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Final Report

Scoping Study for the Development of Design Guidelines for Bioengineering in the Upper Midwest

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16. Abstract (Limit: 200 words)

It has been about fifteen years since soil bioengineering and bioengineering technology have been used in projects to protect slopes and river banks against erosion. Now many consulting firms as well as state and federal agencies promote and practice these techniques. Despite a widespread support of these techniques, many projects have failed. Therefore, it is deemed necessary to develop a set of design guidelines to ensure a higher rate of success.

In order to develop design guidelines for soil bioengineering and bioengineering technology, a pilot study was conducted to determine the amount of work already done in these areas, and to define the existing research needs. This report comprises (a) a summary of literature review, (b) interviews with eleven practitioners in the field, (c) an evaluation of three projects done in Minnesota, (d) current research needs, (e) and a brief evaluation of three sites in the vicinity of the Twin Cities area as potential outdoor laboratories to conduct research in the needed areas. It also includes a summary of a site visit of the department of Soil Bioengineering and Landscape Construction at the University of Agricultural Sciences in Vienna, Austria.

The study shows that a significant number of studies have been done on topics related to soil bioengineering techniques. However, these studies mainly address the problems at a micro scale, and hence, there is a gap between existing knowledge and practice. Therefore, there is an urgent need to not only study some of the fundamental processes and mechanisms involved in soil bioengineering techniques, but also to investigate these processes at a macro scale to evaluate their strengths and impacts when applied to streambanks and slopes.

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Scoping Study for the Development of Design Guidelines for Bioengineering in the Upper Midwest

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Executive Summary

It has been about fifteen years since soil bioengineering and bioengineering technology have been used in projects to protect slopes and river banks against erosion in the U. S. Now many consulting firms as well as state and federal agencies promote and practice these techniques. Despite a widespread support of these techniques, many projects have failed. Therefore, it is deemed necessary to develop a set of design guidelines to ensure a higher rate of success.

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Main highlights of the research needs identified in this study were a) quantifying the bank and bed roughness with the most common plants used in bioengineering techniques, b) studying the added shear strength to banks by vegetation, c) determining the resiliency of different plants under high flow conditions, e) understanding the mechanisms which cause failure of plants under different flow conditions, f) quantifying the shear strength of the commonly used techniques for a range of bank slopes, top soil depths and soil types, and g) determining the shear strength of composite systems, where different plants and techniques are combined.

To conduct research in the needed areas three sites were identified and evaluated as potential outdoor research facilities in the vicinity of the Twin Cities area, Minnesota. The three candidate sites were (1) the two abandoned wasteways near the Falls of St. Anthony located adjacent to the St. Anthony Falls Laboratory, (2) a 7 acre area in the northern part of the UMore Park, a University of Minnesota property allocated for research, and (3) a short reach of the Vermillion River near Empire, MN, located on private property.

Chapter 1. Introduction

After more than a century of hard armoring of creeks, streams and rivers in the proximity of urban areas to ensure protection of properties, biotechnical engineering and soil bioengineering have received a lot of attention for use in slopes and streambank repair and stabilization. Both techniques use live materials and vegetation instead of using strictly "hard" armoring techniques, such as concrete, gabions, or riprap, and are, therefore, more environmentally attractive and can more easily blend into the rest of the streambank. Biotechnical engineering comprises a set of techniques that use a combination of structures and vegetation for stabilizing slopes. The structures and the vegetation work together to prevent slope failure as the biological and mechanical portions of the techniques compliment each other. Soil bioengineering is often considered to be a subset of biotechnical engineering. This practice uses only plants and other natural materials and does not incorporate any structural component. Stems, roots, and natural products must do all of the work to prevent slope failure and bank erosion. In this report, "soft armoring" will refer to both biotechnical engineering and soil bioengineering.

1.1. Brief History of Streambank Stabilization

Most streambanks erode by natural processes, therefore communities living near streams have always had to deal with some erosion problems. Due to the meandering nature of most streams, those living near these bodies of water have had to employ techniques to halt or drastically slow the erosion processes or be ready to move to new areas as the land on which they were living slowly eroded away and washed downstream. Prior to the industrial revolution, the only option available to stabilize eroding banks was with the use of plants and natural techniques. Greenway (1987) and Franti (1997) both mentioned Chinese efforts for using soft armoring for slope stabilization (1, 2). Brush bundles were used as early as the 12th century, and a Chinese engineer named Pan used willow plantings to stabilize embankments in 1591 during the Ming Dynasty. Greenway also described other quantitative efforts to prevent soil erosion through the use of vegetation in Europe and the U. S. throughout the 19th and 20th centuries. However, with the industrial revolution came the development of products like steel and concrete, and among the reasons it became popular in the 20th century to use these materials was the fact that they were cheap and labor for more traditional "soft" techniques was expensive (3). Furthermore, it became possible to design concrete or masonry structures with a high degree of confidence because their strengths to withstand natural forces were relatively easy to estimate. Another benefit of using concrete and masonry structures instead of waiting for vegetation to develop was immediate protection of the slope. It was assumed that these structures would not change shape and would remain in place for a very long time (3, 4). Streams were channelized to control their flow direction, conveyance, and flow depth for a variety of purposes (Figure 1.1). From an engineering point of view, this was ideal and the communities next to rivers and streams benefited in many ways.

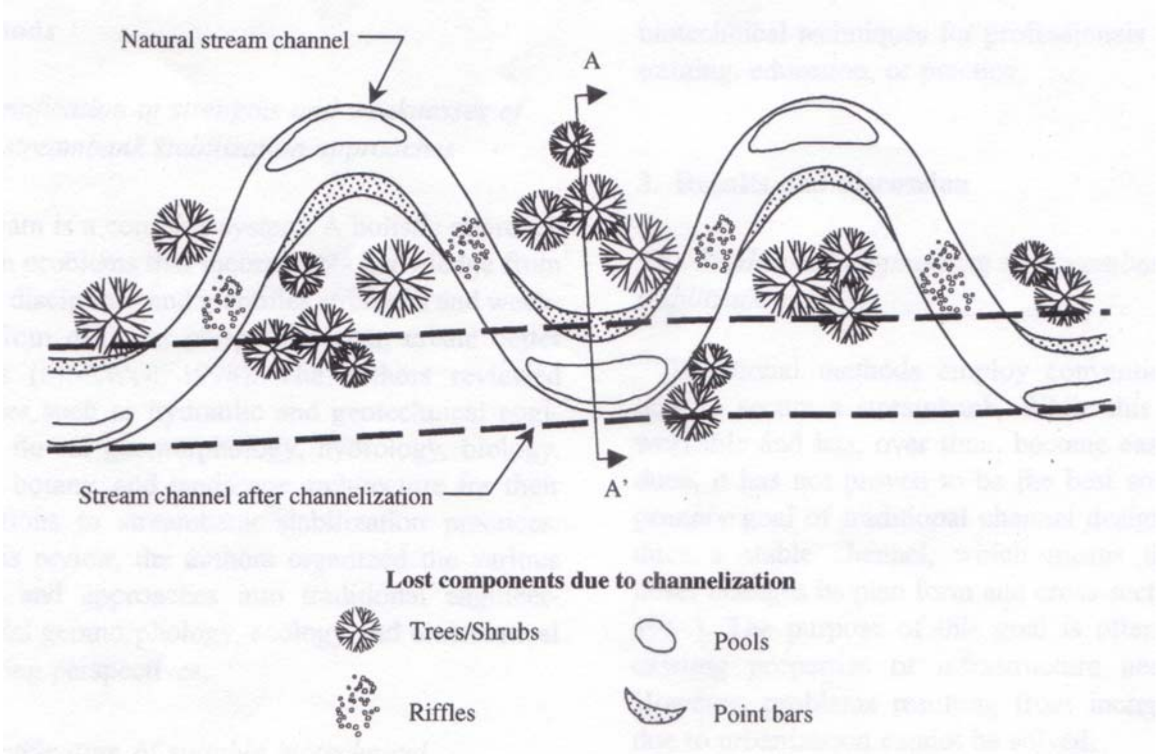


Figure 1.1 Comparison of a channelized stream and a natural stream channel (from Li and Eddleman, 2002).

In recent years, the effectiveness of these "hard" armoring techniques has been re-examined, along with the environmental damage they cause. Some of the benefits of hard armoring, such as a high degree of confidence in the design and immediate protection, still hold true, but these techniques have not proven to be as effective and long lasting as was initially thought. Their use, along with the urge to straighten streams, has resulted in significant loss of a variety of aquatic and riparian habitats as the natural pool-riffle flow patterns, point bars and flood plains were all eliminated or drastically diminished. In addition, the hard armoring techniques and channelization diminished the ability of streams to dissipate the flow energy, therefore increasing flow velocities and subsequently soil erosion and scour further downstream (4). These factors have contributed to the re-evaluation of the use and effectiveness of soft armoring techniques.

The practice of biotechnical engineering and soil bioengineering is more advanced in Europe than in the U.S. because soft armoring practices in Europe have a longer history than in the U. S. Because of Europe's population density, erosion problems in urban settings developed earlier than in U. S. cities. However, it is also true that Europeans did not embrace hard armoring to the extent that the Americans did. According to Gray and Sotir (1996), modern soft armoring techniques in Europe were developed in the 1930s when professionals gathered to develop successful techniques based on the principles of soil bioengineering. Hugo Schiechtl documented these practices in his landmark book *Sicherungsarbeiten im Landschaftbau* which was published in 1973. It was translated into English and published in 1980 under the name *Bioengineering* (5).

The use of soft armoring techniques was never completely abandoned in the U. S., but it did not receive nearly the same amount of attention as it did on the other side of the Atlantic. According to Gray and Sotir (1996), Kraebel (1936) used "live construction" to stabilize erosion problems in southern California (6). Also, the Natural Resources Conservation Service (formerly Soil Conservation Service) was using soft armoring in the 1940s (7). However, the practice of soft armoring in the U. S. began to receive more attention in the 1970s as concerns about hard armoring increased (4). Following the publication of Schiechtl's book, in 1982Gray and Leiser published their book, *Biotechnical Slope Protection and Erosion Control*, which became the standard book for the North American practice (8, 9). Other notable publications include *Use of Vegetation in Civil Engineering* by Coppin and Richards in 1990; *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control* by Gray and Sotir, 1996; and Chapter 16 in the USDA NRCS *Engineering Field Handbook* (1992), titled "*Streambank and Shoreline Protection*" (10). Furthermore, soft armoring techniques have received a lot of attention by field practitioners who have implemented numerous projects in recent years and contributed case studies to the general body of literature. Some of those case studies and the lessons learned from them are discussed in this report.

1.2. Scope of Present Study

The main objectives of this project are (a) to identify the existing science supporting bioengineering techniques, (b) to identify the needed research areas in bioengineering that will help generate the information necessary for producing design guidelines for bioengineering projects, and (c) to identify and evaluate the feasibility of sites near the Twin Cities areas which can be used to conduct research in needed areas.

In this study, first, the processes associated with streambank erosion will be addressed. The discussion will cover general causes of erosion, both natural and anthropogenic, such as geomorphological processes, land use changes, and stream straightening . Then, specific erosion processes will be addressed and the discussion will be broken down into the various processes of (a) surficial erosion and (b) mass movement. An understanding of these processes is necessary in order to address local erosion problems.

Subsequently, role of vegetation as a vital component in soft armoring techniques will be discussed while identifying the advantages and disadvantages of using vegetation in streambank stabilization projects.

There are a few factors that need to be considered for the design of any slope and streambank stabilization project. They are hydrologic factors, geotechnical factors, vegetation factors and fluvial geomorphological factors. These considerations will be discussed in chapters 2 and 3. Following that, a few specific design guidelines will be presented in chapter 4. In chapter 5, summaries of interviews with eleven practitioners from the state agencies and consulting firms will be presented. Chapter 6 is allocated to the evaluation of three projects completed in Minnesota. In chapter 7, unknown or poorly understood variables and mechanisms involved in the practice of soil bioengineering will be identified as potential areas for research. Finally, three potential sites as outdoor research facilities will be evaluated in chapter 8.

Chapter 2. Erosion Processes

There are several processes that may be taking place at any site where streambank erosion is a problem. Some of these problems may be systemic while others may be local processes. To complicate matters, it is possible, and even likely, that more than one systemic problem and more than one local process are present and contributing to the problem at a particular site. Therefore, it is necessary to understand the processes and to know how to identify the processes at work in order to develop a solution that addresses the root of the problem.

2.1. Systemic Causes of Erosion

Three factors have been identified as the most frequent causes of erosion: land use changes, stream straightening, and geomorphologic processes. Land use changes and stream straightening are anthropogenic influences while the geomorphologic processes are natural stream erosion processes. While it may be possible to easily identify the systemic problems at hand, knowing how to properly address them can be quite difficult and is something that is still being heavily researched.

2.1.1. Land Use Changes

Probably the most evident cause of erosion has been urbanization and its dramatic impact on streams and rivers. The land use change from natural vegetation to a watershed with a large percentage of impervious area leads to a significant increase in stormwater runoff volume and storm peak flow. The annual stormwater runoff volume can increase by 2-16 times after urbanization, and as little as 10% watershed imperviousness has been linked to stream degradation (11). Another factor complicating the issue is that the riparian buffer, which is one of the stream's defense mechanisms for reducing the impacts of storm runoff, is often diminished or eliminated in urban settings (12). The effects of runoff increase lead to downcutting of the streambed, followed by widening of the stream channels. This has been thoroughly addressed by Shields et al. (1995a), Rosgen (1996), and Darby and Simon (1999) (13, 14, 15).

2.1.2. Stream Straightening

As discussed before, the process of channelization removes natural meanders from streams, and it often removes the natural series of pools and riffles. Pool-riffle sequences and meanders are essential for dissipating flow energy. By removing these built-in energy dissipaters, flow velocities increase which often result in significant erosion problems downstream. In addition, channelizing streams reduces the flow path length, which reduces the amount of time it takes for a storm surge to move downstream and effectively increases the storm surge velocity. The increase in flow volume and velocity increases the sediment carrying capacity of the stream. In order to fill the sediment carrying capacity, bed and bank materials are entrained into the flow. Furthermore, as streams try to return to their natural meandering patterns, significant amounts of bank materials will be eroded away if the channel is allowed to completely return to its natural form. The morphological differences between a natural stream and a straightened stream can be seen in Figure 1.1.

2.1.3. Natural Erosion Processes and Meandering

It is well-known that many streams naturally meander and stream channels are rarely stable over a long period of time unless they are confined by some other natural forces, such as canyon walls. A look at any morphological history will reveal stream changes if the time scale is long enough. It is essential to have a thorough understanding of fluvial geomorphology before conducting any streambank stabilization project. Leopold (1994) and Rosgen (1996) presented thorough descriptions of fluvial geomorphologic processes present in riverine systems.

2.2. Local Erosion Processes

There are several erosion processes that need to be considered for any soil bioengineering project. Many researchers divide these processes into two categories: surficial erosion and mass movement (1, 3, 16). *Surficial erosion* is governed by hydraulic processes and can be characterized as water removing individual soil particles because the shear stress generated by the flowing water is greater than the cohesiveness or shear strength of the soil. Surficial erosion is characterized by a lack of vegetation and high boundary velocities. *Mass movement* is governed by geotechnical processes and can be described as the erosion of large pieces of a slope when the force of gravity is greater than the forces holding the materials in place, resulting in a slope failure. Gray and Sotir (1996) outlined causes of mass movement and categorized either as those with increase in shear stress or those with a decrease in shear strength (3). Often erosion problems are a combination of both surficial erosion and mass movement instead of one of the processes acting alone (16). A combination of the two processes can be characterized by bed degradation and mass wasting of materials that are eventually washed away. Other factors that influence erosion, as stated by Fischenich (2001a), include: (a) flow properties, e.g. magnitude, frequency and variability, degree of turbulence, shear stress, (b) sediment composition, e.g. sediment size, gradation, cohesion, and stratification, (c) climate, e.g. rainfall depth, intensity, and duration, freezing duration, (d) subsurface conditions, e.g. seepage forces, piping, soil moisture, (e) channel geometry, e.g. width and depth, height, bank slope, bend curvature, (f) biology, e.g. vegetation type, density, root character, and (g) anthropogenic factors, e.g. urbanization, flood control, boating, irrigation (17).

These factors will be briefly discussed below with references for further investigation. The role of vegetation in reducing the effects of erosion will be addressed in section 3.

2.2.1. Surficial Erosion

Surficial erosion can be defined as the detachment and transport of soil particles from the surface layers of soil by wind, water or ice (3). These processes are as follows:

1) Raindrop impact
2) Sheet erosion
3) Rill Erosion
4) Gully Erosion
5) Channel erosion
6) Wave action
7) Groundwater erosion (piping)
8) Ice scouring.

Raindrop impact

The impact of raindrops erodes the soil, and a heavy storm can result in 100 tons/acre of soil particles splashing into the air (3). The effect of rainfall erosion is a function of climate, soil, topography, and vegetation present (3, 18). There are four commonly used empirical models for predicting soil loss from rainfall, and they are the Universal Soil Loss Equation (USLE), the Revised Universal Soil Loss Equation (RUSLE), the Modified USLE (MUSLE) and the Water Erosion Prediction Model (WEPP) (3, 19, 20, 21, 22). All have similar variables and none is the obvious best choice at predicting soil loss (22). They are all limited by the fact that they are empirical formulations and can only predict average annual soil loss (3).

Sheet Erosion

Sheet erosion is essentially the removal of soil from slopes while thin layers or sheets of water flow over the surface during storm events. During sheet erosion two processes occur: detachment and entrainment (23), in which the shear stress of the sheet flow exceeds the shear strength or the cohesion of the soil. In general, rainfall erosion has more severe impacts than sheet erosion. Nevertheless, sheet erosion is still an important mechanism of slope retreat, especially when riparian and bank vegetation has been destroyed by human activities (3, 24). Zhang et al. (2003) developed a model to quantify the detachment of soil particles by sheet flows (25). They studied the influence of flow discharge, slope gradient, flow velocity, shear stress, stream power, and unit stream power on the detachment of natural, undisturbed soil. They found that detachment rates could best be predicted with three relationships: a power function of flow rate (range = 0.009 - 0.07 cfs) and slope gradient (range = 8.8 - 46.6%); a power function of stream power (range = 1- 60 kg s^{-3}), and a power function of flow velocity (range = 1- 3 ft s^{-1}). It must be noted that the coefficients for each of the relationships developed will likely vary with soil type. Evidence of sheet erosion includes lack of vegetation cover, fresh appearance of bank materials, and eroded debris accumulated on the lower bank/toe area (24).

Rill Erosion

Rill erosion is the removal of soil by small but well-defined channels. It is the most common form of erosion directly attributable to rainfall (16). Erosion rates are higher for rill erosion than sheet erosion due to higher flow velocities. In extreme cases, rill erosion leads to gully erosion (3). Abrahams et al. (2001) developed equations to quantify the amount of soil loss through rill erosion (26). To develop their model, they used 1295 different flume experiments for a variety of ranges for flow depths, flow velocities, Reynolds numbers, Froude numbers, bed slopes, sediment sizes, volumetric sediment concentrations, roughness concentrations, roughness diameters, rainfall intensities and flow kinematic viscosities. For the roughness components, they used stones, cylinders, and miniature ornamental trees, and concluded that the model should be applicable for a wide range of surface conditions.

Gully Erosion

Gullies are intermittent stream channels, which can be fairly deep. They form where large volumes of runoff concentrate, such as parking lots during storm events. They are not as significant as rill erosion in terms of total soil loss, but they can cause significant local instabilities (3). There are a few models that have been developed to predict gully erosion. Two such models were developed by Sidorchuk (1999), one for dynamic gully erosion during early gully formation and one for static gully erosion after the gully reaches some sort of equilibrium (27). Sidorchuk tried to verify the results of the models and found that they are very sensitive to the soil and hydraulics at each site and careful calibration is necessary for the models to work accurately. Another model, the Ephemeral Gully Erosion Model (EGEM), was first described by Woodward in 1999 (28). It was developed by NRCS to estimate peak discharge rates and runoff volumes using the SCS curve number, drainage area, watershed flow length, average watershed slope, and 24-hour rainfall and standard SCS rainfall distributions. Some single-event studies were used to verify the model, but data on annual predictions were not yet available. Nachtergaele et al. (2001) tried to validate the EGEM for use in Belgium loess, but found that the model did not work well in the field conditions present (29).

Channel Erosion

Stream channel erosion is the detachment and removal of soil particles from the stream banks or sediments from the stream bed. The two basic processes that take place with channel erosion are detachment and entrainment (23). Just like the case with rill erosion, channel erosion takes place when the shear stresses are greater than the shear strengths or cohesiveness of the soil or sediment. Channel erosion leads to scouring of the bank and undercutting of the toe (24). The effects of channel erosion have been the subject of numerous books and papers. In addition to the basic processes mentioned here, there are other processes, such as sediment transport and channel incision, which have significant impacts on total channel erosion and streambank stability (15, 30, 31, 32, 33).

Wave action

Erosion caused by wave action is primarily a problem on lakes and is minimally discussed in this study. The repetitive crashing of waves on a lakeshore can cause significant erosion problems (3, 9, 24). Lake level and average wave height are the most dominant factors in determining the extent of erosion and degree of protection required. Other factors include bank slope and wave period. Plants will not grow in the crash zone on a lakeshore, so some other form of armoring is necessary in that area. Water levels in most lakes fluctuate during the year, so the crash zone will also fluctuate. Any solution to erosion from wave action will need to withstand a certain degree of flooding and wave crashing, or else some armoring is needed in the fluctuating crash zone (9).

Groundwater Erosion

Local erosion can also occur due to groundwater emerging from a bank. As the groundwater moves through the bank materials, the bank materials become saturated and lose their frictional shear strength. The presence of water within the pores of the soil causes a “buoyant reduction in the normal force required for frictional shear strength by the pore pressure” (26). Saturated soil has a reduced cohesive component, which reduces the strength of the soil (3, 26). This process is also known as piping, and can also be caused by drainage patterns within a bank, resulting in the area into where most of the moisture in the bank drains, causing local instabilities (3, 24).

Evidence includes: pronounced seep lines, pipe-shaped cavities in the bank, notches in the bank associated with seepage layers, and run-out deposits of eroded material on the lower bank (24).

Freeze/thaw and Ice Scouring

Deep freezing of the soil moisture in the bank can cause soil heaves and ice wedging can cleave apart blocks of soil. As soil moisture freezes, "needle-ice" can be formed, which loosens and detaches grains and crumbs at the bank face. In general, freeze/thaw cycles seriously weaken the bank and increases erodibility (24). Localized ice scour can be caused by ice floating downstream and the "surcharging of ice cantilevers" during spring thaws, but it is rarely a significant cause of erosion (24). It can also be caused by ice heave on lake shores (3). Evidence of freeze/thaw and ice scour erosion include a loose, crumbling surface layer of soil on the bank, jumbled blocks of loosened bank material, gouges and disruptions to the bank lines.

2.2.2. Mass Movement

There are two main types of failure by mass movement: translational failure and rotational failure (34, 35, 36, 37). Translational slope failures are shallow slides in which the failure plane is roughly parallel to the surface of the ground. Characteristics of translational slope failures include: ground surface, groundwater level, and sliding surface (Figures 2.1 and 2.2). In mathematical analyses of translational slope failures, slip surface assumed to be parallel to ground surface, and the depth to length ratio of the sliding mass is relatively small (13). Furthermore, the types of slopes most susceptible to translational slope failure are as follows:

- Weathered soil on top of inclined bedrock
- An inclined plane with a weaker material on top of a stronger material
- Glacial till on top of bedrock
- Homogenous slopes of coarse-textured, low-cohesion soil.

Cernica (1995) provides descriptions of the Factor of Safety for slopes with any combination of granular soils vs. cohesive soils and seepage vs. no seepage condition in the slope (35). These types of failures are most likely to be those mitigated by the presence of vegetation.

Rotational or circular failures are generally the more common form of failure on finite slopes. The failure surface is usually somewhat curved, similar to a circular arc, with ends which are more or less flat and a center which has a sharper arc (Figure 2.3). However, with the large variation in soil types and properties, each failure surface is unique. A failure in a homogeneous, isotropic soil will often be fairly circular in shape, but inhomogeneities in the soil profile make the failure surface different from a circular shape. In general, failure surfaces are deep in the slope where shear resistance is low and shear stress is high. Rotational failures are governed by the following forces (35):

- gravity
- effective stress
- shear stress
- pore pressure.

Das (2002) and Cernica (1995) both describe several methods to perform a stability analysis on slopes with a potential rotational failure (35, 37).

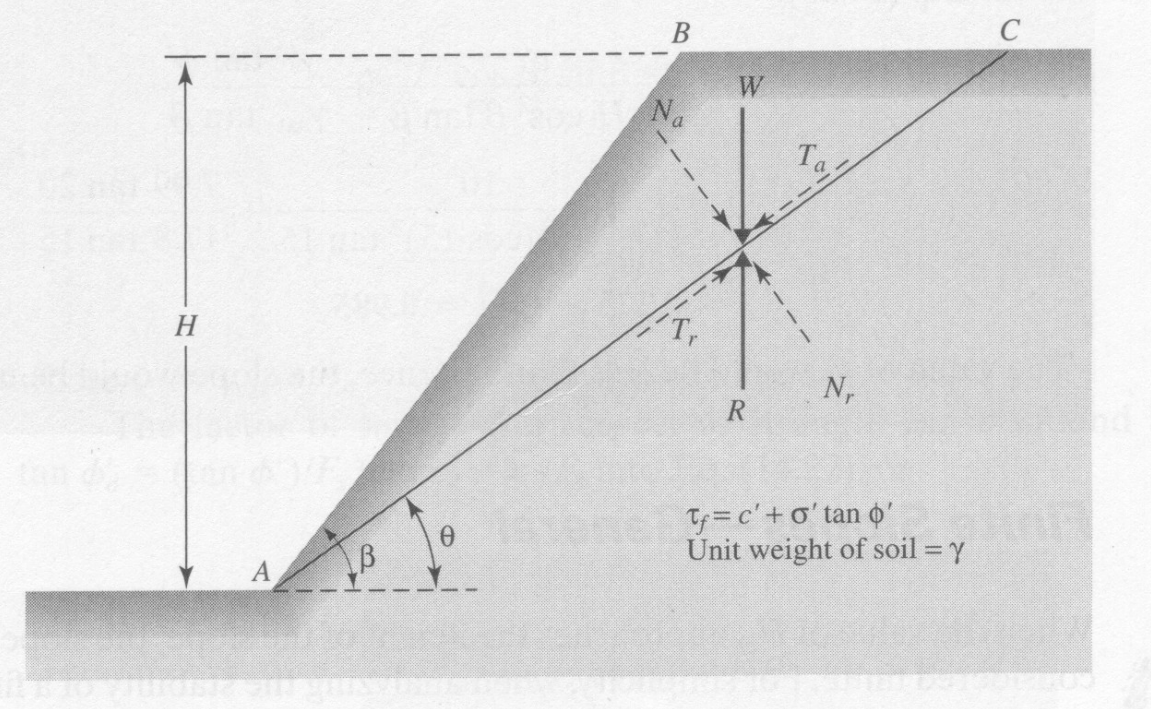


Figure 2.1 Translational failures (from Das, 2002).

