NDOR Research Project Number SPR-1(2) P549
Transportation Research Studies

STREAMBANK STABILIZATION USING TRADITIONAL AND BIOENGINEERING METHODS: A LITERATURE REVIEW

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August 2007

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SPR-1(2) P549		

4. Title and Subtitle	5. Report Date
Streambank Stabilization Using Traditional and Bioengineering Methods: A Literature Review	August 2007
	6. Performing Organization Code
7. Author/s	8. Performing Organization Report No.
David M. Admiraal, Tyler Schemper, and Branden Strahm	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Department of Civil Engineering University of Nebraska – Lincoln W348 Nebraska Hall Lincoln, NE 68588-0531	11. Contract or Grant No. SPR-1(2) P549
12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Research and Special Programs Administration 400 7th Street, SW Washington, DC 20590-0001	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This literature review addresses the process of streambank erosion and how it can be slowed using traditional and bioengineering techniques. The review is divided into four parts: (1) a review of fluvial geomorphology and slope failure mechanics, (2) a brief discussion of traditional structural methods of mitigating streambank erosion, (3) a review of bioengineering erosion control techniques, and (4) a summary of work done on combined structural and bioengineering methods.

Review of relevant literature resulted in the following important conclusions:
1. Streambank erosion is the result of fluvial erosion and mass wasting of steep streambanks. In order to reduce the rate of streambank erosion, solutions should focus on reducing fluvial erosion because fluvial erosion it the critical process.
2. In streambanks with multiple sediment layers, some of the layers are weaker than others. When designing streambank erosion controls, it is important to concentrate on the weakest sediment layers because it is the weakest layers that will control erosion rates.
3. Biotechnical slope stabilization of streambanks is not likely to succeed without structural (non-biotechnical) means to reduce fluvial erosion of the bank toe. Thus, in order to be successful, biotechnical streambank erosion techniques should be used in combination with structural methods. Biotechnical methods can still be very successful, only not below the normal waterline.
4. Native species are more likely to become established than non-native species in biotechnical applications. The review contains a list of species that have been studied as bank stabilizing species. Black willow is the most widely used species and has performed the best in relevant studies.

17. Key Words	18. Distribution Statement		
Bioengineering, Erosion, Streambank Protection	No Restrictions. This document is available to the public from the sponsoring agency.		
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. Of Pages	22. Price
Unclassified	Unclassified	102	

Form DOT F 1700.7 (8-72) **Reproduction of form and completed page is authorized.**

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Roads, the Federal Highway Administration, or the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report. The U.S. government and the State of Nebraska do not endorse products or manufacturers.

ACKNOWLEDGMENTS

This research project would not have been possible without the funding provided by the Nebraska Department of Roads. We would also like to thank the engineers at the Department of Roads for their assistance with this project, and especially Kevin Donahoo and Robert Carnazzo for providing us with project data and administrative advice.

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Chapter 1 Introduction

1.1 Streambank erosion

On a basin-wide scale, the cost of streambank erosion can be very high. Simon et al. (1999) state that bank material can contribute as much as 80% of the sediment load in incised channels, and that bank erosion rates can range from less than 1.5 meters per year to over 100 meters per year, depending on flow conditions, soil properties, and bank protection. Though he cites a reference that is somewhat old, Lawler (1993) states that in 1978 dollars, annual streambank erosion damage in the United States is on the order of $270 million. On the Galaure River in France, researchers have indicated that active bank protection is not even financially worth while. Protecting streambanks is very expensive, but leaving them unprotected can also be expensive. It is important that the engineer who must provide advice about protecting streambanks is well informed about potential solutions.

Streambank erosion is a very complicated process and is still not completely understood. Flow conditions, soil types, and the distribution of vegetation can take on an unlimited number of combinations. There are two parts to the streambank erosion process and both of them are complex. Most of the streambanks that are susceptible to severe erosion are tall and steep. These types of banks are common in Nebraska primarily because of historic straightening of stream channels and the subsequent degradation of the bed that resulted from the straightening. Heavily degraded channels result in steep banks that are often subject to geotechnical failure. Such failure results in mounds of sediment at the base of the bank and a more stable bank with reduced slope. Thus, over time the bank might reach some equilibrium angle were it not for the second part of the process – erosion of the bank toe by hydraulic processes. Bank erosion typically is a result of (1) geotechnical failure followed by (2) hydraulic removal of sediment at the toe of the bank and subsequent undercutting of the bank. This process repeats itself for all channels, whether the channels are disturbed or not. The main difference is that for a disturbed channel, the process may be much more intense. Osman and Thorne (1988) describe this process more thoroughly, and Chapter 2 describes some of the details of analysis of the process.

On the hydraulic side of bank erosion, Lane's relation (Lane, 1955) identifies four parameters that affect the stability of a stream: Stream discharge, bed material gradation (sediment size), sediment load, and channel slope. A change in one of these parameters causes disequilibrium and stimulates a response in the stream morphology. For example, an increase in channel slope will likely cause the bed material to coarsen, the sediment load to increase, or both. As a result, the bed erodes downward and the channel becomes more incised. This same behavior can result from an increase in the stream discharge or a change in the runoff hydrograph characteristics of the stream. Lane's relation is helpful when considering streambank erosion on a watershed scale, it is not quite as helpful when working at point locations along a stream.

As mentioned above, in eastern Nebraska, streambed adjustment has led to deeply incised channels. Rus et al. (2003) did a survey of 151 stream sites in eastern Nebraska. They found that many of the sites had degraded channel beds that were primarily caused by channel straightening (channel straightening results in a net increase in the stream bed slope and increased sediment carrying capacity of the stream) that dates back to as early as the 1890s. Rus et al. observed that the degradation has led to the failure of many bridges, pipelines, and other infrastructure. Like other basins in eastern Nebraska, the Big Blue River Basin exhibits significant degradation, but according to Rus et al., the cause of the degradation in this basin is not likely to be channel straightening.

Streambank erosion is affected by many things, and there are many ways in which people can influence the process. Farming practices, stream modifications, land development, and climate change all have impacts. Streambank erosion is a natural process – people are not the cause of streambank erosion, they only influence the rate and severity of the erosion.

1.2 Factors affecting selection of a streambank erosion control technique

There are many possible streambank erosion control techniques. Perhaps the most popular example is the use of rip-rap longitudinal revetments. Selection of an appropriate erosion control requires the consideration of many factors. According to Bowie (1982), these factors include: bank height, stability of bank material, stability of the channel bottom, channel width, curvature of the stream, bed gradient, availability of protective materials, utilization of property adjacent to channel, allotted resources, and cost of implementation. In the case of straight reaches, requirements are different because velocity distributions are different. Geyer et al. (2000) cite Rosgen (1996) in saying that factors which affect stream migration include: ratio of bank height to bankfull stage, density and depth of roots, vegetation type, streambank material composition and layer stratigraphy, and bank angle.

Henderson (1986) identifies mechanisms which contribute to streambank failure. Mechanisms include: erosive attack at the toe of a bank may lead to failure of the overlying bank, erosion of soil along banks by currents, sloughing of saturated cohesive banks with no drainage, flow slides in saturated silty or sandy soil, erosion by groundwater seepage, erosion of an upper bank or river bottom by waves, freeze-thaw of banks, abrasion by ice and debris in the stream, and shrinking and swelling of clays. Depending on location and site characteristics, all of these processes may influence streambank erosion.

1.3 Bioengineering and nontraditional erosion control techniques

There has been revitalized interest in the use of vegetation to compliment or replace traditional erosion control techniques in recent years. While perhaps the leading factor in this interest has been aesthetics and increased interest in improving our environment, cost and the ability to improve sites that have limited access are also factors (Seibert, 1968; Watson et al., 1997).

Some research has shown that bank erosion and channel migration is only marginally affected by natural vegetation on the outer bank of the channel (Nanson and Hickin, 1986). But most research shows that vegetation does stabilize soils. For instance, Odgaard (1987) did a case study and erosion model for predicting large scale erosion (in reaches and not just individual bends). He investigated the Des Moines and Nishnabotna rivers and compared results. Odgaard found that erodibility of riverbanks was reduced by a factor of 2 or more when banks were lined by mature trees (although he provides no indication of what type of trees).

Gurnell and Gregory. (1995) investigated the impact of various types of vegetation on hydrogeomorphology. They found that vegetation intercepts precipitation that would otherwise be delivered to the soil, affecting partitioning of water between ground and overland flow. This in turn affects the rate of transport through less porous materials. As will be discussed later in this review, limiting the flow of water to soils in the bank can have a profound impact on bank stability because positive pore water pressures reduce the banks ability to remain intact.

According to Gurnell and Gregory, unlike rock and traditional stabilization techniques, vegetation is often sensitive to processes like flood frequency and floodplain hydrology. Various types of plants are very sensitive to changes in hydrologic conditions, and there is a need to choose vegetation that is suitable for current hydrologic conditions. Some vegetation can cause stabilization and growth of mid-channel bars as well as stabilize banks, indicating that even in locations that are relatively damp, appropriate vegetation can be effective.

1.4 Overview

This literature review is intended to provide a broad discussion of what research has been done with respect to streambank stabilization. The focus of the review will be on bioengineering techniques, but other popular methods of streambank stabilization will also be discussed. The literature contains a diverse combination of material, not all of which is easily categorized into subsections. However, an effort has been made to fit the material into the four general chapters discussed below. Chapter 2 is a basic introduction to streambank erosion, both from a hydraulic standpoint and from the standpoint of geotechnical bank failure. In Chapter 3, traditional methods of preventing or reducing streambank erosion are discussed. Chapter 4 introduces bioengineering as a method of reducing streambank erosion and bank failure. Finally, in Chapter 5, combinations of bioengineering and traditional erosion control techniques are discussed.

A large number of books and guides are available for restoration of streams and protecting banks against bank failure (e.g., FISRWG, 1998; Gray and Sotir, 1996; Rosgen, 1996). There are many case studies regarding bioengineering, and the volume of literature on the subject is immense. This literature review does not address every work published on the subject, rather it is intended to outline past work and current knowledge of streambank stabilization – especially quantifiable aspects of the process.

Chapter 2 Introduction to Streambank Erosion

2.1 Introduction

In general, all streambank erosion can be subdivided into two processes. Thorne (1982) subdivides bank erosion into these two categories: 1. *Fluvial Entrainment*, which is the direct removal of sediment on the bed of a river or at the base of a bank, and 2. *Weakening and Weathering*, which consists of climatic effects such as freeze-thaw that weaken the stability of bank material. These two sets of processes occur in conjunction with each other, but fluvial erosion is usually the controlling process (i.e. without fluvial erosion, mass wasting will eventually cease). This leads to Thorne's idea of a basal endpoint control, or the concept that in order to control streambank erosion, one must concentrate on protecting the base of the streambank.

A review of literature describing stream morphology, mechanics of flow in meanders, and slope failure is warranted in order to help the reader understand the benefits of using vegetation for streambank stabilization. Thus, this chapter will begin with a brief discussion of natural hydraulic behavior in streams. Second, the characteristics of flow in river bends will be discussed. Third, streambank and bed adjustments will be discussed. Finally, a description of stable banks and the process of bank failure is provided.

2.2 Classification of natural rivers

Rivers and streams are commonly classified as straight, braided, or meandering. For unaltered streams, slope has the strongest influence on how a stream will behave, but hydrology and bank material are also important. Figures 2.1 and 2.2 show commonly used classification schemes for rivers and streams. Figure 2.1 shows how valley slope influences stream type while Figure 2.2 provides a plan view of various stream types (as per Pg. 5, Para. 1). According to Figure 2.1, straight streams (streams with little or no curvature) have very low slope. Although channels with very high slope may have little or no curvature as well, high slope streams are usually braided, meaning that they are composed of multiple curved sub-channels that flow within the larger channel. Meandering streams have significant curvature and are characterized by one channel that continuously changes direction within a larger floodplain.

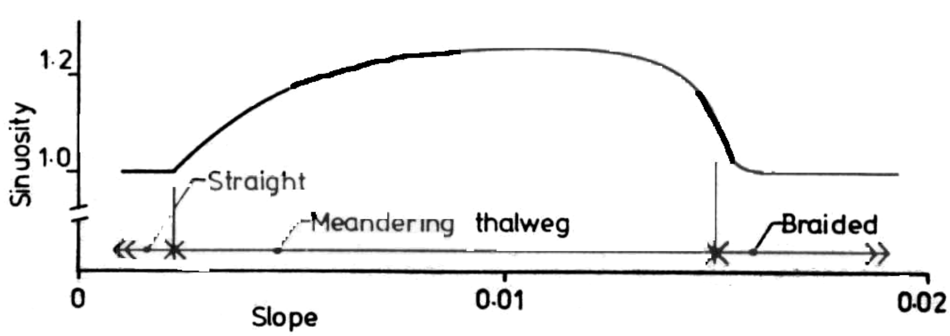

Figure 2.1 River classification (after Callander, 1978)

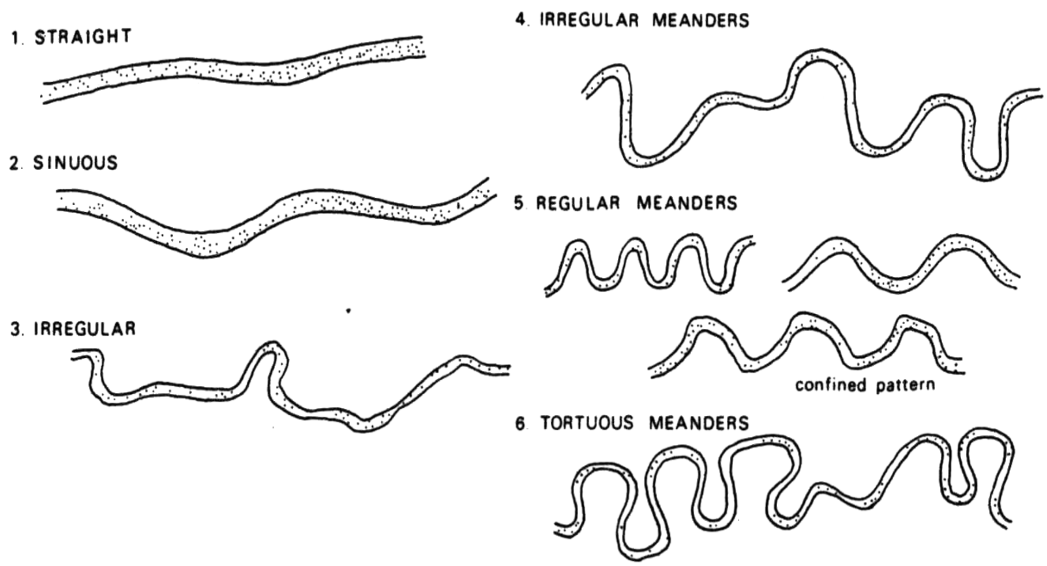

Figure 2.2 River classification (after Brookes, 1988)

The sinuosity of a channel, as used in Figure 2.1, is the ratio of channel length to valley length. The slope in Figure 2.1 is the valley slope. Straight rivers have low slopes and a sinuosity of 1.0 since the channel length is equal to valley length. Even in straight rivers, "the thalweg [deepest part of the channel] tends to wander back and forth from near one bank to the other" (Leopold et al 1964). As valley slope increases, there is more energy available to transport water and sediment. The river expends the energy by changing its alignment, eroding the banks and forming meanders until a quasi-equilibrium state is reached. The length of the meanders in a meandering stream can be related empirically to the dominant discharge in the stream (Leopold et al 1964). Braided streams have the highest slope classification, and have a complex channel form with a sinuosity of 1.0 since the channel is divided by islands and bars at low flows. At higher flow rates, these islands and bars will often be submerged.

Most unaltered rivers in Nebraska meander within a floodplain valley, but there are also some instances of braided channels. Many of the straight channels that are found in Nebraska were artificially straightened, and are slowly readjusting towards a meandering condition. The propensity for streams to meander is natural and can be observed in the field, in the lab, and even on glaciers where the melt water can form a meandering path in the sloped surface of the ice (Callander 1978). Explaining why streams often progress towards a meandering state has proven to be challenging.

In his 1978 paper "River Meandering", Callander divided the hypotheses that have been developed to explain meander formation into two categories. The first is based on sediment transport and the second on dynamic instability theory. Schumm and Khan (1972) found that a change in the type of sediment load that a channel carries can cause meanders to form. This change can be brought about by glaciers altering the landscape or a change in climate that causes more or less rain to fall on a watershed, which will change the type of sediment that will be in the rainfall runoff.

The dynamic instability theory attempts to show that meander formation can be caused by an "unstable response of the bed to a small perturbation" (Callander 1978). To show this theory, the instability of the bed of a straight channel is modeled numerically and different empirical closure equations are used to show how the sediment would be moved by the flow if a small perturbation were introduced in the flow.

Even though there is a natural tendency for open channel flows to meander, several changes must occur for a river to make the transition from straight to meandering as discussed by Ritter (1986). The first change is that the flow pattern in the river must become unstable. When water is flowing in a straight open channel, water primarily moves in the stream-wise direction, but there are two counter-rotating circulation cells that meet at the location of the highest velocity (Figure 2.3). These circulation cells are discussed by Odgaard (1984) and are said to be responsible for the trash line in a river (the presence of small objects floating near the middle of the channel). Movements of water in the span-wise plane of a stream are generally referred to as secondary currents. Secondary currents develop in rivers and streams whether they are straight or meandering, but in meandering channels, secondary currents are accentuated at river bends. For a straight channel to become unstable and begin meandering, the balance of the two counter rotating circulation cells must be upset.

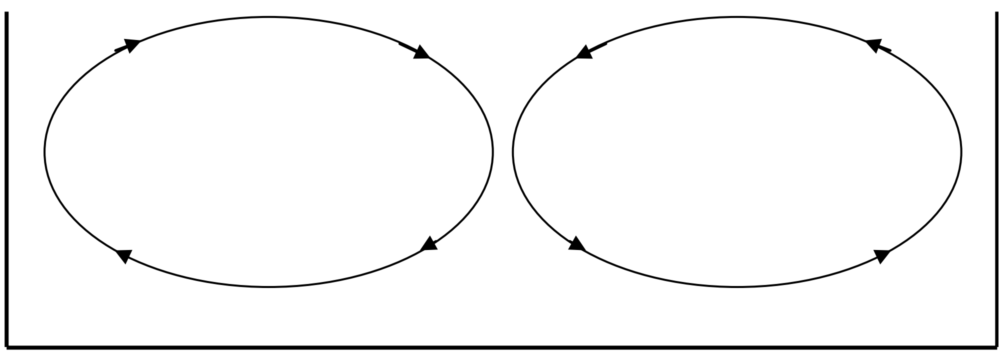

Figure 2.3 Counter-rotating circulation cells in a rectangular channel

The flow can become unstable either by an obstruction in the flow, such as a boulder, or from outside of the flow, such as a tree falling into the stream. These obstructions will cause one of the circulation cells to increase in strength and also cause the stresses at the bank on the outside of the cell to increase. When this happens, then the second requirement for meander formation is that the soil in the valley that the river runs through must be erodible.

Another criterion for meander formation is that stream energy must be dissipated. Since the effective slope of the river will decrease as the length of the channel increases with the lengthening of meanders, the bend shape will be established that most efficiently transports the water and the sediment load present. In most situations:

> "Meandering streams are probably closer to an equilibrium condition than straight streams because (1) meandering tends to dissipate energy in equal amounts along the length of the channel and (2) under the constraints of (1), meandering tends to minimize the total energy expenditure (to do the least work) or the rate of energy expenditure. This is accomplished by adjusting the curvature geometry or the channel gradient" (Ritter 1986).

A meandering river progresses towards an equilibrium condition where the ability of the stream to transport the available sediment from the watershed matches the sediment load. "It is generally acknowledged by river researchers that the sediment-laden flow imposed upon the river from its drainage basin is the cause from which the river channel formation follows as an effect" (Chang 1988). The variables that are adjusted for a river channel to handle the water and sediment load are the channel geometry, slope, meander curvature, channel sinuosity, roughness, and bedforms. An equilibrium state is reached when the power expenditure for a section of the channel is minimized and the water-surface profile, which is usually elevated at the outside of a bend, becomes level through the river bends (Chang 1988). As described by Galay (1983), in equilibrium streams the rate of scour is not zero, rather, the rate of scour and the rate of deposition cancel each other out.

2.3 Principles of flow in curved channels

Water flowing in a curved channel affects and is affected by the banks of the channel. "The form and processes of a meander are determined by the flow of the water in the channel and the response of the material of the bed and the banks to the forces acting on it" (Callander 1978). The water follows the channel's curves, but the water also develops and maintains the curvature of the channel through the processes of sediment transport.

Unlike flow in a straight canal or a straight pipe, the flow of water in a meander has three important velocity components. In Figure 2.4, the behavior of flow in a curved channel is displayed using a representative element of fluid and vectors to define the shear stresses on the element. The notation for describing the dimensions varies from publication to publication, but the three primary directions of stream-wise, span-wise, and vertical are either denoted as *x, y, z,* or *s, r,* and *z* respectively.

The secondary current pattern (circulation cell) for a meander is shown in the cross-section in the middle of Figure 2.4. This pattern shows how a single circulation cell dominates the flow in a meander, forcing the path of highest velocity to the outer bank of the stream. This pattern varies significantly from the balanced circulation cells predicted for a straight channel and shown in Figure 2.3.

Chang (1988) discusses the computation of flow in curved river channels. He writes "the flow through curved channels is characterized by the stream-wise variations in water surface, longitudinal and transverse velocity, flow resistance, strength of circulation, and so on" (Chang 1988). These variations are difficult to model numerically, but with the use of certain assumptions, general methods have been developed.

Elementary fluid mechanics can be used to determine the geometrical profiles of the water surface in a meander.

> "Assuming irrotational flow and, on any vertical line, hydrostatically distributed pressure, the need for a centripetal force to make the water follow a curved path requires that:
>
> $$\frac{\partial h}{\partial n} = \frac{U^2}{g * r} \qquad (2.1)$$

Where h is the elevation of surface above a horizontal datum, n, a radial coordinate, measured outward, U, the velocity along a streamline, and r, the radius of a streamline. That is to say, the surface is tilted and is higher on the outside of the curve than on the inside" (Callander 1978).

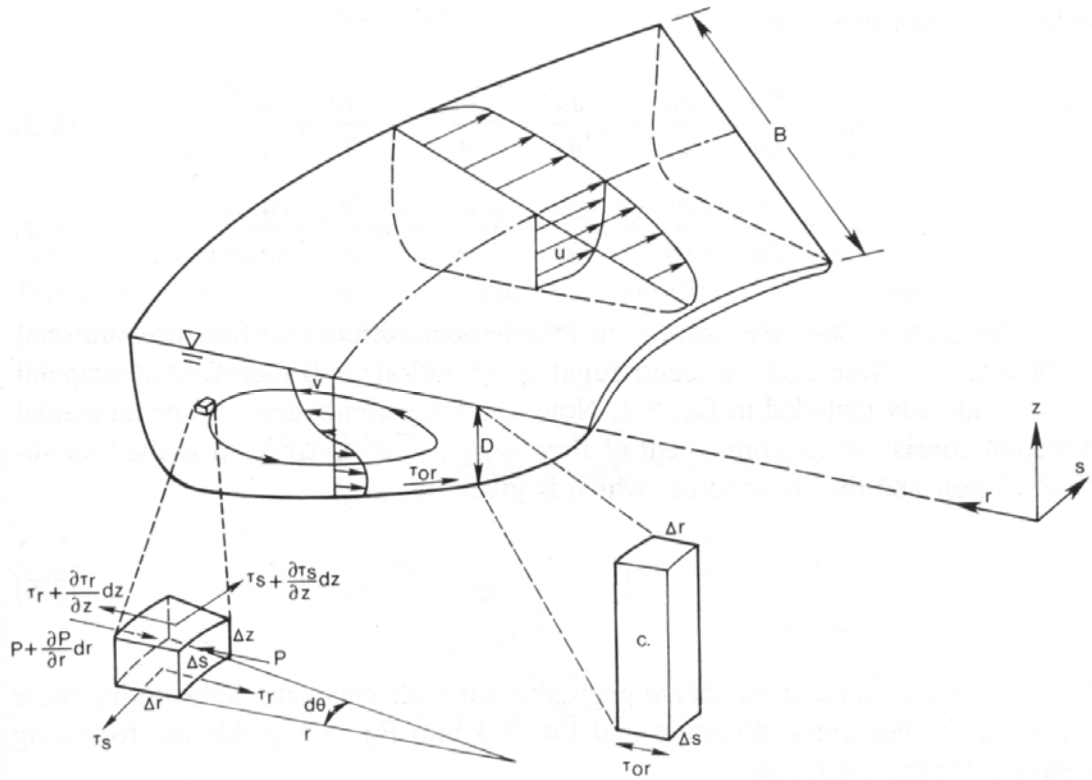

Figure 2.4 Coordinate system of a meander (after Chang 1988)

From Equation 2.1, it can be seen that:

> "…an element of water near the bed takes a path with a smaller radius of curvature than one near the surface, that is, the former moves across the channel towards the inner bank and the latter towards the outer bank. Vertical currents, upward near the inner bank and downward near the outer bank, complete the cell of transverse circulation" (Callander 1978).

Because the degree of curvature of a bend changes, the characteristics of the flow and the channel also change. Chang (1988) relates the change of channel curvature to the growth and decay of the secondary currents. The changes in the circulation can be related to the characteristics of the velocity field and also to the sediment transport in the meander.

According to Bathurst et al. (1979), secondary currents develop due to interaction of the primary flow with large channel features, influencing channel morphology. There are two methods by which streamwise vorticity (or flow rotation) can be induced: 1. The circulation cells can be stress induced if there is a nonuniform distribution of shear and anisotropic turbulence – this is generally only significant in straight, uniform channels, or 2. the cells may be skew induced –

this can occur whether the flow is laminar, turbulent, or inviscid, and is caused by nonuniformity in channel plan form (e.g. a bend). Skew induced cells accentuate erosion at river bends.

Bathurst et al. (1979) state that skew induced rotation occurs because the upper water surface is pulled to the outside of a bend by centrifugal forces, while water near the bed is pulled to the inside of the bend by continuity. The strength of the rotating circulation cell is affected by Reynolds number, radius of curvature, width, depth, position in the bend, and deflection of the arc angle of the bend. A counter-rotating cell is often present as a relic of the previous bend, and it appears to have a strong influence on bank protection. According to Bathurst et al., the counter-rotating cell is only present when there is no shelf (the outer bank of the bend is steep).

According to Bathurst et al. (1979) there are two locations where there are peak shear stresses that may influence bank erosion. One location of peak shear stress occurs at the interface of the two counter-rotating cells (where down-welling occurs). Another stress peak is associated with the core of maximum flow velocity. For designing erosion control, the stress peak associated with the core of maximum flow velocity appears to be more important for very high discharges (when the steepness of the outer bank is diminished because of high stage). For high stage, bank reinforcement should be greatest in the location of peak velocity. For low and medium stages, erosion control should be designed with both peaks in mind.

