

Riverbank stabilization using low cost submersible pumps

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Abstract

Riverbanks are usually stabilized by reinforcing the soil, installing horizontal drains or by regrading the slope. Though well established, these techniques incur problems including ground disturbance, inability to drain deep within the bank, loss of land and expense. A potential alternative is to increase bank stability by actively lowering the water table using submerged pumps, reducing positive pore-water pressure and promoting the development of matric suction. This approach is suitable in critical locations such as bridge abutments, where rapid bank stabilization is required, or where deep drainage is needed. It also has potential as a medium term technique to stabilize banks until vegetation or other reinforcing measures have had time to take effect.

A self contained and inexpensive submersible pump system has been developed and installed in a section of 6 m high incised streambank in Northern Mississippi, as part of the Demonstration Erosion Control (DEC) project. Pumps have been installed in pairs at 2 and 4 m depth, spaced 15 m apart. The de-watered site and an adjacent control site have been continuously monitored for one year, to evaluate rainfall, water volume extracted by the pumps and pore-water pressure. The data have been applied to the ARS Streambank Stability Model to calculate Factor of Safety (F_s), and rates of bank retreat at the two sites have been monitored and compared. Initial results show that the pumps lowered the water table by 0.5-1.0 m over a radius of 7.5-m, reducing pore-water pressures by 5-10 KPa during the critical winter wet period. When the resulting distribution of pore-water pressures was applied in the bank stability model, F_s increased by 15-20% for the site with pumps installed, and remained above the failure threshold throughout the year. By contrast F_s on the control site fell below the failure threshold on several occasions. During the winter period bank retreat was 11 cm for a section of the de-watered site situated above a large woody debris (LWD) structure, compared with 27 cm for a section of bank that was de-watered but not protected with LWD, and 43 cm for the control site. No mass failures were recorded at either portion of the de-watered plot, in contrast to the control plot.

The cost of bank stabilization using submerged pumps was approximately \$40 per m, compared with \$300 per m to stabilize similar banks using rip rap, suggesting that the approach is a viable and cost effective method.

Introduction

Riverbank failure and retreat is a significant threat to bridges and roads, causes loss of farm and residential land and is a major source of sediment in streams. It is a particular problem in the Southeast and Midwest USA where channel incision due to straightening and dredging has led to thousands of kilometers of unstable banks. As part of the US Army Corps of Engineers Demonstration Erosion Control (DEC) Project, the National Sedimentation Laboratory is

conducting experiments on innovative methods of streambank stabilization, to develop low-cost environmentally-friendly alternatives to methods such as slope re-grading and rock armoring. In conjunction with an investigation of the use of large woody debris (LWD) for bank toe protection (Shields *et. al.*, 2001), work is underway to assess the feasibility of stabilizing entire bank profiles by de-watering them using submersible pumps.

Streambank failure occurs when the soil strength in a bank is exceeded by stress. The balance between the two forces can be expressed as a factor of safety (F_s);

$$F_s = \text{Stabilizing forces/Destabilizing forces} \quad (1)$$

When F_s is less than one the bank is unstable and should fail. The main stabilizing forces are soil cohesion and friction, while the principal destabilizing force is the weight of the riverbank. Water plays an important role in bank stability, by affecting the weight and by modifying soil strength. Under saturated conditions pore-water reduces soils shear strength, as defined by the Mohr-Coulomb criterion:

$$\tau_f = c' + (s - m) \tan f' \quad (2)$$

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

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 f^b .

$$c_a = c' + (m - m) \tan f^b = c' + y \tan f^b \quad (3)$$

where c_a = apparent cohesion (kPa); m = pore-air pressure (kPa); and y = matric suction (kPa). Once f^b is known (or assumed) apparent cohesion (c_a) in the soil can be estimated by measuring matric suction with tensiometers or other devices and by using equation 3. 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). On the other hand, de-watering a bank increases matric suction and so apparent cohesion, and bank stability. Bank de-watering occurs naturally through the transpiration of vegetation and artificially by installing horizontal drains. However, there are several sets of circumstances where such drainage is not capable of stabilizing a riverbank. Examples include banks where deeper drainage is required than can be achieved by horizontal drains, where rapid drainage is required or where temporary drainage is needed while a longer term countermeasure such as tree cover takes effect. In these cases stability can be increased by pumping water out of boreholes installed vertically into the riverbank. Borehole pumping draws down the water table, producing a conical depression the radius of which is a function of the permeability of the soil. De-watering has been used as a means of protecting bridge abutments (F. Schultz, Nebraska Dept. of Roads, *oral comm.*) but is generally considered too expensive to be used in less critical situations. However, low cost pumps are available and could potentially extend the application of this technique to more common situations. The objective of this study was to establish if a low-cost pumping system could have an appreciable impact on bank stability and retreat rates.