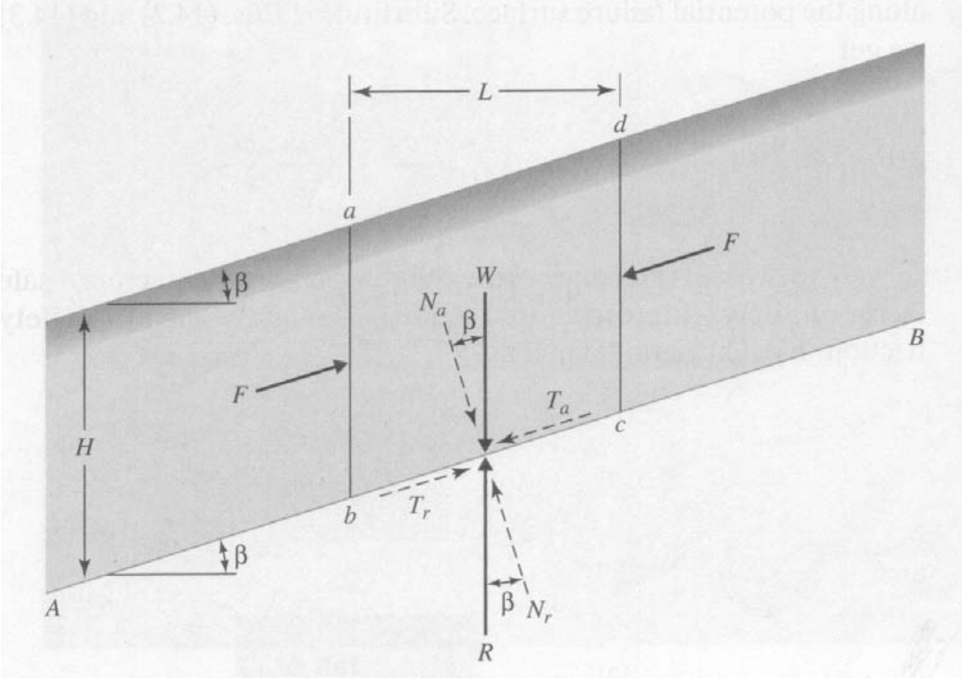


Figure 2.2 Translational failures (from Das, 2002).

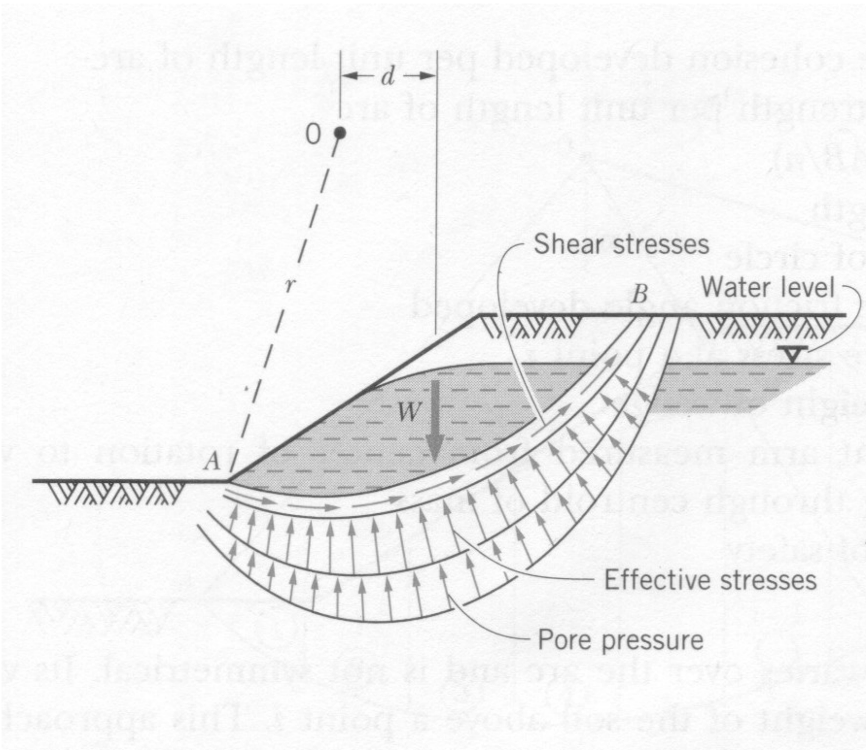


Figure 2.3 Rotational failure (from Das, 2002).

2.3. Combinations of Erosion Processes

As mentioned previously, it is more common for an erosion problem to be some combination of surficial erosion and mass movement processes. An example would be the undercutting of the toe of a bank by channel erosion followed by a slope failure due to the lack of support at the toe. Both types of erosion processes can be seen in the generalized series of six stages of channel response to straightening and modification, as described by Shields et al. (1995a) (13):

1) Initial stage – stable, low gradients, well-vegetated banks,
2) Channel straightening,
3) Channels incision by deepening at knick points,
4) Rapid channel widening as banks attain a critical height and fail,
5) Aggregation in downstream reaches,
6) Slow return to equilibrium.

The channelization that takes place in Stage 2 increases the sediment transport capacity due to the removal of large roughness elements. This can be complicated by restricted sediment supply due to urbanization or upstream impoundments. Therefore, the channel incision, or degradation, in stage 3 occurs because the sediment transporting capacity exceeds the sediment supply and grade controls are weak or absent. Initially, bed erosion and degradation is dominant over widening, but once a critical threshold is reached, the channel can widen very rapidly through a series of mass failures. The widening can occur so dramatically that there have been noted occurrences of increases in cross-sectional area of up to 1000% within a few years (38).

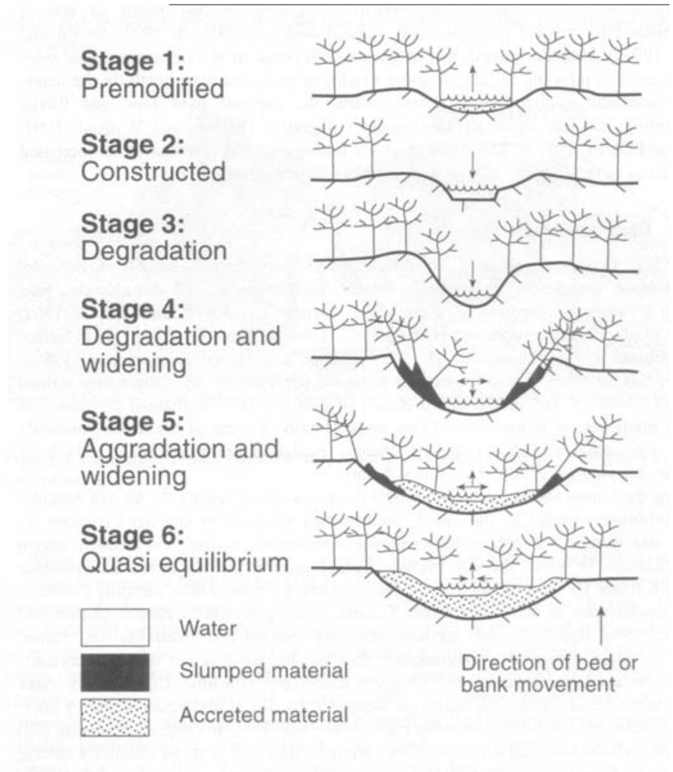


Figure 2.4 Stages of channel response to modifications (from Darby and Simon, 1999).

The study of channel incision and river geomorphology has been the subject of many books. The summary of the processes described above is only the tip of the iceberg and they are critically important to understand before attempting any streambank stabilization project. Leopold (1964, 1994) authored two of the pioneering books on fluvial geomorphology (31, 39). He detailed the numerous processes that are involved in fluvial geomorphology, including forces and velocity distribution in channels, bed load and sediment transport, channel forms and processes. Schumm et al. (1984) also discussed the forces and processes involved in channel evolution, but concentrated on incised channels (32). They developed the Channel Evolution Model to predict incision, degradation and aggradation in streams. A book edited by Darby and Simon (1999) also focused on incised channels (15). Contributing authors identified the causes and controls of channel incision, sediment transport processes, channel evolution, effects of riparian vegetation, and stream restoration strategies. Rosgen (1996) authored a widely used book on the application of fluvial geomorphology for river restoration projects (14).

Chapter 3. Role of Vegetation

Vegetation on slopes and streambanks plays many roles and has many effects, both beneficial and adverse. Vegetation can act as a protective layer between the soil on the bank and the atmosphere or the water in the stream. It influences the way in which water is transferred from the atmosphere to the soil, groundwater and surface drainage systems. It has significant influences on erosion processes because it affects the flow velocity near banks during high water and the volume and peak flows of stormwater runoff. Vegetation also adds to the strength of soil by dropping the soil moisture content below the saturation point, and root systems add tensile strength to the soil (9). The increased flow resistance and reduced velocities contribute to geomorphic stability of streambanks (40, 41). Overall, one can divide the effects of vegetation on slopes and streambanks into two categories: 1) hydraulic and hydrologic effects and 2) mechanical effects.

3.1. Hydraulic and Hydrological Effects

Increased surface roughness and reduced near-bank flow velocity

The presence of vegetation on streambanks increases the roughness of the bank, which acts to decrease the flow velocities and to increase the flow depth (15, 16, 40, 41, 42, 43, 44, 45). According to Graeme and Dunkerley (1993), vegetation may increase the total bank roughness by 45% (46). In flume experiments, Fleener (1994) found that vegetation may also be responsible for a 20% reduction in flow velocity (47). Dudley et al (1998) noted that the drag coefficient, which is a function of vegetation type, is directly proportional to vegetation density (44).

Some open-channel flow publications provide general estimates for Manning’s n roughness coefficient (19), but they tend to use subjective categories, such as “scattered brush, heavy weeds” or “dense willows.” Several researchers have attempted to use more thorough approaches to adjust Manning's n to account for drag. Dudley et al. (1998) compared methods for measuring vegetation density and Fischenich and Dudley (2000) used that information to develop methods to determine drag coefficients that uses the frontal area of the plants (projection of the plant over a plane perpendicular to the flow direction) and the Reynolds number (44, 48). They also acknowledged that the practice of estimating vegetation area, density and their effects on flow is generally new and still being developed, and as more researchers use different methods, the estimates of vegetation density and drag coefficients will become more accurate. Nonetheless, Fischenich (2000) followed this study by providing methods and equations to estimate the Manning’s n roughness coefficient based on the drag coefficient and vegetation density, assuming that they are measured accurately (42). These efforts built on the work done by Petryk and Bosmajian (1975), who were able to determine relationships between unit vegetation density (ft^{-1}), flow depth (ft) and Manning’s n (49). Typical results (Figure 3.1) show that as vegetation density increases (solid line), Manning’s n increases (dotted line).

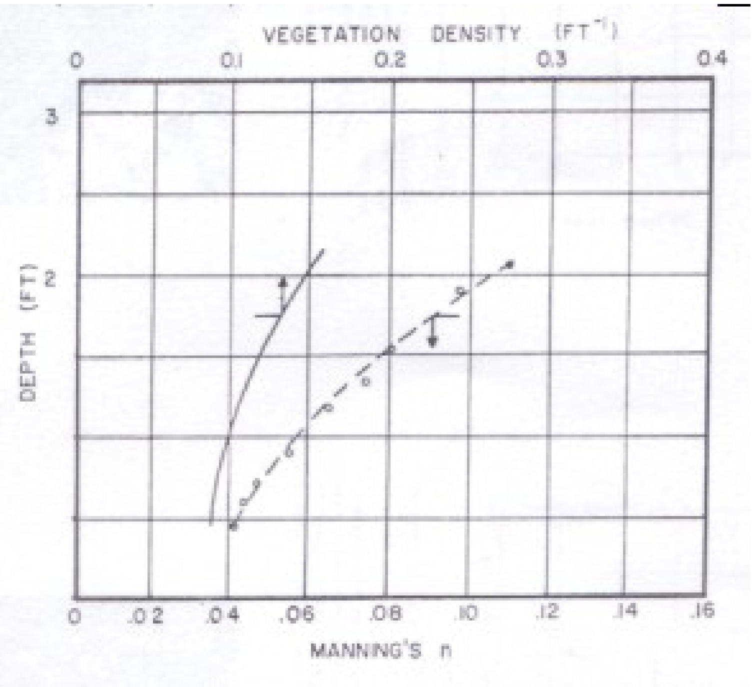


Figure 3.1 The relationships between flow depth, vegetation density (solid line), and Manning's n (dotted line) (from Petryk and Bosmajian, 1975).

Some researchers have argued that the standard use of Manning's n is too arbitrary and does not fully take roughness due to vegetation into account (50). Instead another parameter, called MEI, was first proposed by Kouwen and Unny (1973). The parameter MEI is a function of the number of roughness elements per square meter (M), the modulus of elasticity (E) and the second moment of the cross-sectional area of the stems (I). They were able to derive a relationship between MEI and Manning's n to provide a more accurate estimation of the roughness (51).

In another approach, Stone and Shen (2002) used momentum balance to determine resistance due to vegetation and the velocity within the stem layer (52).

Another factor to consider is the vegetation density, which is not constant over time, i.e. estimated effects on flow are not constant. McKenney et al. (1995) found that as vegetation ages, it becomes less dense and less effective at providing flow resistance (41). For example, they found that a 5-year old stands of sycamore and willow trees had roughness values ranged from 0.081-0.140, however stands of sycamore and willow that were 9-20 years old had roughness values ranged from 0.060-0.091. They also found that mature stands of mixed forest and shrubs of undetermined ages and consisting of several species had a roughness value of only 0.028 and 0.048, respectively.

Yet another factor to consider is the pattern of vegetation. Tall vegetation grouped in staggered patterns is much more effective in reducing flow velocities and shear stress on the bank than parallel patterns (53). Using cylinders to simulate vegetation in a flume, Li and Shen were able to develop equations to determine drag coefficients based on flow velocity, cylinder diameter, and kinematic viscosity. They also found that staggered patterns had a lower shear stress on the sediment. For example, a pattern of 64 cylinders placed in 8 parallel rows had an average boundary shear stress of 0.0235 lbs ft^{-2} while a staggered pattern with only 48 cylinders resulted in a boundary shear stress of 0.0184 lb ft^{-2}, and the shear stresses in their flumes with no cylinder present were on the order of 0.1248 lbs ft^{-2}, or about 5.3 and 6.8 times higher than flumes with simulated vegetation.

Riparian vegetation will bend as flow increases, and as it bends, total roughness decreases (43). The amount it bends depends upon the type and age of the vegetation and the flow velocity. It is a difficult task to accurately estimate the channel roughness when vegetation starts bending as flow increases (50). Figure 3.2 shows the relationship between flow depth and Manning's n for flexible vegetation. As the plants become completely submerged, they bend and the effective roughness coefficient decreases.

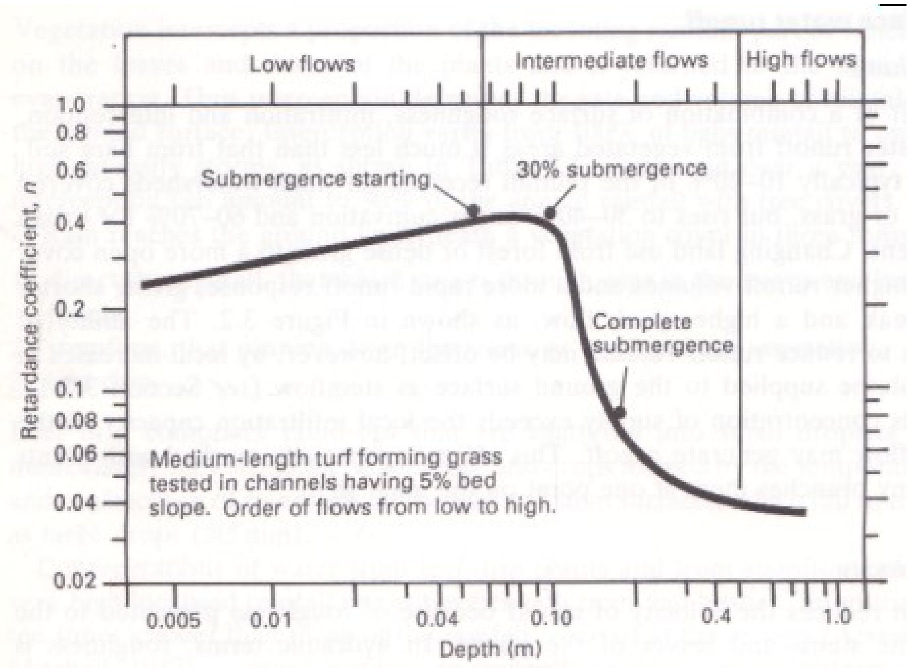


Figure 3.2 Relationships between flow depth and the retardance coefficient (Manning's n) as vegetation is submerged (from Coppin and Richards, 1990).

The net effect of an increase in vegetal presence on a streambank is that near-bank velocities and shear stresses on the bank will decrease. The decrease in shear stresses, in turn, reduces the amount of channel erosion on the toe and bank (54). Thornton et al. (2000) found that by doubling the unit vegetation density from 0.082 ft^{-1} to 0.160 ft^{-1}, the shear stress on the bed was reduced from 2.17×10^{-2} lbs ft^{-2} to 0.948×10^{-2} lbs ft^{-2}. Figure 3.3 shows the effects of vegetation on velocity distribution in channels. Each velocity profile goes with the vegetation to its left.

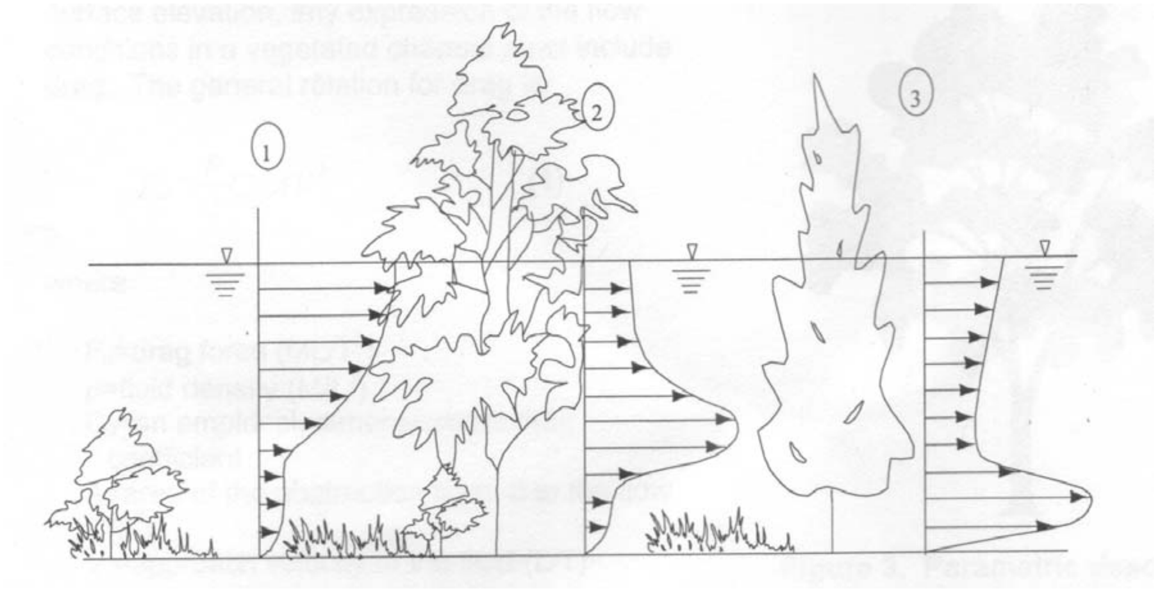


Figure 3.3 Effect of vegetation on velocity profiles (from Fischenich, 2000).

When considering stormwater runoff on the slope, the presence of vegetation on a slope and reduction of runoff velocities reduces sheet erosion, which reduces or eliminates rill erosion and gully erosion (4, 16). The presence of vegetation can reduce soil detachment rates by stormwater runoff by as much as 64%, compared to fallow soils (55).

Since vegetation reduces near-bank velocities, it will cause a loss of conveyance through the entire channel system (4, 15, 24, 44). Masterman and Thorne (1992), Darby and Thorne (1996), and Darby (1999) tested this concern by modeling the effect of vegetation on stage-discharge curves. The model developed by Masterman and Thorne (1992) is a theoretical model and does not consider non-flexible vegetation taller than water depth (56). However, the results indicate that vegetation will have an insignificant (less than 5%) effect on discharge capacity if the channel width-depth ratio is more than 9. However, for channels with a width-depth ratio of less than 9, the vegetation impacts the loss of discharge capacity at an exponential rate with respect to the width-depth ratio. The model developed by Darby (1999) expands on the work done by Darby and Thorne (1996). The model is called HMODEL2 and is to predict stage-discharge curves for channels with non-uniform cross sections, sand and gravel-bed materials, and flexible or non-flexible vegetation. The simulation results of HMODEL2 show that the presence of vegetation will not significantly impact flood risk. The previous work done by Darby and Thorne was only applicable to gravel-bed streams (57).

Interception by rainfall

One of the immediate benefits of vegetation on a slope is the role it plays in intercepting rainfall before it hits the ground (3, 18, 58). This significantly reduces velocities of the raindrops and can reduce the amount of soil erosion by over 95% when compared to bare soil (9), while Gray and Sotir (1996) noted a 99% reduction (3). Not only does the vegetation reduce the raindrop impact erosion, but vegetation has been noted to store a significant amount of rainfall. Morgan and Rickson (1995) describe formulas to estimate interception storage and the effect of vegetation on the reduction of raindrop impact erosion (18). Simon and Collison (2002) noted that rainfall interception by vegetation is one of the factors most commonly overlooked when discussing the effect of vegetation on bank stability (59). They said that most bank failures occur during the winter or early spring, when deciduous vegetation is dormant and canopies are relatively bare. Simon and Collison (2002) also found that intensive rainfall events that are most likely to result in bank failures are those that have the lowest canopy interception rates.

Increased infiltration

Sheet, rill or gully erosion occur when there is excess rainfall, which is a function of the infiltration capacity and moisture content of the soil. During a storm event, the vegetation cover not only postpones the onset of runoff due to interception and canopy storage, but it also increases the infiltration rate due to the presence of organic matter, root growth, decaying roots, and earthworms. Vegetation litter may decrease the infiltration rate, but the net effect often results in a greater infiltration rate and reduced runoff (3, 18). Figure 3.4 shows a comparison between infiltration rates of soil with and without vegetation.

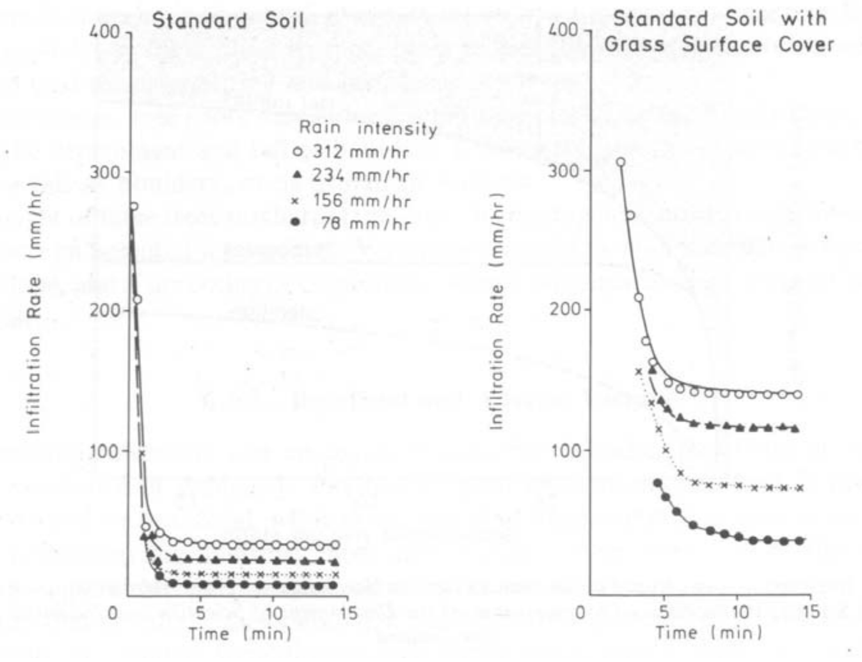


Figure 3.4 Comparison of infiltration rates in vegetated and non-vegetated slopes (from Greenway, 1987).

However, one slight downfall of the increased infiltration is the fact that increased soil moisture content can lead to slope instability (59, 60), which will be discussed in Section 3.5.

Reduction in soil moisture content through evapotranspiration

Instability of slopes occurs when there is a loss of matric suction and positive pore pressures (59, 60). Evapotranspiration by vegetation present on the banks helps reduce soil moisture content. Vegetation lowers the pore-water pressure, which increases soil suction and effectively increases the soil strength (3, 9, 40, 61). Furthermore, the effects of evapotranspiration can contribute to greater infiltration rates as the soil tries to replenish its water content. The increase in matric suction increases the Factor of Safety, which, depending on the species, can contribute to a 10-20% increase (61). Wilkinson et al. (1998) also developed a water uptake model in an attempt to predict the loss of soil moisture due to evapotranspiration. It is based on transpiration rates and leaf area index of individual plants.

In arid regions, there is a concern that evapotranspiration will reduce the soil moisture levels too much so that the plants will not be able to survive. If the plants do not survive, then the vegetation will not be strong enough to prevent slope failure during intensive storm events (24).

Effects on water quality and habitat

Riparian vegetation on the banks and in the flood plains will have a positive impact on water quality by taking up nutrients that may lead to eutrophication and also toxic elements associated with stormwater runoff (4, 16). The riparian vegetation also keeps the stream shaded from solar radiation, therefore, water temperatures remain closer to the suitable temperatures for native fish habitat (16). The net effect is better fish habitat, and certain techniques themselves, such as root wads, have the dual role of providing suitable fish habitat as they dissipate flow energy and protect the toe of the banks. Riparian vegetation is also natural habitat for other riparian species, such as birds, and will create more natural fish habitat as it sheds foliage or dies and falls into the stream (2, 3, 62).

3.2. Mechanical Effects

Soil reinforcement by roots

Numerous researchers acknowledge that soil-root interactions work to strengthen and reinforce an embankment (1, 3, 9, 18, 19, 23, 41, 63, 64, 65, 66). Wu et al. (1979) laid the foundation for the current understanding of soil-root reinforcement when they measured the effect of tree roots on slope stability in Alaska. They determined that soil is reinforced by roots as the shear stress in the soil is transferred to the tensile resistance in the roots. When shear stress is exerted upon the root, the root fiber is deformed and elongated as illustrated in Figure 3.5 (63). In order to come to these conclusions, Wu et al. (1979) measured *in situ* tensile strengths of Sitka spruce trees. They were able to develop a relationship between the tensile strength of the roots, the root-area ratio (the area of the roots per area of soil), and the increase in shear strength of the soil. This relationship was added to the Mohr-Coulomb equation for soil shear strength to provide a means to estimate the total shear strength of a slope. They also compared results from a slope with live trees to a slope that had been recently clear-cut and found a marked decrease in shear strength of the roots. This can be seen in Figure 3.6 where the tensile strength within the dotted line labeled B are from the clear-cut slope and the line marked A is from the uncut slope with live root systems. Figure 3.6 also shows that an increase in root diameter contributes to a greater tensile strength.

