Beyond Root Reinforcement: the hydrologic effects of riparian vegetation on riverbank stability

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Abstract

Riparian vegetation has many well-documented beneficial properties for river restoration and bank stabilization. However, the hydrologic effects of vegetation on bank stability are more ambiguous, poorly quantified, and potentially detrimental in some cases. This paper presents results from an experiment in which the hydrologic effects of different riparian covers were quantified in relation to bank stability. Geotechnical and pore-water pressure data from streambank plots under three riparian vegetation covers (bare, grass and trees) were used to drive the ARS Streambank Stability Model, and the resulting factor of safety (F_s) was broken down into its constituent parts to assess the contribution (beneficial or detrimental) of individual hydrologic and mechanical effects. Data on the mechanical effects of vegetation were obtained in an associated project reported in a companion paper (Simon and Collison, 2001).

Canopy interception was relatively insignificant (approximately 3%) especially during the crucial winter and spring period when most bank failures occur. Interception remained insignificant during the summer as most rain fell in high intensity events that exceeded the storage capacity of the canopy many times over. However, transpiration under the tree cover had a very significant impact on pore-water pressure which persisted through the winter and spring in some cases.

Slope stability analysis based on data collected during bank failures in spring 2000 (following a very dry antecedent period) shows that the mechanical effects of the tree cover increased F_s by 32%, while the hydrologic effects increased F_s by 71%. For grasses the figures were 70% for mechanical effects and a *reduction* of F_s by 10% for the hydrologic effects. However, analysis based on bank failures in spring 2001 (following a wetter than average antecedent period) showed the mechanical effects of the tree cover to increase F_s by 46%, while hydrologic effects added 29%. For grasses the figures were 49% and –15% respectively. During several periods in spring 2001 the hydrologic effects of the tree cover *reduced* bank stability, though this was always offset by the stabilizing mechanical effects. The results demonstrate the importance of hydrologic processes in controlling streambank stability, and highlight the need to select riparian vegetation based on hydrologic as well as mechanical and ecological criteria.

Streambank Stability

Thousands of miles of streambanks in the US are unstable due to channel incision, lateral migration and livestock impacts. Streambank instability is both an on, and increasingly, off-site problem. On-site problems include loss of land, damage to infrastructure, and habitat destruction, while off-site problems include increased sediment supply, release of contaminated sediment from riparian buffers, and downstream silting. Streambank collapse occurs when the driving forces (stress) exceed the resisting forces (strength). The shear strength of saturated soil can be described by the Mohr-Coulomb criterion:

$$\tau_f = c' + (\sigma - \mu_w) \tan\phi' \quad (1)$$

where τ_f = shear stress at failure (kPa); c'=effective cohesion (kPa); σ = normal stress (kPa); μ_w = pore-water pressure (kPa); and ϕ'= effective angle of internal friction (degrees).

In many stream channels much of the bank may be above the water table, and will usually experience unsaturated conditions. Matric suction (negative pore-water pressure) above the water table has the effect of increasing the apparent cohesion of a soil. Fredlund et al., (1978) defined a functional relationship describing increasing soil strength with increasing matric suction. The rate of increase is defined by the parameter ϕ^b.

$$c_a = c' + (\mu_a - \mu_w) \tan \phi^b = c' + \psi \tan \phi^b \quad (2)$$

where c_a = apparent cohesion (kPa); μ_a = pore-air pressure (kPa); and ψ = matric suction (kPa). Once ϕ^b is known (or assumed) apparent cohesion (c') in the soil can be estimated by measuring matric suction with tensiometers or other devices and by using equation 2.

Driving forces for streambank instability include the bank height and gradient, the unit weight of the soil and mass of water within it, and the surcharge imposed by objects (including trees) on the bank top. The ratio of resisting to driving forces is commonly expressed to give a Factor of Safety (F_s), where values greater than one indicate stability and those less than one, instability.