Experimental Design

The study site is on an actively eroding bendway in Little Topashaw Creek in the Yalobusha River watershed, northern Mississippi. The catchment area is 37 km, and the area receives approximately 1300 mm precipitation per year. The channel has incised following downstream channel straightening (Wallerstein, 2000) and is currently 6-m deep. Bank materials at the test site are a mixture of coarse and fine sand. A geotechnical investigation was carried out to gather data for the streambank stability model; the bank has a coarsening upward stratigraphy with coarse sand at the top ($c'=3^\circ$, $\phi'=34$) and fine sand at the bottom ($c'=1$, $\phi'=22^\circ$). Unit weight is 16 kN/m^3 at the top, increasing to 18 kN/m^3 below the upper 1 m soil.

The site is divided into two areas; a control site and a de-watered site. The sites are 25 m apart to ensure that they are hydrologically isolated from one another, but close enough to be comparable in terms of inputs of groundwater and exposure to basal erosion. At the de-watered site two pairs of 5 cm diameter boreholes were installed 15 m apart to depths of 2 and 4 m. One pair of boreholes is located above a LWD structure while the other is above an unprotected portion of the channel. A 4 cm diameter, 12 volt DC submersible pump was installed in each borehole, powered by a 34 amp-hour marine deep-cycle battery. The pumps are activated by a relay system and two 2 cm diameter float switches mounted 5 and 15 cm above the pump. The upper float switch turns the pump on, and it continues to work until the lower float switch falls. This arrangement prevents the pump from continuously cycling on and off as the water level rises and falls in the borehole, or from running dry. A check valve in the discharge hose prevents water from returning to the borehole once the pump has closed down.



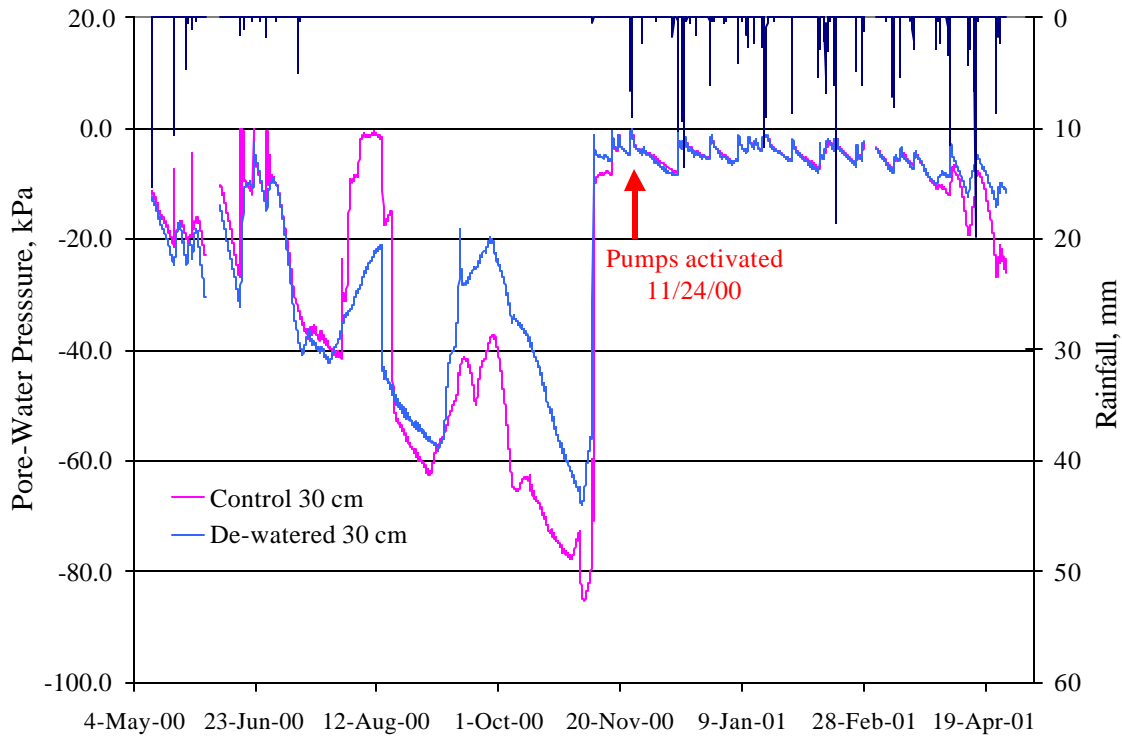
Figure 1. The de-watered plot of Little Topashaw Creek