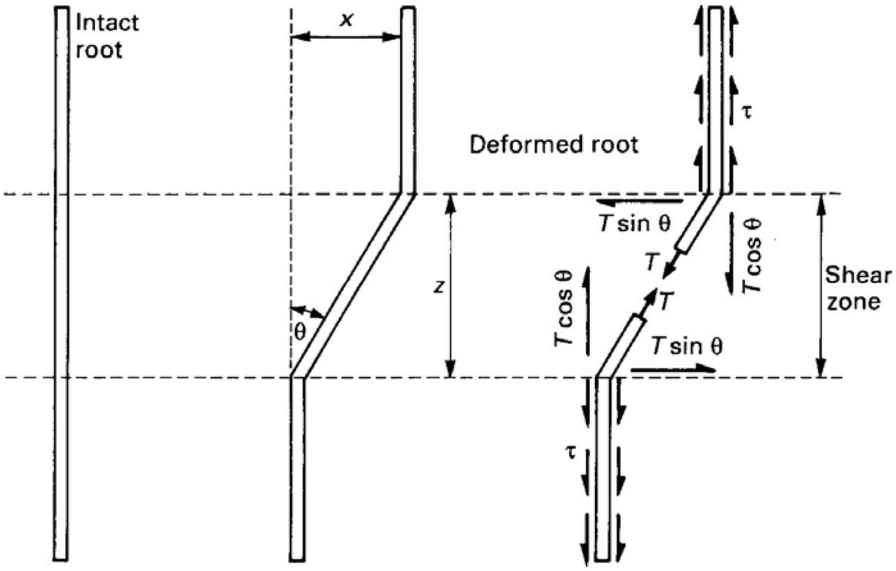


Figure 3.5 Perpendicular root fiber reinforcement model (from Wu et al., 1979).

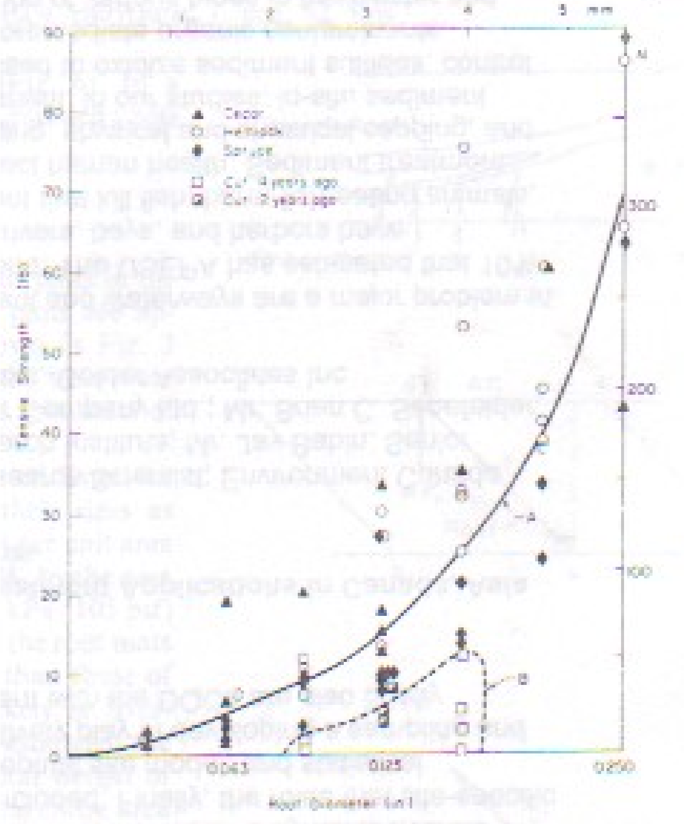


Figure 3.6 The relationship between root diameter and failure load (from Wu et al., 1979).

Following work by Wu et al. (1979), there have been many attempts to quantify the effect of roots on the shear strength increase in soil (64, 65, 66, 67, 68, 69). Most of them have also used the Mohr-Coulomb equation for soil shear strength and have attempted to add a factor to account for the reinforcement performed by the roots (Figure 3.7), similar to Wu et al (1979). Simon and Collison (2002) found that different species and types of vegetation had different influences on the added shear strength of the soil (59). Depending on the species, trees can increase soil strength by 21-366 lbs ft^{-2} and grass roots can add 125-377 lbs ft^{-2} (9, 59, 63) while Tengbeh (1993) found that roots increase soil strength by more than 50% (69). Other results have shown that the overall reinforcement is a function of root strength, friction between the root and the soil, root distribution in the soil, root density, tensile strength, tensile modulus of elasticity, length/diameter ratio, surface roughness, alignment with respect to the failure surface and orientation to the direction of the stresses (9, 18, 66). Some publications, such as Scheichtl (1980) provide information about the root tensile strengths of many species, but information about the root density, or root unit area (the area of roots per area of soil for a given profile), for those species is not necessarily available (5). Figure 3.8 shows that it is possible for a stand of vegetation to penetrate failure planes for either translational or rotational failures, however it is much more common for vegetation to protect against translational failures because the failure planes are usually much more shallow in the soil profile.

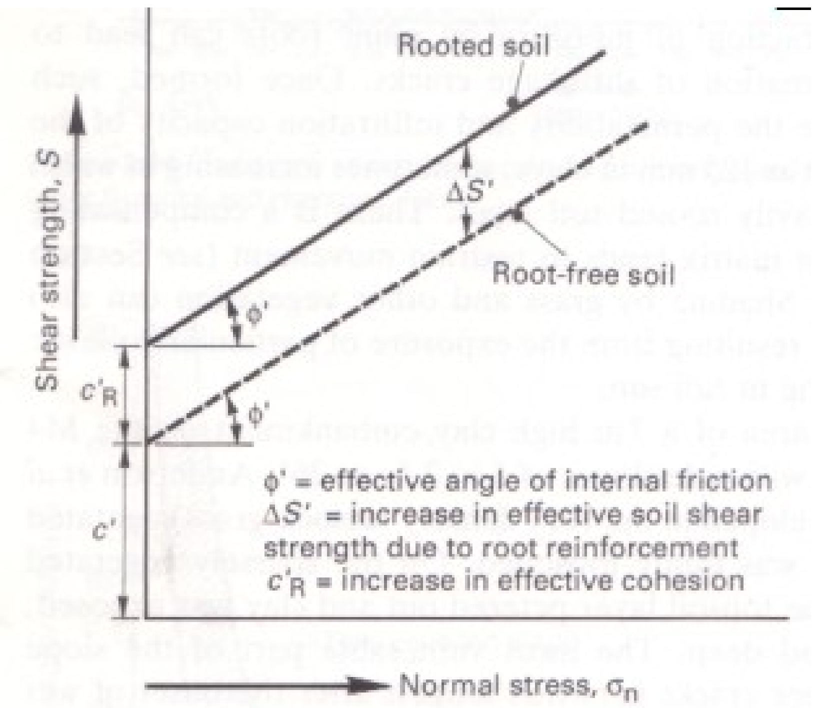


Figure 3.7 **Increase in shear strength due to the presence of roots (from Coppin and Richards, 1990).**

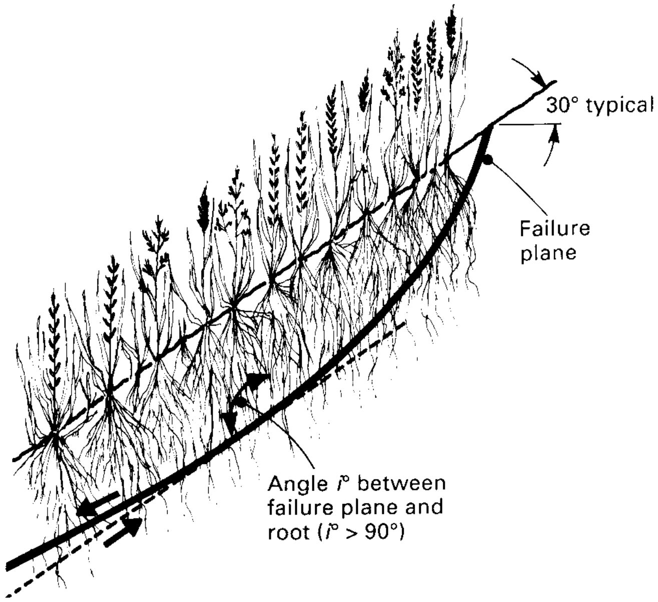


Figure 3.8 Root penetrating a failure plane (from Coppin and Richards, 1990).

Despite all of these efforts, it is still unclear how to quantify, with any confidence, the degree to which a stand of vegetation will increase the shear strength of an entire slope. These studies have concentrated on a small scale reinforcement and have not focused on a large scale, e.g. an entire slope. Even though many models have been published for more than 20 years, there is no evidence in the literature that they have actually been used by practitioners who would have interests in knowing the increase in soil strength due to the presence of vegetation. One reason is that shear properties of tree roots are found to be partly influenced by the size of the testing equipment, level of soil compaction, deformation of the root material and estimated width of the shear zone in the soil. Tensile root properties have been found to be affected by factors such as season, age, root types or species, root preparation before experiment, clamping procedure of the root, and rate of elongation used (70). Therefore, it seems that there would be a lack of confidence in the published values found for tensile strength for various species due to the limitations of the experiment. Another uncertainty inherent to these models is that root tensile strengths can vary widely both between and within species (59), so even if an average tensile strength is widely accepted for a particular species, it would theoretically be possible to have a weak plant with significantly weaker roots than are being counted on to reinforce the slope. Lastly, Gray and Sotir (1996) and Simon and Collison (2002), contrary to results shown in Figure 3.6, showed that root tensile strength decreases with diameter, so the effective reinforcement of a root in any given section of soil will actually decrease over time unless it is proven that one can assume a constant root distribution with an average root diameter, and such research has not been found in the literature (3, 59). Therefore, it has been difficult for practitioners to count on an average tensile strength if there is a significant variability.

Arching and Buttressing

Coppin and Richards (1990), Morgan and Rickson (1995), Gray and Sotir (1996), and Darby (1999) all describe the phenomenon of soil buttressing and arching caused by the presence of a large root mass, usually associated with trees. It occurs when tap and sinker roots of many tree species extend into the underlying bedrock, thereby anchoring them to the slope and also preventing the slope from moving downward. When two trees are close enough and both are anchored into the slope, arching between the buttressed zones can occur. (Figure 3.9)

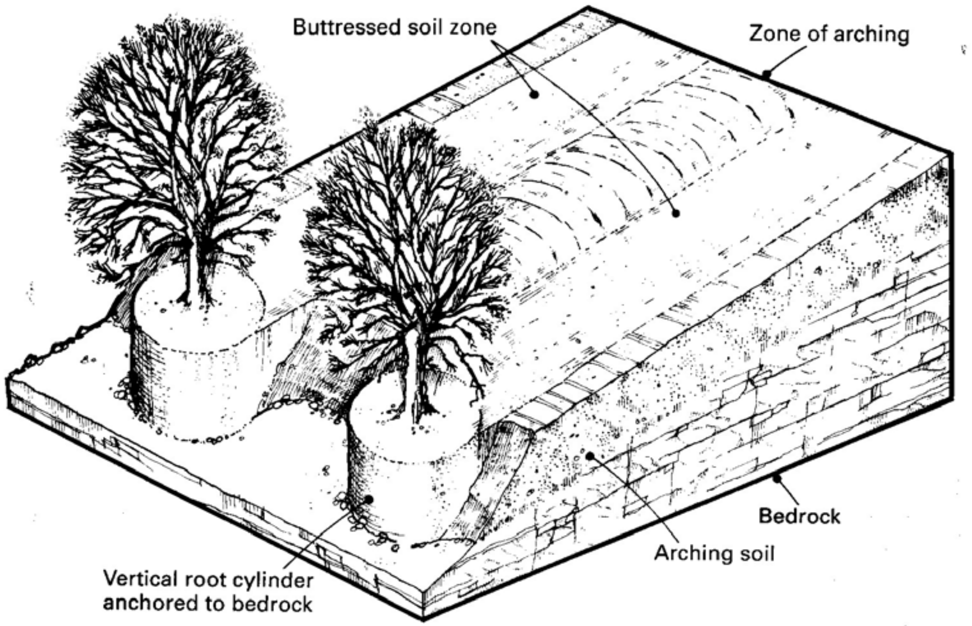


Figure 3.9 Anchoring, arching and buttressing on a slope (from Coppin and Richards, 1990).

None of the publications consulted provided quantification of the effect of arching and buttressing, but Wang and Yen (1974) provided an equation for the maximum allowable distance between trees for the existence of arching (71).

Surcharge

The added weight of vegetation can potentially be a stabilizing force on an embankment as it increases the normal stress on the bank (72). Usually, the effect of surcharge on the stability of a slope, either beneficial or adverse, is only felt for large vegetation, such as trees, and is not generally felt with the presence of grasses or shrubs (1). When weighty vegetation is present, however, the size and location is the primary factor, as can be seen in Figure 3.10.

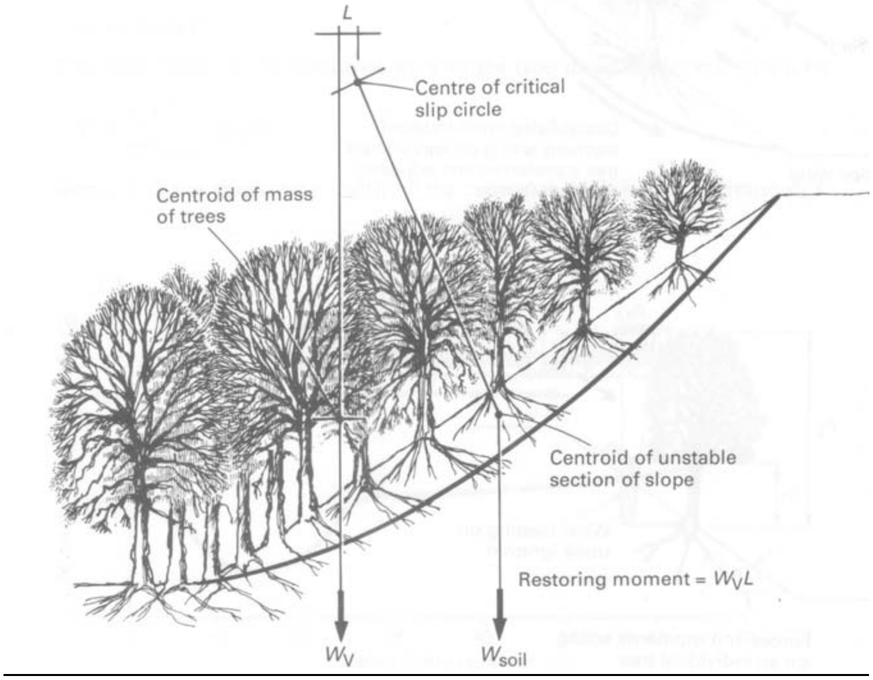


Figure 3.10 Effect of surcharge on the center of gravity on a slope (from Coppin and Richards, 1990).

It is possible that the weight of the vegetation will cause local instabilities (15, 72). In Figure 3.10, the weight of the vegetation acts to lower the center of gravity and increase the stability of the slope. However, if the distribution of trees was reversed and the larger trees were at the top, then it could lead to a rising of the center of gravity and contribute to the instability of the slope. Different studies have shown an increase of surcharge of between 10.4-108 lb ft^{-2}, depending on the species (1, 63, 72). The effect of surcharge is dependent on species, diameter, height, and spacing (1).

Windthrow

Windthrow is the toppling of trees due to strong winds. When considering the effects of windthrow on streambank stabilization, grasses and shrubs are generally not affected by windthrow (15, 19). If large, woody vegetation is blown over, such an event would cause a relatively large, localized area of vulnerability. Abernethy and Rutherfurd (1998) found that in upper reaches, wind thrown trees can be responsible for the transfer of bank sediment to the flow (73).

3.3. Implications of Hydrological and Mechanical Effects

Increased safety factor because of better performance

The hydrological and mechanical effects of vegetation on slopes are usually net increases in the factor of safety (FOS) for the given slope. One of the pioneering studies in this application was done by Wu et al. (1979), who examined the strength of tree roots and its effect on landslides in

Alaska. They developed a formula to estimate the FOS for an infinite slope, in which the reinforcement attributed to the roots is added to the resisting forces (63). In order to do so, they used the relationship they developed between root tensile strength, root area ratio, and increased shear strength. Even though the measurements of tensile strength and root area ratio were done on a "microscale", the average results extrapolated to the entire area under consideration in order to estimate the increase in shear strength. They even accounted for the effects of the wind on the driving forces and the possibility that it could cause instability. However, they concluded that even with winds of 55 mph, there would be a minimal impact on stability. Based on soil moisture content readings in each slope, computed FOS of less than one generally correlated to recent observation of slope failures.

More recently, Simon and Collison (2002) tried to quantify the increase in FOS for a streambank attributable to vegetation. They collected a large data set for their site that included such parameters as soil properties (cohesion, thickness of soil layers, friction angles), measured root tensile strengths, root area ratios, root diameters, and age of individual trees for species present. They also had tensiometers throughout the site to have accurate measurements of soil moisture at different depths (59). Then they used that data and published relationships, such as an equation given by Wu et al. (1979) for the calculation of the distribution of root reinforcement and the FOS formula by Simon et al. (1999, 2000), to predict slope stability and failures (74, 75). Their results were very site specific, however the formula they used for determining FOS, when compared to available data from 2000 and observed bank failures, successfully predicted two bank failures (FOS < 1) on a bare streambank (no vegetation) and one bank failure on a streambank with grasses as the vegetation present. Also worth of note is the fact that the FOS equation used proved no false predictions of bank failure. When they broke down the results into mechanical and hydrological effects, they found differing effects of reinforcement, depending on the species and the type of vegetation used. For the spring of 2000, they found the mechanical effects of tree cover increased the FOS by 32% and the hydrologic effects increased the FOS by 71%. For grasses, FOS increased by 70% and decreased by10%, respectively. They found different values for the following spring due to a wetter than normal condition. They concluded that during the periods when the hydrologic effects of tree cover actually reduced the bank stability, it was offset by the mechanical effects.

Abernathy and Rutherfurd (2000a) used a model called GWEDGEM that was first described by Donald and Zhao (1995) (76). This model is supposed to be able to determine FOS for rotational failures, with use of a wedge method, and was cited by Pitsch (1997) as provided equal to better results than other recognized accurate methods. A copy of the original publication by Donald and Zhao (1995) was unable to be obtained, but according to Abernethy and Rutherfurd (2000a), the GWEDGEM model "fully satisfies force and moment equilibrium while maintaining a kinematically admissible failure mechanism." It divides a slope into wedges, and the boundary between the wedges is not necessarily vertical (65). The user of the program may specify homogeneous or non-homogeneous bank materials, partial submergence, external loading, tension cracking, root reinforcement and pore-water pressures. Bank stability analysis found that root reinforcement resulted in an increase of the factor of safety from 1.75 to 2.13 and comparison to field conditions showed valid predictions. The GWEDGEM model is still under development and future additions will include other effects of vegetation, such as surcharge and evapotranspiration.

Other efforts to quantify the increase in FOS due to plants have primarily focused on hillslopes instead of streambanks as was done by Simon and Collison (2002) and Abernethy and Rutherfurd (2000a). For example, Wilkenson et al. (2000, 2002) describe the results of their Combined Hydrology and Stability Model (CHASM) simulation. This model incorporates the Water Uptake Model developed by Wilkenson et al. (1998) to simulate the effects of evapotranspiration on bank stability (61). They used historical data sets to calibrate and verify the model and were able to successfully predict slope failure, which corresponded to the conditions when FOS < 1. Another effort was done by Morgan and Rickson (1995), who provided another equation for incorporating vegetation into the FOS calculations on a slope using an infinite slope method which is described in Cernica (1995) and Das (2002). The FOS for a slope without vegetation was found to be 1.91, while the FOS on the same slope with vegetation, was found to be 2.96, which is a 55% increase (18). Unfortunately, the example provided by Morgan and Rickson (1995) does not provide information on how the input data were collected, how the equation was derived, or references to obtain that information. Biedenharn et al. (1997) and Franti (1997) also mentioned an increased safety factor and better performance when vegetation was combined with structural techniques, even though Biedenharn et al. (1997) acknowledged that it had been very difficult to quantify (24).

3.4. Other Effects

Low cost and lower long-term maintenance costs

In general the materials needed for soft armoring techniques are much cheaper than those used for hard armoring techniques (2, 3, 24). Coppin and Richards (1990) stated that the life-cycle of the project should also be considered. It is possible that a soft armoring technique will require a larger initial investment for construction until it will be firmly established (9). However, that investment will pay off with fewer repairs and lower long-term maintenance costs later (62). They illustrated this point in Figure 3.11.

It can also be noted that soft armoring techniques are self-repairing to a certain extent. If, for some reason, a small patch of vegetation is uprooted or killed, surrounding vegetation will quickly invade the area, effectively repairing itself (3). Lastly, vegetated slopes have a certain flexibility that hard armored slopes do not because they have a greater ability to expand and contract. Therefore, freeze-thaw cycles do not damage vegetated slopes nearly as much as hard-armored slopes (Stenlund, personal communication).

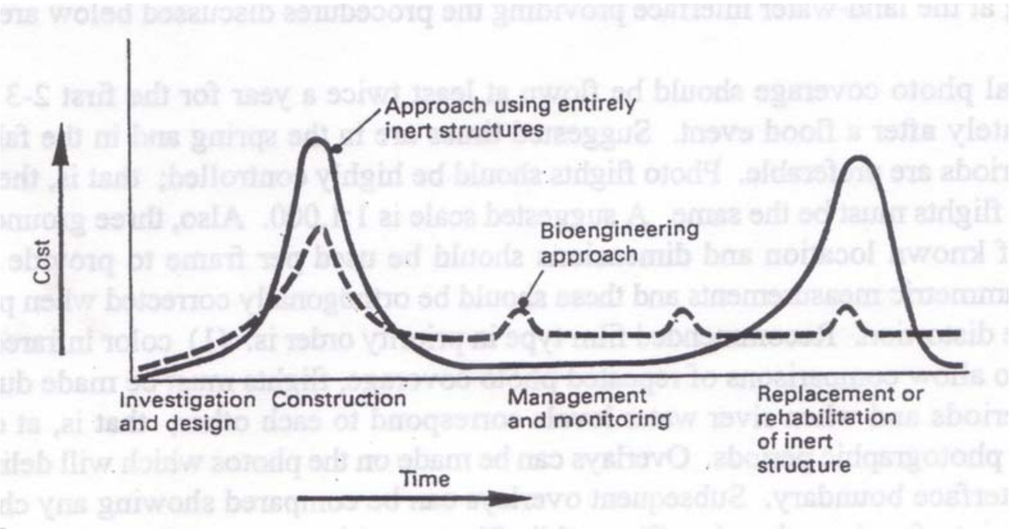


Figure 3.11 Comparison of cost profiles and maintenance of hard armoring and soft armoring techniques (from Coppin and Richards, 1990).

Environmentally attractive

Virtually all researchers and practitioners acknowledge that the use of vegetation in stabilization projects is more aesthetically pleasing than hard armoring methods and vegetative methods blend in with the natural landscape much better (2, 3, 4, 8, 9, 16, 24, 62, 77).

Good for sites where machinery has difficult/limited access

Due to the hands-on nature of installation of many soft armoring techniques, they can be appropriate for sites that have poor or limited access for heavy machinery (2, 3).

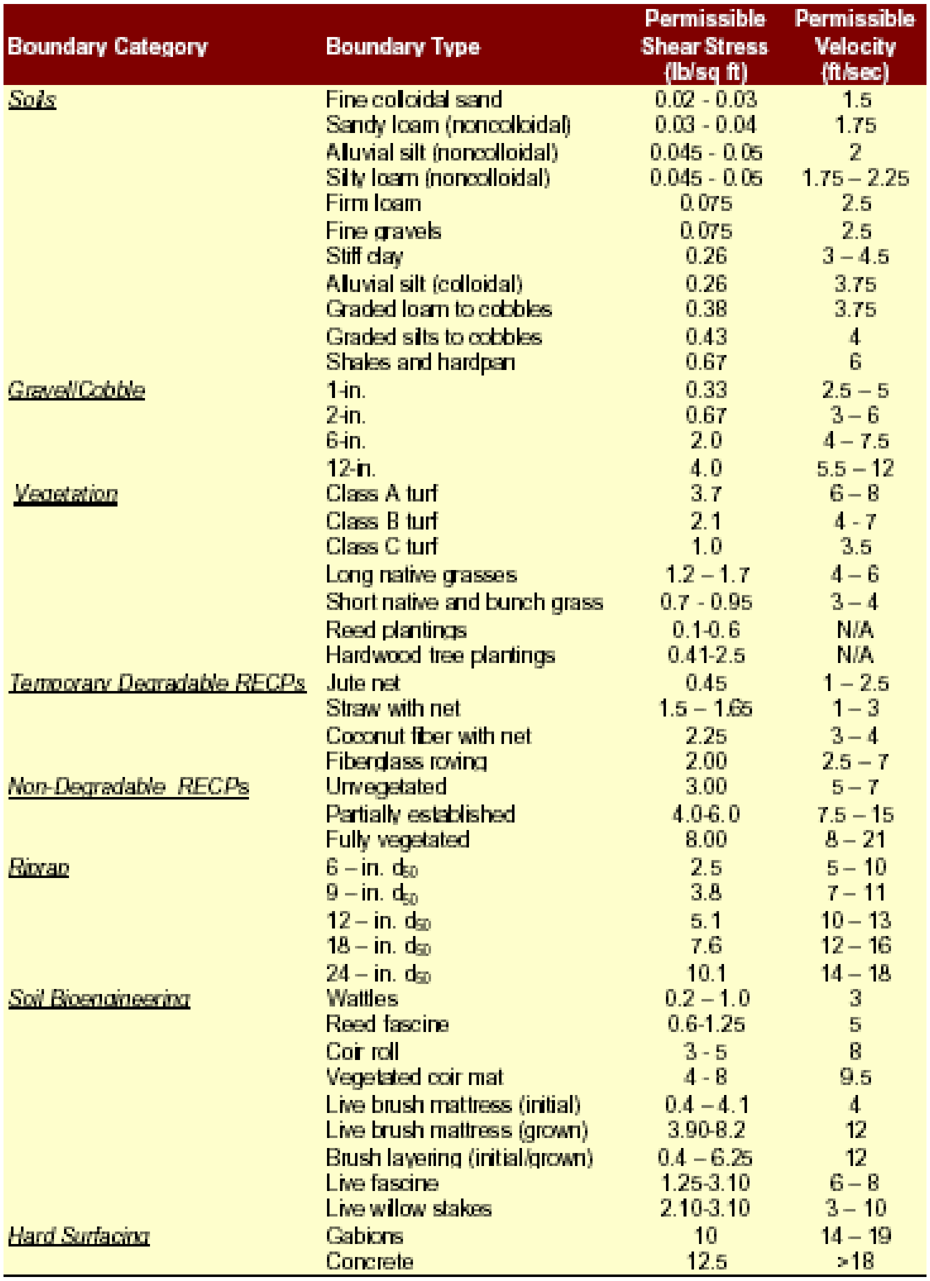
3.5. Limitations of Using Vegetation

Lack of quantitative guidance

There is a significant lack of quantitative guidance available when designing soft armoring projects (9, 12, 24). There are two sources (4, 17) that have been found to provide some guidance for the thresholds which soft armoring techniques are able to withstand. For example, Table 3.1 displays the threshold vales published by Fischenich (2001a).

