

The influence of riparian vegetation on stream width, Eastern Pennsylvania, USA

Nicholas E. Allmendinger[†]

Department of Geosciences and Natural Resource Management, Western Carolina University, Cullowhee, North Carolina 28723, USA

James E. Pizzuto[‡]

Department of Geology, University of Delaware, Newark, Delaware 19716, USA

Noel Potter, Jr.[§]

Department of Geology, Dickinson College, P.O. Box 1773, Carlisle, Pennsylvania 17013, USA

Thomas E. Johnson[#]

Patrick Center for Environmental Research, Academy of Natural Sciences, 1900 Benjamin Franklin Parkway, Philadelphia, Pennsylvania 19103, USA

W. Cully Hession^{††}

Department of Civil and Environmental Engineering, University of Vermont, Burlington, Vermont 05405, USA

ABSTRACT

We surveyed adjacent reaches with differing riparian vegetation to explain why channels with forested banks are wider than channels with nonforested banks. Cross sections and geomorphic mapping demonstrate that erosion occurs at cutbanks in curving reaches, while deposition is localized on active floodplains on the insides of bends. Our data indicate that rates of deposition and lateral migration are both higher in nonforested reaches than in forested reaches. Two dimensionless parameters, α and E , explain our observations. α represents the influence of grassy vegetation on rates of active floodplain deposition; it is 5 times higher in nonforested reaches than in forested reaches. E is proportional to rates of cutbank migration; it is 3 times higher in nonforested reaches than in forested reaches. Differences in width between forested and nonforested reaches are proportional to E/α . In forested reaches, channels are wide with banks that are difficult to erode. Dense tree roots create a low value of E , and the channel migrates slowly. E/α is high, however, because α is very low: shade from trees inhibits the growth of

grass on active floodplains. In nonforested reaches, channels are narrow with banks that are easy to erode. E is high, and the channel migrates rapidly. E/α is low, however, due to a very large value of α : grass grows readily on nonforested convex bank floodplains. Thus, differences in width between forested and nonforested reaches are related to a balance between rates of cutbank erosion and rates of deposition on active floodplains, implying that equilibrium widths develop to equalize rates of cutbank erosion and vegetation-mediated rates of deposition on active floodplains. These results suggest that accurate models of width adjustment should consider the combined effects of bank erodibility and floodplain depositional processes, rather than focusing on these processes in isolation from one another.

Keywords: riparian vegetation, floodplains, bank erosion, hydraulic geometry, width.

INTRODUCTION

The influence of organisms on geological processes is increasingly appreciated by earth scientists (Naylor et al., 2002). The interaction between plants and earth surface processes is particularly significant, both for understanding and interpreting scientific observations (Gran and Paola, 2001; Montgomery et al., 2000) and for land management issues. For example, vegetation plays an important role in recent

initiatives to improve the ecological condition of watersheds, because one of the primary methods of restoring watersheds involves increasing the extent of riparian forests. Many government agencies have official policies encouraging the reversion of streamside areas to mature forests (Hession et al., 2000; USDA-SCS, 1991), and official governmental publications and publications in scientific journals tout the ecological benefits of riparian reforestation (National Research Council, 1992).

Although the influence of vegetation on earth surface processes has been widely studied, it remains poorly understood. Ideas regarding the effects of vegetation are inconsistent and occasionally contradictory. This is presumably a result of the extreme variability of both earth surface systems and vegetation as well as limitations in available theory and observational data. Because of the heightened interest in using vegetation as a tool for restoration, however, rapid advances in scientific understanding are badly needed.

In this paper, we document how riparian vegetation influences the widths of sinuous, mixed-load, gravel-bedded rivers of eastern Pennsylvania. Our research design holds many hydrologic and sedimentologic controls on river width constant, while allowing riparian vegetation to vary significantly. This approach isolates the influence of riparian vegetation and allows us to 1) propose a conceptual model of width adjustment for these rivers, and 2) describe how grasses and trees influence the development of stable equilibrium cross sections in our study reaches.

[†]E-mail: allmendinge@email.wcu.edu.

[‡]E-mail: pizzuto@udel.edu.

[§]E-mail: pottern@dickinson.edu.

[#]E-mail: tjohnson@acnatsci.org.

^{††}E-mail: hession@emba.uvm.edu.

PREVIOUS RESEARCH

Geomorphologists have long recognized the strong influence that vegetation exerts on river channel morphology. The results of many studies indicate, for example, that river channel cross sections are influenced by vegetation type. Andrews (1984) and Hey and Thorne (1986) noted that “dense” vegetation is associated with narrow, deep channels, and “less dense” vegetation is associated with wide, shallow channels. Charlton et al. (1978) reports that channels with grassy banks are 30% wider than channels with forested banks. Others report results that seem to contradict the studies cited above: Davies-Colley (1997), Hession et al. (2003a), Sweeney (1992), Sweeney et al. (1999), Trimble (1997), and Zimmerman et al. (1967) suggest that channels with grassy banks are narrower than channels with forested banks.

Previous studies also indicate that vegetation influences rates of erosion and deposition in rivers. Pizzuto and Meckelnburg (1989), Odgaard (1987), and Micheli et al. (2004) note that rates of bank erosion and meander migration are lower along bends with large trees than along bends without large trees. Stott (1997) compared bank erosion rates in forested and moorland catchments in the United Kingdom; he found that bank erosion rates were lower in forested catchments than in moorland catchments, but he concluded that “there are conflicting reports within the literature regarding the effects of trees on channel bank stability.” Reduced bank erosion rates associated with trees are explained in terms of the form drag and other hydraulic processes by Ikeda and Izumi (1990) and Thorne and Furbish (1995). Large woody debris in the channel may also play a role by deflecting the flow toward the banks, increasing rates of bank erosion and channel width (Montgomery, 1997; Murgatroyd and Ternan, 1983; Trimble, 1997). Riparian vegetation also exerts a strong influence on deposition: many studies demonstrate that floodplain development and channel narrowing are greatly enhanced by vegetation (Graf, 1978; Friedman et al., 1996; McKenny et al., 1995; Moody et al., 1999; Schumm and Lichty, 1963).

Scale is another important consideration in assessing the influence of vegetation on rivers: large channels may not be influenced by riparian vegetation (Nanson and Hickin, 1986; Zimmerman et al., 1967). Apparently, the influence of vegetation is related to the ratio of rooting depth to channel depth—if the roots do not extend to the toe of the banks, then bank erosion processes may be less influenced by vegetation, and the erodibility of the bank sediments and the hydraulics of the flow will become increasingly important (Pizzuto, 1984).

This study is one component of a comprehensive effort to determine the influence of riparian vegetation on riverine ecology and geomorphology in mid-Atlantic Piedmont watersheds with varying levels of urban and suburban development (Hession et al., 2003b; <http://www.acnatsci.org/research/pcer/watershed.html>). Hession et al. (2003b) compared each study reach with forested riparian vegetation to an adjacent reach without forested riparian vegetation. Nonforested riparian zones consisted primarily of grassy and herbaceous vegetation with a few scattered trees, while the riparian zones of forested reaches consisted of mature deciduous forest (quantitative descriptions of vegetative characteristics of the study sites are presented by Hession et al., 2002). Study sites were selected to avoid tributary junctions between reaches, so the supply of water and sediment to each pair of reaches should be similar. This experimental design allows all significant variables except riparian vegetation to be held constant for each pair, so that consistent differences between individual pairs can be attributed solely to the effects of riparian vegetation. Further details are provided by Hession et al. (2000, 2002, 2003a, 2003b).

Hession et al. (2003a) analyzed data from the 12 paired reaches identified during the above mentioned study, and they also were able to include another 14 paired reaches from another study (Sweeney et al. 1999), providing a total of 26 paired reaches. They concluded that forested reaches have greater widths and cross-sectional areas than their nonforested counterparts. All other geomorphic characteristics, including bankfull depth, sinuosity, slope, and median bed particle size are essentially constant when paired reaches are compared: apparently, variables other than width and cross-sectional area do not appear to be influenced by riparian vegetation. Furthermore, increases in width and cross-sectional area associated with riparian forests persist regardless of the extent of urban development in the watershed (Hession et al., 2003a).

Other scientists have compared channel widths in forested and grassy riparian zones, and forested reaches are commonly observed to be wider than grassy reaches (Trimble, 1997; Sweeney, 1992; Davies-Colley, 1997). Previous studies, however, have not been designed to identify the processes that cause the observed differences in width and area.

TERMINOLOGY

Floodplain deposits formed on the convex sides (the “insides”) of laterally migrating river bends play an important role in this study. Terminology used to describe these deposits, however, is not necessarily uniform and could

be the source of considerable confusion. For example, Leopold and Wolman (1960) and Wolman and Leopold (1957) describe a deposit on the inside of a meander bend on Watts Branch in Maryland. The deposit is composed primarily of silt (Leopold and Wolman, 1960), though sizes ranging from gravel to clay are present. The surface of the deposit is covered with grassy vegetation (Wolman and Leopold, 1957, plate 1). Leopold and Wolman (1960) and Wolman and Leopold (1957) use the term *point bar* to describe these deposits and the landform they create. Jacobson and Coleman (1986) and Coleman (1982) divide similar deposits in Maryland into “channel bed” and “point bar” subfacies, and they refer to them as “lateral accretion deposits.” According to Jacobson and Coleman (1986), these deposits consist primarily of sand and gravel, although the point bar subfacies may contain sediment sizes ranging from clay to gravel (no quantitative grain size analyses are presented). Many of these lateral accretion deposits are vegetated (Coleman, 1982). The landforms created by these deposits are termed by Coleman (1982) and Jacobson and Coleman (1986) as “point bars” or “floodplains.” Nanson (1980), on the other hand, restricts the term “point bar” to the largely unvegetated body of sediment on the convex bank. Once point bars are able to support vegetation, Nanson (1980) refers to them as “floodplain ridges.” The American Geological Institute’s *Glossary of Geology* (Jackson, 1997) suggests that a point bar is composed of “sand and gravel.” Other uses of the terms “point bar” and “floodplain” are reviewed by Nanson (1980).

We will use the term *active floodplain* to refer to deposits formed across the channel from migrating cutbanks (Fig. 1). We prefer the term active floodplain to the term point bar for three reasons. First, point bars are a product of river meandering (Jackson 1997), and yet our study sites are located along rivers whose sinuosities are mostly lower than the minimum value of 1.5 commonly used as a threshold for meandering rivers (Jackson, 1997). Second, the deposits that we consider are vegetated and, as we note above, the term “point bar” is sometimes restricted to unvegetated landforms. Third, our data will demonstrate that the deposits in our field area typically contain a considerable amount of silt and clay. Following the usage suggested by the *Glossary of Geology* (Jackson, 1997), these deposits are therefore more aptly described as floodplain deposits rather than as point bar deposits. Finally, “active floodplain” is a commonly used term, so our usage will not introduce new terminology.

The areas of the valley bottom that are not classified as active floodplains will be referred to

VEGETATION AND WIDTH ADJUSTMENT

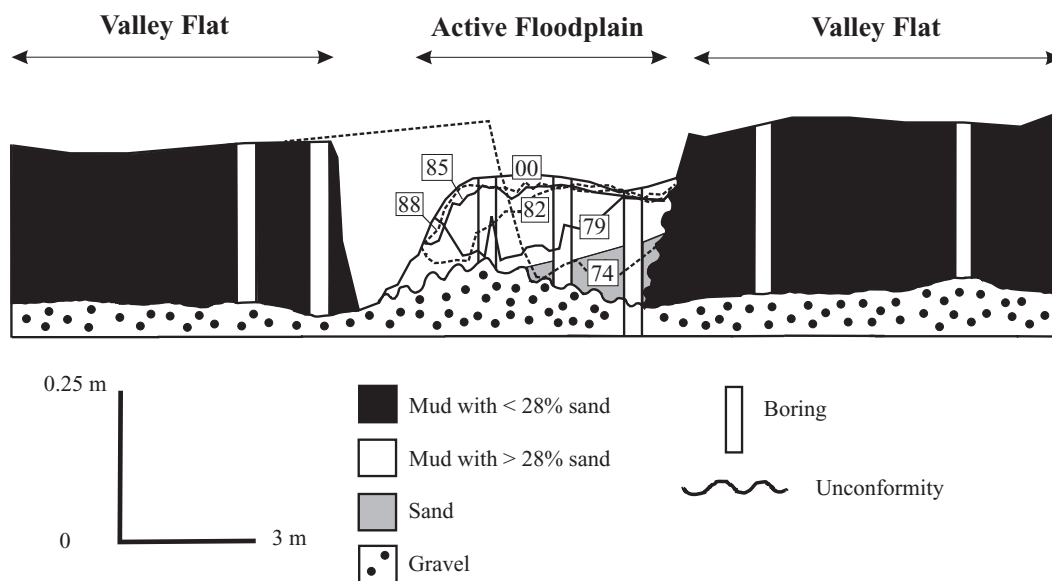


Figure 1. Topography, stratigraphic setting, and evolution of an active floodplain on an unnamed tributary of Conogoguinet Creek. View is upstream. The left bank is only shown for the 1974 and 2000 surveys to enhance the clarity of the figure. The numbers on the diagram refer to the years of the surveys.

in this paper as the “valley flat” (Fig. 1). We have adopted this definition from Coleman (1982).

