer of 2007. This survey also included measurements of turbidity, as determined from Secchi depth, and estimates of bank erosion using an index based on observation of bank erosion.

A Secchi disk is a simple device that is commonly used to quantitatively measure turbidity. It is a 20 cm (8 in.) 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 turbidity 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 agreed at more than 90% of the sites evaluated; this index is presented in Table 1.

Sediment Deposition on Floodplains

Floodplain deposition along the lower Roanoke River was intensively monitored between 2001 and 2004 as part of a larger multidisciplinary effort. The primary method for determining recent deposition rates and patterns was the installation of artificial markers. These markers (clay pads) are made by placing powderized white feldspar clay on the floodplain soil surface, which becomes a firm plastic layer that can be easily identified after coring the soil surface. These clay pads are revisited after inundation, and the depth of sedimentation above the marker surface is measured; deposition may be measured several times over clay pads. Details of the technique are provided in Kleiss (1996) and Hupp et al. (2008). Clay pads were positioned along the entire lower river in floodplain transects that extended, locally, from the levee surface near the bank well into the backswamp; transects ranged in length from a few hundred meters to >2 km. A total of 50 transects were established, comprising 335 pads; the number of pads per transect ranged from 2 to 13 with a mean of 7 pads per transect. Many of the bank transects in the present study are located at or near the natural levee terminus of the floodplain transects.

RESULTS AND DISCUSSION

The results and discussion presented in this section are preliminary, as this study is ongoing. These results cover a 2 yr period of bank-erosion monitoring. Nevertheless, the available point, transect, reach, and ancillary information allow worthwhile analyses. The scope of this paper is limited to bank erosion as determined by erosion pins monitored in transects, and channel morphology,

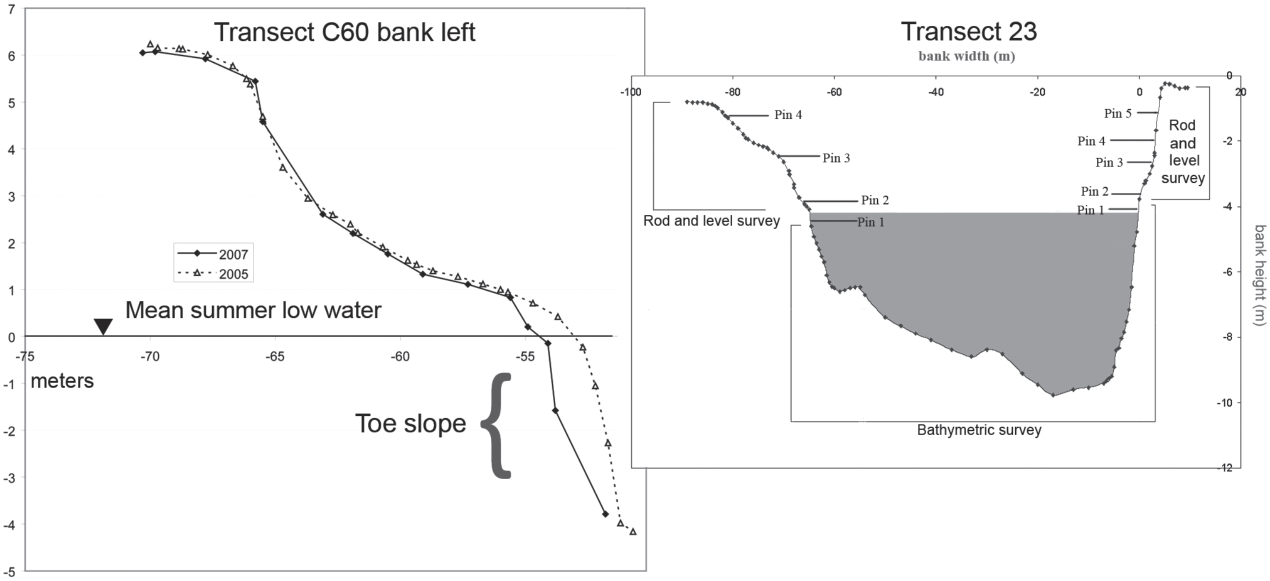

Figure 3. Cross sections of banks at transects 23 (entire) and C60 (left bank). Pin locations and survey methods are shown along transect 23; pins are driven into bank, flush to surface, typically at an oblique angle, normal to bank slope. Shaded part of cross section was surveyed below water surface 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 that the >1 m difference between surveys is largely on the lowermost part of the bank and toe slope.