Hydrologic Effects of Vegetation on Bank Stability

The impact of vegetation can be divided into mechanical and hydrologic effects, with further subdivision into stabilizing and destabilizing effects. The mechanical effects of vegetation are covered in a companion paper (Simon and Collison, 2001), but can be summarized as increased soil strength due to root reinforcement (stabilizing) and increased surcharge due to tree weight (destabilizing). Considering hydrology, vegetation increases bank stability by intercepting rainfall that would otherwise have infiltrated into the bank, and by extracting soil moisture for transpiration. Both processes reduce positive pore-water pressure and encourage the development of matric suction. In contrast, vegetation has several effects that are detrimental to streambank stabilization. Canopy interception and stemflow tends to concentrate rainfall locally around the stem of plants, creating high pore-water pressure (Durocher, 1990), while root development and associated biological activity creates macropores that increase infiltration capacity and concentrate flow deeper into the bank. Collison and Anderson (1996) used combined hydrology-stability modeling to simulate increased infiltration and preferential flow on vegetated slopes in the humid tropics, and demonstrated that the beneficial mechanical effects of vegetation can be outweighed by the hydrologic effects, leading to lower factor of safety values during intense rainstorms in some cases. These effects are most pronounced during and immediately after large rainfall events of the type that are often associated with bank failure.

The hydrologic effects of riparian vegetation are even less well quantified than the mechanical effects. Although data are available on canopy-interception rates for many riparian tree species, there is little information on the degree to which vegetation dries out the material comprising streambanks. Canopy interception for deciduous tree species is typically in the range of 10-20%, (see Coppin and Richards, 1990) but these figures are annual averages. A point that tends to be overlooked when discussing vegetation effects on bank stability is that most bank failures in temperate regions occur during the winter or early spring, when deciduous vegetation is dormant and canopies have been shed. In addition, the high rainfall events likely to be associated with bank failures tend to have the lowest canopy interception rates, since canopy interception is inversely proportional to rainfall intensity and duration. Likewise, transpiration does not generally have much impact on soil moisture until mid-spring.

The hydrologic behavior of streambanks is particularly important in channels with high banks and in dryland areas, since these banks are normally unsaturated, and so are sensitive to increases in moisture content. Decreases in shear strength due to a loss of matric suction are a leading cause of bank failures in incised channels (Simon *et al*., 1999). However, where banks are lower, and in more humid areas, streambanks may be expected to reach saturation during typical winter conditions, yet remain stable because they are not particularly high. Any detrimental hydrologic effects are likely to be much less significant, because common hydrologic conditions already represent a 'worst case'.

There is a general consensus in the literature that the main effects of vegetation on bank stability are mechanical rather than hydrological. To quote Coppin and Richards (1990, p.65) "Although the ability of trees to reduce soil moisture is recognized qualitatively, it has yet to be quantified. The magnitude of their influence on soil strength, however, is likely to be less than that of soil reinforcement by roots, especially at periods critical for slope stability." In order to evaluate this common assumption, and assess the effectiveness of vegetation covers as stability enhancements, it is necessary to quantify all of those effects.

Methodology

Data were collected on the hydrologic and mechanical properties of three vegetation test plots on an unstable incised streambank in northern Mississippi. The data collected include intrinsic soil-mechanical properties (cohesion, friction angle, unsaturated strength parameter and unit weight), matric suction and pore-water pressure under three vegetation treatments, and root tensile strength and distribution for a range of species. The three vegetation treatments were control (short cropped turf), eastern gamma grass (a tall clump grass), and a mature riparian-tree stand (a mixture of sycamore (*Platanus occidentalis*), river birch (*Betula nigra*) and sweetgum (*Liquidambar styroflora*)). The data were used to parameterize a model of streambank stability that incorporates positive and negative pore-water pressures. Additional root data were collected on black willow (*Salix nigra*) and Alamo switch grass (*Panicum virgatum* 'Alamo'). Black willow is widely used in channel stabilization projects, and switch grass is used in erosion control locally.

Field data collection. The research was carried out at the Goodwin Creek Experimental Watershed in the Loess Hills region of northern Mississippi. Mean annual rainfall at the site is 1314 mm and climate is warm and humid. The channel in the study reach has incised approximately three meters historically, to a current depth of about five meters. For at least the last four years the channel has been relatively stable in terms of depth, with slight aggradation accompanying lateral migration by mass failures on the outside of meander bends. The bank cross section is steep, generally between 70 and 90º.

An Iowa Borehole Shear Test (BST) device was used to measure the *in situ* strength of bank layers at different depths in a series of boreholes augered into the streambank. A series of repeated tests were made in a small area, and matric suction was measured in an undisturbed core removed from the point where the BST was operated. In this way it was possible to calculate the unsaturated strength parameter ϕ^b to obtain the relationship between matric suction and effective cohesion using equation 2.

