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FLOODPLAIN GEOMORPHIC PROCESSES AND ENVIRONMENTAL IMPACTS OF HUMAN ALTERATION ALONG COASTAL PLAIN RIVERS, USA

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Abstract: Human alterations along stream channels and within catchments have affected fluvial geomorphic processes worldwide. Typically these alterations reduce the ecosystem services that functioning floodplains provide; in this paper we are concerned with the sediment and associated material trapping service. Similarly, these alterations may negatively impact the natural ecology of floodplains through reductions in suitable habitats, biodiversity, and nutrient cycling. Dams, stream channelization, and levee/canal construction are common human alterations along Coastal Plain fluvial systems. We use three case studies to illustrate these alterations and their impacts on floodplain geomorphic and ecological processes. They include: 1) dams along the lower Roanoke River, North Carolina, 2) stream channelization in west Tennessee, and 3) multiple impacts including canal and artificial levee construction in the central Atchafalaya Basin, Louisiana. Human alterations typically shift affected streams away from natural dynamic equilibrium where net sediment deposition is, approximately, in balance with net erosion. Identification and understanding of critical fluvial parameters (e.g., stream gradient, grain-size, and hydrography) and spatial and temporal sediment deposition/erosion process trajectories should facilitate management efforts to retain and/or regain important ecosystem services.

Key Words: channelization, dams, ecosystem services, fluvial geomorphology, sediment

INTRODUCTION

Human alterations to the landscape such as flow regulation through dam construction, land clearance with upland erosion and downstream aggradation, stream channelization, and canal and levee construction (Figure 1) may lead to channel incision or filling and large changes in sediment supply conditions depending on the geomorphic setting. Most of the world's largest rivers have been dammed (Nilsson et al. 2005). The downstream impacts from dam construction that most affect the floodplain are typically severe reductions in the peak stages, frequency and duration of over bank flows, and sediment transport (Williams and Wolman 1984). Land clearance with upland erosion and downstream aggradation (legacy sedimentation dynamics, Jacobson and Coleman 1986, Pierce and King 2007a) has led to channel and valley filling and sometimes-subsequent channelization. Additionally, stream channelization has been a common, albeit controversial, practice along many rivers in parts of the Coastal Plain Physiographic Province of North America (Simon and Hupp 1992, Hupp and Bazemore 1993; hereafter referred to as "Coastal Plain) to reduce flooding and facilitate row-crop agriculture on floodplains; the impact on the riparian zone is a severe reduction in overbank flow. Levee construction, particularly along the Mississippi River and large tributaries and distributaries has occurred over a long period and has had profound impacts (Mossa 1996, Biedenharn et al. 2000) on streamflow and sedimentation dynamics. In general, all of the aforementioned alterations heavily impact the connectivity of the floodplain to sediment-laden flood flow, either by reductions in connectivity that compromise the trapping function of the ecosystem service or by anomalous connectivity increases that facilitate extreme sedimentation (Hupp et al. 2008). A spectacular analog to the Mississippi River where large sediment fluxes have developed in response to massive alterations is the Yellow River in China (Wang et al. 2005, Wang et al. 2007). The stream-floodplain flux of macro nutrients (N and P), organic material (C), trace elements, and other contaminants that are mediated through sediment dynamics (Figure 2) are likewise affected by these human

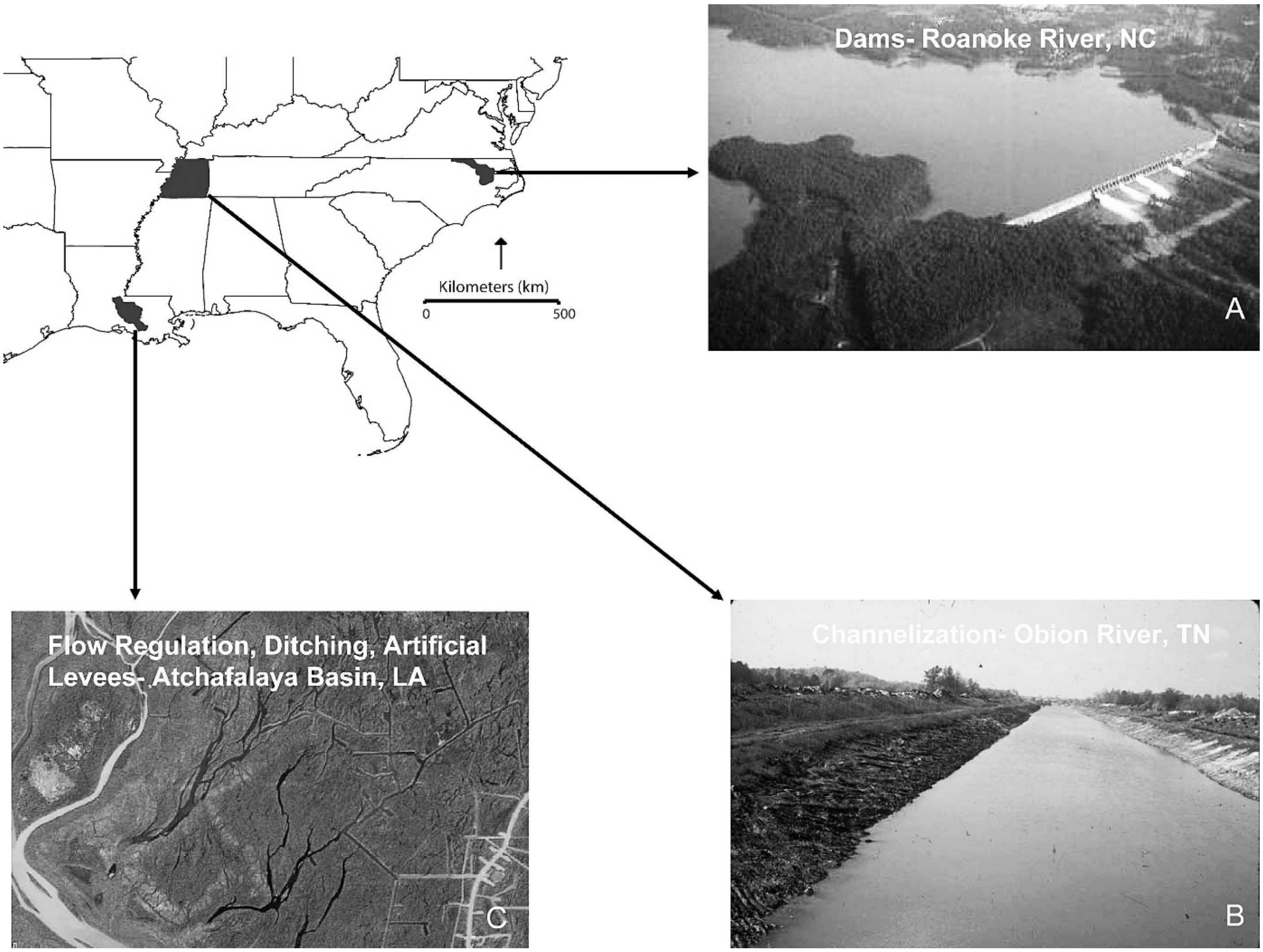

Figure 1. Location map of case studies and photographs of human alterations of stream channels in each. A) John Kerr dam and reservoir on the Roanoke River, North Carolina; B) channelized reach of the Obion River, West Tennessee soon after construction; and C) complex network of natural and constructed levees and channels, and concentrated ditching associated with oil and gas exploration and timber harvesting in the central Atchafalaya Basin, Louisiana. Photographs provided by the U.S. Army Corps of Engineers except for B, by C. Hupp.

alterations. Geomorphic analyses (Leopold et al. 1964, Jacobson and Coleman 1986, Noe and Hupp 2005, Hupp et al. 2008) verify that riparian retention of sediment and associated material is a common and important fluvial process, yet retention time of sediment (Malmon et al. 2005) and biogeochemical transformation during storage may be the most poorly understood, generally unquantified aspects of sediment, both mineral and organic, and associated material (e.g., macro nutrients) budgets (Hupp 2000). Coastal Plain floodplains are the last significant areas for sediment, nutrient, and carbon storage before reaching tidewater and critical estuarine ecosystems.