TABLE 1. BANK-EROSION INDEX, USED ON 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; e.g., bank retreat) apparent on one bank, with 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 unweathered surface.
6	Recent primary mass wasting on both banks.

turbidity, and mass wasting measured from river bathymetric surveys. A preliminary bank-erosion–floodplain-deposition sediment budget (hereafter termed *sediment budget*) based on bank erosion and floodplain-sediment accretion (from a prior National Science Foundation [NSF] study) is also presented.

Bank Erosion

Net bank erosion (channel widening), by transect, was observed on 90 transects, while net deposition occurred on only 12 transects (Fig. 4). This erosion is greater than what would normally be expected on an equilibrated channel, and the literature is replete with examples of the destabilizing effects of dams on downstream reaches. In general, erosion rates increased from the upstream transects (mean 44 mm/yr) to those along the middle study reaches (mean 63 mm/yr), peaking in the vicinity of Hamilton (Fig. 1B), and then diminished (mean 24 mm/yr) toward the downstream transects (Table 2). Mean erosion by transect ranged from 520 mm/yr along a transect near Hamilton (Fig. 4) to nearly zero at many transects. To date, only one transect has captured a mass-wasting event; thus, these rates are conservative. Where there was net deposition, the transect was typically located on a point bar; the greatest mean deposition amount (99 mm/yr) occurred along the point bar directly opposite the cutbank with highest erosion (Fig. 4; near Hamilton). Bank-erosion rates were likely higher along upstream reaches (nearer the dam) immediately after dam closure. Total bank erosion tends to be greatest nearest the dam and attenuates downstream (Williams and Wolman, 1984). However, bank instability appears to migrate downstream (Fig. 4; Table 2), similar to upstream migrating instabilities associated with incised channels (Simon and Hupp, 1992). The upper bank slopes along the upper reaches of the study area are now relatively stable, but remnants of old slump failures are commonly visible. Bank-erosion rates on the Roanoke River (0.52 m/yr maximum) are similar to other published erosion rates (relatively rare in the literature) where human activities have affected natural channel processes. Madej et al. (1994) documented erosion rates of ~0.51 m/yr along a reach of the Merced River, California, that was severely impacted by concentrated human recreational development including bank armoring. Maximum channel widening rates of 1.1 m/yr were documented below a dam on the Green River, Colorado (Merritt and Cooper, 2000). However, where mass wasting was explicitly included in channel-widening estimates, Simon and Hupp (1992) observed mean erosion rates from slightly above 0 m/yr on unaffected reaches to ~1.7 m/yr on actively eroding banks along West Tennessee streams following channelization. Simon and Rinaldi (2000) estimated mean maximum channel-widening rates of >2.1 m/yr along low-cohesion banks, affected by mass wasting in the loess area of the Midwestern United States. Other land uses such as mining may also stimulate channel widening; Kondolf et al. (2002) observed widening rates of 1.7 m/yr along a mine-affected stream in Idaho.

Variation in lower Roanoke River erosion rates occurs among straight and curved (inside and outside banks) reaches.

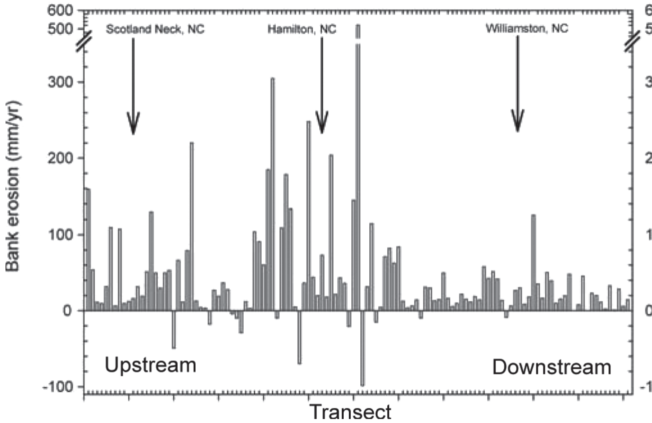

Figure 4. Mean bank-erosion rate on the lower Roanoke River from erosion-pin data from upstream (left) to downstream (right); left and right banks of each transect are shown separately. Observations-transects <0 are net depositional. Approximate locations of stream gauges near Scotland Neck, Hamilton, and Williamston, North Carolina, are shown.

