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EFFECTS OF WET MEADOW RIPARIAN VEGETATION ON STREAMBANK EROSION. 2. MEASUREMENTS OF VEGETATED BANK STRENGTH AND CONSEQUENCES FOR FAILURE MECHANICS

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ABSTRACT

We measured the effect of wet meadow vegetation on the bank strength and failure mechanics of a meandering montane meadow stream, the South Fork of the Kern River at Monache Meadow, in California's Sierra Nevada. Streambanks colonized by 'wet' graminoid meadow vegetation were on average five times stronger than those colonized by 'dry' xeric meadow and scrub vegetation. Our measurements show that strength is correlated with vegetation density indicators, including stem counts, standing biomass per unit area, and the ratio of root mass to soil mass. Rushes appear better than sedges at stabilizing coarse bar surfaces, while sedges are far more effective at stabilizing actively eroding cut banks.

Wet meadow floodplain vegetation creates a composite cut bank configuration (a cohesive layer overlying cohesionless materials) that erodes via cantilever failure. Field measurements and a geotechnical model of cantilever stability show that by increasing bank strength, wet meadow vegetation increases the thickness, width, and cohesiveness of a bank cantilever, which, in turn, increases the amount of time required to undermine, detach, and remove bank failure blocks. At Monache Meadow, it takes approximately four years to produce and remove a 1 m wide wet meadow bank block. Wet meadow vegetation limits bank migration rates by increasing bank strength, altering bank failure modes, and reducing bank failure frequency. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: bank stability; riparian vegetation; shear strength; meander migration; streambank erosion

INTRODUCTION

For a river bank to remain stable, i.e. to maintain a fixed cross-section through time, it must be strong enough to resist fluvial erosion and subsequent mass wasting. Geotechnical models of bank stability imply a direct relationship between bank cohesion and the 'factor of safety' that estimates the risk of bank failure (Thorne, 1978). Herbaceous riparian vegetation increases the apparent cohesion of wet meadow streambanks through root reinforcement of bank soils. Quantifying the effects of riparian vegetation on the apparent soil cohesion and stability of meadow streambanks will improve predictions of how riparian vegetation conservation or restoration may influence the geomorphology of meadow streams.

In a companion paper (Micheli and Kirchner, 2002) we observe that from 1955 to 1995 a wet meadow reach migrated on average six times more slowly than an adjacent dry meadow reach on the South Fork of the Kern River at Monache Meadow. We calculated a tenfold difference in bank erodibility (the susceptibility of bank materials to lateral migration, normalized with respect to flow velocity variations due to channel curvature) for banks with 'dry' xeric meadow and scrub vegetation versus 'wet' hydric graminoid meadow vegetation including sedges (*Carex* spp.) and rushes (*Eleocharis* and *Juncus* spp.). We hypothesized that these differences in bank migration rates and erodibilities were due to the effect of wet meadow vegetation on bank strength. Here we present in-situ measurements of vegetated bank strength and describe how root reinforcement influences bank failure mechanics and channel migration rates.

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Alluvial bank and bar sediments are often composed of silts, sands and gravels, which have significant compressive strength but lack tensile strength or cohesion. The interlocking root networks of wet meadow vegetation reinforce alluvial soils by adding tensile strength to the bank soil matrix. The very fine root networks typical of sedges, for example, comprise large numbers of randomly oriented roots less than 1 mm in diameter. We observed that this dense root reinforcement creates a tough sod layer ranging in thickness from 0·50 to 0·75 m at Monache Meadow.