The purposes of our paper include the description of floodplain fluvial geomorphic responses to flow regulation from dams, valley aggradation and stream channelization, and levee and canal construction using, principally, the lower Roanoke River, NC, the west Tennessee Coastal Plain, and the Atchafalaya Basin, LA, respectively, as examples (Figure 1). We also hope to identify ecological and environmental implications associated with disruptions in the natural trapping function of these floodplains, which should facilitate modeling of these responses and lead toward more targeted management of these critical systems. We believe there are a few common, systematically linked parameters/concepts involved in the dynamic responses to human alterations, whose understanding may allow for an efficient approach to management. Three important unifying concepts may include 1) hydraulic connectivity between streamflow and the riparian zone (e.g., bars, bank, and floodplains), 2)

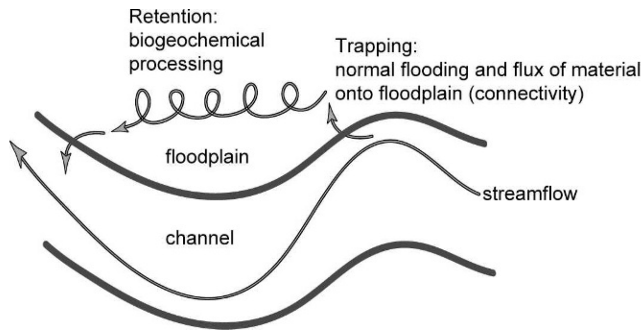

Figure 2. Plan view diagram of generalized floodplain ecosystem services associated with riparian retention along streams in equilibrium. From right to left, flux of material (sediment and associated contaminants) onto the floodplain during high-flow events, material deposition (trapping function/service), biogeochemical transformation during storage (contaminant amelioration function/service), and return of water (including processed material) to stream channel. Retention time of material is variable and poorly known.

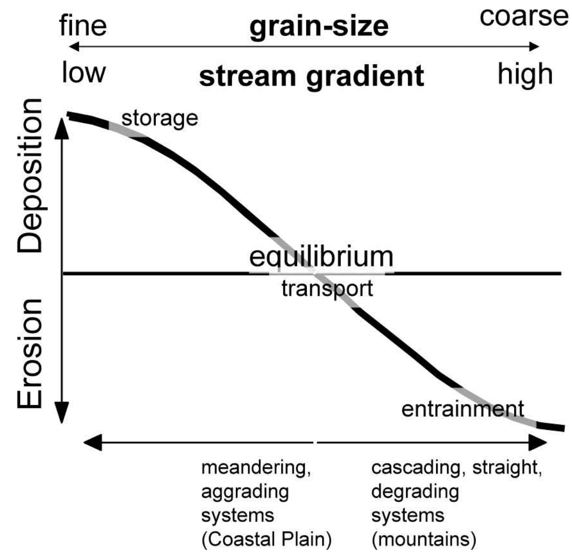

Figure 3. Conceptual gradient of erosion and deposition in relation to channel gradient, sediment grain-size, channel pattern, and general physiography. The equilibrium point represents conditions where there is no significant net deposition or erosion. Most stream systems in equilibrium lie on either side of (but near) this point within the equilibrium area (e.g., Coastal Plain streams lie slightly to the upper left and exhibit a predominance of meandering channels, mild aggradation, and fine-grained sediment load. Adapted from Hupp and Bornette (2003).

spatially migrating impetuses/thresholds for rapid geomorphic change (migrating channel knick-points), and perhaps most importantly 3) dynamic equilibrium in fluvial systems (Hack 1960). Dynamic equilibrium in geomorphology refers to the mutual adjustment of a catchment with its geologic underpinning and the streams that drain it such that a stream is capable of entraining, transporting, and storing the delivered sediment in fluvial landforms in a balanced fashion (typically no excessive net fluvial erosion or deposition, Figure 3). The concept of dynamic equilibrium offers a process-oriented explanation for dramatic responses to some human alterations and may also allow for prediction of the direction (erosion vs. deposition) and magnitude of the change. States of dynamic equilibrium with sustained characteristic fluvial landforms may occur on streams that maintain an erosional regime (e.g., steep mountain streams) or on streams that maintain a sediment-storage regime (e.g., most Coastal Plain streams) (Figure 3). Streams that are not in dynamic equilibrium have been subjected to dramatic, usually rapid, regime shifts; this may happen naturally (e.g., earthquakes) or through human alteration, the subject of this paper.

Floodplains are frequently flooded riparian features that occur at a great extent in the Coastal Plain (Hunt 1967), predominantly in southeastern United States. Floodplains in the context of this paper are inundated at least every one to about three years. Less frequently flooded alluvial features are likely terraces as defined in detail by Osterkamp and Hupp (1984). Coastal Plain floodplains typically are broad, alluvial features with low gradients that develop along meandering streams, many of which terminate downstream in tidal estuaries (Hupp 2000). Coastal Plain systems develop broad bottomlands including floodplains that may regularly flood every year for prolonged periods. In southeastern United States, these floodplains, in their natural state, are typically forested wetlands that support bottomland hardwood forests (Wharton et al. 1982, Sharitz and Mitsch 1993) along with attendant baldcypress/tupelo (*Taxodium distichum* (L.) Richard/*Nyssa aquatica* L.) swamps in the most hydric situations. Floodplains with substantial hydrologic connection to streamflow may trap (riparian retention, Figure 2) large amounts of sediment and associated nutrients and other contaminants (Brinson 1988, Hupp et al. 1993, 2008, Noe and Hupp 2005, in press). Unfortunately, these water quality functions of floodplains may be disrupted or compromised where there has been widespread alteration of fluvial processes by human activity, e.g., dam construction, channelization, and concentrated land use (Mitsch and Gosselink 1993, Sharitz and Mitsch 1993). The long-term impacts from the reduction of floodplain ecosystem services (e. g. sediment trapping) is poorly understood and perhaps also under appreciated.

CASE STUDIES

This paper will focus on case studies of geomorphic processes and sediment and associated material deposition in systems that have suffered dramatic hydrologic alteration, including dam construction, land use and stream channelization, and canal and levee construction. Fluvial geomorphic processes along Coastal Plain rivers in general (Hupp 2000) and forested wetland sediment deposition in particular (Hupp et al. 2008) have received relatively little comprehensive study until the last decade. In addition to new synthetic interpretation, material drawn from previous studies by the authors is used to assess the impacts of channelization, and dam and levee construction. See Simon and Hupp (1992), Hupp (1992), Hupp (2000), Noe and Hupp (2005), Pierce and King (2007a), Pierce and King (2008), Hupp and Noe (2006), and Hupp et al. (2008) for specific objectives, methodological detail, and other relevant literature.

Downstream Effects of Dams, Roanoke River, NC

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 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). Flow regulation often dramatically alters the regime of alluvial rivers through both confined water release scenarios that reduce the frequency and magnitude of high discharge events (Richter et al. 1996) 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). 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 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. Floodplains along dam-regulated rivers are typically flooded much less frequently than non-regulated rivers.

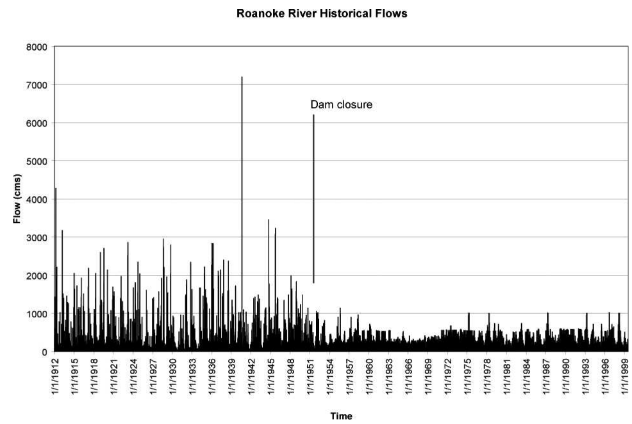

Figure 4. Historical mean daily flows (cms – cubic meters per second) on the regulated lower Roanoke River at the Roanoke Rapids gage (USGS streamflow gage 02080500) from 1912 to 1999. Reduction in peak flow discharge is obvious since about 1950 when the first high dam was completed.