A study performed by Blanckaert and Graf (2001) was one of the most detailed studies available for flow in laboratory channel bends. The test was performed 60º into a 120º bend, with the measurements taken in the outer-bank half of the cross section. "In this study, detailed measurements were made of a rough turbulent flow in equilibrium with its developed bottom topography" with the purpose of "improving our understanding of the flow and turbulence in bends and their relationship to boundary erosion and spreading of pollutants" (Blanckaert and Graf 2001).

By using an Acoustic Doppler Velocity Profiler (ADVP), Blanckaert and Graf were able to measure the three-dimensional velocity components for the flow and then calculate the turbulence parameters. They determined that "The most important features observed in our experiment are the existence of an outer-bank cell of secondary circulation and the reduced level of turbulent activity in the region near the outer bank" (Blanckaert and Graf 2001). These features are important because both "have a protective effect on the outer bank and the adjacent bottom" (Blanckaert and Graf 2001). Figure 2.5 shows the secondary currents as measured by Blanckaert and Graf. The outer bank cell is clearly visible in the upper right corner of the figure.

By measuring velocities at 65 vertical profiles in the outer-bank region, Blanckaert and Graf were able to clearly identify the outer-bank circulation cell and the decreased level of turbulent activity in this region. Both of these features of the flow were observed to shield the outer bank from the high velocity flows. The concluding result of this study was an understanding that the migration and evolution of meander bends depends on the degree of turbulence as well as mean velocities.

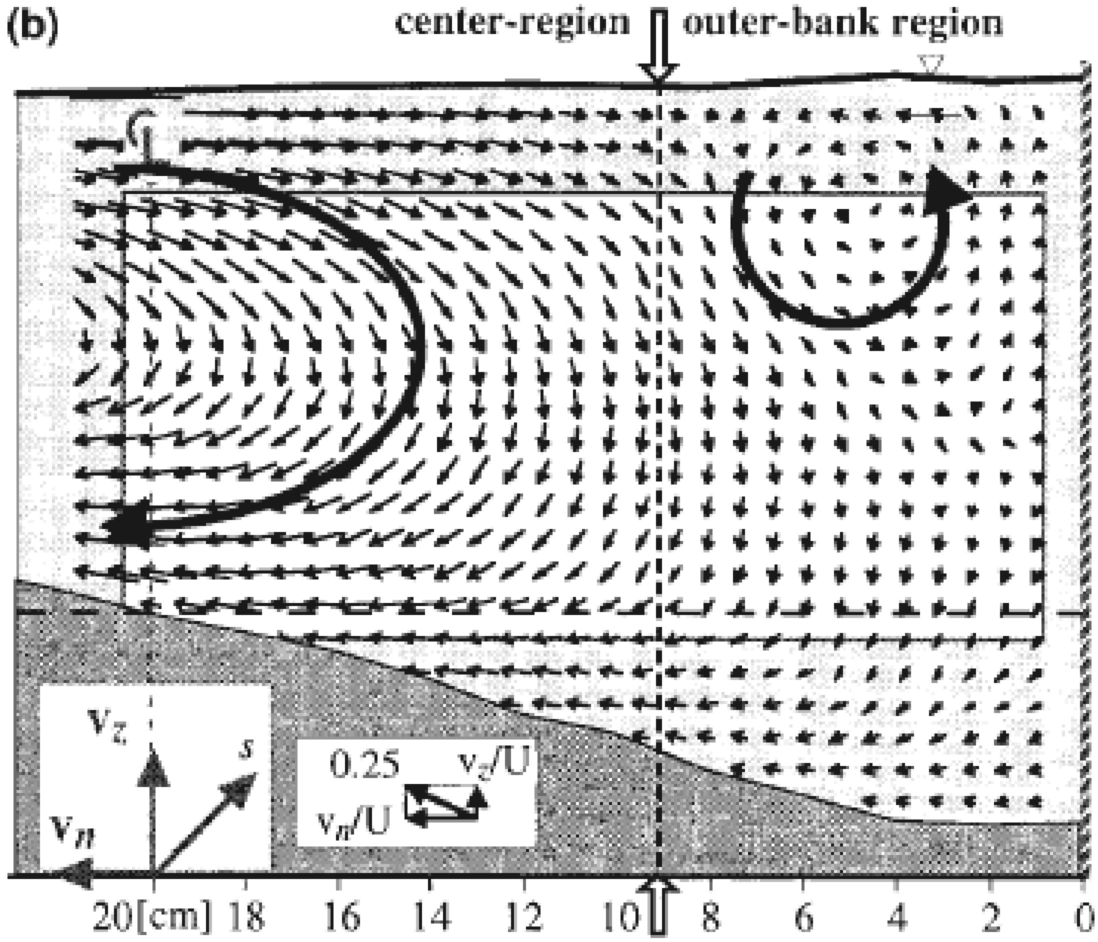

Figure 2.5 Flume study secondary currents (Blanckaert and Graf 2001)

2.4 Sediment transport in meanders

The sediment transport that occurs in meanders is important for the formation and maintenance of the channel geometry. In general, sediment transport in meanders follows the same principles as sediment transport in straight channels. The transport process for channels has been explained as:

> "Flow in the channel generates shear stress on the bed and banks. The magnitude of this stress is directly proportional to the velocity gradient close to the boundary. In order to remain in equilibrium the boundary material must supply an internally derived, equal and opposite shear stress. If the velocity gradient becomes steeper for any reason, a point is eventually reached where the resistance to motion of the boundary material, that is, its ability to supply an equal and opposite shear stress, is balanced by the fluid shear stress. Any further increase in fluid shear stress must result in entrainment of boundary material. The nature of the particle which is entrained depends on the engineering properties of the bank material" (Hey, Bathurst, and Thorne 1982).

Since the velocity of the water changes as it passes through the meander bend, the velocity gradient also changes, causing the sediment transport capacity of the flow to change. This results in both erosion and deposition at locations in the channel bend. The process of sediment transport through a meander can be explained as follows: "Most of the sediment eroded from one bank is deposited on the point bar on the same side of the channel in the next bend downstream. Such scour and fill causes an increase in the amplitude of the meander or migration of the channel along the valley, or both" (Callander 1978).

Because sediment is always moving through meanders, there is a tendency for meanders to migrate over an extended period of time. Hickin and Nanson (1984) studied migration rates for river bends on rivers of different sizes in western Canada. They found that "the relationship between bend migration rate and river size is difficult to isolate because of the confounding effect of intermittent channel migration and the complex relationship between migration and curvature" (Hickin and Nanson 1984).

Determining migration rates for rivers is not a simple task because migration is dependant upon the hydrology of a situation as well as the sediment characteristics. Migration rates are usually studied over long periods of time, on the order of centuries when possible, because the short terms rates are not very useful. Nanson and Hickin (1983) discussed the discontinuous nature of channel migration. The researchers concluded that the migration rates varied by the season and also by where the banks of the river were in the bank erosion cycle.

The bank erosion cycle is related to migration because if the banks are in poor condition, then the sediment can easily be moved away in the next increased flow situation, causing significant migration in a short period of time. Nagata, Hosoda, and Muramoto (2000) divided the bank erosion cycle up into four parts.

1. Bed scouring at the side bank, or outer bank of a meander
2. Bank collapse due to instability of the scoured bank
3. Deposition of the collapsed bank materials at the front of the bank
4. Transportation of the deposited materials

Nanson and Hickin (1983) concluded, "a river bend can be in varying states of readiness to migrate laterally". After the collapse of a bank, the material that is deposited will protect the bank itself. This protection will only last as long as this material is present. As soon as the deposited material is transported away, the cycle will resume.

Nanson and Hickin (1986) comment that bank migration rates are generally related to stream power (the product of discharge and slope) and indicate that in their studies, bank vegetation played very little role in reducing channel migration rates.

2.5 Lane's relation and channel degradation

In addition to lateral migration of streambanks, streambeds can degrade or aggrade, depending on how stable the stream is. At this point, it is expedient to introduce the concept of the sediment balance. Lane (1955) observed that there is a relation between sediment load, sediment size, stream discharge, and channel slope. The relation is depicted in Figure 2.6, produced by Rosgen (1996). Figure 2.6 is intended to demonstrate that if the equilibrium of a stream is upset, the stream adjusts to reestablish equilibrium. For instance, an increase in slope (e.g., by straightening the channel), might cause an increase in sediment load and subsequent degradation.

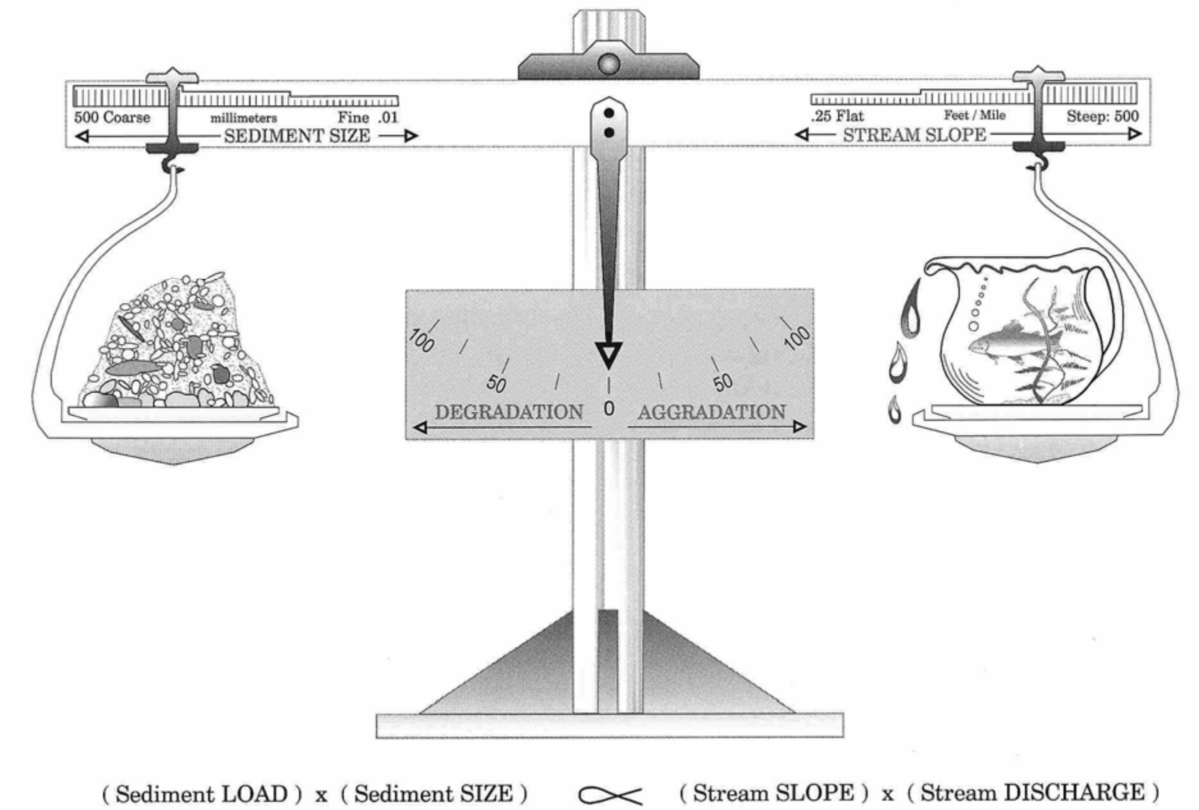

Figure 2.6 Balance between sediment load, sediment size, bed slope, and discharge (Source, Rosgen, 1996 from Lane, 1955)

Rosgen (1996), who is well-known for his courses in stream restoration, provides a detailed classification method for streams. The classification system is too detailed for description in this literature review, but provides insight into why streams behave the way that they do. Rosgen's approach is a holistic approach that promotes restoration of streams as a whole.

Galay (1983) Discussed causes of degradation including both upstream and downstream degradation. Downstream degradation is usually caused by a change in flow parameters like increased discharge, a decrease in available bed material (dam), etc. Upstream degradation is caused by increases in bed slope (e.g., resulting in a head cut). Galay validates his observations with Lane's Relation:

$$S \sim Q_s^a D^b / Q^c \qquad (2.2)$$

Where S is channel slope, Q_s is sediment load, D is sediment diameter, and Q is flow discharge.

According to Galay, upstream progressing degradation occurs fastest because the high slope of the head cut results in high sediment loss. Downstream progressing degradation causes asymptotically reduced slope and thus, bed removal decreases asymptotically. Galay (1983) identifies specific causes of degradation in Table 2.1 The consequences of channel degradation can be dramatic, as shown in Figure 2.7.

Table 2.1. Causes of river bed degradation (after Galay, 1983)

Type of Degradation	***Primary Cause***	***Type of River Change or Engineering Works to Cause Degradation***
Downstream Progressing	Decrease of bed material discharge, $Q_s \downarrow$	(1) construction of high dam (2) construction of low dam (3) excavation of bed material (4) diversion of bed material (5) change in land use (6) storage of bed material
	Increase water discharge, $Q \uparrow$	(1) diversion of flow (2) rare floods
	Decrease in bed material size, $D \downarrow$	(1) river processes
	Other	(1) river emerging from lake (2) thawing of subsurface permafrost
Upstream progressing	Lower base level	(1) drop in lake level (2) drop in level of main river (3) excavation of bed material
	Decrease river Length	(1) cutoff (2) channelization and regulation (3) horizontal shift of base level (4) stream capture
	Removal of control Point	(1) natural erosion (2) removal of dam

Figure 2.7 Degradation leads to bridge failure (after Galay, 1983)

According to Galay, degradation downstream of a high dam is dependent on things like bed material, flow release patterns from the dam, etc. Degradation also occurs downstream of small dams, but only for a limited time (once the dam is full, sediment continues downstream, ending degradation). In some cases, feeding coarse gravel into a river has been suggested for stabilizing the bed. However, tributaries that bring coarse material into a main channel can lead to degradation downstream of the mouth since the coarse material can be deposited as a knickpoint (if the material is too coarse for the main channel to carry). In some cases, warm water in a tributary in a permafrost region can lead to bank failure (if the banks are warmed too much).

A drop in level of the main river may cause degradation in tributaries – high flows in the tributaries with low flows in the main river can create an artificially high energy grade line. If flows in the main river are kept high, there will be backwater.

Galay (1983) points out that in order to predict degradation rates, sediment continuity and sediment transport relations are needed, and sometimes, an empirical relation. Some important factors to consider when modeling transport rates include: bed armoring, the existence of cohesive material or vegetation, erosion of riverbanks, fluctuation of flows, sudden changes in bed material from tributary sources, and existence of engineering works. The common response to the possibility of degradation associated with a project – deal with the problem when it occurs. The reality is that it is much easier to cure before it occurs.

Some of Galay's most important conclusions include: degradation of a main channel usually causes degradation of its tributaries, degradation of tributaries can reduce degradation of a main channel (because of increased sediment load), and degradation can occur very rapidly – many kilometers of stream can be degraded in one flood event. Also, it is better to analyze possible degradation that will result from a project since it is easier to prevent degradation than to cure it.

Parker (1978) discussed the existence of a paradox in the theory of stable bed rivers: rivers with stable banks can still carry bedload. Based on previous theory, channels with bedload cannot be stable, but Parker shows how streams can have stable banks and yet have mobile beds because of transfer of downstream momentum by turbulent diffusion. He develops a model for the prediction of stable straight reaches in coarse gravel rivers.

2.6 Introduction to river stabilization and restoration

In contrast to the paradigm of the 1900's, successful river stabilization and restoration requires more than rock, concrete, or old car bodies. The criteria used to judge a river project have been elevated in recent years. Instead of only considering the immediate needs and issues of humans, the general health of the environment also needs to be considered and concrete channels have not proven to provide suitable habitat for riparian species. The progress of river restoration projects has been documented and design guidelines are becoming more readily available.

One of the reasons that a general set of guidelines has not been developed is that each site has its own intricacies, and how local characteristics affect stabilization structures needs to be considered. The task of river stabilization and restoration is classified as either river engineering or river training. Instead of straightening channels and lining them with concrete, the approach that is considered more often today is to reestablish meanders that have previously been removed from a river channel. The concept of morphological diversity is discussed by Brookes (1988) as a set of criteria that should be considered by an engineer when restoring or stabilizing a river channel. The components of a healthy natural alluvial channel system may include (Brookes 1988):

1. Pools. A pool is a topographically low area created by scour and corresponding to convergent flow at high discharges. It is generally located immediately downstream from the axis of a bend and is characterized by relatively deep, slow-moving water at low flow. The bed material is usually composed of fine-grained sand
2. Riffles. These are topographically high areas corresponding to divergent flow at high discharges. The bed material is composed of a concentration of larger rock sizes, often gravel. At low discharges the flow is fast and the water surface gradient steep. The cross-section is typically symmetrical.
3. Point bars. The inner side of a bend is typically an area of deposition in contrast to the erosion of an outer bank. Accumulation of material forms a point bar adjacent to a pool, producing an asymmetrical profile.
4. Floodplain. A natural river channel and adjacent floodplain are parts of a single system. Rivers overflow their banks on average about once per year and this process may be important in building a floodplain by deposition. Streams with sufficient power erode laterally across the floodplain which is created and continuously modified by the processes or erosion and deposition. Floodplains also include the flat ”bottomlands” adjacent to the banks of rivers.
5. Bank vegetation. Bank vegetation can be added to this idealized model, which provides shade to the channel, bank stability, and organic debris. The preference of fish for stream areas with protective cover has been recognized for a long time. Bank-side vegetation prevents excessive illumination and water temperatures.

These components are indicators of a healthy riverine system, although it is common to have a natural riverine system that does not contain all of the components listed above due to geological factors. Determining which components to develop in a river restoration project depends on local conditions at the restoration site.

The process for returning a straightened or degraded channel back to a healthy system can be a difficult due to the uncertainties of meandering flows. Haltiner, Kondolf, and Williams (1996) suggest that the approach with the least impact be taken and that self-sustaining bioengineering materials be used. Williams (2001) takes it one step further and suggests that it might be better to just remove the obstacles and allow the river to heal itself. Regardless of the method, reestablishing morphological diversity in rivers needs to be approached differently than the river engineering projects of the 1900’s.

2.7 Hydraulic engineering and tractive force applications

For stable channel design of straight channels, a commonly used method is the tractive force method. This method is described in detail by Chow (1959). The tractive force method is the process of calculating the average shear stress on the bed and banks of a channel and comparing it to the minimum shear stress necessary to detach a grain of non-cohesive sediment. The tractive force method is most useful for straight, uniform channels because the relations between average shear stresses and local shear stresses are known for many common channels. For meanders and for cohesive sediment the tractive force method is not as useful. For a straight channel with uniform flow, the average shear stress (τ) on the channel boundary is given by:

$$\tau = \gamma R_h S \qquad (2.3)$$

In which γ is the specific weight of water, R_h is the hydraulic radius of the channel, and S is the energy slope of the channel.

For a trapezoidal channel, Chow (1959) provides correction factors that allow calculation of the maximum local shear stress that occurs on the bed and banks of the channel. Then, if the shear stress at which a grain of bed or bank material will begin to move (or critical shear stress) is known, the stability of the channel can be determined. Since sediment situated on steep banks is acted on by gravity as well as the flow, Chow also provides a correction factor to account for the reduced stability of bank material.

Thorne (1982) describes the forces on a non-cohesive particle on a submerged streambank. As discussed by Chow (1959), such a particle is subject to both gravitational and shear stress forces. Gravity tends to pull the particle down the bank (especially if the bank is steep), and shear stress tends to pull the particle in the downstream direction. The vector combination of the two forces is greater than either of the individual forces. Thorne provides an equation which describes the forces on an individual particle and can be used to predict incipient motion of the particle. Although the tractive force method for non-cohesive particles has a fairly strong theoretical background compared to for cohesive sediments, local shear stresses and critical shear stresses are difficult to determine accurately in all except the most uniform channels. In bends or in a channel with irregular geometry, the tractive force method is not nearly so useful. Consequently, application results are varied.

Cohesive sediments are even less well-understood than non-cohesive sediments because of the difficulty of determining intergranular forces. Researchers often develop empirical relations or do soil erodibility tests for cohesive soils. Because of the large number of possible combinations of cohesive soils, measured erosion rates and empirical relations are generally not universal. Millar and Quick (1998) point out that erosion of cohesive streambanks is not well understood, and that it is very difficult to accurately measure critical shear stress of cohesive sediments in the field. Measuring actual shear stress is also quite difficult.

Additional information about the tractive force method and sediment transport can be found in books by Chow (1959), Graf (1971), and Yang (1996)

2.8 Channel form

According to Hupp and Osterkamp (1996), a river can be divided into different flow areas, including the channel itself. Floodplains are defined as parts of the channel that are submerged once every 1 to 3 years on average. The bankfull stage is the stage at which the floodplain begins to convey flow. Terraces may develop if a stream degrades and a new floodplain develops. When a channel degrades, the old floodplain becomes a terrace and is inundated less often than the 1 to 3 year period typical of a floodplain.

2.9 Streambank adjustment

Wolman (1959) did one of the first multiyear studies of lateral erosion of a stream with cohesive banks. The stream, located in Montgomery County, Maryland, had no woody vegetation on the banks of the reach of interest, and did not appear to be incised. Long pins were placed horizontally in the streambank at two cross sections, and erosion was evaluated by regularly measuring how much of the pins were revealed over time. The reach of interest eroded quite rapidly. Approximately 85 percent of the observed erosion occurred during winter months. Interestingly, the highest flood on record occurred during one of the summers of the testing period, but little bank erosion was associated with this event. Suspended sediment measurements in nearby rivers indicated that 65% of the suspended load was transported during December, January, February, and March. These observations tended to support the idea that most of the bank erosion was associated with sustained discharge (as observed during the winter months) which kept the banks saturated for long periods of time, and frost which also helped keep banks saturated and could comminute surface material.

Pizzuto and Meckelnburg (1989) examined a simple linear equation for bank erosion:

$$v = e(u_b - U) \tag{2.4}$$

In which v is the rate of bank migration, u_b is the near-bank flow velocity, U is the reach-averaged velocity, and *e* is a dimensionless erosion coefficient that is a function of soil type, vegetation, and other site parameters. The equation was tested in a location vegetated with mixed tree species, including silver maple, boxelder, and white ash. Bank sediments in this location were entirely cohesive. Results of the study indicate that near-bank velocity was a strong correlate for predicting streambank erosion rates. The areal density of silver maples along the bank was also correlated to streambank erosion rates, but was not as important as near-bank velocity. Areal densities of the two other dominant species, boxelder and white ash, did not appear to strongly affect bank erosion rates.

Chang (1982) presented a new mathematical model for stream adjustment. The model included water routing (St. Venant), sediment routing (mass conservation of sediment), and changes in width and bed profile (the model applied the stream power concept – the channel widens to meet minimum stream power criterion - with sediment removal limitations).

Osman and Thorne (1988) describe how lowering of the stream bed by degradation increases bank height and decreases bank stability. They discuss the steps that lead to failure of a streambank. The lateral erosion of a streambank is complex in two ways. First, the hydraulic flow associated with erosion can be very complex, and second, the soil behavior is often poorly understood. Osman and Thorne follow the general tractive force procedure for estimating erosion:

1. Calculate shear stress on the river bed and bank.
2. Determine critical shear stress of the bank material
3. If the shear stress is greater than the critical shear stress, determine the rate of erosion of the bank. The rate will be a function of the excess shear stress (the difference between the actual and critical shear stresss).

Once the rate of erosion is determined, the migration of the bank is calculated, and the process is repeated. The modeling process must be repeated continually, because as lateral erosion occurs, the shear stress distribution changes. For accurate results, a numerical model of the flow is probably necessary. Eventually, the lateral erosion is sufficient to undermine the adjacent streambank. This limit can be assessed using streambank stability analysis, as described in Section 2.10.

Vertical and lateral bank erosion rates are a function of bank material properties, geometry, hydrologic properties and flow characteristics. The physical and chemical makeup of the soil in the bank and any salts that might be present in the soil play an important role in the erosion process. Finer clay particles and lower sodium ion levels both reduce erosion by increasing the critical shear stress of the soil. Osman and Thorne outline a procedure for calculating the critical shear stress of the banks. Figure 2.8, demonstrates how chemical and electrical characteristics of the soil can have a substantial impact on the critical shear stress of the soil.

It should be noted that even though geotechnical properties of the bank are important in determining bank failure, flow properties control the rate of lateral erosion of the streambank. After a bank failure, the new toe of the bank must be eroded away before another failure episode can occur.

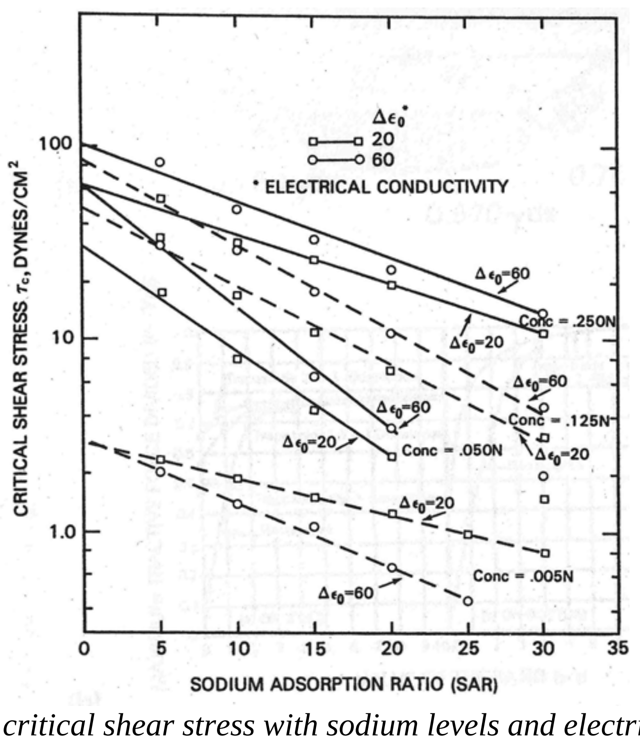

Figure 2.8 Variation of critical shear stress with sodium levels and electrical properties of clays (Arulanandan et al., 1980)

Lawler (1993) provides a thorough review of river bank erosion measurement techniques used before 1993. Measurement techniques include the use of sedimentological evidence, botanical evidence of floodplain deposits, historical sources, surveys, cross-profiling, erosion pins, and photogrammetry. Lawler cites many of the measurements recorded before 1993. The paper is a good source of information about bank erosion measurement techniques and their advantages and disadvantages. Several lateral erosion measurement techniques are identified and thoroughly discussed.

