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QUANTIFYING THE EFFECT OF RIPARIAN FOREST VERSUS AGRICULTURAL VEGETATION ON RIVER MEANDER MIGRATION RATES, CENTRAL SACRAMENTO RIVER, CALIFORNIA, USA

E. R. MICHELI,[a]* J. W. KIRCHNER[b] and E. W. LARSEN[c]

[a] *Energy and Resources Group, University of California, 310 Barrows Hall, Berkeley, CA 94720-4767, USA*
[b] *Department of Earth and Planetary Science, University of California, 307 McCone Hall, Berkeley, CA 94720-4767, USA*
[c] *Department of Geology, University of California, One Shields Avenue, Davis, CA 95616-8605, USA*

ABSTRACT

Riparian forest vegetation is widely believed to protect riverbanks from erosion, but few studies have quantified the effect of riparian vegetation removal on rates of river channel migration. Measured historical changes in a river channel centreline, combined with mapped changes in floodplain vegetation, provide an opportunity to test how riparian vegetation cover affects the erodibility of riverbanks. We analysed meander migration patterns from 1896 to 1997 for the central reach of the Sacramento River between Red Bluff and Colusa, using channel planform and vegetation cover data compiled from maps and aerial photography. We used a numerical model of meander migration to back-calculate local values for bank erodibility (i.e. the susceptibility of bank materials to erosion via lateral channel migration, normalized for variations in near-bank flow velocities due to channel curvature). A comparison of migration rates for approximately 50 years before and after the construction of Shasta dam suggests that bank migration rates and erodibility increased roughly 50%, despite significant flow regulation, as riparian floodplains were progressively converted to agriculture. A comparison of migration rates and bank erodibilities between 1949 and 1997, for reaches bordered by riparian forest versus agriculture, shows that agricultural floodplains are 80 to 150% more erodible than riparian forest floodplains. An improved understanding of the effect of floodplain vegetation on river channel migration will aid efforts to predict future patterns of meander migration for different river management and restoration scenarios.

KEY WORDS: bank erosion; meander migration; riparian vegetation; GIS

INTRODUCTION

Dynamic river channels are required to maintain the health of riparian ecosystems (Greco, 1999), but in the absence of proper land-use planning, river meander migration can threaten floodplain towns and agriculture. Traditional flood control strategies have advocated keeping river channels clear of vegetation, but it has been debated whether the removal of riparian forest vegetation from riverbanks has increased the vulnerability of adjacent lands to erosion. As greater priority is placed on the ecological conservation of our rivers, one of the greatest challenges facing managers today is how to plan for natural processes of riverbank erosion and migration. On the central Sacramento River, a unique coalition between state, federal and private groups has been formed to restore the riparian ecosystem. Balancing habitat restoration with flood protection requires a better understanding of interactions between river channels and floodplain vegetation. If riparian vegetation reduces rates of bank erosion, revegetation of river corridors may provide a cost-effective buffer between a dynamic river channel and floodplain development.

Many geomorphologists and engineers agree that vegetation should usually increase bank stability by increasing bank strength and reducing near-bank flow velocities (e.g. Gregory and Gurnell, 1988; Gray and MacDonald, 1989; Thorne, 1990), but studies are lacking that quantify how, and by how much, riparian vegetation reduces rates of bank erosion. While dense herbaceous vegetation has been shown to effectively reinforce stream banks (Micheli

* Correspondence to: E. R. Micheli, Energy and Resources Group, University of California, 310 Barrows Hall, Berkeley, CA 94720-4767, USA.
E-mail: micheli@vom.com

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and Kirchner, 2002a,b), the effect of forest vegetation is more complex because the weight of trees could add significantly to bank stresses, and because large woody debris could deflect streamflow in ways that accelerate bank scour. In an earlier study of lateral migration patterns of the central Sacramento River, Brice (1977) anecdotally observed that riparian vegetation appeared to effectively limit channel migration. Later researchers discovered that for a small set of midwestern study reaches, channels bordered by riparian forest tended to migrate roughly half as fast as unforested channels (Johannesson and Parker, 1985; Odgaard, 1987). The linear model of meander migration (Ikeda *et al.*, 1981; Johannesson and Parker, 1985; Larsen, 1995) provides a tool for estimating the 'erodibility' of bank and floodplain materials based on historical meander migration patterns. Here we link this linear migration model to a geographic information system (GIS) to analyse historical sequences of river channel and vegetation maps (e.g. Lawler, 1993; Gilvear and Winterbottom, 1994). The advantage of using GIS for historic channel analysis is that the results may be used for ongoing river monitoring and planning.