TABLE 2. VARIATION BETWEEN UPPER AND LOWER BANK-EROSION RATES ALONG UPPER, MIDDLE, AND LOWER STUDY REACHES

	Mean bank-erosion rate (mm/yr)					
River (km)	Lower	Upper	Entire transect	Bank height (m)	Bank-erosion index	Mean channel width (m)
32–95	62.9	9.2	43.9	5.3	1	92.2
96–137	82.8	51.7	63.3	4.1	3	79.8
138–175	23.1	14.6	24.2	1.7	2	82.0

Note: Mean bank height, median bank-erosion index, and mean channel width for the three reaches are shown.

Mean erosion rates were greatest on the outside banks of curved reaches (~65 mm/yr), whereas straight and inside banks of curved reaches average ~40 mm/yr each. 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. Simon and Hupp (1992) documented similar trends among reach types but with order-of-magnitude greater erosion rates when mass wasting was included.

Substantial variation in bank erosion may occur between upper and lower bank segments. Bank erosion, where 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 an order of magnitude less than that of the lower banks (Table 2), suggesting, again, that the highest erosion rates have migrated downstream from the upper reaches and now occur along the middle reaches. A subset of transect sites evaluated by the USFWS (FS transects, n = 10, FS 5 and 7 not included, Fig. 1B) was composed of 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 erode more rapidly than upper banks, whereas along the lower reaches this trend is reversed, albeit less pronounced (Fig. 5). Transect erosion-rate variation (at these intensely monitored sites, FS transects) is distinctly higher on the unstable middle reach than at sites on the lower, more stable reach (Fig. 5). This is perhaps expected, given the vagaries of thalweg impingement and the tendency for secondary bank failures to occur. Secondary bank failure is the collapse of previously failed material from high on the bank slope, which temporarily accumulates low on the bank slope (Simon and Hupp, 1992). Overall bank stability is strongly controlled by low bank erosion, including the toe slope, which is typically under water (Thorne and Abt, 1993; Simon et al., 2000); severely eroded toe slopes often lead to bank failure through mass wasting (Simon and Hupp, 1992). 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. Thus, the widespread observation of mass wasting in the form of slump blocks (yet to be significantly documented in erosion-pin transects) is expected particularly along the active middle study reaches (Figs. 4, 5).

Flow Duration, Mass Wasting, and Turbidity

It may be intuitively obvious that the elevation of flow and the duration of flow at various elevations are prime factors that affect most forms of bank erosion. Yet the development of quantitative causative linkage is difficult and not well documented, partly because the analytical and monitoring constraints during flow events are not normally conducive to real-time measurement (Simon et al., 2000). The stage-only gauge near Hamilton is located centrally in the middle study reaches where bank erosion is presently most active (Fig. 1B). The stage (elevation) and flow-duration relation, as measured by percentage of exceedance (percentage of time flow is at or above a specific elevation), is shown in Figure 6. The percentage of exceedance on most nonregulated streams for mid-bank elevations is in the range of 10%–20% (Osterkamp and Hedman, 1982). However, dam-regulated streams typically maintain abnormally high mid- and low-flow conditions (Williams and Wolman, 1984; Richter et al., 1996). Mid-bank locations along the Roanoke River in the vicinity of Hamilton (Fig. 1) have nearly 50% flow durations (Fig. 6), which are about double that which would be expected along nonregulated streams. Bank elevations distinctly above the low-flow elevation may be inundated 70% of the time or greater. Consistently

