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Modeling Channel Management Impacts on River Migration: A Case Study of Woodson Bridge State Recreation Area, Sacramento River, California, USA

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ABSTRACT / Understanding how hydraulic factors control alluvial river meander migration can help resource managers evaluate the long-term effects of floodplain management and bank stabilization measures. Using a numerical model based on the mechanics of flow and sediment transport in curved river channels, we predict 50 years of channel migration and suggest the planning and ecological implications of that migration for a 6.4-km reach (river miles 218–222) of the Sacramento River near the Woodson Bridge State Recreation Area, California, USA.

Using four different channel management scenarios, our channel migration simulations suggest that: (1) channel stabilization alters the future channel planform locally and downstream from the stabilization; (2) rock revetment currently on the bank upstream from the Woodson Bridge recreation area causes more erosion of the channel bank at the recreation area than if the revetment were not present; (3) relocating the channel to the west and allowing subsequent unconstrained river migration relieves the erosion pressure in the Woodson Bridge area; (4) the subsequent migration reworks (erodes along one river bank and replaces new floodplain along the other) 26.5 ha of land; and (5) the river will rework between 8.5 and 48.5 ha of land in the study reach (over the course of 50 years), depending on the bank stabilization plan used. The reworking of floodplain lands is an important riparian ecosystem function that maintains habitat heterogeneity, an essential factor for the long-term survival of several threatened and endangered animal species in the Sacramento River area.

Sinuous alluvial river channels inherently migrate, creating conflict between bank erosion and human activities near riverbanks. At the same time, active channel migration helps maintain riparian ecosystem structure (Malanson 1993, Bravard and Gilvear 1996). The ability to assess the potential beneficial and harmful impacts of channel migration is essential for river planners seeking to place or remove bank stabilization. In this study, we use a numerical channel migration model (adapted from Johannesson and Parker 1989) to evaluate the potential effects of channel management scenarios applied to a reach of northern California's Sacramento River. While the Johannesson and Parker meander migration model has been used previously to help understand general migration patterns, here we apply it for the first time to evaluate river management plans.

KEY WORDS: Bank erosion; Floodplain evolution; Meander migration model; Sacramento River, Riparian ecosystem; Channel stabilization; River restoration; Land-use planning.

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Although the Sacramento River (Figure 1) is constrained in some places by channel riprap (bank revetment) and artificially constructed levees, portions of the river actively migrate (e.g., Brice 1977, Scott and Marquiss 1984, US ACE 1986). This creates challenges for river planners who strive to protect agricultural and urban development while pursuing the potential ecological and agricultural benefits provided by active channel migration. Recent management scenarios considered for the river have included plans such as repositioning levees to set them back from the river, removing riprap within the active floodway, restoring natural channel floodplain development, and promoting the natural regeneration of a diverse mosaic of forest types at different successional stages (DWR 1998, CALFED 1998, Greco 1999).

Management scenarios that include channel migration are being considered partly because channel migration sustains riparian–forest structural heterogeneity. The resultant diversity of habitats is necessary for

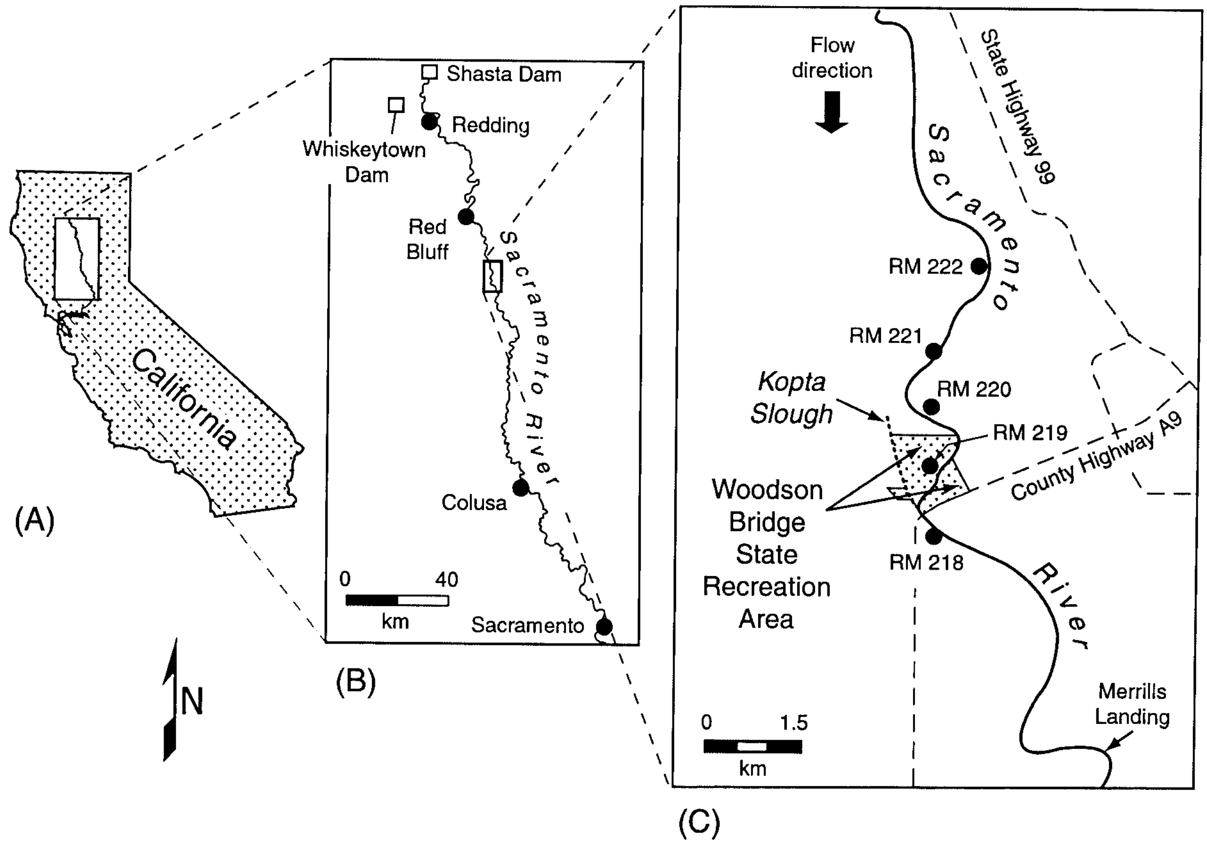

Figure 1. Location maps for the 6.4-km study reach (river miles 218–222) of the Sacramento River, California, USA.

the survival of many species. Greco (1999) has shown that lands recently reworked by the Sacramento River channel (floodplains younger than 20 years) support a greater proportion of early-seral (primary succession) vegetation species and forest structural classes than older (>20 years) floodplain lands that are in later stages of secondary succession. Early and mid-seral forests are important habitat types that support several riparian obligate and facultative animal species whose management status is designated as threatened or endangered under state and federal laws (e.g., Steinhart 1990, Greco 1999, Greco and others 2002). Active Sacramento River channel migration also facilitates gravel recruitment, which is needed for spawning by several endangered salmonid species (Buer and others 1989, Harvey and Watson 1989). Thus, channel migration performs many important riparian landscape and aquatic ecological functions. As planners increasingly consider active migration in planning scenarios, the need for migration modeling increases.