EXPERIMENTAL DESIGN

Previous publications (Hession et al. 2000, 2002, 2003a, 2003b) have demonstrated that slope, sinuosity, grain size, and depth are not significantly different between contiguous paired forested and nonforested reaches of our study areas. Furthermore, because the paired reaches are contiguous, relatively short, and because they do not have any tributary inputs between them, we infer that the discharges in any pair at any particular time are also similar. Differences between forested and nonforested reaches, therefore, are limited to one independent variable (riparian vegetation), and one dependent variable (width; additional variability related to bedrock and other nonaluvial controls is discussed below). Our study therefore may be viewed as a controlled field experiment in which nearly all independent variables are held constant except riparian vegetation. We are particularly fortunate that vegetation only influences one dependent variable (i.e., the width), allowing us to infer direct correlations between changes in vegetation and changes in width.

It is important to note that our approach only considers how *changes* in the independent variable (riparian vegetation) control *changes* in the dependent variable (width): we only investigated *differences* between paired width values, not absolute values of width. Our methods will not allow us to explain or predict absolute values of width because absolute values of width are also influenced by discharge, sediment supply,

and other variables that our experimental design treats as constants.

Our goal was to relate observations of width and vegetation characteristics to specific processes and rates of erosion and deposition. At our study sites, erosion occurs at nearly vertical cutbanks on the outsides of curving channels. The cutbanks are typically composed of bare soil with varying concentrations of roots derived from grasses and trees growing on the floodplain surface near the banks. In the forested reaches, our initial observations suggested that tree roots are abundant, while they appear to be less common in grassy reaches. Initial observations also suggested that the texture of the bank deposits was similar between forested and grassy reaches. Based on these observations, we hypothesized that root type and density controlled rates of erosion at cutbanks, and that differences in texture and other variables were probably less significant. In particular, we hypothesized that forested banks are difficult to erode because of the dense network of tree roots protecting the banks.

Deposition at our study sites occurs at active floodplains located on the insides of bends. Active floodplains are covered with dense grasses in nonforested reaches, but are largely unvegetated in forested reaches. Because most controlling variables are not systematically different between forested and grassy reaches, we developed the hypothesis that differences in deposition rates on active floodplains are controlled by the density of grasses on these surfaces.

To explain how vegetation influences the widths of our study sites, we propose that the width represents a balance between processes of bank erosion and deposition. In particular,

we suggest that the width represents *relative* tendency of the banks to erode or accrete, rather than the absolute value of either process. According to this hypothesis, wide channels are characterized by a tendency for *rapid bank erosion relative to bank accretion* and narrow channels are characterized by a tendency for *rapid bank accretion relative to rates of bank erosion*. Furthermore, we also suggest that differences in bank erodibility are related to differences in root character and density, and that differences in bank deposition (observed, for example, at constant discharge) are related to differences in the density of grasses on active floodplains.

To evaluate the hypotheses described above, we needed to measure 1) rates of bank erosion and deposition, 2) the nature and density of roots in cutbank soils, 3) the texture and stratigraphy of cutbank soils, and 4) the density of grasses on active floodplains. In addition, because active floodplain deposition creates identifiable stratigraphic units whose ages and morphology can be used to constrain rates of deposition and lateral migration, we also needed to define the extent and chronology of fluvial deposits at each of our sites.

Our study group completed an exhaustive search for suitable paired reaches in the Pennsylvania Piedmont physiographic province. While Hession et al. (2002) report geomorphic data from 12 paired sites, only a subset of four of these sites displayed convincing evidence of systematic lateral channel migration in the form of well-developed active floodplains in both forested and grassy reaches. The results presented below show clear trends that allow us to evaluate our hypotheses, but the small sample size does influence our interpretations

(addressed further in the Discussion section of the paper).

STUDY AREAS

The study reported by Hession et al. (2002) includes 12 first- through third-order rivers in the Piedmont portion of the Delaware River watershed in southeastern Pennsylvania (PA DCNR, 2000) and encompasses the northern and western areas of the Philadelphia metropolitan region (Fig. 2). The region supports a fragmented, mixed-hardwood deciduous forest with large areas cleared for agricultural and urban development (DVRPC 1994; Hession et al., 2000). Precipitation in the study area averages ~110 cm/year (NOAA, 2003).

We selected four paired reaches for our detailed study of channel-forming processes of erosion and deposition. All of the reaches are ~20 channel-widths in length. Reaches begin and end with similar bed topography (e.g., if a reach began at the top of a riffle, we made sure that it ended at the top of a riffle). Each reach has at least one location with a well-developed active floodplain located across the channel from an actively eroding cutbank. Many of the active floodplains had trees growing on them, which allowed us to use dendrochronology to estimate recent rates of floodplain growth. All of the sites are located along relatively small channels with drainage basin areas from 0.4 to 13 km² and bankfull widths from 3.3 to 10.9 m (Table 1). Table 1 also demonstrates that the drainage areas for individual forested and non-forested pairs are not systematically different: two of the forested reaches have greater drainage basin areas than the nonforested reaches, one pair has similar drainage basin areas, and one forested reach has a smaller drainage basin area than its nonforested counterpart. As is typical for small streams in the Piedmont region of the mid-Atlantic region (Costa 1975), bedrock exposures are frequently observed at shallow depths below the alluvial deposits at our study sites. For example, we observed at least one bedrock exposure in the stream bed at each forested reach and at each nonforested reach. In addition, we also observed colluvial deposits in the floodplains at all sites (also noted by Lattman [1960] in his study of floodplain deposits along a small stream in Pennsylvania), although colluvium does not necessarily appear along all of our cross sections. Thus, all of our sites are influenced to some degree by nonalluvial hillslope and bedrock processes, as is typical for small streams of the region.

Data from Hession et al. (2003a) describing the watersheds and stream morphology of our

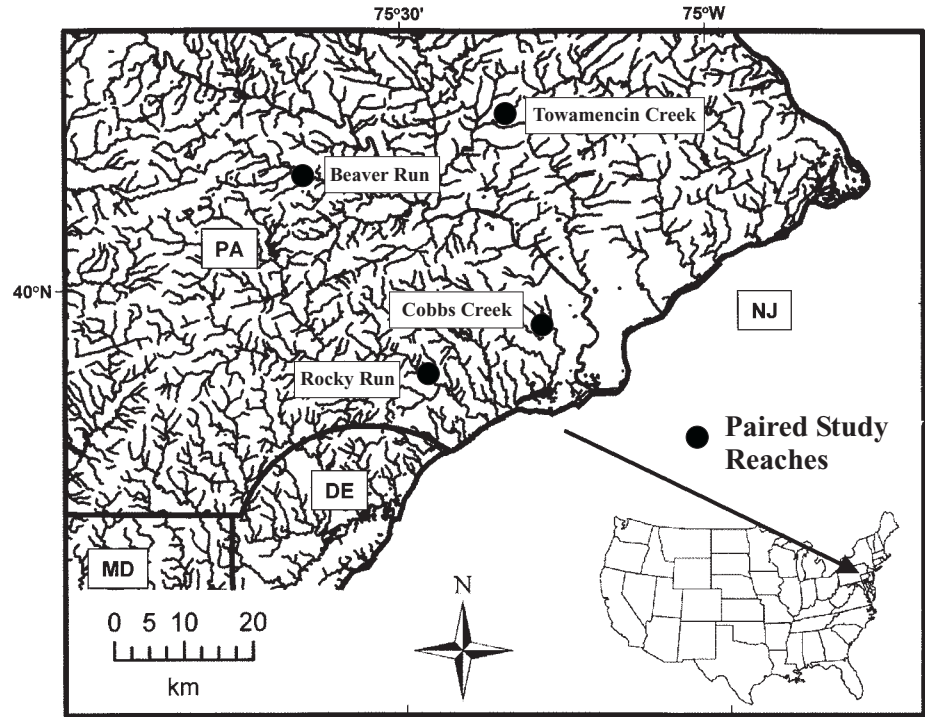


Figure 2. Locations of the four paired reaches in southeastern Pennsylvania.

4 study sites are presented in Table 1. As is typical of the larger population of sites studied by Hession et al. (2003a), the bankfull widths and cross-sectional areas of the forested reaches are larger than the widths and areas of the nonforested reaches, while the depths, grain sizes, and bed slopes do not vary consistently between forested and nonforested reaches. However, the sinuosities of the four nonforested reaches tend to be somewhat higher than the sinuosities of the four forested reaches. The average sinuosity of the nonforested reaches is 1.45, while that of the forested reaches is 1.18, an average difference of 19%. These differences in sinuosity are not typical of the 12 sites studied by Hession et al. (2003b), who noted that the sinuosities of forested and nonforested

reaches were not significantly different. Thus, the four sites, while nearly similar to the larger population of sites studied by Hession et al. (2003b), have paired reaches that differ slightly (and systematically) in sinuosity (the significance of this observation is discussed further in the Discussion section of the paper).

We also include observations from another site near Carlisle, PA, where 25 yr of annual surveys illustrate the temporal evolution of a representative active floodplain (Figs. 1 and 3). The study area is located along an unnamed first-order tributary to Conodoguinet Creek. The watershed is underlain by the Martinsburg/Hamburg Formations of the Shale Bedrock Region, Great Valley Section, Ridge and Valley Province (Potter et al., 1998; Sevon, 1997).

TABLE 1. MORPHOLOGY AND DRAINAGE BASIN CHARACTERISTICS OF THE STUDY SITES

Stream	Drainage area (km ²)	Watershed impervious (%)	Length ¹ (m)	Bankfull width (m)	Bankfull depth (m)	Area (m ²)	Sinuosity	Bed slope (%)	Median grain diameter (mm)
Beaver Run	11.6/12.3	4.8	147/197	7.4/6	0.32/0.33	2.4/2	1.5/1.5	1.15/0.81	64/45
Cobbs Cr.	0.4/0.4	64.4	132/81	5.2/3.3	0.38/0.28	2/0.9	1.1/1.3	2.36/2.32	32/32
Towamencin Cr.	6.9/5.1	52.1	84/76	6.9/4.7	0.42/0.32	2.9/1.6	1/1.7	0.54/0.74	23/23
Rocky Run	7.9/7.5	33.4	133/100	10.9/4.5	0.36/0.39	4/1.8	1.1/1.3	0.85/0.63	16/45

Note: From Hession et al. 2003a.

¹Values are for forested reach/nonforested reach.