Although riparian vegetation is considered to be a potentially significant control on bank stability (Thorne, 1982, 1990; Gregory, 1992), few studies are available on the effects of riparian root networks on in-situ streambank soil shear strength. Gray and Ohashi (1983) studied the behaviour of fibre-reinforced sands and presented a quantitative model of how the aggregate tensile strength of a root network increases apparent soil cohesion and shear strength. Smith (1976) found significant variations in field bank erosion rates as a function of vegetation cover. Waldron (1977) and Waldron and Dakessian (1982) tested the net strength of the root–soil matrix for greenhouse-raised agricultural species. The majority of field root strength studies have examined the effect of upland tree species on the stability of forested hill slopes (Reistenberg and Sovonick-Dunford, 1983; Wu, 1994; Schmidt, 1999). Schiechtl (1980) provided root strength values for some alpine willow and poplar species to inform erosion control planting designs. Gray and MacDonald (1989) measured the strength of individual riparian tree roots on Sacramento River levees and estimated that low root densities (on the order of 1 per cent) could significantly increase bank stability. Abernathy and Rutherford (2001) measured how apparent cohesion due to root reinforcement varied among different tree species on Australia's Latrobe River. Kleinfelder *et al.* (1992) applied a compressive rather than a shear strength test to vegetated streambanks to measure bank resistance to cattle trampling. All of these studies suggest that roots can significantly increase soil strength, but none provides estimates of the in-situ shear strength of soils reinforced by wet meadow vegetation.

We measured the effects of wet meadow vegetation on the shear strength of (1) river banks cutting into wet meadow floodplains located at the outside of river meanders, and (2) point bars forming the inside bank of meanders. At cut banks, wet meadow vegetation creates a 'composite' bank configuration with a cohesive root-reinforced layer overlying a relatively cohesionless layer (Thorne and Tovey, 1981; Pizzuto, 1984). On channel bars, vegetation roots bind bar sands and gravels into a cohesive 'skin' thereby increasing the shear stress required to mobilize bar particles. Reinforcement of cut banks can diminish bank erosion rates, while bar stabilization can indirectly accelerate bank erosion if bar accretion deflects flow against the outside bank (Howard, 1984).

Measurements of the in-situ strength of bar and bank sediments colonized by herbaceous riparian species help us answer the following questions. What fraction of bank strength is attributable to herbaceous vegetation? Can vegetation cover indices be used to estimate the magnitude of root reinforcement and resultant strength? Are there differences between the effects of rush versus sedge species on bar and bank substrate strength? How does wet meadow root reinforcement of floodplain soils shape stable bank configurations, failure block dimensions, rates of failure block removal and therefore resultant channel migration? To address these questions, we develop a methodology for evaluating the effects of herbaceous riparian vegetation on bank failure mechanics, and we also present a model of how vegetation retards bank erosion that may prove applicable to a variety of riparian systems. An improved understanding of the relationship between vegetation and bank stability will enhance conservation and restoration strategies for stream and wetland habitats.

SETTING

In a companion paper (Micheli and Kirchner, 2002) we compare migration rates and bank erodibilities for a wet meadow versus a dry meadow reach of the South Fork of the Kern River at Monache Meadow. The river channel meanders freely through a valley composed of granitic alluvium that in itself is relatively cohesionless (see Table I for channel characteristics). The valley is colonized by two contrasting vegetation communities that may be easily distinguished by field surveys and by aerial photography analysis: 'dry' xeric meadow and scrub vegetation (sagebrush (*Artemesia cana*) and annual grasses); and 'wet' hydric

Table I. Monache meadow channel characteristics (with reference to Olancha Gauge (USGS #11188200), located at the base of the meadow)

Channel characteristic	Value
Channel length	12 km
Average width	30 m
Average depth	1 m
Channel slope	0·001
Bed material median grain size	4 mm
Mean annual flood	11 m^3s^{-1}
Elevation at gauge	2393 m
Drainage area at gauge	380 km^2

Data from Collins (1995).

graminoid meadow vegetation (sedges (*Carex* spp.) and rushes (*Eleocharis* and *Juncus* spp.))(Sarr, 1995). Over the 40-year period between 1955 and 1995, the dry meadow reach migrated an average of six times faster then the wet meadow reach ($1{\cdot}4 \pm 0{\cdot}3$ m a^{-1} compared to $0{\cdot}24 \pm 0{\cdot}02$ m a^{-1}) and, when migration rates were normalized for curvature, the dry meadow banks were roughly ten times more erodible than the wet meadow banks. These observations prompted us to collect in-situ bank strength measurements and to conduct detailed bank surveys to examine the differences between wet and dry meadow bank erosion processes.

