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Streambank Retreat: A Primer

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Cover Figure: Streambank failure caused by fluvial erosion of the bank toe

Introduction

The annual costs of water pollution due to sediment in North America alone approach $16 billion (Osterkamp et al., 1998). According to the US Environmental Protection Agency (USEPA), sediment is a leading cause of water quality impairment (USEPA, 2002). Excess suspended sediments reduce the diversity and abundance of aquatic organisms, reduce reservoir capacity, increase drinking water treatment costs, and serve as a carrier for contaminants such as phosphorus, bacteria, heavy metals and pesticides. While considerable effort has been directed toward reducing erosion from agricultural and urban lands, stream channel degradation has only recently been acknowledged. Studies have shown that sediment from streambanks can account for as much as 85% of watershed sediment yields and bank retreat rates as great as 1.5 m - 1100 m/year have been documented (Simon et al., 2000). In addition to water quality impairment, streambank retreat impacts floodplain residents, riparian ecosystems, bridges, and other stream-side structures (ASCE, 1998).

In a recent article in ***Science***, Bernhardt et al. (2005) estimated over one billion dollars have been spent annually since 1990 on stream restoration in the United States. While restoration activities can range from simple streambank grading to complete stream relocation, the reestablishment of riparian vegetation is typically a priority. Riparian vegetation has long been recognized for water quality improvement (Dillaha et al., 1989; Lowrance et al., 1995; Correll, 1996). Research has shown that riparian vegetation is effective at removing contaminants from overland flow and shallow groundwater (Lowrance et al., 1995). Streamside forests are also critical for maintaining aquatic ecosystems in eastern streams (Palone and Todd, 1997).

In addition to water quality and habitat benefits, riparian vegetation has a significant impact on stream stability and morphology (Mosley, 1981; Thorne and Osman, 1988; Abernethy and Rutherfurd, 2000). Unfortunately, the impacts are complex, poorly understood, and have yet to be fully quantified (ASCE, 1998; Abernethy and Rutherfurd, 2000; Simon and Collison, 2002). An understanding of the processes involved in streambank retreat and the effects of vegetation on those processes is necessary for improved stream restoration design and riparian management.

Streambank Retreat Processes

Streambank retreat, frequently called streambank erosion, occurs by a combination of three processes (Lawler, 1992; Lawler, 1995):

- ***subaerial processes***
- ***fluvial entrainment***
- ***mass wasting***

To provide clarity for the remainder of the article, the author adopted the terminology proposed by Lawler et al. (1997). Specifically, the terms "*fluvial erosion*" and "*fluvial entrainment*" are used to describe the detachment, entrainment, and removal of individual soil particles or aggregates from the streambank face by the hydraulic forces occurring during flood events. The phrases "*bank failure*" or "*mass wasting*" denote the physical collapse of all or part of the streambanks as a result of geotechnical instabilities. Bank erosion and bank failure commonly work in concert to produce "bank retreat" or the net recession of the streambank (Figure 1).