The lower, Coastal Plain, reach of the Roanoke River flows eastward as a largely single threaded meandering stream from near the Fall Line to the Albemarle Sound across Miocene sedimentary material overlain by Quaternary alluvium (Brown et al. 1972). The floodplain along the lower river supports the largest contiguous bottomland hardwood forest on the Atlantic Coastal Plain (Hupp 2000). 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 (Hupp et al. in press), 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 cut banks and many straight reaches appears active, there is limited point-bar development.

Few studies have documented, in detail, bank erosion along regulated Coastal Plain rivers (Ligon et al. 1995) and likely none have linked erosion with equally detailed floodplain sediment deposition information (Hupp et al, in press). 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 (Figure 1A), which controls major water discharges downstream. Two smaller hydroelectric dams are located downstream of the Kerr Reservoir. Flood-control operations on the Roanoke River have had large hydrologic impacts including the elimination of high-magnitude flooding (Figure 4) and a greater frequency of both moderate and particularly low

Figure 5. A) Eroding bank on the lower Roanoke River. Particle-by-particle erosion is evident, note overhanging vegetation near the top of bank in middle ground. B) Large bank failure (mass wasting) on the lower Roanoke River; man is standing on slump block for scale. Photographs by C. Hupp.

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 meters) (Figure 5), particularly along middle reaches between the Fall Line and the Albemarle Sound (Figure 6). Current bank erosion rates are likely a complex response to both recent dam construction and legacy floodplain sedimentation from post-settlement agriculture on the Piedmont. Net bank erosion (channel widening as measured by erosion pins), by transect, was observed on 90 transects positioned along the river, while net deposition occurred on only 12 transects (Hupp et al. in press). This accelerated erosion exceeds that normally expected on an equilibrated channel; the literature is replete with examples of the de-stabilizing effects of dams on channel geomorphology in downstream reaches (Grant et al. 2003). In general, erosion rates increased from the upstream reaches to the middle reaches, and then diminished toward the downstream reaches (Figure 6). Evidence of erosion may take the form of particle-by-particle erosion along straight and cut banks with concave upward profiles often leaving overhanging (undercut root wads) trees and shrubs (Figure 5A), 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 (Figure 5B; Hupp 1999). This material is subsequently entrained by flow and may form a large portion of the suspended sediment load that can be deposited (in this case, on the floodplain) downstream. Mass wasting, based on a bank erosion index (Hupp et al. in press) also peaked in the middle reaches (Figure 6); mass wasting is commonly not included in erosion estimates.

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 (Figure 6). Clarity increased slightly in the lowest reaches near brackish tidal water (Figure 6) as is typical along Coastal Plain rivers (Hupp 2000). This trend in Secchi depth is expectedly and inversely related to bank erosion, which should increase turbidity (Figure 6). 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 bank erosion sites downstream. Thus, it is reasonable to assume that there is a direct relation between increased turbidity and active channel erosion (Figure 6). Most of the sediment input may be derived from the banks (Simon and Hupp 1992). 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).

The floodplain trapping of suspended sediment in forested riparian wetlands is an important water-quality function. The floodplain along the lower

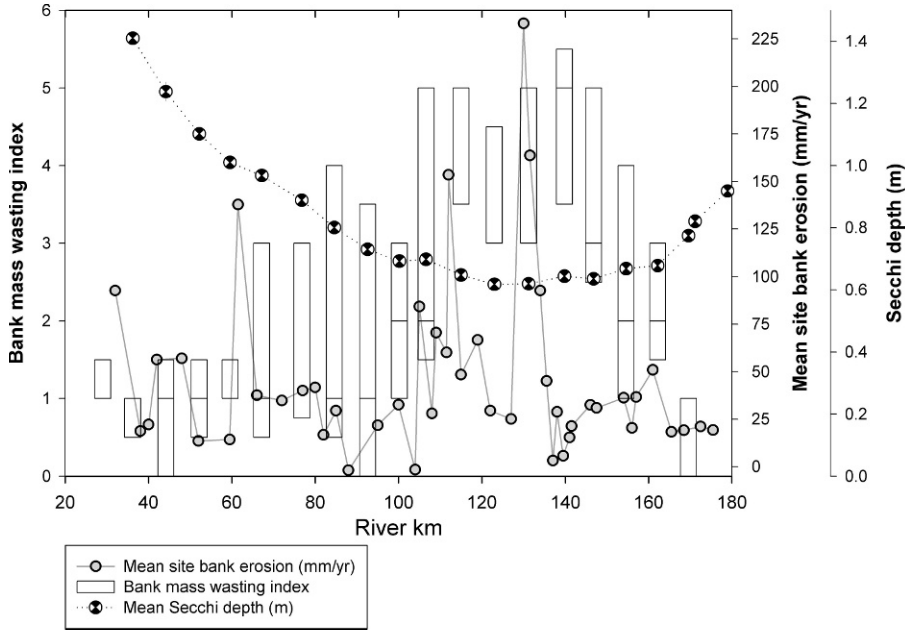

Figure 6. Trends in bank erosion, mass wasting, and water clarity from upstream to downstream (left to right) on the lower Roanoke River, NC. Mean bank erosion estimates were determined from erosion pin measurements (particle-by-particle erosion). Bank erosion index is shown as the median score per 8 km reach and is heavily influenced by mass wasting frequency. Clarity is indicated by mean Secchi depth where the greater the depth the greater the clarity, note inverse relation with bank erosion index where high values increase turbidity. Adapted from Hupp et al. (in press).

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 (Figure 7). This trend is expected given the general increases in bank erosion and mass wasting (Figure 6), at least to the middle reaches, which contributes to the sediment load and provides material for downstream deposition. Sediment budget analyses (Hupp et al. in press) indicate that deposition substantially exceeds erosion along the downstream-most reaches of the lower Roanoke River, which is supported by the reduction of turbidity in the same reaches (Figure 6). Thus, floodplain trapping removes most of the eroded sediment prior to flow reaching the Albemarle Sound and mitigates the erosional impact of the dams on estuarine ecosystems.

Observed rates of sediment and nutrient accumulation were similar to rates measured in the Coastal Plain reaches of rivers in the nearby Chesapeake Bay catchment (Noe and Hupp 2005). Patterns of nutrient and sediment deposition varied across scales depending upon a site's location relative to the dam and its geomorphic setting. Nutrient accumulation rates, like those of sediment, although not as pronounced, differed among the upper, middle, and lower floodplain reaches. Total sediment, mineral sediment, and phosphorus accumulation rates all increased from upper (108 river km from dam) to middle (124 km) to lower (173 km) floodplain reaches, while organic sediment, carbon, and nitrogen accumulation rates were lowest along the upper floodplain reach compared to the similar middle and lower floodplain reaches (Figure 8, Noe and Hupp 2005). Along with sediment accretion rates, these patterns of sediment and sediment-associated nutrient accumulation on the floodplain of the lower Roanoke River demonstrate that the role of the floodplain as a sink for sediment and nutrients has decreased immediately downstream of the dams. In addition, large scale floodplain geomorphology, as indicated by differences in the amount of levee surfaces versus low floodplain areas along the river, also influenced spatial patterns of sediment and nutrient accumulation. Levee surfaces generally dominate in the upper reaches (legacy sediment from colonial agriculture) and diminish downstream relative to low-floodplain surfaces (Hupp et al. in press). Present sediment and nutrient accumulation rates were typically greatest in the backswamps and on low levees along downstream reaches.