METHODS

Bank strength measurements

We tested several techniques for measuring the aggregate effects of root reinforcement on in-situ streambank strength. Ideally, observations of 'real-time' bank failure geometry would allow us to back-calculate the effective strength of vegetated soils at precisely the scale of interest; unfortunately, banks tend to fail when flood flows are peaking or receding, making direct observations difficult. Field measurement techniques, such as the Torvane and pocket penetrometer, may be appropriate for rapid assessments of unvegetated bank strength, but sample too small a surface (on the scale of 1 cm^2) to capture the effect of roots. Other in-situ techniques, such as hydraulic penetrometers and oversized shear boxes, lack portability and can cause levels of soil disturbance that are unacceptable in wilderness areas (Abe and Iwamoto, 1985; Wray, 1986). Trial runs using a conventional laboratory ASTM shear box proved this technique impracticable: it was difficult to cut a sample cube (approximately 125 cm^3) without significantly disturbing the root and soil structure, and the limited shear displacement length of the device was insufficient to cause failure. In addition, the small cross-sectional area, approximately 25 cm^2, was not comparable to the potential failure surface of a cantilevered bank.

We measured the in-situ strength of vegetated bank materials using a large ASTM-standard manually operated geotechnical shear vane with rectangular blades (which produced a cylindrical shear surface 11·5 cm high and 7·6 cm in diameter). An advantage of the large vane is that the activated cylindrical failure surface is closer to the scale of the bank failures we studied. Operating the vane requires two people: one applies force to the vane handle, and one steadies the central axis of the vane. No heavy machinery is required. The applied torque can be measured using a calibrated torque wrench or a spring scale and can then be converted to a shear strength value (Wray, 1986: Richards, 1988).

To prepare a site for a shear strength test, we first removed all above-ground vegetation within a 16 cm diameter circular patch. Vegetation was clipped to within 0·5 cm of the ground surface and stored in plastic sample bags for subsequent vegetation density measurements (see below). The vane was then pounded into the centre of the cleared patch. Torque was applied to the sample using a handle perpendicular to the vane's central axis. The applied torque was measured and converted to soil shear strength according to the ASTM protocol (Richards, 1988). Following the engineering standard, failure is defined to occur when applied torque reaches a maximum. After that point, the soil is weakened and applied torque rapidly decreases as the sample begins to rotate within the cylinder defined by the vane blades. Sample failure appears to be a result of both pulling out and breaking the roots that bind the soil sample.

The majority of strength measurements were made at two types of sites: (1) sedge- and rush-colonized bar surfaces comprising sorted sand and gravel (generally located at the inside of dry and wet meadow bends); and (2) sedge-colonized cut banks and failed slump blocks where the local substrate constituents included silty terrace soils, dense root networks, trapped fluvial gravels, and decaying organic matter (generally located at the outside of wet meadow bends). Samples were located within 30 cm of the water surface and were at or near saturation. (Near-saturation is the likely condition at bank failure, because failures tend to occur on the falling limb of the hydrograph (Lawler, 1993)). Only a handful of failed dry meadow blocks were suitable for sampling, i.e. intact and located close enough to the water surface to be near saturation.

Vegetation density measurements

For each shear vane measurement site, we measured the stem density and the dry biomass of clipped vegetation samples. Stem counts were completed on-site over a five-day period in July 1997. The short sampling duration eliminated the potential for seasonal variability to affect stem density measurements. We defined a 'stem' to be the cylindrical unit at the clipping elevation: in the case of the sedges, this often meant that a stem supported up to ten blades of herbaceous vegetation. Bagged vegetation samples were later dried in an oven at 110 °C for approximately two days until a constant sample weight indicated that all available water had been removed. The dried vegetation was weighed to a precision of 0·10 g, yielding an estimate of above-ground biomass for each shear strength measurement.

At several locations, below-ground soil and root samples were excavated after strength testing in order to assess root densities using a mass ratio technique. The volume described by the shear vane set the sample size. The samples were wet-sieved to separate roots from soils. Roots and soils were dried in an oven to permit calculation of the ratio of below-ground biomass relative to dry soil mass.

Topographic survey and bank inventory

We completed a detailed inventory of bank microtopography for two successive bends located in the wet meadow reach. We used a total station to delineate slump block boundaries and elevations during the summer of 1996. We also measured the dimensions of undercut banks and failed blocks using a tape measure, a level, and an inclinometer to measure bank angles. We repeated the survey of bank boundaries and cross-section measurements of one bend in 1997 to assess changes in channel geometry in response to a single year of bank erosion.