Li and Eddleman (2002) provided similar threshold values for a variety of techniques, however, references in these sources citing field tests are somewhat lacking, and few researchers have cited them as useful tools in the design process. Also, as previously discussed, there are few researchers who have developed methods to estimate the FOS for projects using vegetation. However, despite optimistic results, these methods are still relatively untested (4).

Table 3.1 Stability thresholds for various streambank stabilization techniques (from Fischenich, 2001).



Boundary Category	Boundary Type	Permissible Shear Stress (lb/sq ft)	Permissible Velocity (ft/sec)
Soils	Fine colloidal sand	0.02 - 0.03	1.5
	Sandy loam (noncolloidal)	0.03 - 0.04	1.75
	Aluvial silt (noncolloidal)	0.045 - 0.05	2
	Silty loam (noncolloidal)	0.045 - 0.05	1.75 – 2.25
	Firm loam	0.075	2.5
	Fine gravels	0.075	2.5
	Stiff clay	0.26	3 – 4.5
	Aluvial silt (colloidal)	0.26	3.75
	Graded loam to cobbles	0.38	3.75
	Graded silts to cobbles	0.43	4
	Shales and hardpan	0.67	6
Gravel/Cobble	1-in.	0.33	2.5 – 5
	2-in.	0.67	3 – 6
	6-in.	2.0	4 – 7.5
	12-in.	4.0	5.5 – 12
Vegetation	Class A turf	3.7	6 – 8
	Class B turf	2.1	4 - 7
	Class C turf	1.0	3.5
	Long native grasses	1.2 – 1.7	4 – 6
	Short native and bunch grass	0.7 - 0.95	3 – 4
	Reed plantings	0.1-0.6	N/A
	Hardwood tree plantings	0.41-2.5	N/A
Temporary Degradable RECPs	Jute net	0.45	1 – 2.5
	Straw with net	1.5 – 1.65	1 – 3
	Coconut fiber with net	2.25	3 – 4
	Fiberglass roving	2.00	2.5 – 7
Non-Degradable RECPs	Unvegetated	3.00	5 – 7
	Partially established	4.0-6.0	7.5 – 15
	Fully vegetated	8.00	8 – 21
Riprap	6 – in. d_{50}	2.5	5 – 10
	9 – in. d_{50}	3.8	7 – 11
	12 – in. d_{50}	5.1	10 – 13
	18 – in. d_{50}	7.6	12 – 16
	24 – in. d_{50}	10.1	14 – 18
Soil Bioengineering	Wattles	0.2 – 1.0	3
	Reed fascine	0.6-1.25	5
	Coir roll	3 - 5	8
	Vegetated coir mat	4 - 8	9.5
	Live brush mattress (initial)	0.4 – 4.1	4
	Live brush mattress (grown)	3.90-8.2	12
	Brush layering (initial/grown)	0.4 – 6.25	12
	Live fascine	1.25-3.10	6 – 8
	Live willow stakes	2.10-3.10	3 – 10
Hard Surfacing	Gabions	10	14 – 19
	Concrete	12.5	>18

Not only is there a lack of quantitative guidance for the general techniques, but also there is a similar lack in guidance for understanding some of the critical processes that are at play with these techniques. For example, the difficulties in determining root tensile strength and quantifying root reinforcement of soil as it was discussed earlier. Another example is that hydraulic roughness and erosion resistance have proven to be notoriously difficult to quantify in relation to all types of materials. Most methods to estimate these parameters use empirical calibration and approximations (45). Without better quantitative guidance, the practice of soft armoring will necessarily remain more of an art than a science.

A low degree of confidence in planning and installation

The main deficiency preventing further use and development of soft armoring technique is the fact that they cannot be designed with the same degree of confidence as traditional hard armoring techniques (24). With hard armoring techniques, there are well-established procedures and equations that result in a high degree of confidence in the design. However, there are no such procedures or methods available for soft armoring techniques to provide a high degree of confidence in the strength and reliability of the final design. When soft armoring techniques are used, they tend to be over-designed to account for the lack of confidence in the design. This causes soft armoring techniques to cost more than is necessary. Therefore, more traditional hard armoring techniques are more still widely accepted by the society and contractors (2).

Vulnerability of vegetation during maturation.

Another problem is the vulnerability of vegetation-based solutions during the period in which they are reaching maturity and full strength (12). Vegetation is effective only after a certain period of time, and it is difficult for projects to be designed to provide overall slope stability with the sole use of herbaceous plants (58). Therefore, it is necessary for practitioners to design projects such that they are able to withstand design flows without the added reinforcement benefits associated with vegetation in the event that such a storm occurs during, e.g. the first five years needed for vegetation to reach maturity. Furthermore, there are other uncontrollable factors that have significant influences on the time it takes for vegetation to reach maturity. Exceptionally wet or dry years can cause a reduction in growth and a delay in the time it would take for a young stand of plants to reach maturity. Similarly, extreme events could cause significant mortality of the plants in a young project, resulting in the need to re-plant vegetation.

Limited installation season

Many of the soft armoring techniques require the use of dormant posts that are harvested on site. However, the harvesting and planting of dormant cuttings must be done in approximately a two-month window in the fall after plants have gone dormant, but before winter sets in, or in a similar window in the spring between the harshest part of winter and before the plants come out of dormancy (2, 3, 12, 24)). These limitations make it very difficult for projects to be installed at many sites because there is not enough time to install a great number of projects within those short windows. Furthermore, delays in site preparation could result in missing the best window for planting dormant posts (Stenlund, personal communication).

Deterioration due to mismanagement

Soft armoring techniques require a certain amount of long-term maintenance. These maintenance needs are greater in the short term as the project manager is trying to get the vegetation established, but was displayed in Figure 3.11, maintenance never completely stops and more maintenance is required on a yearly basis than is for hard armoring techniques. If the project is not maintained properly, then there may be detrimental consequences, such as: undesirable species will take over the site; vegetation will not be well established and the erosion will continue unabated; large trees will grow and shade out the vegetation protecting the bank; or minor necessary repairs will go unnoticed (24).

Need for intensive labor and special training

As mentioned previously, soft armoring techniques may require a lot of hands-on labor. This work can be quite intense and could require special training for the contractors who are to install the technique (2, 3).

Limited availability of locally adapted plants

Sometimes there is a limited availability of locally adapted plants that can be effectively used (2). NRCS has regional plant materials centers, such as the USDA NRCS Rose Lake Plant Materials Center in East Lansing, MI, that specialize in finding locally adapted plants that will work in soft armoring techniques (78).

3.6. Summary

A summary of the hydrologic effects of vegetation include the following:

1. Interception of rainfall, minimizing raindrop impact erosion, and reducing total runoff due to interception storage.

2. Increasing surface roughness and slowing both stormwater runoff and near-bank flows on streambanks which reduce shear stresses on the banks and minimize sheet, rill, and gully erosion during runoff events, and channel erosion during flood events.

3. Increasing infiltration which retards the onset of runoff and reduces sheet, rill, and gully erosion.

4. Increasing evapotranspiration which increases the soil moisture deficit for further infiltration.

A summary of the mechanical effects of vegetation on slopes is as follows:

1. Reinforcement of the soil, thus increasing its shear strength

2. Anchoring into deeper firm strata by the root system which provides support for the upper slope via buttressing and arching.

3. By surcharging the slope, the weight of the vegetation increases the normal stress on the slope.

4. Binding soil particles by the root system, which reduces susceptibility of erosion.

Figure 3.12 provides an illustrated summary of the effects of vegetation on slopes.

In summary, the following is a list of the advantages and disadvantages of using vegetation for streambank stabilization:

Advantages of using vegetation:

1. Slows surface runoff.
2. Reduces near-bank flow velocity.
3. Increases strength of bank materials via buttressing, arching, and root reinforcement.
4. Increases safety factor because of soil reinforcement.
5. Intercepts a percentage of rainfall
6. Increases infiltration
7. Reduces soil moisture content through evapotranspiration
8. Improves water quality
9. It is environmentally attractive
10. Can improve terrestrial and aquatic habitats
11. It is good for sites where machinery has difficult/limited access.

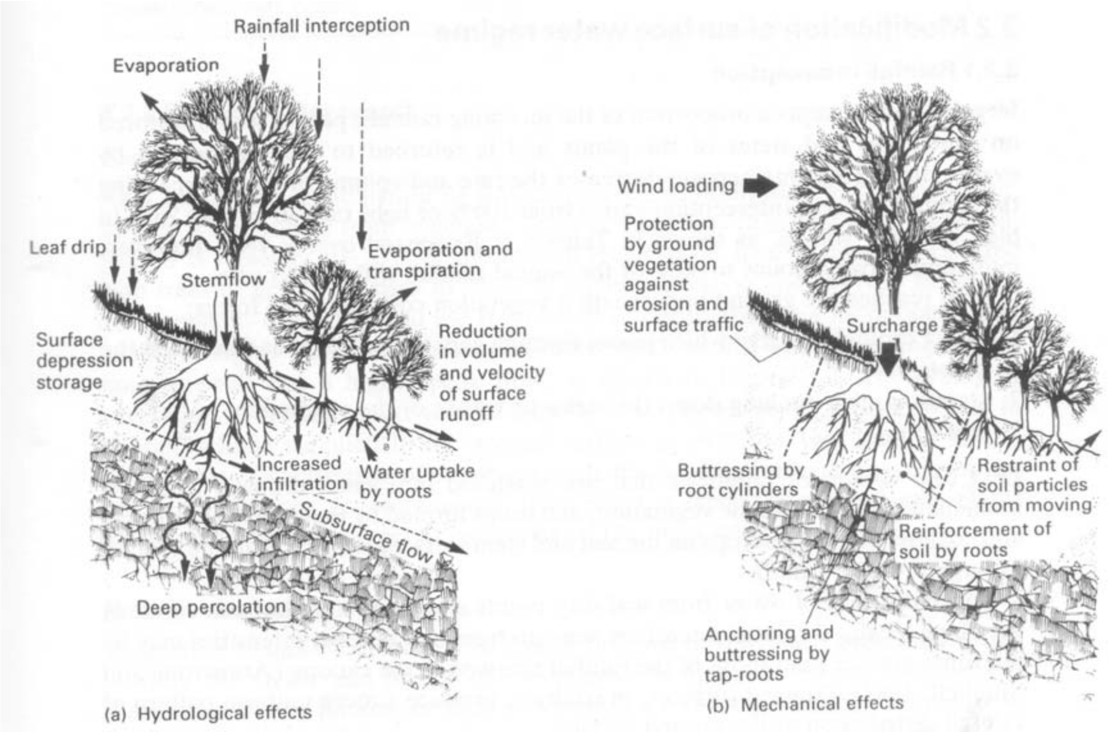


Figure 3.12 Hydrological and mechanical effects of vegetation on slopes (from Coppin and Richards, 1990).

Disadvantages of using vegetation:

1. Can’t be planned and installed with the same degree of confidence
2. Quantitative guidance is limited
3. Vegetation is vulnerable during maturation
4. The installation season is a limited
5. Growth could cause loss of conveyance
6. It can deteriorate due to mismanagement

7. It is labor intensive and requires special training
8. Alternative practices are more widely accepted by society and contractors, and more aggressively marketed
9. Availability of locally adapted plants may be limited
10. Increases flooding due to increased flow resistance
11. Large vegetation can be toppled by strong winds

Chapter 4. Existing Design Approaches

There has yet to be established a standard design approach for bioengineering techniques for stabilizing slopes and streambanks. Most researchers agree on many of the same basic parameters which need to be considered during the design phase of any stabilization project. Outlining each approach would become redundant, therefore the outline of existing techniques will be presented in this section.

4.1. General Factors

During the design phase of bioengineering projects, there are several factors need to be considered as pointed out in the literature. These main factors can be categorized as: 1) hydrologic data, 2) geotechnical data, 3) the characteristics of the native vegetation, and 4) fluvial geomorphological features of the stream. As it is evident the last category is only applicable to streambank stabilization projects. In addition to the above factors, other parameters such as political and economical constraints (77), regulations (79), adjacent land use constraints and control features (bridges and structures) need to be considered to select the most suitable technique for a given project (80). The above four factors are briefly discussed below.

4.1.1. Hydrologic and Hydraulic Data

Necessary hydrologic and hydraulic data for streambank stabilization projects are long-term discharge, flood frequencies, stream cross sections, thalwegs, water surface elevations for low flows and high flows, flow velocities, and anticipated changes to the upstream watershed (3, 10, 24, 77).

It is also necessary to determine the effects of the stabilization on various hydrologic parameters, e.g. surface roughness, flow velocities and water surface elevations. There are models available to estimate the impacts; however each model has some limitations. For example, the computer program HMODEL2 (40) is used for either flexible or non-flexible vegetation. It also gives the friction factor, roughness heights for flexible vegetation and wake velocities for non-flexible vegetation. HMODEL2 computes stage-discharge curves for a channel with specified cross-sectional geometry, gradient, bed-material size, and riparian vegetation characteristics. However, it is only valid for sand- or gravel-bed materials (40).

Stone and Shen (2002) developed a new model using the Moody diagram to estimate the effects of vegetation on channel velocity through an iterative process (52).

Fischenich (2001b) describes potential impacts on the water surface elevations and water velocities that could be attributable to armor techniques, deflection techniques, slope stabilization techniques, and energy reduction techniques (80).

4.1.2. Geotechnical Data

Geotechnical data encompass all soil properties of the streambank, streambed or slopes such as soil moisture, soil structure, bulk density, soil type, depth of impervious layer, porosity, and water repellency and even nutrients, pH, soil water salinity, exchangeable sodium, and toxins (3, 77). However, for a given project, it is necessary to determine the primary causes of the erosion or slope failure and then determine the geotechnical data necessary for the design (3, 24, 58).

4.1.3. Vegetation Data

For aesthetic reasons, it is generally recommended to blend in the project relatively well with the rest of the streambank or the slope. Therefore, site evaluations of the vegetation present prior to construction should be done. It may be possible to use the same vegetation that is already present, or even harvest some vegetation from directly on site. The problems often arise when it is desired to use species in the project which are not present on or near the site. Therefore, it is recommended to conduct an evaluation of the environment to determine the impacts of such practice. It is possible that there could be inhospitable conditions or competing species that will prevent a firm establishment of the desired species (24). In addition to studying species present, other data need to be collected, such as vegetation density, factors affecting the ability of plants to grow on the site, the parameters influencing the future stand of plants, e.g. available sunlight, proximity to the water table, aspect of the slope, soil type, and climatic factors, e.g. air temperatures, ground surface temperatures, length of the growing season, and rainfall (3).

4.1.4. Fluvial Geomorphological Factors

Rivers have a similar range of features, irrespective of their absolute size, which implies that their equilibrium shape and dimensions are governed by the same physical processes which differ only in scale, and by the same controlling factors. For a stream to be stable, it must be able to consistently transport its sediment load, both in size and type, associated with local deposition and scour (14). In the course of carrying out river engineering works for channel stabilization, many rivers have been considerably modified. These changes have adversely affected the stability of the engineered and adjacent reaches and in process destroyed the conservation of riverine areas (45).

According to Watson (2000) any streambank related project should consider six concepts: 1) the river is only part of a system, 2) the system is dynamic, 3) the system is complex, 4) there are geomorphic thresholds which if exceeded, abrupt changes will occur, 5) geomorphic analyses provide a historical prospective and we must be aware of the time scale, and 6) the scale of the stream must always be taken into consideration (81).

For streambank stabilization projects or erosion protection measures, it could be said that the fluvial geomorphological factors contribute the most to the “big picture” since hydrological, geotechnical, and vegetation factors interactively influence fluvial geomorphology. All processes that are taking place within the reach of a stream and the entire watershed should be taken into consideration, or else the stabilization work could become more of a band-aid solution instead of addressing the true cause of the problem (3, 10, 24, 77, 81, 82).

One of the primary factors to be considered is the sediment load in the stream. Newbury et al (1997) stated that stream aggradation and degradation are governed by the stream sediment transport capacity (83). The sediment transport capacity must be in equilibrium with the amount of sediment being transported or else changes to the stream will take place. In other words, for a given slope, channel will adjust its cross-sectional geometry such that its ability to transport sediment is maximized (82). If there is a greater transport capacity than sediment available, then degrading and downcutting will occur. Similarly, if there is more suspended settlement than the transport capacity, then sediment will fall out of the flow and there will be local aggradation, which will potentially cause problems downstream of the reach as the stream continues to maximize its sediment load.

There have been many attempts to develop standardized methods in river bank stabilization projects. Rosgen (1996) wrote a book titled “Applied River Morphology”, in which he classified streams based on slope, sinuosity, width-depth ratio, entrenchment ratio, and landform and channel material (14). He provided a procedure to assess the stream existing conditions and its departure from its pristine conditions. In the last chapter, he introduces the techniques to improve the channel stability and to improve fish habitat. The book has been widely used by practitioners for river restoration projects. Newbury et al. (2000) used Watson’s recommendations to develop a field manual for urban stream stabilization technique of pool and riffles in Manitoba and later in British Columbian streams (83).

Biedenharn et al (1997) describe independent and dependent variables that should be examined when studying the morphology of a stream. The independent variables are basin geology, hydrology, valley dimensions, vegetation, and climate and the dependent variables are channel slope, depth, width, planform, mean bed shear stress, and mean bank shear stress. Bed material composition and changes in channel alignment should also be considered (10, 24). Beschta and Platts (1986) discuss the importance of managing the channel power and energy in order to have any control of the morphology of the stream. They describe channel power as the time-rate loss of potential energy per unit mass of water (84).

4.1.5. Summary

A successful project will consider influences due to fluvial geomorphology, site hydrology, geotechnical influences, and vegetation. Therefore, it is necessary to incorporate a team approach, using engineers, hydrologists, fluvial geomorphologists, biologists, vegetation specialists, and landscape architects to fully consider all of the variables at play (62, 85). Furthermore, the natural channel design considers the function and stability of natural streams and their floodplains and tries to make the project blend in with current surroundings (62).

4.2. Specific Design Approaches

Very limited number of design approaches have been found in the literature. Most authors, including all those cited in the previous section, state numerous parameters should be considered in the design, but seldom a specific procedure is outlined. Four design guidelines have been described below. Most of them do not consider all of the factors that were outlined in the previous section.

One of the most comprehensive design guidelines was found on the USDA Natural Resources Conservation Association webpage (86). It is titled *Stream Corridor Restoration: Principles, Processes, and Practices*. It is a handbook that covers, in detail, all of the processes and factors discussed in this report and more. It details all hydrologic, geomorphologic and vegetation principles and factors that need to be considered. Then it details on how to determine the proper goals of the project, how to get started on a project and, data that needs to be collected. It gives some general design procedures, then discusses monitoring needs and explains the various techniques. The main deficiency of this handbook is the numerous occasions where it requires subjective judgment for the design parameters. However, it gives very good explanations for all the parameters which need to be considered. It could easily be supplemented with other sources to provide more rigorous design approaches.

Fischenich (2001a) has laid out a specific design procedure in addition to specific velocity and stress threshold for various techniques (17). His general design procedure is as follows:

First. Estimate mean hydraulic conditions such as discharge, hydraulic gradient, channel geometry, roughness coefficient using models such as HEC-2, HEC-RAS, WSP2. Use output to compute main channel velocity and shear stress at each cross section.

Second. Estimate local/instantaneous flow conditions and local variability in velocity and shear stress.

Third. Determine existing stability. Compare estimates of local shear stress and velocities to values in table 2 (see Appendix A) in Fischenich, 2001a. If appear stable, no further action needed. If not stable, go to step 4.

Fourth. Select channel lining material. Select based on need.

Fifth. Recompute flow values. Resistance values in hydraulic computations should be adjusted for the selected channel lining.

Sixth. Confirm lining stability. Safety factor FS = τ_{max}/τ_{est} or FS = V_{max}/V_{est}. Should be >1.2-1.3.

The State of Minnesota Storm Water Advisory Group (1998) developed the following procedure (87):

First. Identify problems and causes. Topographical, geotechnical, hydraulic and vegetation factors, as detailed above, should be evaluated.

Second. Identify possible solutions by using professionals from the fields of engineering, biology, soil science, hydraulics, and landscape architecture.

Third. Select alternatives to address the hydraulic and structural aspects of the project.

Fourth. Design the project with proper consideration of those factors previously described in this report. In addition, identify the need for permits; plan site accessibility; decide what tools and equipment are necessary; locate utilities and stormwater conveyance systems that may affect the site; identify erosion control measures; and define work and construction details.

Fifth. Install project. Timing is critical, especially in the case of the usage of dormant plants. Specifications must be very detailed, field checked, and enforced.

Sixth. Inspect and Maintain

The US Army Corps of Engineers (1996) has a slightly similar approach, but the main aim of their procedure is to determine if soft armoring is a viable option else traditional methods will be used (88).

First. Preliminary erosion assessment by local observation or aerial photographs.

Second. Field reconnaissance of the site to obtain design information. Values are assigned to the site based on site conditions. Total score determines stabilization needs.

Third. Determine stabilization options using the appropriate table for natural or artificial shorelines.

Fourth. Consult case history library.

Another design approach by the State of Washington Department of Fish and Wildlife (2002) uses matrices to filter out techniques based on site conditions, reach conditions, and habitat impacts (89). Unfortunately, the criteria for filtering within the matrices, requires subjective judgments, but it is the only publication found that attempts to provide a user with a narrowed list of options based on certain input criteria.

Li and Eddleman (2002) also list stress thresholds, but they couple them with expected costs of the various techniques in cost-strength matrices (4). Then it would be up to the user to determine the proper technique based on expected strength and available funds for implementation of the project.

4.3. Techniques

As mentioned previously, there are three sources that have been found to list threshold stresses or velocities for the various soft armoring techniques (4, 17, 80, 89). Eubanks and Meadows (2002), Gray and Sotir (1996), Schiechtl (1980), Gray and Leiser (1982), Schiechtl and Stern (1997), Franti (1997), and Li and Eddleman (2002) all provide detailed descriptions of the soil bioengineering techniques listed in Table 3.1 and other techniques, along with installation guidelines. Any references listed after the techniques listed below are references that concentrate on that particular technique. The case studies which have used a specific technique have been cited at the end of the summary of the technique. In addition, in each case study, a zone has been introduced in which the technique will be effective. The definition of these zones is as follows (4):

Toe zone: bank portion between bed and average normal stage

Splash zone: portion between normal high-water and normal low-water levels
Bank zone: bank portion above normal high-water level
Terrace zone: bank inland from bank zone.

4.3.1. Live Fascines

Also called wattles, fascines are made of live cuttings that are tied together into linear cylindrical bundles. They are installed in very shallow trenches that usually match stream contours. They can act like check dams to break up the slope length to reduce sheet flow velocities. They are very popular because they can be installed with minimal site disturbance and can be used in conjunction with other techniques, however, they do require a significant amount of moisture. Trenches should be excavated by hand tools to half the diameter of the bundles. Fascines are typically 8 to 10 inches in diameter and branches secured with twine. After the fascines are staked in place, the trench is backfilled until only the top of the bundle is exposed. Sotir and Fischenich (2001) provide detail information about the design and installation of live fascines. They also supply critical stress values for several fascine variations.

Applicable areas: bank zone

Case studies: Akridge et al., 1999 (62); Vaughn and Thombrough, 1997 (91); Kinney and Gulso, 1998 (93); Simon and Steinemann, 2000 (12); Sotir and Fischenich, 2001 (90); Gray and Sotir, 1996 (3); and USDA NRCS, 2002 (92).

4.3.2. Brush Layering and Brush Mattressing

This method is used to restore slopes by constructing a fill-slope consisting of alternating layers of live branches and soil, creating a series of reinforced benches. Large quantities of dormant willow branches are often used. The layers of branches help reinforce the fill, which improves as the branches develop roots throughout the fill area. The tips sticking out from the edge of the bank add to bank roughness, which reduces flow velocities and increases sedimentation. This method is suitable where the toe is not disturbed and rapidly restores riparian vegetation.

Applicable areas: splash zone, bank zone

Case studies: Akridge et al., 1999 (62); Knott, 1997 (94); Piper et al., 2001 (85); Simon and Steinemann, 2000 (12); Gray and Sotir, 1996 (3); Gray and Leiser, 1982 (8); USDA NRCS, 2002 (92).

4.3.3. Live Cuttings, Stakes and Posts

Live cuttings, live stakes, and live posts, when used alone, are essentially a permeable revetment. Even when used alone, they help reduce near-bank velocities that can result in sediment deposition. Live cuttings are often used in conjunction with other techniques by securing materials in place or increasing plantings on a slope. Live cuttings can be from 18 inches to 4 feet in length. Longer cuttings are used for live staking of wattles, while shorter cuttings are used for plantings. Advantages of live cuttings include the fact that they are easy to install and inexpensive. Disadvantages include the fact that they should be planted near the water table or in an area that will be wet enough for them to grow.

Applicable areas: splash zone, bank zone

Case studies: IECA, 1997 (95); Dutnell, 1998 (96); Kinney and Gulso, 1998 (93); Derrick, 1996 (97); Roseboom and White, 1990 (98); O'Malley, 1996 (99); Piper et al., 2001 (85); Shields et al., 1995a (13); Shields et al, 1995b (38); Simon and Steinemann, 2000 (12); Watson et al., 1997 (100); Gray and Leiser, 1982 (8); USDA NRCS, 2002 (92).

4.3.4. Prevegetated Mats

Prevegetated mats are live plants grown on a movable mat of organic material. They come in many sizes and materials and are moved and installed in one piece. Mats are grown in nurseries for up to a year or more to provide a good plant stand. Prevegetated mats are made of coir or other slowly degradable material and can use many types of plants.

Applicable areas: bank zone, terrace zone.

Case studies: N/A

4.3.5. Joint Planting

Joint planting consists of planting live stakes or cuttings with riprap. Root growth below the riprap will improve soil strength and live vegetation will hide the rocks, presenting a more natural look. Furthermore, it provides better habitat than riprap alone and the live stakes help disguise the riprap to make it more aesthetically pleasing. One advantage is that the riprap provides immediate protection for the bank while the root system develops underneath. A disadvantage of this technique is the difficulty of installation. It is often difficult to insert a relatively fragile live stake through riprap, or equally difficult to install the riprap efficiently around stakes that are already in the ground.

Applicable areas: toe zone, splash zone

Case studies: N/A

4.3.6. Live Cribwall

A live cribwall is a box-like interlocking arrangement of log and timber. It is filled with backfill and layers of live cuttings. The live cuttings root inside the crib and extend into the slope. They are especially effective on outside bends and steep slopes. They are complex and expensive, but they are useful where space is limited and streamflow velocities are relatively high. They are effective in stabilizing the toe.

Applicable areas: toe zone.

Case studies: Vaughn and Thombrough, 1997 (91); Moses, 1998 (101); Gray and Sotir, 1996 (3); Gray and Leiser, 1982 (8).

4.3.7. Rootwad

Rootwads are installed by inserting a tree into the bank with the rootwad sticking out into the stream. They are effective in keeping current off the bank. The installation can be rather invasive on the stream and the bank. They are able to withstand very high shear stresses and are often used in combination with other techniques. They provide excellent in-stream habitat as well. Sylte and Fischenich (2000) have developed detailed design and installation procedures for this technique.