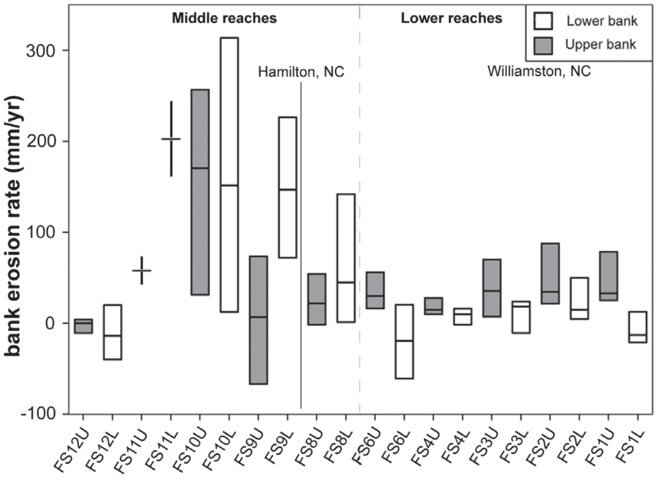

Figure 5. Mean bank erosion rate and variation at selected (triplicate) transect locations along middle and lower reaches of the lower Roanoke River. Location of separation between middle and lower reaches is shown in Figure 1B.

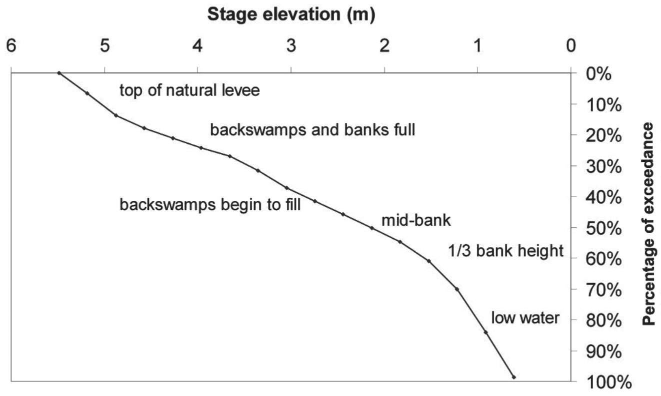

Figure 6. Stage elevation and percentage of exceedance (stage duration) for reaches near the Hamilton, North Carolina, stream-stage gauge (all data from post-dam period). Percentage of exceedance is the amount of time annually that water-surface elevation is at or above a specific location (elevation) on bank.

high low-flow elevations with associated long flow durations are cited as major contributors to channel widening through bank erosion on dam-regulated rivers (Williams and Wolman, 1984; Bravard et al., 1997; Friedman et al., 1998; Brandt, 2000).

Mass wasting, as measured by our bank-erosion index (Table 1), increased from the upper reaches to the middle reaches, where it peaked at 3 (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 ~30 to 175 km below the dam they also show the distinct trend of peaking along the middle reaches (Fig. 7). This trend is generally mirrored by mean transect-pin data plotted at actual transect locations (Fig. 7). Both the bank-erosion index and pin data indicate a relatively stable reach in the vicinity of ~90 km below the dam (Fig. 7), which coincides with a reach where the channel is atypically incised into the indurated Miocene substrata. Median maximum bank-erosion-index values range between 4 and 5 (Fig. 7) over about a 24 km reach beginning just below Hamilton (river km 115, Fig. 1B), indicating that evidence of bank failure occurs along both banks and that many locations have recent (<1-yr-old) slumps. The channel-widening response to dams (Williams and Wolman, 1984) or stream channelization (Simon and Hupp, 1992) is accomplished most effectively through mass wasting. This instability migrates and attenuates, in the case of dam construction, downstream (Williams and Wolman, 1984), which from our data appears to be the case on the lower Roanoke River. Channel-width measurements, taken during river surveys, demonstrate that channel width decreases from upstream (near the dam) to the relatively narrow middle reaches and then increases toward the Albemarle Sound (Table 2). The increase in width near tidal water is typical for Coastal Plain streams (Hupp, 2000; Kroes et al., 2007). However, the downstream decrease in width, observed in the upper reaches of the lower Roanoke River, may be anomalous for alluvial systems. This trend in channel width supports the idea that channel widening was most active along the upper reaches fairly soon after dam closure and has since moved downstream, leaving a widened channel and high but relatively stable banks behind. Mass wasting eventually reduces bank angles so that relative stability may be attained (Simon and Hupp, 1992).