RESULTS

Effects of vegetation on bar and bank material shear strength

Our results show that density of sedges and rushes serves as a good indicator of bank and bar shear strength. Figure 1 indicates a roughly linear relationship between rush and sedge stem count per unit area and shear strength, displaying a slope of approximately 68·4 ± 6·7 kPa per stem per cm^2, with a y-intercept of approximately 16·8 ± 2·5 kPa strength at zero vegetation density. While stem counts provide a rapid field assessment technique for vegetation density, the results described below rely on biomass per unit area as a more accurate indicator. To further refine the analysis, we separated soil strength values as a function of dominant species (sedge versus rush) and substrate grain size, distinguishing between coarse bar materials (median grain size or D_{50} approximately 4 mm) and finer floodplain terrace deposits and terrace-derived slump blocks (D_{50} approximately 1 mm or less). Results are summarized in Table II and described below.

Dry meadow bank strength

The average strength of dry meadow terrace blocks colonized by sagebrush and herbaceous annuals was 8·8 ± 0·8 kPa. We did not sample the above-ground biomass of sagebrush because the extreme difference in

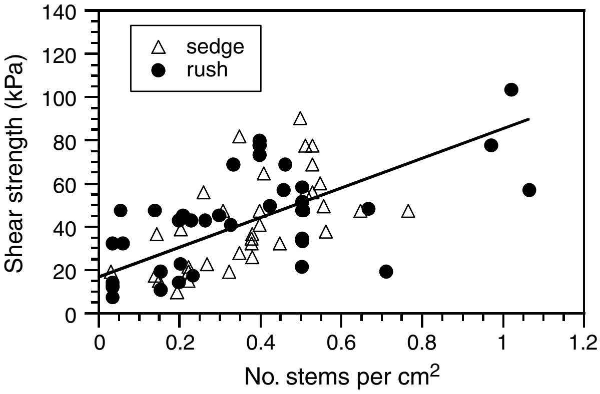

Figure 1. Shear strength versus sedge and rush stem density. The strength of vegetated bank and bar materials increases with stem density, with a slope of 68·4 ± 6·7 kPa per stem per cm^2 and a y-intercept of 16·8 ± 2·5 kPa

Table II. Vegetated bar and bank strength*

Vegetation and substrate	Shear strength (kPa)	Biomass (g m^{-2})	n†
Unvegetated bar	6·2 ± 0·3	0	9
Rush-colonized bar	46·3 ± 0·8	456 ± 7	31
Sedge-colonized bar	38·1 ± 1·3	681 ± 31	23
Dry meadow terrace	8·8 ± 0·8	–‡	10
Sedge-colonized terrace or slump block	43·0 ± 1·2	678 ± 18	20

* Average values ± standard error.
† Sample size.
‡ Dry meadow biomass not measured due to extreme differences in plant morphology.

plant morphology precluded a comparison with sedges or rushes. Exposed dry meadow bank soils displayed root-area ratios (the ratio of root area to soil area for a planar exposure) of less than 5 per cent, as opposed to root-area ratios of nearly 50 per cent observed for sedge- and rush-reinforced soils.

Wet meadow cut bank strength

The impact of sedges on the strength of wet meadow floodplain soils and failed slump blocks is illustrated in Figure 2. Rushes rarely colonize cut bank environments, so the measured effect of wet meadow vegetation on cut bank strength was almost purely attributable to sedges. The soil matrix consisted of floodplain deposits of silt and fine sands, with pockets of coarser channel sand and gravel trapped by vegetation roots. Sedge roots penetrated to approximately 0·50 m from the floodplain or slump block surface. Bank soils included significant amounts of decaying organic matter, primarily root material of antecedent sedge stands. Sedge-colonized slump block materials displayed a maximum strength of 80 kPa, with an average value of 43·0 ± 1·2 kPa, five times the average strength of vegetated dry meadow terrace blocks. Average standing sedge biomass for failed wet meadow blocks was 680 g m^{-2}. The strength of slump block materials lacking vegetation cover (but including dead root material) averaged 13·5 kPa. Sedge reinforcement of terrace materials and failed slump blocks displayed a roughly 0·04 ± 0·01 kPa strength increase per g m^{-2} above-ground biomass.