2.10 Streambank stability

Above the water line, streambank stability is a geotechnical problem that is affected by hydrological influences. The most common form of analysis is a factor of safety analysis. In this form, the force that resists shear failure of the bank is compared to the force that drives failure. The ratio of these two forces is called the factor of safety. When the factor of safety is significantly higher than 1, the bank will not fail, but changes in hydrology or undercutting by hydraulic processes can lead to a change in the relative forces and induce failure. The factor of safety, as given by Osman and Thorne (1988), is shown in Equation 2.5:

$$FS = \frac{\text{Resisting Force}}{\text{Driving Force}} = \frac{F_R}{F_D} \tag{2.5}$$

These forces are made up of different sub-forces, depending on the level of sophistication of the analysis. A typical analysis procedure is provided by Osman and Thorne using the diagram shown in Figure 2.9 to derive the forces

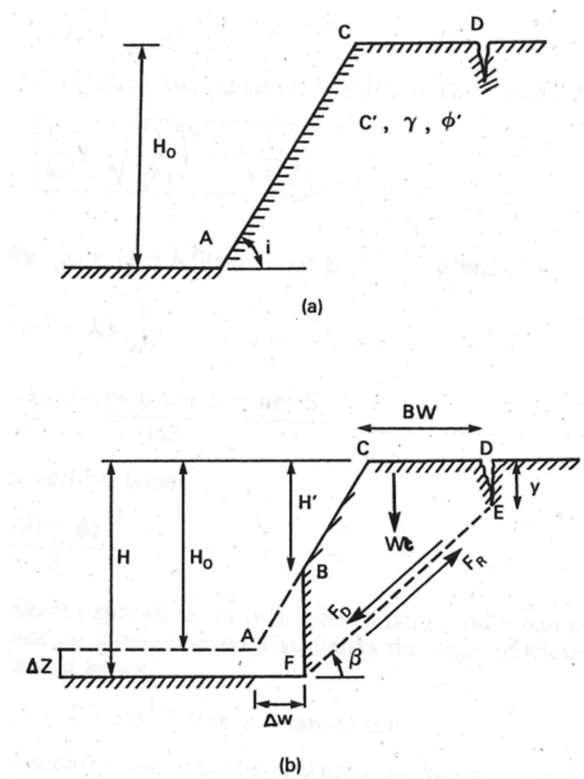

Figure 2.9 Parameters used to analyze streambank stability (after Osman and Thorne, 1988)

In Figure 2.9a, which shows the riverbank prior to lateral erosion, H_0 is the height of the riverbank above the channel bed, *i* is the initial angle of the bank, c' is the effective cohesiveness of the soil, γ is the specific weight and ϕ' is the effective angle of friction. Figure 2.9b shows the bank after lateral erosion has removed the toe of the bank. H is the current height of the river bank above the channel bed, Δw is the change in riverbed width due to lateral erosion, β is the angle of the expected failure plane, y is the depth of tension cracking, H' is the bank height above the top of the removed part of the toe, and Wt is the weight of the section that is likely to fail.

Osman and Thorne give the resistive force, F_R, as a function of the cohesion and the friction angle, and the driving force, F_D, as a function of the block weight and the angle of the failure plane. Some derivation leads to the following equation, which gives the factor of safety in terms of soil and geometric parameters:

$$FS = \frac{\dfrac{(H-y)c'}{\tan\beta} + \dfrac{\gamma}{2}\left(\dfrac{H^2-y^2}{\tan\beta} - \dfrac{H'^2}{\tan i}\right)\cos\beta\tan\phi'}{\dfrac{\gamma}{2}\left(\dfrac{H^2-y^2}{\tan\beta} - \dfrac{H'^2}{\tan i}\right)\sin\beta} \qquad (2.6)$$

According to Osman and Thorne, in order for this equation to be true, some assumptions have to be made:

1. The bank material must be homogeneous.
2. The failure plane must pass through the toe of the bank. Toe failures are often the most common since the failure plane that passes through the toe carries the most bank weight.
3. The derivation needs to be modified to include things like vegetation and hydrological characteristics of the bank.
4. The analysis is for steep banks.

As stated in (3) Equation 2.6 can be modified to include more complex behavior, and may even be practiced numerically to take into account non-homogeneity of the soil or variations in pore water pressure. However, the basic tenet of the equation remains the same: The factor of safety consists of the ratio of the resistive force, which is a combination of forces that act to hold the bank in place, and the driving force, which is a combination of forces that induce bank failure. If the factor of safety is less than one (and if theory is exact), the bank will fail. The greater the factor of safety, the more stable the bank.

Thorne and Osman (1988) provide a case study of two common applications that are associated with streambed degradation. Degradation downstream of a hydraulic structure due to sediment "starved" water, and lateral erosion on the outside of a channel bend. These applications do not appear to be verified with experimental data, but do provide some insight into the complexity of bank erosion.

Thorne and Osman state that bank failure often occurs during the recession limb of a hydrograph because of the increase in pore water pressure within the bank. They also point out that soil properties of deeply incised streambanks are often made more complex by the presence of bank vegetation (which changes the soil structure).

Simon and Collison (2002) use a numerical model to calculate the factor of safety of streambanks with up to five soils layers. The factor of safety equation used by Simon and

Collison is a wedge failure model. The equation is somewhat different than that introduced by Osman and Thorne (1988), but is based on the same factor of safety concept:

$$FS = \frac{\sum c_i' L_i + \left[S_i \tan \phi_i^{\,b}\right] + \left[W_i \cos \beta - U_i + P_i \cos(\alpha - \beta)\right] \tan \phi_i'}{\sum W_i \sin \beta - P_i \sin(\alpha - \beta)} \quad (2.7)$$

In which, c_i' is the effective cohesion of the i^{th} layer, L_i is the length of the failure plane in the i^{th} layer, S_i is the matrix suction force on unsaturated parts of the failure surface, $\phi_i^{\,b}$ is a parameter of the soil that defines the rate of increase of soil strength with increasing matrix suction, W_i is the weight of the i^{th} layer (within the failure surface of soil), β is the bank angle, U_i is the hydrostatic uplift force in saturated parts of the failure surface, P_i is the hydrostatic confining force due to external water levels, α is the failure plane angle, and ϕ_i' is the effective angle of internal friction.

The forces that resist failure in Equation 2.7 include the effective cohesion of the soil, apparent cohesion due to matrix suction, and friction along the failure plane. Friction along the failure plane is caused by components of the weight of the failure surface and hydrostatic pressure on the face of the surface that are normal to the failure plane, and is reduced by buoyancy of saturated soil. The driving force that causes failure is the component of the weight of the failure surface parallel to the failure plane. This force is reduced by hydrostatic pressure acting on the face of the bank.

According to Thorne (1990), cohesive banks can fail by a number of mechanisms. These include saturation of the streambank and subsequent positive pore pressures caused by excessive precipitation, cycles of wetting and drying that produce desiccation cracks, and freezing of soil moisture. Cohesive banks may take one of several forms of failure, depending on the height and slope of the bank and soils properties. Steep banks generally show slab-type or toppling failures, in which large slabs of soil break off the bank. Banks with lower slope generally show rotational failures, in which case the bank has a failure surface that begins at the toe of the bank, and the soil slides into the water. The cutoff angle between the two types of failure is approximately 60 degrees. Bank failures usually occur during the receding limb of the hydrograph, when the bank is saturated (increasing the pore pressure), the weight of the bank increases (because it is no longer submerged), and exfiltrating water tends to increase the likelihood of failure.

Darby and Thorne (1996) produced a paper on riverbank stability analysis that analyzes sloughing, shape of the bank, pore pressure and other properties related to bank failure. Bank failure is based on a factor of safety (FOS) analysis. The paper deals entirely with block failure (sloughing) and the effects of bank geometry on sloughing. The paper addresses:

1. That geometry associated with riverbanks must be accounted for
2. That failure does not always occur at the toe of the bank – a weakness of other methods
3. Hydrostatic vs. pore pressure – Usually pore pressure is simplified too much
4. That the failure plane is not necessarily the same as the bank angle or soil friction angle – a more rigorous technique is necessary.

The method presented in this paper is applicable to steep, non-layered riverbanks with planer failures and includes hydrostatic and pore pressure effects.

The location of the most critical failure is determined iteratively by the method of Darby and Thorne. Limitations of their model include that it is only applicable to steep, cohesive riverbanks that fail on planer surfaces. According to Darby and Thorne, vegetation and seepage effects must be accounted for.

Little et al. (1982) applied a slope stability analysis to the banks of streams in the Yazoo River Basin in Mississippi to determine the limiting slopes and heights of riverbanks. As expected, bank failures generally occurred on the outer banks of bendways in heavily degraded streams. The failures often happened after heavy rains (which increased bank weight) and occurred in locations with tension cracks. There are many similarities between the area observed in this study and eastern Nebraska: many of the streams are heavily degraded, the soil is cohesive, and there is no bedrock control. Initial degradation of the streams is generally caused by the movement of a knickpoint that travels up the watershed.

According to Little et al., for stable streams, bank erosion is much less than for heavily degraded streams. The failure of the bank produces material at the toe that is very susceptible to erosion. For very steep banks composed of cohesive soils, tension cracks often develop prior to failure of the banks, and the resulting failure is slab failure. The failure plane is a surface between the toe of the bank and the bottom of the tension crack.

Little et al. modified a stability analysis performed by Chen (1975) that provides a relation between bank height, bulk unit weight, and soil cohesion. The relation was modified to include the effects of tension cracking. Both mean and worst case (prolonged wet period) conditions were analyzed, and it was found that bank failure was best predicted by the worst case conditions. That is, the stability analysis did a good job of predicting when bank failures were imminent, but only if wet periods were used to define the soil conditions. Little et al. suggest that structural toe revetments are the best method of preventing bank failures, because they protect the toe from further destabilization. Also, their method can be used to help predict the necessary elevation of the toe revetments.

In a study of bank erosion by Andrews (1982), it was apparent that most of the observed bank failures occurred as erosion of a gravel/sand base area followed by the collapse of a cohesive surface layer that would otherwise be less susceptible to erosion. Note that this undercutting is a major problem in some of the degraded rivers of Nebraska. In these streams, a more erodible layer of sand was exposed following degradation of the streambed. Andrews (1982) also noted that the depletion and accumulation of sediment occurred primarily near the banks. This may be because the study river was stable and aggradation or degradation were not prominent.

Pizzuto (1984) studied bank erodibility characteristics of 16 sand bed streams in Minnesota, Iowa, and Nebraska. The streams observed by Pizzuto had sand beds and cohesive banks (a lower sandy layer and an upper cohesive layer). Failure of the upper layer was usually in tension. Cohesion of the upper layer was caused primarily by composition, but in some cases also by vegetation. Most failures occurred on the outsides of bends where flow eroded the lower layer, undercutting the cohesive upper layer. The cohesive material did not hinder erosion of the lower layer. Figure 2.10 shows the process of undercutting, followed by block failure of the upper cohesive layer of sediment. Once the cohesive layer is dissociated from the bank, it is much more easily eroded.

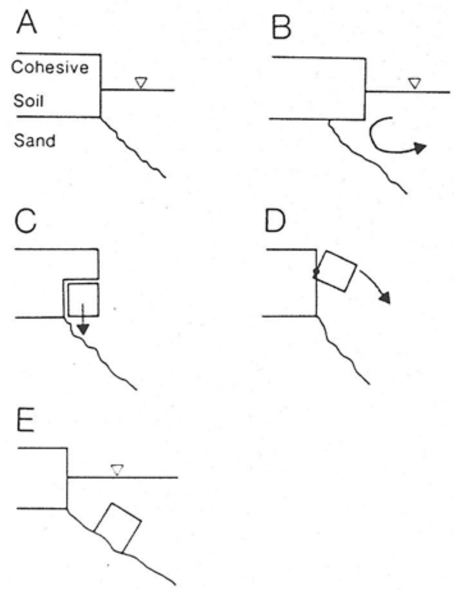

Figure 2.10 Progression of failure of cohesive upper bank (after Pizzuto, 1984). C and D are tension and beam failures, respectively.

Thorne and Tovey (1981) also studied rivers with cohesive banks underlain by a sandy layer. These types of rivers are common, with the lower layer resulting from alluvial deposits and the upper layer caused by deposition during overbank flow. The lower layer is eroded away until the upper layer fails. Fluvial erosion is the mechanism that leads to undercutting of the bank and subsequent geotechnical failure of the upper layer. The geotechnical failure occurs by shear, beam failure, or tensile failure. Shear failure is the downward displacement of an overhanging block by shear, beam failure is when a failure block rotates about a horizontal axis in the block – the block is in tension at the top and in compression at the bottom, and tensile failure occurs when the lower part of a failure block falls away from the upper part due to its weight. Cracks and fissures in the upper layer are extremely important for determining the failure threshold.

The upper layer, though occasionally inundated, is not particularly susceptible to fluvial erosion. Fluvial erosion of a cohesive layer is strongest when the bank is saturated and/or under the influence of frost. The lower layer is primarily eroded by the flow. Pore pressure does not play much of a role in the lower layer since it is non-cohesive. Furthermore, velocity measurements in bends indicate that the lower bank may receive the higher velocities.

Blocks of soil fall from the upper layer when the upper bank fails. The blocks may break apart when they hit the toe, or they may end up in the water where they are eroded by fluvial action. However, if they land above the water line and the river fails to remove them, they can become established with vegetation, or they may break down and cover the lower layer, making the lower layer less susceptible to erosion by fluvial forces. Thus, the failure of the upper layer sometimes leads to armoring of the lower layer. If a block is entrained by the flow, it generally breaks apart quite rapidly due to abrasion.

According to Thorne (1982, 1990), streams with banks composed of composite, stratified sediment layers are quite common. In streams with an erodible non-cohesive layer and a cohesive layer, the non-cohesive layer will often erode away at a much faster rate than the cohesive layer, making the cohesive layer much more susceptible to erosion as well. This characteristic can lead to a change in the rate of erosion if there is a change in bed elevation.

Abam (1997) stated that streambanks degrade in two ways: mass bank failure and fluvial erosion of material (piecemeal removal). Physical processes that influence erosion include:

1. Desiccation and wetting (which weakens cohesive soils). Desiccation may be caused directly by the weather or by continued variation in pool level. High pool levels increase stability since they reduce exfiltration. Soil desiccation leads to tension cracks.
2. Heavy rain leads to wetting of the soil which changes unit weight and shearing resistance.
3. Vegetation adds surcharge weight above the soil (which has a negative effect on bank stability), but roots may provide a great deal of structural support to the banks.

Millar and Quick (1998) also emphasized that streambank erosion was the result of mass failure and fluvial entrainment. They developed a model for predicting streambank erosion for streams with cohesive banks and tested the model against data gathered for Hotophia Creek in Mississippi. Streambank erosion was categorized as either bank-height or bank-shear constrained; mass failure dominated the former case, and fluvial erosion dominated the latter. Like other investigators, Millar and Quick defined a factor of safety to predict the stability of streambanks. However, the factor of safety that they chose for mass wasting was the ratio of the actual height of the bank and the critical height of the bank (the height at which the bank was expected to fail). Using this factor of safety, they developed a rough factor of safety cutoff of 1.25, below which erosion is bank-height constrained and above which erosion is bank-shear constrained. Bank-height constrained channels develop at the critical bank height.

Abam (1993) did a study of the Niger Delta. Bank heights at the delta were 2 to 13 m and translational and rotational geotechnical failures of the banks dominated. Most of the observed bank failures occurred at concave bends of the river: the position was just downstream of the location of maximum curvature. Velocities at bends were sometimes twice the magnitude of velocities observed in the middle of river.

According to Abam, high water levels provided passive resistance to bank failure. Upon recession, however, failure readily occurred because of loss of passive resistance, additional pore pressure (the groundwater falls more slowly than the surface water), and reduced shear strength. Bank failures often occur during the falling limb of a hydrograph because higher groundwater levels within streambanks cause higher pore pressures and lower shear strengths.

Clifton et al. (1981) studied riverbank instability of the South Saskatoon River. Piping of intertill stratified drift was identified as the major cause of riverbank instability. Failures were attributed to watering of lawns and irrigation (leading to increased piping and reduced pore pressures). Installation of subsurface drains reduced incidence of failures. Berms were placed at bank toes to prevent the river from eroding the toe, but most failures were well above the river in the present case.

Burgi and Karaki (1971) also studied the effects of seepage on bank stability. They found that at low velocities erosion due to seepage is dominant. Burgi and Karaki concluded that there was a direct correlation between increases in the lateral hydraulic gradient (of Ground water) and bank erosion. Seepage out of the channel increased side slope stability.

Hagerty (1983) did a field study of riverbank erosion along the Ohio River. The study was done over a 13 month period at five sites. Pins and tubes were installed in the banks to observe erosion rates. Bank material loss was worse for sandy banks. Antecedent moisture appeared to make the problem worse, especially in locations where there were pervious layers of alluvium. Exfiltration was found to be a major factor in bank failure.

Soil cohesiveness resulted in very steep bank faces. Consequently, following storm events, water flowed out of bank faces. There was some evidence that bank failures were most likely after floods of moderate amplitude and that the failures were worse if banks were wetted before rising floods. Freezing and thawing appear to intensify the erosion, especially in areas where the river level itself did not appear to have an effect.

One major factor was the removal of sand from sandy layers when water flowed out of banks. The water flowed into the sandy layers by vertical infiltration during precipitation, but also (possibly primarily) from bank recharge when flood waters rose. After an extended flood, water was observed seeping from a bank for a long time after the flood dropped.

According to Hagerty, loss of bank material was episodic, not continual. Sandy layers were more pervious and also more susceptible to piping. Formation of cracks from desiccation and undercutting was observed – this was important because cracks can lead to failure in cohesive banks. Piping was not as severe in locations with predominant fine-grained sediments or where slack water allowed deposition of material below the banks. In this study, wave action did not appear to be significant for material removal.

Springer et al. (1985) also investigated mechanisms for streambank failure along the Ohio River. One of the predominant mechanisms was due to the soil composition of the bank. As pointed out by Hagerty (1983), the bank had a sandy layer overlain by an upper layer of clay. During high flows water would seep into the sandy layer and as the flow subsided the water would exit the layer. Most failures occurred while the layer was emptying. A computer analysis indicated that the banks were very sensitive to moisture levels. If tension cracks near the streambank became filled with water, the bank was much more susceptible to failure.

Fox et al. (2006) indicated that lateral, subsurface flow can substantially erode bank sediment when it flows out of a streambank face. They developed a sediment transport model for predicting seepage erosion.

Hooke (1979) identified the two main methods of bank erosion as corrasion (direct shearing of material by the flow) and slumping. According to Hooke, rotational sliding (stepped banks) may be a third form of erosion, but sliding was not observed in his study. He states that rotational sliding only occurs in locations with complex stratigraphy. Hooke installed 2 to 3 m long steel pins spaced 30 cm apart. The pins were referenced to a fixed (safe from erosion) base point. The presence of pins did not appear to inhibit or cause erosion. In places with severe erosion, pins were occasionally lost. The factors that were identified that affected erosion included:

1. Flow conditions – the hydrograph
2. Rainfall characteristics of the storm (not just water in the river, but also water in the banks)
3. Time between peak flows (flow in and out of banks)
4. Soil moisture conditions
5. Temperature conditions (primarily frost)

The durations of storms that occurred affected soil moisture. Drying and heating of the banks had an effect on the bank material but did not alone cause erosion. Vegetation may have given some protection during the summer.

A regression performed by Hooke (1979) showed that peak discharge had the strongest impact on mean erosion and the extent of bank eroded, while precipitation had the strongest impact on maximum erosion. Some locations were most strongly impacted by corrasion; smoothed banks provided evidence of this. Following corrasion, what was left above the water was an overhang held together by vegetation.

Other locations had slumping. Slumping was difficult to measure since failures were large. Banks of coarse, sandy material were more likely to slump, and after slumping, material was carried away by the flow. Seepage inflow and outflow appeared to have significant impact on erosion.

The structure of water currents was also observed to play an important role in erosion, especially where bed irregularities cause the currents to impact the banks. These irregularities define where significant corrasion can occur, but banks composed of erosion resistant material can limit the effectiveness of the structures. Direct corrasion is dependent on the peak discharge, whereas slumping is dependent on soil moisture conditions. The erosion is typically worse for coarse, sandy soils. Erosion is also worsened by high moisture levels.

Hooke (1980) looked at the magnitude and distribution of erosion on rivers in Devon, England, and found widely variable erosion rates. Typical erosion rates varied from 0.1 to 1.2 m/yr with a maximum rate of 2.6 m/yr. Hooke demonstrated that there is a square root relationship between erosion rates and catchment area. Hooke also discussed the importance of bank material. Other important factors that influence erosion include local slope, configuration of currents, stage (which influences currents), and position on a bend.

Morgenstern (1963) provides stability charts to help compute the factor of safety of earthen slopes during rapid drawdown. In his study, Morgenstern shows how slope stability is affected by drawdown rate. One conclusion that may be reached from this work is that streams with rapidly changing depths are more susceptible to bank failure.

Thorne (1982) indicated that most bank weakening and weathering is associated with soil moisture. Strength reduction generally occurs because of bank saturation, a condition that leads to positive pore water pressure. Negative pore water pressures tend to hold the bank together in tension, but when the bank becomes saturated, the pore water pressure increases. Bank failures often occur because of increased pore water pressures after heavy rainfall, snow melt, or when there is a rapid decline in river stage. Weathering can be caused by freezing and thawing of pore water. In addition, soils can be leached or softened by water moving through the bank, especially if soils are susceptible to leaching. Surface erosion can occur on the bank face if there is a lack of vegetation protecting it. Vegetation on the bank can reduce surface erosion by several orders of magnitude.

Thorne states that bank failures deposit material at the base of the streambank, increasing the upper bank stability, but fluvial entrainment removes the basal material over time. Preventing streambank erosion often requires protection of basal material from removal by the stream. Thorne points out that long duration intermediate flows can increase erosion a great deal. Even though the intermediate flows may produce a shear stress that cannot remove intact base material, they can generally remove sloughed basal material, exposing the bank to future erosion. In cases where there is some control over flows, Thorne suggests that it is best to release water when the banks are least susceptible to erosion.

Simon et al. (1999) also cite the two stage process as the basis of bank erosion. The river erodes the base of the bank until the bank fails and is deposited in the river, exposing a new section of bank. The new bank may be protected in part by the deposited part of the old bank, at least until it is eroded away.

Bradford and Piest (1977) stated that streambank stability can be extremely difficult to analyze for some soils. Loess-derived alluvium is one example. Bradford and Piest claimed that it was impossible to describe forces resisting failure in the loess soil they were investigating, because soil shear strength changed a great deal with changes in soil moisture content, and because loess can be very anisotropic.

There are many methods available for determining slope stability factors of safety, including both numerical and analytical methods. Fredlund and Krahn (1977) compare six analytical methods of slope stability analysis, including:

1. Ordinary or Fellenius method
2. Simplified Bishop method
3. Spencer's method
4. Janbu's simplified method
5. Janbu's rigorous method
6. Morgenstern-Price method

Spencer's method and the Morgenstern-Price method were the most costly in terms of computer time (up to ten times more costly than more efficient methods). However, these two methods also produce similar factors of safety in a number of examples that were worked out.

2.11 Channel recovery following channelization

There are a number of techniques available for classifying channels and their evolution following human modification. Knowledge about the current state of a channel can help to identify what steps should be taken to improve the channel. When engineering a restoration solution, it is optimal to understand the equilibrium to which the stream is adjusting so that the restoration design may take full advantage of the channel's natural tendencies. Herein, the discussion of channel evolution is limited to incised channels, which are very common in Nebraska. Additional information can be found in many other references, including books by Rosgen (1996) and Thorne et al. (1997).

Harvey and Watson (1986) identified incised channels as those which have degraded beds. Degradation is a response to channelization, a change in land use, or lowering of the downstream base level. Two additional causes of past and present incision include changes in climate patterns and changes from prairie to plow, which may easily be more dramatic than urbanization. Degradation occurs until there is a new equilibrium between slope, bed material, load and flow, according to Lane's relation. The solution to degradation is to control grade, discharge or both.

Degradation can result in:

1. Dewatering of the riparian zone
2. Lower agricultural production
3. Sedimentation of downstream reservoirs and reaches
4. Destruction of aquatic habitat
5. Bridge and culvert failure (due to degradation)

According to Harvey and Watson (1986), following degradation, there are four types of channel modification:

1. Widening, deepening, straightening
2. Clearing brush and snags
3. Diking – levees increase channel depth
4. Bank stabilization

The first three types alter hydraulic and morphologic character of the stream significantly. Degradation generally leads to channel widening and to tributary degradation. Channel widening occurs because degradation allows banks to fail when their steepness becomes critical. Bank failures are due to gravity. Subsequent removal of material by stream erosion allows more bank failure. After the degraded stream becomes wide enough, berms develop at the bank toe, preventing more toe failures.

Harvey and Watson identify five stages of degradation for channels of alluvial valley fill. The stages are shown in Figure 2.11. In Figure 2.11, F is the width to depth ratio. During Stage I, there is very little sediment stored on the bed, and the channel has a U shape. A Stage II channel is observed immediately downstream of a nick-point, and is characterized by steep vertical banks. During Stage III, there is rapid channel widening if the critical bank height is exceeded. Sediment begins to accumulate on the bed during Stage III. Active channel widening continues during Stage IV, but at a reduced rate. Stage V is the new dynamic equilibrium. During Stage V there is little bank erosion except in bendways.

Harvey and Watson suggest that it is very important to choose the proper locations for control structures. Grade controls should be placed to prevent upstream migration of nick-points. They suggest that channels that have reached Stages IV and V have come to a new equilibrium and should be left alone (they do not require fixing). If a grade control is placed in a Stage II or III channel, it must be high enough to allow deposition upstream to stabilize the toes of the banks. This may mean putting in an excessive number of structures since the upstream influence of the structure is short. According to Harvey and Watson, the best place for a grade control is a Stage I reach; in this case, the bank height should not be greater than critical bank height threshold (the height at which bank failure spontaneously occurs). A grade control prevents incision and subsequent channel evolution in the case of a Stage I reach.

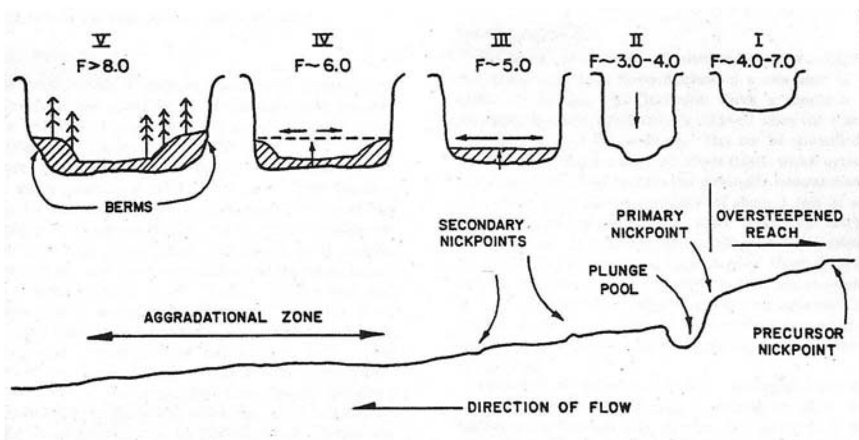

Figure 2.11 Five stages of channel evolution following channel incision (after Harvey and Watson, 1986)

Harvey and Watson also identify three types of failure that occur when the banks become excessively steep: circular arc toe failure, slab failure, and pop-out failure. Slab failures often occur just downstream of head cuts.

