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EFFECTS OF WET MEADOW RIPARIAN VEGETATION ON STREAMBANK EROSION. 1. REMOTE SENSING MEASUREMENTS OF STREAMBANK MIGRATION AND ERODIBILITY

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ABSTRACT

We quantified how rates of stream channel migration in a montane meadow vary as a function of the riparian vegetation community. The South Fork of the Kern River at Monache Meadow, located in California's southern Sierra Nevada range, supports two distinct types of vegetation: a dry meadow community dominated by sagebrush and non-native grasses (xeric scrub and meadow), and a wet meadow community dominated by rushes and sedges (hydric graminoids). We measured rates of lateral stream migration for dry versus wet meadow reaches from aerial photographs spanning a 40-year period (1955–1995). While stream migration rates averaged only $0{\cdot}24 \pm 0{\cdot}02$ m a^{-1} in the wet meadow, the dry meadow channel migrated an average of $1{\cdot}4 \pm 0{\cdot}3$ m a^{-1}. We used a linear model of meander migration to calculate coefficients that characterize bank migration potential, or bank erodibility, independent of channel curvature. These calculations demonstrate that, at Monache Meadow, banks without wet meadow vegetation are roughly ten times more susceptible to erosion than banks with wet meadow vegetation. Where stream bank heights consistently exceed 1 m, low water availability creates riparian habitats dominated by dry meadow vegetation. Thus, channel incision may reduce bank stability not only by increasing bank height, but also by converting banks from wet meadow to dry meadow vegetation. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: bank erosion; riparian vegetation; meander migration; GIS; air photography analysis

INTRODUCTION

Streambank erosion drives temporal changes in river planform morphology. Rates and patterns of meander migration reflect the ability of hydraulic shear forces to erode bank and floodplain materials via fluvial entrainment and mass wasting. Increasing hydraulic shear or increasing bank erodibility should result in increased rates of bank erosion and lateral stream migration (Howard, 1984). Here, we examine variations in channel migration rates and bank erodibility as an indicator of how, and by how much, riparian vegetation may contribute to the bank stability of a montane meadow stream.

Riparian vegetation is often held to potentially enhance stream bank stability (e.g. Thorne, 1990; Gregory, 1992), yet this effect remains poorly quantified. Herbaceous wet meadow riparian species, including sedges (*Carex* spp.) and rushes (*Juncus* spp., *Eleocharis* spp.), are adapted for survival in riverbank environments. These species grow dense root networks that bind bank sediments and resist plant removal by flood scour (Nilsson *et al*., 1989). Unlike riparian trees, herbaceous vegetation does not affect bank erodibility by significantly increasing the roughness of the channel boundary to flow, increasing the mass loading of banks, or producing large woody debris. The most significant effect of wet meadow vegetation on bank erodibility appears to be increased bank strength due to the reinforcement of bank soils by roots. In a companion paper (Micheli and Kirchner, in press), we present direct measurements of in-situ vegetated bank strength and examine how wet meadow vegetation influences bank failure mechanics. This paper and its

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companion quantify the effects of wet meadow vegetation on lateral channel stability. A better understanding of vegetation effects on bank stability should aid in designing river restoration and wetland conservation measures.

Several river meander migration studies report variations in stream migration rates as a function of riparian vegetation (Johanneson and Parker, 1985; Odgaard, 1987; Pizzuto and Meckelnberg, 1989). These studies calibrate a linear model of meander migration (Ikeda *et al*., 1981; Johannesson and Parker, 1989) that assumes that migration rate equals a bank erosion coefficient multiplied by a flow velocity term. Since the flow velocity term includes the cumulative effects of channel curvature on flow shear, bank erosion coefficients provide an estimate of bank and floodplain erodibility normalized for channel curvature (Hasegawa, 1989). Johanneson and Parker (1985) and Odgaard (1987) observed that for a set of rivers in Minnesota and Iowa, riparian forest vegetation appeared to decrease bank erodibility by a factor of two. Pizzuto and Meckelnburg (1995) observed that reductions in bank erodibility due to forest vegetation may vary with species composition. In this paper, we apply a similar methodology to a Californian Sierra Nevada montane meadow to compare migration rates and bank erodibility coefficients for reaches with hydric ('wet') versus xeric ('dry') meadow vegetation.

Throughout the American west, montane meadows have sustained heavy land and water use pressures since European settlement. Many wet meadow streams show evidence of channel incision including high cut banks and channel cross-sections that greatly exceed the capacity required to carry the mean annual flood. Hypothesized causes of channel incision range from grazing to climatic and tectonic change (Collins, 1995). Channel incision can change meadow hydrology by lowering groundwater tables and reducing frequencies of overbank flow. Drying out the riparian zone may result in 'sagebrush invasion', the conversion of vegetation from wet meadow sedges and rushes to xeric upland species including sagebrush and non-native grasses (Ratliff, 1985; Sarr, 1995). It is the goal of this paper to measure how sagebrush invasion, or conversely wet meadow restoration, may affect the lateral channel stability of a montane meadow stream.