Bar strength

Figure 3 displays a roughly linear relationship between standing biomass and vegetated bar material shear strength. Wet meadow reinforcement of bar materials penetrated only to a depth of approximately 10 cm or less. Shear strength for unvegetated bar materials averaged 6·2 ± 0·3 kPa, while rush-vegetated bar materials,

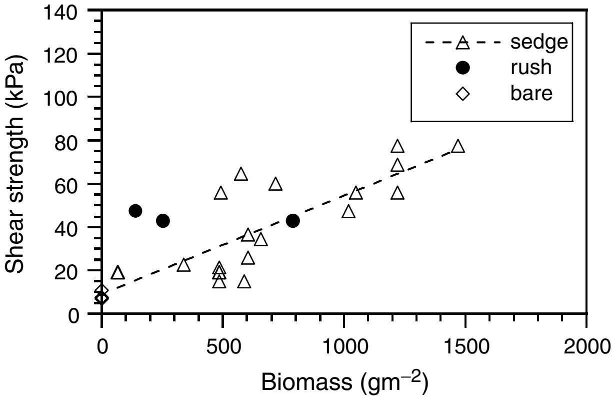

Figure 2. Shear strength versus above-ground biomass: floodplain and slump block substrates. Sedges dominate floodplain terrace blocks, with an increase of roughly 0·04 (±0·01) kPa in strength per g m^{-2} sedge biomass

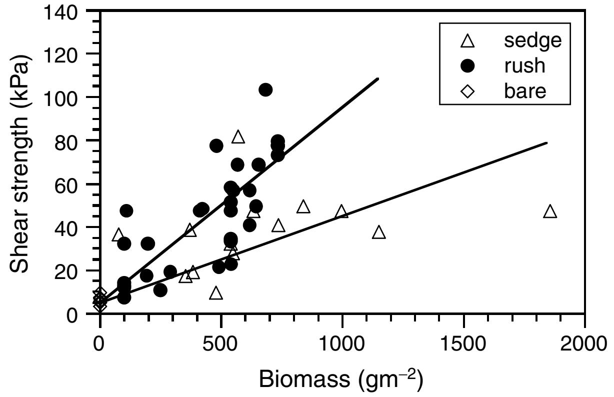

Figure 3. Shear strength versus sedge and rush biomass: bar substrates. Rushes are more effective than sedges at strengthening bar materials, with a 0·09 (±0·01) kPa increase in strength per g m^{-2} rush biomass versus a 0·04 (±0·01) kPa increase in strength per g m^{-2} increase in sedge biomass

with an average standing biomass of 456 g m^{-2}, averaged 46·3 ± 0·8 kPa in strength. Rush species appear to be more effective than sedges at stabilizing bar substrates. Rush reinforcement of sand and gravel substrates is found to be significant at better than the 1 per cent level, contributing 0·09 ± 0·01 kPa shear strength per g m^{-2} biomass. Sedges contributed only 0·04 ± 0·01 kPa shear strength per gm^{-2} biomass, with an average strength of 38·1 ± 1·3 kPa for an average biomass of 660 g m^{-2}.

Shear strength as a function of root density

For a subset of our strength test samples, we collected roots and substrate to calculate the ratio of root mass to soil mass as an indicator of root density. Figure 4 suggests that the root/soil ratio is a highly significant indicator of soil strength (significant at better than the 1 per cent level), with strength increasing linearly with the root/soil ratio with a slope of 1020 (±360) kPa per ratio unit.