Human alterations and natural influences affect fluvial geomorphology and control rates of sediment and nutrient retention by Roanoke River floodplains. Long-term impacts of dam construction may compromise floodplain ecosystem services. Regulat-

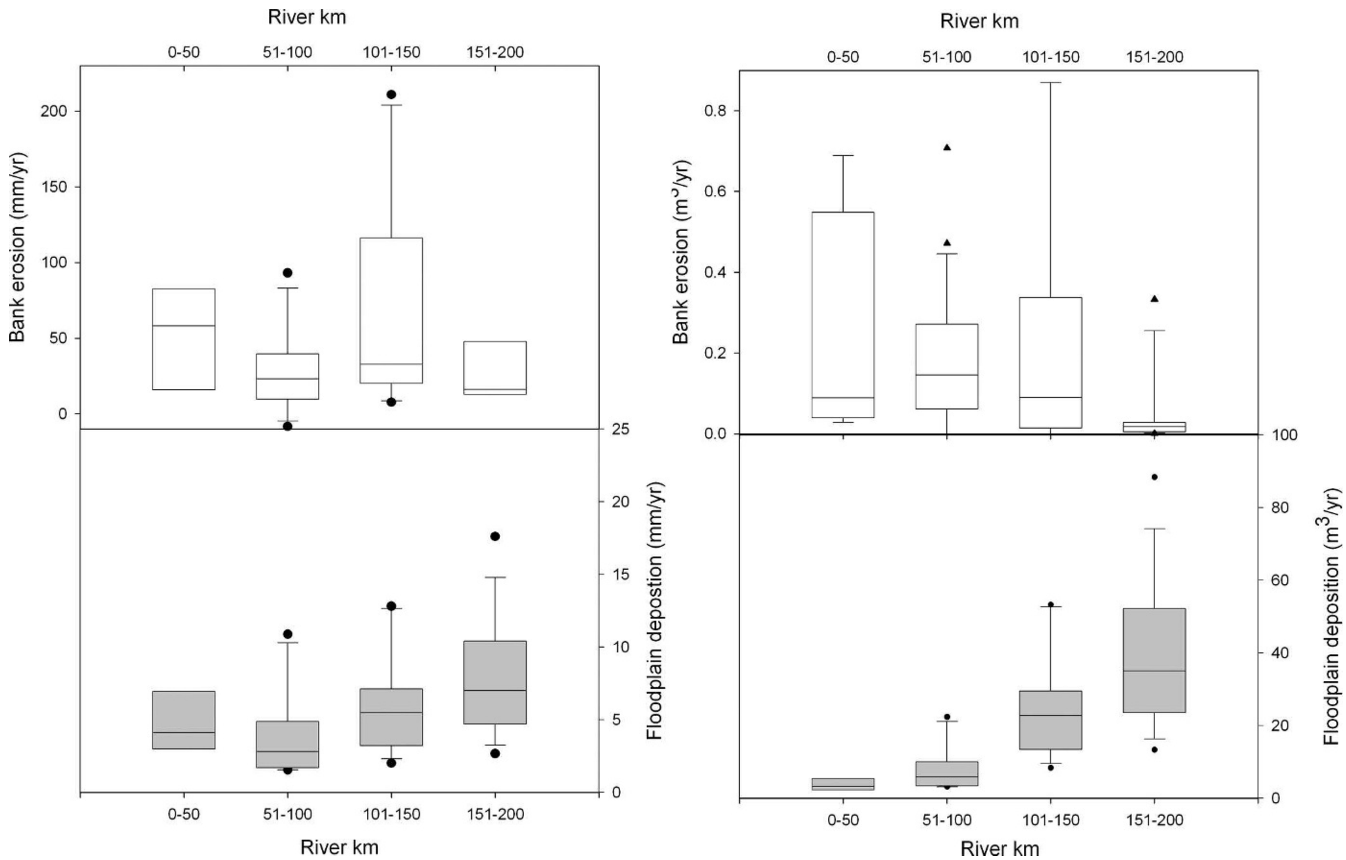

Figure 7. Box plots for rates (mm/yr) of bank erosion and floodplain sediment deposition (left panel) by 50 km reaches from upstream to downstream (left to right) for the lower Roanoke River, NC. Right panel, respective amounts in volume (m^3/yr) of sediment eroded from banks, upper, and sediment deposited on floodplain, lower. Amount of sediment eroded (mean/transect/reach) from banks is high in the upper reaches and particularly in the middle reaches; amount of sediment (mean/transect/reach) deposited on floodplain increases substantially and consistently from upstream to downstream reaches. Adapted from Hupp et al. (in press).

ed flow (loss of flood peaks that build levees) may have forced most of the sediment and associated material trapping to occur in low, backswamp areas of the floodplain and not on the large natural levees along the lower Roanoke River, which ultimately may lead to a high floodplain with little to no topographic relief. As the floodplain surface rises in elevation relative to the widening channel, a negative feedback loop may develop such that the floodplain may trap increasingly less sediment over time. This situation appears to be in force along the river near the dam. These upper reaches have 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 although relatively stable remnants of soil blocks from bank failure are still evident on upper reach banks. The homogenized nature of this elevated floodplain surface would likely adversely affect biodiversity. Also, regulated flow has likely increased bank erosion along most reaches including common straight reaches (Figure 5), which removes considerable riparian edge habitat that may be critical to many species including Neotropical migrant birds.

Effects of Stream Channelization, Channel Incision, and Valley Aggradation, West Tennessee

Channelization is a common, although controversial engineering practice aimed at controlling flooding and draining wetlands. Stream channelization along alluvial areas affects nearly all hydrogeomorphic forms and processes within, upstream, and downstream (Figure 9) of the channelized reach (Simon and Hupp 1992). The biotic environment is likewise severely affected, particularly on the channel banks but also on the adjacent floodplain (Hupp 1992). Many streams on the southeastern Coastal Plain of the U.S. have been channelized, which has severely affected fluvial-geomorphic processes at

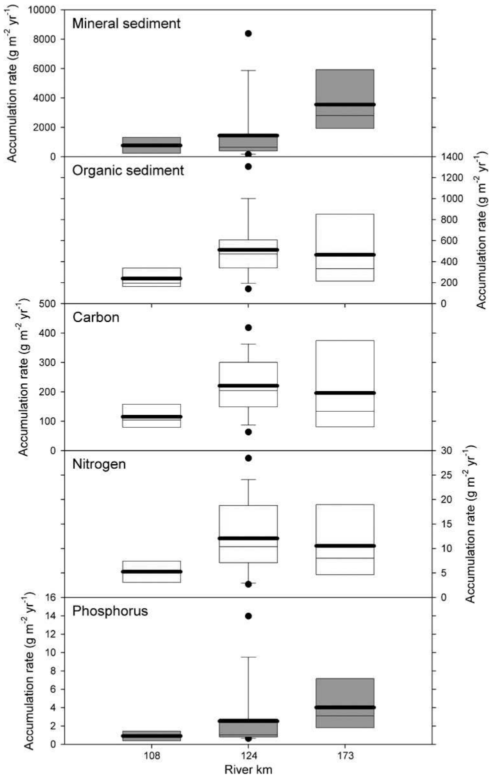

Figure 8. Trends by river kilometer (three reaches, upstream to downstream, left to right) in mineral and organic sediment deposition (gm/yr), and in deposition of macro nutrients (carbon, nitrogen, phosphorus). Note that carbon and nitrogen deposition follows that of organic sediment, while phosphorus deposition follows that of mineral sediment.

Figure 9. Top, incised channelized reach in the Obion River system, West Tennessee, degradation processes dominate, photograph by A. Simon. Bottom, sediment-filled reach, downstream of recent channelization in the Obion River system, aggradation processes dominate. Photograph by C. Hupp.

multiple spatial and temporal scales (Simon and Hupp 1987, Shankman 1993). Severe impacts may migrate downstream and upstream of the channelized reaches including small tributaries, some of which have likewise been channelized (Davis 2007). Here we report on the effects of channelization in west Tennessee where most perennial streams have been channelized. Within reaches upstream of a channelized system the stream channel becomes incised, groundwater elevation is lowered (Tucci and Hileman 1992), and the normal connectivity between the floodplain and stream flow may be eliminated (Kroes and Hupp 2007). Concurrently, the lower reaches may experience increased peak flood stages and flood frequency (Shankman and Pugh 1992); these lower reaches may suffer severe aggradation (Figure 9B) from sediment eroded from upstream reaches (Simon and Hupp 1992) sometimes forming substantial valley plugs (Pierce and King 2007a).