SETTING

The South Fork of the Kern River at Monache Meadow is located on the Kern Plateau of California's southern Sierra Nevada and is managed by the Inyo National Forest (Figure 1). The watershed that drains to the gauge at the base of the meadow comprises approximately 70 per cent steep forested terrain and 30 per cent flat alluvial meadow (additional watershed characteristics are summarized in Table I). The hydrologic cycle is dominated by snowmelt-driven flood peaks (flood frequencies are listed in Table II). The meadow is colonized by two contrasting vegetation communities that may be easily distinguished on the ground or with aerial photography: 'dry' xeric meadow and scrub vegetation (sagebrush (*Artemesia cana*) and annual grasses), and 'wet' hydric graminoid meadow vegetation (sedges (*Carex* spp.) and rushes (*Juncus* and *Eleocharis* spp.)). The river channel meanders freely through a valley-fill comprising granitic alluvium, primarily sand, that in itself is relatively cohesionless. Since floodplain soils and channel geometry are similar for the dry meadow and wet meadow reaches, we argue that significant differences in bank stability may be attributable to the effect of wet versus dry vegetation on bank erodibility.

Livestock grazing constitutes the most significant land use of the meadow. By the turn of the 20th century, the meadow was heavily grazed, as shepherds routinely drove their flocks into Sierran high meadows for summer forage (Ratliff, 1985). Clarence King commented in 1902: 'the Kern plateau, so green and lovely in my former visit in 1864, was now a gray sea of rolling granite ridges darkened at intervals by forest, but no longer velveted with meadows and upland grasses. The indefatigable shepherds have camped everywhere, leaving hardly a spear of grass behind them' (in Wilkins, 1988). Today, regulated numbers of cattle graze the meadow during the summer months and the meadow grasses have returned. The US Forest Service manages Monache Meadow as critical habitat for the endemic Californian Golden Trout (*Onchorrhyncus aguabonita aguabonita*) and is exploring opportunities for ecological restoration including stream fencing and channel manipulation. Managers worry that channel incision may have lowered the water table and

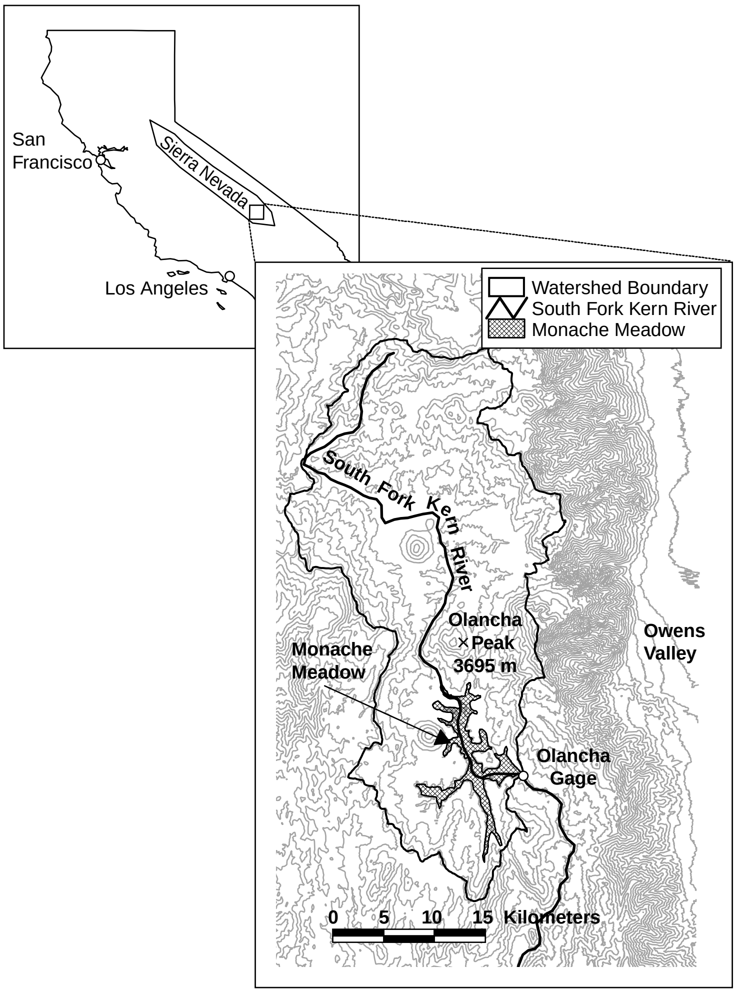

Figure 1. Location map. Monache Meadow is located on the Kern River plateau of California's southern Sierra Nevada range

Table I. South Fork Kern River: watershed characteristics at Monache Meadow

Characteristic	Value
Drainage area	380 km^2
Lithology	Granitic, punctuated by andesitic volcanoes
Gauge elevation	2393 m
Precipitation	300 mm a^{-1}
Meadow area	114 km^2
Meadow channel length	12 km
Growing season	March to June

Data from Collins (1995).

converted wet meadow to dry meadow vegetation communities in the northern (upstream) reach (Collins, 1995).

Table II. Annual peak flood frequency analysis, Olancha Gauge (USGS #11188200)

Recurrence interval (years)	Discharge (m^3 s^{-1})
2	7·3
2·3	11·2
5	24·2
10	46·5
25	85·0
50	94·9
100	95·2

Data from Collins (1995).