SETTING

The Sacramento River (Figure 1) is the largest river system in California, draining approximately 17% of California's land area and yielding 35% of the state's water supply (Buer *et al.*, 1989). It provides valuable aquatic habitat for salmon and, although it is estimated that 89% of the original forest vegetation has been lost, the central reach of the Sacramento River still possesses one of the most ecologically diverse riparian corridors remaining in California (State of California, 1998). The study reach, located between Red Bluff and Colusa (river miles 245–143, Figure 1), is relatively free to migrate, but is constrained in some locations by bridges and bank stabilization projects. Since the mid-19th century, the surrounding floodplain has been progressively converted from riparian forest and tule swamp to agriculture, primarily fruit and nut orchards (Katibah, 1984). The flow of the Sacramento River has been regulated since the early 1940s by Shasta and Keswick dams, located upstream of Red Bluff. River regulation has reduced the magnitude and frequency of high-flow events and has effectively increased low-flow discharges during

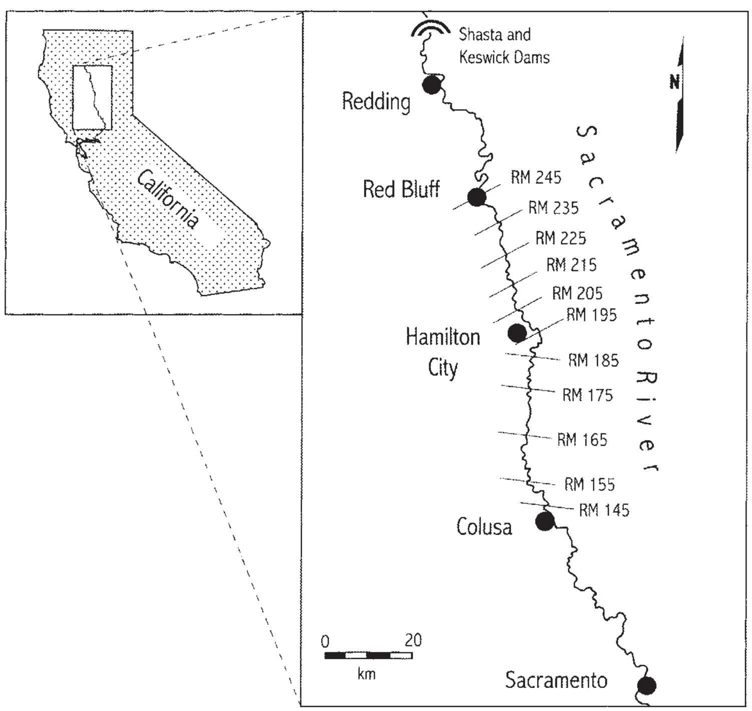

Figure 1. A map of the central reach of the Sacramento River showing the river channel, adjacent towns, gauging stations, and river mile coordinates. The study reach flows from Red Bluff to Colusa through the northern section of California's Central Valley

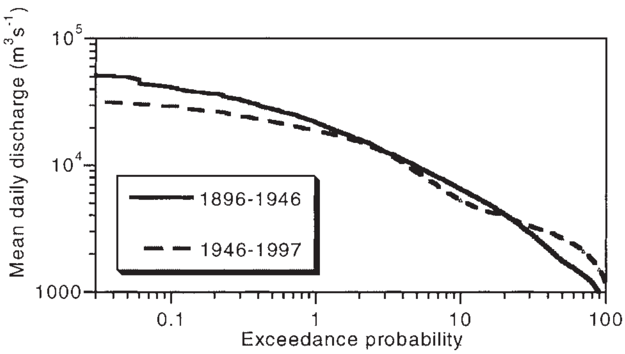

Figure 2. Mean daily discharge versus exceedance probability, 1896 to 1946 and 1946 to 1997 (corresponding approximately to pre-dam and post-dam periods). The effect of river regulation is reflected in the decreased frequency of large floods, and the increased frequency of medium to small flows

the summer and autumn irrigation seasons (Figure 2; Buer *et al.*, 1989). The lower third of the study reach, river miles 185 to 143, is bounded by flood control levees. Given its high resource value, the central reach of the Sacramento River is currently the subject of a multi-agency comprehensive planning process aimed at balancing habitat restoration with flood control and water supply.

MEASURING RIVER MIGRATION AND BANK ERODIBILITY USING A GIS

Superimposing temporal sequences of channel planform maps is a common approach to quantifying the lateral shift of a river channel over time (e.g. Brice, 1977; MacDonald *et al.*, 1993; Gurnell *et al.*, 1994; Gurnell, 1997; Brewer and Lewin, 1998; Dietrich *et al.*, 1999). Performing this analysis in a GIS facilitates calculation of migration rates and provides a digital baseline for future river monitoring (e.g. Winterbottom and Gilvear, 2000). The California Department of Water Resources (DWR) has assembled historic data on channel planform changes, soils, geology, and vegetation cover in a GIS format. The majority of our analysis relies on these historical resources compiled by the DWR.