Each hose is routed through a tipping bucket rain gage that measures water volume before being discharged over the bank into the stream. At each site there is a nest of four tensiometers installed 3 m from the bank edge that can measure both positive and negative pore-water pressure (matric suction). At the de-watered site the tensiometers are located 5 m from one of the pairs of pumps in order to measure approximate average pore-water pressures for the site. The tensiometers are installed at depths of 30 cm, 170 cm, 300 cm and 470 cm. All tensiometers, the pump discharge recorders and a rain gage are recorded every ten minutes. Once per week or after every large rainfall event eight bank-top profile lines are measured to record bank retreat. Four survey lines are in the control plot and four are in the de-watered plot. Within the de-watered plot two lines are on a section of bank above a LWD structure (adjacent to Pumps 3 and 4) while two are above an unprotected bank section between structures (adjacent to Pumps 1 and 2). The control plot is located 10 m behind a LWD structure which provides some shelter from direct hydraulic scour but no bank buttressing. Tensiometer monitoring started in May 2000, with the pumps becoming active on November 24th 2000. The intervening months provided a period during which the control site could be evaluated with the de-watered site to ensure comparability of background conditions.

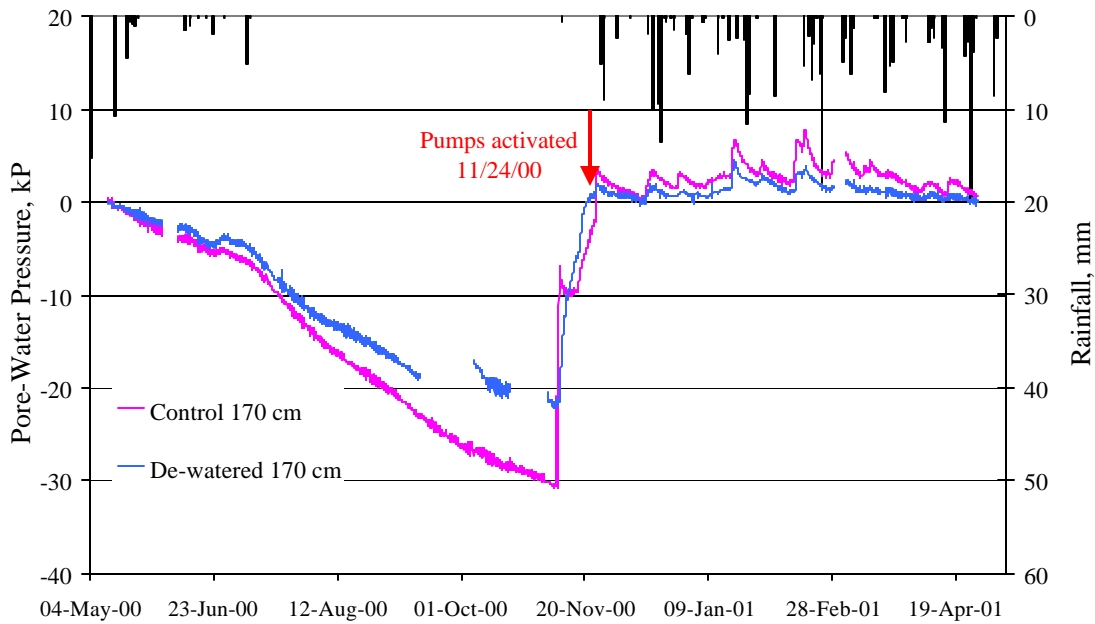
Results

Comparison of control and de-watered site prior to de-watering. From May to November 2000 the pump system was not activated, so for this period both plots were exposed to identical vertical inputs of water, any differences in moisture content being due to lateral inputs or preferential flow. During the relatively wet period from May through July 2000, the 30 and 170 cm tensiometers showed both plots to be very similar, with almost identical pore-water pressures. At 300 and 470 cm the control plot was consistently wetter than the de-watered plot during this period, with pore-water pressures 4-5 kPa higher. During the very dry period from August through November 2000 the upper layers (30 and 170 cm) of the control plot dried out more than the de-watered plot, developing matric suctions 10-20 kPa higher. During this period pore-water pressures at 300 cm depth converged under both plots, to give a difference of less than 1 kPa by the start of the winter rain in November 2000. At 470 cm there was less convergence, and at the end of the dry period the control plot had pore-water pressures 2-3 kPa higher than the de-watered plot.