Applicable areas: toe zone, splash zone.

Case studies: Akridge et al., 1999 (62); Vaughn and Thombrough, 1997 (91); Dutnell, 1998 (96); Moses, 1998 (101); Sylte and Fischenich, 2000 (102).

4.3.8. Tree and Log Revetment

Tree and log revetments are a form of soft armoring that use a series of whole, dead trees/logs that are cabled together and anchored into the bank. They provide toe protection while creating suitable fish habitat. They are inexpensive, but have a limited life and require periodic maintenance. They are not appropriate near important structures in case the revetment gets dislodged during a flood.

Applicable areas: toe zone

Case studies: Roseboom and White, 1990 (98); Piper et al., 2001 (85).

4.3.9. Combination with Erosion Control Products

Manufactured erosion control blankets have proven to be fairly effective in reducing erosion. Their benefit is to provide immediate protection. They degrade very slowly, so they will remain functional as long as they are not dislodged. This characteristics is considered either positive or negative, depending on the user’s perspective, as some prefer all-natural products.

Applicable areas: bank zone, terrace zone

Case studies: IECA, 1997 (95); Vaughn and Thombrough, 1997 (91); Moses, 1998 (101); Cabalka and Trotti, 1996 (103); Lancaster, 1997 (104); Nihill et al., 1997 (105); O’Malley, 1996 (99); Benik, 2001 (106).

4.3.10. Combined Use of Inert Material and Soil Bioengineering.

This method promotes the combination of inert, small-scale hard armoring, usually for toe protection, with soft armoring techniques on the upper banks. One example would be the use of riprap for toe protection, combined with live stakes or a brush mattress on the upper slope. Such projects can be done in such a way as to hide or minimize the visibility of the inert component so aesthetic benefits are maintained. One positive feature of this technique is that there is a fairly high degree of confidence in the design of the inert portions (58).

Applicable areas: toe zone, splash zone, bank zone

Case studies: Akridge et al., 1999 (62); Di Pietro and Brunet, 2002 (58); Vaughn and Thombrough, 1997 (91); Kinney and Gulso, 1998 (92); Piper et al., 2001 (85); Shields, 1991 (107); Shields et al., 1995a (13); Simon and Steinemann, 2000 (12).

4.3.11. Vegetated Geogrids

This method is also gaining a lot of popularity because it has proven to be a very strong technique, yet it doesn't require any additional hard armoring. This method uses natural or synthetic geotextiles that are wrapped around each soil "pillow." The pillows can then be stacked at the desired angle as steep as near 90° angle. Some variations use live cuttings or brush layering in between the pillows for added root mass and for added protection from high flows. Vegetated geogrids are useful in restoring outside bends where erosion is a problem. They provide immediate protection and help capture sediments, which result in rebuilding the toe of the bank. Unfortunately, they are labor intensive, and can be complex and expensive.

Applicable areas: toe zone, splash zone

Case studies: Moses, 1998 (101); Gray and Sotir, 1996 (3).

4.3.12. Coconut Fiber Rolls

In this method, coconut husk fibers that are bound together with twine are utilized. They are effective in trapping sediment, which encourages plant growth within the fiber roll. They are flexible, so they fit to the contours of the streambank. Installation requires minimal site disturbance. They are often used in combination with other techniques. Allen and Fischenich (2000) presented detailed descriptions of the design considerations, construction techniques, and monitoring procedures. They also presented empirical velocity and shear stress thresholds.

Applicable areas: toe zone, splash zone

Case studies: Allen and Fischenich, 2000 (108); Vaughn and Thombrough, 1997 (91); Simon and Steinemann, 2000 (12); Gray and Sotir, 1996 (3).

4.3.13. In-stream Structures

In-stream structures, such as rock weirs and stream barbs, function in much the same way as root wads do. They direct flow away from the banks and dissipate its energy. They are often made out of rock. Rosgen (1996) provides numerous configurations of this technique (14).

Case studies: Akridge et al, 1999 (62); Dutnell, 1998 (96); Kinney and Gulso, 1998 (92); Derrick, 1996 (97); Piper et al., 2001 (85); Shields et al, 1995b (38); Johnson et al., 2001 (108); Johnson et al., 2002 (109).

4.4. Selection Criteria

Only a couple of publications provide any information about criteria that can be used to select the proper technique or combination of techniques for any given project. The State of Washington Department of Fish and Wildlife provide a series of tables that can be used to determine which technique is most appropriate. Fischenich (2001) (Table 3.1) and Li and Eddleman (2002) both provide stability threshold for expected shear stresses, but do not consider other site conditions. Gray and Sotir (1996) provide a simpler table that includes some selected techniques (Table 4.1).

Table 4.1. Selection criteria for a few soil bioengineering techniques (from Gray and Sotir, 1996).

Factor or Failure Process	Intensity or Type of Condition	Live Staking	Live Fascine	Brush-Layering	Branch-Packing	Live Crib Wall	Live Slope Grating	Vegetated Geogrid
Slope gradient	*Steep*		X	X	N/A	X	X	X
	Moderate		X	X	N/A	X	X	X
	Gentle	X	X		N/A	X		
Slope height	*High*	X	X	X	N/A		X	X
	Low	X	X	X	N/A	X	X	X
Soil depth	*Deep*	X	X	X	X	N/A	N/A	X
	Shallow	X	X			N/A	N/A	
Soil erodibility	*High*		X			N/A	X	X
	Moderate		X	X		N/A	X	X
	Low		X	X	X	N/A	X	X
Soil strength	*Moderate*	X	X	X	N/A	N/A	N/A	N/A
	Low	N/A	X	X	N/A	N/A	N/A	N/A
Soil type	*Cut*	X	X	X	X		X	
	Fill	X	X	X	X	X		X
Surficial erosion		X	X		X		X	
Mass movement	*Shallow*	X	X	X	X	X		
	Moderate			X				X

4.5. Monitoring

Virtually every author agrees that monitoring of soft armoring techniques is a must to until they are well established. It is necessary to make periodic small repairs. The effectiveness of these techniques is based on adaptation of the living materials to their new environment, especially if live cuttings had to be brought in from another site.

The following is a list of what should be monitored, according to several researchers:

1. Toe protection (3, 4, 10).
2. Water surface elevations (4, 24).
3. Channel cross-section (4, 24).
4. Channel width-to-depth ratios (4).
5. Streambank and bed erosion rates (3, 4, 24).
6. Change in flow velocities (24).
7. Longitudinal profile (4, 24).
8. Exposing of erodible bank (16).
9. Condition of vegetation (3, 16).
10. Site conditions (3, 16).
11. Unexpected disturbances 3, 16).
12. Rates of maturity (16).
13. Monitoring should last at least 10 years (4).

In addition, the following actions should be taken:

1. Harvesting, if necessary (16).
2. Is the project functioning as designed? (16).
3. Is succession occurring? (16).
4. Identify areas of difficulty and causes (16).

4.6. Documented Sources of Failure

Several researchers have identified and documented sources of failure of soft armoring techniques as a means for others to learn from previous mistakes.

1. Wrong design criteria (6, 87, 98).
2. Right criteria but calculate wrong numbers (98).
3. Project isn’t built as designed (62, 98).
4. Selection of unsuitable species (4, 87)
5. Flood large enough to wash out project before root system established and stabilized bank (4, 12).
6. Drought (4).
7. Soil conditions unsuitable for plantings (4, 87).
8. Soil moisture extraction and other hydrologic effects of woody vegetation were not taken into account when bank stabilized (4).
9. Failure of structural materials (4).
10. Inadequate site preparation, grading and drainage control (4, 6, 87).
11. Livestock grazing (2, 4).
12. Insect infestation (4, 2002).

13. Plant disease (4).
14. Poor timing for planting materials (6, 87).
15. Poor drainage (6, 87).

Chapter 5. Interview Summaries

Common points addressed

Many of the practitioners interviewed stressed some of the same points for successful bioengineering projects. Virtually all agreed that maintenance is the key and should be incorporated into any contract. Some stressed understanding the fluvial geomorphological principles and processes is important for addressing the real cause of an erosion problem on streambanks. Also, many practitioners use in-stream measures to reduce stresses on the bank. Lastly, most of those interviewed say that they use a team of experts on many projects in order to fully consider the many variables that will affect a project.

Contradictory points addressed

There were not any significant points in which those interviewed disagreed, except the approaches to a project. Some practitioners always use a structural component to their projects while others try to avoid them as much as possible. Some concentrate on reducing stresses to a slope while others seem to be more concerned with strengthening the slope. Lastly, some feel that a “library” of case studies would be very helpful for determining proper techniques, but others don’t see it as something that would be especially valuable.

Summary of research needs suggested

The following bullets are areas that one or more of the interviewees mentioned as an area where more information is needed or expressed a desire to see researched. The bullets are categorized into botanical, hydraulic, armoring, and miscellaneous research needs. If a bullet could be appropriately place in two categories, it was listed in both.

Botanical

- Factors, such as soil moisture, that influences the ability of live stakes to take root and grow successfully.
- Ways to expand the window of opportunity to plant live materials.
- Root density over time in relation to how densely stakes are planted and the influence on the stability of the slope.
- Finding plants, such as sedges, that could be grown in the water, near a lakeshore to contribute to the stabilization of the shoreline by dissipating wave energy.
- Infiltration rates under different vegetation cover.
- Dissipation of flow energy by plants.
- Quantification of root reinforcement of soil.
- Threshold velocities for live stakes with respect to stem density, stake length, soil types, and with or without an erosion control blanket.
- Amendments to soil and how it will affect growth of stakes.
- Growth of root mass over time.

Hydraulic

- Effects of in-stream structures on velocities, e.g. rock weirs and rootwads.
- Dissipation of flow energy by plants.
- Infiltration rates under different vegetation cover.
- Quantification of reducing shear stress on banks and the effects on velocity.

Armoring

- Ways to determine if an armored toe is necessary and if so, the necessary degree of hard armoring.
- Effectiveness of different types of toe protection.
- Effects of in-stream structures on bed load transport.
- Downstream impacts of in-stream structures.

Design

- Ways to reduce the over designing of projects, which will reduce costs and enable more stretches of stream to be stabilized.
- A way to select techniques based on stream characteristics, such as type of stream and expected bounce.
- Strengths and weaknesses of each technique, both immediately after installation and once the vegetation has reached maturity.
- Design criteria for biotechnical solutions.
- Accurate means to estimate costs of a biotechnical engineering solution.

Miscellaneous

- Good training of designers and contractors.
- Monitoring of existing projects and documenting causes of failures.
- The effects of ice damming on lake shores.
- Effect of pedestrian traffic on a young project.
- Topographical changes on subsurface stability.
- Effects of in-stream structures on bed load transport.

Jason Moeckel, Minnesota Department of Natural Resources, and Jay Riggs, Dakota County Soil and Water Conservation District

Jason Moeckel and Jay Riggs discussed a few specific projects they have worked on and took us to a project that was under construction. They discussed their general design procedure and the various parameters they consider. They most frequently work on relatively small rivers, such as the Vermillion River and the Buffalo River, so flow velocities generally do not become greater than 5-6 ft s^{-1}. They favor the use of in-stream structures, such as cross vanes, J-hook vanes and root wads that will work to divert the flow away from the eroding bank and minimize stresses on the bank. They prefer not to use any sort of hard armoring, such as riprap, if it is not necessary. On the banks themselves, they favor the use of live stakes, brush layering, and vegetated geogrids. One of the parameters they consider is the sediment size, and they try to maintain sediment transport capacities. They will ask an engineering firm to do some hydrologic analysis and sign-off on the design of some projects.

Mr. Moeckel and Mr. Riggs have several questions that they feel could be addressed with more research. They stated that they did not have sufficient time to monitor many projects, so they felt that much could be learned by an extensive monitoring program of the existing projects. They would also like to know more about the following points:

- Factors, such as soil moisture, that influences the ability of live stakes to take root and grow successfully.
- Ways to expand the window of opportunity to plant live materials.
- Change in the root density over time in relation to how densely stakes are planted and the influence on the stability of the slope.
- Ways to reduce the over-designing of projects, which will reduce costs and enable more stretches of stream to be stabilized.
- Ways to determine if a rock toe or armored toe is necessary.

Jennifer Hildebrand, Erosion Control Specialist, Bonestroo, Rosene, Anderlik & Associates, Inc.

Ms. Hildebrand described her background and some of the work she has done on erosion control problems. She stated that she always used biotechnical engineering, or techniques that combine some sort of hard armoring or erosion control product with vegetation. In her designs, vegetation will contribute to the stability of the slope, but the contribution is never quantified. When first visiting a site, she will gather a lot of visual cues from the site itself, such as adjacent land-uses, soil properties, and types of vegetation. Based on that information, she will look at a problem as more of a "solution-based decision" instead of a methodical approach that a typical engineer would take. Her firm uses a variety of specialists on projects, and she will consult some literature to research techniques before implementing them. She feels that one of the main reasons soft armoring projects fail is that not enough attention is given to maintenance.

Ms. Hildebrand would like to see the following points addressed in future research:

- Quantifying infiltration rates under different vegetation covers.
- Effects of in-stream structures on velocity, e.g. rock weirs and root wads.
- The effects of ice damming on lake shores
- Effect of pedestrian traffic on a young project.

- Topographical changes on subsurface stability
- Effectiveness of different types of toe protection

Jon Hendrickson, Hydrologist, US Army Corps of Engineers
Mr. Hendrickson primarily works on island shoreline stabilization projects in the Mississippi River. On the Mississippi River, wave action is the primary erosive force, and the river current rarely plays a key role in design considerations. When trying to protect against the wave action, the USACOE most often uses techniques to reduce the stresses on the shore instead of techniques to increase the strength of the shore. Strengthening the bank by using riprap is a relatively expensive technique compared to other methods to reduce stresses. The techniques they often use are rock berms, rock groins, and off-shore rock mounds. They have found these methods to be effective in reducing erosion of the shore and the natural seed bank along the river quickly revegetates a bare shore. Sometimes they plant live willow stakes to speed up the process. They do not quantify the reinforcement of the soil by roots. The USACOE has developed a procedure to determine which technique or set of techniques might be most appropriate for a particular site. He has noticed project failures when the designers didn't address the causes of erosion and when maintenance was omitted from the project.

Mr. Hendrickson mentioned the following areas that he felt were in need of further research:

- Design criteria for biotechnical solutions
- Dissipation of flow energy by plants
- Quantification of root reinforcement of soil
- Clarification for when riprap is needed
- A study of existing projects and causes of failures
- Accurate means to estimate costs of a biotechnical engineering solution.

Kevin Biehn, Landscape Architect, EOR Inc.
For designing a bioengineering project, Mr. Biehn uses a team of professionals that would be appropriate for the project, such as engineers, hydrologists, and landscape architects. He stressed the importance of understanding the fluvial geomorphological variables, such as the theories described by Rosgen. Once those variables are addressed, then the soil bioengineering comes naturally into the project. He often uses in-stream structures, such as cross vanes, single vanes, and J-hook vanes that Rosgen describes as a means to reduce shear stresses on the eroding bank. When it comes to the placement of the in-stream structures and choosing the appropriate technique on the bank, he relies on experience, consultation with other practitioners and published case studies. He also believes that many projects are overbuilt at this point, and therefore, they cost more than they really should. But as practitioners gain more experience, they will be able to exclude certain measures that help reduce the cost. He feels that a lot of failures are caused by improper installation, improper design, and poor maintenance.

Mr. Biehn also discussed several research needs, which include:

- Stress threshold values for different soft armoring techniques.
- Quantification of reducing shear stress on banks by in-stream structures.
- Downstream impacts of in-stream structures.

- Stress thresholds of soft armoring techniques immediately after installation.

Brad Kovach, Botanist, and Ron Farmer, Geotechnical Engineer, Short, Elliot and Hendrickson
Mr. Kovach and Mr. Farmer primarily work on stabilizing embankments and lakeshores. They generally use biotechnical engineering where vegetation is combined with some form of hard armoring. The hard armoring portion does the primary work of stabilizing the slope, while the vegetation reinforces the surface soil and prevent surface erosion. Some failures have been caused by a lack of complete understanding of the "bio" part of the bioengineering. Many factors affect plant health and survivability and it is difficult to account for all of them. In general, they say that they do not have trouble designing projects using biotechnical methods, but they have a hard time finding contractors who are able and willing to install a biotechnical project. They have also found that biotechnical solutions cost more than traditional solutions because the contractors are not efficient during construction and the techniques are more labor intensive. The techniques they choose are site dependant and are often determined by the space availability.

Peter MacDonaugh, Landscape Architect, Kestral Design Group
Mr. MacDonaugh is the vice president of the Kestral Design Group and recently completed several bank stabilization projects along Minnehaha Creek. When designing a project, he looks at numerous factors, including hydrologic and geotechnical factors, but he also considers the history of the stream reach and the amount of available space. When deciding which technique to use, he looks to his experiences but also looks at case studies of other practitioners to see how they have solved similar problems and the thresholds beyond which they have experienced failures. Two of the techniques he uses most frequently are live staking and vegetated geogrids. He often uses Rosgen's methods to take into account the fluvial geomorphological factors. He often combines hard armoring of the toe, even up to bankfull discharge, with the soft armoring of the banks. He stresses the need for proper maintenance of each project to ensure success. He went into details about individual projects he had worked on, such as the Minnehaha Creek and the Prior Creek, to explain some of the factors that were considered when making decisions on those sites.

Mr. MacDonaugh feels that the following points can be addressed by further research:

- Threshold velocities for live stakes with respect to stem density, stake length, soil types, and with or without an erosion control blanket.
- Amendments to soil and how it will affect growth of stakes.
- Growth of root mass over time.
- Real cost figures for each technique.
- Monitoring of existing projects.

Sonia Jacobsen, Hydraulic Engineer, NRCS
Ms. Jacobsen has approximately 15 years of experience working with soft armoring techniques. She stresses the importance of understanding the fluvial geomorphological processes that are taking place in a given stream reach before attempting to address the streambank erosion. In fact, she stated that NRCS requires all employees to take a fluvial geomorphology class before they begin to work on streambank stabilization projects. Rosgen's theories are often used at

NRCS, as are the in-stream structures that are described in his book. Once the fluvial geomorphology has been analyzed, a team of professionals is required to consider other parameters, and then the technique or combination of techniques will be selected based on past experiences. Next they check to see if the selected techniques will be able to blend in with the existing bank and vegetation. NRCS also has plant materials centers throughout the country where they attempt to answer questions posed by NRCS engineers. Ms. Jacobsen also seeks their opinions when trying to determine the best species to use in a given situation or technique. She often uses live stakes, fascines, and brush mattresses. She also stated that she didn't feel that soft armoring techniques were any cheaper than traditional methods. She believes that the failures occurred in the past were often due to installing soft armoring techniques where they were not appropriate.

As far as research goes, Ms. Jacobsen stressed the importance of monitoring existing projects in order to gain a better understanding of the techniques themselves and their evolution.

Don Roseboom, Hydraulic Engineer, USGS

Prior to the interview itself, Mr. Roseboom strongly suggested that a copy of a handbook called *Field Manual of Urban Stream Restoration* to be obtained and read before conducting the interview. He contributed to the writing of that handbook and it contains a few case studies of urban stream restoration. Mr. Roseboom and his colleagues have often installed structures in the streams to restore natural pool-riffle sequences. The riffle structures require little maintenance and they have been effective in dissipating stream energy and significantly contributing to stream stability. However they have to be designed carefully so they do not disrupt the bedload transport ability of the stream. He strongly encourages the use of a-jacks (interlocking blocks) for toe protection because they are able to interlock with each other and cannot be easily moved. He also feels that many of the limitations of the soft armoring techniques are due to installation, i.e. the contractors may not completely understand some of the important aspects of installing these techniques.

Mr. Roseboom feels that understanding the effects of both in-stream structures and on-bank stabilization structures on the stream bedload transport capacity should be the vital part of the research.

Fred Rozumalski, Horticulturalist/Landscape Architect, Barr Engineering

Mr. Rozumalski has most frequently worked on lakeshore projects. He always uses some sort of stabilization technique at the toe, either with boulders or a-jacks. He also uses wave barriers to protect a young project. He stated that he would often use biologs for lakeshore stabilization. He stated that he did not feel that a standard design procedure could be developed for soft armoring techniques because there was a lot of finesse to the design. In other words, it is more of an art than a science.

Mr. Rozumalski stated that the following points could be addressed with further research:

- Finding plants, such as sedges, that could be grown in the water, near a lakeshore to contribute to the stabilization of the shoreline by dissipating wave energy.

- The degree of hard armoring that is truly necessary for a given site
- Monitoring of existing projects

Dwayne Stenlund, Plant Biologist, Mn/DOT
The interview was conducted while visiting the Mn/DOT sites. Mr. Stenlund often uses in-stream structures to reduce stresses on banks and feels that temporary vanes should be used more frequently to give vegetation a chance to establish itself. He stated that he believed that all future projects would be required to use in-stream measures. He often uses fascines and has developed an effective way to incorporate willow stakes into riprap by inserting PVC pipes into the ground, placing riprap around the pipes, and then after sometime placing willow stakes into the pipes and removing the pipes from the system. He expressed frustration with the short window for installing many of the components of biotechnical systems. He stated that bioengineering would take off once there are good estimates for the cost of the techniques, good maintenance programs, and better design to find the technique that fits each site.

Mr. Stenlund would like to see the following points addressed in research:

- A way to select techniques based on stream characteristics, such as type of stream and expected bounce.
- Strengths and weaknesses of each technique.
- Methods to expand the window for planting biotechnical techniques.
- Good training of designers and contractors.

Chapter 6. Project Evaluation

6.1. Twelve-mile Creek, Howard Lake, MN

6.1.1. Background

It was desired to include an evaluation of a Mn/DOT project, and this project was chosen at the suggestion of Dwayne Stenlund from the Minnesota Department of Transportation. All data and estimates provided in this evaluation were provided by Dwayne Stenlund during the site visit and subsequent telephone conversations.

The main purpose of this project was to move the 12-mile Creek back into its original channel. When Trunk Highway 12 was being constructed through that part of the state, the channel for 12-mile Creek was diverted so that it ran parallel to the road before it was forced to turn 90 degrees to go through a box culvert and go under the road. This was done to provide the shortest distance possible for the culvert that was needed to carry the stream under the road. However it was decided to move the stream back into its original channel in order to restore the stream to a more natural form and to provide a more natural look. Also, due to the 90 degree turn the stream was forced to take prior to entering the culvert, there were erosion problems that could be averted if the stream was allowed to stay on its natural course under the highway.

6.1.2. Project Description and Treatment Chosen

The main objective of the project was to return the stream to a more natural form in the area where its original channel was located. However, approximately 50-60 years had passed since the channel was originally diverted, so there was little to no evidence of exactly where the original channel had been located. Therefore, it was necessary to excavate a new channel. Riprap was placed on the toe of the banks on the outside bends to the level that was approximated to be the bank-forming discharge elevation. Live willow stakes were planted above the riprap.

6.1.3. Hydraulic Data

The stream was surveyed and vital hydraulic data were measured or estimated, but they were not available for inclusion in this report.

6.1.4. Site Visit and Evaluation

The site was visited on October 15, 2003, with the guidance of Dwayne Stenlund. According to Dwayne, the project was approximately two years old. One of the first observations that was made was that many of the willow stakes were no longer surviving. Either a large storm event drowned them or they were planted too low on the bank. Some willow posts on the upper banks were still alive and doing well. Mr. Stenlund stated that the estimates for the bankforming-discharge elevations turned out to be incorrect. Even though care was taken in determining such data, new culverts can cause unpredictable effects on the water levels, both upstream and downstream of the culvert. In this case, it seems as though the water levels were higher than estimated and drowned out the willows.

On one reach of stream, it was obvious that the riprap had been washed away from the bank and into the stream. This can be seen below in the photos. Even though the willows did not grow well, the bank is well-vegetated with reed canary grass. Reed canary grass is an invasive species that is very competitive. It is characterized has having a fairly thick, but rather shallow root system. Because of its shallow root system, it is not particularly effective in preventing streambank erosion.

It was also noted that the west bank of the stream was beginning to slump and could potentially result in an erosion problem in the future. One other potential problem was noted which was channelized runoff on the slope towards the stream. The problem looked like to be due to construction problems. The channelized flow results in localized slumping in the area where this channel enters the stream and has the potential to cause larger problems later in the life of the project.

6.1.5. Photos

Preconstruction and mid-construction photos were not available. The following photos were taken during the site visit on 10/15/03.

Figure 6.1 The reach initially downstream of the culvert under TH-12. Erosion on the banks can be noted, along in-stream structures that were placed in the stream.

Figure 6.2 Same reach of the stream, but looking back at the culvert. The bank on the right side is showing signs of instability.

Figure 6.3 A bank where it can be seen that the riprap is no longer on the bank. Either the bank has eroded from behind the riprap or the rocks were carried downstream from the upstream bend where riprap was placed.

Figure 6.4 Dead willow posts in the riprap.

Figure 6.5 Another photo looking upstream. The white circle points out the area where there is a localized slumping of the bank. Runoff from the highway surface is directed into that area.

6.2. Minnehaha Creek at 18th Ave. S., Minneapolis, MN

6.2.1. Background

The streambank stabilization work done on the Minnehaha Creek was designed by Kestrel Design Group, Inc. Peter MacDonaugh, vice president of Kestrel Design Group, was one of the practitioners interviewed for this project, and he was also kind enough to take Jeff Weiss and Omid Mohseni on a site visit to some selected sites of the work that was done on the Minnehaha Creek (MHC). This site, between 16th Ave S and 18th Ave S, was randomly chosen for evaluation.

This section of stream was straightened in the 1930's in an effort to control the stream before it went under Cedar Ave in south Minneapolis. This and similar efforts to control the stream at other locations have contributed to erosion problems on MHC. In addition, the MHC watershed has become almost completely urbanized, so the runoff volume and hydrology of the stream have changed dramatically since the time the stream was straightened. The stream and the park that surrounds it are very high profile attractions in south Minneapolis. The park and its bike and walking paths are regularly used by local residents. Furthermore, there are many expensive homes that line the creek and the parkway. Therefore, erosion problems on MHC have a negative effect on the aesthetics of the park, threaten city streets, and could threaten valuable property.

Information in this report is from materials supplied by Kestrel Design Group and the conversation with Peter MacDonaugh during the site visit.

6.2.2. Project Description

Due to the channel straightening and watershed changes, there were some erosion problems on MHC. Downcutting has been documented, which would lead to a deeper channel, and eventually, wider banks. For the site between 16th and 18th Avenues, there were a few main goals: 1) Restore the sinuosity and stability of the channelized reach, with full point bar development; 2) Create an abandoned oxbow storm water wetland to precipitate and filter stormwater sediment; 3) Increase the stormwater/wetland storage in this portion of the floodplain; 4) Increase fish and wildlife habitat; 5) Salvage channel substrate and reuse in new meander. Trugg's survey of 1853-1856 of MHC and old aerial photos were used to learn more about the historical sinuosity that was present in the reach before it was straightened. The project was completed in 2000.

6.2.3. Hydraulic Considerations

The computer program, HEC-2, was used to estimate 50, 100, and 500 year flows on MHC. This data, along with the data on the cross sections of each reach, were used to estimate total stream flow, channel water surface elevations, channel velocities thalweg, and topwidth of the streamflow for both the upstream and downstream sections for each reach. For example, the above data for the 100-year flood at the upstream section at 18th Ave S are 1307 cfs, 821.27 ft, 2.93 ft/sec, 814.6 ft, 6.67 ft, and 347.84 ft, respectively.