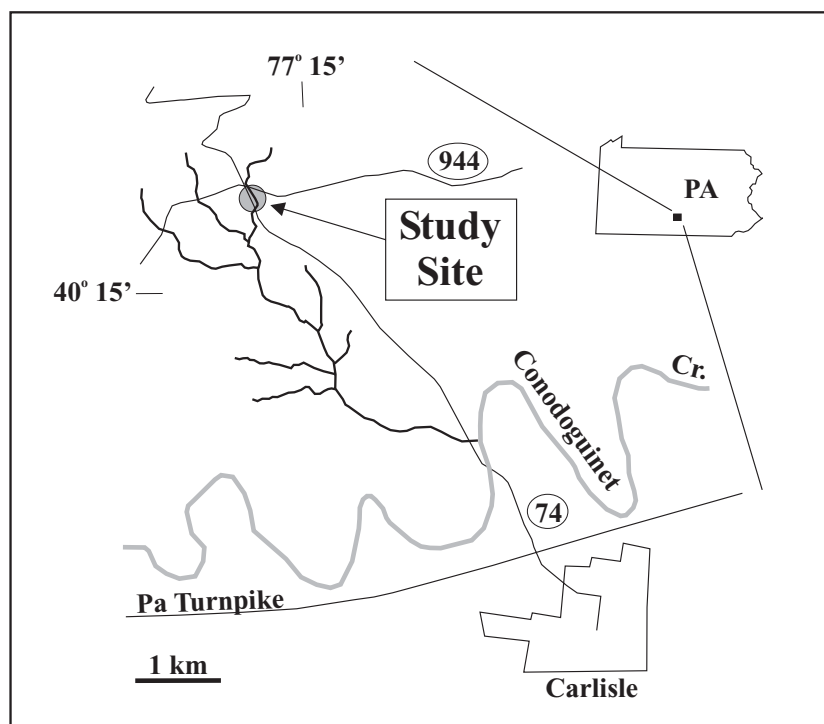


Figure 3. Location of the study site on an unnamed tributary of Conodoguinet Creek.

METHODS

Determining Channel Morphology, Alluvial Stratigraphy, and Bank Process Rates

We surveyed channel cross sections following methods described by Hession et al. (2000, 2002, 2003a, 2003b) at the four paired sites and by Potter et al. (1998) along the tributary to Conodoguinet Creek. We also made geomorphic maps of the paired reaches using a TOPCON total station. We surveyed points along the edges of the riverbed, along eroding cutbanks, and along erosional scarps that mark the boundary between the area of active floodplain deposition and the more extensive valley flat. We made the maps to determine the area of accumulating active floodplains.

We used an Eijkelkamp peat auger to obtain sediment samples at all the sites. We used these data to make stratigraphic cross sections along surveyed topographic profiles. We also took sediment samples from the active floodplains by digging with a shovel or a bucket auger and from the entire height of eroding cutbanks by scraping with a shovel. We used standard methods to determine the weight percentages of mud (mud is defined here as sediment finer than 0.0625 mm, following the Udden-Wentworth scale [Prothero, 1990]), sand and gravel (Folk, 1974). We also classified the sediments in each

distinguishable soil horizon within the cutbanks using standard methods (USDA, 1998).

We determined rates of bank erosion and active floodplain accumulation over relatively short (annual) and long (decadal) time scales. For the annual rates of erosion and deposition, we resurveyed a single monumented cross section in each reach during the same year as its initial survey. Because different sites were surveyed at different times, the elapsed times between surveys varied from 5 months to 1 yr (because of the potential for seasonal differences in erosion and deposition rates, we rely on the longer term estimates for quantitative analyses, but the shorter term estimates provide useful perspective and verification of methods used to determine longer term rates). For the decadal time scales, we used geomorphic maps and dendrochronology. We identified all the trees on each active floodplain and cored them with an increment borer (Allmendinger et al., 1999). We counted annual rings to date all the trees. We assume that the thickness of sediment above the original (nonadventitious) roots of the tree is the net amount that has accumulated during the life of the tree. Dividing the thickness of sediment by the age of the tree provides an estimate of the rate of active floodplain accumulation (Hupp and Bazemore, 1993).

The reach-averaged long-term (i.e., decadal) rate of lateral channel migration was estimated using the following expression:

This equation is based on the hypothesis that the accommodation space required for active floodplain formation is created by lateral migration of the channel. We also assume that 1) the age of the oldest tree is approximately equal to the minimum age of the active floodplain, and 2) the channel width has remained approximately constant through time. It directly follows from these hypotheses that the surface area of the active floodplain is equal to the areal extent of lateral migration of the stream channel during the period of active floodplain development.

Grassy Vegetation on Active Floodplains

We measured the density of grassy vegetation on the active floodplain in two ways. We used the “board test” described by Kouwen (1988) to provide a measure of the height, stiffness, and density of grassy vegetation (board tests are not used on trees). We also directly measured the mass of the grassy vegetation on each active floodplain.

We speculate that friction caused by grassy vegetation results in lower flow velocities over the floodplain surface, inspiring more rapid deposition of suspended sediment. We needed some measure that could represent the frictional characteristics of vegetation to verify this assumption. The board test provides such a measure. It involves dropping a pine board flat onto a vegetated surface; the height of the center of the board above the ground is then measured. The results of the board test, referred to here as the “board height,” have been directly related to the friction factor imposed by grassy vegetation on the flow (Kouwen, 1988).

We also measured the mass of grassy vegetation on the active floodplains by harvesting all the plants in a randomly selected one-square-meter plot and weighing them in the field. On floodplains where vegetation grows in distinct zones of different densities, we sampled from a one-square-meter plot in each zone and averaged the results from each plot.

We did not quantify the mass or density of trees on the active floodplain because only a few trees were growing on convex-bank floodplains in both forested and nonforested reaches.

Estimating Cutbank Erodibility

We measured the shear strength of the cutbanks using a hand-held shear vane device manufactured by Pilcon Engineering, Ltd. We made 10–20 measurements at each site. Each measurement was made in bare soil without obvious large roots approximately halfway between the water surface and the top of the bank. Measurements were spaced at ~1 m intervals streamwise along the channel. All measurements were completed

in the summer months and corresponding forested and nonforested reaches were sampled on the same day to facilitate comparisons.

We measured the abundance of both tree roots and grass roots in the cutbanks. We assumed that large roots belong to trees and that small roots belong to grassy vegetation. Thus, our methods allow us to draw inferences regarding how the roots of grasses and trees influence bank erodibility in our paired forested and nonforested reaches.

We recorded the presence or absence of large roots along at least ten vertical sections in the cutbank of every study reach. We consider roots to be “large” if they are greater than 1.0 cm in diameter. Vertical sections were one meter apart, and the individual sampling points on each section were spaced 10 cm apart. The sampling points extended from the top of the bank to the water surface. A 61 cm long nail was driven into the bank until it met resistance. When the nail struck a root, it would make an audible “thud,” whereas if it struck a rock, it would make an audible “clink.” We infer that roots large enough to stop the nail were large roots, probably belonging to trees. Many individual tests were performed in each soil horizon along the bank. We report the fraction of positive observations as an estimate of the areal density of tree roots at a given distance from the top of the bank.

We made visual estimates of the abundance of small roots (less than 2 mm in diameter) using standard methods (USDA, 1998). We sampled a single vertical section in each reach. The number of samples in a given section depended on the number of distinctive horizons visible in the soil profile. We inspected the cutbanks for visible differences in root density and texture, and divided them into horizons.

RESULTS

Floodplain Development Through Time

Figure 1 presents data from the “central meander” of the tributary of the Conodoguinet Creek near Carlisle, Pennsylvania (Potter et al., 1998). A topographic profile was surveyed, seven cores were obtained, and sediment was sampled at 9 locations for grain size analysis. Five samples were obtained from the active floodplain and the other four samples were obtained from deposits of the valley flat. Topographic surveys were available for 1974, 1979, 1982, 1985, 1988, 1992, 1994, and 1997–2000; only a few of these are illustrated in Figure 1 for clarity. The concave bank (on the left side of the diagram) is only included for the first (1974) and last (2000) surveys so that the evolution of the active floodplain can be clearly perceived.

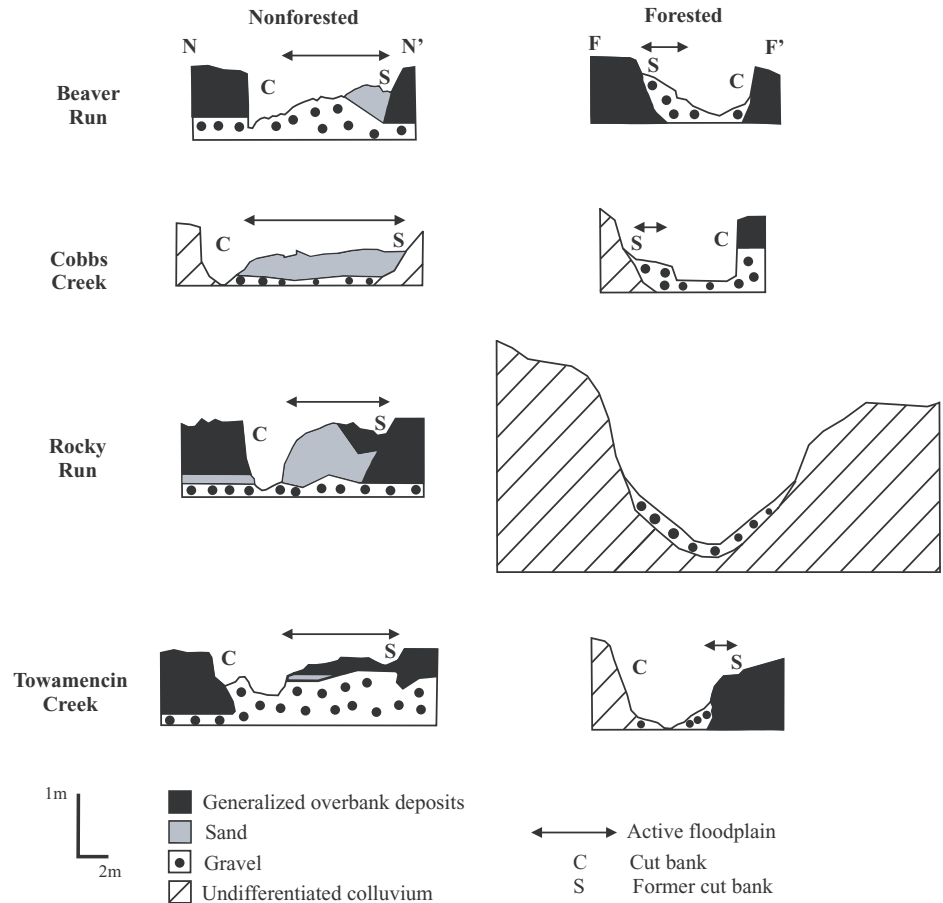


Figure 4. Stratigraphic cross sections at each of the four paired nonforested and forested study reaches. Locations of the cross sections are illustrated in Figure 8.

In 1974, the channel was straight (Potter, unpublished data) and the channel cross section was approximately trapezoidal. From 1974 until 2000, a bend developed and the channel migrated toward the left side of Figure 1. As the channel migrated, erosion occurred at the cutbank and sediments draped onto and over the convex bank of the river gradually built the active floodplain. The active floodplain grew primarily by lateral accretion but also by vertical accretion, as floodwaters deposited thin layers a few centimeters thick on the upper surface of the developing floodplain. This pattern of deposition is similar to the oblique accretion defined by Nanson and Croke (1992) and observed by Moody et al. (1999) and Brakenridge (1984). Because rates of vertical accretion have been relatively slow, the uppermost part of the original riverbank surveyed in 1974 remains preserved as a distinct scarp between the active floodplain and the valley flat. The surveys also clearly indicate that the channel bottom remained at the top of the gravel deposit illustrated in Figure 1, and therefore the

uppermost surface of the gravel is mapped as an erosional unconformity.

Grain size data indicate that the active floodplain deposits are coarser than the deposits of the valley flat (and hence, the cutbanks as well). Analyses of the percentages of sand in the valley flat deposits are all less than 28%, with a mean of 17% and a range of 12%–27%. Percentages of sand in the active floodplain are all greater than 28%, with a mean of 35% and a range of 29%–45%. These deposits are finer grained than those of the paired reaches described below, probably because of the shale bedrock underlying the watershed of this unnamed tributary (Potter et al., 1998).