Turbidity, as measured by Secchi depths taken during the 2007 river survey, increased (low Secchi depth) from near the dam toward the actively eroding middle reaches (Fig. 7). Turbidity

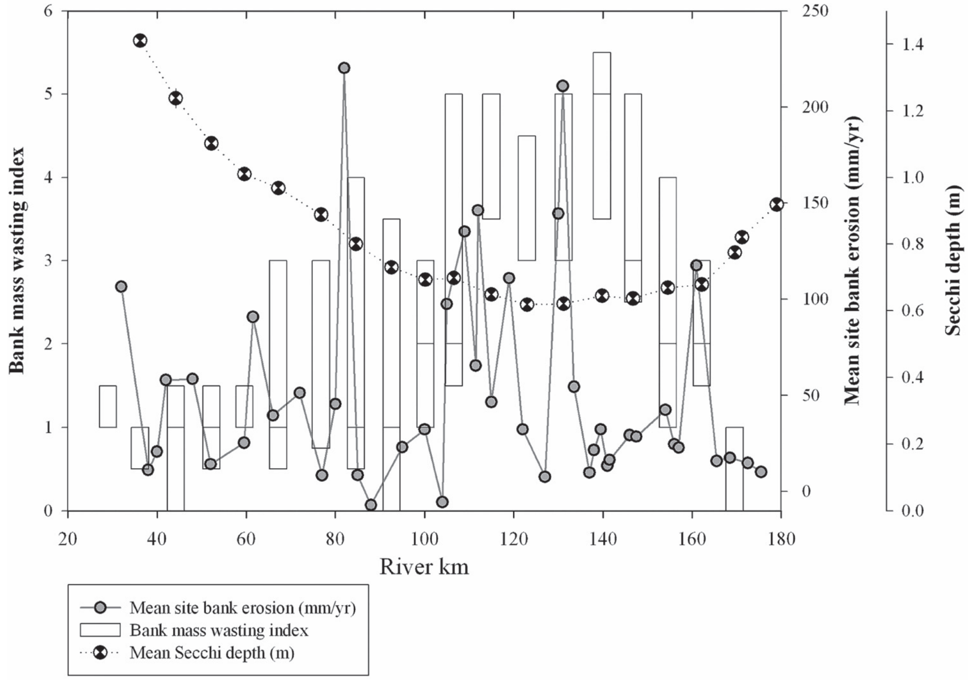

Figure 7. Trends in mean bank erosion, bank-erosion index, and turbidity (Secchi depth) from upstream to downstream by river kilometer. Mean bank erosion is obtained directly from transect-pin data; bank-erosion index and turbidity are averages over sequential river segments, ~8 km each.

decreased slightly in the lowest reaches near brackish tidal water (Fig. 7), as is typical along Coastal Plain rivers (Hupp, 2000). This trend in Secchi depth is expectedly and clearly inversely related to both bank erosion (pin measurements) and mass wasting (Fig. 7). 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 tributaries or from erosion and entrainment of bed and bank sediments. There are no substantial tributaries entering the Roanoke River between the dam and our downstream-most bank-erosion sites. It is reasonable to assume that a direct relation exists between turbidity and channel erosion (Fig. 7), most of which may be derived from the banks as noted in similar situations by Simon and Hupp (1992). Additionally, variation in flow velocity associated with power generation (peaking) may facilitate bank erosion, especially particle-by-particle entrainment, which also may lead to bank-toe removal and subsequent bank failure.

The early results of this study offer an example of channel widening that occurs in response to upstream dams. This response is different from the response demonstrated along several streams in the western United States where substantial channel narrowing has occurred (Allred and Schmidt, 1999; Grant et al., 2003). The Coastal Plain geologic setting may in large part explain these divergent results. The highly erodible beds and banks of these almost completely alluvial systems allow for rapid erosion following dam completion (Williams and Wolman, 1984; Ligon et al., 1995). The channel incision associated with this erosion increases effective bank heights, which lead to bank failure and ultimately channel widening (Simon and Hupp, 1992; Simon et al., 2000).

Sediment Budget

A sediment budget was estimated for the lower river by separating the study site into four 50-km-long river segments beginning just below the dam and continuing downstream. Bank-erosion rates were converted to volumes by assigning each transect a width of 1 m and multiplying the bank height by the erosion rate; 9, 22, 17, and 11 bank transects were used in each segment, respectively, downstream. Bank heights decrease from nearly 7 m near the upstream transects to <1 m 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.