6.2.4. Treatment Selection

Using Rosgen's methods, it was determined that this stream fell into the C4 or C5 type channel. The following in-stream techniques are rated suitable for C4 streams: bank placed boulders, bank cover, floating log cover, straight away submerged shelter, vortex rock weir, W weir, bank placed root wads, and rock or log vanes. Bank placed boulders and rock weirs were used on this site.

Vegetated geogrids were installed on the banks, along with live stakes.

6.2.5. Site Visit and Evaluation

The site was visited in September, 2003. The willows had become well-established and it was possible to see the energy dissipation being done by the rock vanes. No signs of erosion were obvious. The toes were protected by ripraps (boulders) with d_{85} of about 2 feet.

Because MHC is an outlet for Lake Minnetonka, it will occasionally run very high for an extended duration in an effort to control the water levels on Lake Minnetonka. This was the case in 2002, when the creek ran at near bankfull for nearly 5 months. Even though this was only 2 years after the project was finished, the treatments held up well and there were no signs of damage.

6.2.6. Photos

Preliminary photos from pre-construction and mid-construction were not available. The following photos were taken during the site visit.

Figure 6.6 MHC site at 18th Ave. S. Boulder cover below, willows on top of bank.

Figure 6.7 Rock vane and eddies in the water.

Figure 6.8 Rock vane, boulder toe, and willows.

Figure 6.9 Boulder toe and vegetated geogrids at a site slightly upstream of the 18th Ave. S. site.

6.3. Elm Creek, Truman, MN

6.3.1. Background

This site was selected for evaluation at the suggestion of Sonia Jacobsen, Hydraulic Engineer from NRCS, who was contacted and interviewed as part of the requirements to interview practitioners for this contract. It was selected, in part, because Ms. Jacobsen felt it was a very typical soil bioengineering project that NRCS works on and she played a role in the design and installation of the project. Furthermore, it was installed 5 years ago, so it has had a chance to fully develop and experience flooding conditions.

The background information about this project comes from two sources. One is a design report supplied by Ms. Jacobsen and the other is from the case study report on the NRCS website: http://www.mn.nrcs.usda.gov/technical/eng/soilbioeng.html.

6.3.2. Project Description

This project is on Elm Creek, near the town of Truman, MN, in Martin County in southern Minnesota. A bend on Elm Creek was eroding farmland and threatening a township road. Therefore, the objective was to control the erosion on the streambank next to the road and prevent further encroachment.

The project was installed in October 28, 1998. It was designed by Steve Becker, the area NRCS engineer, and Steve Maurice, the District Conservationist for Martin County. NRCS Practice Standards were consulted for the design.

A total of 400 feet of streambank was stabilized. The original bank height was 9 feet, and it was cut back to a 2.5:1 slope. The final slope length was 22 feet. Rock riprap covers the lower 11 feet, and brush layering, live fascines, and live stakes cover the upper portions of the slope. A fluvial geomorphology assessment was made; the riprap was installed up to the channel forming discharge elevation.

6.3.3. Hydrologic Considerations

Stream gauges are not present on Elm Creek, so floodwater regression equations from the USGS were used to estimate extreme flood events at the site. Three nearby stream gauges on creeks with similar watersheds were used for the regression. Those streams were the Blue Earth River (east branch) near Bricelyn, Little Sioux River near Spafford, and LeSueur River near Rapidan. Using the regression equation, it was estimated that the streamflow and stream velocity with the water level at the top of the riprap would be 335 cfs and 2.7 ft/sec, respectively. The 2-year and 10-year, 24-hour flood events were estimated to be 850 cfs and 3000 cfs, respectively. A bridge is located approximately 300 feet downstream of the site. Water surface profiles from the bridge were not calculated, but the bridge abutments were expected to decrease the stream velocity at the site. Elm Creek has a drainage area of 230 square miles at this point. The creek has a channel slope of 0.2% and the bend in the project site has a radius of curvature of 90 feet.

During site inspections, a small natural gully was observed that had formed on one portion of the bank. It was decided to install a rock chute in the natural gully to continue to provide an inlet for local runoff, but maintain a stable bank that would not eventually compromise the nearby township road. The drainage area that feeds that rock chute was computed to be 46 acres, with an average landslope of 1%.

6.3.4. Treatment Selected

It was decided to use rock riprap to stabilize the lower bank approximately to the level of channel-forming discharge. This discharge elevation was determined by correlating the flow evaluation from 1 to 1.5 year storm events with the elevation of specific field indicators, such as natural vegetation thresholds, established root zones, bank scouring marks, and water stains.

Live staking, live fascines, and brush mattresses were selected for use on this project because of the relatively low expected velocities and low cost of these techniques. Also, a stream barb was installed on the lower end of the project to redirect flow towards the middle of the stream. The total cost of the project was $32,445, or about $80 per linear foot.

Pictures from the installation and from 1 year after installations were taken from the website previously mentioned and are presented at the end of the report.

6.3.5. Site Visit and Evaluation

On October 10, 2003, Omid Mohseni and Jeff Weiss from the University of Minnesota visited the site. In general, the site looked quite stable and no obvious signs of erosion were noted. Due to the dry autumn, the creek was dry during the visit, so it was possible to see the bottom of the stream. Without a previous baseline, it is impossible to tell what changes to the channel had occurred, but significant sedimentation had occurred upstream of the stream barb. It was also noted that some ripraps were moved into the middle of the stream channel, but it was not clear if it was installed that way or if stream flows since installation had moved the riprap from the toes into the channel. This was mentioned to Ms. Jacobsen, and she relayed this information on to the area engineer to get more information. The area engineer reported that the extra rock was likely placed by the contractor in order to dispose of it without having to pay to have it hauled away.

The vegetation on the bank looked healthy, despite the dry autumn. It was noted that the areas planted with brush layering and live stakes had a much thicker stand of willows than the area planted with live fascines. It was possible to easily walk through the area with live fascines, but it was difficult to do so in the other areas.

6.3.6. Photos

The site was installed by NRCS employees attending a soil bioengineering training session as a field exercise (from http://www.mn.nrcs.usda.gov/technical/eng/soilbioeng.html). The project was installed in approximately 6 hours. The willow was cut in the two days prior to installation.

Figure 6.10 Power trimmer used to cut plant materials for fascines and brush mattress.

Figure 6.11 Frame used to construct fascines on site; made of 2x4's.

Figure 6.12 Fascine installation on northern end of site; brush mattress on southern end; rock toe to channel forming discharge.

Figure 6.13 Installation of horizontal fascines; coir mesh, seed & mulch between fascines.

Figure 6.14 Installing diagonal fascines.

Figure 6.15 View of finished horizontal fascines in foreground and diagonal fascines in background by people.

Figure 6.16 Diagonal fascines to convey water and take up water along slope.

Figure 6.17 Stacking fascine at toe and placing stakes for brush mattress.

Figure 6.18 Placing cuttings in brush mattress.

Figure 6.19 Brush mattress constructions.

Figure 6.20 Covering brush mattress with topsoil (soil was to wet for machinery).

Figure 6.21 Brush mattresses with log anchors.

Figure 6.22 Project nearing completion; fascines on north end and brush mattress in foreground.

Figure 6.23 The installation crew; Class finished all work in less than 3 hours.

Figure 6.24 Site before any work done.

Sept. 1999 - 1 Year Later

Figure 6.25 Overview.

Figure 6.26 Sediment deposited on top of rock toe in upstream part of curve.

Figure 6.27 Soil washed from techniques immediately above the rock toe.

Figure 6.28 Sediment bar below stream barb.

Figure 6.29 Growth coming where willow ends covered with soil.

Photos from October 10, 2003

Figure 6.30 Looking upstream. Fascines are in the foreground and brush mattresses are in the background.

Figure 6.31 Fascine area, looking downstream.

Figure 6.32 Brush mattress area.

Figure 6.33 Brush mattress – up close.

Figure 6.34 Entire channel. Note rocks from riprap in center of channel.

Figure 6.35 Upstream end of the site.

Figure 6.36 Sedimentation behind stream barb.

Other photos, courtesy of Sonia Jacobson, NRCS

Figure 6.37 Stream inundated, May, 2001.

Figure 6.38 May, 2003.

Figure 6.39 May, 2003.

Chapter 7. Research Needs

In the previous sections, the techniques and accomplishments in soil bioengineering to protect stream banks and slopes were discussed in detail. Interviews with soil bioengineering practitioners indicated that in many respects, the practice is more of an art than a science. Most practitioners are able to determine which technique would be appropriate for a particular site based on experience. Some design guidelines exist, but practitioners inherently know which technique or combination of techniques will fit into the site, develop completely, and successfully protect the area in question through experience.

There have been very few controlled experiments performed to determine permissible shear stresses and velocities of commonly used soil bioengineering techniques. Therefore, the effect of various site conditions on the strength of each technique is unknown, as is the rate at which each technique gains strength as vegetation matures.

Some guidelines exist for determining which technique will be appropriate for a site based on various criteria (Gray and Sotir, 1996; Washington DFW, 2002). However, such guidelines are rather subjective in nature, so it could be possible to select a less than optimal technique because the user's selection criteria differed from the author's. For example, one of the criteria in the table provided by Gray and Sotir (1996) is slope gradient, with "steep, moderate, and gentle" being the three categories to choose from with no quantitative guidelines to help the user determine which category should be assigned to given site conditions.

Site condition variables include: soil type, slope gradient, flow velocities, slope direction, slope height, climate conditions, and soil erodibility, among others. A soil type at a project will not change dramatically over a short period of time, but there is a very large range of soil types and properties. Therefore the performance of one technique in one soil type cannot necessarily be expected to be the same in a different soil type. Similarly, there is a range of climatic conditions that can be expected, but what conditions will be seen from year to year cannot be predicted. However, the exact influence of soil properties is not well-understood, so it remains unknown to what extent lessons learned in one case study will be applicable to the next project.

Even though there are installation guidelines for many techniques presented in some sources, the layout of each technique can have an impact on its strength, at least in the short term. For example, if live willow stakes are used in three different projects with identical hydraulic, soil, and climate conditions, but are planted with different densities, the effective strength of the bank will vary from site to site, at least in the short term before the willows spread over the entire bank. Likewise, different diameter sizes could be used in brush mattresses. It is difficult to have standard measurements when working with live materials because each living organism is unique. The thresholds listed do not take into account these variances.

One of the most significant limitations for using some soil bioengineering techniques is that the use of live or dormant materials requires installation during short windows of time during the spring and fall. Therefore, construction of the project must be timed such that the plant material can be installed at the proper time. If the optimal window for planting is missed, the chances of success for the project are diminished. However, if there are ways to expand the window of time by finding ways for non-dormant cuttings to be used, then soil bioengineering techniques can be installed throughout the summer and many more projects can be installed during a calendar year.

In order to develop design guidelines for the bioengineering techniques used to protect stream banks and slopes, there are many questions which need to be addressed. Some of the questions stem from the projects done by the practitioners. Overall, one can divide the questions into two groups: 1) erosion processes and 2) slope stability processes. In both groups, the main unknown to determine is the shear strength of the system. However, in addition to shear strength, the engineers and practitioners should pay attention to other consequences of using these techniques in the design guidelines. The research areas outlined below will focus on the estimate of the shear strength and other considerations which play key roles in the design guidelines.

7.1. Erosion Processes

Stream banks are primary areas subject to erosion processes. Any stream bank treatment impacts both the stream bank shear strength and the flow shear stress by affecting the flow depth. To develop any design guidelines for stream bank protection techniques, it is necessary to determine the impacts of the technique on bank roughness. The available information is very limited and often quite empirical and requires further investigation as outlined below:

a) Determine the bank and bed roughness with the most common plants used in bioengineering techniques. The research should address different vegetation, with different densities and during different stages of maturity. In addition, it is necessary to determine the bank roughness based on the combination of plants used in these techniques. Most common vegetation plants are *Salix sp.* (willows), *Cornus sp.* (dogwoods), *Spartina pectinata* (Prairie Cordgrass), *Carex sp.* (sedges), and *Panicum virgatum* (Switchgrass). In addition, there are plants seeds used and distributed by MnDOT mainly for transportation related projects. In a meeting with MnDOT representatives the most commonly used seeds should also be selected for testing. A botanist should be consulted regarding the strength of plants with respect to shading condition, soil type and required moisture content. The design guidelines should address the plants physiological characteristics and where they are most suitable.

b) Determine the added shear strength to banks by vegetation when used in the bioengineering techniques.

To determine both roughness and shear strength, one could measure the velocity distribution near the bank and across the stream cross-section.

c) Determine the resiliency of different plants under high flow conditions.

d) Study the mechanisms which cause failure of plants under different flow conditions, e.g. abrasion, duration of submergence, eddies, uplift forces. To study different mechanisms acting on plants, the relationship between flow velocity and forces acting on plants need to be determined.

e) Determine the shear strength of the commonly used techniques for stream bank stabilization. The experiments should be done for a range of bank slopes, top soil depths and soil types. The data provided for these techniques by Gray and Sotir (1996) are qualitative and are not valuable for any design guidelines, and the quantitative data provided by Fischenich (2001) do not give other necessary details regarding these techniques. The tests results can also help improve some of the details of the techniques, e.g. the minimum distance between fascines. It is also essential to compare the success of these techniques using dormant plants versus plant stock and times of year for planting them, and whether the dormant materials have to be refrigerated after cutting and prior to planting.

f) Determine the shear strength of the composite system, where different plants and techniques are combined. It is important to determine the best composition of these techniques and how a combination of several plants affect the overall strength of the system, and how one type of plant or a technique restricts the effectiveness or livelihood of another plant.

To determine the shear strength of these techniques and the commonly used plants on stream bank protection projects, it is essential to provide high flow velocities at which tearing and erosion start occurring. Riprap can withstand shear stresses associated with mean average velocities of 5 to 18 fps. It is likely that most bioengineering techniques will not withstand velocities above 10 fps (Fischenich, 2001; interview with Jay Riggs). Nevertheless, to ensure the effectiveness of these techniques in comparison to hard armoring techniques, the research facility should be capable of creating velocities comparable to that which riprap can withstand. In addition, in many bioengineering practices, bank toe is reinforced by riprap. Using the velocity distribution, combinations of hard armored toes and soft armor slopes should be tested to determine the minimum hard armoring required for these techniques. Under these circumstances, tests on higher velocities, e.g. about 15 fps, are deemed necessary.

Tests to determine the bank and bed roughness should be conducted on straight reaches. However, tests regarding the shear strength of bioengineering techniques should be conducted on both straight reaches and bends. Most bioengineering techniques are applied to the outer bends of streams and creeks, where banks and toes are subject to higher shear stresses.

g) Determine the shear strength of treated slopes to rill, sheet and gully erosion. For rill, sheet and gully erosion, one can apply artificial rain, using rain makers, to slopes with different slopes and soil types. The tests should be done in different seasons, i.e. spring, summer and fall, when plants provide different protection for slopes. The test will help determine the minimum required density of different live or dead stakes used, e.g. in brush layering, brush mattress, or soil wrap, and the minimum distance between fascines. Similar tests have been done by Bruce Wilson to determine the resistance of different geogrids to rill, sheet and gully erosion. The artificial rainfall pattern should resemble the rainfall patterns of the region which could create the most severe conditions for the slope surface.

h) In-stream structures: In-stream structures provide desirable fish habitat and reduce shear stress on stream banks and toes. The reduction in the shear stress under different flow conditions needs to be quantified. Furthermore, in-stream structures impact bed load and sediment transport locally and downstream of protected areas. The impacts have not yet been evaluated. The impacts can be evaluated by monitoring some sites on meandering rivers over an extended period of time.

7.2. Slope Stability Processes

Slopes are subject to (1) rill, sheet and gully erosion, and (2) mass movement along the plane of failure. To determine the effects of bioengineering techniques for slope protection projects, the above two processes need to be evaluated separately. The erosion processes were addressed in section 2.1. In this section, we only address the mass movement processes.

The main question regarding the impacts of bioengineering techniques on mass movement is the effects of vegetation on the plane of failure, i.e. how the plane of failure shifts due to presence of the root system. To answer this question, there is a need to determine the added shear strength to the soil by the root system. There is already a library of data provided by plant biologists and botanists. In addition, Colin Thorne, in England, is currently conducting a comprehensive research study on plant root systems. The data will help us to mathematically analyze the conditions under which the slope will fail. However, the slope stability analyses require reliable amounts of information regarding the added shear strength of plant roots to the system. Despite the availability of such a library, the knowledge of root-soil interactions is in its infancy and there is still a need to determine the added shear strength of the root system to the plane of failure. To determine the added strength, we need to determine:

a. The root tensile strength

b. The shear strength of the root fibers

c. The bonding shear strength between root and soil

The lowest level of strength among the above three will be added to the plane of failure. However, this addition depends on the effective area of the root system with respect to the total area. The effective area depends on the density of the plants, the density and age of the root system and the soil type. Unfortunately, it is not a well defined parameter and there is a strong need to determine this parameter. Therefore, there is a need for laboratory testing. However, the overall effect should be investigated in an outdoor research facility.

For slope failure due to mass movement, prior to any testing, it is necessary to conduct a geotechnical analysis to determine the plane of failure and the saturation level under which the failure occurs. The mathematical analysis should be verified in an outdoor research facility for different untreated slopes and soils. Then the slope should be treated by the most commonly recommended practices. Eventually measurements should be made to determine the effects of the practice on the slope stability.

Chapter 8. Potential Outdoor Research Facilities

As it was explained in section 7, there are many unknowns in soil bioengineering which should be further researched. Currently, there are several outdoor laboratories in Europe studying different topics of soil bioengineering. Before exploring the potential sites in the Twin Cities area, a site visit was made to the Department of Soil Bioengineering and Landscape Construction of the University of Agricultural Sciences in Vienna, Austria, which has an existing outdoor research facility for soil bioengineering techniques. Researchers from both the St. Anthony Falls Laboratory and the University of Vienna decided that a close collaboration and sharing of results between laboratories would enhance our understanding of the science of soil bioengineering.

In this section, a summary of the visit and the technical data obtained from the facility of the University of Vienna, and the visits of three potential sites in the vicinity of the Twin Cities area will be presented.

8.1. The Soil Bioengineering Test Flume in Vienna

The soil bioengineering test flume of the University of Vienna was constructed on the Wien River in 1996 to assess bank slope stability under different structures and vegetations. The Wien River is about 34 km in length and partly flows through an urban area of Vienna with a torrent discharge regime. Vienna is a city of approximately 1.7 million inhabitants and is divided into 23 districts. The flooding of the Wien River can affect several sections of nine districts of the city.

The first effective flood protection measure was realized by the end of the 19th century. In order to protect the urban area, six retention reservoirs with an overall capacity of 1,700,000 yd^3 (1,300,000 m^3) were constructed where the river enters the urban environment. As illustrated in Figure 8.1, the stretch of the river in the urban area was stabilized by a concrete bed and masonry walls.

The "New Wien River" revitalization project was launched in 1995. One of the chief goals of the restructuring work was to bring the water and banks back to public attention and to make it accessible and usable for the citizens of Vienna along its 9 miles (15 km) of urban stretch. Ecological aspects were highly relevant for the retention areas, where valuable wetland habitats were developing. Technical targets of the project were on the one hand to install a separate waste-water channel and on the other hand to provide more efficient flood protection using the existing retention reservoirs.

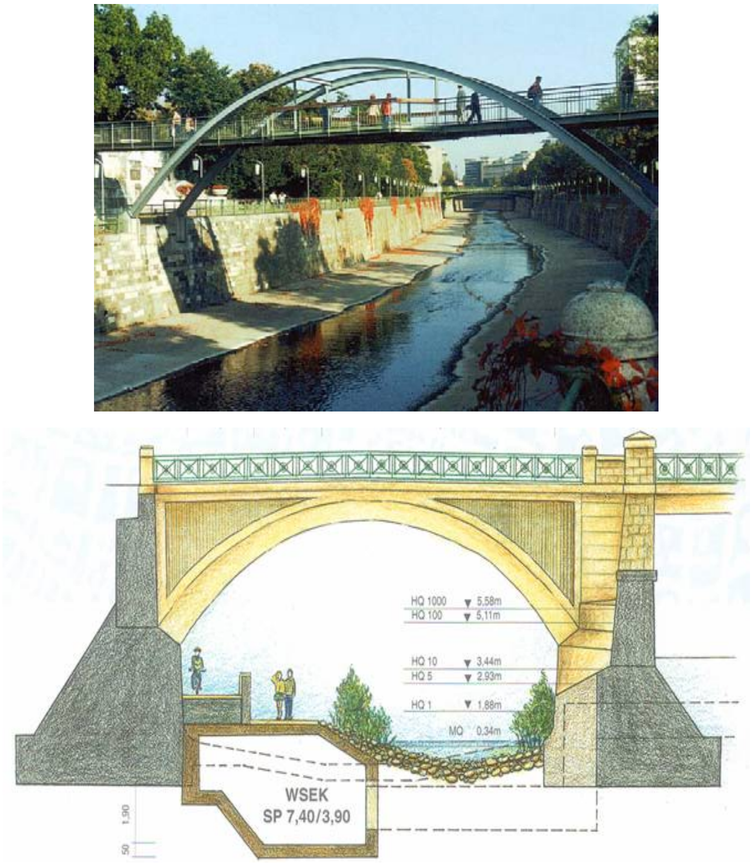


Figure 8.1 Existing and the future design of the Wien River cross section.

Plans for revitalizing the urban stretch were primarily based on the use of bioengineering techniques. A test flume was constructed to assess the stability of bed and banks under different loading methods (Gerstgraser, 2000). The soil bioengineering test channel is located directly in the Wien River at the outskirts of the city (Figure 8.2).

The construction of the test flume began in 1996 with a run of sheet piling that divides the test channel into two parts which can be flooded separately. The flume was completed in 1998, and was tested for three soil bioengineering techniques.

Figure 8.2 Construction of the test flume

The flume is 560 ft (170 m) long (Figure 8.3), with a width varying from 20 to 26 ft (6 to 8 m), and a maximum height of 10 ft (3 m). Artificial floods are simulated by opening a sluice gate which is located just upstream of the test flume. The sluice gate serves as a wicket dam with a 458,000 yd^3 (350,000 m^3) retention reservoir. During artificial flooding, a discharge from 700 to 1,300 cfs can be achieved for 40 to 60 minutes.

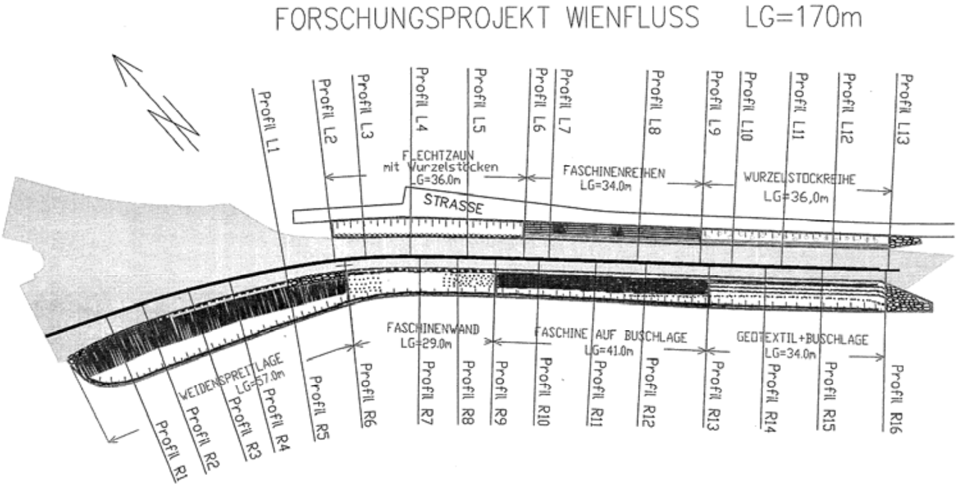


Figure 8.3 Plan view of the flume.

Three soil bioengineering structures were constructed in 1998 from woody plants as shown in Figures 8.4 to 8.6 (Gerstgraser, 2000).

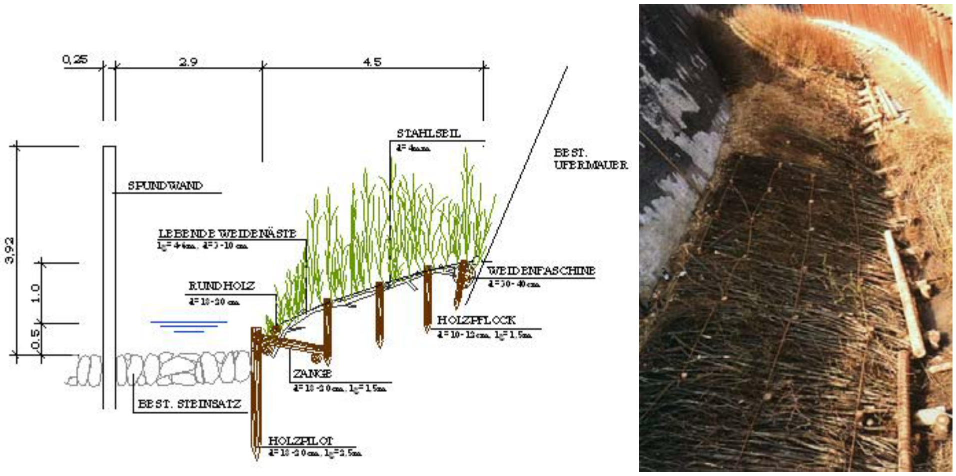


Figure 8.4 Brush mattress with willows. All dimensions are in meters (1 m = 3.3 ft).

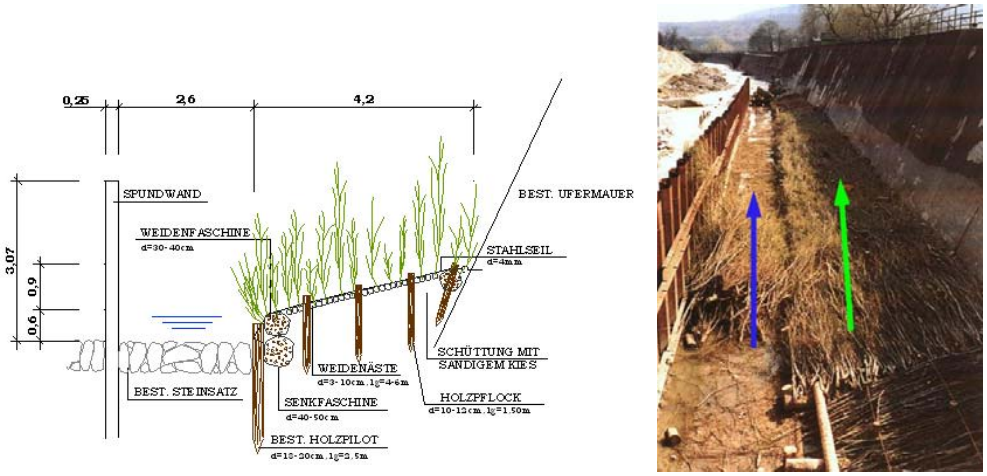


Figure 8.5 Branch layer. All dimensions are in meters (1 m = 3.3 ft).