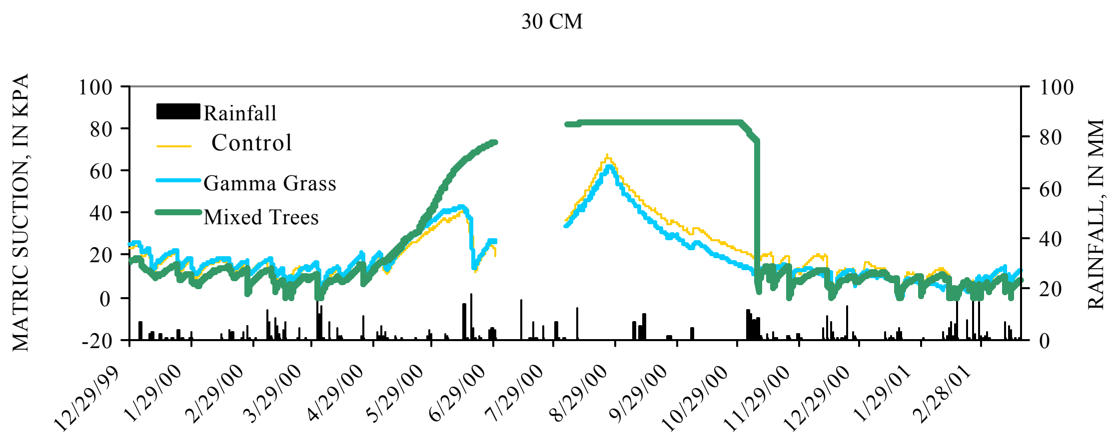
Bank hydrology was monitored using tensiometers which recorded pore-water pressure (positive and negative) every ten minutes. At each of the three vegetation treatment plots, a nest of five tensiometers was installed, at depths of 30, 100, 200, 270 and 433 cm. Streamflow level was also recorded every ten minutes using two submerged pressure transducers mounted in the channel. Open sky rainfall, stemflow and canopy throughfall under the riparian tree plot were recorded on tipping bucket rain gages every ten minutes, with an additional array of 12 manual rain gages (10 in the woody stand and two in the open) measuring rainfall and throughfall every day on which rain occurred.

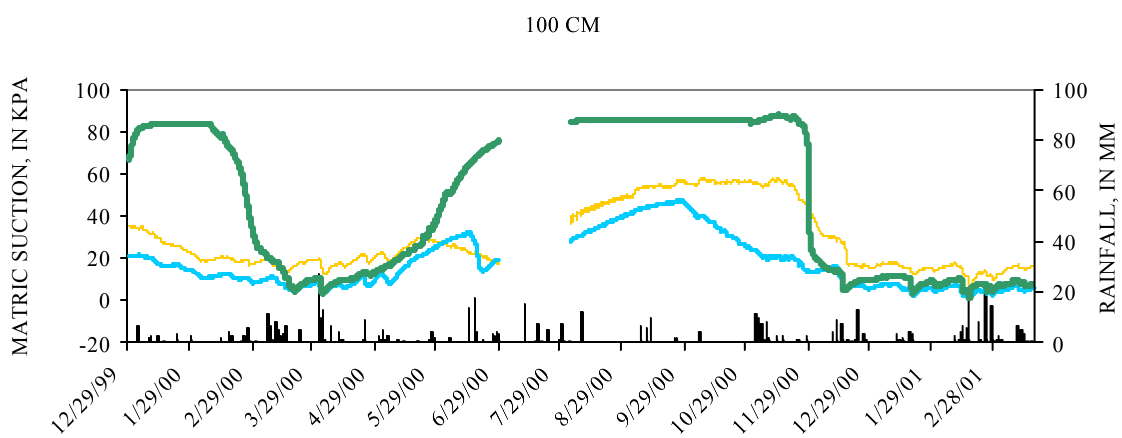
Numerical modeling of bank stability. To assess vegetation effects on bank stability hydrologic and mechanical data were used in a numerical model of bank stability. The ARS Streambank Stability Model is a further development of the wedge failure type developed by Simon and Curini (1998) and Simon *et al*. (1999). The model is a Limit Equilibrium analysis in which the Mohr Coulomb failure criterion is used for the saturated portion of the wedge, and the Fredlund *et al.* (1978) criterion is used for the unsaturated portion. In addition to positive and negative pore-water pressure, the model incorporates layered soils, changes in soil unit weight based on moisture content, and external confining pressure from streamflow. The model divides the bank profile into up to five user definable layers with unique geotechnical properties. When driven with temporally and spatially distributed pore-water pressure data from the tensiometer nests, the output is a time series of F_s. In this study the model was parameterized with data from each of the three vegetation plots. Identical bank profiles and intrinsic soil-strength properties (c', ϕ', ϕ^b) were used for all three plot simulations, while measured pore-water pressures, soil weight due to moisture content and increased cohesion due to roots (c_r) were applied uniquely to each plot. For the mixed tree plot averaged values of c_r, root depth distribution and surcharge due to tree weight were used to reflect the three species (see companion paper, Simon and Collison, 2001). In addition to the combined effect simulations, model runs were carried out isolating the individual effects of root reinforcement, pore-water pressure and surcharge, to enable quantification of these components. Additional simulations were performed using the mechanical effects of two alternative covers; black willow and Alamo switch grass. Since independent pore-water pressure data were not available for these treatments we assumed that pore-water pressure under black willow was identical to that recorded under the riparian tree cover, and that switch grass could be represented by data from the gamma grass cover.