Channelization increases stream power that facilitates sediment entrainment (erosion from bed and banks) and transport within the system (Schumm et al. 1984, Bravard et al. 1997). In the upper reaches of a channelized system, channel bank-failure and sediment transport typically occur (Figure 9a). In contrast, lower reaches tend to accumulate large amounts of sediment because of decreased stream gradients and channel obstructions, such as debris jams, and slow water velocities facilitate deposition of the increased sediment load. Aggradation of sediment in the lower reaches can simultaneously cause a filling and widening of the channel, which has been identified as a recovery process of channelization (Schumm et al. 1984, Simon and Hupp 1987). However, increases in deposition rates in these lower reaches can also disrupt functional processes of wetland systems (Happ et al. 1940, Brierley and Murn 1997). Examples of floodplain alterations as a result of channelization include: disturbed surface and sub-surface hydrologic connectivity (Shankman and Pugh 1992, Tucci and Hileman 1992), altered sedimentation rates (Happ et al. 1940, Pierce and King 2008), reduced lateral channel migration that creates sloughs and oxbow lakes (Shankman 1993), loss of aquatic habitat (Hohensinner et al. 2004), reduced growth and premature mortality of floodplain tree species (USDA 1986), loss of plant species diversity (Miller 1990), changes in plant species composition (Oswalt and King 2005, Pierce 2005), and negative effects on fish and wildlife communities (Hunter et al. 1993, Hoover and Kilgore 1997).

Past land-use practices, in west Tennessee, contributed to hillslope erosion and floodplain aggradation and now facilitate contemporary channel erosion and sedimentation. In the 1800s, the region was rapidly colonized and forested areas of the loess regions were cleared and replaced with agricultural fields of corn, cotton, and tobacco (Wilder 1998). Clearing of the upland areas resulted in erosion and gullying of erodible loess and sandy soils (Saucier 1994); increasing sedimentation rates in downstream reaches from 2–9 mm/yr (before settlement) to 30 mm/yr (post-settlement) (Wolfe and Diehl 1993). Streams became clogged with sediment and debris, reducing channel flood capacity and causing frequent and prolonged flooding in the bottomlands (Morgan and McCrory 1910). Several periods of stream channelization occurred to alleviate flooding and facilitate row-crop agriculture beginning at the turn of the last century but prominently in the 1920s, again in the 1940s, and most recently (Figure 1b) in the 1970s (Simon and Hupp 1992). Over 260 km of streams were channelized; shortening them by 44%, lowering their bed elevation by 170%, and increasing the stream gradient by 600% (Speer et al. 1965, Robbins and Simon 1983, Simon and Hupp 1992). The Obion-Forked Deer River system suffered considerable alterations while the impacts to the Hatchie River were restricted to its tributary system (USDA 1986, Simon 1994); the mainstem Hatchie River is the only major river in the region largely unchannelized.

Historically, the high meandering rate and low gradient of the rivers did not allow for substantial transport of the sand. However, channelization greatly increased their stream power and facilitated sediment transport, resulting in dramatic geomorphic changes (Diehl 2000, Pierce and King 2008). Channel incision in the upper reaches of the channelized systems creates bank instability (Figure 10) and continues to contribute a significant amount of sediment into the stream systems. The accumulation of sediment in the lower reaches (Schumm et al. 1984, Wyzga 2001) can lead to the formation of valley plugs (Happ et al. 1940, Diehl 2000, Pierce and King 2007a, Pierce and King 2008).

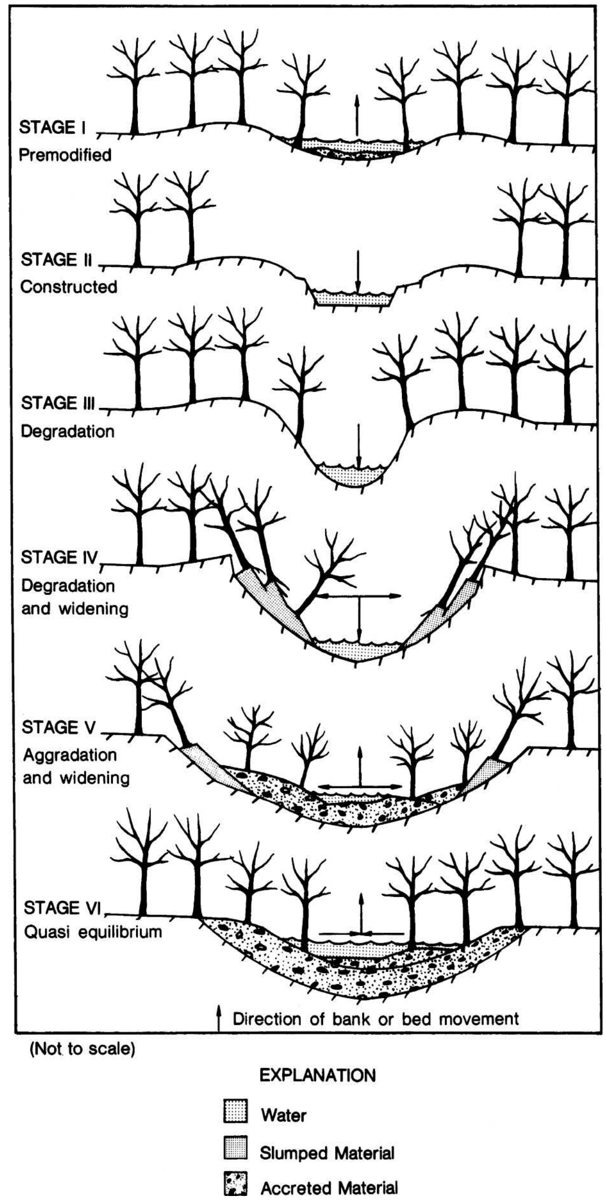

Figure 10. Diagram of six-stage channel evolution model of Simon and Hupp (1987). Degradation, channel incision begins in stage 3, continues in stage 4 with associated channel widening, widening continues in stage 5 but channel bottom aggrades. Stream initially reacts through vertical processes (arrows) after channelization then both vertical and lateral processes operate, ending with a shift to lateral process domination and mild aggradation. Adapted from Hupp (1992).

Valley plugs (Figure 11) are areas where the entire channel becomes filled to or above bank elevation with sediment, forcing floodwater and sand bedload out into the floodplain (Happ et al. 1940). Valley plugs typically form in the lower reaches of systems, where debris jams form or where the stream gradient decreases causing deposition of sediment. At valley

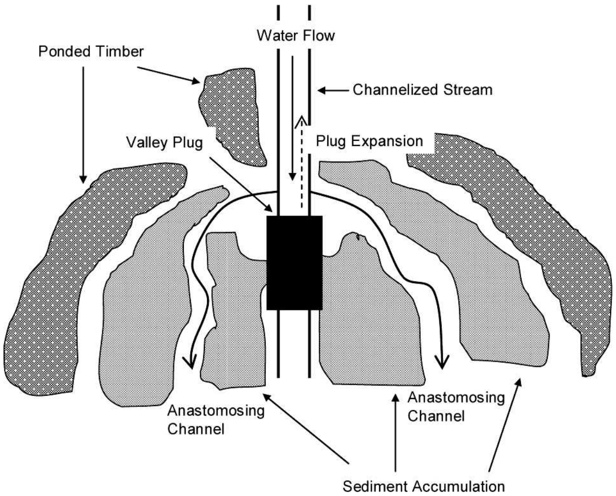

Figure 11. Diagram of the effects of valley plug (black rectangle) formation along channelized streams including anastomosing channels around channel and floodplain deposits with ponded timber near valley sides. Adapted from Pierce and King (2007a).

plugs, sediment is spread across the floodplain as the stream diverges from the main channel forming anastomosing channels throughout the floodplain (Pierce and King 2008) (Figure 12). There is little information on the time scale involved in valley plug formation or their processes of development. The plugs in the Hatchie River tributary system are thought to have formed in the 1970s when most of the tributaries were channelized (Pierce and King 2007a). Valley plugs may expand upstream as new sediments are delivered to the plug, but the rates of expansion may be extremely variable. Field observations suggest that distributaries that form near the head of the plug are also unstable and may be reworked or abandoned as the plug evolves (Figure 12). However, distributaries that do persist can create a new channel that diverts flows around the plug. In these cases, there are typically multiple plugs located over the channelized reach of the stream. Channel filling, sand splays, and vertical accretion associated with valley plugs typically occur in much greater quantities than in unaltered systems (Happ et al. 1940, Pierce and King 2007a, Pierce and King 2008).