Defining a channel centreline

For each historic channel planform map, we digitized a channel centreline to represent the channel location for a specific year. Most of the channel planform data used here are printed in the river atlas appendix to the 1984 Middle Sacramento River Spawning Gravel Study published by the DWR (State of California, 1984). For years when the channel banks were delineated during low-flow conditions, we simply digitized a line located midway between the low-flow water lines to represent the channel centreline. We tested the reliability of this method by comparing channel centrelines digitized by two different analysts, which revealed that digitizing uncertainty was approximately 5% of the total channel width, or approximately 15 m. Since DWR did not quantify the spatial uncertainty in the aerial photography used to map the channels, we estimated the potential maximum geometric error due to tilt and terrain effects (assuming no rectification) following Bolstadt (1992). Assuming photography of 1 : 10 000 scale, terrain of less than 250 m relief, and camera tilt of up to 4.2° (a typical maximum value), the expected positional error is on the order of 20 m. By summing the geometric and digitizing errors in quadrature, we estimate total digitizing and rectification error of individual channel centrelines at ± 25 m.

For years where the channel banks are defined by a peak-flow high-water mark, it is inconsistent to use the midpoint of the channel to represent the centreline for highly curved bends, since flood flows tend to preferentially inundate shallow bar zones on the inside of bends. Since the 1946 channel coverage was plotted based on a peak flood, in this case we used straight reaches to define a reference channel width, and then digitized a channel centreline one-half of this distance from the outside bank of meander bends. We double-checked this centreline by ensuring that the 1946 centreline did not cut off any curvature present in the 1937 channel.

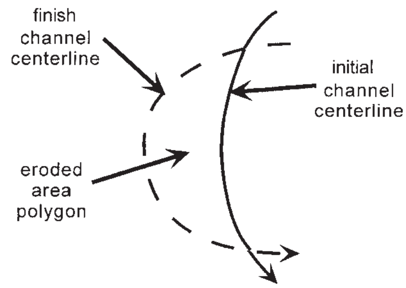

Figure 3. Eroded-area polygon. An eroded-area polygon is created by intersecting two channel centrelines from different time periods. The average stream length over the time interval is equal to one-half of the polygon perimeter. Reach migration rates are calculated by dividing the polygon area by the average stream length, a simple, reproducible measure of the magnitude of shift in channel location normal to the original channel centreline

Lateral migration measurements

We measured lateral migration by mapping sequential channel centrelines in an ArcInfo software environment and by quantifying the change in location of a channel centreline over time using a unit we term the 'eroded-area polygon'. An eroded-area polygon is created by intersecting two channel centrelines mapped at two different points in time (Figure 3). This approach is similar to that applied by MacDonald *et al.* (1993) to a set of Minnesota streams. ArcInfo calculates the area and perimeter of the eroded polygon, from which we calculated the average distance migrated perpendicular to the channel centreline. The lateral migration distance is equal to the polygon area divided by the average stream length for the polygon (with average stream length equal to one-half of the polygon perimeter). With the aid of a GIS, this eroded-area polygon method may be easier to reproduce than alternative methods such as Hickin orthogonal mapping (Hickin, 1975; Hickin and Nanson, 1984).

We used the GIS to confine our analysis to reaches that were clear of any mapped channel restrictions. We used the DWR geology and riprap coverages to eliminate any polygons that appeared confined by either resistant geologic units, bridges, or bank stabilization projects. For river miles 185 to 145, we eliminated polygons where flood control levees impinged on the channel alignment. We plotted migration results for the remaining freely migrating reaches as a function of the DWR river mile marker (increasing in the upstream direction) corresponding to the midpoint of the eroded-area polygon. The river mile coordinates are based on a historic channel alignment; we estimate that the potential error in downstream distance coordinates is approximately 0.2 miles. We use river miles here because it is the standard baseline for agencies managing the Sacramento River.

Calculating bank erodibility coefficients

Rates of lateral channel migration are controlled by the magnitude and duration of stream flow, bank and floodplain resistance to erosion, and quantities and patterns of sediment deposition (Howard, 1984). If we eliminate sediment deposition from the problem by assuming no net change in sediment storage over the study reach, a simple model of meander migration would balance the force of flow shear against the resistance of bank materials to erosion. For a given channel geometry and discharge, the distribution of flow stresses on the channel banks and bed is a product of the velocity distribution within a bend (Dietrich and Smith, 1984). However, streamflow within a bend 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). We used a linear model of meander migration to account for the integrated effects of channel curvature on lateral migration rates (Ikeda *et al.*, 1981). This model has been validated for rivers in Japan by Hasegawa (1989), and in the USA by Johanneson and Parker (1989), Pizzuto and Meckelnburg (1989), and Larsen (1995). By using the model to estimate streamflow parameters, we converted our migration measurements to quantitative estimates of bank erodibility, as described below.