Hupp and Simon (1991) discuss the progression of channelized streams from degraded streams to streams that are in equilibrium with vegetation on their banks. The progression described by Hupp and Simon is depicted in Figure 2.12. The stages include (1) the stage prior to modification, (2) channel modification, (3) degradation of the bed following downstream modification, (4) further degradation and widening by mass wasting of the banks, (5) continued widening and aggradation, and (6) quasi-equilibrium.

New vegetation compliments the deposition of sediment during the late part of stage 4 and throughout stage 5. **Plants cannot begin to take root until degradation ceases.** After the initial period of degradation, plants begin to take hold on new deposits of sediment. These deposits generally come from additional degradation occurring upstream. New plants tend to intensify local deposition by fixing the sediment with their roots. In addition, initial stands of new woody vegetation on accreted soil are often very dense, helping to trap sediment. Due to competition for light and other resources, these dense stands eventually thin out as the new equilibrium is reached.

Hupp and Simon identify several species as the pioneer species of disturbed banks. These species include: black willow, river birch, and silver maple. These species form dense stands that help to fix sediment during the accretion process of Stage 5. Boxelder, green ash, and eastern cottonwood are also common but do not grow in dense stands. Black willow, river birch, silver maple, boxelder, sycamore, and cottonwood all have the ability to form adventitious roots, which allows these trees to grow in regions where sediment is rapidly accumulating by deposition. This is an important characteristic for any woody species that is establishing in an area recovering from channel disturbance. Vegetation usually becomes established low on the banks first, which helps to anchor the toe of the streambank. The development of this vegetation reduces bank angle and increases soil stability through development of root mass. Even after the stream reaches quasi-equilibrium, mass wasting will likely continue to occur on outside bends.

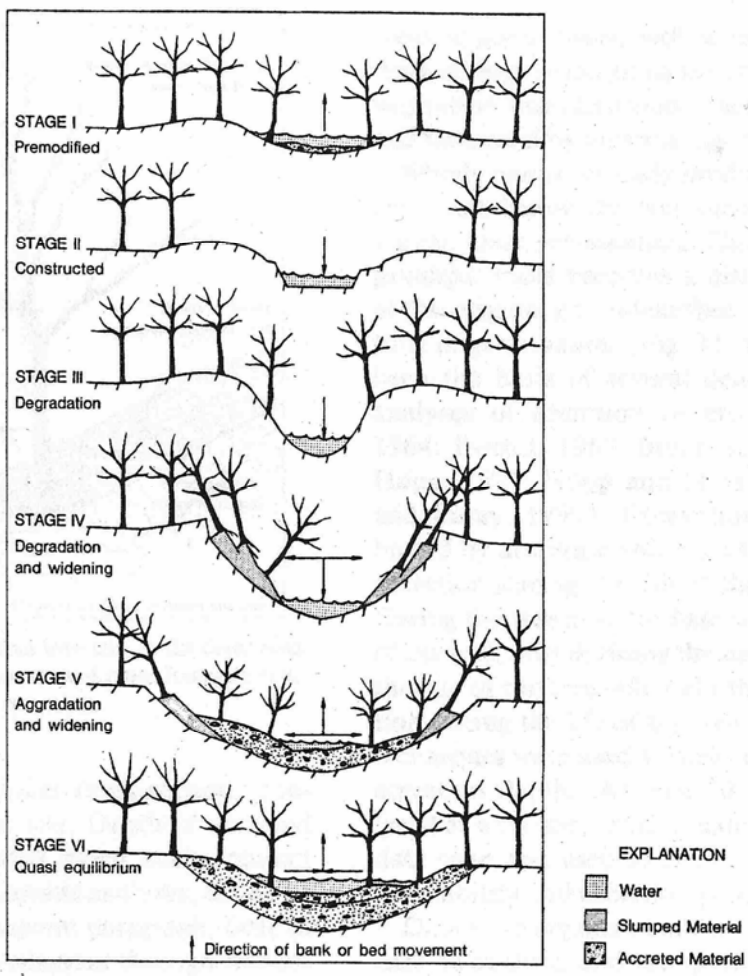

Figure 2.12 Six stage model of channel evolution after channelization. Arrows indicate accretion and degradation. (after Hupp and Simon, 1991).

Heede (1986) discusses the effects of stream base level (bed elevation) changes. Heede points out that streams are dynamic and that steady state is very short-lived. If humans interfere, adjustment processes are initiated. Lowering the base level can cause degradation throughout a stream network. However, raising the base level does not generally have the same effect (at least not on the same time scale). [Author note: Antelope Creek in Lincoln, NE has a natural hard point just southeast of 27th St. and Normal St. Channel characteristics immediately upstream and downstream of the hard point are significantly different. This is what should be expected in places where hard points have been installed prior to channel incision]

According to Heede, stream energy generally controls the sediment load. If the load into a reach is smaller than the energy capacity of the stream, sediment is picked up. If the load into the reach is larger, sediment is deposited. Stream adjustments which have a big impact on stream energy include: bedform changes, bed armor formations, width, pattern, and longitudinal profile changes. An increase in the long-term discharge of a stream usually leads to an increase in channel width, depth, and wavelength, and a decrease in the slope. An increase in the sediment load leads to an increase in channel width, a decrease in depth, an increase in wavelength, an increase in slope, and a decrease in sinuosity.

Riparian systems are severely affected by degradation. Degradation can lead to groundwater loss along streambanks. On the other hand, aggradation can lead to groundwater excess (drowning of a riparian system). Sometimes engineering is necessary for the reestablishment of vegetation. However, Heede suggests that engineering and vegetative controls require flexibility and caution. As engineers, we cannot accurately predict the magnitude of stream response. A good plan includes:

1. Recognition that added controls may create new critical locations (failure locations)
2. Contingency to develop additional control plans if necessary
3. Sufficient funding for upkeep

Check dams can be installed to increase bank stability upstream of the point of installation. To raise the base level of a long reach, multiple check dams are required from downstream to upstream. If possible, it is often preferable to prevent degradation altogether, because it is usually less costly than installing multiple check dams, and it is usually more effective. When check dams must be installed, they increase bank stability by promoting aggradation, raising the effective toe of the upstream streambanks.

Check dams are grade control structures since they decrease the water slope. Good check dam designs require apron and bank protection downstream of the dams because flow separation is likely to occur in this location, leading to scour. Flow separation can also occur at other bank protection devices (e.g. rip-rap, dead tree or brush placements). The resulting eddies can amplify erosion. It is always best to have smooth transitions upstream and downstream of controls.

When grade controls are installed, the length of the sediment wedge upstream of the control should be estimated as part of the plan. Large streams will have larger responses to changes because they have more available energy. When a grade control is installed, base levels will be increased, leading to aggradation upstream. This can make upstream areas more susceptible to occasional flooding. Vegetation will increase bank roughness and can also ameliorate flooding.

Heede points out that downstream of grade stabilization (grade controls and dams) degradation will continue at a faster rate since the water is sediment starved. This effect is made obvious by observing the impact of large dams such as the Aswan Dam – there is no replenishment of sediment downstream of the Aswan Dam, instead, sediments are picked up by the sediment starved Nile River. Consequently, stream adjustments and development of a new equilibrium take time. For example, the Upper Missouri River has head cuts on tributaries that are still moving upstream.

Chapter 3 Traditional Stabilization Techniques

3.1 Introduction

The traditional approach to combating streambank erosion is to use artificial devices to absorb the energy of the flow in the channel. Although vegetation has long been used to prevent erosion, both passively and actively, it has recently become an engineering focus. In this chapter, structural and mechanical stabilization techniques will be explored. The use of vegetation for bank stabilization will be treated in a later chapter. Most of the techniques presented in this chapter are relatively old and will be reviewed with the help of only a few sources.

3.2 Riprap

Riprap blankets consist of rock material that is installed on the banks of a stream to directly protect against erosion. Keown et al. (1977) describe the procedure for installing riprap. Usually, the bank is graded to an appropriate slope, the bank is lined with a bedding material to prevent leaching of the bank through the coarse riprap, and then riprap is placed on top of the bedding. An appropriately sized riprap must be chosen so that it does not erode under expected flow conditions. For best stability, elongated, angular stones are preferred to round, smooth stones, but design generally only specifies size of the stones used in the riprap. The riprap blanket should be about 1.5 or more median diameters in thickness, and must be properly tied into the bank at the upstream and downstream ends. Recommended maximum slopes are 2:1 (H:V) but 3:1 is more common. Riprap blankets are also sometimes referred to as longitudinal dikes or rock revetments. Riprap blankets can be expensive because of the large amount of material that may be required. Figure 3.1a shows a longitudinal dike.

Maynord (1987) developed relations for appropriately sizing riprap. He used physical models to determine the diameter of riprap necessary to withstand hydraulic and gravitational erosive forces. Maynord provides relations for sizing riprap diameter for both straight and curved channels.

3.3 Transverse dikes and weirs

Dikes are commonly installed to protect banks from erosion. They also tend to increase the roughness on the edges of a channel, increasing depth and decreasing flow velocity. Three of the most commonly used types of dikes are longitudinal dikes, spur dikes, and vane dikes.

Spur dikes (also called jetties or transverse dikes) are installed perpendicular to or at a slight incline to the flow (angled upstream into the flow), extending from the shoreline into the stream. Spur dikes greatly reduce near-shore water velocities, but also reduce the effective flow area of the channel. Sediment is deposited in low velocity areas behind spur dikes. Keown (1977) divides transverse dikes into: 1. permeable and 2. impermeable dikes. Permeable dikes are often constructed by driving timber piles into the bed at specific intervals. The dikes reduce flow along the outer bank and cause deposition between the dikes. Deposition increases the effectiveness of the dikes. Wire and timber fences have also been installed in the place of permeable dikes. The fences trap debris and encourage the deposition of sediment. Impermeable dikes are usually made of stone that is dumped on the bed of the river and extend from the shore out into the flow. Impermeable dikes force all of the flow towards the center of the stream and can help deepen the channel. A spur dike is shown in Figure 3.1b.

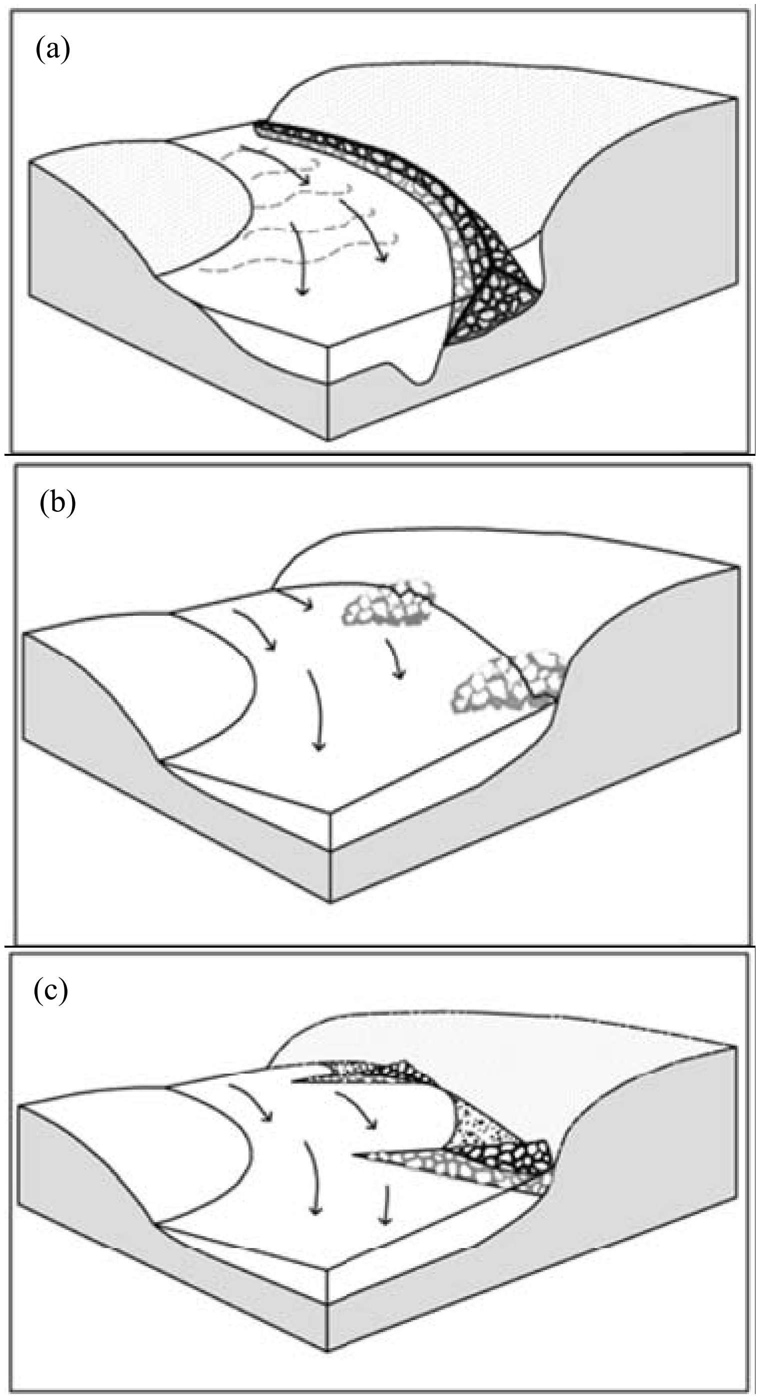

Figure 3.1 Structural bank protection methods including (a) a longitudinal dike, (b) spur dikes, and (c) bendway weirs (after McCullah and Gray, 2005)

Bendway weirs are submerged spur dikes that are built on the outside bank of a bend and are angled upstream. Bendway weirs are less costly than revetments and do not reduce effective flow area as much as spur dikes. Water flows over a bendway weir perpendicular to the weir. The angle of the weirs protects the outside bank by causing water to turn away from the bank. Vane dikes are installed to guide the direction of the flow. Vanes deflect the flow away from areas where erosion is undesirable. These dikes are also less costly than other types of dikes. If designed properly, vane dikes and bendway weirs can be relatively non-intrusive, and better for natural habitat than other forms of river training structures. A bendway weir is shown in Figure 3.1c.

All dikes impede stream flow by increasing bank roughness and/or reducing flow area.

3.4 Pavement and mattresses

Keown et al. (1977) list a variety of pavements and mattresses. Like riprap, pavement and mattresses are used to line the erodible outer banks of streams. Concrete pavement is cast in place and is very effective at preventing erosion. However, it is also very expensive. Articulated concrete mattress consists of blocks of concrete that are tied together with corrosion resistant wire. Concrete mattress is also expensive, but more flexible than pavement because it does not have to be cast in place. Interstices between the blocks of concrete can allow sediment behind the blocks to be eroded away over time, possibly leading to failure of the mattress. Both of these methods are limited to locations with good access to heavy machinery, and are not commonly used in small streams. Asphalt pavement and blocks have also been tried, but have not been particularly successful and in most cases were determined to be uneconomical. Mattresses can also be fascine mattresses (bundles of untreated tree stems) or timber and brush mattresses. These two types of mattresses are generally used when the material necessary to construct them is readily available. Their performance is not very good in terms of longevity because continual wetting and drying can lead to excessive rot.

3.5 Submerged vanes

Submerged vanes were first introduced to provide a low cost form of erosion control. The vanes are discussed in detail by Odgaard and Kennedy (1983) and Odgaard and Mosconi (1987). The general idea was to make use of the energy of a small part of the flow to redirect a larger portion of the flow. By installing vanes on the bed of the river, secondary currents could be induced in the flow that would cause the entire flow to turn. Vanes are situated on the bed of a bend and affect the dominant circulation cell such that momentum on the outer bank is substantially reduced. Figure 3.2 shows the layout of two typical submerged vanes.

3.6 Other methods

An attempt has been made to cover the more commonly used structural erosion control techniques. However, there are many other techniques. For example, Keown et al. (1977) describe a variety of other mechanical methods, including the use of log revetments, jacks, tires, and even automobile bodies to protect against erosion. In addition to Keown et al. (1977), the report by McCullah and Gray (2005) and the handbook by Biedenharn et al. (1997) are good sources of information about structural and biotechnical streambank stabilization techniques.

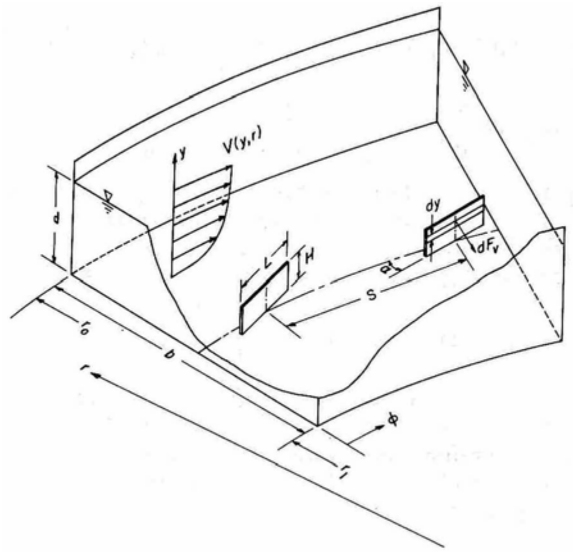

Figure 3.2 Layout of Iowa Vanes within a bend (after Odgaard and Kennedy, 1983)

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Chapter 4 Bioengineering Stabilization Techniques

4.1 Introduction

In this chapter, important aspects of using vegetation to stabilize soils and streambanks will be discussed. There has been a great deal of research on the use of vegetation to stabilize soils. Some of the research is specifically dedicated to reducing streambank erosion, but there is also a great deal of research on slope stabilization in non-riparian areas. A significant component of streambank stabilization is preventing riverbanks from sloughing, and much of the research in this area is not specific to just streambanks.

According to Bache and Macaskill (1981), the primary advantage of using vegetation as an engineering medium is that it is capable of regenerating following damage. The primary disadvantage is that vegetation can only survive in specific environments. Plants require appropriate flow, substrate, light, and nutrient availability. Without these components, vegetation is ineffective for stabilization purposes. Plants can also hinder flow of water and make channel maintenance more difficult. A large quantity of foliage can reduce the erosive capability of flow by slowing it down, but additional drag can also remove some plants and take the soil with them. Vegetation can also be susceptible to pests, disease, and damage by humans, and it is least resilient in the winter and spring when damage by ice and flow is most severe.

Keown et al. (1977) also identify the ability of vegetation to regenerate as a major advantage of vegetation. Grassy species have the advantage of taking less time to become established, but woody species are generally more resistant to erosion. Well established grass species can reduce water velocities at the soil surface by as much as 90%.

4.2 Stabilization of highway cut slopes

We begin with a brief review of research in the area of stabilization of highway cut slopes. Much of the work in this area can also be applied to the stabilization of streambanks. Gray and Sotir (1996) is a good general reference of the application of bioengineering for stabilizing slopes, whether near streams or in other areas.

Gray et al. (1982) analyzed the use of vegetation for stabilizing slopes. They found that herbaceous species (grass and forbes) intercept rain, bind particles, filter soil in runoff, dissipate energy of runoff, and maintain good infiltration. Woody species (trees and shrubs) also limit sliding by root reinforcement, deplete soil moisture, and stabilize by the process of soil arching (buttressing – tree roots extending up a slope can transfer stress to the base of the slope).

According to Gray et al. (1982), most roots cannot prevent deep rotational slope failures or undercutting by waves and currents at the base of a slope. They recommend installing a wall at the base of an unstable slope to protect the toe, decrease the effective slope, and allow for buttressing. If wattles (bundles of willow) are used, they should be placed in trenches parallel to contours so that downslope runoff deposits sediment in them. A stable grade should be 1.5:1, but 2:1 is better. Gray et al. suggest using willow to stabilize slopes, but also state that native vegetation is best since it is proven to grow well in the general area. Unfortunately, large quantities of native vegetation are often difficult to obtain. It is also best to disturb the worksite as little as possible when stabilizing the slope.

Gray and Sotir (1992) did a side-by-side comparison of rockfill with a rock buttress toe and vegetation for bank stabilization. They recommended harvesting materials between November and April when plants are dormant. Willow, dogwood, alder, poplar, and viburnam were used in the present study. Vegetation was placed in the form of small to large stems and branches were placed along contours in regular intervals up a slope. Installed stems and branches immediately acted to protect the bank from failure by reducing erosion and spreading out loads laterally. Development of adventitious roots added additional protection. Gray and Sotir noted that simulations showed that the critical failure circle of the slope always passes through the toe of the slope, underscoring the importance of reinforcement at the toe.

4.3 Impacts of vegetation on slope stability

Collison and Anderson (1996) used a two-dimensional finite difference model to predict soil pore pressures on vegetated and unvegetated slopes. They modeled the effects of vegetation and macropores. Figure 4.1 shows the results of their model. In general, vegetation results in lower pore pressures, an important result because lower pore pressures help to stabilize slopes. Figure 4.2 demonstrates how roots and vegetation may help to protect slopes. Collison and Anderson suggested that grass cover is a practical alternative to woody species because grass is not as heavy (not as much weight surcharge for the slope) and has deep roots.

Collison and Anderson (1996) state that when considering the impacts of vegetation on stability, both mechanical and hydrological effects should be considered. Mechanical effects include soil strength reinforcement by roots and increased normal load. Hydrological effects include interception of precipitation, evapotranspiration, and increased infiltration and permeability. Generally, plants lead to a net reduction in water content and water table height.

Referring to Figure 4.2, according to Collison and Anderson, in temperate climates subsoils can be thin and roots may penetrate the entire subsoil layer. In humid climates, deep soils make root penetration an unlikely source of protection except where shear on the unstable slope penetrates the ground surface (e.g., at the toe and the top of the slope). In other words, if the roots cannot penetrate deep enough into the soil, failure is likely to occur below the root mass and so roots do little to protect against slope failure.

Figure 4.3, from Collison and Anderson (1996) shows that trees may be a detriment to slope stability until after their root ball develops substantially. This may take until the tree is fully grown (as much as 20 years). The increase in permeability due to root ball formation can lead to a reduced Factor of Safety for soils with low saturated conductivities. The increase in permeability only occurs for soils with low permeabilities, but the point is that the introduction of vegetation does not guarantee increased bank stability in all situations.

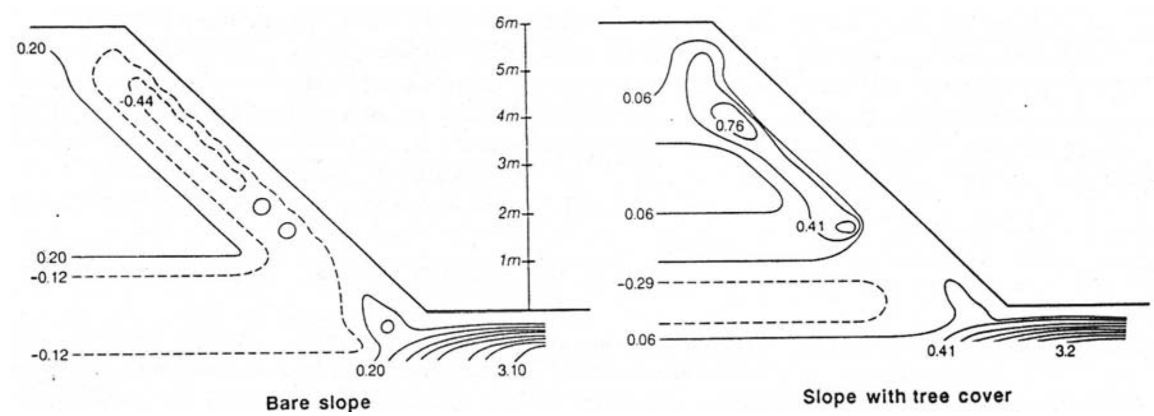

Figure 4.1 Pore pressure distributions in a bare slope vs. pore pressure distributions in a vegetated slope. Saturated permeability is $1*10^{-6}$ m/s (after Collison and Anderson, 1996)

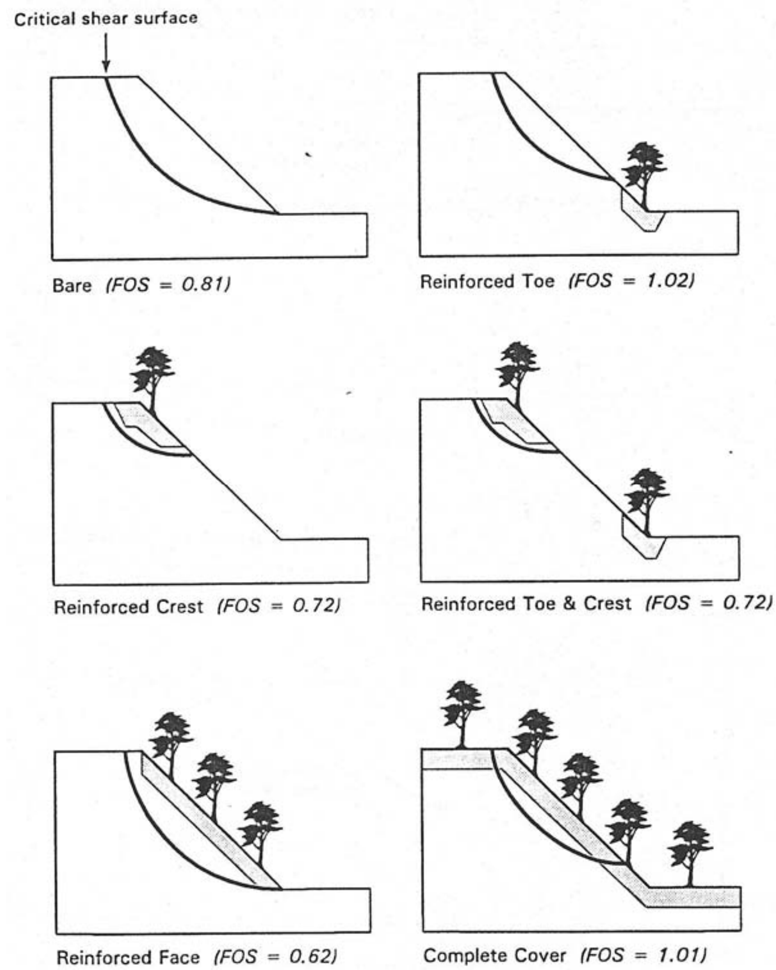

Figure 4.2 Effect of vegetation on the location of the failure surface. The shaded area is the extent of root penetration as modeled. Saturated permeability is $1*10^{-6}$ m/s. Note that toe support is most effective for stabilization purposes (after Collison and Anderson, 1996)

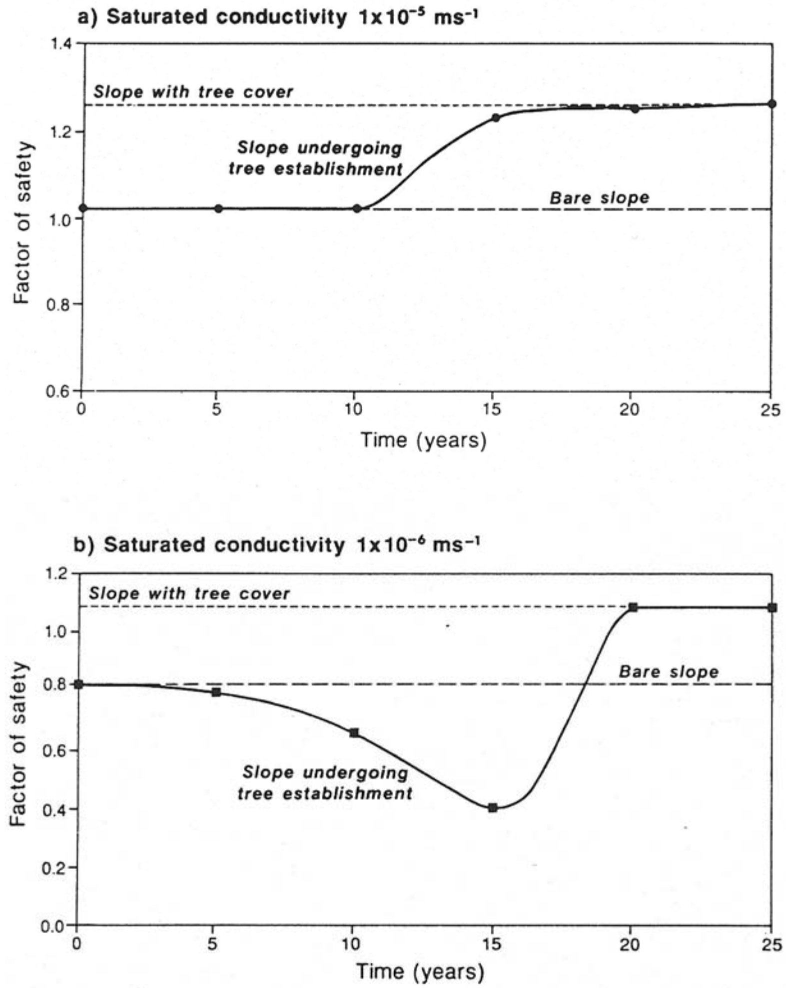

Figure 4.3 Effect of permeability on slope stabilization during stabilization period. In low permeability soils, initial effect of vegetation is negative. (after Collison and Anderson, 1996)

Riestenberg and Sovonick-Dunford (1983) investigated a land slide near Cincinnati, Ohio. They found that tree roots increased the factor of safety against sliding by nine times. The trees in their study included sugar maple, ash, and buckeye. The colluvium that covered hillslopes that were investigated were susceptible to failure at slope angles of about 12 to 14 degrees when bare, but slope angles of up to 35 degrees were stable when forested. Woody roots help prevent slides when they passed through potential slip faces.