Extensive study of the fluvial-geomorphic adjustments of the Hatchie River tributary systems has been conducted and illustrates these valley plug effects (Pierce and King 2007a, 2008). Deposition rates in floodplains of unchannelized streams were within the range of deposition rates reported in previous studies and consisted of typical overbank floodplain deposits, silt and clay particles. Deposition rates measured at valley plug sites were an order

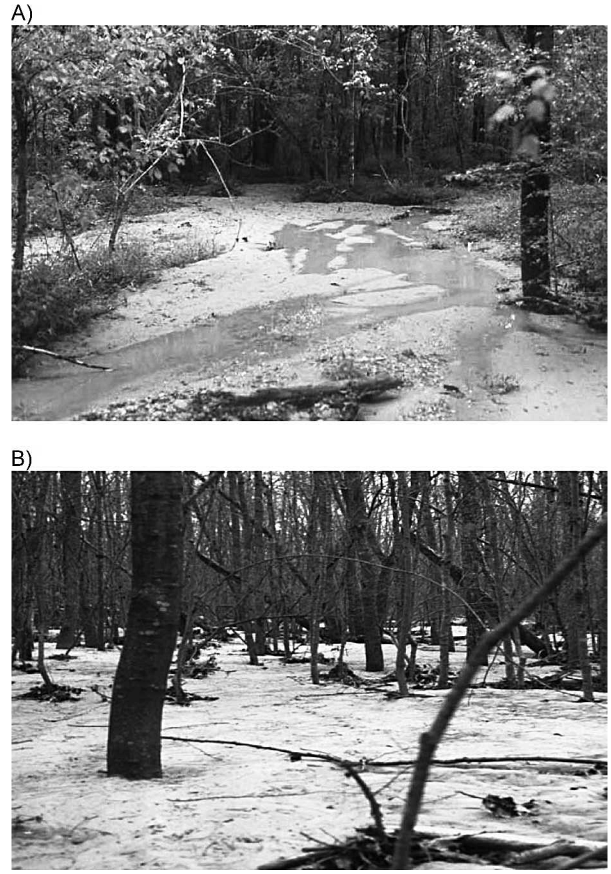

Figure 12. A) Filled channel in a valley plug, note relatively coarse material (sand) in channel. B) Extensive sand deposition across floodplain near a valley plug. Both photos along channels in the Obion-Forked Deer River system in West Tennessee. Photographs by A. Pierce.

of magnitude greater (about 17 mm/yr) than deposition rates at unchannelized sites and the deposits consisted mostly of coarse sand (Pierce and King 2007a). Indeed, they are greater than most published rates (Hupp 2000) anywhere on the Coastal Plain. Valley plugs force most stream flow onto the floodplain, which allows for the deposition of sand farther from the stream high in the valley section rather than in main channel and occasionally on natural levees (Happ et al. 1940, Pierce and King 2008).

Future deposition rates at valley plug sites may be extremely variable, as high deposition can dramatically change the floodplain morphology over short time periods and alter depositional patterns (Pierce and King 2008). The valley plugs in the Hatchie River catchment have forced sediment several hundred meters into the floodplain on both sides of the channel. Deposition now increases with increasing distance from the main channel up to the valley wall, which differs from the typical pattern of decreased deposition as one moves away from the main channel in unaltered systems (Pierce and King 2007a). Valley plugs also have the potential to rapidly expand upstream over short time periods and affect different floodplain areas. Thus, the rate of plug expansion and duration of high deposition rates on the associated floodplain may be extremely variable and depend mainly on upstream processes. In addition, valley plugs are not restricted to relatively small basins, such as the Hatchie River tributary system, but are also common in large basins within the region, such as the Forked Deer River basin in West Tennessee (Oswalt and King 2005).

Floodplain plant communities have also been affected by channelization and formation of valley plugs. The Middle Fork Forked Deer River, part of the larger Obion River system in West Tennessee, is influenced by both channelization and valley plug formation (Oswalt and King 2005). Alterations to the driving abiotic processes (flooding and sedimentation) have caused a shift in floodplain tree species composition. The resulting forest is dominated by disturbance tolerant species, mainly red maple (*Acer rubrum* L.), instead of typical species such as sweetgum (*Liquidambar styraciflua* L.), overcup oak (*Quercus lyrata* Walt.), willow oak (*Q. phellos* L.), and cherrybark oak (*Q. falcata* var. *pagodaefolia* Michx.) (Oswalt and King 2005). Similar results were also found at valley plug sites on the Hatchie River tributary system, with red maple and box elder (*Acer negundo* L.) dominating the floodplain forests (Pierce 2005). Germination and establishment of typical floodplain tree species are also influenced by the altered sedimentation and hydrologic processes that may prolong the recovery process (Walls et al. 2005, Pierce and King 2007b).

Conceptual models have been developed to understand the geomorphic re-adjustments and recovery processes of channelized streams (Figure 10, Schumm et al. 1984, Simon and Hupp 1987). However, neither discuss valley plug formation, common in west Tennessee and northern Mississippi, and their affect on fluvial-geomorphic processes. In the Simon and Hupp (1987) and Hupp (1992) model of channel evolution/vegetation re-colonization following channelization, the final two stages involve aggradation and widening of the channel (Stages V and VI, Figure 10), leading to the recovery of both the vegetation and a meandering channel. Schumm et al. (1984) described similar stages and processes of channel recovery following channelization. However, their conceptual model of recovery includes all stages of recovery occurring simultaneously along the gradient of the channelized stream from the headwaters to the confluence with other streams. The aggradation stage (Stage V) and recovery stage (Stage VI) of Simon and Hupp (1987) correspond to low-gradient areas of the depositional zone in the model of Schumm et al. (1984), where the channel widens and becomes shallower because of accumulating sediment until the channel and banks become stabilized. Valley plugs typically form in these low-gradient areas because of reduced flow velocities. Valley plugs may be a part of the aggradation process of channel recovery following channelization but the accumulation of sediment has been exacerbated by the geology of the region, past land-use practices, and unstable gullies and stream banks that contribute sediment to the systems, resulting in extremely high deposition rates of coarse material. Valley plugs and the associated high deposition rates may therefore be controlled by both basin-level factors (geology and land-use) and site-level factors (stream gradient, debris jams, and channel recovery processes).

The formation of valley plugs may be a part of the recovery process from channelization. However, the time-scale needed for systems to recover and the associated costs on the integrity of floodplain systems and floodplain functions, such as flood storage, water quality enhancement, wildlife habitat, and timber value (Happ et al. 1940, Diehl 2000, Oswalt and King 2005) may be difficult from a conservation perspective. Restoration efforts on channelized streams may focus on selected sites for stabilizing sediment supply into these systems, reducing the transport capacity of channelized streams, and stabilizing bed-level adjustments within the catchments. Dredging of within channel sediment deposits and other site-specific disturbances may compromise restoration efforts by setting back natural recovery processes (Figure 10). Cooperation at the catchment scale may facilitate restoration efforts. The geomorphic instability of the region necessitates that restoration efforts take a catchment-scale approach and recognize the importance of enhancing natural recovery mechanisms to restore equilibrium conditions, floodplain functions, and rehabilitate the ecosystem (Hillman and Brierley 2005, Palmer et al. 2005).

Effects of Levee and Canal Construction, Atchafalaya Basin, Louisiana

Many Coastal Plain riparian areas, like the Atchafalaya Basin, are the terminal storage points of riverine sediments and biogeochemical transformation of associated material before reaching saltwater. The Atchafalaya River Basin (the area between the Mississippi River and the Atchafalaya distributary) contains the largest relatively intact, functioning riparian area in the lower Mississippi Valley and the largest contiguously forested bottomland in North America. Sediment accretion rates on these floodplains may be among the highest of any physiographic province in the U.S. (Hupp et al. 2008). Recent studies have shown that coastal lowlands may be an important sink for carbon (Raymond and Bauer 2001, Ludwig 2001) and associated nutrients (Noe and Hupp 2005), which may be stored in these systems as organic rich sediment (nitrogen) or mineral sediment (in the case of phosphorus). This organic material presumably is from both autochthonous and allochthonous sources.