MEASURING STREAM MIGRATION USING REMOTE SENSING AND A GEOGRAPHIC INFORMATION SYSTEM

The application of a geographic information system (GIS) to aerial photography analysis provides a good framework for measuring stream channel changes over time. Detecting rates of meander migration using temporal sequences of channel planform data is an established technique (e.g. Brice, 1977; Gurnell *et al.*, 1994; Gurnell, 1997), and using a GIS to relate migration rates to environmental parameters is an increasingly common practice (e.g. Lawler, 1993; Gilvear and Winterbottom, 1994). The advantage of completing a historic channel change analysis in a GIS format is that resource managers may use the results as a baseline for future river monitoring.

Mapping stream channels and riparian vegetation using aerial photography

Historic stream channels and adjacent riparian vegetation cover were mapped using aerial photography, which we converted to a digital format and rectified using desktop image processing tools. We used black and white aerial photography dated August 1955 (scale 1 : 11 750), July 1976 (scale 1 : 20 000) and September 1995 (scale 1 : 10 000). We used a drum scanner set at 600 dpi to convert 36 inch by 36 inch photographic prints into digital images. The digital photographic images were imported into Arc/Info and stored in a raster grid format.

We georeferenced the 1995 image to the USGS 7·5 minute Monache Mountain quadrangle using 20 ground control points including road intersections and an abandoned air strip. We rectified the 1995 image using a rubbersheet command (‘warp’) in Arctools. This command stretches or compresses the image in as uniform a manner as possible in order to match the basemap locations of ground control points. We established an additional 12 ground control points on the 1995 image, including mature trees and rock outcrops, by surveying their locations during the summer of 1997. These additional points allowed more accurate georeferencing of the 1955 and 1976 images to the rectified 1995 image.

We estimated residual georeferencing error by leaving one ground control point ‘free’ while rubbersheeting the image to the remainder of the ground control points, and then comparing the actual and mapped location of the free point. We repeated this procedure for each ground control point to generate spatially variable uncertainty estimates, with residual spatial error (the difference between the actual and the mapped location of a feature) estimated at $\pm$5·0 m for regions close to the channel. This value is contrasted to errors of up to 90 m estimated for non-rectified images of the same scale and relief (Bolstadt, 1992). By comparing maps digitized by different individuals, we estimated potential error introduced in digitizing ground control points and channel attributes at $\pm$2·0 m for the 1 : 20 000 scale image (which would correspond to an error of $\pm$1·0 m for the 1 : 10 000 scale image). By propagating the rectification and the digitizing uncertainty, we estimated the total average spatial uncertainty of individual mapped features at $\pm$5·4 m. Working in a digital format allowed us to zoom in on the channel and accurately digitize channel banks and a channel centreline.

We mapped vegetation using a series of USFS low-altitude 1994 colour photographs (scale 1 : 2 000) in combination with the 1995 black-and-white image (scale 1 : 11 750) to define black-and-white vegetation

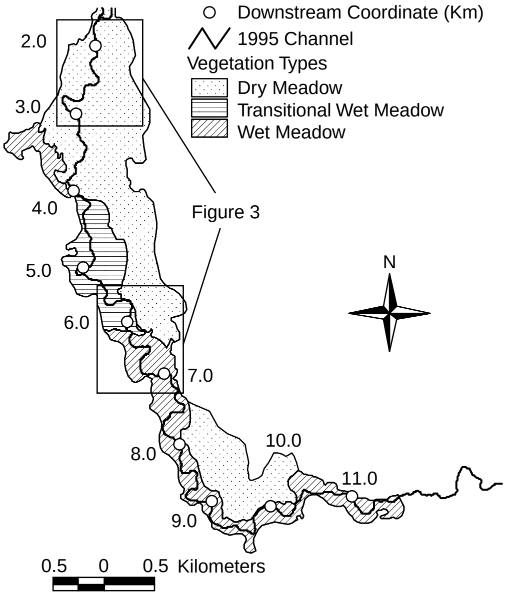

Figure 2. South Fork of the Kern River and surrounding meadow plant communities, from 1995 aerial photographs. Dry meadow, dominated by sagebrush, borders the channel from downstream coordinates km 2·0 to km 4·0. Wet meadow, dominated by sedge species, borders the channel from km 6·0 to km 8·0. Between these two communities, from km 4·0 to km 6·0, lies a transitional wet meadow supporting both wet meadow and dry meadow herbs

image ‘signatures’ (feature pattern and saturation). High soil moisture contents and dense plant spacings give the wet meadow a significantly darker signature than the dry meadow. Sagebrush regions of dry meadow display a characteristic stippling due to the regular spacing between *Artemesia* plants. The xeric dry meadow zone included the following vegetation cover categories: dense sagebrush, sagebrush interspersed with bare ground, and dry herbaceous meadow dominated by non-native annual herbaceous species. The wet meadow zone included a dense sedge meadow category and a category we labelled ‘transitional wet meadow’ that also included some patches of herbaceous dry meadow vegetation. We verified vegetation categories during the summer of 1996. The 1955 and 1976 images were interpreted using black-and-white vegetation signatures verified for the 1995 image. Figure 2 shows that in 1995, dry meadow vegetation dominated the channel from river kilometres 2 to 4, while wet meadow vegetation dominated river kilometres 4 to 10.