This study was carried out in an area where trees are the dominant species. Broken roots were most likely to have failed in tension and not shear; this is an important discovery in terms of testing since the shear strength is likely different than the tensile strength. Tree roots of the sugar maple were observed as predominantly parallel to the ground surface, though some grew all the way to the weathered bedrock below the soil. It was these roots that broke off during the investigated mudslide. After testing roots from the relevant species, Riestenberg and Sovonick-Dunford found that the tensile shear strength (Force per Area) was highest for fine roots.

Tree surcharge (the weight of the trees above the soil) was found to be only 0.5% of the weight of the soil in the landslide and was deemed negligible. For the present landslide, it was estimated that roots provided 80 to 85% of the force that resisted slope failure; soil frictional strength provided the other 15 to 20%.

Shields and Gray (1992) studied the effects of vegetation for helping to stabilize sandy sloped levees at a site along the Sacramento River. Soil types were thoroughly analyzed at study sites. The study sites included a control site that was partially covered with mostly herbaceous plants: mostly grasses and sedges and California rose (*Rosa californica*). Sites with wood species included many valley oak (*Quercus lobata*) and Cottonwood (*Populus fremontii*). Trenches were dug to accurately measure root densities. Of the species studied in this article, herbaceous species displayed the highest root densities in the upper 30 cm of the soil and may be best for shallow sloughing. Woody species may be more effective for preventing deep-seated sliding since their roots were generally deeper. Most roots were confined to the upper 0.5 m of depth for both woody and herbaceous species. Roots significantly strengthened levee slopes, at least in the upper layers. There was little evidence that the presence of woody roots would promote piping through the levees, though this cannot be ruled out.

Simon and Collison (2002) examine the mechanical and hydrologic influence of plants on streambank stability. Three different vegetation covers were examined: mature trees, clump grasses, and bare/cropped turf grass. Equation 2.7 was used to evaluate the stability of the bank. Simon and Collison provide a detailed breakdown of the effects of vegetation on soil stability.

Mechanical benefits of the vegetation are primarily due to the roots. Roots interwoven with soil make a very strong composite material. Smaller roots tend to increase the soil strength more than large roots, and Simon and Collison indicate that a number of researches have identified grasses and shrubs as better stabilizers for this very reason. Plants that grow above the soil surface add a “Surcharge” of weight to the failure surface. The surcharge weight usually increases the probability of bank failure, though it also increases the normal force along the friction plane, increasing the resistive frictional force.

Hydrologic effects of the vegetation include interception of rainfall and evapotranspiration. These two functions reduce the amount of water in the soil, increasing matric suction and reducing the chance of failure. Simon and Collison also point out that these functions are less active during the winter and early spring when many failures occur. Tree canopies tend to concentrate runoff in local areas, and roots tend to induce better infiltration of runoff. These two effects can increase local soil saturation and reduce matric suction.

Six species of cover were investigated by Simon and Collison: Black willow, sweetgum, river birch, sycamore, gamma grass, and Alamo switch grass. The field study was extensive and included measurements of soil shear strength, root tensile strength, surcharge, pore water pressure, stream stage, and other data. Of the species studied, the river birch and the sycamore appeared to have the deepest roots, but the roots of all species appeared to be confined to the upper meter of soil. Simon and Collison pointed out that root depths of many plants generally do not reach below 0.5 to 1.0 m deep. This is an important observation in areas where there is a significant amount of degradation and the expected failure plane is well below the root zone. Although the switch grass did not have deep roots, it did have dense roots in the upper 0.4 m of soil. Figure 4.4 shows the factors of safety calculated for the different vegetation types using

Equation 2.7, a numerical model and data from a dry year and a wet year. All forms of vegetation studied increased the factor of safety of the streambank. For woody species, pore water pressure effects had a significant influence on the factor of safety. For the grasses, root cohesion was most important for increasing the factor of safety.

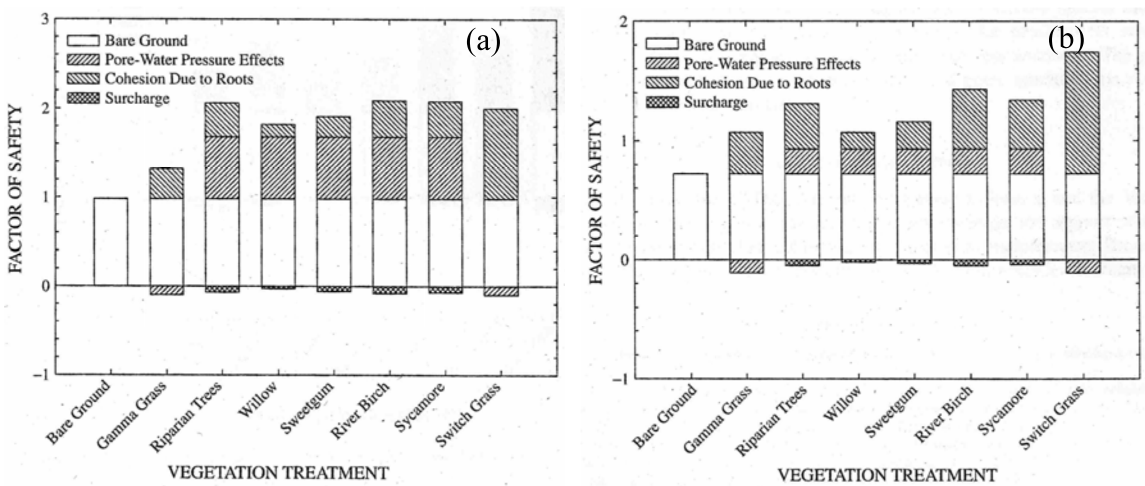

Figure 4.4 Impacts of vegetation on factor of safety for different species during (a) a dry year, and (b) a wet year. (After Simon and Collison, 2002)

A major finding of the research of Simon and Collison is that the hydrologic impact of vegetation on soil stability is as important as the mechanical impact. For grasses, mechanical effects were important because of high root densities, while increased infiltration resulted in a reduction in performance. Trees did not fare quite as well, especially the willow, which is a commonly used stabilization species.

Thorne (1990) states that the presence of vegetation tends to reduce soil erodibility by strengthening the soil. A high density of small roots is better for strengthening the soil than a low density of large roots. According to Thorne, vegetated banks are in general better drained than unvegetated banks, reducing soil pore pressures and increasing soil strength. Thorne suggests that quick growing species are better able to establish a bank than slow growing species, which tend to get destroyed before they can reach an effective size. Also, plants will be most effective at reducing erosion if they can develop roots at or below the low-water zone. According to Thorne, a mixture of riparian and terrestrial plants is best.

The weight of vegetation on the top of the bank can reduce bank stability if the bank is steep enough; as stated previously, this effect is called surcharging. Trees located at the tops of banks can be problematic because they not only increase the weight of the bank, but they may create a rotational moment about the bank crest because of asymmetrical growth or wind loading. Thus, it is preferable to have stands of trees rather than sparsely placed trees. Surcharging by herbaceous vegetation is not usually an issue.

Thorne (1990) states that when water flows over submerged vegetation, the vegetation has higher flow resistance than an unvegetated surface, thereby reducing flow velocity near the bed. Turbulence near the bed is also dampened. The effective resistance of vegetation is complex, especially for non-woody vegetation, which may bend with increasing flow. Woody vegetation may be detrimental for high velocity flows because local acceleration around the non-bending material can cause rapid local erosion. Contrary to the generally held belief that vegetation reduces flow conveyance, increased flow resistance for large rivers is minimal, because bank roughness tends to be much less significant than bed roughness for channels with high width to depth ratios.

Gray (1974) identifies the effects that vegetation has on stability as: reinforcement by roots, soil moisture depletion, surcharge by weight (additional weight above and beyond soil), and by wind throwing (root wedging). Gray states that the first three effects are beneficial. Surcharge apparently reduces the creep rate on slopes (at least to some extent). Roots increase soil shear strength by as much as 2 to 3 times. Gray observed soil creep on slopes in normal and denuded forests –the creep rate was much higher in denuded forest areas, especially after trees started decaying.

4.4 Impacts of vegetation on natural river dynamics

Toledo and Kauffman (2001) looked at the effects of channel incision on root biomass. In their study, root biomass was determined at several field sites. At each field site, the biomass was determined both above and below a stream channel head cut. Unincised channels had much higher root biomass counts, and the depths of the roots were greater than for incised channels. Toledo and Kauffman suggested that the increased levels of biomass were in part due to a higher groundwater table, and that channel incision promotes increased lateral erosion rates because of hindered root development (when present, high densities of roots greatly reduce lateral erosion). Higher groundwater levels also had a positive impact on biodiversity.

Hupp (1992) studied vegetation recovery patterns along channelized rivers in west Tennessee. The study included nearly 150 sites along 15 streams. Hupp found that following degradation and mass wasting, recovery accretion along the streambanks coincided with the highest density of stem development of new species of pioneer species. The first place where trees began to establish themselves was at the base of the streambank, near the toe. The species that were most likely to grow during the initial stages of recovery were fast growing plants that produce many seeds, including black willow, river birch, boxelder, silver maple, and cottonwood. Secondary growth in this region was dominated by ironwood, green ash, sweetgum, American elm, and bald cypress. This secondary growth occurred during the late stages of bank recovery. After the final stages of recovery, oaks (e.g. overcup, water, cherrybark, and willow oak) began to establish themselves.

Hickin (1984) investigated the effects of natural vegetation on river dynamics. The vegetation had five effects that were observed in the study: 1. Flow resistance, 2. Bank strength, 3. Bar sedimentation, 4. Formation of log-jams, and 5. Concave-bank bench deposition.

According to Hickin, vegetation causes discontinuities in rating curves since it is a factor in bed roughness. Vegetation also binds sediment and increases soil strength. Observed bank slopes are proportional to the soil shear strength. Banks bound by roots offer far greater resistance to lateral erosion. Thus, vegetation increases the tendency of rivers to meander rather than braid.

The binding effect of vegetation is probably most important in channels of low-slope – channels that can barely erode unvegetated banks.

Dislodged plant material can cause deposition in places where the plant material is deposited, leading to bar formation. Large plant material can also cause the formation of a cut-off if a log-jam blocks a meander (causing breaching of the meander).

Micheli and Kirchner (2002a) used aerial photographs taken over a 40-year period to examine the effects of vegetation on lateral migration of streams in the southern Sierra Nevada Range. Vegetation was classified into two types: dry meadow communities (consisting of sagebrush and non-native communities) and wet meadow communities (consisting primarily of rushes and sedges). Banks with dry meadow vegetation were generally 1.2 to 2.0 m high while wet meadow banks were 0.7 to 1.2 m high. Thus, water availability dictated the local vegetation type. Lateral migration rates were about 6 times as high for banks with dry meadow vegetation. Erodibility coefficients of dry meadow banks were approximately 10 times as high as erodibility coefficients of wet meadow banks. Micheli and Kirchner maintain that it is unlikely that the increased height of the dry meadow streambanks is entirely responsible for the increased bank migration rates, though it is partly responsible (stability of banks decreases with increasing bank height). They identify channel incision as a possible cause of increased lateral erosion.

Micheli and Kirchner (2002b) studied the shear strength of soils reinforced with wet meadow vegetation including rushes and sedges. By measuring shear strength of the bank soil, Micheli and Kirchner showed that the soil shear strength was directly related to the plant density. Table 4.1 shows soil shear strengths measured by Micheli and Kirchner at their test site. They found that rush species were better for stabilizing bar substrates than sedges, but that sedges were more effective for stabilizing actively eroding cut banks. The sedges formed a dense network of interlocking roots in a layer that was between 0.5 and 0.75 m deep at their study site. When the stream undercuts networks of dense sedges, the block on which the sedges are growing does not fail as quickly as unvegetated blocks do. Furthermore, when the block eventually does fail and falls into the stream, the dense mass of sedge roots in the block acts to retard lateral erosion much more than an unvegetated block would.

Table 4.1. Increases in shear strength attributed to rush and sedge root formation (after Micheli and Kirchner, 2002b)

Vegetation and Substrate	***Shear strength (kPa)***	***Biomass (g/m^2)***	***Sample Size***
Unvegetated bar	6.2 ± 0.3	0	9
Rush-colonized bar	46.3 ± 0.8	456 ± 7	31
Sedge-colonized bar	38.1 ± 1.3	681 ± 31	23
Dry meadow terrace	8.8 ± 0.8	Not measured	10
Sedge-colonized terrace or slump-block	43.0 ± 1.2	678 ± 18	20

Ikeda and Izumi (1990) used a mathematical model to examine how the presence of vegetation affects channel geometry of straight gravel rivers. Bank stability is not the focus of the paper by Ikeda and Izumi, rather, the transfer of negative momentum from the banks to the flow is explored. When vegetation on the bank of a river is submerged, it reduces longitudinal momentum near the bank, reducing the width of the river. For a constant discharge, the presence of the vegetation also leads to deepening of the channel, because the bed shear stress is redistributed so that there is less shear stress near the banks.

Millar and Quick (1993) developed an analytical model of streambank erosion. The model includes procedures for calculating flow resistance, continuity, velocity, bed and bank shear stress, bank stability, and sediment transport. The analytical model was developed to assess the equilibrium geometry of alluvial channels. It was found that channels with vegetated banks were generally narrower, deeper, and had lower slope than unvegetated channels with similar flow characteristics. In essence, it is predicted that the removal of bank vegetation will lead to channel widening.

Hupp and Osterkamp (1996) discussed the interaction between riparian vegetation and fluvial geomorphology in four different regions: high gradient streams in humid regions, coastal plain streams, Great Plains streams, and arid southwestern streams. Hupp and Osterkamp point out that many of the species that reestablish riverbanks after a channel disturbance (e.g., channelization) belong to the subset of the species that grow along the banks of relatively undisturbed channels. These species are clearly adapted to growing in disturbed areas. Species that typically grow along undisturbed streams and were observed growing in recently disturbed areas along west Tennessee streams included: black willow (*Salix nigra*), silver maple (*Acer saccharinum*), sycamore (*Platanus occidentalis*), boxelder (*Acer negundo*), eastern cottonwood (*Populus deltoids*), and green ash (*Fraxinus pennsylvanica*).

Plum Creek, in Colorado, is a sand bed stream that is braided. Species that are reestablishing along this creek following a recent flood include: Sandbar willow (*Salix exigua*), crack willow (*Salix fragilis*), peachleaf willow (*Salix amygdaloides*), yellow willow (*Salix lutea*), eastern cottonwood (*Populus deltoids*), indigobush (*Amorpha fruticosa*), narrowleaf cottonwood (*Populus angustifolia*) and alder (*Alnus incana*).

Smith (1976) studied the lateral migration of streams in Banff Park in Alberta and found that a 5 cm thick, dense mat of roots helped stabilize streambanks. The stabilization provided by the roots was quite high, and was attributed in part to cold local temperatures, which inhibited decay of dead roots. In this way, colder climates can help to reduce erosion along vegetated channels.

4.5 Comparisons between vegetated and unvegetated banks in field studies

Geyer et al. (2000) compare the migration of streambanks with different types of vegetation. The study was done in Kansas and Pre- and post- aerials are used for the comparison. The flood of 1993 had out of bank discharge. According to their measurements of lateral streambank movement, cropland lost an average of 47.3 m of soil, grassland lost 23.9 m, forest and single row trees showed deposition of 3.2 and 0.7 m, respectively. Trees include: cottonwood (*Populus deltoides Marsh*), box elder (*Acer negundo L*), elm species (*Ulmus* sp.), hackberry (*Celtis occidentalis L*), willow species (*Salix* sp.), silver maple (*Acer saccharinum L*) and sycamore (*Platanus occidentalis L*). Channels were slightly entrenched to entrenched, with moderate to high sinuosity.

Beeson and Doyle (1995) examined 748 river bends for erosion after a major flooding event in the 1990s. The reaches examined included vegetated and non-vegetated bends. Non-vegetated bends were on the order of five times as likely to show appreciable erosion as vegetated bends. Predominant species included cottonwood, cedar, spruce, and fir (in that order). Willow was a predominant bush along streambanks. No effort was made to identify species beyond vegetated and non-vegetated. Also, only significant erosion was detected – no actual migration distances were provided. The work statistically proves that vegetation reduces erosion of streambanks, but the magnitude of the impact is not enumerated. Channel migration was identified using pre- and post-flood aerial photos.

Allen (1990, 1991) studied erosion along shorelines at several lakes across the nation including lakes in Nebraska and South Dakota. A biotechnical erosion control was defined by Allen as the use of plant materials in combination with other structural elements to prevent soil erosion. Plants provide surface and subsurface soil protection, stems dampen waves, and roots bind soil. The advantages of using vegetation include lower cost, wildlife and fishery diversity, improved water quality, and the fact that it is more aesthetically pleasing.

According to Allen, the best pattern of vegetation includes: 1. A zone of emergent grasses and grasslike plants, 2. A zone of flood-tolerant plants at about mean high water level, and 3. A higher zone of flood tolerant trees. Allen did four case studies of biotech methods at reservoir shorelines. Some problems included: unpredictable changes in water level causing failure of species that were not drought tolerant enough (i.e., the water line was unmanageable). Much of the vegetation at the Holmes Lake project was destroyed by Canada Geese (*Branta canadensis*). Surviving vegetation included river bulrush (*Scirpus fluviatilus*), prairie cordgrass (*Spartina pectinata*), and soft-stem bulrush (*Scirpus validus*) but only because they were concealed in dense smartweed growth (*Polygonum sp.*).

At Lake Sharpton, Allen found that soft-stem bulrush, narrow leaved cattail (*Typha angustifolia*), Garrison creeping foxtail (*Alopecuris geniculatus*), and giant reed (Phragmites australis) can all be readily established (in the absence of geese). Perhaps this is not a surprise considering the aggressive nature of these species. The most important conclusions were that vegetation must be controlled or protected from herbivores and the water levels must be adequate. Also cuttings should be installed to depths where contact with moist soil can be maintained. In the follow-up study, introduction of a geese exclusion fence apparently allowed thick stands of softstem and river bulrush to develop at Holmes Lake. There was also a substantial decrease in annual weedy species.

4.6 The effect of roots on soil strength

Abernathy and Rutherford (2001) state that plants reduce pore water pressures and directly reinforce bank material with roots. Root reinforcement is affected by root strength, interface friction between roots and soil, and root distribution. The ability of roots to reinforce banks decreases exponentially from the tree center and with depth for both River Red Gum and Swamp Paperbark. Abernathy and Rutherford Mapped root networks of the two species. They determined the dimensionless root area ratio (RAR) which is the ratio of the cross sectional area of the roots to the cross sectional area of the slice of soil being examined. Figure 4.5 shows the root area ratio as a function of the distance from the center of the tree and depth (note that large roots tend to produce scatter in the results).

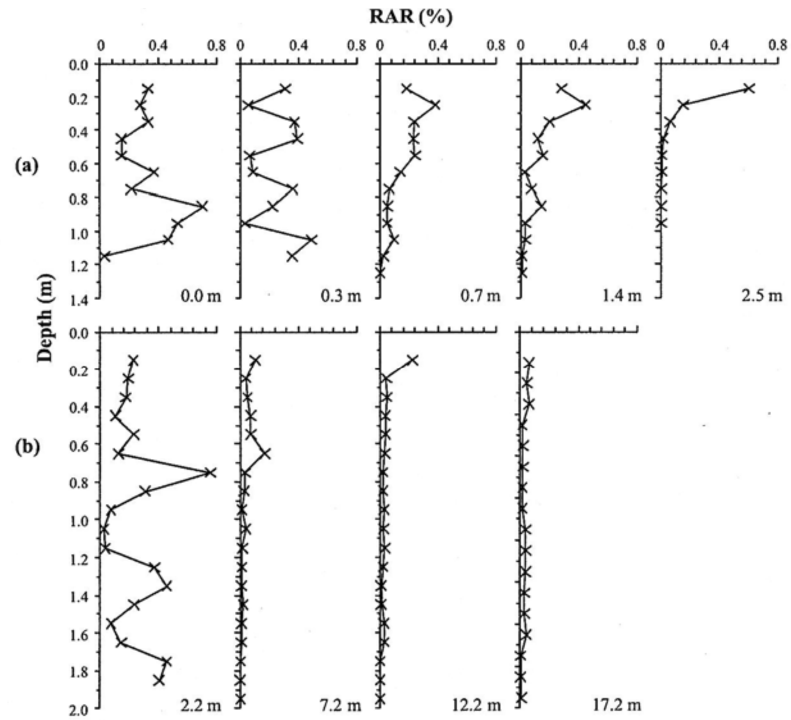

Figure 4.5 Root area ratio as a function of depth and distance from the center of the tree for (a) swamp paperbark and (b) river red gum (after Abernathy and Rutherford, 2001).

Abernathy and Rutherford also tested root strength. Roots were pulled from the soil with an in situ device and the force needed to do so was measured. Minimum root strengths for tested roots were on the order of 1 Mpa and greater. Based on the RAR and root strength, Abernathy and Rutherford produced the soil strength diagrams for root systems that are shown in Figure 4.6. c_r is the apparent cohesion due to presence of roots where:

$$s = c' + c_r + (\sigma - u)\tan\phi'$$

s is the shear strength of soil-root composite, c' is effective cohesion, σ is normal stress, u is pore-water pressure and ϕ' is effective angle of internal friction. Figures 4.5 and 4.6 make it clear that it is inappropriate to apply average root reinforcement estimates over an entire riverbank profile

Results for the two tree species appear to be quite different, indicating that choice of tree species for soil reinforcement is an important decision. Root tensile strengths appear to be orders of magnitude higher than soil shear strengths and root distribution is apparently more of an issue than tensile strength when selecting species. The large River Red Gum, with its broad root system, can protect large areas of the bank, but only the upper bank. The Swamp Paperbark is able to become established near the toe, and affords more protection in this location.

In a related paper, Abernathy and Rutherford (2000a) investigated failure planes associated with bank failure as affected by the presence of tree roots; they used a soil failure model to do this (GWEDGEM). Root reinforcement from Australian trees (*Eucalyptus camaldulensis* – River Red Gum and *Melaleuca ericifolia* – Swamp Paperbark) provides strong protection against erosion. Addition of root reinforcement can increase the factor of safety of the bank from 1.0 to 1.6. Root reinforcement improves stability despite hydrologic conditions. According to Abernathy and Rutherford, Swamp Paper Bark trees are small and flexible and can withstand flooding. These trees are probably similar to Sandbar Willows. Suckers provide establishment down to the bank. Swamp Paper Bark trees grow in dome shaped stands with heights of 0.5 to 10 m. River Red Gum trees grow higher up and are sensitive to flooding during the first few years. River Red Gums grow as individual trees with typical heights of about 20 m and maximum heights of about 45 m. Root networks of both species are severely hampered by permanently saturated soil (in fact, there are few trees that can grow in permanently saturated soil). In terms of bank stability, the worst case is when a prolonged wet period is followed by rapid drawdown (heavy banks with negative pore pressure). According to Abernathy and Rutherford, the trees improve stability the most when roots of the trees cut across the locations where likely failure planes intersect the bank surface.

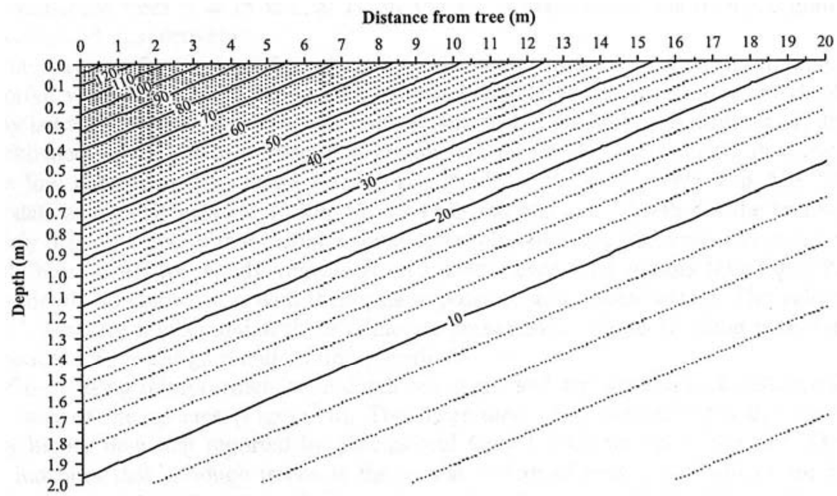

Figure 8. Apparent cohesion due to river red gum root reinforcement (c_r), isopleths are kPa

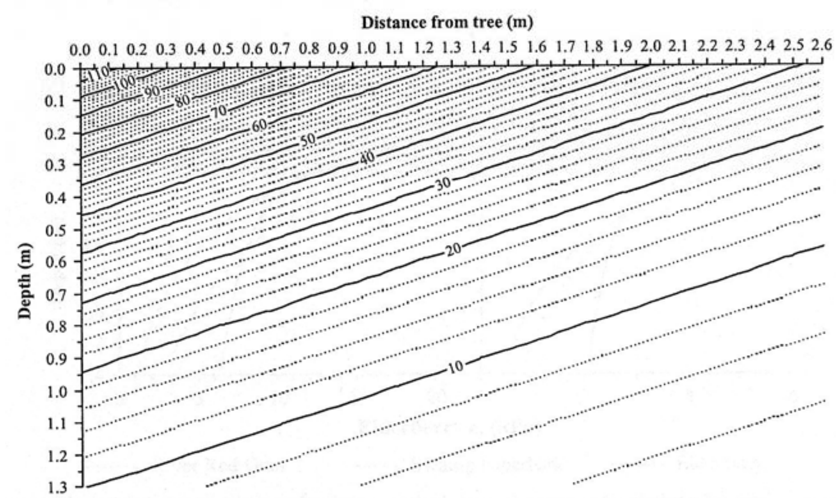

Figure 9. Apparent cohesion due to swamp paperbark root reinforcement (c_r), isopleths are kPa

Figure 4.6 Apparent cohesion as a function of depth and distance from center of tree for River Red Gum and Swamp Paperbark trees (after Abernathy and Rutherford, 2001).