In this study, we model and consider the planning implications of four specific channel management scenarios for a 6.4-km reach of the Sacramento River, California. We simulate 50 years of migration, using a channel migration model that is based on mathematical–physical algorithms for flow and sediment transport (the main physical processes responsible for channel migration). Because the model is based on physical processes, it can accommodate changes in input variables and can predict the consequences of conditions, such as flow regime changes or bank stabilization measures, that have not existed in the past. Unlike empirically based models that tend to focus on local conditions, the physically based numerical model integrates the effects of local morphology and upstream conditions.

In this paper we describe Johannesson and Parker's (1989) channel migration model and how we calibrate it and apply it to our study reach. Discussion of model mechanics and detailed calibration and validation procedures are addressed elsewhere (Larsen 1995, Thomas 2000). Simulated channel migration patterns that result from applying the model to different channel management plans are presented. For each channel stabilization scenario, we calculate channel migration rates and the areal extent of floodplain reworked by simulated migration. Newly reworked floodplain (land eroded on one bank and subsequently deposited along the other) plays an important ecological role in allowing the colonization of early-seral riparian vegetation communities. This study suggests how different channel migration scenarios might affect future riparian forest development along our study reach.

Study Reach Description

The Sacramento River, which flows from northern California to the San Francisco Bay (Figure 1A), is the largest river in California, with a watershed that is approximately 540 km long and 270 km wide. It supplies over half the water used by the state (US ACE 1986). The upstream reach, from Shasta Dam at river mile (RM) 312 to Red Bluff (RM 245), is primarily bedrock controlled; thus its migration is limited. The middle reach, from Red Bluff (RM 245) to Colusa (RM 144), is free to migrate along 52% of its length. Along the remaining 48% of the middle reach, artificial levees or riprap confine the channel. South of Chico Landing (RM 181), artificial levees flank both sides of the river and the width between levees ranges from 0.4 to 1.6 km. From Colusa to the San Francisco Bay delta (RM 0), levees on each bank almost entirely confine the river. Along this reach it behaves hydraulically and ecologically much like a stable canal.

Throughout this paper we refer to river locations in river miles (RM) in order to be consistent with named locations cited in previous works. The United States Army Corps of Engineers and the California Department of Water Resources have collected and tabulated extensive data on the river using this nomenclature for spatial referencing. The Corps established the river mile designation in 1964. However, due to subsequent channel migration, river mile designations are now essentially place names and no longer accurately indicate distance along the channel centerline. To illustrate, note the relative distances between RM 222, 221 and 220 (Figure 1C).

Because much of the river is free to migrate between Red Bluff and Colusa, this reach provides an excellent opportunity for using simulations to evaluate bank stabilization measures. We located our study reach at RM 222–218 (Figure 1B and C) because this area has experienced significant migration in the past 100 years (Figure 2) and because river managers are concerned about this area. Erosion along this reach threatens one of the largest remaining stands of late-seral (old-growth) valley oak (*Quercus lobata*), a once-common Sacramento River vegetation community type that is now rare (DWR 1998). Channel migration along this reach may also harm Woodson Bridge State Recreation Area facilities and the Woodson Bridge structure itself.

Between Red Bluff and Colusa, the Sacramento River is primarily a single-thread sinuous channel. The slope, averaged over a minimum of 5 km, ranges from 0.0002 m/m to 0.0007 m/m (WET 1988). The riverbed material is primarily sand and pebbly gravel with a median grain size that ranges from 5 to 35 mm in the reach RM 215–144 and from 20 to 70 mm in the reach RM 245–215 (WET 1988). The channel banks are composed of sand and gravel with isolated patches of erosion-resistant rock types. Between RM 240 and RM 195 the average bank height from thalweg to top of the bank is 7.5 m, ranging from 5 to 12 m (DWR 1995).

Historical maps and aerial photographs taken at low flows (less than 225 m^3/sec) show that within our study reach, the channel gradually and continuously migrated from 1896 to 1937 (Figure 2A), and again from 1952 to 1978 (Figure 2C). During the intervening time period, 1938 to 1952, the channel episodically migrated, and channel cutoffs occurred. Periods of gradual and continuous channel movement of the Sacramento River during the past 100 years have coincided with periods of low annual flow, whereas periods of episodic and rapid movement coincide with, and are driven by, periods of high annual flow. For example, from 1937 to 1947 (Figure 2B), the study reach experienced several large floods, including some estimated to have 50- and 100-year recurrence intervals (DWR 2000). During this 10-year period, the meander-bend apex at Copeland Bar bend (RM 220.5) moved almost 1000 m to the southwest, depositing behind it a substantial new area of floodplain. In 1938 the channel was cut off (RM 219.5–218), forming a backwater (a still pool directly connected to the main channel) at Kopta Slough (Figure 2B and C). Following the period of extended flooding that fueled the events at Copeland Bar and Kopta Slough, Sacramento River flows were low (1947–1952) and the channel moved very little (Figure 2B).

Sacramento River channel migration has been substantially reduced by the construction of Shasta Dam, which was built in 1945. The main effect of the dam on Sacramento River discharge has been the reduction of peak flows (winter) and the increase of low flows (summer) (CALFED 2000). Thus, while low annual flows during the period 1947–1952 resulted in little channel migration, the migration was probably further limited by reduced peak discharges due to regulation by Shasta Dam.

Sacramento River channel migration is limited locally by geologic constraints and by human-made con-