The model solves the 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 4). The linear model requires the following inputs: a channel centreline digitized from channel planform maps, a channel slope measured from topographic maps, a dominant 'bankfull' discharge based on a flow

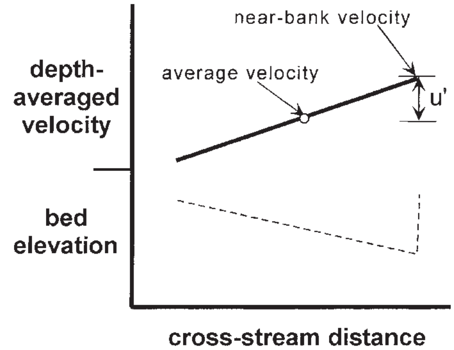

Figure 4. Linear model outputs. The linear model estimates a linear cross-stream distribution for depth-averaged velocities. The velocity perturbation (u') equals the maximum near-bank velocity minus the mean cross-section velocity

Table I. Linear migration model input parameters (after Thomas 2000)

Parameter	Reach 1 RM* 243–211	Reach 2 RM 211–174	Reach 3 RM 174–143
Channel slope	0.0005	0.0004	0.00025
Median bed grain size (D_{50})(mm)	35	20	15
Before 1946			
Discharge ($m^3 s^{-1}$)	3700	4000	4000
Average depth (m)	4.7	4.9	4.9
Average width (m)	372	375	375
After 1946			
Discharge ($m^3 s^{-1}$)	2500	2700	2700
Average depth (m)	3.9	4.1	4.1
Average width (m)	356	360	360

* RM, CA Department of Water Resources (DWR) river mile.
Estimates of dominant discharge magnitude and cross-section before and after 1946 are based on the record at the Bend Bridge gauge. Channel slope and median bed grain size were based on measurements summarized in State of California 1984.

frequency analysis and channel cross-section surveys, an average width and depth based on maps and topographic surveys, and a median bed grain size based on pebble counts and bulk samples. We divided the channel into three reaches (river miles 243–211, 211–174, and 174–143) based on transitions in the longitudinal profile, and we adjusted flow inputs to reflect the installation of Shasta Dam in the early 1940s using the historical gauge record (Thomas, 2000). Specific input values used for this analysis are summarized in Table I. Since these inputs define a channel cross-section area, slope, and discharge, a Manning's coefficient for channel roughness ranging from 0.02 to 0.03 is specified implicitly.

Using a single dominant flow to represent a distribution of flows for different time periods is a major assumption of the linear meander model (Ikeda *et al.*, 1981). To check whether this assumption is reasonable for our data set, we analysed the flow records for the three time periods used in the comparison of agricultural versus riparian floodplain erodibilities. A plot of discharge versus exceedance probability for each time period (Figure 5) does not appear to reveal significant differences in flow distributions.

Ikeda *et al.* (1981) argue that rates of meander migration should be proportional to the perturbation (u') from the mean velocity (the difference between the velocity near the outside bank and the mean velocity; see Figure 4), since u' can be shown to represent the magnitude of shear forces acting on the bank (Larsen, 1995). Because u' approximates bank shear forces, an erodibility coefficient E_o may be defined that expresses the vulnerability of the bank to shear forces imposed by the flow, such that:

$$M = E_o \, u'$$

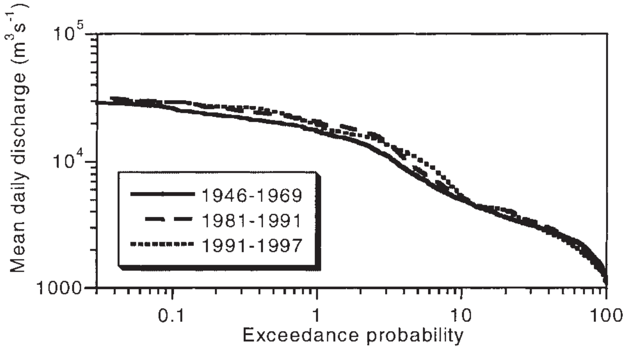

Figure 5. Mean daily discharge versus exceedance probability. Flow exceedance curves are similar for the three time intervals over which migration rates and erodibilities were calculated for agricultural and forest reaches

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. The erodibility coefficient may be expressed as:

$$E_o = M/u'$$

and is dimensionless if the two velocities M and u' are measured in the same units. Dimensionless values of E_o are small (on the order of 10^{-8}), since the average rate of bank migration is typically many orders of magnitude slower than the velocity of streamflow. Thus, the model allows us to normalize migration measurements with respect to cross-stream flow velocities in order to calculate a dimensionless erodibility value for each eroded-area polygon.

We linked centreline u' velocity perturbation values to individual eroded polygons in the following manner. We calculated u' values at nodes spaced 0.5 channel widths along the centreline. By intersecting eroded-area polygons with the centreline u' nodes, a set of u' velocity perturbation values in order of downstream distance was assigned to each polygon. We determined the migration direction for each polygon (towards the left bank versus right bank). We then isolated the maximum u' value acting in the direction of migration to represent the maximum flow force acting over the polygon reach. We calculated E_o values for each polygon by dividing the migration rate by the selected u' value. Using the maximum velocity perturbation to calculate erodibility values makes the results conservative, i.e. they are probably under-estimates of the average bank and floodplain erodibilities. For the analysis of 50-year average bank erodibilities we averaged the u' values that we calculated for the initial and final channel centrelines, since there was the potential for significant change in centreline alignment over the study period. For the decade-scale analyses, we calculated u' values for the initial channel only, since channel planform change was minimal over the study interval.