Differences between the control and de-watered plots prior to de-watering are probably due to slight differences in local soil moisture movement and permeability. The data suggest that the control site may be slightly better drained than the de-watered site, with commensurate drying in the upper layers and wetting in the lower layers. The response of the 470 cm tensiometers suggests that subsurface flow may be concentrated under the control plot at this depth, possibly as a result of heterogeneities in bank materials. The differences largely cancel out when averaged across the whole bank profile, and the plots are believed to be reasonably comparable. The greatest difference, at 470 cm, has the least effect on bank stability, and is excluded from the bank stability analysis described below because the potential shear surface lies above this depth.

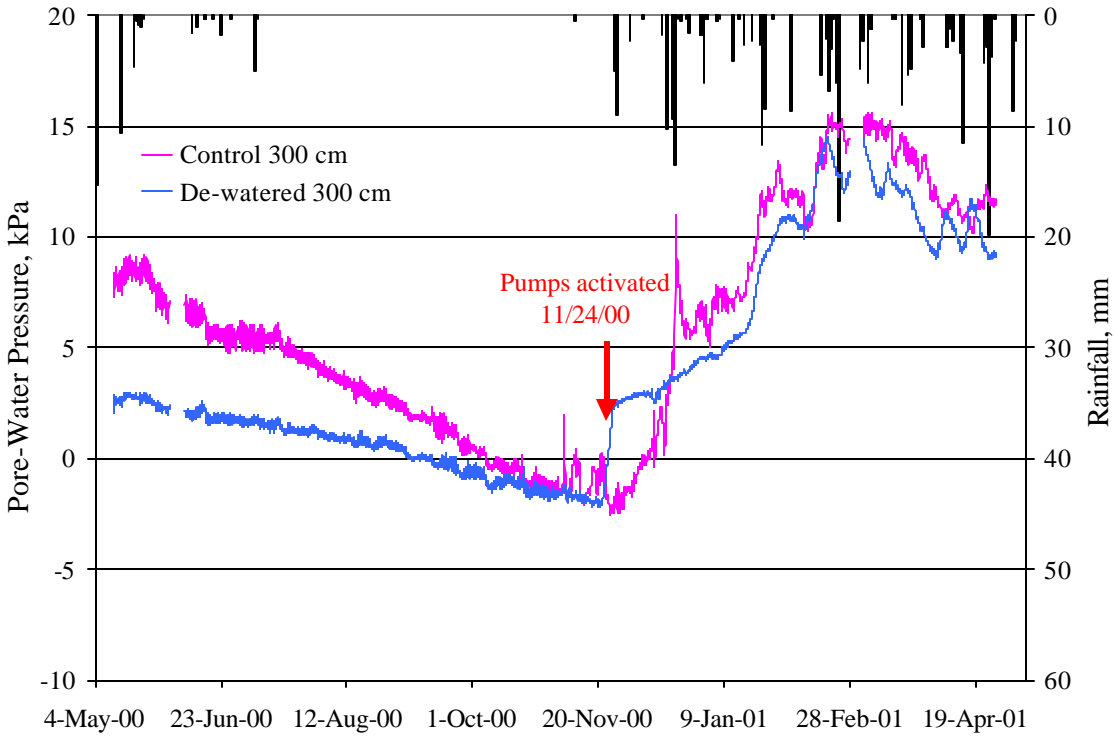


a)