Quantifying rates of meander migration

We mapped patterns of lateral channel migration by superimposing the 1955, 1976 and 1995 stream channels on top of each other using Arc/Info software. Inspection of channel migration sequences for the dry meadow versus the wet meadow (Figure 3) shows qualitatively that rates of channel migration are significantly higher in zones of dry meadow vegetation than in wet meadow zones. We quantified rates of lateral channel migration in each vegetation community using a map unit we term the ‘eroded area polygon’, delineated using a technique similar to that of MacDonald *et al*. (1993). An eroded-area polygon is created by intersecting two channel centrelines mapped at two different points in time (Figure 4). For typical patterns of meander migration, each eroded-area polygon captures the net migration of a bend over the elapsed time period. Given a residual spatial uncertainty of $\pm 5{\cdot}4$ m for each channel centreline, the propagated uncertainty for measurements using two centrelines is $\pm 7{\cdot}6$ m, or $\pm 0{\cdot}33$ m a^{-1} for migration measurements spanning a 20-year time period.

Arc/Info calculates the area and perimeter of each eroded-area polygon, from which it is a simple matter to calculate the average distance migrated perpendicular to the channel centreline. The average stream length for the polygon over the time interval equals one-half of the polygon perimeter, while the average distance migrated lateral to the channel centreline is equal to the polygon area divided by the average stream length.

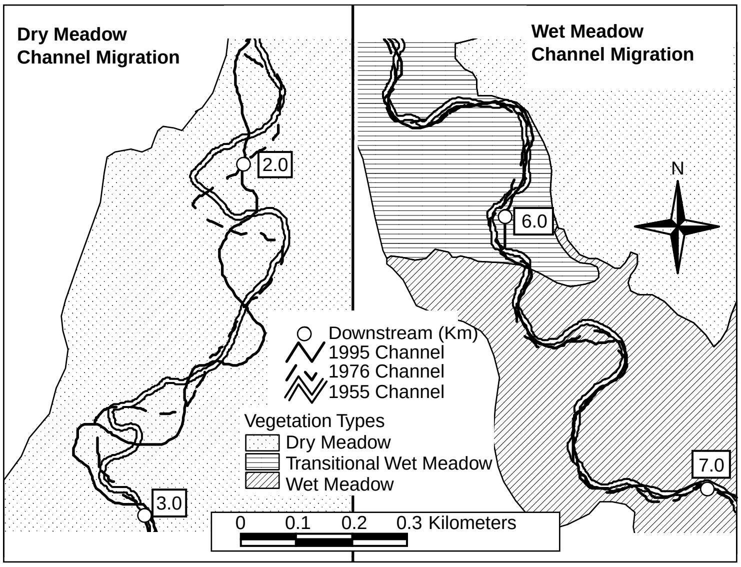

Figure 3. Comparison of channel migration in dry and wet meadow communities. The channel has migrated up to 100 m across the dry meadow, but has remained relatively stable in the wet meadow over the study period (1955 to 1995)

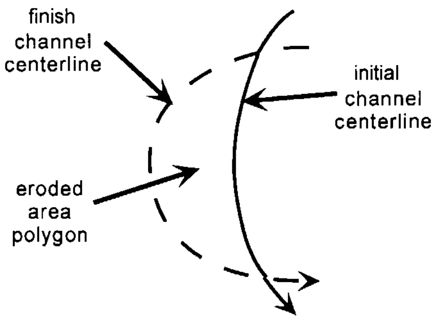

Figure 4. Eroded-area polygon. An eroded area polygon is created by intersecting stream centreline segments from two different time periods. The average stream length equals the average of the two stream segments bordering the polygon, or one-half of the polygon perimeter. The average distance migrated normal to channel centreline equals the polygon area divided by the average stream length

Lateral distance migrated may be calculated for a series of eroded-area polygons along a stream reach and plotted using the midpoint of the polygon to locate the measurement along the channel centreline. This GIS-based eroded-area polygon method is likely to be more reproducible than alternative migration measurement methods such as Hickin orthogonal mapping (Hickin, 1975).

Our lateral migration measurements for the two time intervals, 1955 to 1976 and 1976 to 1995, are displayed in Figure 5 and summarized in Table III. We observe that for the first and second time intervals, the dry meadow reach migrated on average 1·3 m a^{-1} and 1·5 m a^{-1}, respectively, while the wet meadow migrated on average 0·23 m a^{-1} and 0·25 m a^{-1}, respectively. Given the residual spatial uncertainty of the aerial photographs, the inferred migration rates in the wet meadow are similar to our limit of detection.