We analysed the sensitivity of u', and in turn E_o, to potential errors in the model input parameters (see Table III). For each 1% error in model input, the potential error in E_o is as follows: 0.6% per 1% error in channel width, 0.3% per 1% error in channel depth, 0.4% per 1% error in channel slope, and 0.9% per 1% error in stream discharge.

Riparian cover analysis

Three vegetation maps dated 1952, 1987, and 1994 were available for the central reach of the Sacramento River. Our objective was to match vegetation maps to contemporary centreline coverages that spanned approximately a decade to ensure a measurable amount of migration while minimizing the error inherent in assuming a fixed vegetation pattern over time. For the 1952 vegetation map, we analysed migration for the period from 1946 to 1969 (complete centrelines were not available for a shorter time interval); for the 1987 vegetation map, we analysed migration from 1981 to 1991; and for the 1994 vegetation map, we analysed migration from 1991 to 1997. In order to designate a migration polygon as representative of either riparian forest or agriculture, we intersected the eroded-area polygon coverages with the vegetation coverages using the ‘clip’ command in ArcInfo. We inspected each polygon to determine whether more than 50% of the polygon length had migrated through riparian or agricultural land cover categories. Thus, the riparian cover designation represents the dominant vegetation along the channel bounding each polygon and allows a comparison of migration rates and erodibilities for floodplains composed of riparian forest versus agricultural land.

RESULTS

A comparison of 50 years of migration before and after the installation of Shasta dam

In order to gain a perspective on century-scale channel migration rates on the central Sacramento River, we calculated migration rates during the first 50 years of our historical map record (1896 to 1946) and during the last 51 years (1946 to 1997). This analysis provided a comparison of migration rates roughly before and after the installation of Shasta dam in 1941. If we assume that during the earlier time period riparian forest dominated a greater fraction of the floodplain than during the later time period (Katibah, 1984), our results may reflect the net impact, if any, of riparian forest vegetation removal on bank erodibility.

We found that mean migration rates are 50% higher for the 1946 to 1997 interval (4.2 ± 0.1 m a^{-1} or 0.011 channel widths per year) than for the 1896 to 1946 interval (2.8 ± 0.2 m a^{-1} or 0.008 channel widths per year) (Table II). Bank and floodplain erodibilities over the 1896 to 1946 interval averaged $16.5 \pm 1.2 \times 10^{-8}$, while erodibilities for the 1946 to 1997 interval averaged $25.8 \pm 2.9 \times 10^{-8}$ (Table II). Bank erodibility was thus approximately 56% higher during the later time period. Part of the difference in bank erodibility between these two periods may be due to the progressive conversion of floodplains to agriculture (which proceeded rapidly after the construction of Shasta Dam in 1941).

A comparison of migration rates and bank erodibilities for floodplain agriculture versus riparian forest

Migration measurements, combined with an analysis of historical riparian vegetation cover maps, show that the central Sacramento River tends to migrate more quickly through agricultural land than through riparian forest (Figure 6, Table III). For the 1949 to 1969 interval, migration rates for agricultural land were, on average, 152% higher than for riparian forest (5.8 ± 0.6 m a^{-1} versus 2.3 ± 0.3 m a^{-1}). Agricultural bank erodibilities for this interval averaged 142% higher than riparian forest ($39.4 \pm 3.7 \times 10^{-8}$ versus $16.3 \pm 2.3 \times 10^{-8}$). During the 1981 to 1991 time interval, migration rates and bank erodibilities for agricultural land averaged 8.2 ± 1.1 m a^{-1} and $78.7 \pm 13.5 \times 10^{-8}$, respectively, while migration rates and bank erodibilities for riparian forest averaged 4.2 ± 0.4 m a^{-1} and $43.9 \pm 5.0 \times 10^{-8}$. For the last time interval, 1991 to 1997, migration rates for agricultural land averaged 11.2 ± 1.4 m a^{-1} and erodibilities averaged $66.5 \pm 8.4 \times 10^{-8}$, while migration rates for riparian forest averaged 5.9 ± 0.6 m a^{-1} and erodibilities averaged $26.9 \pm 2.8 \times 10^{-8}$. This last time interval shows the greatest difference in erodibility between the two land-use categories, with the erodibility of agricultural land 153% higher than that of riparian forest.

SUMMARY AND DISCUSSION

Our results show that the central reach of the Sacramento River tends to migrate more quickly through agricultural land than through riparian forest. Removal of riparian forest vegetation appears to accelerate migration rates and

Table II. A comparison of river migration rates and bank erodibilities, 1896 to 1946, 1946 to 1997

	1896–1946	1946–1997
Average migration rate (m a^{-1})	2.8 ± 0.2 (116)	4.2 ± 0.1 (88)
Average bank erodibility ($\times 10^{-8}$)	16.5 ± 1.2 (83)	25.8 ± 2.9 (74)
Average velocity perturbation (m s^{-1})	0.65 ± 0.03 (83)	0.52 ± 0.02 (74)

Values are shown as means $\pm$ the standard error, with the number of values shown in parentheses. Migration rates represent the mean lateral channel shift per eroded area polygon. Erodibility coefficients are calculated using the linear meander model.