Stratigraphic Data From Paired Reaches

Figures 4 and 5 represent stratigraphic and topographic cross sections of the valley flat and active floodplains at the paired reaches. Topographic cross sections indicate the locations of eroding cutbanks, from which we infer

VEGETATION AND WIDTH ADJUSTMENT

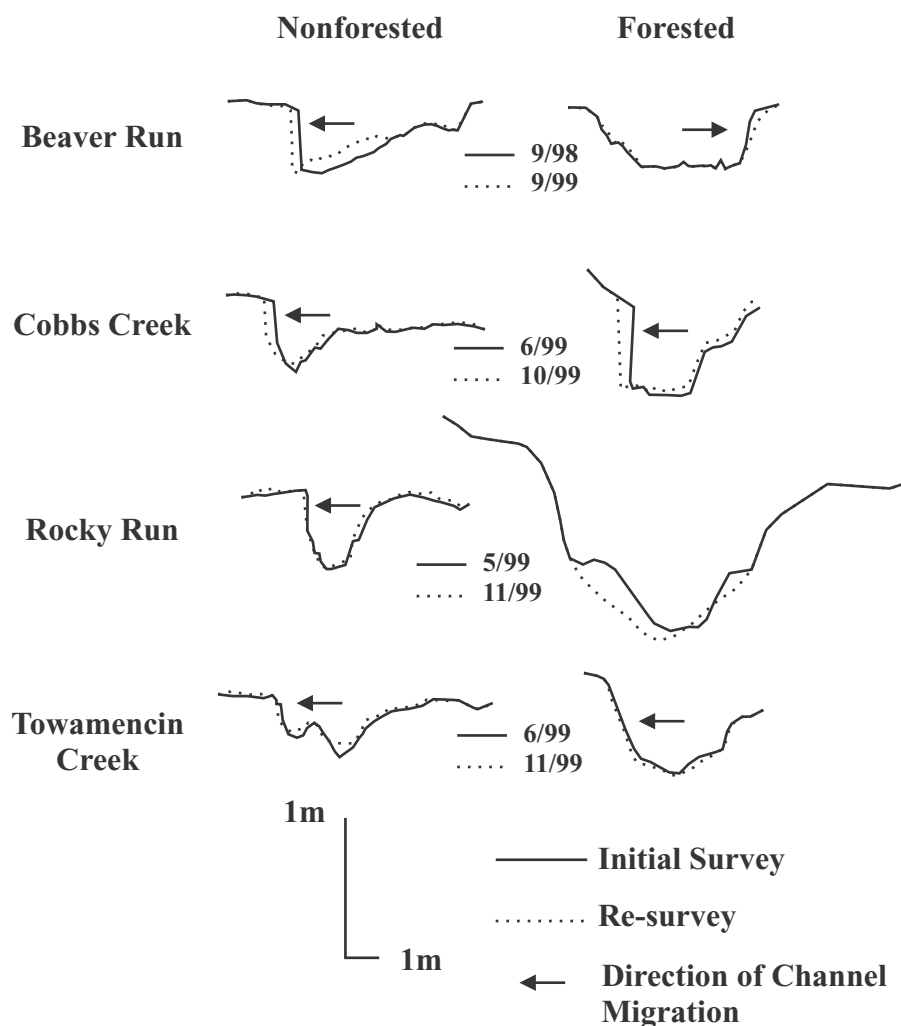


Figure 5. Topographic cross sections showing patterns of erosion and deposition over a period of ~1 yr at each of the four paired nonforested and forested study reaches.

the directions of channel migration illustrated in Figure 5. Figures 4 and 5 also indicate that the active floodplain and the valley flat are separated by an abrupt scarp. Consistent with the data from the unnamed tributary of the Conodoguinet Creek, we interpret this scarp as an erosion surface that represents the location of a former bank of the river. Thus, the active floodplain deposits are bounded by unconformities, and they may therefore be classified as allostratigraphic units similar to those defined on the Amite River in Louisiana by Autin (1992). This also suggests that the active floodplains are younger than the floodplain deposits underlying the valley flat.

The cross sections of Figure 4 indicate the sediment characteristics of stratigraphic units of our study sites. Both the valley flat and active floodplains have a basal layer of gravel. Depos-

its of the valley flat are mapped as “generalized overbank deposits;” they consist of massive sandy silt with occasional thin beds of sand. The active floodplains are either composed entirely of gravel, or, in some cases, the basal gravel is overlain by sand. Thin beds of mud are present in some active floodplain deposits. Colluvium borders the channel at the locations of the cross sections of one of the nonforested sites and three of the forested sites (both colluvium and localized bedrock exposures may be found along all of our study reaches, even though they do not occur along all the cross sections). At the forested reach of Rocky Run, floodplain deposits are absent, and the channel is bordered primarily by colluvium. These data reinforce the conclusion that these relatively small river channels are not fully alluvial but are influenced to varying degrees by bedrock and hillslope processes.

Grain size analyses of sediment samples demonstrate that active floodplains contain less mud than valley flat deposits sampled from the cutbanks (Fig. 6). The mud content in the active floodplains averages ~27% (standard deviation = 19%) while the mud content in the cutbanks averages ~49% (standard deviation = 24%). Using 8 samples from the floodplains and 8 samples from the cutbanks, the Mann-Whitney U test predicts that there is only a 4% probability that these samples could come from the same population; thus, the difference in grain size between the active floodplains and the valley flat deposits is statistically significant. Furthermore, the extensive gravel deposits of the active floodplains were not included in these samples because we could not core through these deposits, so the statistics quoted above actually underestimate the relatively coarse-grained nature of the active floodplains.

Rates of Bank Erosion and Floodplain Deposition

Based on the resurveys of the monumented cross sections, cutbanks are migrating laterally almost 9 times faster in the nonforested reaches than in the forested ones (Figs. 5 and 7, Table 2). Short-term migration rates in the nonforested reaches averaged 0.75 m/yr (standard deviation = 0.63 m/yr), while those in forested reaches averaged 0.09 m/yr (standard deviation = 0.17 m/yr) (Fig. 7A). A Kruskal-Wallis one-way analysis of variance for these 8 reaches demonstrates that there is a significant difference between these migration rates ($p = 0.04$).

Active floodplains are larger and more distinctive in the nonforested reaches than in the forested reaches (Fig. 8). Active floodplains in the nonforested reaches occupy ~5 times more surface area than those in the forested reaches (Fig. 7B). On average, active floodplains occupy 400 m² (standard deviation = 150 m²) in grassy reaches but only 88 m² (standard deviation = 46 m²) in forested reaches.

The trees growing on the active floodplains are approximately the same age in the forested and nonforested reaches (Table 3). The average age of trees growing on the active floodplains in the nonforested reaches is 12 yr (standard deviation = 6 yr), while the average age of those in the forested reaches is 11 yr (standard deviation = 4 yr). Our estimates of the decadal net lateral accretion rates suggest that the active floodplains in the nonforested reaches accumulate 4.9 times faster than those in the forested reaches. The long-term, reach averaged lateral migration rate for the nonforested reaches is 0.34 m/yr (standard deviation = 0.13 m/yr) (Table 2), while the corresponding rate for forested reaches is only

0.07 m/yr (standard deviation = 0.07 m/yr). A Kruskal-Wallis one-way analysis of variance demonstrates that there is a significant difference between these lateral accretion rates ($p = 0.02$). The values reported here are similar to meander migration rates reported by Pizzuto and Meckelnburg (1989) for the Brandywine Creek in southeastern Pennsylvania. Pizzuto and Meckelnburg (1989) observed migration rates of 0.26 m/yr for banks without large trees and rates of 0.04 m/yr for bank with large trees.

Estimates of net vertical accretion rates based on dendrochronology suggest that active floodplains are vertically accreting 8.6 times faster in the nonforested reaches than in the forested ones (Fig. 7C and Table 3). Active floodplains in the nonforested reaches are accumulating vertically at an average rate of 1.9 cm/year (standard deviation = 1.4 cm/year), while those in forested reaches accumulate at an average rate of 0.2 cm/year (standard deviation = 0.3 cm/year). A Kruskal-Wallis one-way analysis of variance demonstrates that there is a significant difference between these vertical accretion rates ($p = 0.02$).

Grassy Vegetation on Active Floodplains

The board height was 3.8 times greater in the nonforested reaches than in the forested ones (Fig. 9 and Table 4). The average board height in the nonforested reaches was 33.5 cm (standard deviation = 30.8 cm), while the average board height in the forested reaches was 8.7 cm (standard deviation = 14.2 cm). Active floodplains in nonforested reaches supported ~5 times more grassy vegetation mass than those in the forested reaches. Active floodplains in the nonforested reaches supported an average of 1.96 kg/m² of grassy vegetation per square meter (standard deviation = 0.60 kg/m²), while those in the forested reaches supported an average of 0.38 kg/m² (standard deviation = 0.28 kg/m²) (Table 4). A Kruskal-Wallis one-way analysis of variance for 246 data points demonstrates that there is a significant difference between the board test results for the forested and nonforested reaches ($p = 0.00$).

Measures of Cutbank Erodibility

Qualitative classification of the soil horizons suggests that the cutbanks of the forested reaches tend to be sandier than those of the nonforested reaches, though differences are relatively small. Figure 10 indicates that most of the cutbanks in forested reaches are loamy sand or sandy loam, while nonforested reaches include more loam, sandy clay, clay loam, and other finer grained soil types.

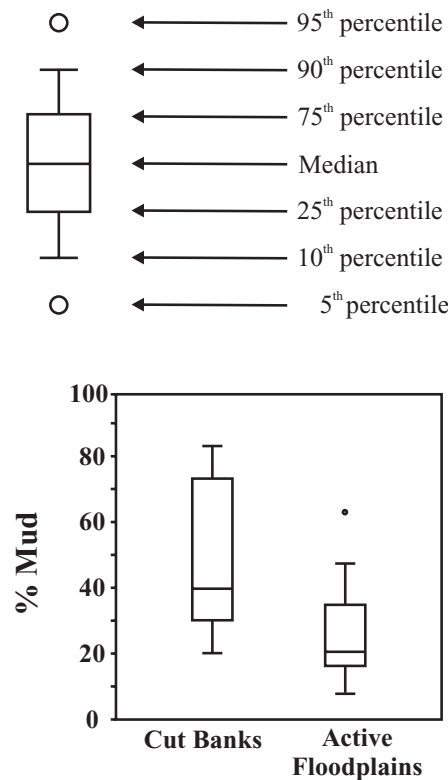


Figure 6. Box and whisker diagram showing the percentages of mud in active floodplains and cutbanks.

Quantitative analyses do not show significant differences, possibly because the samples included varying thicknesses of gravelly sediments sampled from the base of the cutbanks. No significant differences in % sand, gravel, or mud were noted between forested and nonforested reaches.

The soils of cutbanks in the nonforested reaches have shear strengths that are 1.7 times greater than those in the forested reaches (Fig. 11). In the nonforested reaches, the average strength at failure was 43.13 KPa (standard deviation = 23.02 KPa), while in the forested reaches the average strength was 25.07 KPa (standard deviation = 18.89 KPa). We observed this difference in every study site except for Towamencin Creek where the soil of the forested cutbank was stronger than the soil of the nonforested cutbank. A Kruskal-Wallis one-way analysis of variance for 234 data points demonstrates that there is a significant difference between the vane shear results for the forested and nonforested reaches ($p = 0.00$).

A total of 884 points were sampled at the 8 reaches for the presence or absence of large

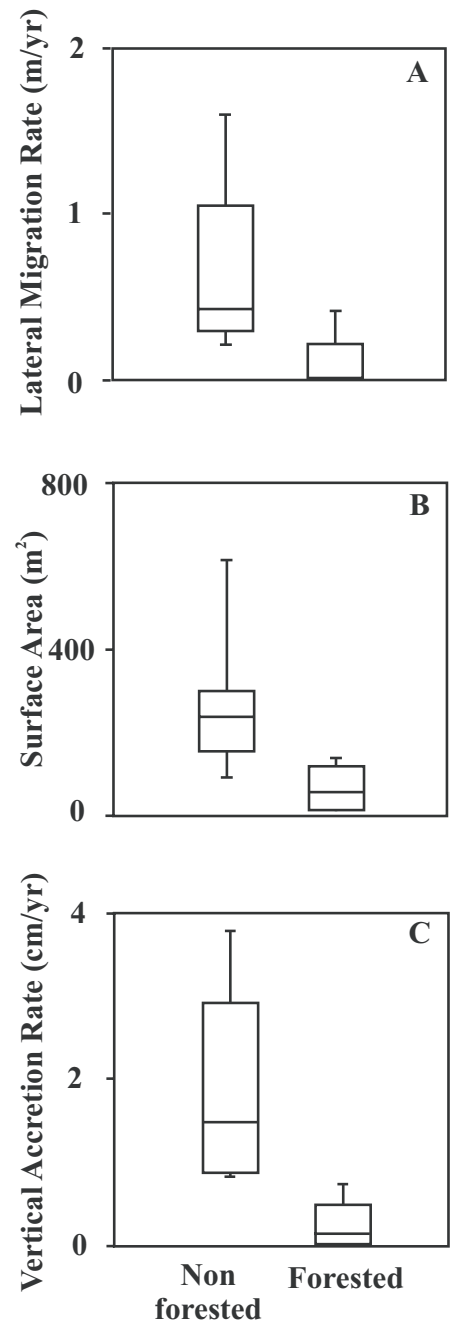


Figure 7. Box and whisker diagram illustrating (A) annual lateral migration rates, (B) surface areas of active floodplains, and (C) vertical accretion rates for nonforested and forested study reaches.

roots. Results of a chi-square test indicate that there is a significantly greater chance of hitting a tree root in a forested reach cutbank than in a nonforested reach cutbank. Large roots are roughly 8.1 times more abundant in the forested

VEGETATION AND WIDTH ADJUSTMENT

TABLE 2. RATES OF GEOMORPHIC PROCESSES IN PAIRED REACHES

Study site and reach	Active floodplain vertical accumulation rate (cm/year)	Short-term migration rate [†] (m/year)	Long-term migration rate (m/year)
Beaver Run, forested	0.2	0.00	0.14
Beaver Run, nonforested	2.1	0.50	0.39
Cobbs Creek, forested	0.0	0.00	0.05
Cobbs Creek, nonforested	0.8	1.68	0.37
Rocky Run, forested	NA	NA	NA
Rocky Run, nonforested	0.9	0.28	0.15
Towamencin Creek, forested	0.7	0.34	0.02
Towamencin Creek, nonforested	3.8	0.53	0.46
Forested mean	0.2	0.09	0.07
Forested standard deviation	0.3	0.17	0.07
Nonforested mean	1.9	0.75	0.34
Nonforested standard deviation	1.4	0.63	0.13

[†]The elapsed time between surveys is indicated in Figure 5.