Wet meadow bank inventory

Mapping the microtopography of two wet meadow bends in the 1996 and 1997 field seasons revealed that failed bank blocks can survive relatively infrequent flood flows and effectively prevent further bank erosion. A sketch map of one bend is shown in Figure 5. Three general types of wet meadow banks were observed: vertical banks, undercut banks displaying a stable cantilever, and banks where a failed cantilever or slump

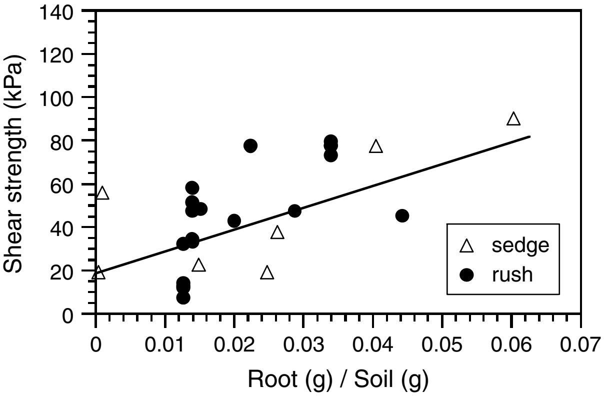

Figure 4. Shear strength versus root/soil mass ratio. Shear strength increases at a rate of approximately 1020 (±360) kPa per dimensionless root/soil mass ratio unit

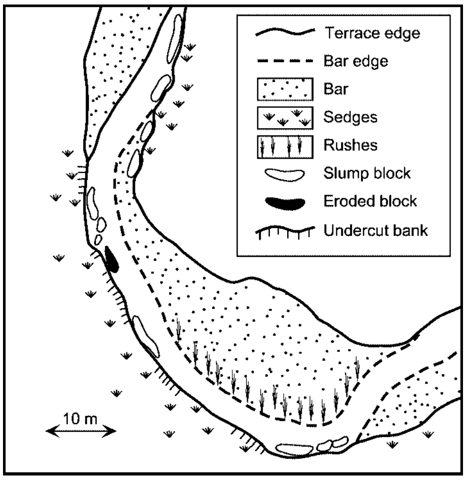

Figure 5. Sketch map: aerial view of a wet meadow bend. Mapped features include a number of slump blocks protecting actively eroding banks. The dark block was removed by the 1996–1997 winter flows

block was present at the base of the bank. In 1996 the actively eroding boundary of this wet meadow bend displayed approximately 25 per cent vertical bank, 15 per cent undercut bank, and 60 per cent slump block protected bank. Failed slump blocks ranged in width from 0·4 to 1·3 m, with an average block width of 0·71 ± 0·01 m, and ranged in length from 2·5 to 22 m, with an average block length of 9·3 ± 0·3 m. A second survey of this bend in 1997 revealed that only one block, approximately 0·90 m wide and 4·7 m long, had been removed by the 1996–1997 season of flow, which peaked with an estimated discharge of 55 $m^3 s^{-1}$ at the Olancha gauge (a flow exceeding the ten-year recurrence interval event). The remainder of the bank boundary displayed little change.

DISCUSSION

While rushes appear more effective than sedges at stabilizing coarse bar surfaces, in the field there was little evidence that rushes survived annual floods or controlled bar morphology in the course of our resurveys of the wet meadow bend. Thus, rushes do not appear to significantly increase the size or strength of bars in a way that would increase the erosion pressure on the opposite cut bank. By contrast, sedge reinforcement dominates the morphology of actively eroding cut banks, with the thickness and width of bank cantilevers determined by sedge root depth and strength, respectively, as discussed in more detail below. Strength test results and field observations suggest that sedges may be very effective at stabilizing vertical cut banks, undercut banks, and banks protected by failed slump blocks.

When the Kern River erodes into the wet meadow floodplain, a channel bank is produced which is strong enough to maintain a vertical wall. Stream flow will tend to preferentially erode unvegetated bank material below the root-reinforced layer, undermining it and carving out a shelf or cantilever. Thus, vegetation root depth sets cantilever thickness. Geotechnical models of bank stability suggest that roots also control the maximum stable width of a cantilevered riverbank block. For example, Thorne and Tovey (1981) use the method of moments to calculate the factor of safety (the ratio of stabilizing versus destabilizing forces) for a cantilevered block. Maximum stable cantilever block width can be estimated by solving for a width that provides a factor of safety equal to one.