The floodplain-deposition volume (based on clay pads in transects and floodplain length from the NSF study) and bank-erosion approximations were made for each segment using mean clay-pad and erosion-pin rate data (Fig. 8); 8, 10, 17, and 13 floodplain transects were used in each segment, respectively, downstream. Floodplain areas were determined using USGS topographic maps (contour interval, 1.53 m, 5 ft), whereas bank heights were directly surveyed at transect sites. The conversion from erosion-deposition rates to volumes (m^3/yr) more clearly illustrates the inverse downstream relation between bank erosion and, particularly, floodplain deposition (Fig. 8) and provides for a more realistic framework for establishing a sediment budget. From the forgoing discussions, it is assumed that upstream bank erosion on the mainstem largely provides the material for downstream floodplain deposition.

The sediment budget was developed using the mean bank-erosion and floodplain-deposition volumes (Fig. 8) and multiplied by the 50 km segment length. The organic proportion of deposited sediment was calculated using loss on ignition (LOI) methods on 72 samples collected in 2002. The organic portion of the deposition estimate (16.5%) was subtracted to allow the comparison between mineral soil loss on the bank and mineral soil accumulation on the floodplain; most bank material was derived from massive postcolonial deposition and presently contains little to no organic material (P. Townsend, 2007, written commun.). The lower Roanoke River system is net depositional. Deposition exceeds erosion increasingly from near the dam toward the Albemarle Sound (Fig. 9). The sediment budget predicts a surplus of 2,800,000 m^3/yr, assuming that (1) measured floodplain-sedimentation rates can be applied equally across broad bottomlands, (2) sediment transport from upstream of the dam is negligible, and (3) bank pins and floodplain clay pads reflect all of the erosion and deposition within the system. The sediment surplus may be partly explained by the numerous mass-wasting events that have not been sufficiently documented by the bank-erosion pins. Some of this sediment may be transported out of the system, but many studies (e.g., Meade, 1982) have shown that as much 90% of suspended sediment is trapped within the system.

Only one transect of 106 in 2 yr of monitoring captured a primary mass-wasting event (T23BR), 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). Mass wasting appears to play a substantial role in bank erosion along this regulated river, may account for the large floodplain-deposition volumes downstream, and should be taken into account for realistic sediment budget computation.

CONCLUSIONS

The lower Roanoke River has undergone 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 cutbanks and straight and inside bend reaches, where 77% of transects (90) underwent erosion. Bank-erosion rates increased from the upstream transects to those along the middle study reaches and then diminished toward the downstream transects. Mean erosion by transect ranged from near zero to 520 mm/yr in the middle reaches. Both erosion by largely particle-by-particle removal and mass wasting presently peak in the middle reaches (95–137 river km below the dam). This middle part of the study area also demonstrates higher