Waldron and Dakessian (1981) used a root model to predict the behavior of roots in saturated clay loam. The plants modeled in this study included pine (*P. ponderosa*) and barley (*Hordeum vulgare*). Direct shear measurements of these plants in saturated clay loam were conducted to verify the models. They found that failure of the roots ability to reinforce the soil was most likely due to slippage of the root and not due to failure of the roots in tension. Thus, the ability of the roots to grip the soil is very important.

Waldron and Dakessian (1982) state that plants increase slope stability by removing soil water and reinforcing the soil mechanically. They compared the shear resistance of twelve species of plants including seven grasses to the shear resistance of fallow soil. This was done at both the 0.3 m depth and the 0.45 m depth. The plants that were tested included barley (*Hordeum vulgare*), alfalfa (*Medicago sativa* cv. Sonora), yellow pine (*Pinus ponderosa*), Blando brome (*Bromus mollis*), hardinggrass (*Phalaris tuberosa*), greenleaf sudangrass (*Sorgum bicolor sudanense*), Palestine orchardgrass (*Dactylis glomerata*), Wimmera 62 ryegrass (*Lolium rigidium*), Topar pubescent wheatgrass (*Agropyron trichophorum*), Anza wheat (*Triticum oestivum* cv. Anza), lana vetch (*Vicia dascarpa*), and coast live oak (*Quercus agrifolia*). At the 0.3 m depth alfalfa increased soil strength over that of fallow ground by a factor of 3 to 5 when the shear displacement was 25 mm. Hardingrass, ryegrass, orchardgrass, and oak also did well, increasing soil strength by a factor of about three for the 25 mm shear displacement. Bromegrass and pine increased soil strength by a factor of about two to three, and vetch, Sudangrass, and Anza wheat did very little to protect the soil from failure. At the 0.45 m shear depth, pine performed best, followed by hardingrass, ryegrass, alfalfa, and oak, all strengthening the soil about 2 to 3 times the strength of fallow soil. Trees did as well as most grasses in increasing shear resistance, but took much longer to establish (3 to 5 years) when compared with grasses (~ 7 to 8 months).

Waldron (1977) directly measured the shear resistance of alfalfa (*Medicago sativa*), barley (*Hordeum vulgare*), and yellow pine (*Pinus ponderosa*) in saturated soils. He found that the alfalfa roots dramatically increased soil shear resistance, but that barley and yellow pine were only marginally effective for improving shear resistance over a range of soil displacements.

Kleinfelder et al. (1992) measured the compressive strength of 122 samples of soils from vegetated streambanks. They compared compressive strength to root concentration and found that moderate vegetation significantly strengthens soils, and that higher root densities only provide incremental amounts of strengthening. In their study, the greatest sample strength was for Nebraska sedge. Kleinfelder et al. also found that resistance to shearing increases with deformation. That is, the greatest amount of resistance to failure is observed after the soil has already deformed somewhat.

Vanicek (1973) investigated how a variety of woody species are adapted to grow on steep slopes by a mechanism in which the tap or secondary roots change direction. The change in direction helps to stabilize the slope by causing the majority of the root mass to grow upslope of the tree. The mechanism is primarily in woody species. Along abrupt banks of streams, sudden changes of direction of the roots of oak (*Quercus*), maple (*Acer*), Lime (*Talia*), and spruce (*Picea*) were observed. The roots would veer away from the banks to less waterlogged areas, presumably because of the need for aeration.

Wu et al. (1979) studied the stability of forested areas in Alaska following logging. They measured soil strengths for soils containing tree roots and found that the effectiveness of tree roots for increasing soil strength decreases significantly after the tree is cut down and roots begin to deteriorate.

Wu (1994) provides a summary of the influences of vegetation on slope stability. Essentially, the vegetation affects stability in several ways: the vegetation adds to the load by increasing the weight of the soil on the slope, the vegetation reduces pore water pressure in the soil by extracting moisture from the soil (a positive effect, because reduced pore water pressure means increased soil strength), and roots from the vegetation increase the tensile strength of the soil.

Wu provides a nice summary of factor of safety calculations for bank slopes, and also a nice summary of how soil strength (s_r) is affected by different types of roots and different root area ratios (a_r, ratio of the area of the cross section of the roots to the cross section of the total soil. Thus, high root density will translate to high root area ratios). Wu includes Table 4.2, which shows the tensile strengths of various roots. If root density is known, this information can be used to help estimate the tensile strength of a soil sample. Note, however, that the tensile strength has a very large variance in most cases.

Table 4.2 Tensile strengths of various roots (after Wu, 1994)

		Tensile strength (MPa)	Young's modulus (MPa)	Reference
Salix	Willows	9–36	200–300*	Hathaway and Penny (1975)
Populus	Poplars	5–38	200–300*	Hathaway and Penny (1975)
Alnus	Alders	4–74		
Pseudotsuga	Douglas fir	19–61		
Acer sacharinum	Silver maple	15–30**	600**	Beal (1987)
Tsuga heterophylia	Western hemlock	27	170**	Beal (1987)
Vaccinum	Huckleberry	16		
Hordeum vulgare	Barley	15–31	40–90	Waldron and Dakessian (1981)
	Grass, forbs	2–20		
	Moss	2–7 kPa		Wu (1984b)

Data are from Schiechtl (1980), except where otherwise noted.
* values were estimated from stress-strain curves
** roots were tested without removing bark; cross-sectional area includes area of bark

Wu also provides a graph showing the relation between soil shear strength and area ratio. The relation is given for three species in Figure 4.7, below.

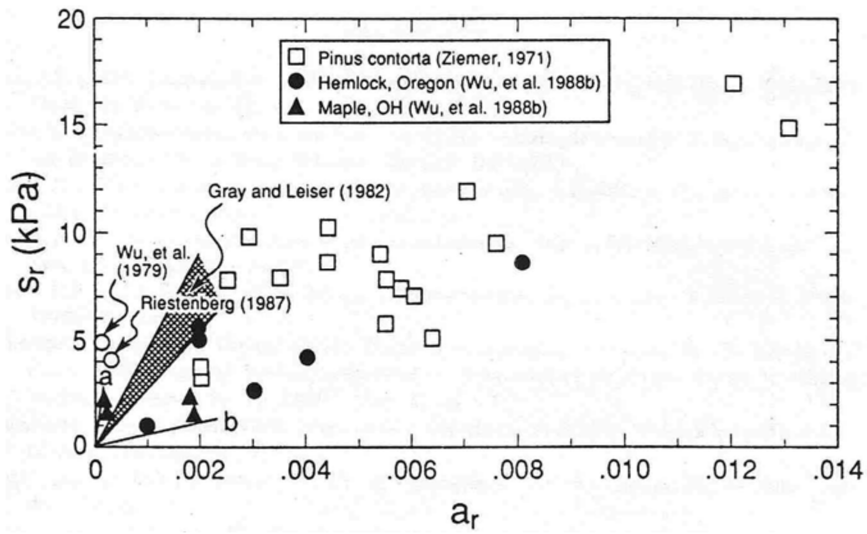

Figure 4.7 Comparison of soil shear strength with root area ratio (after Wu, 1994)

4.7 Soil additives and implications about root influence

Although soil additives are not bioengineering techniques for slope stabilization, they do offer some insight into how roots work to bind soil. Thus, a small amount of information about soil additives is added herein.

Benson and Khire (1994) investigated the use of HDPE strips to reinforce sand. They found that mixtures of sand and fine strips of HDPE could substantially increase the shear strength of a soil mixture. Ultimately, the use of such techniques in bank fill could reduce susceptibility to erosion. Especially when used in combination with bio techniques (e.g., grass cover on an engineered soil). The advantage of using such techniques is that HDPE strips are not susceptible to decay in saturated soils. The disadvantage, of course, is that some uses of the technique would be considered pollution.

Gray and Ohashi (1983) investigated the use of natural and synthetic fibers or wire to reinforce sand. Results were compared with predictions of the strength of fiber reinforced sand. Shear strength increases were:

1. Directly proportional to the area ratio of the fibers
2. Greatest for initial fiber orientations of 60 degrees relative to the shear plane
3. Almost the same whether the sand was loosely or densely packed.

Results are helpful for understanding root stabilization and stabilization with low modulus synthetics.

Gray and Ohashi did experiments in a laboratory apparatus to test the shear of different fiber reinforced materials. They stated that the fibers had to be long enough in order to avoid pullout. Area ratios of the fibers used in the tests were similar to typical area ratios of root masses measured in forested slopes. Test results showed that shear strength increases with the number of fibers and that 60 degree oriented fibers have the highest shear strength.

Extensible inclusions (inclusions that extend) allowed greater post-peak shear resistance. It is likely that roots are extensible. This means they can stretch and that if the load only moves a small distance they can maintain shear resistance. Increasing length of fiber reinforcements increases strength, but only up to a point. Length helps to provide surface area for skin friction between the fibers and sand. Increasing length probably adds strength up until fibers reach a failure mode.

4.8 Effectiveness of vegetation as an energy dissipater

Bonham (1983) investigated the effectiveness of using vegetation to dissipate boat wash wave energy. He looked at Common Reed (*Phragmites australis*), Bulrush (*Schoenoplectus lacustris*), Reed Mace (*Typha angustifolia*), and Sweet Flag (*Acorus calamus*). According to Bonham, about two thirds of the energy of a wave was dissipated by 2 meters of bed for each of these species.

4.9 Potential detrimental effects of placing vegetation

Abernethy, B. and Rutherford, I.D., (2000b) found that the weight of riparian trees is not likely to destabilize banks except if the banks become very steep. The weight of trees (20 – 30 m wattle trees) contributes only about 4 % to the weight of bank slump blocks in typical failures along the Latrobe River. The additional weight of water due to changes in the groundwater table is likely to have a much more significant effect. An exception is if tree roots are shallow because the penetrable soil is shallow (a layer of roots over a more impenetrable layer) - then there can be shallow-planer failure. However, analysis shows that banks prone to shallow planer failure are typically steep and subject to failure despite the presence of trees above the bank. Banks with trees are slightly less stable than banks without trees if the bank is already prone to failure (trees make the bank slightly worse based on the analysis). In summary, tree surcharge (additional weight added by trees) only marginally influences riverbank stability, and usually only in cases where root systems are shallow or end on a planer soil formation (e.g., soil above very hard clay).

Henderson (1986) suggested that the placement of vegetation often increases flow resistance, resulting in greater normal depths.

Rowntree and Dollar (1999) discuss the effects of willows that were planted in the 1950s. Since then, vegetation has stabilized the banks of the river they were studying, making it narrower (the river has constricted). Because of the vegetation, the river is more likely to have overbank flow in times of flood, which may lead to increased meander cut-offs and avulsion. Rowntree and Dollar found that higher vegetation density leads to narrower width and smaller form ratio and channel capacity. The potential for overbank flooding clearly increases. Tree roots extend out into the stream, stabilizing a shelf and causing sedimentation. The extra weight of bank trees can cause slumping of banks. The trees may continue to grow, but even if they die, they obstruct the channel. Dense root matting definitely stabilizes banks, but too much stabilization can actually cause constriction of the channel.

4.10 Grass-lined channels

Grass lined channels are channels that are designed to infrequently carry flow. The grass used to line the channels cannot be submerged continually, but will help to resist erosion during episodic flooding events. Using grass to resist erosive forces is restricted primarily to channels leading from small catchments and overflow spillways.

Kouwen and Li (1980) describe an alternative method of channel design for channels lined with flexible vegetation. The method takes into account that roughness changes as the plants bend over. Their solution was to use the flexibility properties of the plants to determine the relative roughness, and to use the relative roughness to calculate a friction factor. It appears that the method was intended for grass-lined vegetated channels only.

Kouwen (1988) describes a mechanical method of determining physical properties of grass in grass-lined channels. The method requires the dropping of a board to determine flexural characteristics of the grass in the channel. The effective roughness of the grass when it is submerged can then be calculated. The method makes it easier to determine flow properties of grass channels in situ.

Temple (1980) applied the tractive force method to assess the ability of vegetation to withstand shear stress induced by the flow. Temple suggested using the formula for average shear stress: However, Temple also suggested modifying equation 2.3 by partitioning the energy slope into two components: the energy slope associated with shear at the soil boundary and the energy slope associated with drag on the plants. Temple suggests that this method is superior to permissible velocity methods used in previous applications. Temple (1985) applies the method to grassy slopes that have been mown and found that regular mowing does not have a strong impact on the shear stress induced by the grass.

Temple (1983) also demonstrates how to apply the tractive force method to grass channels, which have a roughness behavior that is considerably more difficult to analyze than typical open channel roughness. When a bioengineered slope becomes inundated, the effective roughness of the slope is more complex than for a typical smooth or rough surface, because the vegetation elements reach out into the flow.

Temple and Alspach (1992) observed the ability of grass lined channels to withstand erosion after being submerged for five weeks, and then observed the subsequent recovery time of the grass lined channels. The channel that was studied was lined with 50% tall fescue, 20% little bluestem, and 20% bermudagrass by number of stems. The channel was inundated with water for nearly five weeks, causing the plants to suffocate. Plant death appeared to begin at approximately 200 hours from the start of the test, and destruction of the grass lining appeared to be complete after approximately 800 hours of inundation. Following the test, recovery of the grass lining took approximately two years, with bermudagrass dominating the recovery. This information is useful, because it establishes some criteria of plant selection and the best locations for implementation based on how long various locations are likely to be inundated during the year.

Bache and Macaskill (1981) say that according to Whitehead (1976), a well established grass cover can handle the following scenarios:

Velocity	< 2 m/s	3-4 m/s	~5 m/s
Duration	> 10 hr	Several hours	Briefly

This recommendation is only for temporary inundation. Deep channels with higher flows require the use of rock revetment. Vegetation is useful for covering soil on banks, but only above the normal level of flow.

4.11 Riparian buffers

Castelle et al. (1994) review effective buffer size requirements. They suggest buffer widths of between 5 and 100 meters to meet different buffer functions. Castelle et al. point out that buffers control erosion by blocking sediment and debris flow, stabilizing streambanks and edges, and promoting infiltration. Castelle et al. state that roots help maintain soil structure and retain soil.

Qiu and Prato (1998) also discuss riparian buffers. In agriculture, riparian buffers help stabilize soil, but also reduce the movement of, absorb, and trap nutrients, sediment, organic matter, pesticides, and other pollutants.

If grazing is allowed on streambanks reinforced with vegetation, the results can reduce the effectiveness of the erosion control strategy (Myers and Swanson, 1992). Marlow et al. (1987) studied how grazing impacts streambank stability and found that grazing has a significant impact on the degree of change of the stream channel profile. They also found that as bank moisture decreased, the rate of change of the streambank profile also declined.

Thornton et al. (1997) did a laboratory study of the deposition and retention of sediment when sediment laden water flows through vegetation. Four plant species were used in the study, including: corn (*Zea mays*); carex (*Carex praegracilis*); Kentucky bluegrass (*Poa pratensis*); and a mix of field grasses that included Needle grass (*Stipa comata*), June-grass (*Koelesia macrantha*), clover (*Trifolium paarryi*), and Thuber fescue (*Festuca tharberi*).

Water was mixed with sediment prior to entering the test section. The deposition of sediment in plant beds was measured for 6 hours. The plants had stem lengths of 1 to 35 cm. Following the tests, clear water was passed through the test section for 2 to 6 hours and retention of sediment was measured. Based on their data and a dimensional analysis, Thornton et al. found that sediment deposition amounts were inversely proportional to stem length and retention was directly proportional to stem length. That is, plants with shorter stems trapped more sediment and plants with longer stems retained more of the sediment that was trapped.

4.12 Implementation of vegetation in bioengineering projects

Darby (1991) describes the use of willow cuttings to stabilize a streambank during a road construction project. The willows were installed as a live boom, mattresses, live stakes, and joint planting. These four types of installations are described in great detail. Though the outcome of the project is described as successful overall, there is not quantification of where the willow plantings had problems and where they were extremely successful.

Watson et al. (1997) present a case study of using willow posts to reduce streambank erosion along Harland Creek in Mississippi. The posts are willow cuttings that are 8 to 15 cm in diameter and 3 to 4 meters in length. With the help of an auger, they are inserted into the ground at depths of 2 to 2.5 meters, and develop adventitious roots and branches. Watson et al. identify eight benefits of the use of willow posts:

1. The posts help to pin possible failure surfaces of the streambank.
2. The willows extract water from the soil, increasing slope stability.
3. Willow root growth helps to mechanically strengthen the soil.
4. The posts protrude from the surface, providing additional roughness, and reducing near-bank velocities.
5. Sedimentation on the banks is enhanced.
6. The willows stimulate colonization by other plants.
7. Debris and blocks from upslope failures are trapped.
8. The posts can be used to anchor other stabilization structures along the streambank toe.

The unit cost of installing the willows was significantly less than installing riprap and other non-biological methods. Survivability of the willows was on the order of 30 to 60 percent. Survival rates were tested for willow post base elevations of -0.6 to 2.5 m above the low water level. Survivability was low for willows that were planted with their bases below the low water level of the stream, but for posts that were planted so that their bases were approximately 0.3 m or more above the low water level, survival rate improved. The greatest survivability rates occurred when a longitudinal toe was used to reinforce the streambank.

Fourteen reaches were stabilized and observed during this study. Of these reaches, six had willow posts installed. The other reaches had mechanical erosion control methods, including longitudinal toes and bendway weirs. Of the six willow post sites, one had to be repaired because of excessive lateral erosion – a longitudinal riprap toe was added to this reach.

Watson et al. recommend using the ratio of the radius of curvature and the width of a bend to assess whether or not willow posts should be used. They recommend not using willow posts if the ratio is less than 2.0, and suggest installing a longitudinal toe in this case.

For channels subject to degradation, Bowie (1982) suggested that it is important to install grade controls before installing vegetation. Bowie also stated that native species showed the best success rates. Bowie sited the most common forms of erosion as direct erosion from water contact and mass failure from slumping. Causes of slumping include: (1) saturation of upper soils which weakens them and makes them heavy, (2) foundation deterioration by seepage, and (3) toe erosion by the river (direct erosion).

Brookes (1990) discussed a detailed plan for implementation of a channel restoration (not just stabilization). He also discusses some indicators of whether or not success will occur.

Brookes says that conventional river engineering has some negative ecological and morphological impacts. Restoration of features should include pools and riffles, sinuosity, point bars, substrate and roughness, cross section, etc. According to Brookes, a restoration is more likely to be a success if discharge exceeds bank full at least once per year. Longer return periods are more likely to fail. It is important to excavate natural cross sections if possible (not trapezoidal) because cross section shape influences erosion.

Brookes suggests that bends and discontinuities in the bed should be avoided in locations where restored and unaltered channels have confluences. Steps of a good restoration project include: Establishing project objectives, a feasibility and planning study, design, construction, clean-up, a maintenance plan, and post-project appraisal.

Brookes also notes that most restoration techniques are not applicable to braided, high energy channels. Projects must be appraised over long periods to assess success. Monitoring of biological populations is a useful process, both before and after implementation.

Henderson (1986) says that it is important to know native species and local growing conditions. Vegetation must be able to withstand inundation, provide protection year-round (or at least at times of erosion), be able to become well-established even in poor soils, and have a form that can withstand erosive flows. Hydraulics, weather and habitat should be considered when construction is to be done (the time of construction should not be randomly chosen).

Fry (1938), who did his research in Wisconsin, suggested the use of willows, particularly sand bar willows (Salix *longifolia*) for bank stabilization. He suggested to first reshape the bank to a 1:1 slope. The next step is to place willow poles in shallow trenches that are perpendicular to the bank and are spaced at 4 to 5 foot intervals (from the edge of the water to the top of the bank). Thatched willow brush should be placed over the exposed bank and hog wire can be used to hold the brush in place. Later, Fry found that the willow brush itself is quite effective for sprouting new willows. Brush type willow is recommended since the roots form a denser mat. The added advantage of willows is that they shade streams.

Seibert (1968) provides a useful guide for implementation of bioengineering techniques. He describes four riparian zones: a zone of submerged aquatic species, a low-depth zone (The base of this zone is submerged for half the year), a zone that is flooded during periods of high water (shrubs and trees should grow in this zone), and a zone that is rarely flooded (probably dominated by trees). In the first zone, aquatic species can protect the banks by providing cover and energy dissipation, but implanting these species is difficult and not possible in areas of high velocity. The second zone can be effective, especially for limiting wave erosion, but it requires depths of less than 1 m, and less than 0.3 m is better. The second zone is not possible in steeply banked areas. Giant reed (*Phragmites*) is an example of a second zone plant. Plant shoots dissipate momentum and roots stabilize soil, but again, the second zone has a limited depth range. The third zone is probably the most effective for most streams and consists of woody plants like willow (*Salix*) and alder (*Alnus*). Black poplar (*Populus nigra*) can be used in gravelly soils. Alder has the advantage of a dense root system that can develop very deeply. However, willow is more easily established since it readily produces suckers, shoots, and secondary roots. Alder requires planting each tree and does not reproduce as readily. Planted banks should be 1:2 (V:H) or 1:3 though vertical banks are possible. Trees should be planted just above the mean water level in summer. Perennial turfs can be planted between trees spaced at 0.5 to 1 m (maximum). The fourth zone, harder woods, is not effective for erosion control primarily because of location. When possible, implementation should aim for succession from third to fourth zones.

Seibert also describes known methods for planting vegetation in the four zones.

4.13 Optimal placement of vegetative erosion controls

Abernathy and Rutherford (1998) investigated a river in Australia. They did their study because native vegetation is emerging as the method of choice for erosion control. They state that it is necessary to establish vegetation in locations where it will most effectively meet project goals. A decision-making method for assessing the role that vegetation plays in streambank erosion control throughout a watershed is provided.

Three bank erosion processes were observed throughout the watershed that Abernathy and Rutherford studied:

1. Subaerial preparation – this is the most dominant form of erosion in upper reaches of watershed. Wind thrown trees transfer sediment to flow. This occurs in small catchments
2. Fluvial entrainment. Here, flow resistance of vegetation is a crucial factor. This process occurs in middle order basins
3. Mass failure – dominated by bank slumping and retreat (mostly downstream) Increased bank shear strength due to root structure is very important for preventing mass failure. Tree slumping and altered bank hydrology appear to play a minor role in this process. The process is observed in large catchments.

Based on these observations a critical region where vegetation will help the most is assessed.

Abernathy and Rutherford also compare plant characteristics to changing channel scale. Their goals include: understanding bank erosion processes (note that different processes dominate in different locations), describing how vegetation influences each process, determining properties of vegetation that affect each process, and quantifying effects of vegetation on processes in different parts of the watershed. Location specific processes include:

1. Upper reach erosion: bank loss and bank undercutting during tree fall. Flow is deflected into banks by large woody debris. Root balls can redirect flow at the bank.
2. Bank scour further downstream: scour on the outer banks of bends (the influence of large woody debris decreases).
3. Fluvial erosion at lowest reaches: scour is concentrated at outer banks. Fluvial erosion dominates at the base of steep outer banks. The toe erodes away, resulting in mass failure of upper banks – lack of vegetation makes matters worse.

Wind thrown trees redirect flow into banks and can cause excessive soil loss. Frost heave, desiccation, rainsplash and micro-rill development on exposed banks are all important in upper reaches. Flow obstruction is also a factor. Higher up in the watershed the water table is shallow and only a shallow root system is possible; this leads to weaker trees. Lower in the watershed deeper rootsystems are possible because the permanent water table is further down (as defined by the distance of base flow below bankfull).

Banks can be protected from freeze-thaw by grasses. Root systems can protect against desiccation by preventing soil from cracking due to the loss of water. Vegetative cover also reduces loss of water (except by evapotranspiration).

Within middle reaches stream power is reduced because of the presence of vegetation. Vegetation backs up the flow and reduces near-bank velocities. Thus, localized erosion is reduced since stream power and local erosion are directly correlated (Bagnold, 1977). Effective control of erosion by vegetation declines in the downstream part of the watershed. Standing vegetation within the flow is very effective (but difficult to establish).

Mass failure occurs when the bank height grows to the point where undercutting of roots takes place and entire bank falls into river. Roots help stabilize the upper bank and also provide strength to the soil. If the roots are very high above the water, plants do little to prevent erosion, and large masses of soil fall into the stream. Vegetation is still good and reduces mass failures. The vegetation does not eliminate collapse, but it may slow it down. If a bank is too steep, revegetation is not possible.

Li and Shen (1973) showed that patterns of vegetation placement affected flow resistance and sediment yield. Plants grouped in staggered patterns were much more effective for increasing flow drag and reducing sediment yield. This might have some bearing on the optimal planting patterns of willow posts to optimize bank protection.

Nanson and Hickin (1986) analyzed bank erosion in 18 mid to high energy rivers in Canada. They found that vegetation does not typically reduce erosion in these types of rivers because roots only extend one to two meters below the surface, and fluvial erosion can take place below this level in most large rivers. In deeper channels, the bank is typically eroded from below the root line and eventually the undercut bank collapses, leaving the established vegetation unprotected.

4.14 Plant types

In a review of past research, Lyons et al. (2000) compared the benefits of grassy vegetation with the benefits of woody vegetation along streambanks. They cited the following benefits of grassy vegetation: lower direct bank erosion, suspended sediment is trapped more effectively, and grassy channels generally lead to narrower channels with undercut banks (for habitat). Woody vegetation (e.g., willows) was more practical for high, and steep banks, wider channels, and diverse substrates.

Falling trees and branches can lead to damage of erosion protection. This can happen either indirectly, by gouging the bank and creating a location that is more susceptible to erosion, or directly, the root mass of a tree can fall in a stream and turbulence around the root mass can increase erosion. Grass covers banks more completely and can be very effective if well-established, but in many locations it requires maintenance or woody vegetation will take over. Willows, one of the most commonly used stabilization trees, are short-lived and also require maintenance in many locations.