CALCULATING BANK ERODIBILITY COEFFICIENTS

Rates of lateral channel migration tend to increase with bend curvature (Hickin and Nanson, 1984). However, the velocity distribution of streamflow within a bend (and thus the distribution of stresses on the banks and

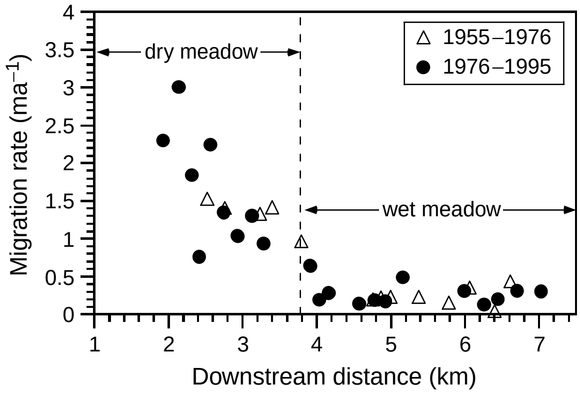

Figure 5. Channel migration rates versus downstream distance. Channel migration rates in the dry meadow range up to 3 m a^{-1}, decreasing with distance downstream, whereas channel migration rates in the wet meadow are consistently less than 0·7 m a^{-1}

Table III. Migration rate and erodibility summary

	Dry meadow	Wet meadow
Migration (m a^{-1}) ± SE		
1955–1976	1·3 ± 0·4	0·23 ± 0·02
1976–1995	1·5 ± 0·1	0·25 ± 0·01
Erodibility × 10^{-7} ± SE		
1955–1976	3·7 ± 0·5	0·58 ± 0·02
1976–1995	8·4 ± 0·7	0·64 ± 0·03

SE = standard error.

bed) depends not only on the geometry of the bend itself, but also on the curvature of the channel above the bend (Ikeda *et al*., 1981; Furbish, 1991). To account for the cumulative effects of channel curvature on lateral migration rates, we converted our migration measurements to estimates of bank erodibility using a numerical model of streamflow in bends and resultant meander migration developed by Ikeda *et al*. (1981). This model has been applied successfully to rivers in Japan by Hasegawa (1989), and in the USA by Johanneson and Parker (1989), Pizzuto and Meckelnburg (1989) and Larsen (1995).

Estimating stream velocities and bank erodibilities using a linear model

The model solves the three-dimensional equations of motion for flow and sediment transport using a perturbation expansion on curvature to estimate linear cross-stream profiles for bed elevations and for depth-averaged flow velocities (Figure 6). The model calculates the magnitude of near-bank velocities at points evenly distributed downstream based on channel geometry and a 'dominant' discharge (typically the two-year return interval flow). Ikeda *et al*. (1981) argue that rates of meander migration should be proportional to the perturbation (u') from the mean velocity, where the perturbation equals the difference between the velocity near the outside bank and the mean velocity. The model assumes that if depth-averaged velocities increase linearly across the channel, u' should be proportional to the magnitude of shear forces on the bank. If u' approximates the bank shear forces, then an erodibility coefficient E_o may be defined that expresses the vulnerability of the bank to erosion, such that:

$$M = E_o u'$$

where M is the bank migration rate (m a^{-1}), E_o is the erodibility coefficient, and u' (m s^{-1}) is the cross-stream velocity perturbation. Because M and u' are both velocities, the erodibility coefficient E_o ($E_o = M/u'$) is dimensionless if M and u' are measured in the same units. Dimensionless values of E_o are small (on the order of 10^{-7}), since the average rate of bank migration is typically many orders of magnitude slower than the velocity of streamflow.

The linear model requires the following inputs: a channel centreline digitized from aerial photography, a channel slope measured from a topographic survey, a dominant discharge based on the flow frequency analysis and channel survey, an average channel width and depth based on the channel survey, and a median bed grain size based on pebble counts and bulk samples. Input values are summarized in Table IV. These model inputs define the channel cross-sectional area, slope and discharge, thus jointly implying a Manning's n value of 0·043 for channel roughness.

We intersected the eroded-area polygons with u' values calculated at points spaced 0·5 channel widths along the channel centreline, and selected the maximum velocity perturbation in each eroded-area polygon to represent the magnitude of flow shear. We then calculated E_o values for each eroded-area polygon by dividing the mean migration rate for the polygon by the maximum velocity perturbation value. Using the maximum velocity perturbation to characterize the magnitude of hydraulic shear over the entire polygon renders our estimates of bank erodibility conservative, i.e. calculated bank erodibilities are potential underestimates of the polygon average.

We analysed the sensitivity of u' and E_o to potential errors in model input parameters (Table III). For each 1 per cent error in model input, the potential error in E_o is as follows: 0·6 per cent per 1 per cent error in channel width; 0·3 per cent per 1 per cent error in channel depth; 0·4 per cent per 1 per cent error in channel slope; and 0·9 per cent per 1 per cent error in stream discharge.

Comparison of the calculated erodibility coefficients for banks with dry versus wet vegetation reveals that the dry meadow reach is on average 6·4 times more erodible than the wet meadow reach for the 1955 to 1976 time interval, and 13 times more erodible than the wet meadow reach for the 1976–1995 time interval (Table IV, Figure 7).