The Atchafalaya Basin wetland (5670 km^2) is about 70% forested and the remainder is marshland and open water. Most of the generally north-south trending Basin is bounded by flood-protection levees on the east and west separated by 20 to 30 km; the Basin has an average discharge of about 6410 m^3/s, among the top five in the U.S (Demas et al. 2001). The forested wetlands are generally of three major types: 1) typical bottomland hardwoods (Sharitz and Mitsch 1993) on levees and higher floodplains, 2) baldcypress/tupelo swamps on low backwater floodplains, and 3) young stands of predominantly black willow (*Salix nigra* Marshall) that have developed on recently aggraded point and longitudinal channel bars (silt and sand). Most of the relatively young forests (70 years or less) have grown since lumbering of old growth baldcypress and bottomland hardwoods was completed by the early 1930s (King et al. 2005). Additionally, the filling of open water areas since the middle of the last century (Tye and Coleman 1989), has created numerous and extensive surfaces for forest establishment. All flow within the Basin is regulated by structures upstream operated by the Corps of Engineers (Figure 1C). Flow in many of the bayous and canals may carry high sediment loads resulting from the ambient alluvial nature of both the Mississippi and Red Rivers and, in some cases, due to substantial resuspension of channel sediment.

Over the past several decades the Atchafalaya Basin has experienced rapid and substantial amounts of sediment deposition. Approximately 25% of Mississippi River flow on an annual basis and all of the Red River flow passes through the Basin. The entire suspended- and bed-sediment load of the Red River and as much as 35% of the suspended and up to 60% of the bed sediment load of the Mississippi River (Mossa and Roberts 1990) is now diverted through the Atchafalaya Basin. Many open water areas in the Basin have now filled (Roberts et al. 1980, Tye and Coleman 1989, McManus 2002). Regionally, the Basin provides a sharp contrast to most of the remaining Louisiana coastal area, which is sediment starved and experiences subsidence and coastal erosion. The Atchafalaya Basin is a complex of many meandering bayous and lakes that have been altered dramatically by natural processes and human impacts (Figure 1d) including channelization and levee construction for oil and gas exploration and transmission, timber extraction, flood control, and navigation (Hupp et al. 2008). The pervasive natural geomorphic process affecting the Basin is and has for the past few centuries been that of a prograding delta (Mississippi delta complex, Fisk 1952), which had filled much of the Basin with sediment by 1970 (Tye and Coleman 1989). The Grand Lake area, in the south, continues to fill as shown by rapid sedimentation in what was recently open lake. The Basin suffers simultaneously from exceptionally high sedimentation rates at sites with high connectivity to the main river and from hypoxia in stagnant areas with little connection to the main river. Both of these results may be detrimental to socially and economically important crawfish and fin-fish fisheries (Demas et al. 2001).

The Atchafalaya Basin traps substantial amounts of suspended sediment annually. Some areas have the highest documented ''normal'' sedimentation rates in forested wetlands of the United States, some backswamp locations exceeded 110 mm/yr as measured above artificial markers. Unusually high deposition rates may also occur in valley plugs (Pierce and King 2008) and during episodic events (e.g., major floods; Jacobson and Oberg 1997). Hupp et al. (2008) estimated an annual average 13.4 kg/m^2 of sediment with a mean 12% organic material is trapped in the central part of the Basin. Thus, the central part of the Basin annually traps a net $6.7 \cdot 10^6$ Mg of sediment, of which $8.2 \cdot 10^5$ Mg are organic material. Sediment accumulation rates are likely low in the upper basin where much of the floodplain has already filled (short hydroperiod) and a relatively high elevation bottomland exists. In contrast, much of the lower basin, which was previously open water, began filling more recently (McManus 2002) is distinctly low in elevation relative to the upper and central parts of the Basin, and continues filling today. The annual sediment trapping rates of mineral and organic sediment in the Atchafalaya Basin correspond to $6.4 \cdot 10^8$ kg C/yr, $2.0 \cdot 10^7$ kg N/yr, and $7.5 \cdot 10^6$ kg P/yr, estimated using average floodplain sediment nutrient concentrations in mineral and organic sediments from other Coastal Plain floodplain studies (Noe and

Hupp 2005). These N and P accumulation rates represent 5% and 27%, respectively, of their annual loading rates to the Atchafalaya Basin (Turner and Rabalais 1991, Goolsby et al. 2001). It should be noted that these are coarse estimates that do not account for movement of sediment within the Basin, separate autochthonous from allochthonous sources of nutrients, or account for long-term biogeochemical processing of nutrients in deposited sediments (Noe and Hupp 2005). Furthermore, these estimates rely on the assumption that Atchafalaya floodplain sediment nutrient concentrations are similar to other Coastal Plain floodplains. The large amount of sediment in retention allows for important biogeochemical transformations that potentially reduce contaminant, nutrient, and carbon inputs into the Gulf of Mexico.

Depositional patterns within the Basin vary and shed considerable light on understanding the factors that facilitate sedimentation, including: 1) high connectivity to sediment-laden river water, 2) long hydroperiods, 3) multiple sources flow, and 4) low-flow velocities due to flows from opposite directions. Human intervention such as cutting new canals or plugging existing channels has resulted in highly altered flow paths that may conduct substantially more or less sediment-laden water than previously and in some cases have led to flow reversals and hydraulic damming depending on the flood stage (Hupp et al. 2008). Levees both constructed and natural may be relatively high in elevation (about 4 m above sea level), have a relatively short hydroperiod, have very low contemporary sedimentation rates (< 3 mm/yr), and relatively high amounts of organic material. Some backswamp sites may be stagnant and low in elevation with relatively decreased sedimentation rates and high percentages of organic material. Other sites have moderate to relatively high sedimentation rates, particularly on low levees where sedimentation may be uniform across the floodplain (Figure 13A) or concentrated on levees or backswamps (Figure 13B, C). Sites that have the highest rates of sediment deposition also have great connectivity to sediment laden water and are typically associated with sediment sources other than or in addition to the nearest channel (Figure 14). In contrast, backswamps with poor connectivity to sediment-laden river water tend to have low deposition rates and may become stagnant and hypoxic (Hupp et al. 2008).

The greatest percent organic material in the sediment tends to be in sites with low mineral-sediment deposition rates; this organic material is thus presumably autochthonous. However, in a few high-deposition rate sites the percentage of organic material was also high, which suggests that some

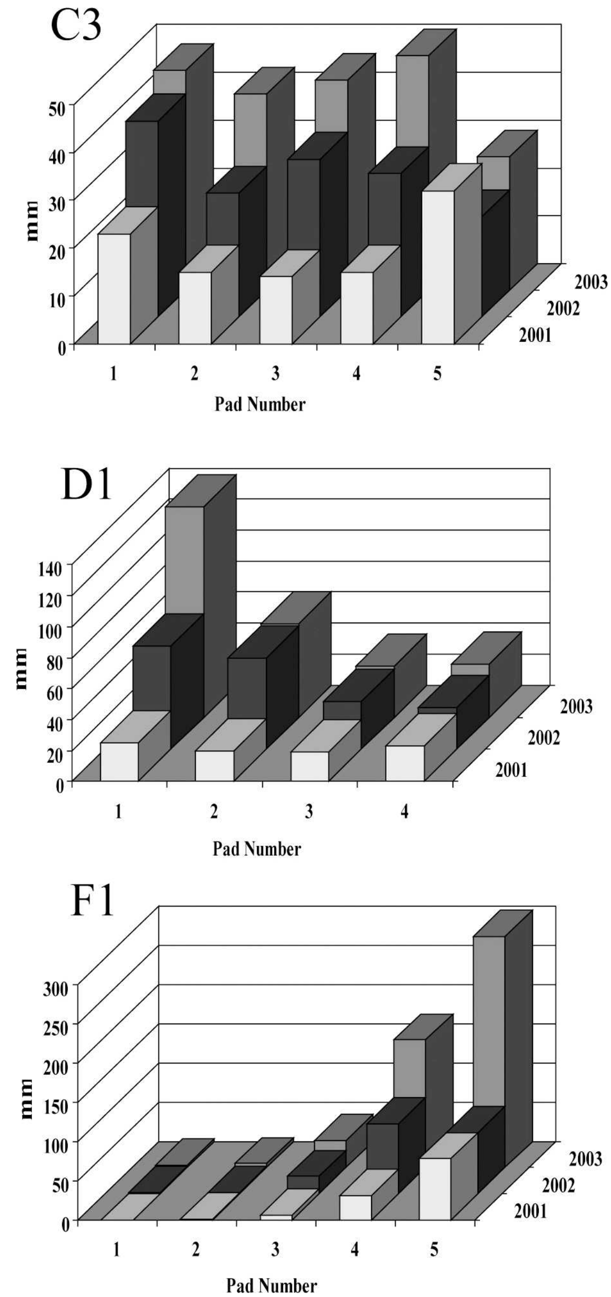

Figure 13. Variation in spatial patterns of sediment deposition at three sites in the central Atchafalaya Basin for the period 2001 through 2003. Pad numbers along a single transect begin on the levee (1) and end in the backswamp (4 or 5). A) Illustrates relatively uniform sediment deposition that may be characteristic of high elevation sites with low deposition rates or, conversely, of low sites in formerly open water with high deposition rates; B) Represents sites whose sediment source is the adjacent channel where sedimentation is highest on the levee and diminishes toward the backswamp (common along many Coastal Plain streams); and C) Illustrates sites where water in the adjacent channel rarely overtops the levee but is impacted from sediment-laden water from floodplain sources away from the adjacent channel. Adapted from Hupp et al. (2008).