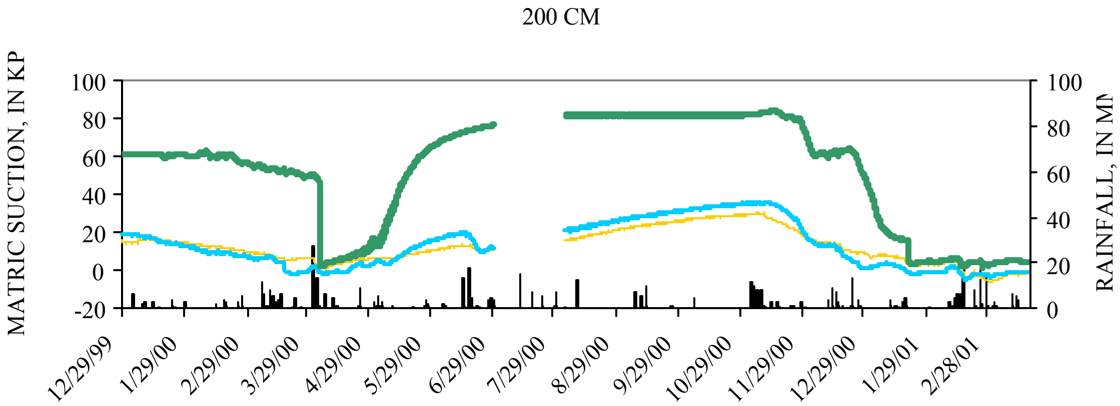
Results

Intrinsic bank properties. Inspection of the bank profile and boreholes revealed four layers within the bank. The stratigraphy can be divided into two major layers of approximately 1 and 2 meters thickness, representing early and late Holocene alluvial deposits. At the base, the bank rests on a thin layer of cemented sand and gravel overlying clay. Strength testing shows the late Holocene layer to be fine sand with little or no cohesion (<2.7 kPa, ϕ'=28°). Most of the apparent cohesion in this layer is due to matric suction. The early Holocene silt unit by comparison has greater cohesion (6.3 kPa, f' = 27°), and acts as a semi-permeable boundary below the upper layer, contributing to the development of higher moisture contents and pore-water pressures in the late Holocene unit after rainfall. Most bank failures occur within the two Holocene layers.

Hydrologic effects of vegetation. Canopy interception under the mixed tree plot was negligible during the study period, accounting for 2.9% of total rainfall. This figure is low compared to typical literature values for deciduous woodland, but is largely explained by the seasonality and intensity of rainfall in the area. Approximately two thirds of annual rain falls between October and April, when canopy cover is absent. In addition, summer rain mostly occurs in very high intensity events that greatly exceed the storage capacity of the canopy and pass through as throughfall. In some respects the canopy had adverse effects on bank stability; although stemflow was small in percentage terms when weighted for canopy area, it provided a concentrated source of water for infiltration around the tree trunk. Delivery of effective rainfall around the trunk was orders of magnitude higher than the average rainfall rate over the whole canopy area, with several events contributing more than 10 liters of stemflow.