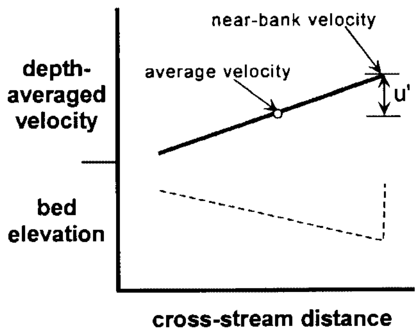

Figure 6. Linear perturbation model outputs. The linear model of meander migration developed by Ikeda *et al.* (1981) estimates linear profiles for cross-stream bed elevations and depth-averaged velocities. The velocity perturbation u' equals the near-bank velocity minus the mean velocity calculated for the channel midline

Table IV. Linear model input parameters

Parameter	Value
Discharge	20 m^3 s^{-1}
Bank height	1·0 m
Channel width	30 m
Channel slope	0·001
Bed median grain size (D_{50})	4 mm
Manning's n roughness	0·043

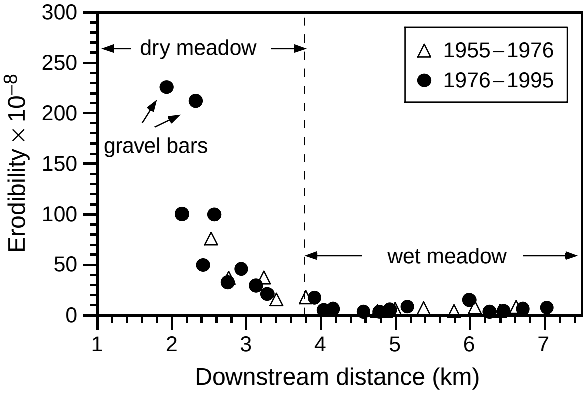

Figure 7. Bank erodibility versus downstream distance. Bank erodibility decreases with downstream distance through the dry meadow, and is consistently low in the wet meadow. The two maximum erodibility values show where the channel has migrated back through recently deposited gravel bars, rather than through floodplain terrace

Flow frequency analysis

Analysing peak and mean daily flow distributions provides a basis for evaluating whether the linear meander migration model's representation of cumulative flow with a single dominant discharge is reasonable or not. We compared peak and mean daily discharge characteristics for the two time periods of analysis as described below (1955–1976, 1976–1995).

The USGS Olancha gauge (number 11188200) located at the base of Monache Meadow measured streamflow continuously on the South Fork of the Kern River from 1957 to 1967, and intermittently thereafter until 1978. We adopted the recurrence intervals assigned by the USGS for the Olancha flow record (Collins, 1995). We extended the peak flow record using streamflow data collected at the Onyx, CA, gauge (number 11189500) located approximately 73 km downstream at an elevation of 1275 m and with a drainage area of 1372 km^2. For the ten-year record between 1955 and 1966, we calculated a correlation coefficient of 0·82 for peak discharges at the two gauges using the method described in Salas (1980). The extended record for the Olancha gauge (Figure 8) shows that the maximum recorded peak flow value of 60 $m^3 s^{-1}$ occurred in water year 1969, corresponding to a flow recurrence interval of approximately 15 years (see Table II). Between 1955 and 1976, ten peak flows met or exceeded the mean annual flood flow of approximately 11 $m^3 s^{-1}$.

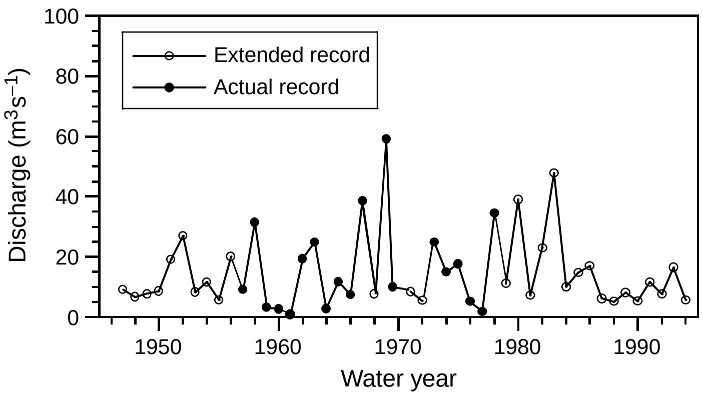

Figure 8. Annual peak flows at Monache Meadow. Filled circles show values measured at the USGS Olancha gauge (USGS #11188200), while open circles show values estimated from the Onyx gauge, 73 km downstream (USGS #1189500). Peak annual flows exceeded the estimated bankfull discharge for the wet meadow channel (11 $m^3 s^{-1}$) ten times during the first time interval (1955–1976) and nine times during the second time interval (1976–1995)

Between 1976 and 1995 the mean annual flood was exceeded nine times. Calculated exceedance probabilities for daily mean flows at the Onyx gauge for the 1955 to 1976 and 1976 to 1995 time intervals (Figure 9) show that the two time periods are relatively similar in terms of peak and mean flow distributions. This analysis helps to justify our assumption, in our erodibility analysis, that the dominant discharges for the two time periods were similar. The relatively consistent amounts of average migration over the two time periods may in fact reflect the similarity of peak and mean flow distributions (Figures 8 and 9).