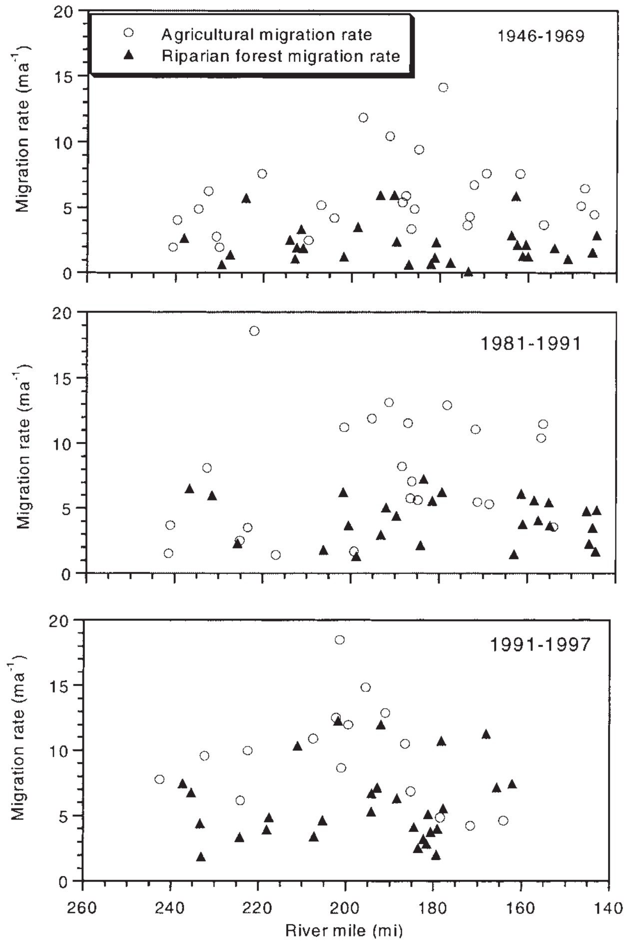

Figure 6. Migration versus river mile, 1946–1969, 1981–1991, and 1991–1997. Each point shows the average distance migrated normal to the channel centreline per eroded-area polygon. River mile coordinates correspond to the polygon midpoint. Agricultural reaches are shown as open circles while riparian forest reaches are shown as solid triangles. Riparian and agricultural polygons are distributed relatively randomly with respect to downstream distance

increase bank erodibility by roughly 80 to 150%. In two out of three cases, floodplain erodibility values closely mirror mean migration rates. This reflects the fact that while variations in calculated velocity perturbations are generally much less than one order of magnitude, measured migration rates can vary up to two orders of magnitude. Thus, while normalizing migration rates with respect to curvature-induced variations in flow velocities makes hydraulic sense, over a reach of significant length, calculation of mean migration rates alone may suffice to capture differences in floodplain erodibility.

Our results reflect a strong effect of riparian forest vegetation on rates of river channel change. Riparian vegetation could limit rates of channel migration by either (1) increasing bank strength or (2) increasing channel roughness. Both of these vegetation effects are reflected in the erodibility coefficient E_o. Riparian forest vegetation strengthens banks by reinforcing bank soils with roots or by providing large woody debris for incorporation into bank materials. DWR field personnel with over 20 years' experience on the river indicated that actively eroding banks generally do not contain buried wood (K. Buer, personal communication, 2000); thus, root reinforcement would seem a more likely source of bank strength. Gray and MacDonald (1989) estimated that Sacramento River riparian root densities on the order of 1% could depress the potential plane of bank failure and increase the bank stability of an artificial levee by up to a factor of four. However, typical riparian forest root depths on the Sacramento River are less than 20% of bank height (State of California, unpublished data, 1994). Bank erosion is generally initiated at the bank toe, below the zone of root influence. However, an indirect effect of root cohesion is that

Table III. Migration and floodplain erodibility analysis

	Agricultural floodplain		Riparian forest floodplain	$((A-R)/R) \times 100$* (%)
1949–1969				
Average migration rate (m a^{-1})	5.8 ± 0.6 (27)		2.3 ± 0.3 (30)	152
Average bank erodibility ($\times 10^{-8}$)	39.4 ± 3.7 (27)		16.3 ± 2.3 (30)	142
Significance level of agricultural vs. riparian erodibilites		$p < 0.0005$		
1981–1991				
Average migration rate (ma^{-1})	8.2 ± 1.1 (24)		4.2 ± 0.4 (26)	95
Average bank erodibility ($\times 10^{-8}$)	78.7 ± 13.5 (24)		43.9 ± 5.0 (26)	79
Significance level of agricultural vs. riparian erodibilites		$p < 0.008$		
1991–1997				
Average migration rate (ma^{-1})	11.2 ± 1.4 (18)		5.9 ± 0.6 (29)	89
Average bank erodibility ($\times 10^{-8}$)	66.5 ± 8.4 (18)		26.9 ± 2.8 (29)	153
Significance level of agricultural vs. riparian erodibilites		$p < 0.0005$		