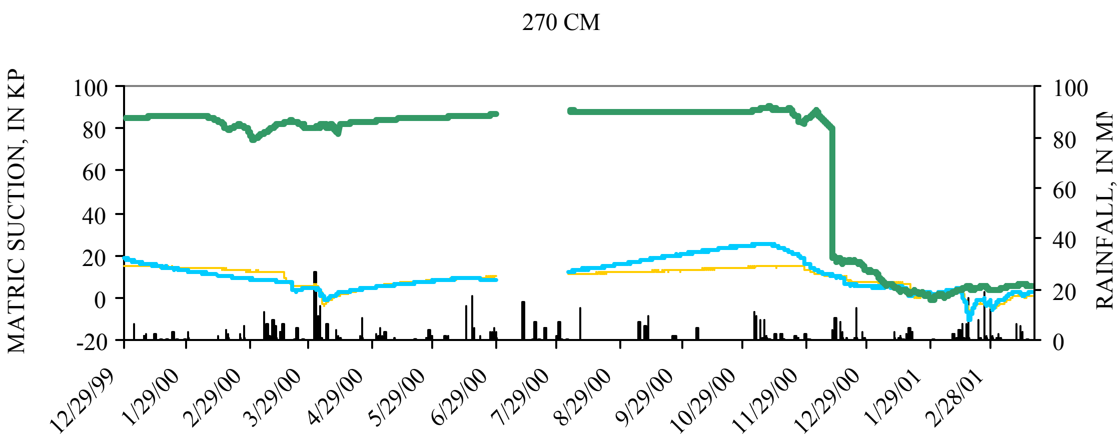


Figure 1. Pore-water pressure response to rainfall for the three streambank vegetation covers

Pore-water pressure monitoring reveals significant differences between the three vegetative covers (Figure 1). Note that due to an artificial irrigation experiment during July 2000, data for this period have been removed from the record. The tensiometers used to monitor pore-water pressure have an upper limit of 83 kPa, above which values appear to 'flat line'. At 30-cm there is little difference between the plots during winter and spring, although the tree cover is slightly wetter (lower matric suction) than either clump grass or the control site from December 1999 until May 2000. During summer and fall very high suctions are developed. A striking feature of all of the records is the difference between the tree plot and the other two plots prior to the onset of the winter, wet season. Matric suction under the tree plot is 40 to 60 kPa higher than under the other treatments. The tree cover experiences brief periods of 'negative suction' (positive pore-water pressure) after rainfall events in the spring, indicating increased infiltration capacity and the development of a perched water table in the root zone. The steep decline in suction under this cover indicates enhanced infiltration rates via macropores, probably along root pathways. This represents one of the potential detrimental effects of woody vegetation. After

May, the tree site dries out faster than the other sites owing to greater rates of evapotranspiration, rising above the maximum measurable suction of 83 kPa by August.

Comparison of the tensiometer results from 100 cm reveals significant differences between all three covers. The control site and the grass plot broadly track each other, with the control consistently maintaining a suction around 10 to 20 kPa higher than the grass, indicating that stemflow may be concentrating water to depth in the grass plot. This is even more pronounced in the tree plot, further pointing to the potential negative effects of rapid delivery of water along root- and faunal-induced macropores. Evidence for preferential macropore flow is not confined to the vegetation covers however, with all three treatments showing response times to the April 4th event that exceed matric conductivities.

In general, the deeper the tensiometer, the slower the response to the onset of rainfall under all treatments as rainwater infiltrates from the surface downward. The tree cover shows the maintenance of the previous summer's soil-moisture deficit through February 2000, at which point rapid wetting occurs at 100 cm. This wetting is associated with a series of relatively small rainfall events and the effect is translated to the deeper tensiometers with time as the 270 cm instrument begins to respond in early April. The 270 cm tensiometer also demonstrates the threshold effects of wet winter conditions; throughout the 1999-2000 winter high tensions were maintained at this depth suggesting that all water was absorbed by dry soil higher in the profile, but in December 2000 a threshold was clearly crossed and rapid wetting occurred at this depth.

The tensiometer data suggests that there is relatively little hydrologic difference between clump grasses and a control (cropped grass) cover, except during rainfall events when there is evidence for higher infiltration rates and preferential flow under the grass cover. The cropped grass of the control site was observed to recover from the winter faster than the clump grass, which has a longer dormant period. There is some evidence from the tensiometers to suggest that the control cover was transpiring earlier, and that the clump grasses did not start to transpire until May. This is supported by field observations of stem growth at around the same time.

Although the streambank under the tree cover maintained the greatest average values of matric suction, and, therefore, provided hydrologic benefits most of the time, rapid wetting at depth during spring 2001 led to brief periods when the tree plot was wetter than either the grass or bare plots, and thus caused a detrimental hydrologic effect.