Stott (1997) compared bank erosion on moorland with erosion in forested areas and found that erosion rates were higher in the moorland areas. The primary reason cited for the higher rate of erosion in moorland areas was a lack of protection against frost action. Incidence of frosts in the moorlands was approximately twice as high as in the forested areas, and most of the erosion occurred during the winter.

Hupp (1983) investigated the types of vegetation that grow in different parts of a river channel up through the flood plain. While this article does not directly discuss the ability of plants to prevent erosion, it does give some idea of what types of plants grow at different levels between the normal water surface elevation and the flood plain. This study was done in Kentucky and included approximately fifty species of natural riparian vegetation. The bank area was divided into two vegetation zones, and each of the species was given an importance ranking based on coverage, density, and frequency of occurrence. The point of this study was not to identify plants that do a good job of preventing erosion, but to determine dominant natural vegetation types in riparian areas. However, knowing which plants grow best in different zones will provide an indication of which species will be successful in erosion control plantings. Among the most successful plants were hazel alder (*Alnus serrulata* (Aiton) Willd.), black willow (*Salix nigra* Marshall), Joe-Pye weed (*Eupatorium maculatum* L.), sensitive fern (*Onoclea sensibilis* L.), and royal fern (*Osmunda regalis* Willd). The article provides information about how common each of the approximately 50 plants was in each of the two zones. This article provides a nice listing of some of the species that occur naturally in riparian areas.

Whitlow and Harris (1979) provided a thorough review of the flood tolerance of a wide variety of plants. This review provides a great deal of insight in regards to what plants can survive in periodically inundated areas. The report separates the United States into regions and identifies the relative flood tolerance of many woody and herbaceous species. For example, in the Missouri region, a long list of plants is separated into categories of very tolerant, tolerant, somewhat tolerant, and intolerant. One nice aspect of this report is that it contains a great deal of detail about species survival. For instance, one table contains estimated percentage of survival of a large variety of species when subjected to 30 day floods, another table lists a variety of species and the maximum flood frequency of locations where the species were found. When selecting new species for bank stabilization, this review appears to be an excellent resource.

4.15 Compilations of bioengineering techniques

Bioengineering techniques have been around for some time, and there are a number of detailed guides and books pertaining to the subject. This section includes a list and brief description of some of these manuscripts. The reader is encouraged to review these texts if the material appears to be of interest. Some of the reports are available on-line.

Schiechtl (1980) presents a broad review of bioengineering techniques used in Europe, including stabilization techniques for both earthworks and waterways, and discusses many methods for stabilizing slopes with plants. Schiechtl also presents information about the suitability of various plants for stabilization purposes, and how to properly install the plants.

A more recent book by Schiechtl and Stern (1994) discusses bioengineering techniques for streambank stabilization in great detail. This book is very thorough in listing advantages and disadvantages of many bioengineering techniques as applied to streambank stabilization. Properties of a wide variety of species are also listed, however, many may not be applicable or available in North America.

The USDA (1995) produced an engineering field handbook that includes a chapter (Chapter 16) on streambank and shoreline protection. The guide is available on-line. The handbook includes guidelines for sizing rock riprap, choosing plants for soil bioengineering, and general shoreline and streambank protection design considerations.

Gray and Leiser (1982) wrote a book which covers soil erosion, vegetation for slope protection, toe-wall construction for unstable slopes, and a wide variety of case histories, among other things. Details associated with implementation and costs of many bioengineering techniques are outlined in this book.

The U.S. Army Corps of Engineers Waterways Experiment Station produced a guide for Bioengineering for Streambank Erosion Control (Allen and Leech, 1997). The guide is available on-line and contains documentation of successful bioengineering techniques in the U.S. and Europe. When possible, stream velocities were recorded to provide some idea of the threshold velocities of some of the bioengineering treatments that were investigated.

Chapter 5 Combined Techniques

5.1 Introduction

Most vegetation cannot take root in saturated soils, leaving soil below the waterline unprotected. Vegetation can do a lot to reduce geotechnical failure and erosion by fluvial forces on banks that are only infrequently submerged, but it does little to protect against fluvial erosion below the normal waterline. Combining a structural method below the waterline with a biotechnical method above the waterline is likely the best alternative. This chapter describes some of the work that has made use of both structural and biological erosion control methods in combination.

5.2 Structural toe with vegetated bank

By far, the most common combination of structural and biological erosion control methods is a structural toe with a vegetated bank. Thorne (1990) states that experience has shown that vegetation by itself is usually insufficient for preventing bank erosion, and that the accepted safe procedure is to provide toe stabilization with suitable upper bank protection which may consist of some form of vegetation.

Bowie (1982) describes installation of vegetation based on work done in Mississippi. The goal of vegetation is to provide a dense cover that prevents erosion without restricting flow. Vegetation is required to: withstand expected inundation, provide protection all year, become well-established in adverse conditions, be long-lived, establish a good root system that can withstand flow drag, have many tough, resilient stems that emerge from the bank, and be low maintenance.

Bowie says that the bank must be preshaped to work properly. Typical problem sites have vertical banks, and 2:1 (H:V) slopes are typically required for working and plant establishment. The installation recommended by Bowie is a: nonerodible toe (rip-rap) seeded with native black willow (*salix nigra*); a 2:1 lower bank reinforced with rock, cellular concrete blocks or concrete cap blocks; a 5:1 bench covered with herbaceous, woody species; and a 2.5:1 upper bank covered with grasses. Bowie also discussed the use of annual rye grass (*Lolium multiflorum*) and unhulled bermudagrass (*Cynodon dactylon*) for cover on the upper bank. The described method worked despite an event with velocities of 3.7 m/s at the channel center and 0.75-1 m/s near the banks. There were no observed failures. Table 5.1 lists all of the species that were used in the study by Bowie (1982).

Bowie gives two designs, but testing was not complete because more time was necessary for plant establishment. Plant establishment and maintenance are keys to success.

Table 5.1 Species used in study done by Bowie (1982)

Plant species	**Scientific name**	**Notes**
Alamo switchgrass	*Panicum virgatum*	All grasses did will when planted by seed
Appolow sericea	*Lespedeza cuneata Applow*	
Bahiagrass	*Paspalum notatum Pensacola*	
Bermudagrass	*Cynodon dactylon*	
Black willow	*Salix nigra*	Did better than other willows
Bristly locus	*Robinia fertilla arnot*	
Boston ivy	*Parthenocissis tricuspidata*	Sprigging works best for ivys (not seed)
Buffalograss	*Buchloe dactyloides*	Probably requires sun
Crown vetch	*Coronilla varia Penngift*	Weed
English ivy	*Hedera helix E.*	
Indigo bush	*Amorpha fruticosa*	
Indigo	*Indigofera psewdotintoria*	
Maiden cane	*Panicum hemitomon*	
Multiflora rose	*Rosa multiflora*	Weed
Reed canary grass	*Phalaris arundinacea*	Weedy
Reedgrass, common	*Phragmites communis*	
River birch	*Betula nigra*	
Sericea lespedeza	*Lespedeza cuneata*	
Streamco willow	*Salix purpurea streamco*	Low drought survival
Subterranean clover	*Trifolium subeterraneum L.*	

Henderson (1986) states that the "use of vegetation for bank protection is most effective when used in combination with structural components." A composite revetment design prescribed by Henderson is shown in Figure 5.1. In another design, a stone toe is placed parallel to the bank and the toe is connected to the upper bank by stone tiebacks. Tiebacks are placed at intervals (in vertical strips). Between tiebacks vegetation grows thick enough to hide the tiebacks.

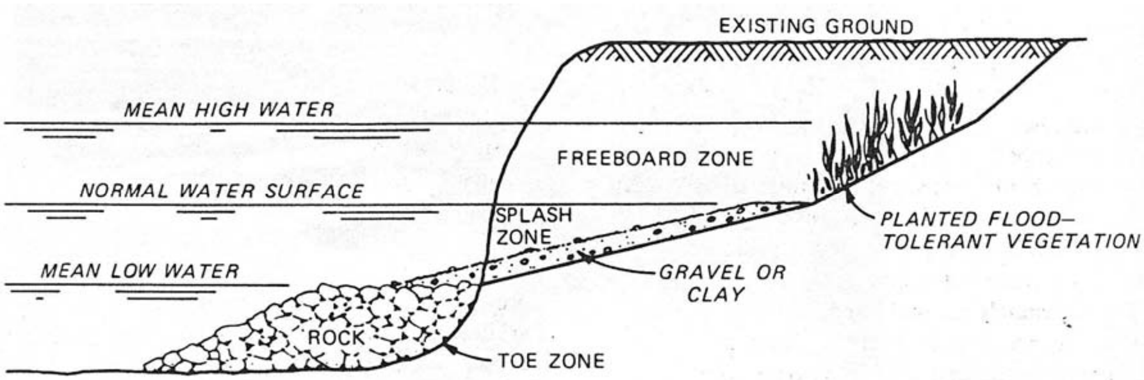

Figure 5.1 Composite revetment design (after Henderson, 1986)

Logan et al. (1979) produced a guide for implementing vegetation based erosion control on streambanks of the Missouri River. They concluded that: (1) side slopes should have slopes of no more than 1:1 (H:V), (2) adequate topsoil should be placed on the slopes – they recommend at least 4 inches of soil, (3) plant materials should be selected based on site, (4) handling of plant materials is very important for good survival rates, and (5) site monitoring and management is necessary – they recommend at least three years of monitoring.

The procedure described by Logan et al. is to modify a steep bank to make a mildly sloped bank that is reinforced with vegetation and has a structural toe. The toe is described as rock revetments or a series of hard points and details are given of their construction. For bank modification, Logan et al. recommend a maximum slope of 1:1 where the steep bank is cut back and a maximum slope of 3:1 where fill is placed, in order to make the existing slope milder. If possible, a 3:1 cut slope and an 8:1 fill slope is desirable.

Placement of the toe and vegetation species is determined by zone. Logan et al. describe four zones: (1) the terrace zone, (2) the bank zone, (3) the splash zone, and (4) the toe zone. The terrace zone is the portion of the bank that is only subject to fluvial erosion by occasional flooding. The terrace zone is not typically flooded for a 60-day duration more than once every 2 to 3 years. The bank zone is flooded more frequently than the terrace zone. The bank zone is located above the normal water level, but is periodically subject to river currents, ice and debris. The bank zone may be under water for a 60-day duration once every 2 to 3 years. The splash zone is located between the average and normal low water levels of the river. The splash zone is normally under water for at least 6 months a year and is subject to more erosive forces than any of the other zones. The toe zone is located below the splash zone and determines where the top of the reinforcing hard points and revetments should be. The top of the toe should be above the normal low stage, and preferably above the average normal stage.

According to Logan et al. Species should only be planted above average normal stage in the splash, bank, and terrace zones. Table 5.2 describes their recommendations for the bank and splash zone. Recommendations for the terrace zone are also given in Logan et al. (1979) but are not included herein. The table includes name, scientific name, plant source, and planting method. These species might also be useful for smaller streams in the region if an effort is made to determine the zones within which they should be planted, but it should be noted that some of the species are considered weedy and a botanist should be consulted before implementation.

Logan et al. also provide detailed information about preparing the banks, planting vegetation and monitoring.

Bonham (1983) suggested that many emergent species do a great job of absorbing energy from boat wash, but require a shallow, near-bank area. Propeller turbulence tends to deepen near the bank, and can undercut stands of emergent vegetation. Bonham's suggestion is to put structural energy dissipation in the deep area just beyond the vegetated shelf. The energy dissipation device could be a stack of tires held in place by a vertical timber pile. Prior to boat motors, submerged vegetation (macrophytes) used to protect shelves better, but macrophytes cannot withstand high shear.

Table 5.2 Recommended species for Missouri River streambanks (after Logan et al., 1979)

Zone	Name	Scientific Name	Plant Source	Planting method
Splash	Cattail	*Typha latifolia*	Local rhizome collection	Sprigging
	Softstem bulrush	*Scirpus validus*	Local rhizome collection	Sprigging
	Hardstem bulrush	*Scirpus acutus*	Local rhizome collection	Sprigging
	American bulrush	*Scirpus americanus*	Local rhizome collection	Sprigging
	Swamp smartweed	*Polygonum coccineum*	Local seed collection	Seeding
	Pale smartweed	*Polygonum lapathifolium*	Local seed collection	Seeding
	Giant mannagrass	*Glyceria grandis*	Local seed collection	Seeding
	American mannagrass	*Glyceria striata*	Local seed collection	Seeding
	Common reed	*Phragmites communis*	Local rhizome and seed collection	Sprigging and Seeding
Bank	Reed canarygrass	*Phalaris arundinacea*	Commercial seed	Seeding
	Creeping foxtail	*Alopecurus arundinaceus*	Commercial seed	Seeding
	Northern reedgrass	*Calamagrostis inexpansa*	Local rhizome and seed collection	Sprigging and Seeding
	Prairie cordgrass	*Spartina pectinata*	Local rhizome and seed collection	Sprigging and Seeding
	Meadow fescue	*Festuca elatior*	Commercial seed	Seeding
	White sweetclover	*Melilotus alba*	Commercial seed	Seeding
	Yellow sweetclover	*Melilotus officinalis*	Commercial seed	Seeding
	Crownvetch	*Coronilla varia*	Commercial seed	Seeding
	Peachleaf willow	*Salix amygdaloides*	Limited commercial	Bare rootstock
	Diamond willow	*Salix rigida*	Limited commercial	Bare rootstock
	Sandbar willow	*Salix exigua*	Local cuttings	Bare rootstock
	Yellow willow	*Salix lutea*	Commercial	Bare rootstock
	Bebbs willow	*Salix bebbiana*	Local cuttings	Bare rootstock
	Red osier dogwood	*Cornus stolonifera*	Commercial	Bare rootstock
	Hawthorn	*Crataegus chrysocarpa*	Commercial	Bare rootstock

Mifkovic and Petersen (1975) discuss protection of the Sacramento River streambanks against erosion. According to Mifkovic and Petersen, the only effective method for preventing destructive erosion of the levee system along the Sacramento River is to use rock revetments. However, the need to improve habitat along the river led to a study of implementing combined vegetative and traditional stabilization of the banks. Study tests showed that by itself vegetation was not able to withstand bank erosion. However, vegetation was an effective erosion control above the sustained high water elevation. Concrete blocks with voids to allow vegetation to grow in interstices were not as effective or economical as traditional stone lined banks.

Results of the study included the following recommendations: First, replace vegetation that does not adversely affect flood stages and that was lost during construction of bank protection, and plant new vegetation in non-critical flow areas. And second, use stone revetments along riverbanks where erosion is severe. Place revetments at 2:1 (H:V) slope, instead of the standard 3:1 slope. The steeper revetment increases the usable land above the revetment where vegetation can be planted. The vegetation planted on the buffer above the revetments would also help prevent erosion. It was also suggested that on 3:1 slopes, vegetation could be better established on the rock revetments, improving aesthetics.

Porter and Silberberger (1960) planted a variety of plants along the banks of Buffalo Creek/River in New York and examined the effects. The bank material was often unsuitable for plant growth. The toe and lower banks were rip-rapped and the upper banks were seeded. Porter and Silberberger found that combinations of grasses and willows were superior to just willows (they used timothy, ryegrass and alsike clover for grasses).

Problems encountered by Porter and Silberberger included: low soil moisture, hard packed soil from construction, Nitrogen deficiencies, effective scheduling of construction (late construction did not allow vegetation to establish). Solutions to the problems included: mulching, fertilizer, and stockpiling top soil. For willows they recommended planting only in the spring. They also recommended cutting back willows in the nursery during the winter before planting.

Vetches and trefoils established quickly but provided no cover during the winter and were weak. Fescues were mixed in and provided good cover throughout the winter. However, there was nothing that would protect against large ice flows, and no vegetation was observed that could stabilize the critical toe of an eroding bank. Porter and Silberberger compared vegetation to equivalent stone diameter in terms of ability to withstand erosion. The comparison is given in Table 5.3.

Table 5.3 Ability of grasses to withstand shear (after Porter and Silberberger, 1960)

Grass stand	Allowable shear (psf)	Equiv. Stone (inches)
Fair stand of short dormant	0.9	2
Good stand of short dormant	1.1	2
Good stand of long dormant	2.8	5.5
Excellent stand of short green	2.7	5.5
Good stand of long green	3.2	6.5

Shields et al. (1995a) studied four combinations of controlling streambank erosion through vegetative and structural means. The four combinations were vegetation alone, vegetation with structural protection at the toe, graded bank with vegetation alone, and graded bank with structural protection at the toe. Testing occurred over 10 years with 8 additional years of limited observation. Sixteen woody and thirteen herbaceous species were tested.

It was found that the best woody species for protecting the bank was black willow since it had a relatively high survival rate. Multiflora rose also did well, but it is invasive. Of the herbaceous species, Alamo switchgrass and Sericea lespedeza performed best. Many of the inspected sites reverted to native species, and the plantings that worked best were native plants. For the most part, stands of non-native pioneers require maintenance to avoid succession.

Shields et al. suggest that bank failure by mass wasting is the most catastrophic form of erosion, and that the only practical forms of protection against mass-wasting are grading of the bank (to reduce slope) and adding a structural toe. Without a structural toe, the bank is susceptible to additional lateral erosion, which may lead to additional mass wasting. The form of structural toe protection recommended by Shields et al. is the longitudinal stone dike. If a channel is still in the process of degrading, no form of bank protection is likely to be effective.

Shields et al. (1995b) did a case study of a combination of willow post plantings (*Salix spp.*), groins with spur dikes, and stone toe stabilization structures on Hotophia Creek in northwest Mississippi. The willows had a 30% survival rate. Survival rate was highest on sandbanks and did not appear to be affected by bank height and bank angle, though Shields et al. did recommend planting the posts deep enough to reach groundwater. The mortality of many of the willow posts was due to suffocation by kudzu (*Pueraria lobata*), an exotic species.

After restoration, the habitat of the study site improved, primarily because groin extensions promoted an increase in the depth of scour holes. According to Shields et al., the groin extensions were underdesigned, so that when large scour holes developed the extensions subsided. They suggest increasing the width of the extensions from 1 m to 2 m, though this is likely a site specific recommendation.

Henderson and Shields (1984) provide a detailed review of a variety of structural and combined techniques related to the environmental aspects of bank stabilization. They discuss the proper installation of revetments, gabion baskets, Kellner jacks, vegetation, and a number of other river bank protection techniques. The emphasis of the report is on environmental aspects of streambank stabilization, but installation information is also covered in depth.

Shields (1991) identified some of the potential detrimental and beneficial effects of wood vegetation on revetments. Negative effects included reduced conveyance, possible reduction in bank stability, reduced visibility for bank inspections, and reduced access to the banks. Some benefits of vegetation include reinforcement of bank soil, stabilization of riprap, and increased habitat. Shields (1991) attempted to assess how erosion along the Sacramento River was affected by the presence of woody vegetation. For many years, removal of woody vegetation from levees along the Sacramento River has been prescribed maintenance (which in many instances has been neglected). Over 60 percent of the reach that was examined is revetted with quarry stone or cobble. Shields estimated that about 11 percent of the revetted areas had woody vegetation. For revetments of similar material and age, damage rates were lower if woody vegetation was present. However, the number of sites that had woody vegetation was too few for the results of the study to be definitive.

Seibert (1968) gives many examples of bioengineering used in combination with other methods. He shows examples of bioengineering used in combination with stone facing and paving (longitudinal revetments). This is especially important in cases where the bank will not be sufficiently protected during the process of root development.

Jackson and Van Haveren (1984) presented a design for restoring a channel in a location with coarse sediment. They used critical shear stress to determine a viable geometry of the channel, and depended on vegetation to complete the stability of the channel (there was more risk of failure prior to the establishment of vegetation). Gabians were placed in order to reduce the risk of failure caused by a high flow year. Although Jackson and Van Haveren (1984) state that the reach they were repairing might repair itself over time, their claim is that repairing the reach will substantially reduce recovery time. However, upstream causes of the channel failure must also be mitigated for the project to be a success.

Keown et al. (1977) recommend woody species at the toe of a slope and grassy species above the toe as a good combination to prevent against erosion. Many species cannot withstand prolonged periods of submergence and are only effective for short high water periods.

5.3 Combined mattresses and vegetation for slope stabilization

According to Keown et al. (1977) matting can also be used in conjunction with vegetation to help prevent erosion of slopes. A common example of this is straw matting through which vegetation can grow, reinforcing the erosion resistance provided by the matting alone. Another method of stabilizing banks is to use cellular concrete blocks. The blocks provide significant erosion control in the case of complete submergence, and at the same time, allow vegetation to grow through their interstices in unsubmerged locations. The vegetation helps reinforce the integrity of the blocks.

5.4 Riprap and vegetation

Generally, the U.S. Army Corps of Engineers design and maintenance manuals advise the removal of vegetation from riprap protection zones because: 1. Woody vegetation can cause local acceleration that dislodges riprap, 2. Root growth can displace riprap material, 3. Voids left in the bank by dead roots make the bank more susceptible to failure, and 4. Inspection is more difficult. Thorne (1990) states that although these rules are true for some species, not all species will have the same level of negative impact on a riprap revetment.

Miers (1977) says that willows can be planted between revetment stones. The willows prevent erosion on berms. Alders can be planted as succession species with a transition to hardwoods. It may be necessary to reinforce the shore at the bottom of the bank to just below the edge of the water since vegetation is ineffective below the water surface (for the most part).

Chapter 6 Conclusions

6.1 Conclusions

The intention of this literature review was to determine what aspects of biotechnical streambank erosion control have been studied in past research. Included are reviews of related hydraulic processes, bank stabilization, and traditional bank stabilization techniques. Although this review is intended to be thorough, it is not likely comprehensive, since there is a great deal of literature available on the subject of streambank erosion. Nevertheless, the review covers most of the subjects of interest as related to streambank erosion control. Some important conclusions of this literature review include:

1. Streambank erosion is the result of two processes: mass failure and fluvial entrainment. Control of fluvial entrainment by hydraulic action is critical for controlling streambank erosion. Lateral streambank erosion is controlled by fluvial processes; that is, even in incised channels, toe material must be removed before mass wasting will occur (Thorne and Tovey, 1980). Thus, it is very important to protect the streambank toe, regardless of what is done to stabilize the streambank from nonfluvial geotechnical failure. A longitudinal toe is one strongly suggested means of structural stabilization.
2. Many of the articles cited herein suggest that streambank stabilization without structural means is often a failure because the fluvial erosion leads to mass wasting regardless of how well-established streambank vegetation becomes. The advantage of using vegetation in combination with a structural technique is that the structural technique does not have to be as widely applied, possibly resulting in cost savings and improved aesthetics.
3. In streams with both cohesive and non-cohesive layers of sediment, the non-cohesive sediment tends to erode much more quickly than the cohesive layer, making the cohesive layer extremely susceptible to erosion also. This is especially true if the non-cohesive layer underlies the cohesive layer. In regions with multiple layers of soil, it is essential to emphasize protection of the weakest soil layer. Erosion of a sand layer is more likely than erosion of a clay layer, and if the sand layer is below the clay layer, undercutting will make the clay layer much more susceptible to erosion.
4. Degradation of streambeds usually leads to mass wasting of streambanks because the heights of the streambanks become too great. Dramatic examples of degradation have resulted from land use changes (e.g. urbanization, changes in agricultural practices, etc.), straightening of channels, and climate change. If a channel is still in the process of degrading, no form of bank protection is likely to be effective.
5. Streams with rapidly changing water depths are more susceptible to bank failure because of pore pressure effects and seepage.
6. An important benefit of streambank vegetation is that it prevents removal of surface soils by overland runoff. Bank vegetation can reduce surface erosion by several orders of magnitude.

7. Planting vegetation on an excessively high, steep bank will change the process of mass wasting. Not so much by stabilizing the bank with roots, because the slip face is often well below the root line, but because the vegetation helps to soak up extra moisture, decreasing the weight of the bank and reducing pore pressures. Lower pore pressures result in increased soil strength (Simon and Collison, 2002).
8. Plant roots do little to prevent lateral streambank erosion except in the cases where fluvial erosion occurs primarily above the lower root line. Most plant roots cannot grow below the normal water line and if most of the fluvial erosion occurs below the root line, plants can do little to stop it. Plants can improve bank stability, but stream hydraulics controls the lateral erosion.
9. Some literature has shown that tree roots produce good shear resistance to soil failure but take much longer to establish than grasses; grasses can produce significant soil strengthening at shallow depths and can become established in one or two seasons (Waldron and Dakessian, 1982).
10. Unfortunately, the hardiness required to withstand soil erosion and flooding also limits the available selection of suitable plants. A number of the species recommended in the literature are invasive, exotic, and/or weedy. It is recommended that all bioengineering projects be implemented only after being approved by a botanist who knows which plants are not illegal or problematic.
11. Bioengineering methods for stabilizing banks appear to be dominated by the use of willow because of its ability to grow fast in wet conditions. Black willow (*Salix nigra*) is considered to be one of the most successful species for stabilizing streambanks Grasses may be more effective higher on destabilized banks.
12. A number of authors have stated that native species perform best in terms of establishment and survival. Selecting plants based on how much they will be inundated is also important.
13. Banks should not be too steep to promote growth of plants. Some authors recommend slopes of 2:1 (H:V) or lower.

In summary, streambank stabilization projects should avoid trying to overuse vegetation as an erosion control method. Stabilize the bank toe (the part of the bank that is normally below the water line) with structural means. The upper bank can be stabilized with carefully selected vegetation, considering plant establishment, root development, moisture depleting potential, and whether or not the plant is native. Recommended species include willows and native grasses, depending on distance above the waterline.

6.2 Potential future research

There has been a great deal of research on velocity distributions in typical meanders, structural bank stabilization techniques, and case studies of bank stabilization using bioengineering techniques (e.g. willow posts). Although there has been a lot of research done on streambank stabilization using bioengineering and other techniques, there appears to be some places that could stand more work. In particular, it is currently difficult to guarantee project success for bioengineering projects. Any research that can be done to help determine probability of project success would be good. There are many bioengineering guides available – it would be unwise to produce another without a clear, specific focus. Future research in this area should be careful to address specific aspects of erosion control with attention to carefully quantifying results, maintaining accuracy, and identifying characteristics that affect project success. Potential research includes the following topics:

1. It is important to identify appropriate streambank stabilization plant species and their habitat requirements for the region in question. An attempt was made to list possible stabilization species in this literature review, but many of the species are not appropriate for local use. It would be extremely useful to divide the region of application (e.g., Nebraska) into sub-regions according to what plants will grow in those sub-regions, and then deciding which of the plants perform best as erosion control species. Regionalized identification of native species that grow along streams in Nebraska and have a good root base would be a good start for developing a strong biotechnical stabilization program in Nebraska.
2. There does not appear to have been a lot of studies of the usefulness of deep root species like native prairie grasses for streambank stabilization. I believe that such species might be capable of developing extensive root systems that can reduce soil water pressures and mass wasting, and slow fluvial erosion. A combined effort that includes both botany and geotechnical engineering could provide insight about some of the benefits of using native prairie species to help fight streambank erosion.
3. A lot has been done to investigate water flow patterns in symmetrical meanders, but there has been little success in developing a simple, adequate method of determining what the flow patterns are in irregular stream bends. This type of research may need to be broken into smaller parts in order to achieve success. Accurate results may require sophisticated numerical models.
4. It is still difficult to identify the best erosion control procedure… most past research has been qualitative or site specific. There are many types of erosion control methods to choose from and no guarantees that any one method is the best. Whether or not enough research can be funded to provide strict guidelines is questionable, but a procedure could be developed to help evaluate and quantify the effectiveness of individual methods.
5. Finally, it would be useful to develop methods to rapidly evaluate relevant soil characteristics and hydraulic behavior at field sites. For example, a method to quickly assess the ability of a plant to withstand erosive action would be useful for determining if that plant has potential for stabilizing streambanks. Such methods would help in the development of a database of species with good erosion control characteristics for streambank stabilization.