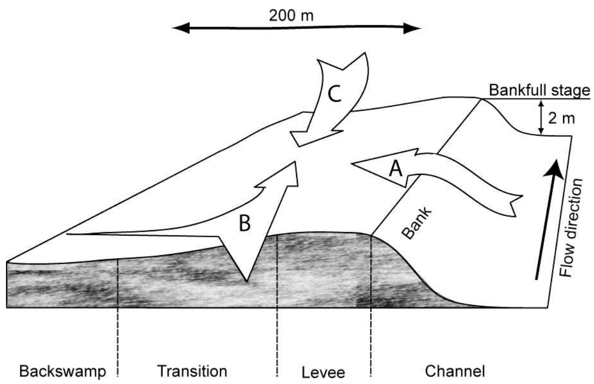

Figure 14. Diagram of potential sediment sources for riparian retention for a given floodplain site:A) from overbank flow from the adjacent channel; B) from upstream flow across the floodplain; and C) from downstream flow across the floodplain. A site may be affected by any or all sources; opposing flows may create a hydraulic dam and facilitate sediment deposition. Adapted from Hupp et al. (2008).

areas may be trapping large amounts of allochthonous organic material. Coarse sediments (sand) were most common on levees and along sloughs associated with levee crevasses. Sedimentation rates and size clasts diminished from the levee to the backswamp where the adjacent channel is the dominant source of floodplain inundation.

Human altered hydrologic patterns, from small scale opening or closing of single bayous to the diversion structure at the head of the basin on the Mississippi River, have increased the severity of local non-equilibrium sedimentation patterns throughout the Basin. Although sediment trapping and aggradation are normal near the mouths of large alluvial rivers, hydrologic alterations have created areas with excessive deposition where there was once open water and, conversely, prevented river water from flowing in other areas that now experience periods of hypoxia. The impact of these alterations has been felt in the Basin for many decades, possibly as far back as the initial levee construction on the Mississippi River. The Atchafalaya Basin may serve as a model area for restoration of coastal areas where wetlands are receding. High sedimentation regimes, as a wetland constructional process, may provide for an important buffer in hurricane-prone areas and provide valuable ecosystem services.

SYNTHESIS

Fluvial geomorphic systems, by nature, tend to maintain a dynamic equilibrium (Hack 1960) among ambient sediment load, water discharge, and channel geometry (Osterkamp and Hedman 1977). Streams or reaches of streams are typically deemed "in equilibrium" when the stream and its hydrogeomorphic form and process are sufficiently (but not overly) competent to entrain, transport, and store the sediment provided by the associated catchment in a balanced fashion (Hack 1960). Equilibrium conditions may occur in a zone around the boundary between net erosion and deposition (Figure 3). For instance, streams in mountainous areas may have a naturally net erosion (entrainment) stream regime, while streams in the Coastal Plain tend to have a naturally net depositional (storage) stream regime (Hupp 2000). Streams in between these two geographic settings, such as those in the Piedmont, may have a sediment transport dominated regime as shown in the conceptual gradient (Hupp and Bornette 2003) of stream conditions (Figure 3). Sediment grain size, stream gradient, and channel pattern (meandering, cascading, and straight) may adjust along the conceptual gradient to maintain near equilibrium conditions. Human alterations (dams, levees, channelization, and land use) within the catchment or along the stream that substantially affect one or more important fluvial parameters may lead to disequilibrium conditions. For instance, dramatic shifts in stream gradient may initiate a period of pronounced fluvial adjustment and excessive erosion or deposition, or both. Streams in equilibrium typically do not exhibit pronounced directional changes in sediment size, stream gradient, or channel pattern, which may be indicated by severely eroded banks or highly depositional floodplains.

The natural hydraulic connectivity of a site is critical to maintaining important ecosystem services of floodplains; many human alterations substantially affect this connectivity. Severe reductions in connectivity can lead to hypoxia. Whereas, severe increases in connectivity may lead to deposition rates that bury ecosystems and lead to reduced hydroperiods. Reduction of sediment load and confined discharges that result from dams may cause downstream reaches to be starved of sediment and facilitate channel erosion and bank failure. Channelization and levee construction affect fluvial systems in similar ways but are facilitated by increases in channel gradient that affect flow velocity and erosion upstream, while downstream deposition (valley plugs) may occur from constricted flow and high sediment loads. Loss of stream and floodplain connectivity in upper reaches and the reduced gradient of lower reaches force sediment and material trapping processes to move upstream (or downstream in the case of dams). As this process moves, it initiates recovery processes of the system that may also reduce topographic relief and create relatively high floodplains with low internal relief that may affect biodiversity. In other situations, the active floodplain may become restricted within highly incised banks reducing the original floodplain to terraces with little to no flooding, substantially reducing floodplain habitat. This negative feedback will reduce the sediment and material trapping function of the floodplain over time. The homogenized nature of floodplain surfaces may affect the hydroperiod, which, in turn, may affect nutrient loading and cycling with cascading negative effects on plant and wildlife biodiversity.

Although human alterations to hydrology and geomorphology have had definitive impacts on floodplain ecosystems, the large Coastal Plain floodplains of the southeastern United States still have important functioning capacities to improve water quality. These systems annually accumulate very large amounts of mineral and organic sediment and its associated carbon, nitrogen, and phosphorus. As we have shown, floodplain accumulation rates are increased at some locations (e.g., associated with land clearing in catchment and valley plugs) and decreased at other locations (e.g., dam and channelization impacts) depending on the specific hydrogeomorphic alteration and setting. We estimate that the extensive Coastal Plain floodplains of the Roanoke River and Atchafalaya Basin, as well as those of the Chesapeake Bay catchment (Noe and Hupp in press), currently cumulatively trap $9.7 \cdot 10^{12}$ g/yr of sediment, $7.7 \cdot 10^{11}$ g/yr of C, $4.0 \cdot 10^{10}$ g/yr of N, and $1.1 \cdot 10^{10}$ g/yr of P. These trapping rates can translate into large percent retention of annual river loads. The C fluxes represent 1.3% of the total C sequestration of North American wetlands and 14.6% of C sequestration by freshwater mineral wetlands in the conterminous U.S. (Bridgham et al. 2006), due in part to the much higher sedimentation rates observed in our focal systems compared to the mean estimate for freshwater mineral wetlands. Investigation of lowland fluvial systems may be critical towards our understanding of global carbon cycling, nutrient accumulation, and biogeochemical processes which in turn have direct implications for natural remediation, aquatic "dead zones", and global climate change (Hupp and Noe 2006). The high sediment and contaminant trapping and C sequestration functions of Coastal Plain floodplains suggest that natural resource managers including engineers, policy makers, and constituency groups might focus efforts that buffer these ecosystem services from the deleterious impacts of hydrogeomorphic alterations by, for instance, maintaining or restoring the "natural" hydrologic connectivity of streamflow with adjacent floodplains. This kind of effort by land managers would require catchment- rather than local-scale analyses to detect and interpret large-scale processes that may profoundly affect most sites within a basin.

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