Bank stability modeling. Figure 2 shows output from the bank stability model for the period September 1999 to March 2001, showing estimated F_s for the three vegetation plots. Values below 1 indicate predicted mass failure. Two periods of observed mass failure are indicated, in April 2000 (bare site only) and February 2001 (bare and grass sites). The model successfully captured these failures, with F_s less than 1 for the plots at the time of failure, but at no other time. The figure clearly shows the increased stability due to the tree cover at the start of winter 2000, with the previous summer and fall's soil moisture deficit maintaining high matric suction and so stability. During the same period grass had approximately the same pore-water pressure distribution as the bare site, and the increase in F_s was due to root reinforcement. Rainfall preceding the April 2000 bank failure markedly reduced the F_s of the tree-covered bank, but at the point of minimum stability it still had a F_s value of 1.99, compared to 1.22 for the grass site and 0.98 for the bare site. As late spring began, F_s under all three covers rose in response to higher matric suctions, with the greatest recovery occurring under the tree cover as transpiration picked up. A very large soil moisture deficit was built up under the tree cover, which provided protection through to January 2001. During the wetter than average winter of 2000-01 we saw a greater decline in F_s under all three covers, culminating in a second set of failures that occurred during February-March 2001.

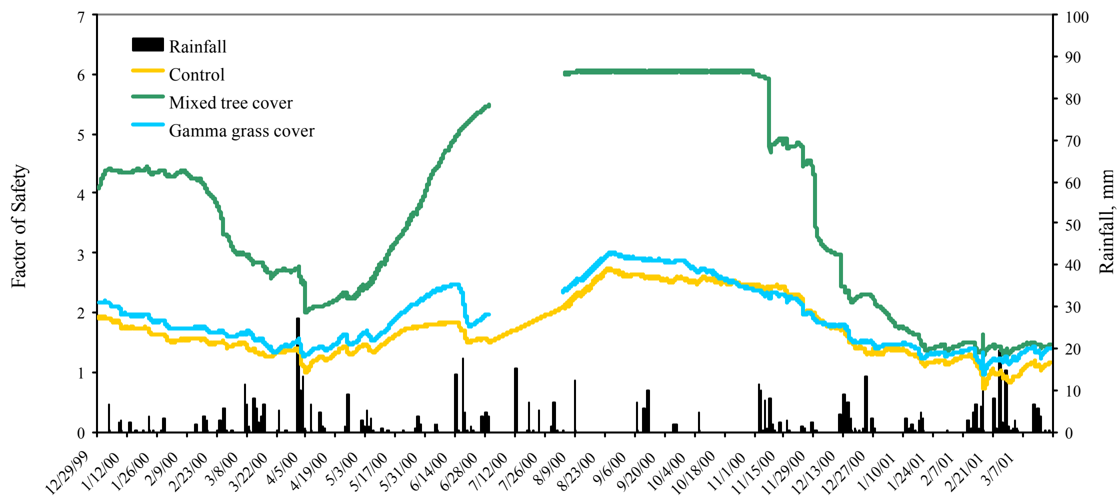
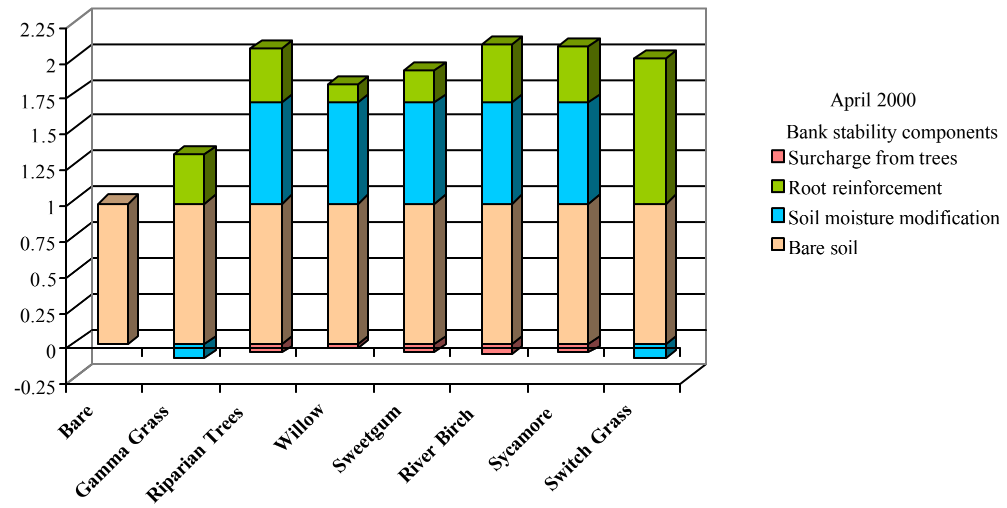