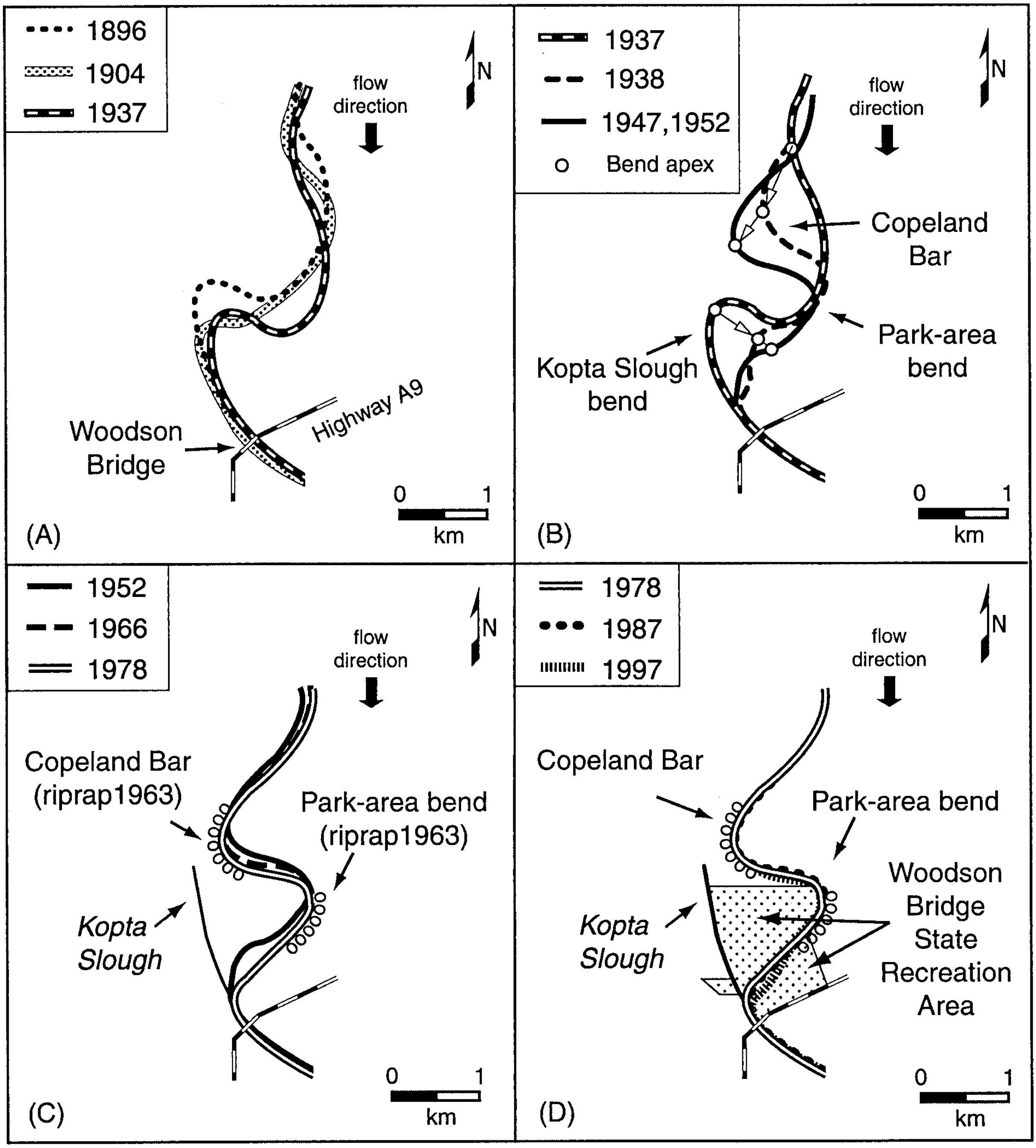

Figure 2. Site history of channel centerlines from 1896 to 1997. (**A**) Between 1896 and 1937, gradual channel migration occurred north of Woodson Bridge. (**B**) Between 1937 and 1947, the apices of the two bends just north of Woodson Bridge moved more than 1000 m, forming substantial new floodplain in both areas. In 1938, the channel was cut off at Kopta Slough bend and formed a backwater in the location now occupied by Kopta Slough (see 2C). Between 1947 and 1952, the channel location was stable. (**C**) In 1963, riprap was installed at Copeland Bar and at the park-area bend. (**D**) After 1978, the channel location has been stable at the riprapped bends.

straints such as riprap, levees, and other bank stabilization measures. In our study area, the erosion-resistant terrace deposits of the Riverbank Formation crop out along the western edge of Kopta Slough and act as a geologic constraint, limiting channel migration along the southern portion of the study reach. In 1963, the US Army Corps of Engineers installed riprap on the outside cut-bank of Copeland Bar and the bend immediately downstream (Figure 2C), preventing bank erosion in the riprap area (Figure 2D).

Methods

Meander Migration Model

The Johannesson and Parker meander migration model and variations of it have been used to predict and analyze the channel migration of a range of rivers, including rivers in Minnesota (Parker 1982, Johannesson and Parker 1985, MacDonald and others 1991), in New York (Beck and others 1984), and the Mississippi River (Larsen 1995). Johannesson and Parker (1989) used the model to predict wavelengths of meandering rivers with results comparing favorably to laboratory and field data. Pizzuto and Meckelnburg (1989) confirmed the relationship between migration rates and velocity (Equation 1) assumed by the model. Howard (1992, 1996) used a version of the model to simulate floodplain sedimentation and morphology associated with meander migration. Furbish (1991) has used similar equations to describe the formation of complex meander sequences. Recently, a version of the model was used to examine conditions affecting meander initiation and growth (Sun and others 2001). Because Sacramento River conditions fall within the range of conditions tested by previous applications, we expected the model to work well for our study reach of the Sacramento River.

The meander migration model assumes that the local bank erosion rate is proportional to a local velocity factor such that:

$$M = E_o u'_b \qquad (1)$$

where M is the bank erosion rate (meters per year), E_o is a dimensionless bank erodibility coefficient of the order 10^{-8}, and u'_b (meters per second) is a velocity factor equal to the difference between the velocity near the bank and the reach-average velocity. The terms u'_b and E_o are described in the following subsections.

Modeled velocity. The crux of the model as applied here is the calculation of the velocity field. This is done in a coordinate system that follows the path of the channel centerline. The downstream variation of the vertically averaged downstream velocity at each model node is expressed as the sum of the reach-average downstream velocity U and a velocity "perturbation" u' (the local deviation from the reach-average velocity) that varies across the stream. The reach-average downstream velocity U is constant for the study reach and is the quotient of the characteristic discharge (explained below) divided by the characteristic cross-sectional area of the channel. The velocity perturbation near the channel bank u'_b is the velocity factor in equation 1. Nodes are spaced one half-channel width apart. Analyses show that this spacing captures the processes responsible for determining the velocity distribution (Thomas 2000). The analytic solution for the velocity results from simultaneous solutions of six partial differential equations representing the fluid flow field and bedload transport, which determine channel behavior (Johannesson and Parker 1989). The downstream and cross-stream conservation of momentum are expressed using a version of the shallow-water equations. Downstream bedload transport calculations are based on Engelund and Hansen (1967), and cross-stream bedload transport is related to downstream transport using a relation derived by Ikeda (1982) that is well described in Parker and Andrews (1985). The conservation of fluid and sediment mass is represented with traditional conservation-of-mass equations (e.g., Furbish 1997). The near-bank velocity perturbation u'_b calculated by these equations peaks somewhat downstream from the meander-bend apex. Therefore, the simulated meanders tend to migrate downstream and in the cross-stream direction, as occurs in natural streams (Hooke and Redmond 1992). The final expression for velocity is the result of a convolution integral (Furbish 1988). The mathematical expression for this indicates that the velocity at a given point is the result of the local conditions and the integrated effects of conditions upstream.

Local velocity varies with discharge, so the model requires an estimation of a characteristic discharge that mimics the integrated effect of the variable natural flow regime. In effect, this assumes that bank erosion resulting from the cumulative effect of discrete individual flow events can be modeled as a continuous process (Howard 1992). The rationale is the same as that used in traditional geomorphic analyses that relate channel form and processes to the bankfull or dominant discharge (Wolman and Leopold 1957, Wolman and Miller 1960). For this study we have chosen the two-year recurrence-interval flow as the characteristic discharge. Accordingly, it is not intended that the model simulate the effects of particular flow events, but that it produce estimates of long-term rates of erosion or channel migration. Assuming a single continuously acting characteristic discharge that produces continuous and gradual erosion is a useful simplification (Howard 1992). Large events produce large erosion responses, and near-bank water level fluctuations produce bank collapse. Usable theoretical models do not exist for these processes. To reduce error in calibration and prediction that can be introduced by these discrete events, we used time periods that are as long as possible (50-year

Table 1. Hydraulic variables used to model channel migration of our study area

Input variable	Description	Original value	Final adjusted Value
Q_2	2-yr recurrence interval discharge (cms)	2,720	2,720
H_2	Average depth at Q_2 (m)	4.4	3.7
W_2	Width at Q_2 (m)	350	360
S	Longitudinal water surface slope (m/m)	0.00075	0.00075
D_{50}	Median bed particle size (mm)	25	25
D_{84}	84th percentile particle size (mm)	65	65

intervals). Nonetheless, inaccuracies may arise due to assuming that bank erosion is continuous. Shasta Dam has also altered the historic occurrences of high flow events, which tend to cause the most erosion on the Sacramento River. Even if the dam did not alter average flow rate, reduction of peak flows might affect long-term erosion rates.