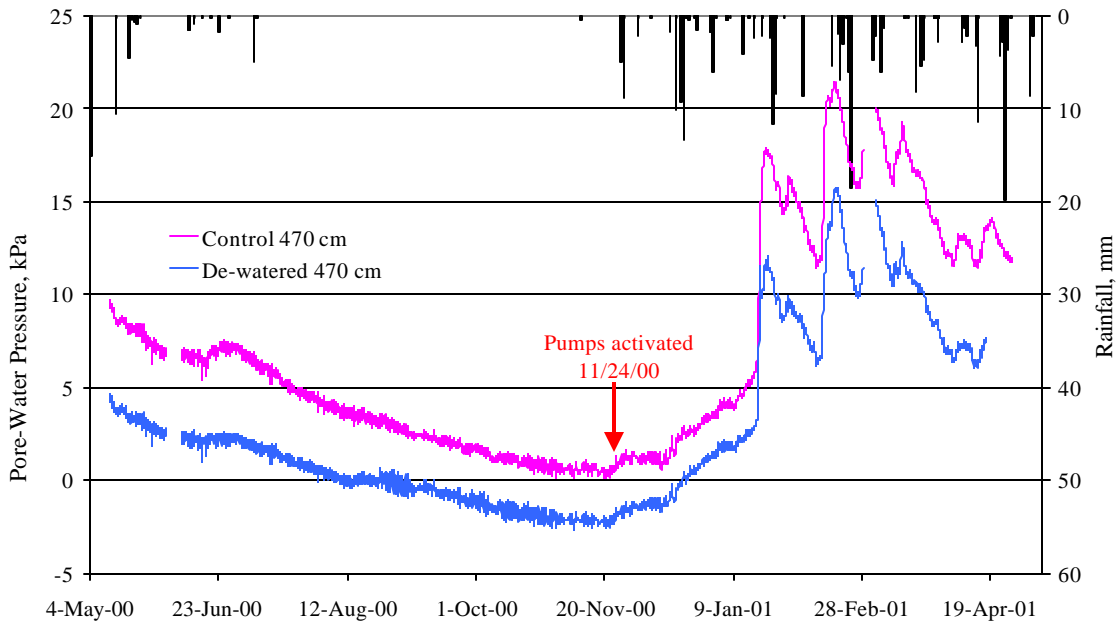


b)

Figure 2. Pore-water pressure response to rainfall a) 30 cm depth; b) 170 cm depth



c)



d)

Figure 2. Pore-water pressure response to rainfall c) 300 cm depth; d) 470 cm depth

Comparison of control and de-watered sites during de-watering. Between November 2000 and May 2001 (the time of writing) the de-watered plot has been continuously pumped in response to elevated water levels in the bank, though equipment problems with the initial installation meant that not all pumps were active at all times required until March 2001. All tensiometers show the bank wetting up rapidly from a driest state prior to the arrival of heavy rainfall in November 2000. Wettest conditions were reached in late February 2001, after which slow drying occurred. At 30 cm both plots converged once rainfall began, and closely resembled each other until the beginning of April 2001, when the control plot began to dry out more rapidly than the de-watered site. These results are in line with expectations; the pumps are not expected to have much impact on soil moisture this far above the water table, and at 30 cm both sites are responding to near-surface fluxes of rainfall, drainage and evaporation rather than movements of the water deeper in the bank profile. At 170 cm activating the pumps caused a modest but noticeable cross-over between the relative pore-water pressures of the control and de-watered plots, with lower pore-water pressure on the de-watered site, especially during peaks in water level. For the most critical peaks the reduction in pore-water pressure was 2-4 kPa for the de-watered plot. A similar trend occurred at 300 cm, where the de-watered plot maintained a slightly lower pore-water pressure and a less flashy response to rainfall. Pore-water pressure during peak events was again 2-3 kPa lower on average than under the control plot. At 470 cm the response to de-watering was more pronounced; during peak water levels the pore-water pressure under the de-watered plot was approximately 6-7 kPa lower than the control plot, compared with a reduction of 2-3 kPa prior to pump activation.

Overall, the results, though not dramatic, show a slight reduction in pore-water pressure as a result of de-watering the plot. As expected the reduction is most pronounced during peak water levels, when the pumps are most active. Comparing the critical periods when pore-water pressures were highest, the de-watered bank maintains pore-water pressures 2-7 kPa lower than the control site at all depths except for 30 cm. Activation of the pumps and collection of pump discharge were beset by technical problems in January and February which reduced the effectiveness of both the system and data collection, but both equipment and data were reliable from March 2001 onwards. Pump discharge values were; January at least 381 liters (l), February – data unreliable, March 1478 l, April 504 l. From March pump discharge was monitored individually, enabling us to identify which pumps produced the most water. The pattern is consistent, but not systematic. During March and April Pump 1 (4 m, borehole pair A) generated 616 l while Pump 2 (2 m, borehole pair A) generated only 1 l. By comparison in borehole pair B, Pump 3 (2 m) generated 1235 l while Pump 4 (4 m) generated only 130 l. These results again suggest that movement of groundwater through the site is very heterogeneous, probably as a result of the lenses of coarser and finer bed material that compose the bank materials.