Assuming that root strength contributes to the tensile rather than compressive strength of a soil, we calculated representative stable block widths (*b*) for both the dry meadow and wet meadow banks using the following relationship (Thorne and Tovey, 1981):

$$b = \sqrt{\frac{\sigma_t t^2 + \sigma_c c^2}{\gamma h}}$$

given $h = c + t$ and $\sigma_c/\sigma_t = c/t$, where h = total block height (m), c = block height under compressive stress (m), t = block height under tensile stress (m), σ_t = tensile strength (kN m^{-2}), σ_c = compressive strength (kN m^{-2}), and γ = saturated bulk density (k Nm^{-3}) (see Figure 6). We assume that the shear strength of soils without vegetation is primarily a product of compressive strength, while gains in shear strength due to roots are primarily tensile. This analysis yields an estimated maximum width of a stable cantilever for the dry meadow bank that is on the order of 0·1 m, as compared to a maximum stable cantilever width of 1·0 m for the wet meadow bank. Our predictions compare favourably with our field measurements of sedge-reinforced bank profiles: since water-worn blocks average approximately 0·70 m in width after failure, it seems credible that blocks prior to failure would average approximately 1 m in width. Stability analysis inputs and outputs are summarized in Table III.

The ratio between block width and bank height appears to be a good indicator of the likelihood of block detachment after failure. Once a wet meadow bank fails, the width of the block often exceeds the bank height, so immediate detachment and removal are rare. Failed slump blocks are often found attached to wet meadow banks, with only a slight tension crack at the plane of failure. By contrast, detachment of dry meadow blocks

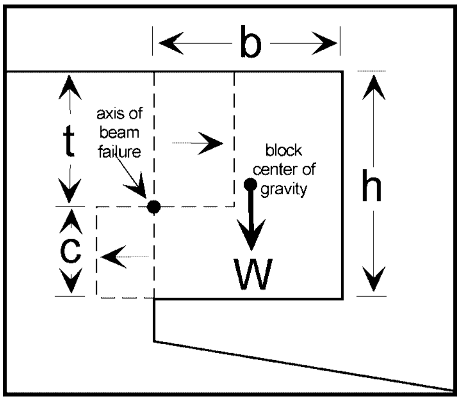

Figure 6. Cantilever stability diagram. The diagram represents a cross-section of an undercut bank. A cantilever with width *b*, height *h* and weight *W* (acting at the centre of gravity), generates tensile stresses along boundary *t* and compressive stresses along boundary *c*. Stability is defined by a balance of moments around the axis of failure (which is perpendicular to the plane of the cross-section shown)

Table III. Stability analysis summary

Stability analysis term	Dry meadow	Wet meadow
Saturated unit weight γ (kN m^{-3})	2·9	2·9
Tensile strength σ_t (kPa)	5	45
Compressive strength σ_c (kPa)	10	15
Total bank height (m)	>1·0	<1·0
Cantilever block height h (m)	0·25	0·50
Block height under tension t (m)	0·13	0·33
Block height under compression c (m)	0·13	0·17
Stable cantilever width b (m)	0·14	1·00
Migration rate (m a^{-1})	1·50	0·25
Failure frequency	>10 failures per year	1 failure per 4 years

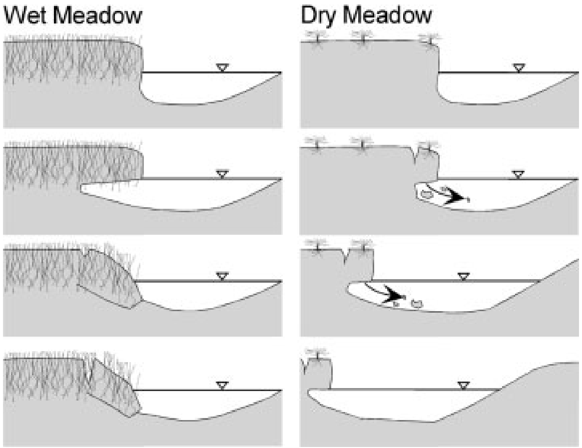

Figure 7. Failure mechanisms: dry versus wet meadow. Sedge-reinforced wet meadow banks typically fail only after the flow has undermined a large cantilever block. Failed blocks normally remain attached to the bank, and armour it against further erosion. Dry meadow banks fail more frequently and in smaller blocks. The blocks typically detach completely from the bank, and are rapidly broken up and removed by the flow. Approximately four years is required to undermine and remove a wet meadow block, compared to a few weeks for a dry meadow block

after failure is almost certain given the narrow block width, bank heights exceeding 1·0 m, and the low tensile strength of dry meadow soils, as illustrated in Figure 7.