Bank erosion coefficient in the model. Although the model analytically calculates the velocity field in some detail, it represents bank erodibility by an empirically estimated coefficient. Bank erosion processes could be modeled mathematically (Thorne 1982, Hasegawa 1989a, b), but precisely estimating the input values for these expressions would require impractical amounts of field data. As equation 1 indicates, the rate of erosion is a product of the erodibility coefficient and near-bank velocity. Hasegawa's (1989a) analysis suggests that bank erosion is related to five factors in addition to the near-bank velocity. These are the: (1) longitudinal flow velocity, (2) longitudinal rate of change of bed elevation, (3) relative depth of bed scour, (4) relative magnitude of the transverse component of near-bottom fluid flow velocity, and (5) relative bank height. Hasegawa uses an order of magnitude analysis to show that the first four of these five factors are much smaller in magnitude than the near-bank velocity and can be ignored. The fifth, relative bank height, is also commonly ignored (e.g., Howard 1992). Because bank height is relatively constant in our study reach, we assumed that its influence could be subsumed in the coefficient-velocity model. The simulations reported here use a dimensionless bank erodibility coefficient that varies spatially along the study reach, with an average of 3×10^{-7}. This value is consistent with erosion rates observed on the Sacramento River (Micheli and Larsen 1997). The erosion coefficient is calibrated as described below.

Input Variables for the Model

The model requires the following six input values reflecting the hydrology of the watershed and the hydraulic characteristics of the channel: initial channel planform location, characteristic discharge, reach-average median particle size of the bed material, width, depth, and slope. The reach-average width and depth are measured at the characteristic discharge, and slope is the average water surface slope for the reach. Using these data, the model calculates other parameters required to predict channel migration. For a detailed description of the calculation process, see Johannesson and Parker (1989).

Channel planform centerlines. Delineating river channel centerlines depends on the magnitude of discharge (Q) chosen to define the edges of the channel from which the centerline is derived. High flows create wider channels with less sinuous centerlines than low-discharge flows (Brice 1977). Methods of defining channel edges range from visual estimates using channel planform maps and aerial photographs to detailed hydrodynamic modeling using digital elevation models. We combined orthographic photography with topographic map overlays to estimate channel edges visually and define the active floodplain, tops of point bars, and edges of large regions of dense vegetation. Field observations on the Sacramento River indicate that the wetted-channel edges at the two-year recurrence-interval discharge covers the tops of point bars and inundates most gravel-bar islands in braided sections of the main channel. For the purpose of channel edge delineation, areas of large, dense vegetation are assumed to occupy slightly higher elevations. Therefore, we chose these densely vegetated areas to define the upper limits of the two-year flow. Using the criteria described in this paragraph, we estimated channel edges and drew centerlines one half-channel width from the cut-bank (outside of bend) of the channel margin.

Discharge. We chose 2720 cms (m^3/sec) as our characteristic discharge (Table 1) based on a recurrence-interval analysis of Sacramento River peak discharges for the years 1964–1980 at the Vina gauge near Woodson Bridge. This analysis was performed using gage records for the post-Shasta Dam period (DWR 2000).

Width, depth, slope, and particle size. The meander migration model requires input of reach-average width and depth at the two-year recurrence interval flow. We calculated these values from a typical channel cross-

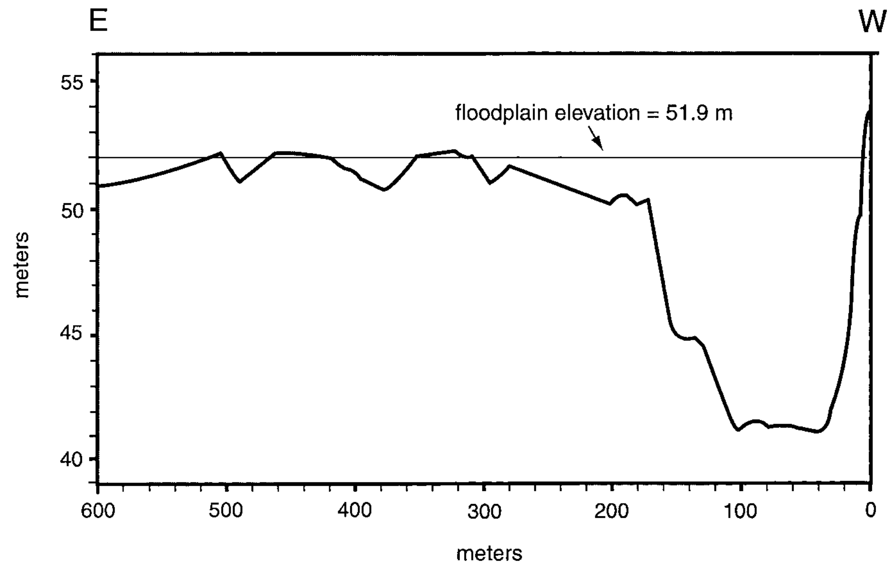

Figure 3. Cross-section profile at river mile 218.4, Sacramento River (adapted from DWR 1994). Formative flow was estimated to be at the floodplain elevation (51.9 m) indicated by the top of the extended bar surface 350 m from the west river bank.

section for our study reach that was surveyed at RM 218.4 near Woodson Bridge by the California Department of Water Resources (DWR 1994) (Figure 3). We assumed that the two-year recurrence interval discharge elevation was located roughly at the highest point of a bar top situated 350 m from the west bank. The cross-sectional area below the floodplain elevation, divided by width of channel at the floodplain elevation, resulted in a section-average depth of 4.4 m. Based on this cross section and the adjustment process that is described below, we use 360 m for the model-input water surface width and 3.7 m for section-averaged depth (Table 1). Thomas (2000) determined similar average width and depth values (380 m and 4.2 m, respectively) at eight cross sections between RM 193 and RM 244. Reach-average water-surface slope of these eight sites is 0.00075 m/m (Thomas 2000) and reach-average particle size of the bed material is 25 mm (DWR 1994). Sensitivity analyses that show how inaccuracies in input data affect model output are discussed elsewhere (Micheli and others in preparation).

The width and depth at the two-year recurrence interval flow must be hydraulically consistent with relationships that describe flow in open channels. We used two methods, both of which assumed uniform, steady flow, to adjust initial estimates of the width and depth input data. The first was Manning's n roughness relationship (Henderson 1966):

$$U = 1/n\ R^{2/3} S^{1/2} \tag{2}$$

where U is the reach-average downstream velocity (meters per second), n is the Manning's roughness coefficient, R is the hydraulic radius (meters), and S is the reach-average water surface slope (meters per meter). The second method was the Law of the Wall (Middleton and Southard 1984) or logarithmic vertical velocity profile:

$$u/u^* = 1/k \ln (z/z_0) \tag{3}$$

where u (meters per second) is the local downstream velocity of the fluid at the elevation z (meters) above the bed; u^* (meters per second) is the shear velocity, which is defined as the square root of the bed shear stress divided by the fluid density; k is the dimensionless von Karman constant (traditionally assumed to be 0.40); and z_0 (meters) is the elevation above the bed at which the velocity apparently goes to zero. The Law of the Wall is the basis of an empirical relative roughness equation (Wolman and Leopold 1957, Limerinos 1970):

$$U/u^* = 6 \log(H/D_{84}) + c_1 \tag{4}$$

where U (meters per second) is the vertically averaged downstream velocity, u^* (meters per second) is the shear velocity, H (meters) is the mean depth of flow at the observed discharge, D_{84} (meters) is the particle size which exceeds 84% of the particle sizes, and c_1 is an empirical constant.