Figure 2. Factor of safety versus time for the three streambank vegetation covers

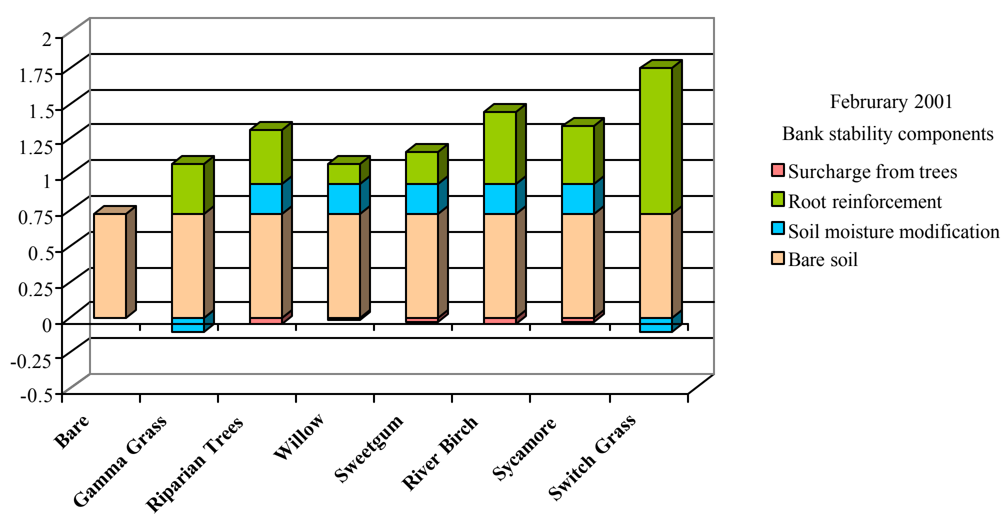
Evaluating components of bank stability due to vegetation. The periods of observed bank failure provide us with an opportunity to break down the contributions of vegetation to bank stability, by using the model to assess each attribute (root reinforcement, surcharge and modified pore-water pressure) separately and in combination. The April 2000 period was initially taken and separate simulations were performed adding in each component one at a time to identify the addition or subtraction from net F_s (Figure 3a). The figure shows F_s for the bare soil as the basic condition, with stabilizing effects on top and destabilizing effects shown below. Bare ground F_s during this period was 0.98, reflecting the bank failure of April 4th. F_s on the gamma grass plot was increased by 35% by adding in root reinforcement effects, but reduced by 10% due to the detrimental effects of wetter soil conditions, to give a net increase of 24%. For the mixed tree cover root reinforcement increased F_s by 39%. Strikingly, the hydrologic effects were more beneficial than the mechanical effects, increasing F_s by 71%. Surcharge reduced F_s by 7%, leaving a net F_s of 1.99 (103% increase).

In order to evaluate the effectiveness of individual species for bank stabilization, data from the root studies were applied in the stability model. Since there is only a single hydrologic plot for riparian trees, this was taken as the condition for all four tree species. An average value of surcharge was applied to all trees except black willow, for which a value of half the average was used to reflect the smaller specimens found. For switch grass, hydrologic data from the gamma grass plot were used. While the substitution of hydrologic data from one species to another limits the findings somewhat, it enables a first assessment to be made of the relative effects of each vegetation type on bank stability.

The results (Figure 3a) show significant differences in F_s for the different tree species. River birch and sycamore had the greatest benefit, with an increase in F_s due to root reinforcement of 42% and 41% respectively. Surcharge reduced F_s by 8% and 7% respectively, leaving a net value of 2.01 for both species when the 71% increase due to enhanced matric suction was added (105% increase in F_s). Black willow and sweetgum caused much smaller increases in F_s due to root reinforcement, at 14% and 23% respectively. The reductions in F_s due to surcharge were 3% and 6% respectively, leaving net values of 1.79 for black willow (83% increase), and 1.85 (89% increase) for sweetgum once hydrologic effects were added. Switch grass had the greatest root reinforcement effect of any species tested, with an increase in F_s of 104%. Offset by the decrease of 10% due to soil moisture increases this left a net F_s of 1.9 (94% increase) compared to 1.22 (24% increase) for gamma grass.



a)



b)

Figure 3. Minimum factor of safety for all species during a) a dry year (Spring 2000), and b) a wet year (Spring 2001) subdivided by vegetation effects