Bank retreat monitoring. Bank edge monitoring began in November 2000, and retreat began to occur in December 2000 by a mixture of small mass failures on the control plot and weathering on both plots. The control plot and the pump-only portion of the de-watered plot initially experienced similar retreat rates, associated with wetting up after the first rainfalls of the winter, and freeze-thaw weathering and erosion. However, retreat slowed and stopped sooner on the de-watered site and total erosion was significantly less. The pump and LWD portion of the de-watered plot experienced much slower retreat, with only minor sloughing off the bank face. By the time of the wet conditions in February 2001 only minor retreat occurred at all three sets of survey lines, indicating that equilibrium had been reached. Little if any basal scour occurred

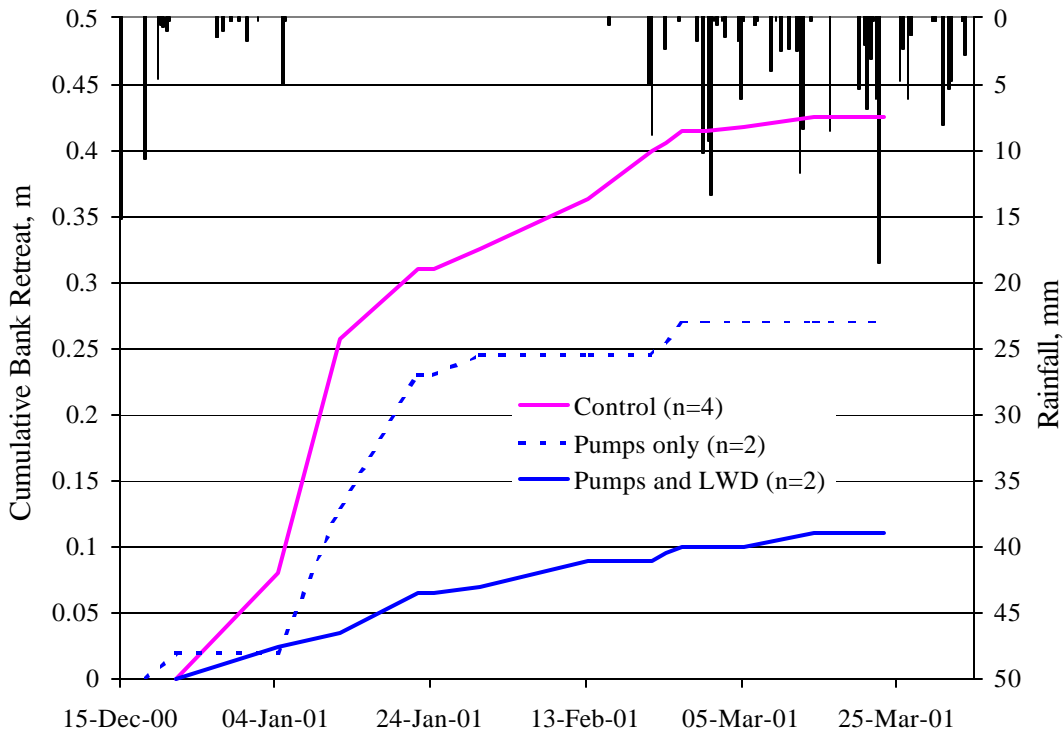


Figure 3. Cumulative bank edge retreat for the three treatments.

during the study period, so all retreat is due to bank processes rather than toe processes. Average cumulative bank retreat for the period December 2000 – April 2001 (inclusive) was; control 0.43 m, de-watering and no LWD 0.27 m, de-watering and LWD 0.11 m.

The results show benefits from both the pumps and the IWD. The LWD below the de-watered plot trapped some bank material that failed during construction (prior to bank retreat monitoring), and trapped additional material from upstream during a series of high flows. This provides some buttressing for the lower bank and may be stabilizing the bank face by preventing plastic deformation and bank undermining, as appears to be happening at the pump and LWD lines. The combination of pumps and LWD appears to provide a significant benefit over a single treatment.

Bank Stability Modeling

In order to quantify the effect of de-watering on bank stability, the ARS Streambank Stability Model was employed. This is a limit equilibrium wedge model that simulates the physical processes of bank failure by shearing using the Mohr-Coulomb criteria for saturated portions of the bank, and the Fredlund *et. al.* (1978) criteria for unsaturated sections. The model divides the bank into up to five layers with user-definable thickness, soil properties and bank geometry. Data from the tensiometer nests was used to run the model for the period May 2000 – April 2001 for both control and de-watered plots. Identical bank profiles and soil properties were used in both simulations, with all differences in Factor of Safety (F_s) being due to changes in pore-water pressure between the two treatments. Two stability scenarios were run for each plot; assessment

of the stability of the whole bank profile, and assessment of the upper vertical portion of the bank.