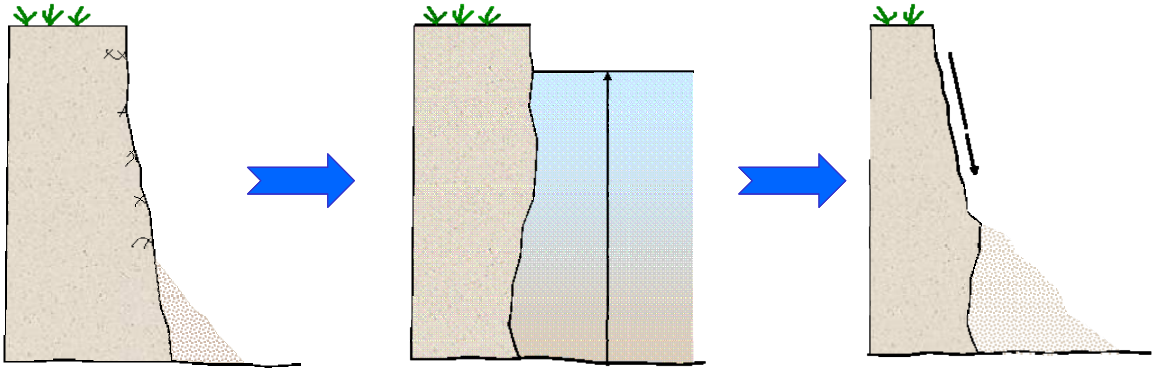

Figure 1: Streambank retreat processes
(Freeze-thaw cycling or desiccation cracking reduce soil strength, streambank soils are eroded during high flows, and the upper bank fails due to slope instability).

Subaerial Processes

Subaerial processes are climate-related phenomena that reduce soil strength (e.g. frost heave, soil desiccation; Figure 2). Controlled mainly by climatic conditions, subaerial processes are largely independent of flow. They dominate streambank retreat in the upper reaches of river systems, delivering soil directly to the stream channel and making the banks more vulnerable to flow erosion by reducing the packing density of soils and destroying imbrication (Thorne and Tovey, 1981). Measured average erosion rates due exclusively to subaerial processes range from 13 mm/yr (Prosser et al., 2000) to 40 mm/yr with peaks as high as 181 mm/yr (Couper and Madock, 2001). Subaerial processes are sometimes described as "preparatory processes" because they increase the susceptibility of soil to erosion at high flows (Wolman, 1959; Lawler, 1993).

Fluvial Erosion

Fluvial entrainment/erosion is the direct removal of soil particles or aggregates from the stream bed or banks by flowing water. The erodibility of noncohesive soils (gravels, sands, and some silts) is a function of soil grain size distribution, shape, and density. Alternatively, the fluvial erosion of cohesive soils is extremely complex and is related to soil properties and test conditions (Grissinger, 1982). Simply determining which soils are cohesive is difficult: repulsive and attractive forces exist in soils and the net force is often a function of both the physical and chemical properties of the soil. Soils with a plasticity index less than 10 are commonly classified as cohesionless, although this criterion is frequently inadequate in describing soil behavior (Hanson, 1991).

Considerable research has been conducted on the fluvial erosion of cohesive soils, but the results are often contradictory and few design data are available. Grissinger (1982) presented a comprehensive summary of previous research. Most studies were conducted using laboratory methods with small remolded samples. Test equipment has included straight and circular flumes, pinhole devices, rotating cylinders, disks and impellers, and submerged jet devices (Allen et al., 1999). These studies have shown that the fluvial erosion of cohesive soils is determined by the soil structure and the interaction between the soil pore water and the eroding fluid (Heinzen, 1976). While noncohesive soils erode as individual grains, cohesive soils erode as aggregates (ASCE, 1998). Additionally, the shape of the bank surface influences near bank hydraulic stresses and soil entrainment (Grissinger, 1982). These two considerations suggest that laboratory studies using small remolded samples may not be applicable to field conditions. Indeed, research has shown that remolded soils have lower critical shear stresses and higher overall erosion rates than undisturbed samples (Heinzen, 1976).

Figure 2: Soil cracking due to desiccation
(Camera lens cap is 5.5 cm in diameter).

Since erosion is a surface phenomenon, and surface soils equilibrate quickly to changes in pore water pressure and stream chemistry, the erodibility of cohesive soil is affected by test conditions. The temperature of the eroding fluid, the soil antecedent moisture content, the rate of soil wetting, and the suspended solids concentration and chemistry of the eroding fluid influence soil erodibility (Grissinger, 1982). Soil bulk properties, such as vane shear strength, compressive strength and dry unit weight, are not good indicators of the erosion potential of cohesive soils (Arulanandan et al., 1980).