Limerinos (1970) obtained a constant (c_1) of 3.2 and Wolman and Leopold (1957) obtained 2.83. We used an average of the two, i.e., $c_1 = 3.0$. The Manning's n (equation 3) and the log velocity profile (equation 4) methods were used to adjust our original estimates of width and depth to ensure that width, depth, and velocity values obtained from both equations were hydraulically consistent and would result in velocities from both methods that matched within 0.1 m/sec. By this method, we established final adjusted input variables for the model (Table 1).

The values from these calculations result in a calculated Manning's n of 0.032 and a calculated mean velocity at the two-year recurrence interval discharge (by both methods) of 2.0 m/sec. Although width and depth values could be further refined, sensitivity analyses (Micheli and others, submitted, 2002) show that use of more refined values does not significantly alter model simulation results. An independent analysis of eight cross-section sites on the Sacramento River between RM 260 and RM 169 yielded an average Manning's n of 0.032, and an average mean velocity at the two-year recurrence interval discharge of 1.7 m/sec (Thomas 2000).

Model Calibration

The meander migration model hinges on numerical terms that describe two opposing forces: the forces created by flowing water impinging on the bank, and the resistance of the bank material to those forces. The model calculates flow velocities causing the impinging forces and uses an empirically calibrated bank resistance coefficient to represent the resisting forces. The model predicts local migration as the product of a near-bank velocity u'_b and an erosion coefficient E_o. Our calibration procedures used measured migration (M) and calculated near-bank velocities u'_b to back-calculate local bank-erosion coefficients (E_o) at points along the channel margin.

Calibrating the erosion coefficient. To calibrate the erosion coefficient, one must know where the channel planform centerline was located during two separate time periods. For our calibration, we chose 1947 and 1978, two years for which centerlines could be accurately defined. The bank erosion coefficient calibration consists of adjusting the coefficient in the simulated migration until the simulated migration from 1947 to 1978 closely matches the observed migration in the same time period.

On freely meandering rivers with few anthropogenic or geologic controls (such as the Mississippi River before human influence), one can calibrate erosion coefficients so that observed and simulated migrations match in great detail (Larsen 1995). However, an exact calibration for our study reach was difficult because the reach includes a cutoff and regions of erosion-resistant bank material. In our modeling, we did not permit the river centerline to move into the geologic constraint of the highly resistant Riverbank Formation. By using an erosion coefficient of zero for this area, we modeled both this geologic control and the riprap in our study reach for zero erosion. In addition, between the two years studied, the observed channel shifted suddenly once, in one small area, near the current channel at the Woodson Bridge State Recreation Area. Due to the limited extent of this observed shift and because the calibration in other areas matched well in magnitude and pattern, we integrated the effects of the rapid movement into an assumed continuous movement.

Calibrating using a single time sequence and applying it to another time sequence assumes that the geologic and hydrologic conditions in the application period are similar to the conditions in the calibration period. As the river changes location, the bank material and mechanical properties can change. During the 50 years of simulated migration, the river channel remained within the same rock type (DWR 1994); therefore, we assumed constant geologic conditions. We chose a 50-year time period for calibration in order to integrate the effects of different hydrologic conditions and to average-out the effects of large floods.

Our calibration sought overall agreement of bend shape near bend apices rather than perfect point-by-point agreement between the locations of the observed and simulated channel centerlines. Our greatest concern was Copeland Bar bend and the bend just upstream from Woodson Bridge (hereafter called the park-area bend) (Figure 2B). These are the bends that are largely responsible for erosion into the park. In addition, because they are high-amplitude bends, they tend to migrate significantly. Both bends are eroding into similar lithologic units (Quaternary alluvium), a fact that supports our calibration of a single, sufficiently accurate erosion coefficient for both of them. While the calibrated simulated migration between 1947 and 1978 (Figure 4) does not precisely match the observed channel centerline for that period, the pattern and rough magnitude of channel movement is correct, particularly at the two major bends. In particular, the magnitude of simulated and observed channel migration matches well at the park-area bend. The area near the apex of the park-area bend is critical for considering potential migration into the recreation area. Although we feel that our calibration is generally right for our study site, any calibration is essentially subjective and relies on the judgment of the modeler. We are currently developing a quantitative method of evaluating our calibration.

Model assumptions. The mathematical modeling of physical processes inherently assumes simplifications of reality. In our model, we make the assumptions that:

- channel reach-average width, depth, and slope are constant;

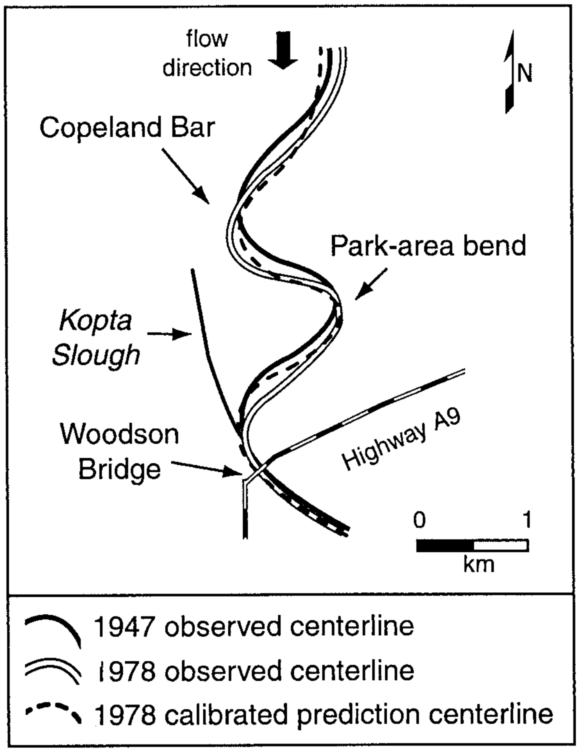

Figure 4. Channel centerline locations showing results of the calibration simulation. The solid black line shows the observed Sacramento River channel centerline in 1947, the open line shows the observed centerline in 1978, and the dashed line shows the (calibrated) modeled centerline in 1978. This modeled line was determined by adjusting the erosion coefficient locally along the channel until the simulated 1978 location matched the observed 1978 location.

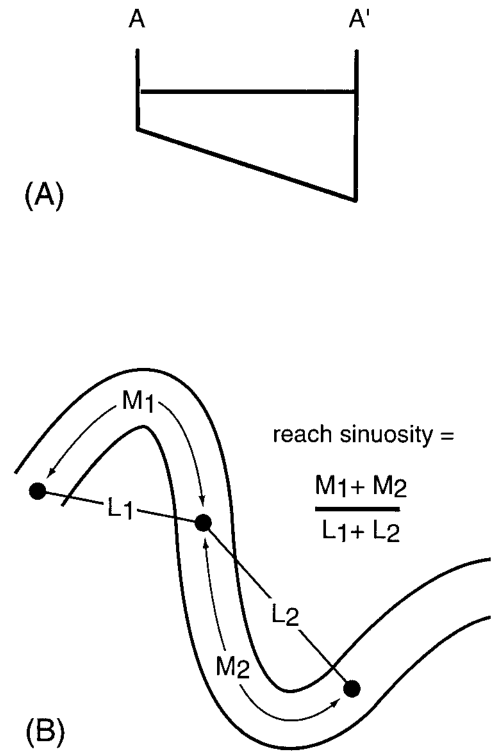

Figure 5. (**A**) Diagram of a typical channel showing the linear approximation of the cross-stream bed slope at a hypothetical cross section A–A′. (**B**) Schematic channel planform shown to explain our reach sinuosity calculation. "M" is the distance along the curved arc of the channel bend, measured from inflection point to inflection point. "L" is the straight-line distance between inflection points. This definition of sinuosity stresses bend curvature and ignores valley curvature.