Though these results are interesting, they represent vegetation effects during an unusually dry period; April 2000 followed the driest antecedent six-month period on record (18 years) at the Goodwin Creek watershed (37% of mean six-month rainfall). Spring 2001 was much wetter (124% of mean six-month rainfall, the fourth wettest period on record), presenting an opportunity to test the hydrologic effects of vegetation in less favorable circumstances. Figure 3b shows the vegetation cover broken down into separate effects during the February 2001 bank failure episode. Mechanical effects have been incorporated using the same values as before, with the new tensiometer values used to calculate F_s. The most striking feature is the reduction in overall stability due to wetter ground conditions and reduced hydrologic benefits in the tree species, and increased detrimental hydrologic effects in the grasses. In the case of gamma grass the net effect of vegetation was insufficient to bring net factor of safety above one, a finding validated by bank failures in the grass plot during this period. For the mixed tree cover the overall factor of safety was reduced by 37%, with the hydrologic benefit reduced from 71% to 29%. The increase in F_s due to root reinforcement was 53%, while surcharge again reduced F_s by 7%. For grasses, root reinforcement increased F_s by 49% and hydrologic effects reduced F_s by 15% (net 33% increase in F_s). Whereas in April 2000 the hydrologic effects contributed 35% of the overall F_s of the streambank and root reinforcement contributed 19%, in February 2001 the pattern was effectively reversed, with hydrologic effects contributing 16% to F_s and root reinforcement 30%. With mechanical effects becoming more important than hydrologic effects, grasses were favored over most tree species, with switch grass the most effective cover.

This analysis overlooks a potentially more interesting situation which occurred both before and after the period of minimum bank stability in 2001. Analysis of the tensiometer values and factor of safety during this time reveals that there were periods when the hydrologic conditions under the mixed tree plot were more *adverse* (higher positive pore-water pressures and lower matric suctions) than under the bare plot. During the period of greatest adverse conditions, hydrologic effects reduced the factor of safety of the mixed tree plot by 11%. Although in this instance this did not coincide with periods of bank failure, it confirms that vegetation can have detrimental hydrologic effects on bank stability, when increased infiltration capacity is able to overcome the soil moisture deficit built up over the antecedent period.

Discussion and Conclusions

Riparian vegetation is generally considered as a mechanical aid to bank stabilization, with the hydrologic effects viewed as negligible (Coppin and Richards, 1990). *A key finding of this research is that the hydrologic effects are as important as the mechanical effects, and can be either beneficial or detrimental, depending on antecedent rainfall.* For the conditions investigated in April 2000, hydrologic effects (enhanced matric suction) increased F_s by 71% for mixed trees. By comparison grasses produced a detrimental hydrologic effect due to increased infiltration rate and delivery of water to depth during rainfall events, and F_s was reduced by 10%. The hydrologic effects were almost entirely subsurface processes; canopy interception was negligible (2% of rainfall), largely due to the timing (winter/early spring when the deciduous trees were dormant) and high intensity of most rainfall. By contrast, during the wetter second period of bank instability (February 2001) the hydrologic effects of the trees increased stability by only 29%, compared to 53% from root reinforcement. On the gamma grass plot hydrologic effects reduced F_s by 15% during this period, contributing to bank failure. Had the antecedent rainfall been slightly higher, or the timing of individual rainfall events been slightly different the hydrologic effects of the mixed tree cover could also have been detrimental. A question raised by the work is whether the detrimental hydrologic processes, combined with surcharge, can ever outweigh the beneficial effects of root reinforcement and antecedent moisture reduction. Our findings suggest that this is possible though likely to be a rare occurrence; at the time that hydrologic effects were reducing F_s on the tree plot by 11%, net mechanical effects (root reinforcement minus surcharge) were increasing it by 25%.

The results suggest that much more consideration needs to be given to the hydrologic role of riparian vegetation in influencing bank stability, particularly where vegetation is modified during land use change or as part of a river restoration or management scheme. Riparian zone managers seeking to use vegetation to increase streambank stability need to select species as much for their hydrologic properties as for their ecological and mechanical attributes. It is arguable that tree species should be selected for attributes such as winter/spring canopy cover and transpiration rates, overall transpiration volumes, and rooting depth as well as for mechanical factors such as root strength and root area ratio. This suggests that coniferous species may have an important role to play in bank stabilization. The research also demonstrates the potential for selected clump grasses to be used as effectively as trees to increase stability through root reinforcement.

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