A number of soil parameters influence the susceptibility of a cohesive soil to erosion, including grain size distribution, soil bulk density, clay type and content, organic matter content, and soil pore water content and chemistry (Grissinger, 1982). Research has shown that increases in the silt-clay content of soils increases their resistance to entrainment (Thorne and Tovey, 1981; Osman and Thorne, 1988). In contrast, soils with high silt-clay contents are more susceptible to the effects of subaerial processes, which make the soils less resistant to erosion by hydraulic forces (Couper, 2003).

It is well recognized that the resistance of streambank soils to fluvial entrainment changes over time as soil moisture and temperature fluctuate. Several researchers have observed that bank erosion is greatest during the winter and have attributed this to freezing of streambanks (Wolman, 1959; Lawler, 1986; Stott, 1997). Freezing of the streambank surface causes a migration of soil water to the bank surface, increasing the local moisture content. Also, as the soil water freezes and expands, it increases the soil volume (Lawler, 1993). This increase in moisture content and decrease in density due to freeze-thaw cycling makes soils more susceptible to fluvial erosion.

Bank Failure

Bank failure, also known as mass wasting, occurs when the weight of the bank is greater than the shear strength of the soil (see cover figure). It often results from increases in bank height or bank angle due to fluvial erosion and the presence of tension cracks (ASCE, 1998). Mass wasting depends on bank geometry and stratigraphy, properties of the bank materials, and the type and density of bank vegetation (Thorne, 1990).

Mass failures often occur following floods. Precipitation and a rising stream stage increase the moisture content and weight of bank soils. At the same time, apparent soil cohesion is decreased through the reduction of matric suction. If rainfall is prolonged, positive pore pressures may develop, resulting in a decrease in frictional soil strength. Additionally, the bank height or angle may be increased as flood waters scour the channel bed or bank toe (basal area). These changes, combined with a rapid loss of confining pressure as the stream stage recedes, can trigger mass failures (Figure 1).

Effects of Vegetation on Streambank Stability

Little quantitative data are available on the effects of vegetation on streambank stability (Abernethy and Rutherfurd, 1998; Simon and Collison, 2002). It is generally established that vegetation influences the chemical and physical properties of streambanks, as well as the local microclimate. The following sections describe the effects of vegetation on the three processes implicated in streambank retreat. Also, the impacts of woody versus herbaceous plants are compared.

Riparian vegetation has multiple effects on subaerial processes. A dense cover of vegetation absorbs the energy of rainfall, reducing soil detachment by raindrop impact (Coppin and Richards, 1990). Vegetation insulates the streambank from extreme temperature fluctuations (Abernethy and Rutherfurd, 1998). This insulation minimizes the occurrence of freezing and cracking due to desiccation (Thorne, 1990).

The influence of vegetation on stream hydraulics has long been recognized (Zimmerman et al., 1967). Vegetation provides increased channel roughness, directing flows towards the center of the channel and reducing flow velocities and shear stresses along the banks (Thorne and Furbish, 1995). Since sediment transport capacity is proportional to flow velocity to the sixth power (v^6), small decreases in stream velocity can result in large changes in sediment transport (Thorne, 1990). Additionally, vegetation damps near bank turbulence and weakens secondary currents in river bends, further reducing fluvial erosion (Thorne and Furbish, 1995). It should be recognized that the effects of vegetation on stream hydraulics varies with season, stream stage, and stream width to depth ratio, particularly for herbaceous species (Thorne and Osman, 1988; Masterman and Thorne, 1992). Additionally, the spacing of vegetation along a stream is a crucial determinant of the distribution of hydraulic stresses (Pizzuto and Mecklenburg, 1989).

Vegetation has multiple effects on the distribution of energy and sediment in a stream. Along streams with forested riparian buffers, fallen trees create series of step pools, dissipating stream energy and providing sediment storage (Beschta and Platts, 1986). Hupp (1999) noted that roots growing under stream channels may provide grade control to limit headcut migration. Additionally, vegetation can act as a nucleus for the creation of sediment bars; vegetation is effective in trapping washload (Thorne, 1990). These benefits may be offset by the fact that the presence of downed trees and isolated stands of vegetation can produce locally severe scour of the stream bed and banks, although the magnitude of this effect depends on the size of the stream or river (McKenney et al. 1995).