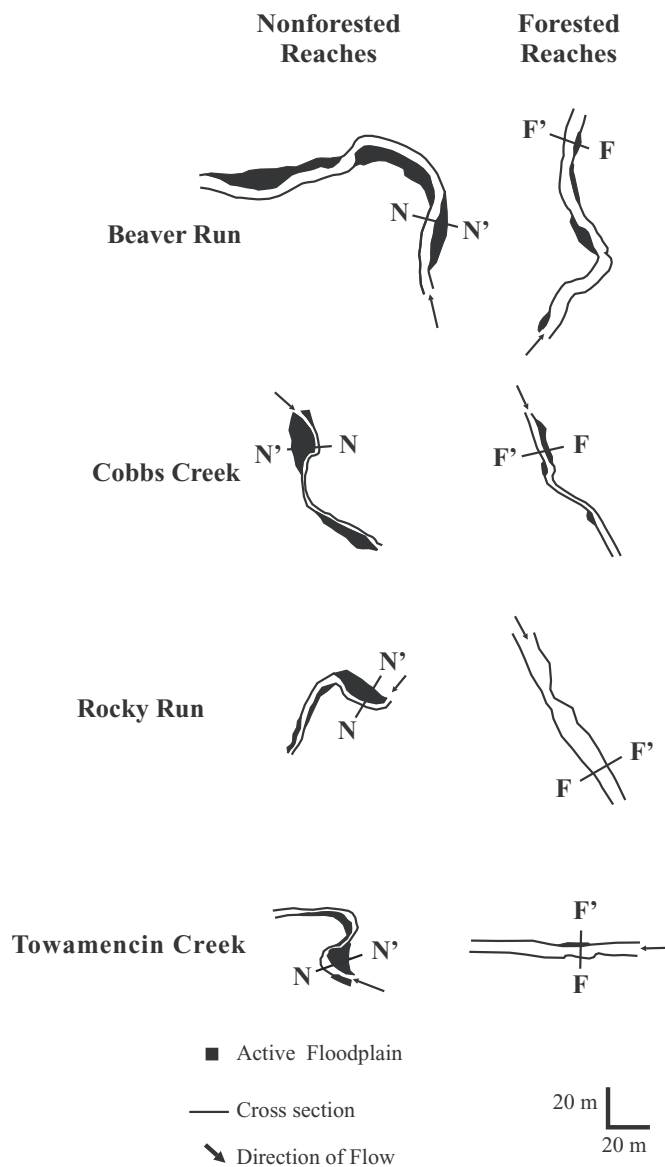


Figure 8. Geomorphic maps illustrating locations and orientations of the cross sections, directions of water flow, and areal extent of active floodplains.

reaches than in the nonforested reaches. The average fraction of large roots struck while sampling the forested reaches (total # of nails driven/ # of “thuds” heard) is 0.26 (standard deviation = 0.44). The average fraction of large roots struck while sampling the nonforested reaches is 0.03 (standard deviation = 0.18). A standard Chi-square analysis demonstrates that there is significant difference in the abundance of tree roots in the cutbanks between forested and nonforested reaches ($\chi^2 = 93.72$). In both the forested and nonforested reaches tree roots are poorly correlated with depth from the top of the bank (Fig. 12); tree roots appear to be randomly distributed throughout the cutbanks in both forested and nonforested reaches.

Small roots are only abundant within the upper 40 cm of the cutbanks in both the forested and nonforested reaches (Fig. 12). The average abundance is slightly higher in the nonforested reaches, but a Kruskal-Wallis one-way analysis of variance for 49 different horizons in the eight reaches suggests that there is no significant difference between the two reaches ($p = 0.69$).

DISCUSSION

Stratigraphy

Active floodplains of our study area form by lateral migration during the expansion of bends in the channel. They typically intersect the valley flat in an abrupt scarp that we interpret as a former riverbank. Active floodplains of our study area are significantly coarser grained than deposits underlying the valley flat. In our paired reaches, convex-bank floodplains are composed primarily of sand and gravel with scattered beds of silt and clay. Convex-bank floodplains are bounded by unconformities, and may, therefore, be classified as allostratigraphic units. Our stratigraphic data and surveyed cross sections therefore suggest a recent history of floodplain formation by lateral migration similar to that described by Leopold and Wolman (1960) and Wolman and Leopold (1957) along Watts Branch in Maryland. Similar deposits have been documented in previous studies of the Mid-Atlantic Piedmont (Coleman, 1982; Jacobson and Coleman, 1986; Pizzuto, 1987). However, we do not observe the distinctive paleosol in valley flat deposits noted by others that represents the floodplain elevation before European settlement. Nonetheless, the active floodplains we define at our study reaches are equivalent stratigraphically to the “Very Recent” deposits defined by Jacobson and Coleman (1986). However, Jacobson and Coleman date their “Very Recent” floodplains to the beginning of the 1930’s, while the convex-bank

floodplains we describe have a minimum age of roughly one decade.

Bank Erodibility

Soils in the cutbanks of the forested reaches have lower shear strengths, higher sand contents, and higher concentrations of large roots than those of the nonforested reaches. The abundance of small roots is probably not significant because they are only present in the upper part of the bank, leaving the toe of the bank unprotected from erosive stress exerted by the flow (Pizzuto, 1984). Large roots are probably more important than soil strength in controlling the susceptibility of banks to erosion (Micheli and Kirchner, 2002; Riestenberg and Sovonick-Dunford, 1983; Wu et al., 1979), and thus we speculate that forested cutbanks are more difficult to erode than nonforested cutbanks (independent validation of this hypothesis is presented below in the section on “Relative Magnitudes of α and $E \dots$ ”).

Bank erodibility is often represented by a dimensionless coefficient E in models of river channel migration (Ikeda et al., 1981; Odgaard, 1987; Pizzuto and Meckelnburg, 1989). The coefficient E is a proportionality constant that relates the velocity adjacent to the cutbank (U_b , with units of m/s) to the rate of bank retreat:

$$\text{Rate of cut bank retreat} = E \times U_b$$

Our results suggest that E is relatively high in grassy reaches and relatively low in forested reaches. Similar results have been obtained by Micheli et al. (2004), Odgaard (1987), and Pizzuto and Meckelnburg (1989).

Why Grassy Reaches are Narrower than Forested Reaches

The morphology, rates of lateral migration, and vegetation characteristics of our study sites are summarized in Figure 13 (while the results of Fig. 1 illustrate how these forms are created). Nonforested reaches are narrow with dense grasses on the active floodplains. In the nonforested reaches, deposition rates on active floodplains (and lateral migration rates) are high. Forested reaches, on the other hand, are wide with few grasses on the active floodplain. Deposition rates on active floodplains (and lateral migration rates) in the forested reaches are low.

We propose that the difference in width between forested and nonforested reaches is related to a balance between rates of cutbank erosion and rates of deposition on active floodplains. Essentially, our interpretation is that equilibrium widths develop to equalize rates of

TABLE 3. DENDROCHRONOLOGY DATA FOR TREES FROM ACTIVE FLOODPLAINS

Tree species	Site	Reach	Growth rings (#)	Sediment thickness (cm)
Black Walnut (<i>Juglans nigra</i> L.)	Cobbs Creek	nonforested	15	8.0
Alternate Leaf Dogwood (<i>Cornus alternifolia</i> L.f.)	Cobbs Creek	nonforested	9	10.0
Broadleaf Willow (<i>Salix glaucophylloides</i> Fern.)	Cobbs Creek	nonforested	7	0.0
Spice Bush (<i>Calycanthus occidentalis</i>)	Cobbs Creek	forested	15	0.0
Spice Bush (<i>Calycanthus occidentalis</i>)	Cobbs Creek	forested	8	0.0
Coastal Plain Willow (<i>Salix caroliniana</i>)	Towamencin Creek	nonforested	5	19.0
Boxelder (<i>Acer negundo</i> L.)	Towamencin Creek	forested	16	11.0
Spice Bush (<i>Calycanthus occidentalis</i>)	Beaver Run	forested	7	2.0
Spice Bush (<i>Calycanthus occidentalis</i>)	Beaver Run	forested	10	1.0
Sycamore (<i>Platanus occidentalis</i> L.)	Beaver Run	nonforested	11	0.0
Sycamore (<i>Platanus occidentalis</i> L.)	Beaver Run	nonforested	11	22.5
Sycamore (<i>Platanus occidentalis</i> L.)	Rocky Run	nonforested	25	18.0
Sycamore (<i>Platanus occidentalis</i> L.)	Rocky Run	nonforested	12	14.0
Forested mean			11.2	2.8
Forested standard deviation			4.1	4.7
Nonforested mean			11.9	11.4
Nonforested standard deviation			6.1	8.5

cutbank erosion and vegetation-mediated rates of deposition on active floodplains.

We develop these ideas quantitatively below using a very simple analysis. Our primary purpose is to use these equations to present our hypotheses clearly; the ideas involved are intricate and are difficult to understand when expressed using words alone. We discuss the limitations of our results and interpretations in a separate section.

First, we consider a state of quasi-equilibrium characterized by equal time-averaged rates of cutbank retreat and convex-bank lateral accumulation. Under these conditions, the channel is simply assumed to be migrating laterally without changing form (i.e., with equal rates of convex bank accumulation and cutbank erosion) as illustrated in Figure 13. Second, to emphasize how vegetation influences the rate of lateral accumulation on active floodplains, we parameterize the

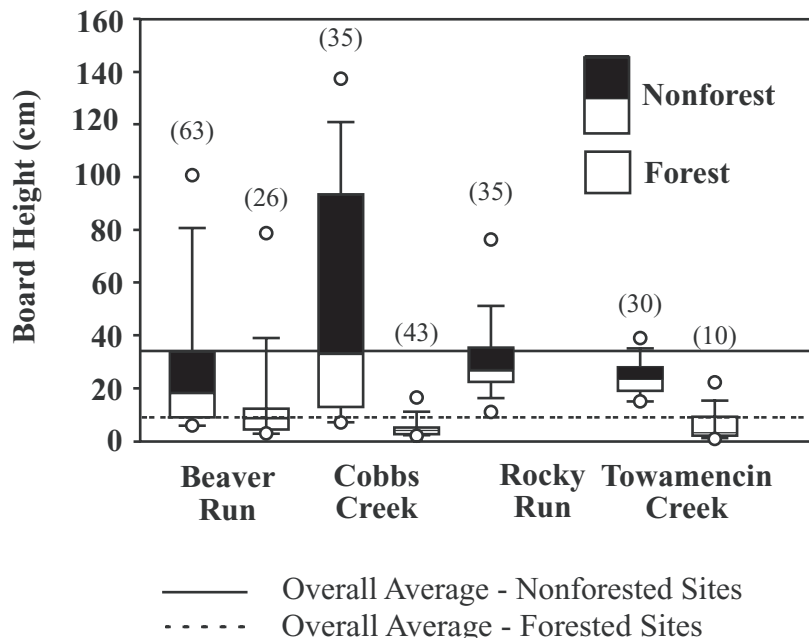


Figure 9. Box and whisker diagram illustrating board height data for all study reaches.