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Appendix A Plant Characteristics

This appendix contains a listing of many of the species that have been considered for biotechnical streambank stabilization. The species are listed in alphabetical order by their Latin name and contain notes about location and implementation when relevant. **Note: some of the species cited in this table are considered invasive, and weedy species are not necessarily identified in the table. A botanist should be consulted before implementing any of the listed species.**

Species	Common Name	Reference	Location	Comments
Acer negundo	Boxelder	Hupp and Osterkamp (1996)	West Tennessee	Species that dominate reestablishment of riverbanks after a disturbance in coastal plain area.
Acer negundo	Boxelder	Pizzuto and Meckelnburg (1989)	Chadds Ford, PA	Does not significantly reduces rate of bank migration in areas where densities are high
Acer negundo	Boxelder	Hupp and Simon (1991)	West Tennessee	Common, but stands are not so dense, becomes established after willow and birch. Withstands layering of soils by way of adventitious roots.
Acer negundo	Boxelder	Hupp (1992)	West Tennessee	Pioneering species, can tolerate moderate mass wasting of banks and bank accretion. Very common at study sites.
Acer saccarhinum	Silver maple	Hupp and Simon (1991)	West Tennessee	Formed dense riparian stands, becomes established after willow and birch. Withstands layering of soils by way of adventitious roots.
Acer saccarhinum	Silver maple	Hupp (1992)	West Tennessee	Pioneering species, can tolerate moderate mass wasting of banks and bank accretion. Very common at study sites.
Acer saccharinum	Silver maple	Hupp and Osterkamp (1996)	West Tennessee	Species that dominate reestablishment of riverbanks after a disturbance in coastal plain area.
Acer saccharinum	Silver maple	Pizzuto and Meckelnburg (1989)	Chadds Ford, PA	Significantly reduces rate of bank migration in areas where densities are high
Acer saccharum	Sugar maple	Riestenberg and Sovonick-Dunford (1983)	Cincinnati, OH	Mixture of three tree species increased factor of safety of slopes by nine times (ash, sugar maple, buckeye)
Aesculus glabra	Buckeye	Riestenberg and Sovonick-Dunford (1983)	Cincinnati, OH	Mixture of three tree species increased factor of safety of slopes by nine times (ash, sugar maple, buckeye)
Agropyron trichophorum	Topar pubescent Wheatgrass	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Alnus	Alder	Seibert (1968)	Germany	Softwood zone plants. This is the most useful zone for streambank protection. In general, softwoods are commonly planted in this zone, but it is also possible to plant herbaceous species for protection.
Alnus incana	Alder	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Alopecurus arundinaceus	Creeping foxtail	Logan et al. (1979)	Missouri River	Plant by seeding. Seeds obtained from a commercial source. Species should be planted in the bank zone.
Amorpha fruticosa	Indigobush	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel. [noxious weed in some states]
Betula nigra	River birch	Hupp and Simon (1991)	West Tennessee	Formed dense riparian stands, Early establishment on disturbed banks. Withstands layering of soils by way of adventitious roots.
Betula nigra	River birch	Simon and Collison (2002)	Goodwin Creek, Mississippi	Performed best of all woody species in this study

Betula nigra	River birch	Hupp (1992)	West Tennessee	Pioneering species, can tolerate moderate mass wasting of banks and bank accretion. Very common at study sites.
Bromus mollis	Blando brome	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Buchloe dactyloides	Buffalo grass	Bowie (1982)	Mississippi	Probably requires significant sunlight.
Calamagrostis inexpansa	Northern reedgrass	Logan et al. (1979)	Missouri River	Plant by sprigging and seeding. Rhizomes and seeds can be collected locally. Species should be planted in the bank zone.
Carex	Sedges	Seibert (1968)	Germany	Reed bank zone plants. More useful than aquatic zone plants for stream protection, but may be difficult to implement in rivers because depth must be shallow in location of planting
Carex spp.	Unspecified sedge	Micheli and Kirchner (2002a, b)	Southern Sierras, CA	Produced dense root networks that reduced sediment removal by scour. Appears to greatly increase bank strength by root reinforcement of soil.
Carpinus caroliniana	Ironwood	Hupp (1992)	West Tennessee	Secondary establishment on streambanks. Moderately common at study sites.
Cornus stolonifera	Red osier dogwood	Porter and Silberberger (1960)	Buffalo, NY	Produced excellent results in Vermont in a previous study
Cornus stolonifera	Red osier dogwood	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks are available commercially. Plant in the bank zone.
Coronilla varia	Crown vetch	Porter and Silberberger (1960)	Buffalo, NY	Good establishment, poor winter cover, week above ground [weedy]
Coronilla varia	Crown vetch	Logan et al. (1979)	Missouri River	Plant by seeding. Seeds obtained from a commercial source. Species should be planted in the bank zone.
Coronilla varia Penngift	Crown vetch	Bowie (1982)	Mississippi	Weed
Crataegus chrysocarpa	Hawthorn	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks are available commercially. Plant in the bank zone.
Cynodon dactylon	Bermuda Grass	Temple and Alspach (1992)	Oklahoma	Studied inundation of 50% fescue, 20% little bluestem, and 20% bermuda grass. Death of the grass lining appeared to begin at about 225 to 500 hours of submergence. All plants appeared dead after 800 hours of submergence. Bermuda grass appeared to recover the best of all species but appeared to require a recovery time of about two years.
Cynodon dactylon	Bermuda grass	Bowie (1982)	Mississippi	All grasses did well when planted by seed
Dactylis glomerata	Palestine orchardgrass	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Eleocharis spp.	Unspecified rush	Micheli and Kirchner (2002a, b)	Southern Sierras, CA	Produced dense root networks that reduced sediment removal by scour. Appears to greatly increase bank strength by root reinforcement of soil.
Festuca arundinacea	Tall fescue	Porter and Silberberger (1960)	Buffalo, NY	Worked well when combined with crown vetch or birdsfoot trefoil

Festuca arundinacea	Tall Fescue	Temple and Alspach (1992)	Oklahoma	Studied inundation of 50% fescue, 20% little bluestem, and 20% bermuda grass. Death of the grass lining appeared to begin at about 225 to 500 hours of submergence. All plants appeared dead after 800 hours of submergence. Bermuda grass appeared to recover the best of all species but appeared to require a recovery time of about two years.
Festuca elatior	Meadow fescue	Logan et al. (1979)	Missouri River	Plant by seeding. Seeds obtained from a commercial source. Species should be planted in the bank zone.
Festuca rubra	Red fescue	Porter and Silberberger (1960)	Buffalo, NY	Worked well when combined with birdsfoot trefoil
Fraxinus	Ash	Riestenberg and Sovonick-Dunford (1983)	Cincinnati, OH	Mixture of three tree species increased factor of safety of slopes by nine times (ash, sugar maple, buckeye)
Fraxinus americana	White ash	Pizzuto and Meckelnburg (1989)	Chadds Ford, PA	Does not significantly reduces rate of bank migration in areas where densities are high
Fraxinus pennsylvanica	Green ash	Hupp and Osterkamp (1996)	West Tennessee	Species that dominate reestablishment of riverbanks after a disturbance in coastal plain area.
Fraxinus pennsylvanica	Green ash	Hupp and Simon (1991)	West Tennessee	Common, but stands are not so dense
Fraxinus pennsylvanica	Green ash	Hupp (1992)	West Tennessee	Secondary establishment on streambanks. Moderately common at study sites.
Glyceria grandis	Giant mannagrass	Logan et al. (1979)	Missouri River	Plant by seeding. Seed can be collected locally. Species should be planted in the splash zone.
Glyceria striata	American mannagrass	Logan et al. (1979)	Missouri River	Plant by seeding. Seed can be collected locally. Species should be planted in the splash zone.
Glycerietum aquaticae	Reed grass	Seibert (1968)	Germany	Reed bank zone plants. More useful than aquatic zone plants for stream protection, but may be difficult to implement in rivers because depth must be shallow in location of planting
Hordeum vulgare	Barley	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Juncus spp.	Unspecified rush	Micheli and Kirchner (2002a, b)	Southern Sierras, CA	Produced dense root networks that reduced sediment removal by scour. Appears to greatly increase bank strength by root reinforcement of soil.
Lespedeza cuneata	Sericia lespedeza	Shields et al. (1995)	Northwest Mississippi	One of two herbaceous species that consistently outperformed ten other species planted for erosion control.
Lespedeza cuneata Applow	Appolow sericea	Bowie (1982)	Mississippi	All grasses did well when planted by seed.
Liquidambar styroflora	Sweetgum	Simon and Collison (2002)	Goodwin Creek, Mississippi	Performed moderately in this study to limit bank failure.
Liquidambar styroflora	Sweetgum	Hupp (1992)	West Tennessee	Secondary establishment on streambanks. Moderately common at study sites.
Lolium rigidium	Wimmera 62 ryegrass	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.

Lotus corniculatus	Birdsfoot trefoil	Porter and Silberberger (1960)	Buffalo, NY	Good establishment, poor winter cover, week above ground [considered to be an invasive species]
Medicago sativa cv. Sonora	Alfalfa	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Melilotus alba	White sweetclover	Logan et al. (1979)	Missouri River	Plant by seeding. Seeds obtained from a commercial source. Species should be planted in the bank zone.
Melilotus officinalis	Yellow sweetclover	Logan et al. (1979)	Missouri River	Plant by seeding. Seeds obtained from a commercial source. Species should be planted in the bank zone.
Numphaeion	White water-lily	Seibert (1968)	Germany	Aquatic zone plants. Only useful for low velocity areas and likely difficult to establish artificially.
Panicum virgatum	Alamo switchgrass	Bowie (1982)	Mississippi	All grasses did well when planted by seed.
Panicum virgatum 'Alamo'	Alamo switch grass	Simon and Collison (2002)	Goodwin Creek, Mississippi	Good mechanical root properties, pore water properties degrade performance – outperformed all other species in this study during a wet year.
Panicum virgatum 'Alamo'	Alamo switch grass	Shields et al. (1995)	Northwest Mississippi	One of two herbaceous species that consistently outperformed ten other species planted for erosion control. May require some maintenance (e.g., burning) to encourage new growth.
Parthenocissis tricuspidata	Boston ivy	Bowie (1982)	Mississippi	Sprigging works best for ivys (not seed).
Paspalum notatum Pensacola	Bahiagrass	Bowie (1982)	Mississippi	All grasses did well when planted by seed.
Phalaridetum arundinaceae	Reed-grass	Seibert (1968)	Germany	Reed bank zone plants. More useful than aquatic zone plants for stream protection, but may be difficult to implement in rivers because depth must be shallow in location of planting
Phalaris arundinacea	Reed canary grass	Bowie (1982)	Mississippi	Weedy
Phalaris arundinacea	Reed canarygrass	Logan et al. (1979)	Missouri River	Plant by seeding. Seeds obtained from a commercial source. Species should be planted in the bank zone.
Phalaris tuberosa	Hardinggrass	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Phragmites communis	Common reed	Logan et al. (1979)	Missouri River	Plant by sprigging or seeding. Seeds and rhizomes can be collected locally. Species should be planted in the splash zone.
Phragmitetum	Common reed	Seibert (1968)	Germany	Reed bank zone plants. More useful than aquatic zone plants for stream protection, but may be difficult to implement in rivers because depth must be shallow in location of planting
Pinus ponderosa	Western yellow pine	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Platanus occidentalis	Sycamore	Hupp and Osterkamp (1996)	West Tennessee	Species that dominate reestablishment of riverbanks after a disturbance in coastal plain area.
Platanus occidentalis	Sycamore	Hupp and Simon (1991)	West Tennessee	Develops stands later in the process of reestablishment by vegetation. Withstands layering of soils by way of adventitious roots.

Platanus occidentalis	Sycamore	Simon and Collison (2002)	Goodwin Creek, Mississippi	Performed fairly well to limit bank failure.
Polygonum coccineum	Swamp smartweed	Logan et al. (1979)	Missouri River	Plant by seeding. Seed can be collected locally. Species should be planted in the splash zone.
Polygonum lapathifolium	Pale smartweed	Logan et al. (1979)	Missouri River	Plant by seeding. Seed can be collected locally. Species should be planted in the splash zone.
Populus angustifolia	Narrowleaf cottonwood	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Populus deltoides	Eastern cottonwood	Hupp (1992)	West Tennessee	Pioneering species, can tolerate moderate mass wasting of banks and bank accretion. Moderately common at study sites.
Populus deltoides	Eastern cottonwood	Hupp and Simon (1991)	West Tennessee	Common, but stands are not so dense. Develops stands later in the process of reestablishment by vegetation. Withstands layering of soils by way of adventitious roots.
Populus deltoides	Eastern cottonwood	Hupp and Osterkamp (1996)	West Tennessee	Species that dominate reestablishment of riverbanks after a disturbance in coastal plain area.
Populus deltoides	Eastern cottonwood	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Populus fremontii	Cottonwood	Shields and Gray (1992)	Sacramento River	Found that woody species had deeper root systems than herbaceous species, but herbaceous species appeared to have higher root densities. Note that this study was done in California, and there were few species for comparison purposes.
Potamion	Pondweed	Seibert (1968)	Germany	Aquatic zone plants. Only useful for low velocity areas and likely difficult to establish artificially.
Quercus agrifolia	Coast live oak	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Quercus lobata	Valley oak	Shields and Gray (1992)	Sacramento River	Found that woody species had deeper root systems than herbaceous species, but herbaceous species appeared to have higher root densities. Note that this study was done in California, and there were few species for comparison purposes.
Quercus spp.	Oaks	Hupp (1992)	West Tennessee	Final establishment of streambanks – after recovery
Ranunculion fluitantis	Water crowfoot	Seibert (1968)	Germany	Aquatic zone plants. Only useful for low velocity areas and likely difficult to establish artificially.
Rosa californica	California rose	Shields and Gray (1992)	Sacramento River	Found that woody species had deeper root systems than herbaceous species, but herbaceous species appeared to have higher root densities. Note that this study was done in California, and there were few species for comparison purposes.

Rosa multiflora	Multiflora rose	Shields et al. (1995)	Northwest Mississippi	One of two woody species that consistently outperformed five other species planted for erosion control. Not recommended because it is invasive
Rosa multiflora	Multiflora rose	Bowie (1982)	Mississippi	Weed
Salix	Willow	Seibert (1968)	Germany	Softwood zone plants. This is the most useful zone for streambank protection. In general, softwoods are commonly planted in this zone, but it is also possible to plant herbaceous species for protection.
Salix amygdaloides	Peachleaf willow	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Salix amygdaloides	Peachleaf willow	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks have a limited commercial source. Plant in the bank zone.
Salix babylonica	Weeping willow	Rowntree and Dollar (1999)	Bell River S Africa	Establishment may increase out of channel flow because of reduced channel cross section, increased roughness
Salix bebbiana	Bebbs willow	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks can be obtained locally as cuttings. Plant in the bank zone.
Salix caprea	Goat willow	Rowntree and Dollar (1999)	Bell River S Africa	Establishment may increase out of channel flow because of reduced channel cross section, increased roughness
Salix exigua	Sandbar willow	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Salix exigua	Sandbar willow	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks can be obtained locally as cuttings. Plant in the bank zone.
Salix fragilis	Crack willow	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Salix lutea	Yellow willow	Hupp and Osterkamp (1996)	Plum Creek, CO	Species that dominate reestablishment of riverbanks after a disturbance in the high plains. Note that the stream on which these species were found is an aggrading, sand bed channel.
Salix lutea	Yellow willow	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks are available commercially. Plant in the bank zone.
Salix nigra	Black willow	Hupp and Osterkamp (1996)	West Tennessee	Species that dominate reestablishment of riverbanks after a disturbance in coastal plain area.
Salix nigra	Black willow	Hupp and Simon (1991)	West Tennessee	Formed dense riparian stands, Early establishment on disturbed banks. Withstands layering of soils by way of adventitious roots.
Salix nigra	Black willow	Simon and Collison (2002)	Goodwin Creek, Mississippi	Did increase high bank stability substantially
Salix nigra	Black willow	Hupp (1992)	West Tennessee	Pioneering species, can tolerate moderate mass wasting of banks and bank accretion. Very common at study sites.
Salix nigra	Black willow	Shields et al. (1995)	Northwest Mississippi	One of two woody species that consistently outperformed five other species planted for erosion control.
Salix nigra	Black willow	Bowie (1982)	Mississippi	Survival was better than for other willows.

Salix purpurea	Purple osier willow	Porter and Silberberger (1960)	Buffalo, NY	Produced excellent results in Vermont in a previous study
Salix purpurea streamco	Streamco willow	Bowie (1982)	Mississippi	Low drought survival
Salix rigida	Diamond willow	Logan et al. (1979)	Missouri River	Plant bare rootstocks. Rootstocks have a limited commercial source. Plant in the bank zone.
Schizachyrium scoparium	Little Bluestem	Temple and Alspach (1992)	Oklahoma	Studied inundation of 50% fescue, 20% little bluestem, and 20% bermuda grass. Death of the grass lining appeared to begin at about 225 to 500 hours of submergence. All plants appeared dead after 800 hours of submergence. Bermuda grass appeared to recover the best of all species but appeared to require a recovery time of about two years.
Scirpetum lacustris	Bulrush	Seibert (1968)	Germany	Reed bank zone plants. More useful than aquatic zone plants for stream protection, but may be difficult to implement in rivers because depth must be shallow in location of planting
Scirpus acutus	Hardstem bulrush	Logan et al. (1979)	Missouri River	Plant by sprigging. Rhizomes can be collected locally. Species should be planted in the splash zone.
Scirpus americanus	American bulrush	Logan et al. (1979)	Missouri River	Plant by sprigging. Rhizomes can be collected locally. Species should be planted in the splash zone.
Scirpus validus	Softstem bulrush	Logan et al. (1979)	Missouri River	Plant by sprigging. Rhizomes can be collected locally. Species should be planted in the splash zone.
Sorgum bicolor sudanense	Greenleaf sudangrass	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Spartina pectinata	Prairie cordgrass	Logan et al. (1979)	Missouri River	Plant by sprigging and seeding. Rhizomes and seeds can be collected locally. Species should be planted in the bank zone.
Taxodium distichum	Bald cypress	Hupp (1992)	West Tennessee	Secondary establishment on streambanks
Tripsacum dactyloides	Eastern gamma grass	Simon and Collison (2002)	Goodwin Creek, Mississippi	Poor results as seen by failures – root strength is primary reinforcer. Pore water properties are very poor.
Triticum oestivum cv. Anza	Anza wheat	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.
Typha latifolia	Cattail	Logan et al. (1979)	Missouri River	Plant by sprigging. Rhizomes can be collected locally. Species should be planted in the splash zone.
Ulmus americana	American elm	Hupp (1992)	West Tennessee	Secondary establishment on streambanks. Moderately common at study sites.
Vicia dascarpa	Lana vetch	Waldron and Dakessian (1982)		Studied shear resistance of roots of 12 species of plants. Alfalfa did best at the 0.3 m depth. Vetch, Sudangrass, and wheat did poorly.

Appendix B Implementation Plan

This literature review was conducted for the purpose of determining when traditional methods of grade control are needed to complement bioengineering techniques for stream stabilization. Since bioengineering methods alone are unlikely to succeed below the normal water line and when channel incision is actively occurring, a combination of bioengineering methods and traditional grade stabilization methods will need to be employed.

A guide has been compiled that contains information such as: the best methods of planting different vegetation types, criteria for plant selection, and when the use of plants is likely to be unsuccessful. While the focus of the literature review is on biological erosion controls, information about traditional methods (such as revetments, dikes, and weirs) is also provided. Furthermore, studies that combine traditional methods with bioengineering methods have been reviewed and presented. The information provided about traditional and combined methods offers guidance about whether or not biological erosion controls are practical in a variety of situations.

This report will be used as a reference and guide by highway designers and environmental permit managers at the Nebraska Department of Roads. It will be used to help identify the erosion processes that are active in a stream and to formulate the most effective methods for streambank stabilization and restoration.

Glossary

Accretion – deposition of sediment resulting in expansion of the streambank or bed.

Adventitious roots – roots that form on parts of a plant where they are not normally found, such as leaves, stems, and trunks. Many floodplain species are able to develop roots on their trunks as a response to changing floodplain conditions, like erosion or deposition of floodplain soil.

Aggradation – accumulation of sediment on the bed of a stream, leading to a rise in the base level of the stream.

Antecedent moisture – soil moisture that is present prior to the arrival of the storm of interest. Antecedent moisture is caused by an earlier event, such as an earlier storm or flooding.

Bioengineering – as related to streambank erosion, bioengineering is the use of vegetation or plants to reduce fluvial and surface erosion.

Braided – a channel is said to be braided if it is composed of multiple curved sub-channels that flow within a larger channel. Braided streams are high energy streams that generally carry a large quantity of sediment.

Channel migration –movement of the normal conveyance channel within a larger floodplain. The rate of channel migration is generally slow but can be significantly affected by changes in flow, sediment load, bed slope, sediment composition, or alignment of the channel.

Channelization – straightening a stream to increase its carrying capacity, reduce the amount of land it uses, improve the utility of the land through which it flows, or for some other purpose.

Cohesive sediment – sediment that is so fine that its particles experience attractive intermolecular forces that prevent them from being easily separated.

Corrasion – erosion of the bank of a stream that occurs when fine material carried by the flow rubs against the bank. The abrasive action of the moving material causes failure of the bank.

Critical shear stress – the limiting shear stress above which erosion occurs.

Degradation – erosion of sediment from the bed of a stream, causing lowering of the base level of the stream.

Desiccation – the process of drying out. In the present context, extreme drying of cohesive soils.

Entrainment – removal of sediment from a surface by air or water.

Exfiltration – seepage of groundwater from a low area where the water table is high.

Extensible – able to stretch or lengthen as tensile force increases.

Factor of safety – the ratio of the forces that resist and drive streambank failure. A factor of safety that is greater than one indicates that a streambank is not as likely to fail.

Fascine mattresses – bundles of untreated tree stems used to line banks for erosion protection.

Fluvial – used to describe all topics relating to flowing water.

Fluvial entrainment – removal of sediment by flowing water, water-based erosion.

Fluvial erosion – see fluvial entrainment.

Gabians – cages that are usually made of galvanized steel wire and filled with rock. The advantage of gabians over loose rip-rap is that smaller stones can be used since the wire cage holds the stones together so that they act as one unit.

Geomorphology – the study of landforms, how the originate, and the processes that change them.

Geotechnical failure – the collapse or slippage of a large quantity of soil situated on a steep slope.

Head cut – an abrupt change in the base elevation of a streambed. In streams with beds composed of highly erodible soil, head cuts tend to rapidly move upstream because they concentrate a large quantity of erosive energy in the vicinity of the head cut.

Hydrogeomorphology – geomorphology associated with water related processes.

Hydrograph – a diagram that shows how flow rate changes with time at a particular stream location. A hydrograph might be used to show the flow rate in a stream that results from a given storm event.

Incised – a channel is incised if degradation has caused the bed of the channel to cut far below the original floodplain of the channel. Usually, channel incision leads to the development of a new floodplain.

Knickpoint – see head cut.

Mass wasting – the down-slope motion of rock, soil, and other materials under the influence of gravity. Along streambanks, mass wasting is a continual process that occurs as a result of the undercutting of the banks and subsequent removal of the failed bank material by the stream.

Meander – a bend or curve in a river. Meanders grow naturally as a result of disproportionate erosion along the inner and outer banks of the channel bend. Even straight channels with erodible banks will eventually form meanders.

Migration – see channel migration

Morphology – the study of the shape and form of things.

Nick-point – see head cut.

Overburden – the excess weight of objects resting on a soil slope that is subject to geotechnical failure. Overburden usually increases the probability of slope failure. In this report, overburden generally refers to the weight of vegetation on the slope face.

Permeability – the ability of soil to convey water. Porous soils are permeable and impervious rock is impermeable.

Piping – erosion of soil from within a streambank by groundwater seeping from the bank. As piping occurs, the ability of the soil to convey more water increases since piping results in the formation of low resistance flow passages. In dams, piping can lead to rapid failure of the dam.

Pore pressure – for soils with low permeability, moisture within the soil is confined to pores and is not very mobile. The pressure of the water within these pores can be measured and is referred to as pore pressure. Cohesive forces and low permeability may prevent soils from draining after a rapid drop in piezometric head, resulting in negative pore pressures. These negative pore pressures increase the strength of cohesive soils.

Recession Limb – the part of a hydrograph that shows the decrease of flow rate in a stream following the end of a storm.

Revetment – structures placed on streambanks to absorb the energy of water flowing in the stream. The structures prevent bank erosion.

Riprap – a permanent cover of rock used to stabilize streambanks.

Riparian – alluding to the region of the interface between land and a flowing body of water. For example, riparian vegetation is vegetation that grows along the edges of streams.

Saturation – in the present report, soil is saturated when all of its available pore space is filled with water.

Scour – the removal or erosion of sediment by flowing water.

Secondary currents – flow patterns that occur in the plane that is perpendicular to the mean flow direction.

Sediment carrying capacity – the maximum amount of sediment that can be carried by a flow. If the amount of sediment in a flow exceeds its carrying capacity, some of the sediment will be deposited.

Shear stress – the force per unit area exerted by water on the bank or bed of a stream that is parallel to the direction of motion of the water.

Sinuosity – the ratio of channel length to valley length. Sinuosity is a descriptor of the intensity of meandering that a particular stream displays.

Starved water – a flow that is not carrying the amount of bed sediment that it is capable of carrying is said to be starved, and will pick up sediment from the bed.

Stratigraphy – referring to layers of soil or rock of varying composition.

Surcharge – see overburden.

Surface erosion – erosion of the soil surface by overland flow.

Thalweg –a line drawn through the lowest points on a stream bed along the length of the stream. The thalweg defines the deepest part of the channel.

Toe – the base or bottom of a slope.

Tractive force – average shear stress.

Trash line – the interface between two counter-rotating cells or secondary currents in a stream. So-called because trash tends to gather at the interface during periods of high flow.

Valley slope – the gradient of the floodplain of a channel.

Wind throwing – trees planted at the tops of banks are more susceptible to being blown over or toppled by strong winds. This is referred to as wind throwing.