While considerable research has been conducted on fluvial entrainment, little quantitative information is available on the effects of vegetation on soil erosion by concentrated flow (Mamo and Bubenzer, 2001a). It is believed the root systems of woody and herbaceous plants physically bind bank soils in place, increasing the critical shear stress (Coppin and Richards, 1990). Wynn and Mostaghimi (2006) found increases in the density of larger diameter roots (diameters of 2-20 mm) decreased soil erodibility. Additionally, roots exudates may increase soil cohesion chemically (Amarasinghe, 1992). Odgaard (1987) studied erosion along meander bends of two major rivers in Iowa and determined that erosion along wooded streambanks was half that along sparsely vegetated banks. Vegetation indirectly affects soil erosion by changing soil physical and chemical properties including soil organic matter, aggregate stability and bulk density (Mamo and Bubenzer, 2001a,b).

Researchers have also found that woody and herbaceous roots significantly increased slope stability over bare conditions (Waldron and Dakessian, 1982; Shields and Gray, 1992). The root systems of woody and herbaceous plants act to stabilize banks by increasing soil shear strength (Simon and Collison, 2001). Soils are strong in compression, but weak in tension; shear stress in the soil is transferred to tensile stress in the roots. Even small increases in root density can substantially increase soil strength (Abernethy and Rutherfurd, 2001). Micheli and Kirchner (2002) measured a linear relationship between riparian meadow root biomass and soil shear strength, with riparian vegetation increasing soil shear strength as much as 800%.

Changes in soil strength are a function of root size, distribution, and tensile strength. Several researchers have found a nonlinear inverse relationship between root strength and root diameter (Waldron and Dakessian, 1981; Abernethy and Rutherfurd, 2001; Simon and Collison, 2001). Large roots (> 15– 20 cm in diameter) do little to increase shear strength, but instead act as soil anchors (Simon and Darby, 1999). Additionally, the stems of woody plants act as soil buttresses and arches, further protecting banks against mass failure (Abernethy and Rutherfurd, 1998). Roots typically fail by tensile or bond failure, although scour of exposed roots also occurs (Wu, 1984). The ability of roots to resist pullout is a function of root length, branching patterns, root tortuosity, and soil type (Abernethy and Rutherfurd, 2001).

Benefits of Herbaceous versus Woody Vegetation

There is considerable debate in the literature regarding the relative merits of herbaceous versus woody riparian vegetation. Several researchers have noted that streams were 2 - 2.5 times wider with forested riparian buffers than with grass buffers (Zimmerman et al., 1967; Davies-Colley, 1997; Trimble, 1997; Hession et al., 2000). Several authors claim this occurs because the grass acts to armor streambanks and trap fine sediments (Murgatroyd and Ternan, 1983; Sweeney, 1993; Trimble, 1997; Davies-Colley, 2000; Lyons et al., 2000; Simon and Collison, 2001). This information has prompted some researchers to predict that watershed afforestation may lead to increased sediment yields (Smith, 1992; Davies-Colley, 1997; Davies-Colley, 2000; Lyons et al., 2000) and that stream sediment yields could be reduced by converting riparian forests to grass (Trimble, 1997). Alternatively, others have shown that forested streams are narrower than streams with herbaceous buffers (Gregory and Gurnell, 1988). A study in British Columbia determined major bank erosion was 30 times more prevalent on nonforested versus forested meander bends (Beeson and Doyle, 1995). In a study following the 1993 Kansas floods, Geyer et al. (2000) showed that areas with herbaceous buffers experienced an average of 24 m of bank erosion while areas with forested buffers experienced soil deposition.