VEGETATION AND WIDTH ADJUSTMENT

TABLE 4. PROPERTIES OF GRASSY VEGETATION GROWING ON ACTIVE FLOODPLAINS

Stream	Reach	Mass of vegetation (kg)	Average board height (cm)
Beaver Run	forested	0.59	16.0
Beaver Run	nonforested	1.52	29.7
Cobbs Creek	forested	0.59	5.3
Cobbs Creek	nonforested	2.82	50.5
Rocky Run	forested	0.00 [†]	0.0 [†]
Rocky Run	nonforested	1.58	31.4
Towamencin Creek	forested	0.35	10.2
Towamencin Creek	nonforested	1.93	33.0
Forested mean		0.38	8.7
Forested standard deviation		0.28	14.2
Nonforested mean		1.96	33.5
Nonforested standard deviation		0.60	30.8

[†]There is no active floodplain in the Rocky Run forested reach

$$U = \frac{Q}{WH} \quad (4)$$

We assume in this analysis that the appropriate channel-forming discharges in contiguous forested and nonforested reaches are the same, but we note that this is an assumption that we cannot rigorously test.

Inserting equations (3) and (4) into equation (2) and solving for the width leads to:

$$W = \left(\frac{E}{\alpha} \right) \left\{ \left(\frac{Q}{H} \right) \left(\frac{u_b}{D_r} \right) \right\} \quad (5)$$

Because Q and H are constant between adjacent pairs, the middle term on the right-hand side of equation (5) will be constant when comparing forested and nonforested reaches. Furthermore, the significant variables that influence near bank velocity u_b (see Johanneson and Parker, 1989) and the deposition rate D_r (these include the bed material grain size, the bankfull depth H , and the channel bed slope) are also constant, with the exception of sinuosity. Because sinuosity varies by only 20% between forest and nonforested paired reaches of our study site (and not at all in the larger population of study sites of Hession et al. [2003a]), we argue that u_b/D_r can be treated as a constant without excessive error when comparing forested and nonforested reaches. This suggests that 1) the width W will vary primarily with the ratio of E/α when comparing adjacent forested and nonforested reaches, and 2) the other two quantities in parentheses on the right of equation (5) are less significant.

Table 5 illustrates how equations (2) and (5) can be used to provide a provisional explanation of our field observations. In forested channels, E is low, but the low density of grasses results in a very low value of α . Thus, the ratio E/α is high (despite low values of E) and the channel is wide. Because W is large, and because Q and H are constant between paired reaches, equation (4) indicates that U is relatively low in forested reaches, and the left side of equation (2) indicates that the channel will migrate slowly (a low migration rate will be expected with low values of both U_b and E). In grassy channels, E is high, but the dense grasses result in a very high value of α . The ratio E/α is small (despite high values of E), and the channel is narrow. A small width is associated with a relatively high velocity (equation (4)), and therefore the channel migrates rapidly (high values of both E and U_b). Thus the ratio E/α provides a significant control over the width of our paired reaches, and the width is related via the near-bank velocity and E to rates of lateral migration.

deposition rate in terms of the accumulation rate in the absence of vegetation (D_r), and a dimensionless coefficient (α) that represents the effects of vegetation:

$$\text{Rate of lateral accumulation} = \alpha \times D_r \quad (1)$$

The parameter alpha (α) represents a variety of processes, including the hydraulic resistance offered to the flow as well as the ability of dense grassy roots to increase the erosion resistance of new active floodplain deposits. The numerical value of α is equal to 1 where no vegetation is present and it exceeds 1 when vegetation is present. According to our results, the dense grassy vegetation of nonforested reaches creates a relatively high value of α , while the sparse grassy vegetation of forested reaches creates a relatively low value of α .

At equilibrium, the rate of cutbank retreat is equal to the rate of lateral accumulation:

$$EU_b = \alpha D_r \quad (2)$$

According to Johanneson and Parker (1989), the near bank velocity U_b scales with the reach-averaged velocity, U , such that

$$U_b = U u_b \quad (3)$$

In equation (3), u_b is a dimensionless near bank velocity that depends on the radius of curvature, friction factor, and sediment grain size (because it is dimensionless, it does not depend on the discharge, flow depth, or width). The reach-averaged velocity can be expressed in terms of a channel-forming discharge, Q , the mean depth, H , and the width, W :

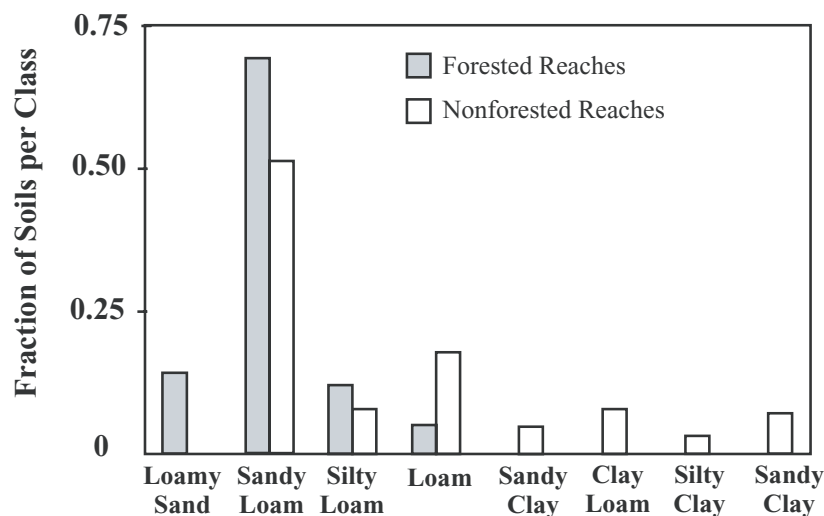


Figure 10. Histogram illustrating the relative abundances of different soil types found in the cutbanks of forested and nonforested study reaches.

These arguments suggest that the presence or absence of dense grassy vegetation on active floodplains is the critical variable for explaining the differences in morphology and dynamics of our paired study reaches. In forested reaches, armoring by tree roots creates banks with low erodibility (i.e., low E). Sparse grasses on point bars, however, cause very low accumulation rates that counteract the effect of low bank erodibility, creating wide, slowly migrating channels. In contrast, the cutbank toe of non-forested reaches is devoid of roots, resulting in high erodibility (i.e., high E). However, dense grasses on convex-bank floodplains create very high accumulation rates that counteract the effect of high bank erodibility, creating narrow, rapidly migrating channels. In both cases, the presence or absence of grasses overcomes the expected influence of bank erodibility. Thus, the density of grasses on point bars, as represented by the parameter α in our illustrative quantitative model, is the key variable for explaining the differences in width between paired forested and nonforested reaches of our study area.

The Relative Magnitudes of α and E in Forested and Nonforested Reaches

An approximate estimate of the relative values of α in the nonforested and forested reaches can be obtained by writing equation (1) as a ratio:

$$\frac{\text{nonforest migration rate}}{\text{forest migration rate}} = \frac{\alpha_n D_m}{\alpha_f D_f} \quad (6)$$

where the subscript f refers to the forested reach and the subscript n refers to the nonforested reach. To simplify equation (6), we argue that D_r should have similar values in nonforested and forested paired reaches because the slope, bed material, depth, and grain size are similar (Hession et al., 2002). This approximation is not exact: sinuosity varies on average by ~20%, and this variation is likely to lead to a similar magnitude of variability in D_m/D_f . By accepting this variability D_m/D_f can be canceled from equation (6) with a relatively small error (i.e., on the order of 20%), leading to equation (7):

$$\frac{\alpha_n}{\alpha_f} = \frac{\text{nonforest migration rate}}{\text{forest migration rate}} \quad (7)$$

According to the data of Table 2, the ratio of long-term migration rates is 0.34/0.07 or ~5, suggesting that deposition rates on active floodplains in the nonforested reaches are enhanced by a factor of 5 due to the presence of grassy vegetation.

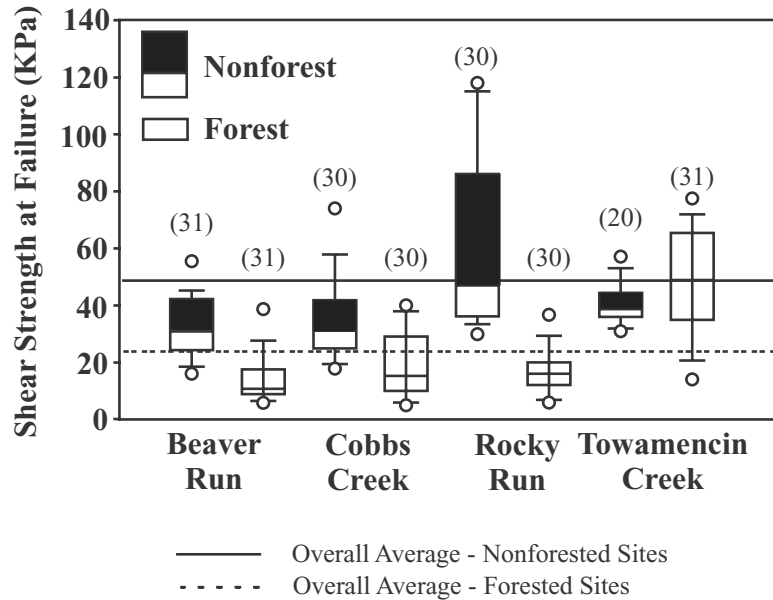


Figure 11. Box and whisker diagram illustrating vane shear data for all study reaches.

An estimate of the ratio E_n/E_f can be obtained by forming a similar ratio from equation (5), noting, as argued above, that the second and third quantities in parentheses in equation (5) may be canceled with an error of ~20%. This leads to:

$$\frac{W_f}{W_n} = \frac{E_f \alpha_n}{E_n \alpha_f} \quad (8)$$

Rearranging equation (8):

$$\frac{E_n}{E_f} = \frac{W_n \alpha_n}{W_f \alpha_f} \quad (9)$$

Noting that α_n/α_f is approximately 5 and that W_n/W_f is ~5/8 (Table 1 and Fig. 13), a value of 25/8 or ~3 is obtained for E_n/E_f suggesting that, for a given velocity, banks in the nonforested reaches erode 3 times faster than banks in the forested reaches. These estimates also reinforce the qualitative results presented in Table 5 and the conclusions derived from them. Because the value of 5 for α_n/α_f is larger than the value of 3 for E_n/E_f variations in grassy vegetation on convex bank floodplains can overcome variations in bank erodibility between forested and nonforested reaches. These observations help to clarify how grassy vegetation plays a key role in width adjustment in these streams.

Implications for River Restoration

Many restoration designs rely on regional reference curves that relate channel morphology

to discharge or drainage basin area (Dunne and Leopold, 1978; Rosgen, 1996). Reference curves are used to approximate the size and shape of quasi-equilibrium stream channels in a region. These curves do not consider differences in riparian vegetation between reaches (Hession, 2001). Our results clearly demonstrate that vegetation exerts a profound influence on both form and process in rivers. Restoration designs that effectively account for riparian vegetation could result in more accurate predictions of channel morphology and could provide greater control of rates of erosion and deposition in restored channels (Hession, 2001).

As an example, consider the common practice of using vegetation to reduce rates of cutbank erosion. According to our results, planting trees on a cutbank will reduce rates of channel migration as the trees grow and the roots increase in size, leading to smaller values of E . However, our results indicate that reducing E will also reduce E/α , and the channel width will decrease, a result that may not be intended or desirable. Furthermore, if the trees grow large enough to shade active floodplains, the growth of grassy vegetation could be impeded, reducing α , and increasing the ratio E/α and hence the channel width. If this occurs, planting trees could ultimately increase the channel width, and the sediment supplied to downstream reaches would also increase because less sediment would be trapped on developing active floodplains.