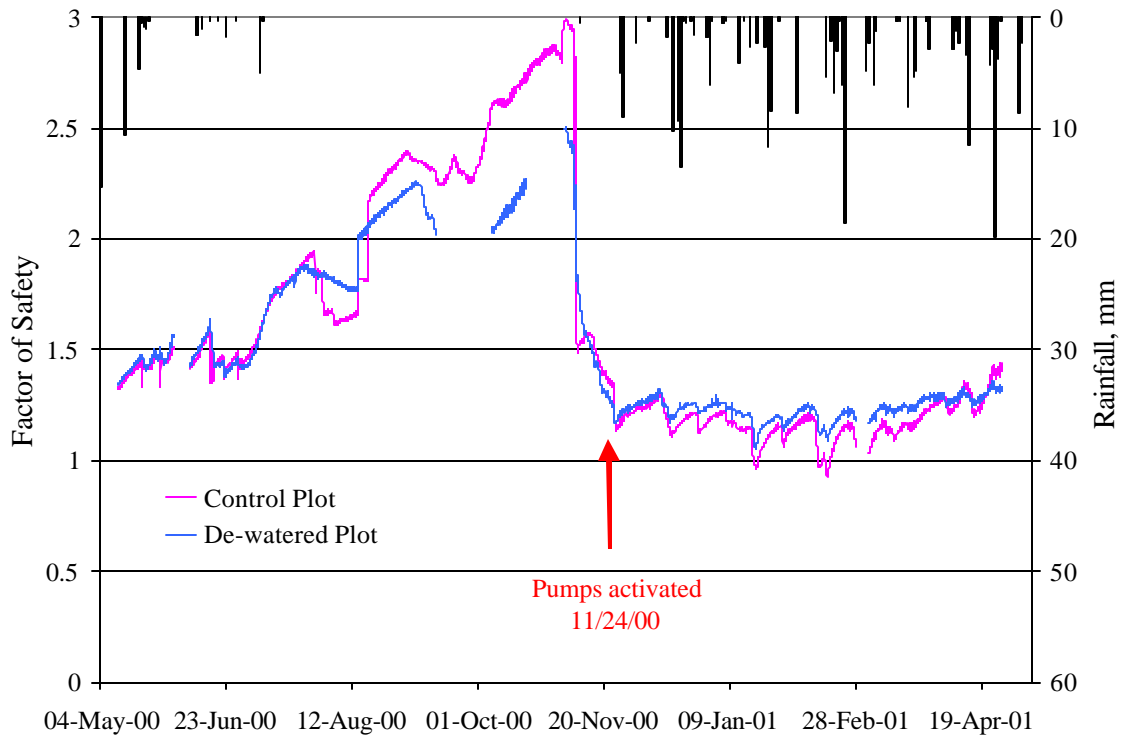
Whole bank stability. In this assessment pore-water pressures recorded by the upper three tensiometers are used in the analysis. Prior to activation of the pump system, model output (Figure 4a) shows factor of safety (F_s) rising for both plots during the summer and fall of 2000 as the banks dry out from the previous winter and spring. From May through July both plots have almost identical F_s values, reflecting the similar values of positive pore-water pressure between the two plots. From July, F_s on the control plot rises faster as matric suction in the upper soil layers on that plot increases more rapidly than on the de-watered plot. F_s declines rapidly for both plots with the start of the rainy season in November 2000. As water levels rise the pump system becomes active on the de-watered plots, and from this point onwards we can see the de-watered plot maintain higher F_s values until the end of April 2001 when more rapid drying in the upper layer of the control plot again raises stability. The crucial point is the difference in F_s at times of lowest stability; during January and February 2001 F_s on the control plot twice falls below one, indicating mass failure, while for the de-watered plot it remains at approximately 1.1 to 1.2. Though this difference is slight, it is critical, showing that the de-watered plot retains a small safety margin at the times of lowest stability.