- water surface and riverbed are straight lines from one bank to the other (Figure 5A);
- any riprap in place or emplaced in the channel will be maintained and will withstand the largest flood;
- riprap does not degrade or erode ($E_0 = 0$); and
- based on our calibration, progressive channel movement predicted by the model will correspond to the integrated long-term effects of many years of different bank erosion rates.

Results

We describe four separate simulation runs, based on four different channel management scenarios. The section of river located upstream of Copeland Bar bend migrates roughly the same amount in all four simulations throughout the 50-year simulation period (Figure 6A–D). Because the migration of this part of the reach is relatively constant for all simulations, we focus our analysis of land reworked and channel sinuosity on the more dynamic downstream portion of the study reach (Copeland Bar and park-area bends; Figure 6A).

Simulation 1: No Riprap in the Study Reach

Channel management scenario. Simulation 1 (Figure 6A) illustrates potential channel migration without the constraint of riprap. This is not a management scenario currently under consideration, but we model it to better understand migration tendencies of the study reach.

Model predictions. The model predicts substantial movement at both the Copeland Bar bend and at the park-area bend. Initially (1997), these bends are similar in shape, but the simulations suggest that the Copeland Bar bend will migrate about twice as far downstream as the park-area bend. Substantial erosion is predicted on the outside bank of the park-area bend near its apex. However, the channel at the south end of the bend does not move significantly east toward Woodson Bridge during the modeling time period. No move-

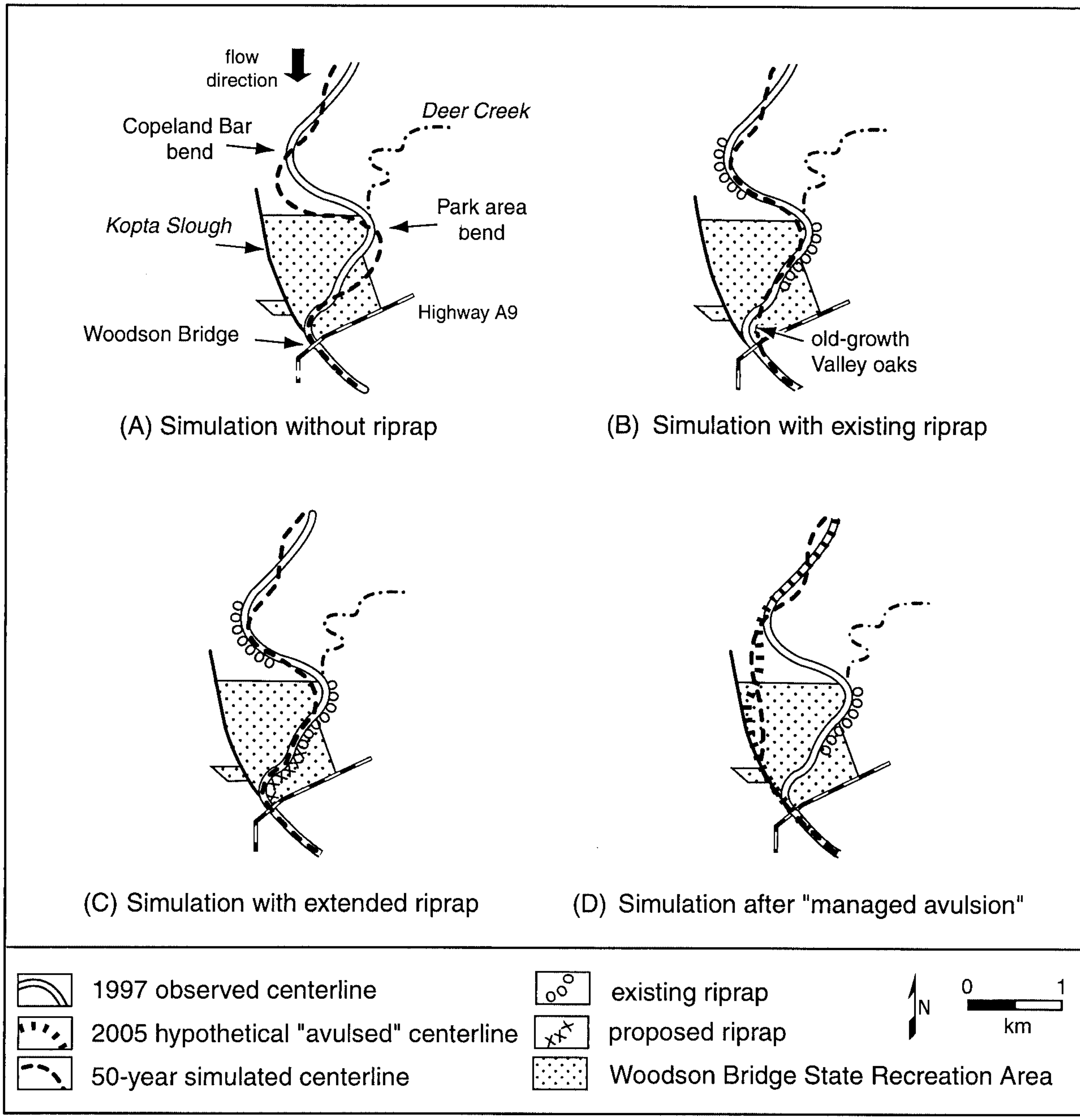

Figure 6. Channel centerline locations showing 50 years of simulated migration assuming that (**A**) the channel is unconstrained by riprap, (**B**) riprap is maintained in its 1997 location, (**C**) riprap near the state recreation area is extended, and (**D**) the channel is relocated to Kopta Slough.

ment occurs immediately downstream of Woodson Bridge due to the well-lithified cliff on the outside of the bend. Within Copeland Bar bend and the park-area bend, the total area of land reworked by meander migration for the simulated 50 years is 48.5 ha at an average migration rate of 0.008 widths per year. The pre- and postmigration sinuosities of this portion of the study reach are 1.4 and 1.6, respectively (Table 2).

The migration patterns of the two bends differ because the upstream and downstream conditions of the two bends differ. Upstream from Copeland Bar bend, the river has low sinuosity. Thus, in the model, the momentum of the water entering Copeland Bar bend will have a greater component in the down-valley direction. In contrast, the park-area bend is preceded immediately upstream by the more sinuous Copeland Bar

Table 2. Comparison of channel sinuosity and area-of-land-reworked predicted by channel migration simulations

Simulation	Figure	Sinuosity pre/ post migration (m/m)	Land reworked (ha)	Channel length (m)	Migration rate	
					meters/year	widths/year
1	6A	1.4/1.6	48.5	3460	2.8	0.008
2	6B	1.4/1.3	12.1	2860	0.8	0.002
3	6C	1.4/1.3	8.5	2680	0.6	0.002
4	6D	1.1/1.1	26.5	2890	1.8	0.005

bend, which delivers water that has flow velocity (and therefore momentum) in the cross-valley direction. In addition, the bend immediately downstream from the park-area bend is constrained, a condition that may affect the park-area bend. Accordingly, the migration of the park-area bend is less down-valley, and more cross-valley.

Simulation 2: Current Riprap Maintained

Channel management scenario. Simulation 2 (Figure 6B) illustrates river behavior if the existing riprap is maintained and no other action is taken.