The application of these ideas in practice can only be achieved, however, if specific methods are developed that can be used to predict the

VEGETATION AND WIDTH ADJUSTMENT

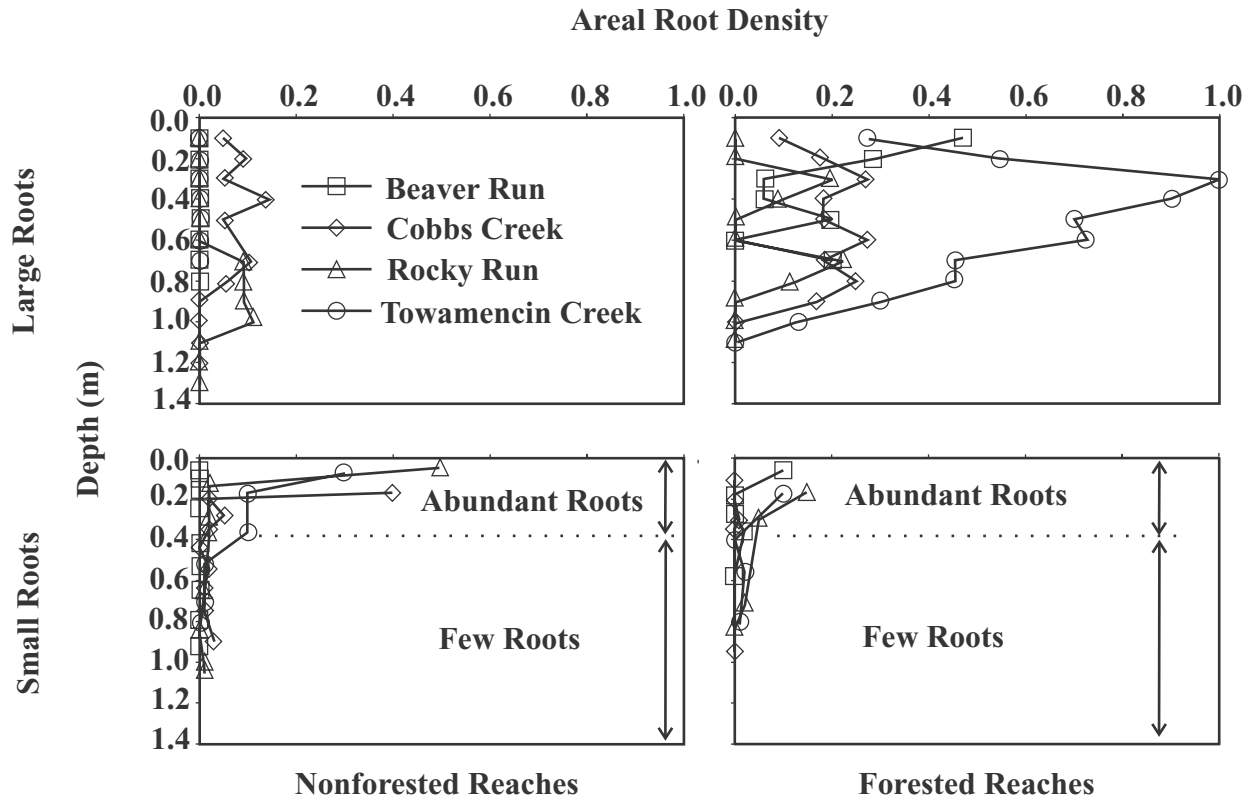


Figure 12. The areal density of large and small roots as a function of depth for all study reaches.

values of E and α for different soils, vegetation, and hydraulic characteristics. This will require focused research to identify the links between vegetation characteristics and the specific processes of erosion and deposition that result in bank erosion and the development of active floodplains.

Limitations of Our Interpretations

The results of our study are limited by several important factors. First, we have only studied four sites where active floodplains are well developed. A much larger sample size would presumably provide results of greater generality and reliability. Second, these four sites were not perfect examples of the larger population of paired reaches studied by Hession et al. (2002). Pairs of Hession et al.'s (2002) study are similar in depth, slope, grain size, and sinuosity, but the four forested sites selected for this study tended to have lower sinuosities than the nonforested reaches (although the depth, slope, and grain sizes are similar). The effects of this bias in sinuosity are unclear, but it is possible that some differences in migration rates and other processes are related to differences in sinuosity rather than

to differences in riparian vegetation. Differences in sinuosity likely create errors on the order of ~20% in our quantitative estimates of the ratios of E and α between the nonforested and forested reaches. Finally, our research methods were designed to hold as many variables constant as possible, allowing us to explore the *differences* in width between paired reaches that were presumably related to differences in riparian vegetation. A more general method is needed, however, that includes all significant variables (such as discharge and sediment supply, for example) and that could provide a basis for determining the absolute value of width at a reach.

These limitations provide a useful context for interpreting the provisional quantitative model presented above. The equations presented here are not intended to be either comprehensive or general. They do allow us, however, to clearly present hypotheses regarding the influence of riparian vegetation on width adjustment that would be difficult to describe precisely using words. In this sense, they are only intended to facilitate interpreting the results of our very controlled field study. Future research leading to more comprehensive models should be a high priority.

CONCLUSIONS

Our results define characteristic morphologies and processes in small, laterally migrating, gravel-bedded rivers of eastern Pennsylvania. Two and a half decades of observations of an unnamed tributary of Conodoguinet Creek illustrate how active floodplains form primarily by lateral accretion during bend development. Rates of vertical accretion are relatively low, so that 1) active floodplains are lower in elevation than the surrounding valley flat, and 2) the former bank of the river is preserved as an abrupt scarp between the active floodplain and the valley flat. We also studied contiguous forested and nonforested reaches with well-developed active floodplains to explain why forested reaches tend to be wider than otherwise similar nonforested reaches. We found that active floodplains are considerably smaller in reaches with forested riparian zones than in reaches without forested riparian zones. Rates of floodplain formation and cutbank erosion are both low in forested areas compared to nonforested areas. Due to the well-developed forested canopy, grassy vegetation on active floodplains is sparse in forested areas but abundant in nonforested reaches. High

root densities in forested reaches create banks that are difficult to erode, despite the occurrence of soils with greater shear strength in nonforested reaches.

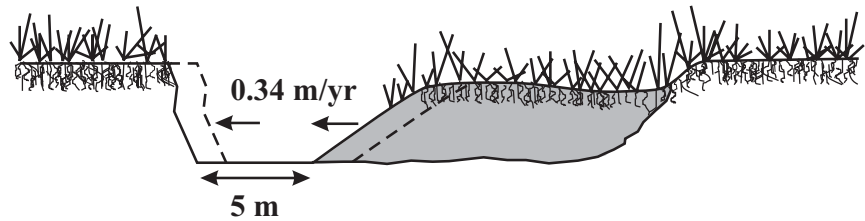
We use our field observations to define and provisionally quantify two dimensionless parameters that reflect the intensity of cutbank erosion and active floodplain accumulation. Cutbank erosion for a given near bank velocity is represented by a dimensionless bank erosion parameter E . The effectiveness of grassy vegetation in promoting sediment accumulation on active floodplains is represented by a dimensionless coefficient α . Our results and analysis suggest that E is 3 times larger in nonforested reaches than in forested reaches. We speculate that the value of E is controlled by the high density of large roots in cutbanks. The parameter α is 5 times larger in nonforested reaches than in forested reaches. Differences in α are likely related to differences in the density of grassy vegetation on accumulating active floodplains.

We propose that the widths of these channels are related to the ratio E/α . In forested reaches, channels are wide with banks that are difficult to erode. E is low and the channel migrates slowly. E/α is high, however, because α is very low due to the lack of grassy vegetation on active floodplains. In nonforested reaches, channels are narrow with banks that are easy to erode. E is high, and the channel migrates rapidly. E/α is low, however, due to a very large value of α related to dense grassy vegetation on active floodplains. Thus, bank erodibility and floodplain depositional processes must be considered together to explain the morphology of these laterally migrating alluvial channels.

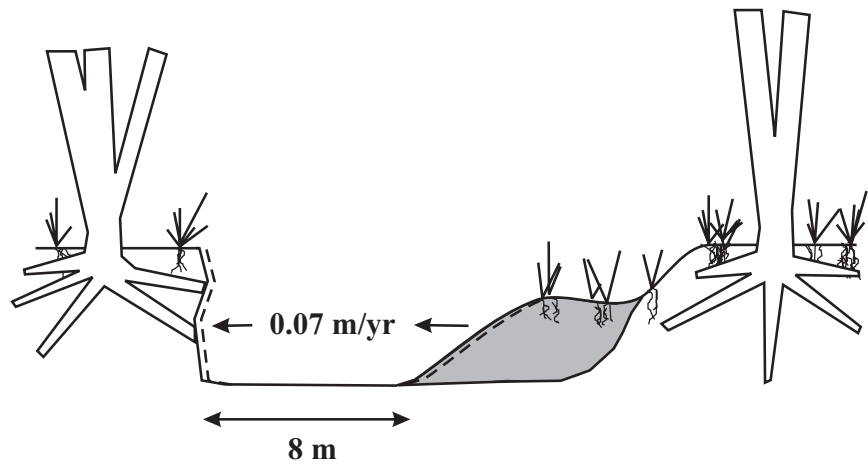
ACKNOWLEDGMENTS

This research was supported in part by grant R 825798-01-0 from the U.S. Environmental Protection Agency (EPA) STAR Grants program to the Patrick Center for Environmental Research, Academy of Natural Sciences. Because the research described in this paper has not been subjected to U.S. EPA's peer and policy review, it does not necessarily reflect the views of that agency. NEA was also partly supported by the National Science Foundation grant BCS-9986238 (to JEP) while this research was being completed. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. Responsibilities of coauthors are: 1) NEA helped with site surveys, analyzed all the vegetation, performed most of the data analysis, prepared most of the figures, and wrote the initial draft of the entire paper; 2) JEP helped with site surveys, did the stratigraphic analysis, edited the entire paper and figures, and wrote most of the Discussion section; 3) TEJ and WCH assisted with field surveys and manuscript preparation; and 4) NP surveyed the tributary of Conodoguinet Creek. The Stroud Water Research Center developed the original idea that riparian vegetation affects channel morphology and

Non-Forested Reach: narrow, rapidly migrating



Forested Reach: wide, slowly migrating



Active floodplain
 Bank erosion
 Active floodplain accretion

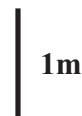


Figure 13. Summary of the morphology, stratigraphy, and rates of erosion and deposition of nonforested and forested study reaches. A state of quasi-equilibrium is assumed, such that the channels migrate laterally without changing width.

TABLE 5. QUALITATIVE RELATIONSHIPS BETWEEN VARIABLES ILLUSTRATING WHY FORESTED REACHES ARE WIDER AND MIGRATE MORE SLOWLY THAN NONFORESTED REACHES

Reach type	E	α	E/α	Relative width	Near bank velocity [†]	Lateral migration rate [‡]
Forest	Low	Very low	High	Wide	Low	Very low
Nonforest	High	Very high	Low	Narrow	High	Very high

[†]Near bank velocity is computed as $(u_b Q)/(WH)$.

[‡]Lateral migration rate is computed as EU_b .

VEGETATION AND WIDTH ADJUSTMENT

stream ecosystems in this region (Sweeney, 1992). Many of Noel Potter's geomorphology students from Dickinson College helped to monitor the unnamed tributary to Conodoguinet Creek. Thoughtful and detailed reviews by Doug Thompson, an anonymous reviewer, and by Associate Editor Frank Pazzaglia greatly improved the manuscript. Remaining errors are the sole responsibility of the authors.