FIELD SURVEY AND BANK MATERIAL CHARACTERIZATION

During the summer of 1997, we surveyed the river channel and established a set of bank profile stations to characterize variations in channel geometry or bank material along the study reach that might influence bank stability independent of riparian vegetation. The field team surveyed bank elevations, thalweg elevations, low flow water surface elevations, and selected cross-sections using a total station. At 13 cross-section stations we inventoried bank strata by measuring the cut bank profile and recording a stratigraphic log. We used a Torvane and a pocket penetrometer to measure the soil cohesion of unvegetated soil strata (saturating exposed soils with a hand-held spray bottle and then calculating an average of five cohesion measurements for each bank stratum). These measurements were intended to reveal any major differences in alluvial sediments residing below the influence of vegetation, rather than to characterize bank strength in general, which is clearly a product of materials and geometry at a scale greater than that captured by pocket measuring devices. The companion paper (Micheli and Kirchner, in press) goes further into methods for characterizing bank strength and explores in detail the scaling of effects of vegetation on apparent bank cohesion and failure mechanics.

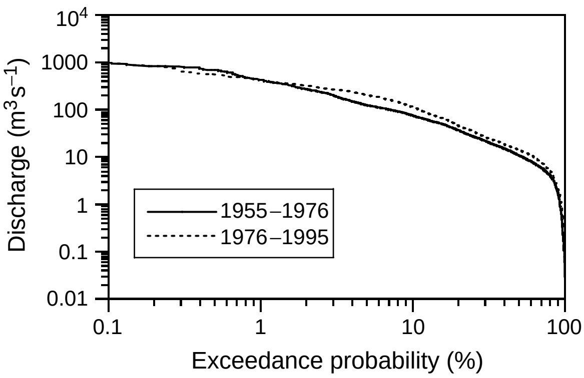

Figure 9. Exceedance probabilities for daily flows at the Onyx gauge, 73 km downstream from Monache Meadow. There do not appear to be significant differences in the mean daily flow distributions for the 1955–1976 and 1976–1995 time intervals

Table V. Unvegetated bank soils analysis

Downstream distance (km)	Meadow type	Torvane (kg cm^{-2})	Penetrometer (instrument units)	Sample size
1·40	Dry	2·6 ± 0·3	1·3 ± 0·3	20
2·24	Dry	2·4 ± 0·3	1·4 ± 0·3	20
3·30	Dry	2·2 ± 0·4	1·7 ± 0·2	25
3·98	Dry	2·1 ± 0·2	1·8 ± 0·2	20
4·50	Wet	2·1 ± 0·3	1·3 ± 0·2	20
6·29	Wet	2·5 ± 0·2	1·4 ± 0·1	20

Bank strengths shown as strata average (with five samples per strata) ± SE (standard error).

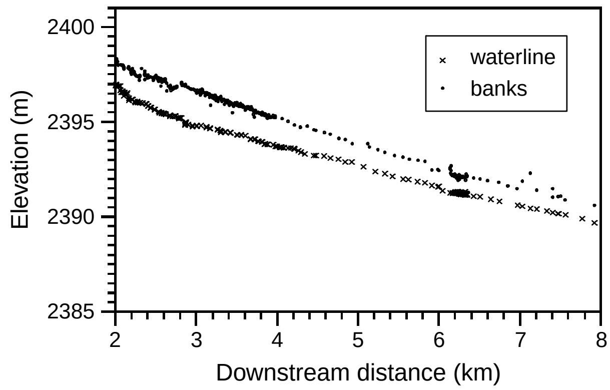

Figure 10. Longitudinal profile and relative bank height. Profiles were surveyed 6–8 August 1997, during summer low flows. Relative bank heights are shown as the distance between the water surface and floodplain terrace elevations. Bank heights through the dry meadow (river km 2 to 4) generally exceed 1 m, while bank heights through the wet meadow (river km 4 to 8) are generally less than 1 m. Channel slopes decrease with distance downstream in the dry meadow

Exposed bank stratigraphy did not vary significantly with downstream distance. Typical strata were composed of fine to medium sands interbedded with silt-sand mixtures. Where wet meadow vegetation lined the banks it contributed organic matter to surface soils and tended to trap coarse bed sediments. The strengths of bank strata below the rooting zone, as measured with the Torvane and pocket penetrometer (Table V), showed no clear difference between alluvial soils beneath the wet and dry meadow communities. The companion paper explores how riparian meadow vegetation affects the strength of bank soils.

The longitudinal profile and relative bank heights for the study reach are shown in Figure 10. Inspection of the longitudinal profile reveals that channel slope through the study reaches averaged 0·0010, with slightly higher values (up to 0·0013) in the dry meadow. The gradual decrease in slope through the dry meadow provides an explanation for why dry meadow migration rates also tend to decrease with distance downstream (Figure 5). We also observed that bank heights, measured here as the difference between the low flow water elevation and the adjacent terrace elevation, are consistently higher through the dry meadow than the wet meadow. Dry meadow bank heights range from 1·2 to 2·0 m while wet meadow bank heights range from 0·7 to 1·2 m. Active channel width remained relatively constant at roughly 30 m through the wet and dry reaches. The cross-channel terrace-to-terrace distance was generally greater for the dry meadow reach, with bends displaying large sand bars ranging in width from 50 to 100 m, relics of rapid channel migration within the last 50 years.