Bank top stability. For the bank top modeling only pore-water pressures from the upper two tensiometers are used in the analysis. Bank top stability follows a similar pattern to whole bank stability, but the influence of the upper soil layer results in a much more volatile F_s pattern, with very high values in the summer due to matric suction, and rapid losses in the winter as suction is lost. Once wetting occurs following the November 2000 rainfall, the F_s declines to a critical value. As with the whole bank simulation, we can see the control site fall below the stability threshold on two occasions in January and February, while the de-watered site remains just above this limit. Though the difference is again slight it is enough to prevent instability. By the end of February upper soil layer drying raises the F_s on both plots, and recover continues into the spring.

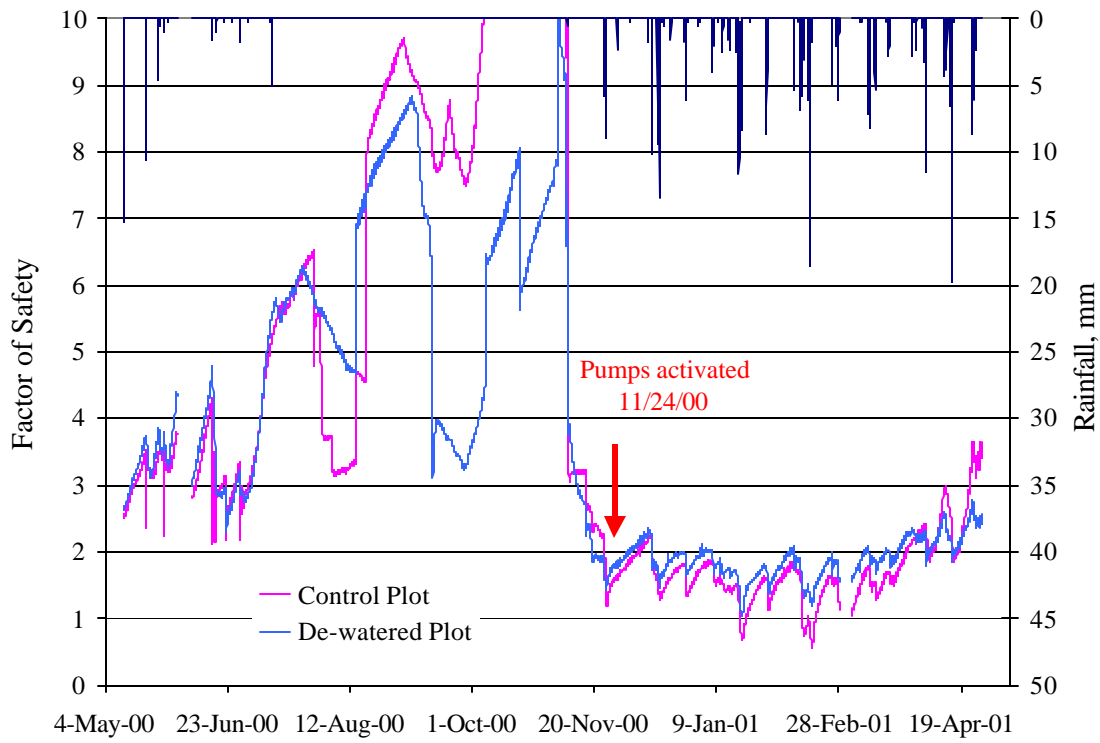
Comparison of figure 3 with figure 4b shows a close, though not perfect, correspondence between times when the model predicted bank top instability and the observed occurrences of retreat.

Discussion and Conclusions

The experiment at Little Topashaw Creek has demonstrated a linkage between treatment (de-watering and control), pore-water pressure, bank factor of safety and observed bank retreat. Although the reduction in pore-water pressure on the de-watered site and the resulting increase in F_s is not great, it was sufficient to raise the bank stability above the failure threshold at all times. This numerical evidence is supported by observations of the rate of bank retreat at the different treatments. Provided the pumps are located at the correct location relative to the critical water table height, they can be installed in such a way as to ensure that stabilization occurs at exactly the point needed. The de-watering system used is relatively inexpensive compared with other methods of bank stabilization; total cost for the test plot is \$1200. The system stabilizes 30 m of bank at a cost of \$40 per m. This compares with costs of approximately \$300 per m for stabilization using regrading and riprap. Although de-watering will not be used in a large number of bank stabilization situations, the effectiveness of such an inexpensive system widens the scope of possible applications.



a)



b)

Figure 4. Factor of safety of a) the whole bank profile b) the bank top for the control and de-watered plots ($F_s < 1$ indicates bank failure)

References

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