Model predictions. The existing channel stabilization (riprap) limits the movement of the river at both the Copeland Bar and park-area bends. With the riprap maintained, the model predicts that the Copeland Bar bend apex migrates downstream, and the channel shifts to the southeast in the upstream part of the bend. At the park-area bend, the bend apex shifts downstream and erosion occurs downstream from the riprap toward the eastern bridge abutment. This erosion removes a small portion of the old-growth valley oak forest in the recreation area and might extend far enough downstream to threaten the bridge itself (Figure 6B).

The model predicts severely constrained migration for both bends. As the bends are trapped against the riprap, they tend to lose their rounded shape, growing more angular near their apices. With increased angularity, bends increase flow velocities at the apex and increase scour at the toe of the bank. Increased bank scour tends to undermine the riprap. Simulated channels “slide along” the riprap, with the apex moving downstream. When the high-velocity core of the flowing water reaches the end of the riprap and is abruptly unconstrained, it causes erosion immediately downstream from the riprap. These migration patterns are typical of constrained bends.

Within the Copeland Bar and park-area bend portion of the study reach, the area of land reworked by 50 years of simulated migration is 12.1 ha, at an average migration rate of 0.002 widths per year. The pre- to postmigration sinuosity decreases from 1.4 to 1.3 (Table 2). This decrease probably results from the constraint on bend evolution imposed by the riprap.

Although simulation 1, which has no riprap, predicts significantly more total land eroded than does simulation 2, it also predicts that the river will not move into the bridge or the valley oak forest within the next 50 years. In contrast, simulation 2 predicts more erosion toward the bridge and forest. This contrast illustrates how bank protection at one location can increase the rate of bank erosion at a point downstream.

Simulation 3: Riprap Extended from Park-Area Bend to Woodson Bridge

Channel management scenario. Simulation 3 (Figure 6C) shows the river’s behavior if the riprap were extended from the existing riprap at the park-area bend to the existing stabilization at Woodson Bridge.

Model predictions. For most of the channel, this simulation’s predictions are identical to predictions for simulation 2. The only difference is that under the conditions of simulation 3, the river is restrained from moving toward the bridge and the model predicts less reworked floodplain (8.5 ha) from 50 years of migration. The average migration rate (0.002 widths per year) and the pre- and postmigration sinuosities of the reach (1.4 and 1.3) are similar to those predicted in simulation 2 (Table 2).

Simulation 4: Riprap Removed at Copeland Bar and Channel Relocated

Channel management scenario. Simulation 4 (Figure 6D) shows the channel migration subsequent to removing riprap and relocating the river to an assumed 2005 channel location described below.

Background and assumptions. Simulation 4 assumes physical realignment of the channel from its present location in order to direct it away from areas where erosion is a concern and to allow more opportunities for floodplain reworking. The management goal is for the river to recapture its historical (pre-1930s) channel, now known as Kopta Slough. Field observations indicate that at high flows (greater than the two-year recurrence interval), the river commonly overtops the Copeland Bar riprap and enters a small channel linking the bend with Kopta Slough. All or part of the river could quickly recapture this slough if the riprap at the bend were removed. Therefore, we simulated channel relocation as occurring in one step.

If the channel were allowed to avulse on its own, the initial location of the realigned channel (which we call the 2005 channel, based on an arbitrary year in which realignment could occur) could not be predicted precisely. This scenario assumes that a new channel will be artificially excavated. For the purpose of modeling, we defined a hypothetical cut-off centerline to connect the current channel at Copeland Bar bend to the 1904 channel at Kopta Slough. This path was chosen along a topographic low and based on a meander shape appropriate for the channel hydraulics. Because the hydraulics of the river strongly depend on the curvature of the channel, the precise location (shape) of the relocated channel will determine the resulting movement. The path that we have chosen is not highly sinuous (Figure 6D).

Model predictions. Simulation 4 suggests that the 2005 channel is likely to maintain a longer period of progressive migration before cutoff than would migration of the more sinuous 1997 channel (simulations 1, 2, and 3). After 50 years of migration (2005–2055), the sinuosity of the channel (1.1) remains unchanged, possibly due to the downstream bend being constrained by the nonerodible Riverbank Formation. Within the Copeland Bar and park-area bend portion of the study reach, the predicted area of land reworked for 50 years is 26.5 ha, at an average migration rate of 0.005 widths per year (Table 2).

Although the simulation suggests that the 2005 channel will migrate rapidly and rework a significant area of land, the model suggests that with relocation of the channel, the erosion into the park and toward the bridge will be reduced significantly. Because the west side of Kopta Slough is bounded by the Riverbank Formation, the river will not move substantially in this area. All the movement of a relocated channel will take place in the region to the east of the geologic control, which is north of the valley oak stand of concern (Figure 6B) and west of the current channel. These areas are currently undeveloped and present a good management opportunity for allowing formation of substantial new (reworked) floodplain and for promoting regeneration of riparian vegetation communities.

Discussion and Conclusions

Our study demonstrates how the numerical model can be applied to understand the behavior of migrating river channels, including the effects of interactions between hydraulic and geologic controls. We evaluated management scenarios that included no action, removing existing riprap, adding riprap, and relocating the channel. The numerical model simulates future channel migration under each scenario and illustrates how each management scenario could affect future riparian ecosystem development. Channel migration promotes ecosystem structural diversity by influencing riparian vegetation regeneration and maintaining heterogeneity within vegetation communities (Greco 1999).

Models are abstractions of reality, not exact replicas. Because processes that cause migration are too complex and variable to be predicted absolutely, the study simulations do not necessarily precisely predict river behavior or location. Our simulations help us understand channel migration tendencies. Predictions might be improved by coupling the numerical model with a more thorough historical analysis and more site-specific empirical relationships combined with long-term field studies. Despite these limitations, our model simulations adequately reveal migration tendencies that can be used for management plans.

Simulated Channel Migration Pattern

The migration simulations show that different channel stabilization scenarios lead to different future channel planform configurations. They also illustrate how upstream conditions combine with local morphology to determine migration patterns. Contrasting simulation 1 with simulation 2 illustrates that although riprap might effectively stop erosion at an upstream bend, it could increase erosion downstream. Simulation 1 suggests that while the unconstrained channel might cause significant erosion near the two bends upstream of the recreation area, it would cause little erosion in the recreation area itself. This is because the planform shape and the hydraulics related to the bend curvature of simulation 1 direct the momentum of the water away from the riverbanks in the recreation area and limit erosion there. Simulation 2 suggests that maintaining the existing riprap on the two upstream bends would prevent bank erosion where riprap is installed, but would also cause the river to erode near Woodson Bridge and the stands of late-seral valley oak. The simulations indicate that if the channel were relocated, subsequent channel migration would provide 26.5 ha of newly-created floodplain, encouraging colonization of early-seral (primary succession) riparian forest community types.

As unconstrained river channels migrate, they tend to increase in sinuosity with time (Harvey 1989) until they reach a point where they cut off. In this study, we calculated sinuosity by taking the sum of the arc length between inflection points of individual bends and dividing that by the sum of the straight-line distance between those inflection points (Figure 5B). Simulation 1 (unconstrained channel) shows an increase in sinuosity from 1.4 m/m to 1.6 m/m (over 50 years) in the two bends upstream from Woodson Bridge (Table 2). In these bends, when the riprap stabilizes the channel (simulations 2 and 3, Figures 6B,C), it constrains outward channel movement, and sinuosity decreases from 1.4 m/m to 1.3 m/m in both cases. The riprap at these two sequential bends tends to straighten the channel because it forces the channel to move downstream while at the same time restricting outward channel migration. Decreasing sinuosity (straightening) increases the channel slope, which leads to increased bedload transport. In turn, this can cause bed degradation and scour near the toe of the riprapped bank.