DISCUSSION

Our remote sensing measurements show that average migration rates in the dry meadow are approximately six times greater than those for the wet meadow, and that bank erodibility is on the order of ten times greater for the dry meadow for both time intervals. In addition, our results strongly suggest that channel bed elevation constrains the spatial distribution of wet meadow vegetation in Monache Meadow. A comparison of the topographic survey and vegetation map reveals that the bank height of the wet meadow channel is typically lower than 1 m, while dry meadow bank heights consistently exceed 1 m. Increasing bank height can reduce bank stability directly by increasing the weight of bank materials that are prone to mass wasting. Could increased bank height alone be responsible for the extent of destabilization we observe for the dry meadow channel? The geotechnical engineer's 'factor of safety' may be used to estimate how increased bank height due to channel incision may affect bank stability. The factor of safety is the ratio of stabilizing to destabilizing forces on a bank, with failure occurring at factors of safety less than one. The simplest model to calculate the factor of safety for a streambank is that of Osman and Thorne (1988), in which the factor of safety varies directly with cohesion and friction angle and inversely with soil bulk density, bank slope and bank height. An increase in bank height from 1·0 to 1·5 m would decrease the factor of safety at most by one-third. It seems unlikely that a decrease in bank stability of this magnitude alone could produce a tenfold increase in bank erodibility.

More significant for bank stability may be the effect of bank height on valley hydrology and, in turn, the distribution of wet meadow vegetation. We found that a flood on the order of a 100-year event is required to overtop the dry meadow banks, while the mean annual flood is capable of overtopping the wet meadow banks. Surveyed differences in bank height and channel slope may be used to estimate the frequency of overbank flow for the dry versus wet meadow using Manning's equation. Assuming uniform flow, with a maximum cross-sectional area of 120 m^2, a local slope of 0·0013, and an estimated Mannings' roughness of 0·043, a discharge exceeding 98 $m^3 s^{-1}$ would be required to overtop the banks throughout the dry meadow channel. By contrast, due to a lower bank height and cross-section area, a discharge of only 11 $m^3 s^{-1}$ would be required to overtop wet meadow banks. A discharge of 11 $m^3 s^{-1}$ has a return interval of roughly 2·3 years, whereas 98 $m^3 s^{-1}$ exceeds the estimated hundred-year flood (Table II). Our findings are consistent with Farrington's (1998) HEC-RAS analysis of our 1997 channel survey, which showed that the current wet meadow zone coincides with the zone inundated by the two-year flood. Increased bank height also increases the distance from the floodplain surface to the groundwater table. A study of wet meadow distribution in Kern Plateau valleys found that wet meadow vegetation could not colonize surfaces greater than 0·75 m above groundwater (Sarr, 1995); our survey results suggest that this threshold is exceeded where bank heights exceed approximately 1 m. If the greater bank heights through the dry meadow are a product of channel incision, it is likely that Monache Meadow once supported a greater area of wet meadow prior to channel incision.

One way to test whether the conversion of wet meadow to dry meadow is ongoing in Monache Meadow would be to monitor the boundary between the two vegetation communities. The meadow region mapped as 'transitional wet' in September 1995 (occupying the transition between dry and wet meadow at river kilometres 4·0 to 6·0; Figure 2) appeared in the July 1955 aerial photographs to be more saturated and to contain greater densities of wet meadow vegetation. This difference might be due to interannual changes in vegetation cover in response to variations in precipitation. Alternatively, it is possible that a wave of bed incision is responsible for drying out this zone of meadow. In this case, the velocity of the incision wave downstream equals roughly 50 m a^{-1}, the distance migrated by the transitional wet meadow/wet meadow boundary (2·0 km) divided by the time elapsed between the two photographs (40 years). Continued monitoring of bed elevations and vegetation composition in this transitional zone may resolve whether channel grade is stable or whether incision and vegetation conversion may continue in the future.

The furthest upstream extent of dry meadow channel occupies a transition between a steep montane channel and a flat alluvial valley and is therefore likely to be a depositional zone for sediment. Field evidence for rapid depositional events in this zone includes coarse sand deposits lacking distinct bedding in bank strata and splayed patterns of historical overbank sediment deposition. Channel incision may also affect lateral bank stability by accelerating sediment deposition on bars, which in turn may accelerate stream migration through 'bar push', the deflection of flow by a bar against the opposite bank (Howard, 1984; Dietrich *et al.*, 1999). Estimating the magnitude of this effect would require detailed measurements of sediment supply and deposition.

PRINCIPAL FINDINGS

- GIS tools provide a valuable framework for rectifying aerial photography, quantifying residual spatial uncertainty, mapping vegetation, and measuring stream migration in alluvial systems.
- At Monache Meadow, streambanks with dry meadow vegetation (sagebrush and annual grasses) migrate, on average, six times faster than streambanks with wet meadow vegetation (sedges and rushes).
- Erodibility coefficients, which characterize the susceptibility of stream bends to migration independent of stream curvature, reveal that the erodibility of dry meadow streambanks is roughly ten times greater than the erodibility of wet meadow streambanks.

- A bank height of 1 m may constitute a geomorphic threshold between dry and wet meadow regimes in this Sierran montane meadow. Channel incision beyond this threshold may trigger the conversion of riparian vegetation from wet to dry meadow and significantly destabilize streambanks.

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