Average values are shown as means $\pm$ the standard error, with the number of values shown in parentheses. Migration rates represent the mean lateral channel shift per eroded area polygon. Erodibility coefficients are calculated using the linear meander model.
* Percentage by which agricultural value exceeds riparian forest value, where *A* equals agricultural migration or erodibility value and *R* equals riparian forest migration or erodibility value.

when a bank fails, undermined riparian vegetation often remains attached to the bank edge, with the potential to reduce near-bank flow velocities.

Thus, while the impact of vegetation on geotechnical bank stability may be significant, field observations also indicate that reaches bordered by riparian forest have greater channel roughness than those bordered by agricultural land. Forested banks along the Sacramento River are often strewn with downed trees and trapped debris, while reaches cutting through orchards display vertical cut banks composed of exposed soils. Bank vegetation removal not only reduces bank strength and protective cover, but also reduces the hydraulic roughness of the channel. Reducing bank roughness effectively increases near-bank flow velocities and may shift the peak near-bank velocity downstream. Thorne and Furbish (1995) conducted a vegetation removal experiment in the field and measured a significant downstream shift in the location of the maximum near-bank stream velocity. Assuming that meander migration mirrors the flow field, vegetation removal could cause greater migration in the downstream versus the cross-stream direction, and could therefore result in perhaps a less sinuous channel pattern over time.

Our results do not address the potential effect of soil variability on erosion rates. In order to refine this analysis for site-specific applications, it would be necessary to assess how variability in bank soil texture and cohesion may influence local river migration rates. Since the river migrates through a floodplain constructed by past episodes of channel migration, bank soils range from cohesive clays deposited in old oxbow lakes to erodible granular deposits formed during peak flood events. However, detailed field mapping would be required to generate soil distribution data at this scale. DWR personnel have observed during the course of a bank-erosion monitoring programme that the most rapid migration tends to occur where the banks are composed of coarse sands and gravel (K. Buer, personal communication, 2000). Future monitoring will quantify this effect by applying shorter-term migration measurements in combination with detailed bank soil mapping.

If soil variability is a significant control on bank erosion rates, a related question is whether farmers preferentially cleared agricultural land based on soil type. If farmers chose to clear more erodible lands first, then our comparisons of bank erosion rates through agricultural land versus riparian forest may simply reveal the influence of soil type on bank erodibility. While we lack the necessary data to thoroughly test this hypothesis, we note that a preference to clear erodible soils first should reveal a pattern of decreasing erodibility of agricultural lands over time, a pattern not reflected in our results, as discussed below.

Our results show a trend toward higher migration rates over time (Figure 7), with migration rates roughly doubling over 50 years, concurrent with the progressive conversion of the floodplain from riparian forest to agriculture.

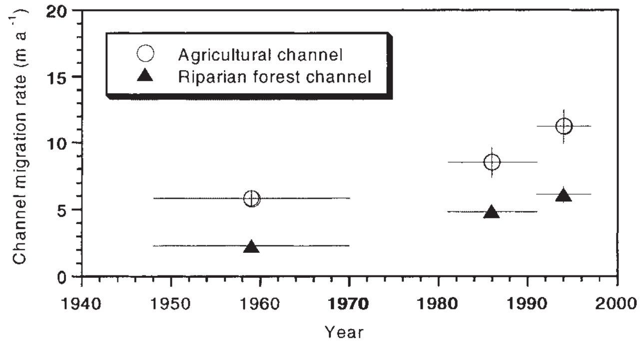

Figure 7. Summary graph showing how average migration rates and bank erodibilities for agricultural and riparian forest floodplain (Table III) have changed over time. The marker shows the midpoint of the migration analysis time period, while the horizontal bars show the full range of the time period. Vertical bars show the standard error of migration measurements (which in some cases do not exceed the marker height)

It is likely that this trend is not a product of increased floodplain erodibility alone, but is also a result of interactions between bank strength and sediment transport. A question beyond the scope of this present study is how variations in sediment transport due to mining, dam installation, and other channel alterations may have influenced historical rates and patterns of meander migration. Future studies will need to consider feedbacks between variations in flow, sediment load, and floodplain erodibility as additional controls on river migration rates.