Thorne (1978) suggested that the process of composite bank erosion may be divided into two components separated by cantilever failure: (1) fluvial erosion (particle-by-particle removal of cohesionless materials); and (2) basal cleanout (removal of cohesive bank failure products). The effects of increased block width include: (1) decreasing the shear stress on unvegetated materials beneath the stable cantilever; (2) decreasing the risk of block detachment after failure; and (3) increasing the size, mass and cohesion of failed blocks. The first effect reduces rates of fluvial erosion of cohesionless sediments underlying the vegetated layer, while the second and third effects result in an increased block residence time at the toe of the bank. The greater the cohesion of failed bank materials, the greater the force required to remove them (Wood *et al.*, 2001). Once a block has failed, vegetation densities may increase due to enhanced water availability, which helps to further stabilize the block in place. Often failed blocks display a root-reinforced toe, buried several centimetres below low-flow bed elevations, that appears to have been built up over multiple seasons.

The net effect of wet meadow vegetation on bank failure processes is that larger and longer-duration flows are required to undermine and remove bank failure blocks. Our short-term monitoring of a wet meadow bend revealed that 60 per cent of an actively eroding bank was protected by failed slump blocks (Figure 5). The El Niño flows of 1997, which corresponded to greater than a ten-year flood, succeeded in removing only one failed slump block, with measurable bank erosion occurring over less than 5 per cent of the length of the entire bend.

The frequency of block failure and removal can be estimated by dividing average migration rates by block width (e.g. Gabet, 1998). An average block width of 1·0 m and an average migration rate of 0·25 m a^{-1} (Micheli and Kirchner, 2002) imply that an average of four years of flow is required to undermine and remove a wet meadow block, while only a few weeks are required to undermine and remove a dry meadow block (Table III). Inspection of actively failing banks suggests that the only way to detach a slumped wet meadow block is by eroding the tension crack behind the block, thus separating the block from the floodplain terrace, and then scouring the bed elevation below the block toe. Over the short term, bed lowering during high flows may help remove slump blocks that have become separated from the floodplain. Over the long term, any trend towards channel incision could tend to reduce the residence time of failed slump blocks. Our results, considered with those of Micheli and Kirchner (2002), indicate that where incision of the Kern River has converted the riparian vegetation from wet meadow to dry meadow, bank strength has been reduced by a factor of five (Table II), and bank erodibility has been increased by a factor of ten.

PRINCIPAL FINDINGS

- At Monache Meadow, rushes (*Eleocharis* and *Juncus* spp.) are more effective at stabilizing coarse bar surfaces than sedges (*Carex* spp.), while sedges dominate finer floodplain terrace deposits and are responsible for the formation of cantilevered cut banks.
- Reinforcement of bank soils by herbaceous riparian vegetation can increase the shear strength of soils by up to eightfold. We measured shear strength increases of 0·09 (±0·01) kPa per g m^{-2} of above-ground dry biomass for rush-reinforced bar substrates and increases of 0·04 (±0·01) kPa per g m^{-2} of above-ground dry biomass on sedge-reinforced slump blocks.
- Soil shear strength increases roughly linearly with the ratio of dry root biomass to dry soil mass in a given volume of soil. Soil shear strength increases at a rate of approximately 1020 (±360) kPa per unit root biomass–soil mass ratio.
- By increasing the tensile strength of bank soils, wet meadow riparian vegetation increases the stable width of an undercut bank by a factor of ten. By increasing the size, mass and cohesion of failed cantilever blocks, wet meadow vegetation prolongs the period of basal cleanout required before a new cycle of bank erosion can commence.
- Based on a comparison of stream migration rates with failure block dimensions for the South Fork of the Kern River at Monache Meadow, we estimate that over the period from 1955 to 1995, approximately four years was required for wet meadow block failure and removal, as opposed to only several weeks of flow required to undermine and remove a dry meadow block.
- These results provide a mechanistic explanation of how wet meadow vegetation serves to limit rates of lateral stream channel migration.

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