With regard to subaerial processes, the exposure of the streambank soil to solar radiation and atmospheric cooling has a significant impact on soil drying and freezing. Wynn and Mostaghimi (2006) compared the impact of woody and herbaceous riparian vegetation on streambank subaerial processes in the eastern US. They found streambanks with herbaceous vegetation had higher soil temperatures and lower soil moisture during the summer, as compared to forested streambanks. In contrast to summer conditions, the deciduous forest buffers provided little protection for stream banks during the winter: the forested stream banks experienced diurnal temperature ranges two to three times greater than stream banks under dense herbaceous cover and underwent as many as eight times the number of freeze-thaw cycles. In the United Kingdom, Stott (1997) found that soil temperature and moisture regimes were moderated by coniferous forests in comparison to more open moorland vegetation. Soil temperature in the evergreen forest was an average of 3.7ºC higher.

Both herbaceous and woody vegetation provide increased hydraulic roughness, although the effects of herbaceous vegetation are reduced at high flows because grasses and forbs bend over in the flow. Additionally, herbaceous vegetation is absent or reduced during the winter when most channel erosion occurs. As a result of reduced stream width, velocities in grass channels have been found to be greater than those with forested vegetation (Horwitz et al., 2000)

In addition to hydraulic effects, vegetation type appears to influence stream sediment regime. Bedload transport rates under forested buffers are 2 - 6 times those measured under herbaceous buffers (Murgatroyd and Ternan, 1983; Stott et al., 1986; Kirby et al., 1991; Reed, 1999). Reed (1999) attributed this difference to a greater water surface slope in forested sections and increased sediment storage in grassed reaches.

Differences in rooting density and distribution between herbaceous and woody vegetation has implications for both fluvial erosion and streambank stability. In general, herbaceous has a high density of very fine roots (diameters < 0.5 mm) in the upper 30 cm of the soil surface (Simon and Collison, Wynn et al., 2004). In contrast, roots with diameters greater than 0.5 mm are more common for woody vegetation and those roots are more evenly distributed in the soil profile. Considering research has shown that erosion resistance has a direct relationship with the density of roots greater than 0.5 mm in diameter, forested vegetation likely provides better protection against stream bank erosion (Wynn and Mostaghimi, 2006). Additionally, because herbaceous roots are concentrated in the upper soil profile instead of at the toe of the streambank (where hydraulic stresses are greatest), undercutting of grass banks is commonly observed (Davies-Colley, 1997).

There is considerable evidence that vegetation significantly increases slope stability, reducing the occurrence of mass failures (Waldron, 1977; Waldron and Dakessian, 1981 and 1982; Abernethy and Rutherfurd, 2000; Simon and Collison, 2001). This increased stability is due primarily to mechanical reinforcement, although reductions in pore water pressures due to evapotranspiration can further strengthen streambanks. Alternatively, increases in soil moisture due to higher infiltration rates under vegetation can also decrease stability, although these decreases were offset by the increase in mechanical strength from the roots (Simon and Collison, 2001). Some researchers have found grasses provide greater structural strength due to the large number of very fine roots (Murgatroyd and Ternan, 1983; Trimble, 1997; Lyons et al., 2000; Simon and Collison), while other studies have shown trees were more effective for bank stabilization (Waldron et al., 1983; Beschta and Platts, 1986; Johnson et al., 2001).

As indicated in the discussion above, the jury is still out regarding the relative importance of herbaceous versus woody riparian vegetation for streambank stability. Riparian vegetation has a strong influence on both stream morphology and stream ecology. Personal observations in the field have shown that forested streams in the eastern US have nearly vertical, stable streambanks that provide habitat for aquatic species native to that region. Other riparian ecosystems that were historically dominated by native grasses may benefit from herbaceous riparian buffers. Ultimately, further studies are necessary to evaluate the impact of vegetation type on stream morphology for effective stream and river management.

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