REFERENCES CITED

- Allmendinger, N.L., Pizzuto, J.E., Johnson, T.E., and Hession, W.C., 1999, Why channels with grassy riparian vegetation are narrower than channels with forested riparian vegetation: EOS, Transactions of the American Geophysical Union Fall Meeting Supplement, Abstract H32D-10, v. 80, no. 46, F-401.
- Andrews, E.D., 1984, Bed material entrainment and hydraulic geometry of gravel-bed rivers in Colorado: Geological Society of America Bulletin, v. 95, p. 371–378.
- Autin, W.J., 1992, Use of alloformations for definition of Holocene meander belts in the middle Amite River, southeastern Louisiana: Geological Society of America Bulletin, v. 104, p. 233–241, doi: 10.1130/0016-7606(1992)104<3.CO>2.
- Brakenridge, G.R., 1984, Alluvial stratigraphy and radiocarbon dating along the Duck River, Tennessee: Implications regarding flood-plain origin: Geological Society of America Bulletin, v. 97, p. 1,467–1,475.
- Charlton, F.G., Brown, P.M., and Benson, R.W., 1978, The hydraulic geometry of some gravel rivers in Britain: Wallingford, UK, Hydraulics Research Station, Report IT 180, 48 p.
- Coleman, D.J., 1982, An examination of bankfull discharge frequency in relation to floodplain formation [Ph.D. dissert.]: Baltimore, The Johns Hopkins University, 192 p.
- Costa, J.E., 1975, The effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland: Geological Society of America Bulletin, v. 86, p. 1,281–1,286.
- Davies-Colley, R.J., 1997, Stream channels are narrower in pasture than forest: New Zealand Journal of Marine and Freshwater Resources, v. 31, p. 599–608.
- Delaware Valley Regional Planning Commission, 1994, Land-use in the Delaware Valley 1970–1990, Analytical Report #2: Philadelphia, Delaware Valley Regional Planning Commission, p. 126.
- Dunne, T., and Leopold, L.B., 1978, Water in Environmental Planning: San Francisco, W.H. Freeman, 818 p.
- Folk, R.L., 1974, The Petrology of Sedimentary Rocks: Austin, Texas, Hemphill, 182 p.
- Friedman, J.M., Osterkamp, W.R., and Lewis, W.M.J., 1996, The role of vegetation and bed-level fluctuations in the process of channel narrowing: Geomorphology, v. 14, p. 341–351, doi: 10.1016/0169-555X(95)00047-9.
- Graf, W.L., 1978, Fluvial adjustments to the spread of tamarisk in the Colorado plateau region: Geological Society of America Bulletin, v. 89, p. 1,491–1,501.
- Gran, K., and Paola, C., 2001, Riparian vegetation controls on braided stream dynamics: Water Resources Research, v. 37, p. 3,275–3,283, doi: 10.1029/2000WR000203.
- Hession, W.C., 2001, Riparian Forest and Urban Hydrology Influences on Stream Channel Morphology: Implications for Restoration, in Proceedings of the ASCE Environmental and Water Resources Institute's (EWRI's): Orlando, Florida, May 20–24, World Water and Environmental Resource Congress.
- Hession, W., Johnson, T.E., Charles, D.F., Hart, D.D., Horwitz, R.J., Kreeger, D.A., Pizzuto, J.E., Velinsky, D.J., Newbold, J.D., Clason, T., Compton, A.M., Coulter, N., Fuselier, L., Marshall, B.D., and Reed, J., 2000, Ecological benefits of riparian reforestation in urban watersheds: Environmental Monitoring and Assessment, v. 63, p. 211–222.
- Hession, W.C., Charles, D.F., Hart, D.D., Horwitz, R.J., Johnson, T.E., Kreeger, D.B., Marshall, B., Velinsky, D.J., Newbold, J.D., Pizzuto, J.E., 2002, Riparian Reforestation in an Urbanizing Watershed: Effects of Upland Conditions on Instream Ecological Benefits, final report to EPA of STAR Grant R 825798–01–0, 47 p.
- Hession, W., Pizzuto, J.E., Johnson, T.E., and Horwitz, R.J., 2003a, Influence of bank vegetation on channel morphology in rural and urban watersheds: Geology, v. 31, no. 2, p. 147–150.
- Hession, W.C., Johnson, T.E., Charles, D.F., Horwitz, R.J., Kreeger, D.A., Marshall, B.D., Pizzuto, J.E., and Velinsky, D.J., 2003b, Ecological benefits of riparian reforestation in urban watersheds, in Clar, M., Carpenter, D., Gracie, J., and Slate, L., eds., Protection and Restoration of Urban and Rural Streams: Reston, Virginia, American Society of Civil Engineers, p. 373–382.
- Hey, R.D., and Thorne, C.R., 1986, Stable channels with mobile gravel beds: Journal of Hydraulic Engineering, v. 112, p. 671–689.
- Hupp, C.R., and Bazemore, D.E., 1993, Temporal and spatial patterns of wetland sedimentation—West Tennessee: Journal of Hydrology, v. 141, p. 179–196.
- Ikeda, S., and Izumi, N., 1990, Width and depth of self-formed straight gravel rivers with bank vegetation: Water Resources Research, v. 26, p. 2,353–2,364, doi: 10.1029/90WR00812.
- Ikeda, S., Parker, G., and Sawai, K., 1981, Bend theory of river meanders; I, Linear development: Journal of Fluid Mechanics, v. 112, p. 363–377.
- Jackson, J.A., ed., 1997, Glossary of Geology: Alexandria, Virginia, American Geological Institute, 4th edition, p. 784.
- Jacobson, R.B., and Coleman, D.J., 1986, Stratigraphy and recent evolution of Maryland Piedmont floodplains: American Journal of Science, v. 286, p. 617–637.
- Johanneson, H., and Parker, G., 1989, Linear theory of river meanders, in Ikeda, S., and Parker, G., eds., River Meandering: Washington D.C., American Geophysical Union, p. 181–213.
- Kouwen, N., 1988, Field estimation of the biomechanical properties of grass: Journal of Hydraulic Research, v. 26, p. 559–568.
- Lattman, L.L., 1960, Cross section of a floodplain in a moist region of moderate relief: Journal of Sedimentary Petrology, v. 30, p. 275–282.
- Leopold, L.B., and Wolman, M.G., 1960, River meanders: Geological Society of America Bulletin, v. 71, p. 769–794.
- McKenny, R., Jacobson, R.B., and Wertheimer, R.C., 1995, Woody vegetation and channel morphogenesis in low-gradient, gravel-bed streams in the Ozark Plateaus, Missouri and Arkansas: Geomorphology, v. 13, p. 175–198, doi: 10.1016/0169-555X(95)00034-3.
- Micheli, E.R., and Kirchner, J.W., 2002, Effects of wet meadow riparian vegetation on streambank erosion, 2, Measurement of vegetated bank strength and consequences for failure mechanics: Earth Surface Processes and Landforms, v. 27, p. 687–697, doi: 10.1002/ESP.340.
- Micheli, E.R., Kirchner, J.W., and Larsen, E.W., 2004, Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, Central Sacramento River, California, USA: River Research and Applications, v. 5, doi: 10.1002/rra.756.
- Montgomery, D.R., 1997, What's best on the banks?: Nature, v. 388, p. 328–329, doi: 10.1038/40976.
- Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., and Dietrich, W.E., 2000, Forest clearing and regional landsliding: Geology, v. 28, no. 4, p. 311–314, doi: 10.1130/0091-7613(2000)028<3.CO>2.
- Moody, J.A., Pizzuto, J.E., and Meade, R.H., 1999, Ontogeny of a flood plain: Geological Society of America Bulletin, v. 111, p. 291–303, doi: 10.1130/0016-7606(1999)111<2.3.CO>2.
- Murgatroyd, A.L., and Ternan, J.L., 1983, Impact of afforestation on stream bank erosion and channel form: Earth Surface Processes and Landforms, v. 8, p. 357–369.
- Nanson, G.C., 1980, Point bar and floodplain formation of the meandering Beaton River, northeastern British Columbia, Canada: Sedimentology, v. 27, p. 3–29.
- Nanson, G.C., and Croke, J.C., 1992, A genetic classification of floodplains: Geomorphology, v. 4, p. 459–486, doi: 10.1016/0169-555X(92)90039-Q.
- Nanson, G.C., and Hickin, E.J., 1986, A statistical analysis of bank erosion and channel migration in western Canada: Geological Society of America Bulletin, v. 97, p. 497–504.
- National Research Council, 1992, Restoration of aquatic ecosystems: Washington D.C., National Academy Press, 576 p.
- Naylor, L.A., Viles, H.A., and Carter, N.E.A., 2002, Biogeomorphology revisited: Looking towards the future: Geomorphology, v. 47, p. 3–14, doi: 10.1016/S0169-555X(02)00137-X.
- NOAA, 2003, <http://www.ncdc.noaa.gov/pub/data/coop-precip>.
- Odgaard, A.J., 1987, Streambank erosion along two rivers in Iowa: Water Resources Research, v. 23, p. 1,225–1,236.
- PA Department of Conservation and Natural Resources, 2000, Physiographic Provinces of Pennsylvania, www.dcnr.state.pa.us/topogeo/maps/map13.pdf.
- Pizzuto, J.E., 1984, Bank erodibility of sand-bed streams: Earth Surface Processes and Landforms, v. 9, p. 113–124.
- Pizzuto, J.E., 1987, Sediment diffusion during overbank flows: Sedimentology, v. 34, p. 301–317.
- Pizzuto, J.E., and Meckelnburg, T.S., 1989, Evaluation of a linear bank erosion equation: Water Resources Research, v. 25, p. 1,005–1,013.
- Potter, N., Hartman, D., Delano, H.L., and Sevon, W.D., 1998, Geomorphology in the Northern Cumberland Valley, PA, including the Carlisle Deluge of 1779: Guidebook for the 17th Annual Field Trip, Harrisburg Area Geological Society, 49 p.
- Prothero, D.R., 1990, Interpreting the Stratigraphic Record: New York, W.H. Freeman, 410 p.
- Riesterberg, M.M., and Sovonick-Dunford, S., 1983, The role of woody vegetation in stabilizing slopes in the Cincinnati area, Ohio: Geological Society of America Bulletin, v. 94, p. 506–518.
- Rosgen, D., 1996, Applied River Morphology: Wildland Hydrology, 379 p.
- Schumm, S.A., and Lichty, R.W., 1963, Channel widening and floodplain construction along Cimmaron River in southwestern Kansas: U.S. Geological Survey Professional Paper 352-D, p. 71–88.
- Sevon, W.D., 1997, Preliminary landform map of Pennsylvania: Pennsylvania Geological Survey, unpublished map, 4th ser., scale 1:500,000.
- Stott, T., 1997, A comparison of stream bank erosion processes on forested and moorland streams in the Balquhider catchments, central Scotland: Earth Surface Processes and Landforms, v. 22, p. 383–399, doi: 10.1002/(SICI)1096-9837(199704)22<43.3.CO>2-W.
- Sweeney, B.W., 1992, Streamside forests and the physical, chemical, and trophic characteristics of piedmont streams in eastern North America: Water Science and Technology, v. 26, p. 2,653–2,673.
- Sweeney, B.W., Bott, T.L., Jackson, J.K., Kaplan, L.A., Newbold, J.D., Standley, L.J., Hession, W.C., Horwitz, R.J., Ferreri, C.P., Finley, J.C., Grotfelty, C.E., and Johnson, J.B., 1999, Riparian vegetation, stream geomorphology, and the structure and function of stream ecosystems in eastern North America: Bulletin of the North American Benthological Society, v. 16, p. 148.
- Thorne, S.D., and Furbish, D.J., 1995, Influences of coarse bank roughness on flow within a sharply curved river bend: Geomorphology, v. 12, p. 241–257, doi: 10.1016/0169-555X(95)00007-R.
- Trimble, S.W., 1997, Stream channel erosion and change resulting from riparian forests: Geology, v. 25, p. 467–469, doi: 10.1130/0091-7613(1997)025<3.CO>2.
- United States Department of Agriculture, 1998, Field Book for Describing and Sampling Soils, Version 1.1., 212 p.
- United States Department of Agriculture-Soil Conservation Service, 1991, National manual for assisting ASCS cost sharing programs, Part 539: Washington D.C., National Bulletin 300-1-4, 35 p.
- Wolman, M.G., and Leopold, L.B., 1957, River flood plains: Some observations on their formation: U.S. Geological Survey Professional Paper, v. 282-C, p. 107.
- Wu, T.H., McKinnell, W.P., III, and Swanston, D.N., 1979, Strength of tree roots and landslides on Prince of Wales Island, Alaska: Canadian Geotechnical Journal, v. 16, p. 19–33.
- Zimmerman, R.C., Goodlett, J.C., and Comer, G.H., 1967, The influence of vegetation on channel form of small streams, Symposium on river morphology: International Association of Scientific Hydrology, v. 75, p. 255–275.

MANUSCRIPT RECEIVED BY THE SOCIETY 18 JULY 2003

REVISED MANUSCRIPT RECEIVED 8 JUNE 2004

MANUSCRIPT ACCEPTED 10 JUNE 2004

Printed in the USA