Examining the relationship between the magnitude of flow shear versus the migrated distance for agricultural and riparian forest eroded-area polygons raises several summary points. The slope of a linear regression through these data is a graphic means of estimating bank erodibility (E_o) (Figure 8). The linear regressions for agricultural reaches are displaced in the positive direction, revealing overall greater channel migration in response to similar values of applied flow shear, as reflected in mean migration rate values (Table III). Further, the slopes of linear regressions tend to be steeper for agricultural reaches than for riparian forest reaches, indicating that agricultural land is more sensitive to localized changes in flow shear, as reflected in mean erodibility (E_o) values (Table III). In fact, the slopes for riparian forest reaches are rather flat, suggesting that an effect of riparian forest on channel migration may be to minimize variation in bank erosion rates despite local variations in channel curvature along the meandering reach, resulting in uniform migration rates along the outside of meander bends. A pattern of relatively uniform bank erosion rates along regular meanders has been observed on the Lower Truckee River, Nevada, during time intervals in which the channel was lined by dense riparian forest (Micheli, 2000).

Finally, Figure 8 shows that in the later time intervals the maximum flow shear (u') values tend to be greater in riparian forest than in agricultural reaches. Since channel curvature drives the magnitude of u', this suggests that over time the most highly curved meander bends developed in riparian forest zones. If the bank strength and roughness provided by riparian forest mitigates the erosive effects of variations in flow velocities due to channel curvature, then our results suggest that deforestation may lead to a less sinuous channel over time, as mentioned in the discussion of bank roughness above.

This analysis was restricted to episodes of progressive migration only; instances of channel migration by channel avulsion and cut-off processes were excluded. Clearly, a complete understanding of the effect of vegetation on meander bend behaviour must ultimately include how floodplain vegetation inhibits or facilitates cut-off formation. Feedbacks between bank erodibility and overbank flow dynamics need to be considered; if riparian vegetation reinforces the outside of a progressively migrating bend, how does this affect the dynamics of channel cut-off formation? Resolving questions of this scope will require an analysis of higher-resolution remote sensing and field data collected at decade or less time intervals.

PRINCIPAL FINDINGS

The central Sacramento River channel migrated, on average, 50% faster between 1946 and 1997 (4.2 ± 0.1 m a^{-1}) than between 1896 and 1946 (2.8 ± 0.2 m a^{-1}) (Table II). Bank and floodplain erodibilities over the 1896 to 1946

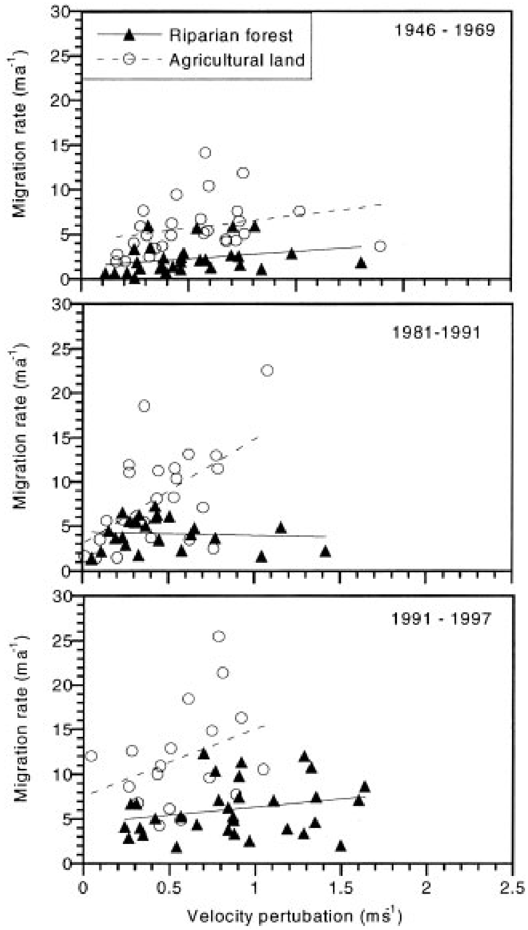

Figure 8. Migration rate versus velocity perturbation, 1946 to 1969, 1981 to 1991, and 1991 to 1997. Agricultural migration rates are generally higher than riparian forest migration rates for similar magnitudes of flow shear (as estimated by the velocity perturbation u'). The slopes of linear regressions drawn through agricultural values also tend to be steeper, indicating that channel migration rates in agricultural reaches are more sensitive to increases in flow shear

interval averaged $16.5 \pm 1.2 \times 10^{-8}$, while erodibilities for the 1946 to 1997 interval averaged $25.8 \pm 2.9 \times 10^{-8}$ (Table II). Bank erodibility thus increased by approximately 60% between the two time periods. This increase in bank erodibility occurred during a period of rapid conversion of riparian floodplains from forest to agriculture.

A comparison of migration rates and bank erodibilities for reaches bordered by agricultural land versus reaches bordered by riparian forest showed a consistent trend of more rapid channel migration through agricultural land. For the three time intervals analysed (1946 to 1969, 1981 to 1991, 1991 to 1997) migration rates were consistently higher for agricultural land by roughly 150%, 95%, and 90%, respectively, and bank erodibility values were higher by 140%, 80%, and 150%, respectively.

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