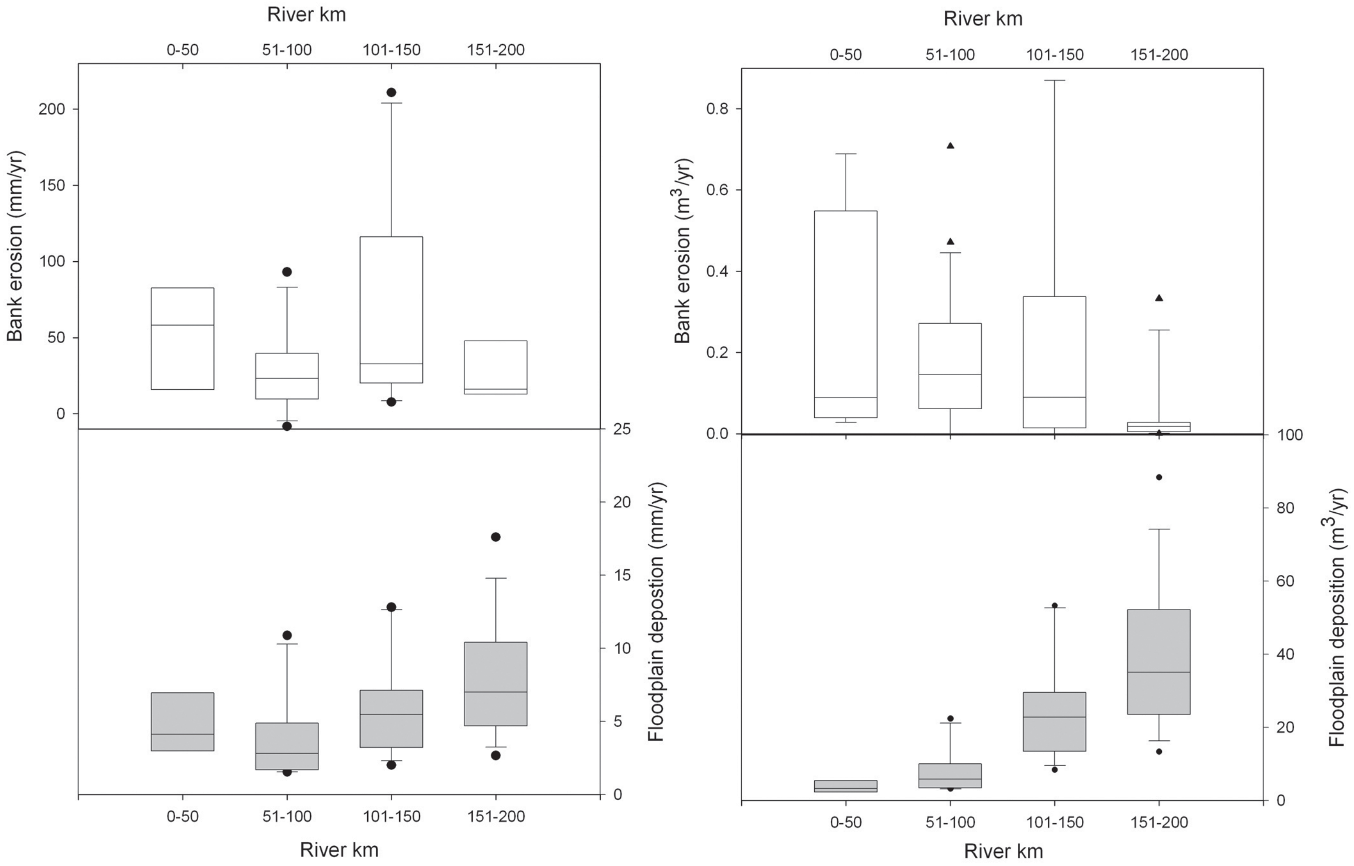

Figure 8. Trends in bank-erosion and floodplain-deposition rates, left panel, and volumes, right panel, divided by 50-km river-reach segments from upstream to downstream. Note the inverse relation between bank erosion and floodplain deposition, particularly as revealed in volume estimates.

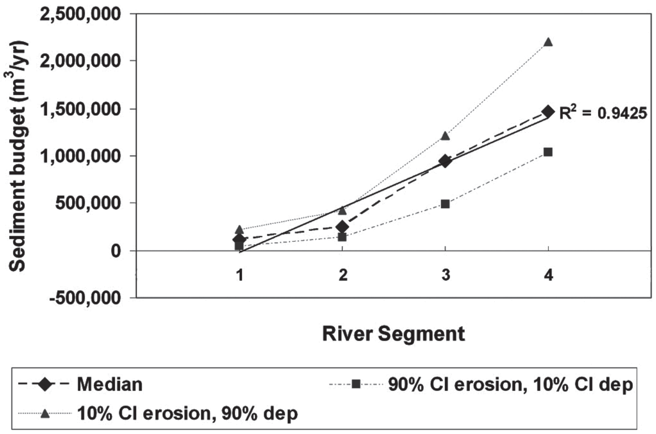

Figure 9. Bank-erosion–floodplain-deposition sediment budget by sequential 50-km river-reach segments, upstream to downstream (see Fig. 8), including calculations based on the erosion and deposition volumes of 10% and 90% confidence intervals (CI); dep—deposition.

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, which is conducive to bank toe removal and, thus, bank failure. Rotational failures are common and indicative of deep-seated bank instability. 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; no significant tributaries 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 (floodplain) with a surplus of ~2,800,000 m^3/yr. Much 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.

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