Cutoffs

For simulations 1, 2, and 3, we assumed that in our modeled time periods, channel migration would occur gradually. We ignored the possibility of channel cutoff because in the past 100 years major Sacramento River cutoffs have only occurred at sinuosities greater than those achieved in our simulations (DWR 1984, WET 1988). Our simulation results are limited to 50 years and do not address a longer time frame during which channel avulsion may occur.

Simulation 4 (Figure 6D), a managed channel relocation, demonstrates that channel cutoff reworks a substantial amount of land following relocation. Such reworking is an important fluvial process that facilitates and influences riparian vegetation community succession (Greco 1999). We assume the relocated (cutoff) position and do not model it. Because cutoff processes differ from river to river (Brice 1977) and, perhaps, from location to location on a given river, analytic methods of predicting channel cutoff need to incorporate the hydraulic controls and cutoff mechanisms appropriate for the site in question. We are currently empirically analyzing the geometric conditions (e.g., sinuosity, water surface slope, channel curvature) associated with historical Sacramento River cutoffs in order to adapt the numerical model to simulate channel cutoff on the Sacramento River.

Simulation Implications for Land Reworked and Channel Migration Rates

A migrating channel reworks floodplain land, and the area of land reworked is directly proportional to migration rates. Furthermore, areas of land reworked and channel migration rates are both related to channel sinuosity. Rates of migration (and therefore land reworked) seem to be greatest for mid-range, rather than highest-range, bend curvatures (Hickin and Nanson 1975, 1984). The range of bend sinuosities (and therefore bend curvatures) in our simulations was mid-range, and within this range our data suggest that more sinuous unconstrained channels erode land at a faster rate. To quantify the area of land reworked by river migration, we calculated the area between the current channel centerlines and the centerlines predicted by our simulations. Our simulated unconstrained channels reworked two to five times the land reworked by our constrained channels (Table 2). Of the two planning scenarios that represent unconstrained channels (simulations 1 and 4), the more sinuous channel of simulation 1 reworked nearly two times the land (48.5 ha) than the less sinuous channel of simulation 4 (26.5 ha).

MacDonald and others (1991) describe the average channel migration rate as the land reworked divided by the mean channel length. Using the methods of MacDonald and others (1991), we calculated channel migration rates of 0.002 to 0.008 channel widths per year for migration simulations (Table 2), which compare well with 0.009 to 0.018 channel widths per year measured by Brice (1977) for 78 years of observed Sacramento River migration. MacDonald and others reported similar observed rates for the Upper Mississippi River and some of its tributaries (0.005 to 0.010 channel widths per year). The fact that our simulated rates compare well with observed rates gives us confidence in our calibration and simulations methods.

Although simulation 1, which is based on removing all riprap in the study reach, reworks the most land, this fact alone does not make it the preferred management scenario. Because the land east of the current channel is developed and privately owned, allowing erosion there is not a feasible option at this time. Even if such an option were available, the implications of channel migration after the 50-year modeling period must be considered. The more sinuous channel of simulation 1 is likely to cut off more quickly than the channel with a managed avulsion (simulation 4). Such a cut-off might threaten the bridge and the recreation area and might cause erosion of developed private property.

Our modeling efforts in simulation 4 suggest that at least five benefits would result from relocating the channel to the west where it would reoccupy part of Kopta Slough: (1) erosion pressure is relieved on Woodson Bridge State Recreation Area and the valley oak communities located there, (2) erosion pressure is relieved on the bridge infrastructure, (3) the newly relocated channel would rework substantial floodplain area and provide new riparian habitat, (4) the newly exposed substrate from the abandoned portion of the former channel (the oxbow lake) would provide new opportunities for colonization by riparian vegetation, benefiting several threatened and endangered animal species native to the Sacramento River ecosystem (e.g., Greco and others 2002), and (5) if a mildly sinuous channel configuration is chosen for the managed avulsion, chances of cutoff occurring in the near future would be reduced.

The relocation of the channel to Kopta Slough could be accomplished by removing the Copeland Bar riprap and by enlarging the current overflow channel that leads to the slough. By rerouting all of the water from the Sacramento River to the Kopta Slough channel, the only water remaining in the former Sacramento River channel would be the runoff from Deer Creek (Figure 6). The creek would enter the abandoned channel roughly 1.5 km downstream from the managed cutoff location, rejoining the main river channel just north of the recreation area. The Dear Creek flow volume is roughly only 4% of the Sacramento River volume (based on comparisons of two-year recurrence interval flows), so bank erosion from the mouth of Deer Creek to the confluence with Kopta Slough should be minimal. The old Sacramento River channel would probably become a depositional region until it adapted to an appropriate size for the Deer Creek flows occupying it. Riparian vegetation would likely colonize the abandoned channel, a process that has been observed at several locations on the river.

Model Performance

We calibrated the numerical model over a time period during which no rapid river migrations or channel avulsions occurred. Accordingly, our simulations are most consistent with gradual channel migration typically occurring during lower flows. The next 50 years will most likely include high flow events which may cause the patterns simulated by the model to be attained in less than 50 years.

The numerical model differs significantly from empirically based methods of predicting migration. Empirically based methods (e.g., DWR 1995) assume that meander migration of a local point is related to the conditions at that point only. For example, Hickin and Nanson's (1975, 1984) important work relates local migration to the radius of local channel curvature. This is almost correct. Parker (1982) shows that such a model neglects the influence of upstream conditions. Furbish (1991) stresses that accurate velocity modeling at a location requires inclusion of the cumulative effects of upstream conditions. The hydrodynamic portion of the migration model that we use describes bank migration caused by the integrated effects of local conditions and of upstream flow and curvature (Johannesson and Parker 1989, Furbish 1991, Howard 1992). Our simulations show that upstream conditions significantly affect downstream migration patterns, clearly illustrating the benefits of considering these upstream effects. Specifically, riprap located upstream from the recreation area triggers more erosion in the recreation area than would occur if the riprap were absent.

The numerical model can be used to simulate conditions that have not existed historically but are of interest to resource managers. Recently, Larsen (CALFED 2000) applied the model to the reach studied in this paper in order to determine the effect of decreased Sacramento River discharge on channel migration and floodplain formation. The analysis suggested that for every 1% decrease in discharge in formative flow, net migration would decrease by 1.25% (CALFED 2000). This result stems from the nonlinear relationship between near-bank flow velocity and channel discharge, and it points out that not only are process-based models useful in situations where historical observations are not available, but they can also reveal results that may not be obvious with empirical methods.

Numerical migration modeling is important to river managers because it can be used to evaluate the long-term effects of bank stabilization measures. To our knowledge, this is the first time a numerical meander migration model has been applied to evaluate river channel stabilizations plans. Modeling benefits include the ability to quantitatively assess downstream impacts of bank stabilization and to assess the impacts of changes in hydrologic conditions. In the case of the Woodson Bridge study reach, our simulations suggest that a management strategy that allows active channel migration will lead to reworking of significant floodplain area, help to maintain riparian ecosystem heterogeneity, and reduce bank erosion near critical portions of the Woodson Bridge recreation area.

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