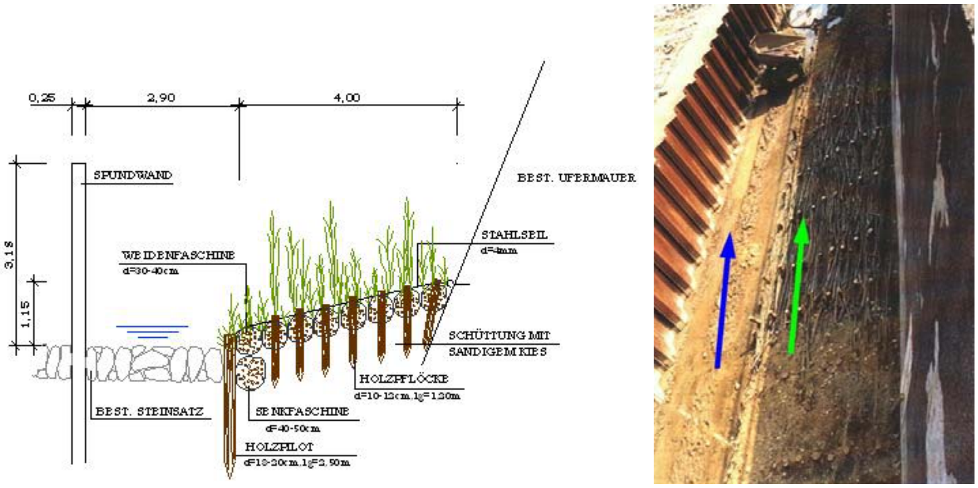


Figure 8.6 Fascine layer. All dimensions are in meters (1 m = 3.3 ft).

The first step they took was to create a stable slope for vegetation. The bank was reshaped to an optimal slope and boulder rip rap was positioned from toe to the bank full elevation. A brush mattress was installed to physically armor the bank. After the bank was covered with branches, wire was placed over the brush mattress and wrapped around the stakes to form a network over the mattress. Then the stakes were driven into the bank and, "live" stakes were placed throughout the brush mattress. The brush mattresses and fascines were partially covered with soil, therefore only some branches and buds were exposed to light. A native grass mix above the brush mattress and two rows of shrubs were planted to complete the project. Figure 8.7 shows the areas where these techniques were implemented.

The research focused on the hydraulic impact of vegetation in successive growth stages. An ADV (Acoustic Doppler Velocimeter) and an ADP (Acoustic Doppler Profilers) were used to acquire local and cross-sectional velocity data (Figure 8.8). Velocity distributions were acquired at a fixed cross-section. Discharge was only measured using the water level in the retention reservoir and the opening of the gate. In addition, water level was measured at five other cross-sections. Figure 8.9 shows the velocity distribution at the fixed cross-section and the influence of the vegetation on the flow conductance.

Figure 8.7 View from upstream to downstream of the flume.

Figure 8.8 Measuring devices: acoustic Doppler profiler (left), acoustic Doppler velocimeter (right).

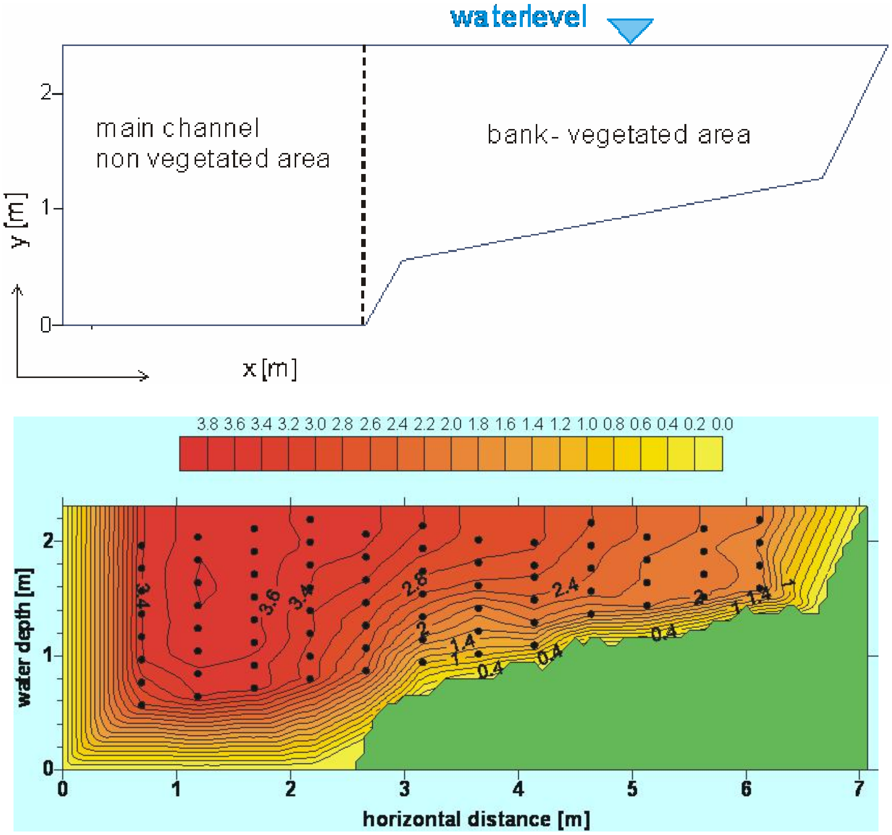


Figure 8.9 Velocity profile along the vegetated and non-vegetated area. Velocities are in m/s (1 m/s = 3.3 fps).

In order to explain the interaction between vegetation and flow parameters, it was necessary to characterize the vegetation during the test period, i.e. several years. Parameters such as the number of shoots per plant and per unit area, i.e. density, the basal diameters of the shoots and their diameters at a height of 3.3 ft (1 meter), the shoot length, and the shape of the crowns were collected once a year. Analysis of these data on an annual basis provided an overview of vegetation development (Figure 8.10). Typical growth patterns indicated how plants coped with the applied loads. The data in Figure 8.11 show how at a fixed discharge, mature plants increase the water level and decrease the velocity and subsequently the shear stress on the banks.

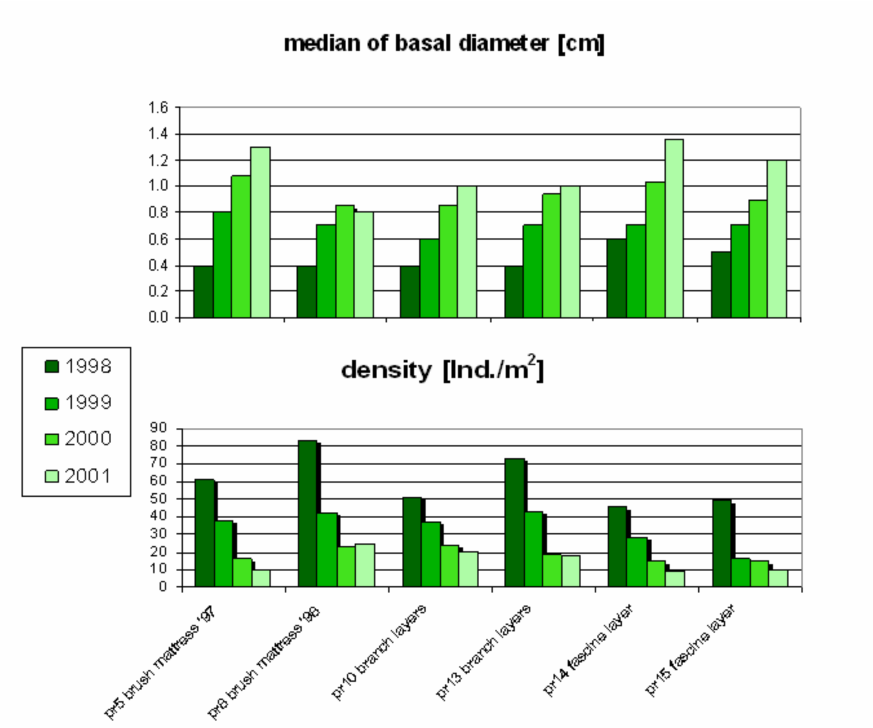


Figure 8.10 Variation in time of median basal diameter and vegetation density in different sections of the flume.

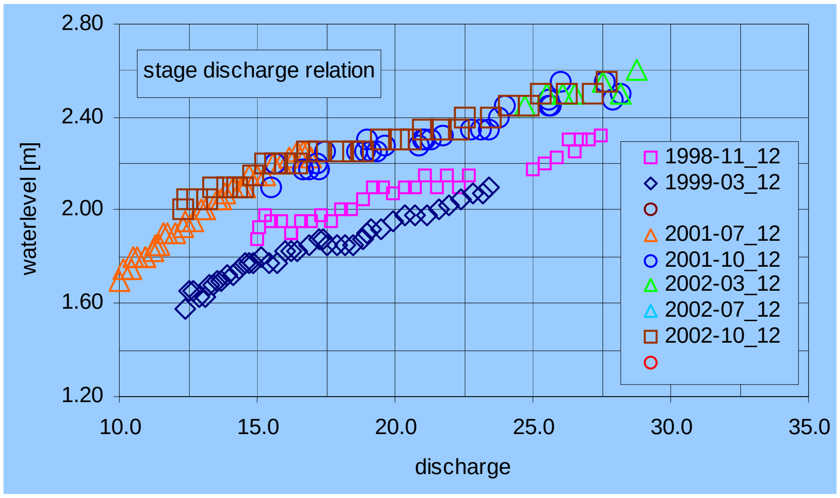


Figure 8.11 **Relationship between water level and discharge observed during floods in 1999 and 2001. Velocities are in m/s (1 m/s = 3.3 fps).**

The project done by the Department of Soil Bioengineering and Landscape Construction of the University of Agricultural Sciences in Vienna represents a very unique example of soil bioengineering research. The flume is well designed but there are some problems evident and expressed by the researchers of the University of Vienna. The major concerns are as follows:

- The frequency of tests under artificial floods depends upon the number of floods occurring in the Wien River and stored in the reservoir prior to testing. The records show a maximum of 3 runs per year.
- During the experiments, discharge was not constant due to changes in the water level in the retention reservoir. In addition, the duration of each run was relatively short comparing to the typical duration of a torrential flood.
- The intensive velocity data acquisition was only provided at a single cross-section (270 ft (82 meters) from the inlet). Therefore it was impossible to obtain velocity patterns along a channel with a non-uniform geometry.
- Simultaneously installing different bioengineering techniques along the same flume can create unfavorable hydraulics conditions due to downstream effects (under subcritical flows).
- It was not possible to evaluate the behavior of vegetation in all seasons due to the limitations pointed out earlier.
- Due to changes in geometry along the flume, a uniform flow was not realized during the experiments.

8.2. Site 1: St. Anthony Falls, Minneapolis

The St. Anthony Falls site is located on Hennepin Island in the heart of Minneapolis. Currently, there are two abandoned wasteways on the islands which used to convey part of the Mississippi River water to the lower St. Anthony Falls impoundment. The wasteways which are located on the left bank of the Mississippi River are ideal sites regarding space, access, water requirement, and security. The dimensions of the sites are illustrated in Figure 8.12 and the wasteway are designated as zone 1 and zone 2.

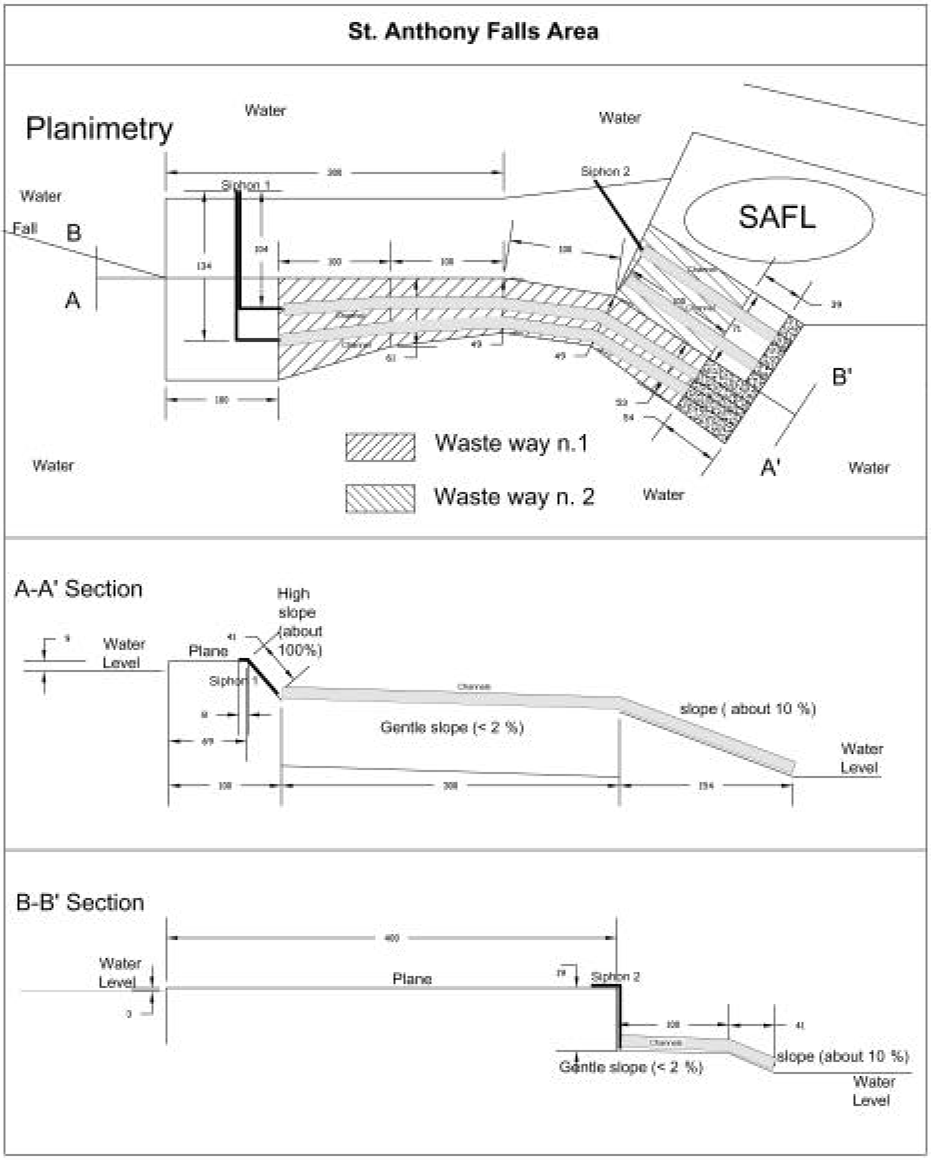


Figure 8.12 Plan view and profiles of the St. Anthony Falls wasteways.

Wasteway no. 1 is 400 ft long and 49 ft wide at its narrowest section. The bed slope ranges from 0% to 20%. Figures 8.13 and 8.14 are the photos of wasteway no. 1 taken in spring of 2004. Wasteway no. 2 is 100 ft long and 71 ft wide, with a bed slope ranging from 0 to 15% (see

Figures 8.15 and 8.16). Only 300 ft of wasteway no. 1, and 100 ft of wasteway no. 2 can be utilized for research. The width of the wasteways will allow planning for up to four flumes. By inserting a wall in the middle, up to eight flumes can be built.

Figure 8.13 Wasteway no. 1: View from upstream looking downstream.

Figure 8.14 Wasteway no. 1: View from downstream looking upstream.

Figure 8.15 Wasteway no. 2: View from upstream looking downstream.

Figure 8.16 Wasteway no. 2: View from downstream looking upstream.

Water can be supplied to the wasteways from the upper St. Anthony Falls impoundment using siphons. Two small pumps will be required for priming the siphons. The systems can be used to supply up to 300 cfs for short durations and constant and continuous discharge, e.g. 20 cfs, throughout the year. Flumes will behave like by-passes, so the supplied flow will be discharged back into the Mississippi River. Table 8.1 shows the values of discharge and velocity for different pipe diameters. Trapezoidal cross sections can be built and graded to investigate the effect of the vegetation and different techniques on the banks.

A longitudinal wall dividing the cross section in two symmetric rectangular trapezoidal cross sections can be helpful to test different techniques at the same time (Figure 8.17).

Table 8.1 Siphon design results.

	Diameter (in)	Discharge (cfs)	Velocity (fps)
Wasteway 1	32	76	13.6
	42	144	14.9
Wasteway 2	32	93	17
	42	172	18

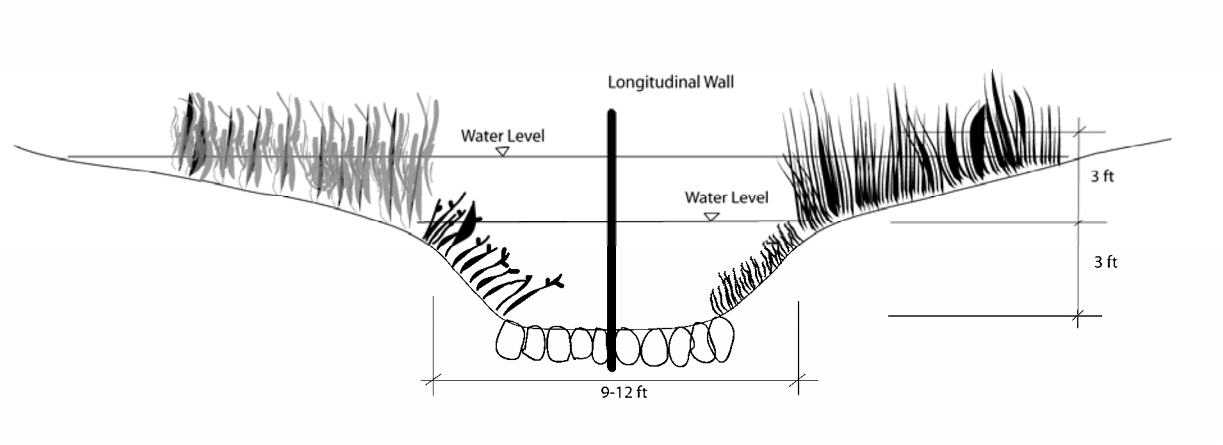


Figure 8.17 Schematic of a test flume cross section with a dividing wall.

The initial cost to prepare the site is summarized in Table 8.2. The cost includes the piping (material and labor) and the earth work. The property should be rented from Xcel and this cost is not included in the cost analysis. There have been some initial negotiations with Xcel representatives about the wasteways, and currently it seems Xcel welcomes any initiatives to utilize the wasteways as an outdoor research facility. To convert the wasteways into an outdoor research facility for soil bioengineering, the Federal Energy Regulatory Commission, and local agencies, e.g. the City of Minneapolis, the Minneapolis Park Board, the Department of Natural Resources and the St. Paul District of the US Army Corps of Engineers should approve the plan.

Table 8.2 Initial cost for the site preparation near SAFL.

Total estimated cost for soil	\$ 90,000
Estimated volume of soil per channel (zone 1) = 4500 yd^3	
Estimated volume of soil per channel (zone 2) = 1500 yd^3	
Total Pipe Cost	\$ 57,000
Total estimated length of siphon 1 =146 ft	
Total estimated length of siphon 2 =164 ft	
Pumps, valves and fittings	\$ 17,000
Labor for piping	\$ 60,000
Dividing wall materials	\$ 66,000
Labor for construction of the dividing wall	\$ 40,000
Total Estimated Cost	**\$ 330,000**

Compared to the facility visited in Vienna, following are the potential advantages of the St. Anthony Falls wasteways:

- Almost any time of the year, artificial floods with constant flow can be simulated.
- Velocity distribution can be measured along the entire flume.
- Multiple parallel flumes can be built to compare techniques or processes.
- Plants can be evaluated under flooding conditions throughout the year.

8.3. Site 2: A Reach of the Vermillion River near Empire

This site is private property along the Vermillion River to the east of State Highway 52 and the County Highway 66 intersection (Figure 8.18). The Vermillion River is a meandering river located in the South-East of the Twin Cities Metropolitan area. It is a remarkable monitoring site due to a relatively small spatial scale and high erosional-depositional activities (Figures 8.19 to 8.25).

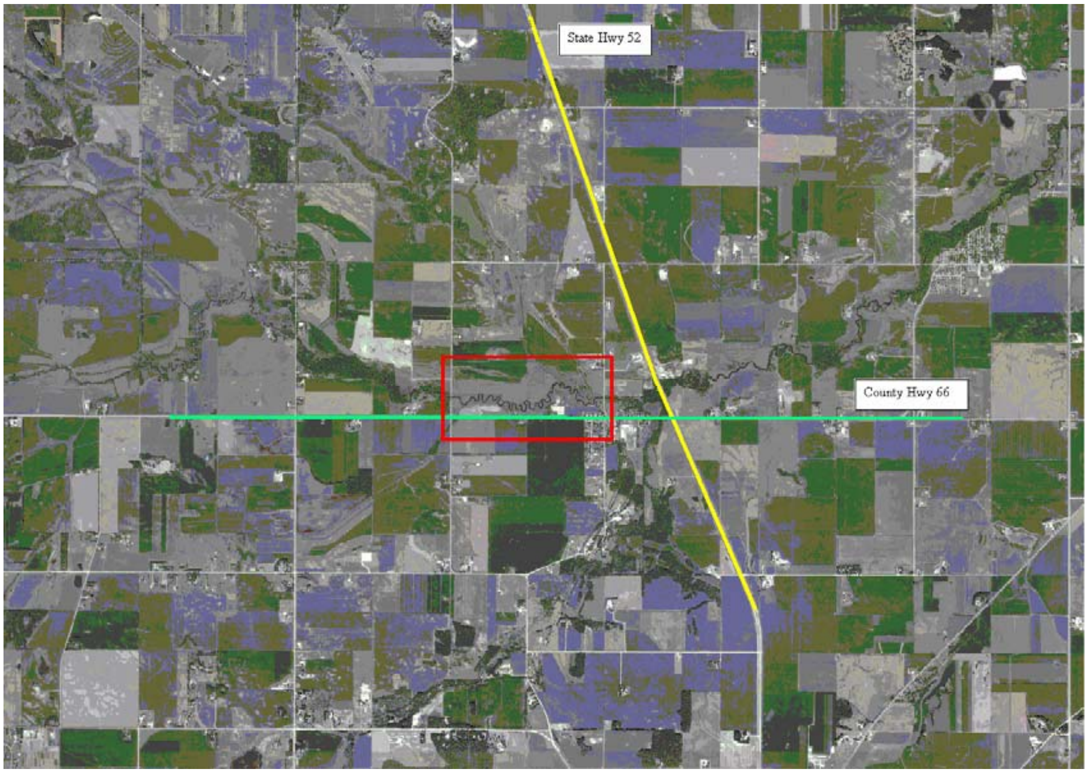


Figure 8.18 Dakota County, Vermillion River (State Hwy. 52 and County Hwy. 66)

Figure 8.19 Vermillion River, 1940

Figure 8.20 Vermillion River, 1970

Figure 8.21 Vermillion River, 2003

Figure 8.22 Vermillion River: Evolution of the center line.

Figure 8.23 Bank erosion along a bend

Figure 8.24 View of the meandering river with three bends visible.

Figure 8.25 Erosion on the flood plane shows a cutoff.

This site is proposed as an outdoor research facility for monitoring bioengineering practices. Since some parameters cannot be controlled at this site, e.g. flow rate, the work at this site will resemble fieldwork more than laboratory work. Fieldwork can be inconclusive due to lack of control over all boundary conditions and the input data. Fieldwork also takes longer than laboratory work. Nevertheless, a field monitoring site does provide answers to some key questions such as:

- How does a treated bend influence erosional and depositional processes in the downstream reach?
- What are the other factors which affect success or failure of a soil bioengineering technique?

A survey was done along the red line in the property shown in Figure 8.26. Figure 8.27 shows the cross sections and the water level along the surveyed line of Figure 8.26. From Figure 8.27 it is evident that the bed slope is about 0.09 % and the river sinuosity is equal to 2.

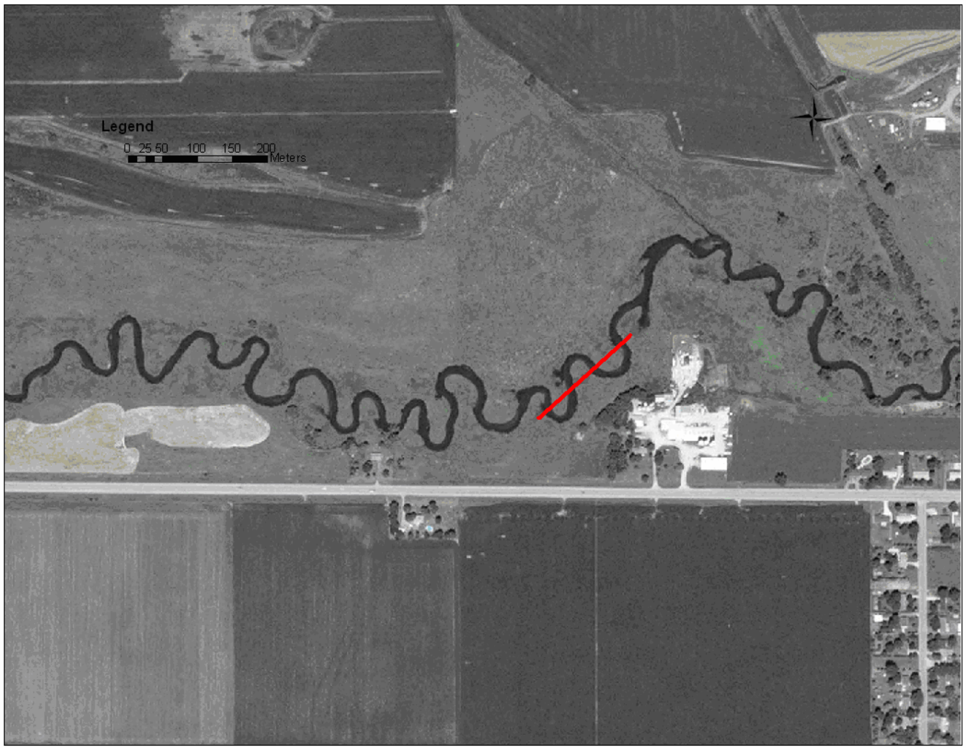


Figure 8.26 Red line tracks the surveyed section.

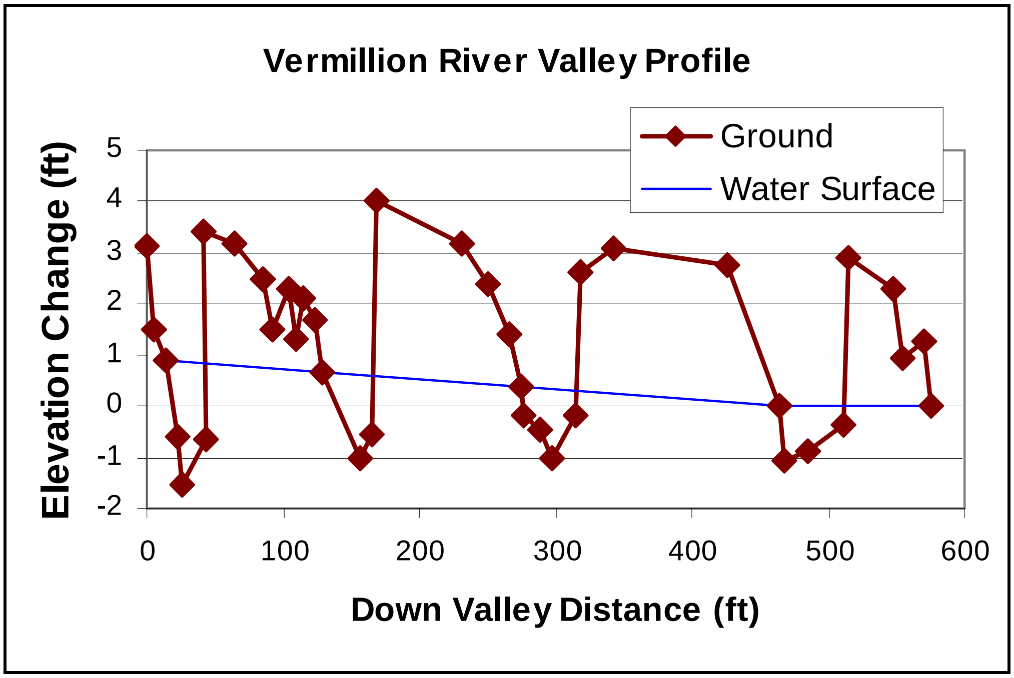


Figure 8.27 Ground and water level profiles along the surveyed section.

Figures 8.28 to 8.30 give the hydrological data collected at the USGS gaging station no. 05345000 near Empire which is located about 1 mile upstream of the site. Historical data show that 5 % of the time the river exhibits a discharge higher than 220 cfs. This corresponds to a water depth of about 4.5 ft and a mean velocity of 2 fps. To explore the effects of a flow with a mean velocity of 4.5 fps, one should probably wait a few years to encounter high flow conditions.

The initial cost for converting this site to a research facility includes the building of a shed to store tools and instruments. This cost is estimated to be about $50,000. There is also the cost of renting of the property which will be determined during negotiations with the owner. Currently, the owner is willing to rent this property to the university.

Overall, the site access is easy from the highway, and the particular area to be investigated is about a mile long and includes ten bends. It is on private property and well protected. Therefore, one can place expensive instrumentation on it for monitoring the site. By focusing on the flow regime and its influence on the erosional-depositional activities, it will be possible to describe the role of the vegetation on bank protection. The main limitation of this site is that discharge, velocity and water level elevations cannot be imposed, therefore a longer monitoring time is necessary.

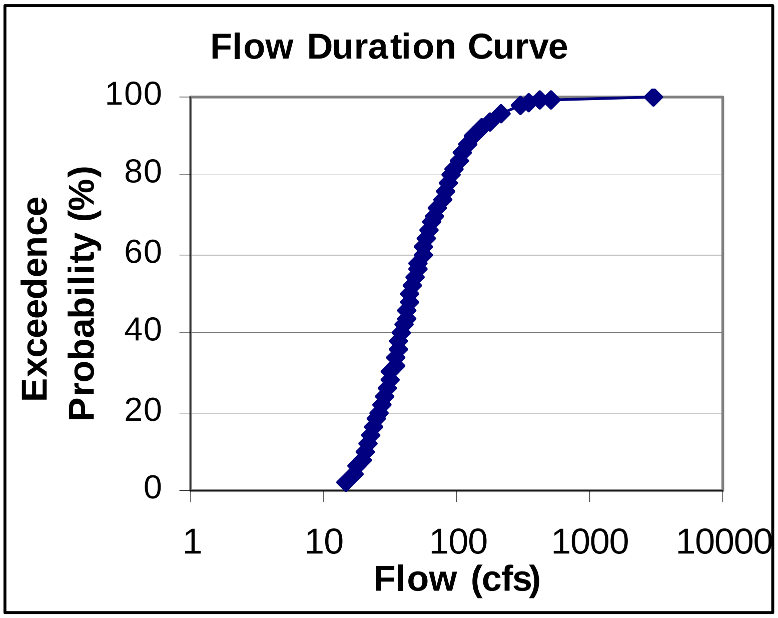


Figure 8.28 Probability of flow exceedance at gaging station no. 05345000.

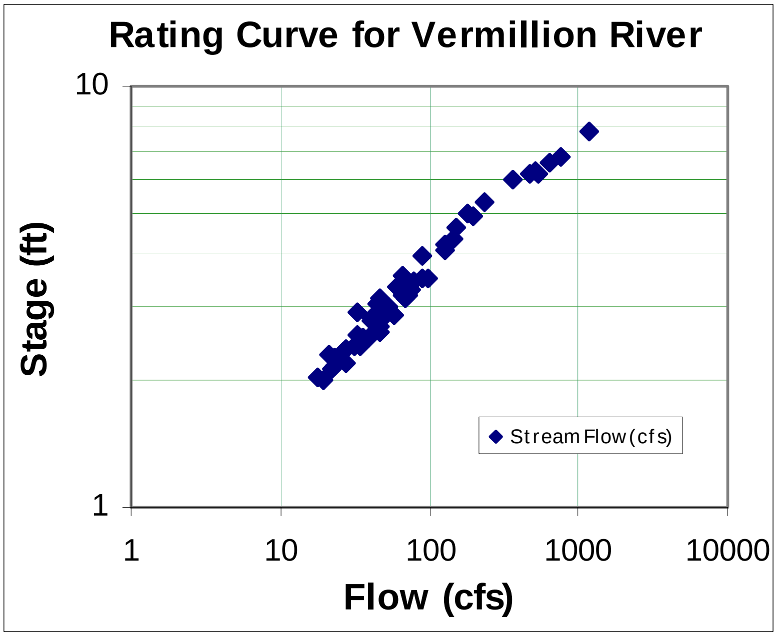


Figure 8.29 Rating Curve of the Vermillion River at the USGS gaging station no. 05345000 near Empire, about one mile upstream of the site.

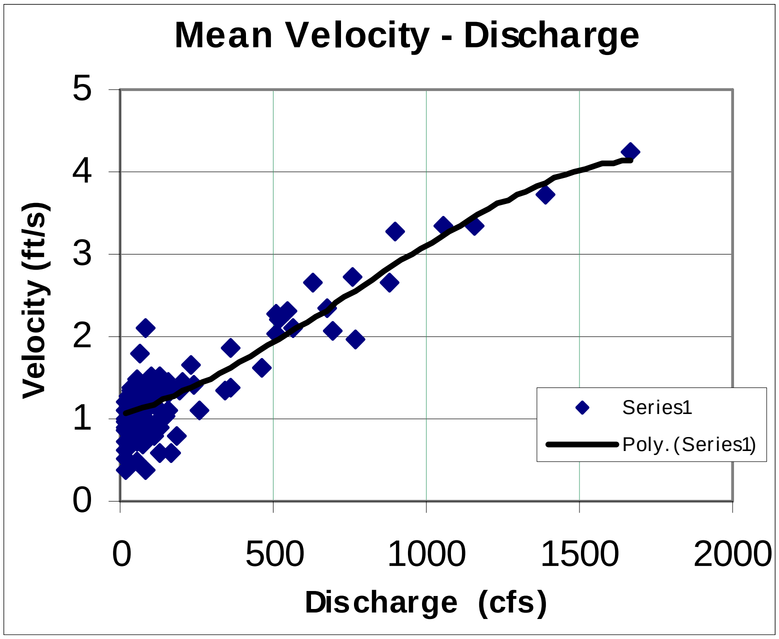


Figure 8.30 Flow and mean velocity relationship of the Vermillion River at the USGS gaging station no. 05345000 near Empire, about one mile upstream of the site.

8.4. Site 3: UMore Park in Dakota County

The University of Minnesota Outreach, Research and Education Park (UMore Park) is located in Dakota County at the edge of the city of Rosemount and Empire Township (Figure 8.31). The research sector comprises 3,200 acres. Its major goal is meeting field research needs and facilitating those activities.

The park has a flat topography in most part which is suitable for agricultural research. The topography becomes rolling in the northwest end of the park which is not currently in use by any research groups of the University (Figure 8.32).

There is no lake or perennial stream within the park which can supply the required flow for an outdoor research laboratory. However, the Empire Waste Water Treatment Plant (EWWTP) located in Farmington, MN has been discharging the treated water into the Vermillion River is planning to double the size of the plant by the end of 2004. In recognizing that doubling the discharge of treated wastewater could harm the environmentally sensitive Vermillion River, the EWWTP has chosen to pump the treated wastewater through a 13-mile pipe to be built from the EWWTP to the Mississippi River in Rosemount. The pipeline is designed to be placed near 145th St, northern boundary of the park. The pipeline is estimated to convey 10 cfs. This flow should be sufficient for experiments under base flow. However, to simulate high flow velocities, the uptake from the EWWTP's pipeline should be stored in a detention pond.

After a day searching for a suitable site within the park boundaries, the northwestern part of the park, south of 145th St., was selected as an ideal area for an outdoor soil bioengineering research laboratory (Figure 8.33). The area is about 7 acres and close to the EWWTP's pipeline, therefore, the cost of a pipeline to divert the flow is relatively small. Because of its rolling topography, the earth work to build a detention pond will not be massive.

Since there is no lake or stream to discharge the outflow from the flume into, water should be recycled, especially during high flow conditions. Recycling will allow a constant water level in the pond and the potential to create a steady state flow conditions in the flume.

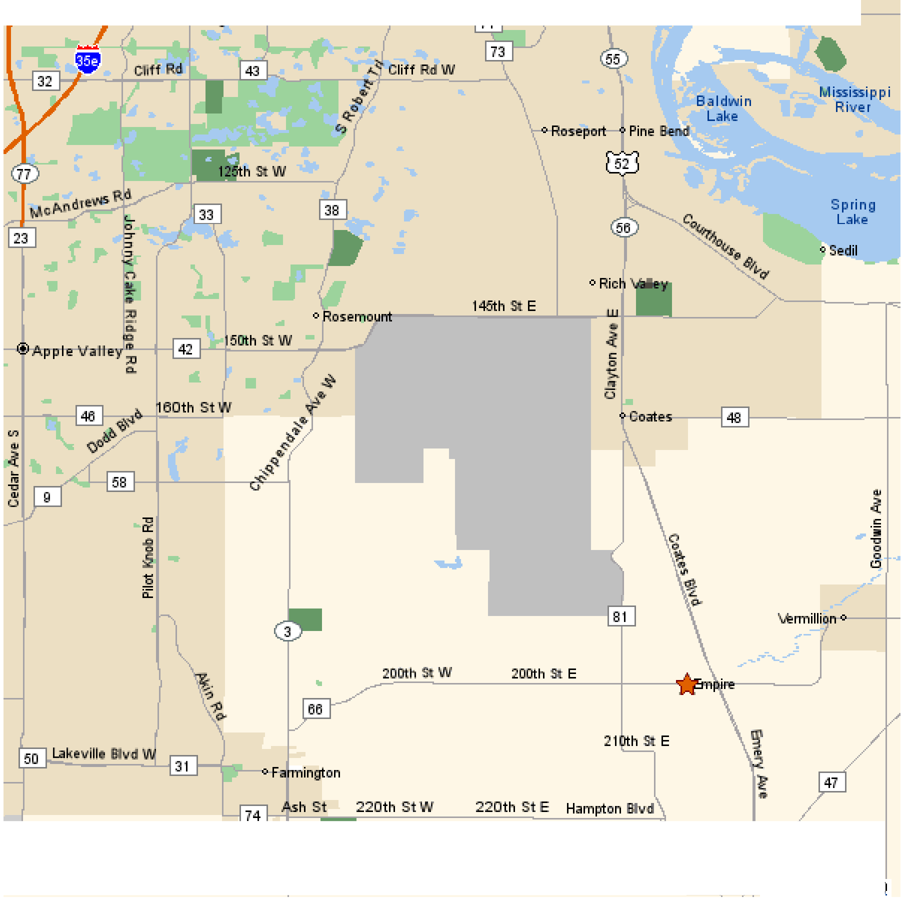


Figure 8.31 The shaded area is the UMore Park located to the northwest of Empire, MN.

The main design parameter for the pond will be its water level and not its volume. To recycle the flow, a pump station should be designed to pump up to 200 cfs (Figure 8.34). It is very likely that during high flow conditions, the area next to 145th Street happens to be flooded up to contour line 910 ft.

The top soil of the area drains well, i.e. there is a significant water loss (Figure 8.35). Since water is being recycled, the water loss through the pond cannot impact the operation. Up to 10 cfs flow from the EWWTP can easily replace the water loss. However, the flume bed and bank need to be treated with less permeable soils.

The initial cost to prepare the site is about $1.3M (Table 8.3). The cost includes the piping and the earth work. If recirculating 200 cfs is the only option, then there will be an additional cost of $2M for the pumps and pump station. The property is owned by the University, therefore, there is no rent associated with the long term cost. Compared to the facility visited in Vienna, following are the potential advantages of the UMore Park:

- Almost any time of the year, artificial floods with constant flow can be simulated.
- Velocity distribution can be measured along the entire flume.
- Multiple parallel flumes can be built to compare techniques or processes.
- Plants can be evaluated under flooding conditions throughout the year.

Compared to the site at the St. Anthony Falls, more flumes can be constructed and tested at UMore Park, nevertheless, the initial cost is significantly higher than that for St. Anthony Falls.

Table 8.3 Initial cost for the site preparation at UMore Park

Total estimated cost for earthwork	$ 740,000
Estimated volume = 37,000 yd^3	
Concrete structures: intake, inflow structure, etc.	$ 200,000
Total Pipe Cost	$ 80,000
Total estimated length of pipes =400 ft	
Labor for piping	$ 80,000
Valves, fittings, etc.	$ 20,000
Dividing wall materials	$ 140,000
Labor for construction of the dividing wall	$ 80,000
Total site preparation	**$ 1,340,000**
Pumps and Pump Station for recirculating 200 cfs	$ 2,000,000
Total Estimated Cost	**$ 3,340,000**

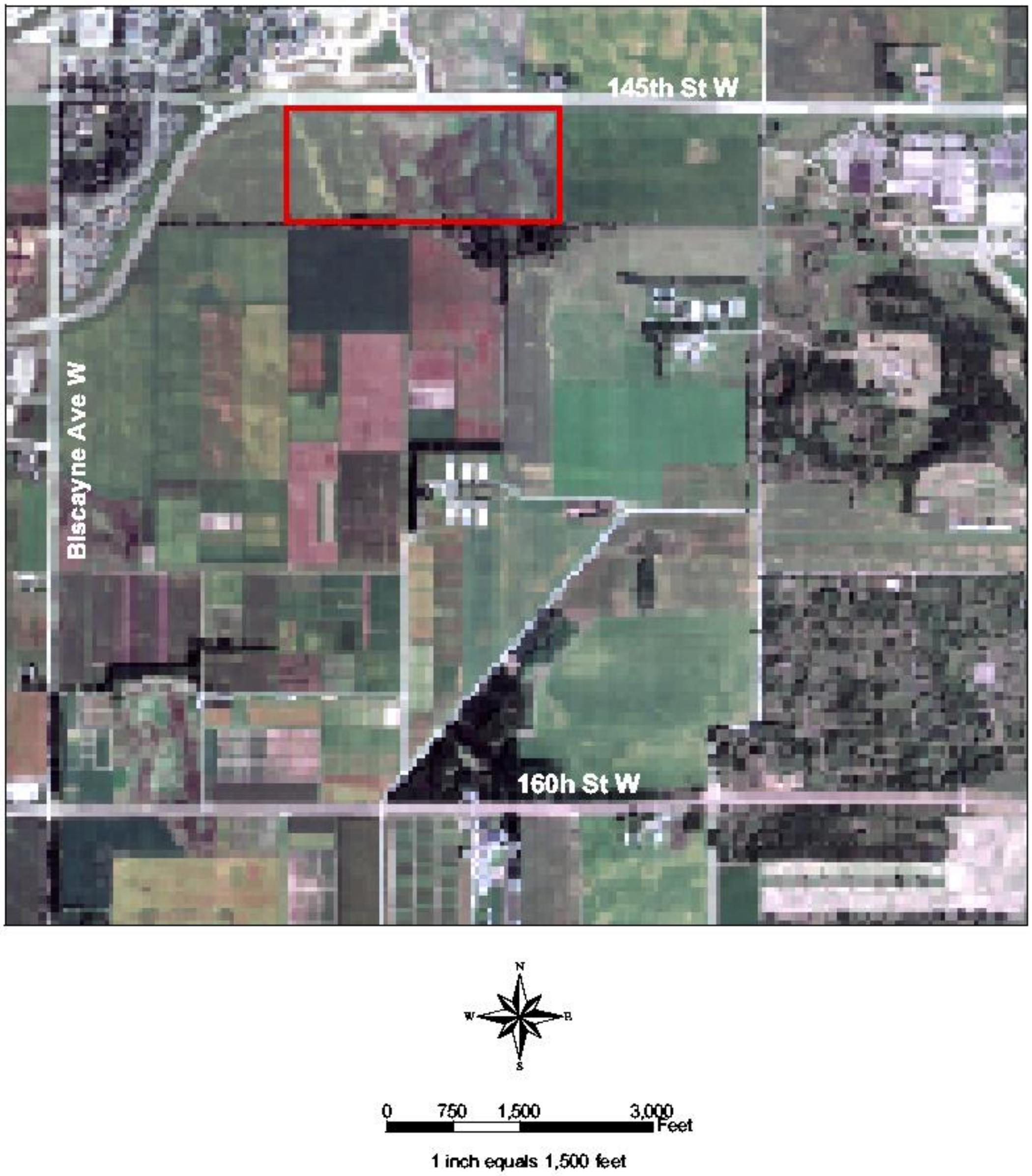


Figure 8.32 The candidate outdoor research site within the boundaries of UMore Park.

Figure 8.33 Looking north, a panoramic view of the potential site in UMore Park for the soil bioengineering research laboratory.

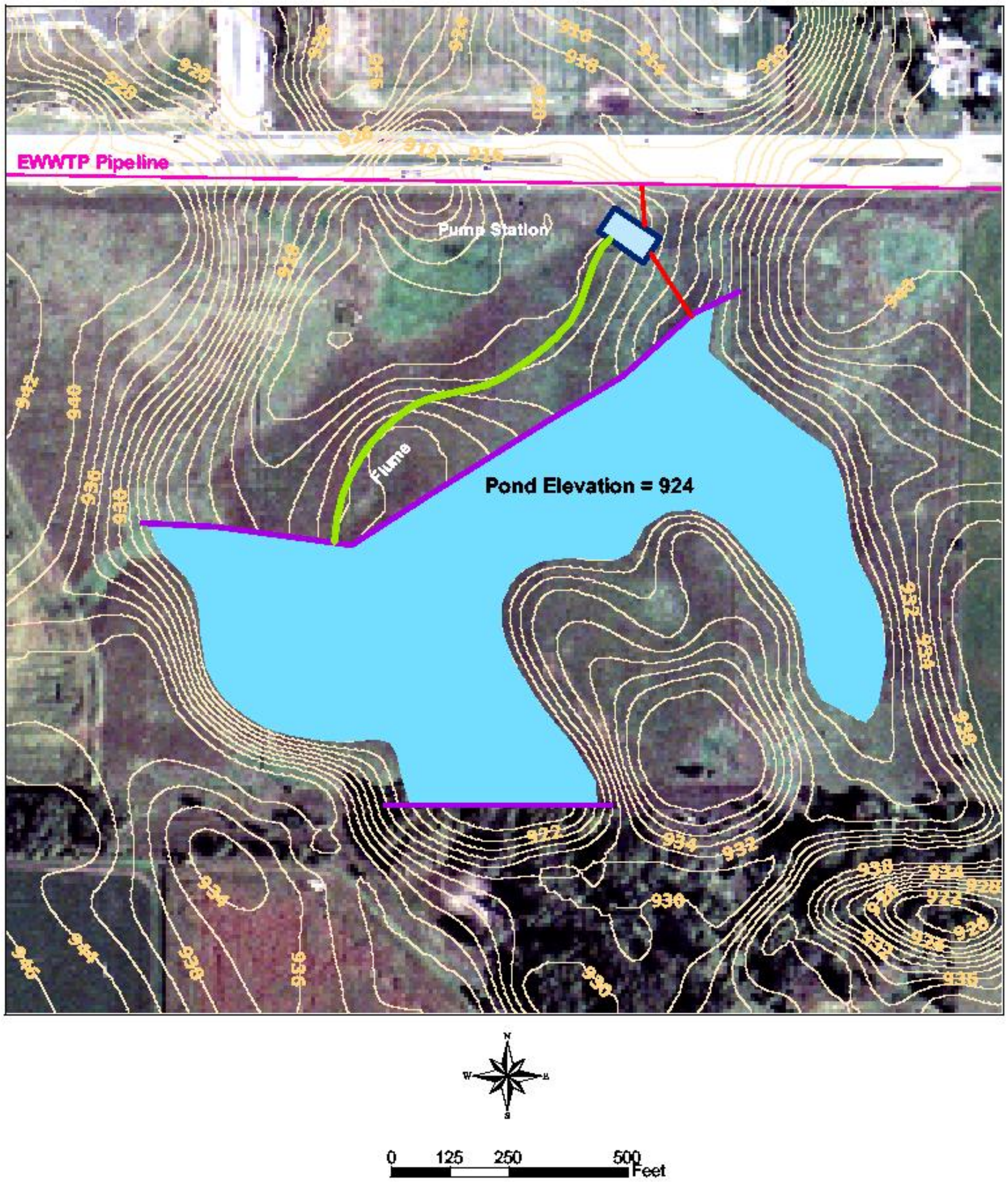


Figure 8.34 The layout of the pond, pipeline, pump house and the flume in UMore Park.

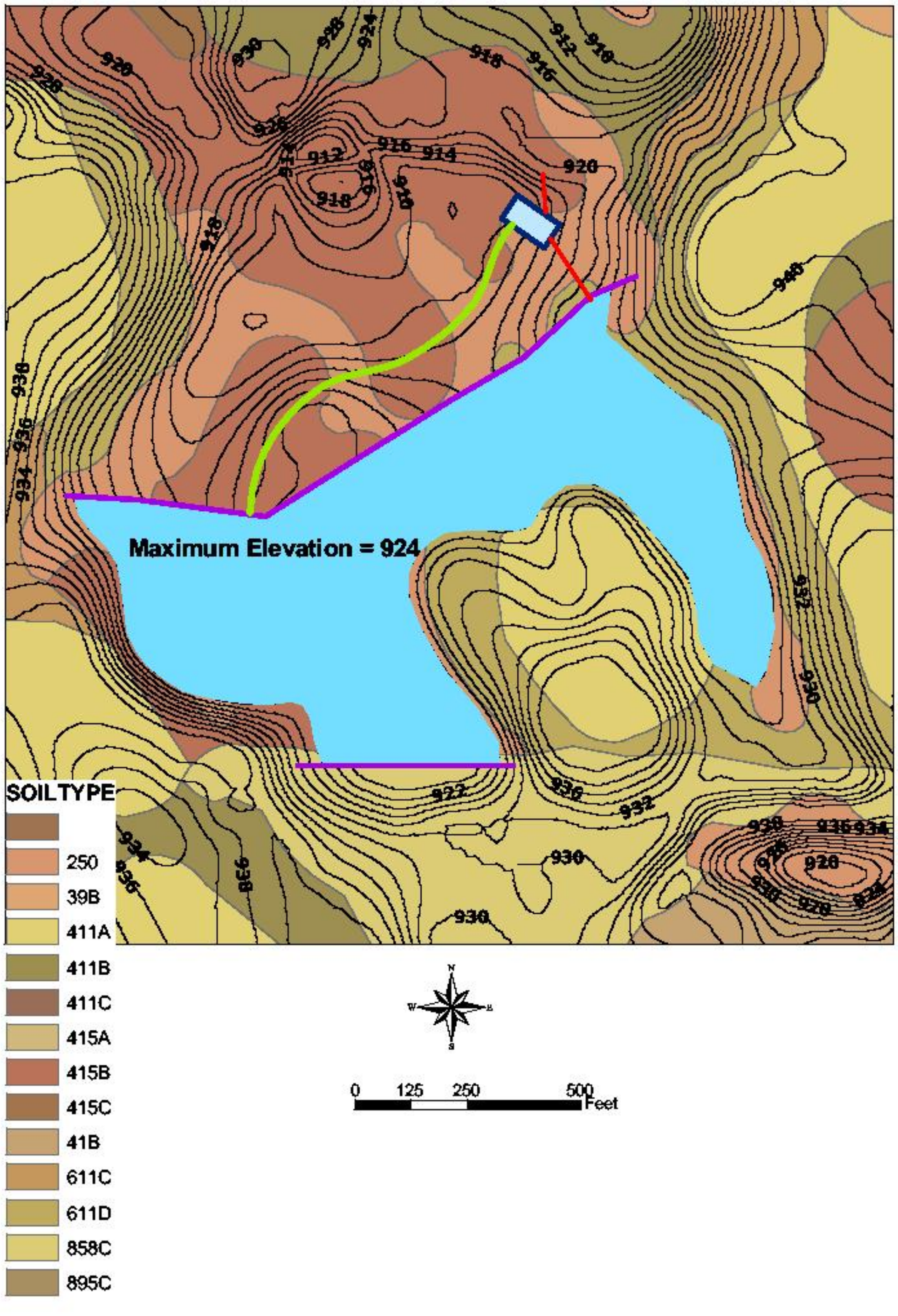


Figure 8.35 Soil types in the vicinity of the potential outdoor facility. The soils shown in the figure drain moderately well to well, i.e. according to NRCS hydrologic groups A and B. Therefore, there will be a significant water loss from the pond.

Chapter 9. Summary and Conclusion

In order to develop design guidelines for soil bioengineering and bioengineering technology, a pilot study was conducted to determine the work done in these areas, and to define the existing research needs and the potential sites for an outdoor research facility. The pilot study included a literature review, interviews of 11 practitioners in the field, three site visits and project evaluations and a summary of research needs.

The study, specifically the interviews, shows that despite an increasing popularity in using the soil bioengineering techniques to protect streambanks and slopes, the field is more of an art than a science. A significant number of studies have been done on different topics related to soil bioengineering techniques, however, the studies mainly address the problems at a micro scale, and hence, there is a gap between existing knowledge and practice. Therefore, there is an urgent need to not only study some of the fundamental processes and mechanisms involved in soil bioengineering techniques, but also to investigate these processes at a macro scale to evaluate their strengths and impacts when applied to streambanks and slopes.

Main highlights of the research needs identified in this study were a) quantifying the bank and bed roughness with the most common plants used in bioengineering techniques, b) studying the added shear strength to banks by vegetation, c) determining the resiliency of different plants under high flow conditions, e) understanding the mechanisms which cause failure of plants under different flow conditions, f) quantifying the shear strength of the commonly used techniques for a range of bank slopes, top soil depths and soil types, and g) determining the shear strength of composite systems, where different plants and techniques are combined.

In addition to the literature review and interviews, a site visit of the Department of Soil Bioengineering and Landscape Construction of the University of Agricultural Sciences in Vienna, Austria, and three site visits and site evaluations were done for a potential outdoor research facility in the vicinity of the Twin Cities area, Minnesota. The three candidate sites were (1) the two abandoned wasteways near the Falls of St. Anthony located adjacent to the St. Anthony Falls Laboratory, (2) a 7 acre area in the northern part of the UMore Park, a University of Minnesota property allocated for research, and (3) a short reach of the Vermillion River near Empire, MN, located on private property.

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