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Assessing the Effects of Alternative Setback Channel Constraint Scenarios Employing a River Meander Migration Model

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ABSTRACT / River channel migration and cutoff events within large river riparian corridors create heterogeneous and biologically diverse landscapes. However, channel stabilization (riprap and levees) impede the formation and maintenance of riparian areas. These impacts can be mitigated by setting channel constraints away from the channel. Using a meander migration model to measure land affected, we examined the relationship between setback distance and riparian and off-channel aquatic habitat formation on a 28-km reach of the Sacramento River, California, USA. We simulated 100 years of channel migration and cutoff events using 11 setback scenarios: 1 with existing riprap and 10 assuming setback constraints from about 0.5 to 4 bankfull channel widths (bankfull width: 235 m) from the channel. The percentage of land reworked by the river in 100 years relative to current (riprap) conditions ranged from 172% for the 100-m constraint setback scenario to 790% for the 800-m scenario. Three basic patterns occur as the setback distance increases due to different migration and cutoff dynamics: complete restriction of cutoffs, partial restriction of cutoffs, and no restriction of cutoffs. Complete cutoff restriction occurred at distances less than about one bankfull channel width (235 m), and no cutoff restriction occurred at distances greater than about three bankfull widths (~700 m). Managing for point bars alone allows the setbacks to be narrower than managing for cutoffs and aquatic habitat. Results suggest that site-specific "restriction of cutoff" thresholds can be identified to optimize habitat benefits versus cost of acquired land along rivers affected by migration processes.

River meandering and associated bend cutoff processes are necessary to establish and maintain riparian, oxbow lake, and riverbank ecosystems (Hupp and Osterkamp 1996; Scott and others 1996). However, riverbank erosion control measures—most notably rock installed along the bank (called riprap)—prevent river channel movement. This in turn can have detrimental effects on riparian habitat (Chapin and others 1997; Vitousek and others 1997; National Research Council 2002). In addition, constraints and levees disconnect floodplains from the stream ecosystem by curtailing overbank flows. Linkages between floodplain and aquatic systems are critical to maintain in order to provide diversity and productivity (Junk and others 1989; Bayley 1995; Power and others 1995). Riprap can also negatively impact the function of stream channel hydraulics, often by increasing flow depth, velocities, and bed and bank shear stresses (Knighton 1998). Additionally, bank hardening (e.g., riprap and near-bank levees) is expensive to maintain and can be an unreliable flood control measure (Tobin 1995; Pintor 2005). Levees that are set back from the channel and that function as setback channel constraints have been suggested as means to help maintain dynamic riparian systems while still providing flood control (Dwyer and others 1997; Gergel and others 2002). At the same time, lands adjacent to alluvial rivers are some of the most agriculturally productive in the world, making their acquisition expensive. If setback constraints, including levees, are to be put into practice, it is necessary to optimize their cost/benefit ratio. Despite the interest in levee and constraint setbacks, little research has focused on the relationship between constraint distance and the resulting potential for habitat creation.

Near-bank riprap-lined levees limit channel migration and associated bend cutoff processes. Channel migration and bend cutoff processes create the physical characteristics necessary for both riparian and oxbow

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lake ecological communities (Merritt and Cooper 2000; Richter and Richter 2000; Tockner and Stanford 2002). These are key processes controlling and creating the natural range of heterogeneity in the riparian habitat mosaic (Schiemer and Zalewski 1992; Naiman and others 1993). In addition to the land-reworking and habitat creation benefits of continuous channel migration, bend cutoff processes produce oxbow lakes and associated surrounding riparian habitat (Strahan 1984). These wetland ecosystems provide critical wildlife habitat and support a rich biodiversity (Morken and Kondolf 2003). Riparian and oxbow areas provide a complex mosaic of habitats that support high species diversity within a relatively confined area. Flood waters also generate ephemeral habitat for fauna in stream ecosystems (Bayley and Li 1992). Conversely, limiting floodplain inundation patterns has the potential to harm much-valued fish populations (Gutreuter and others 1999; Limm and Marchetti 2003).

To properly consider both environmental and societal constraints on river systems, more effective ways are needed to plan and manage for river channel constraint (CALFED 2000). Any analysis of setback constraint effects on riparian forest habitat integrity must consider the temporal and spatial dynamics of influential processes such as river meandering, channel cutoff, and flooding. Such analyses can be difficult because they integrate hydrogeomorphic modeling with ecological modeling. Various models are used for different aspects of this comprehensive modeling, including river meander migration models (e.g., Larsen 1995; Larsen and Greco 2002), one-dimensional flood analysis models (e.g., Hydrologic Engineering Center–River Analysis System 2003), and vegetation succession models (Baker and Walford 1995; Richter and Richter 2000). Management and research efforts have focused on the fact that benefits accrue from setting back constraints and levees (CALFED 2000), but few efforts have quantified how benefits vary as a function of levee and/or constraint setback distance (Bozkurt and others 2000) or design.

Much of the research on levee and constraint setbacks described in engineering journals describes channel geometry and flow parameters, but does not predict potential biotic response (e.g., Shields and others 2003). Likewise, studies in conservation research journals have tended to report the importance of flow regulation (Poff and others 1997; Richter and Richter 2000) for sediment transport and recruitment rather than environmental benefits. Yet, river management guidelines increasingly require a balance between flood and water supply agendas and environmental considerations (Water Engineering and Technology Inc. 1988; Sacramento River Advisory Council 1998; Golet and others in press).

In this article, we use a physical process-based river channel migration model to simulate the area of land reworked and bend cutoff dynamics on the Sacramento River, California, under different setback constraint scenarios. We evaluate the geomorphic responses of various setback constraint scenarios using the model to predict the planform effects of riprap and setback levees on river meander dynamics. The effects of various setback constraint scenarios are examined by calculating the area of floodplain deposited each year (land reworked), the number of cutoffs, and the area of abandoned channel regions predicted by the river movement modeled. We also estimate the area of oxbow lake habitat created. The results of this work can be integrated with other models to better determine how the integrity of riparian ecosystem processes, such as vegetation recruitment and wildlife habitat formation, might be enhanced and restored by removing riprap and establishing setback constraints and levee systems.

Methods

Study Area: Geologic Setting

The Sacramento River in central California, USA flows south through the Sacramento Valley (Figure 1) over sedimentary rocks and recent alluvium. The Sacramento Valley is 96 km wide and 418 km long and lies in a structurally controlled basin bordered by the Cascade and Sierra Nevada mountains to the east and the Coast Ranges of California to the west (Harwood and Helley 1987) (Figure 2). The total drainage area of the river is 6.8×10^4 km^2, or more than half of the total drainage area of the San Francisco Bay, The bay is located on the western coast of California.

River locations along the Sacramento River are commonly referred to in river miles (RM) (Figure 1) (e.g., Larsen and Greco 2002). The US Army Corps of Engineers established the river mile designation in 1964, but due to subsequent channel migration, river mile designations are now essentially place names and no longer accurately indicate the distance along the channel centerline.

Four major tectonic units comprise the Sacramento River watershed (Figure 2); (1) the Great Valley sedimentary sequence, located in the Coast Ranges; (2) the Franciscan formation, also part of the Coast Ranges; (3) the Klamath Mountains to the north and northwest, which form an island arc terrane composed of marine sediments and granitic plutons; and (4) areas

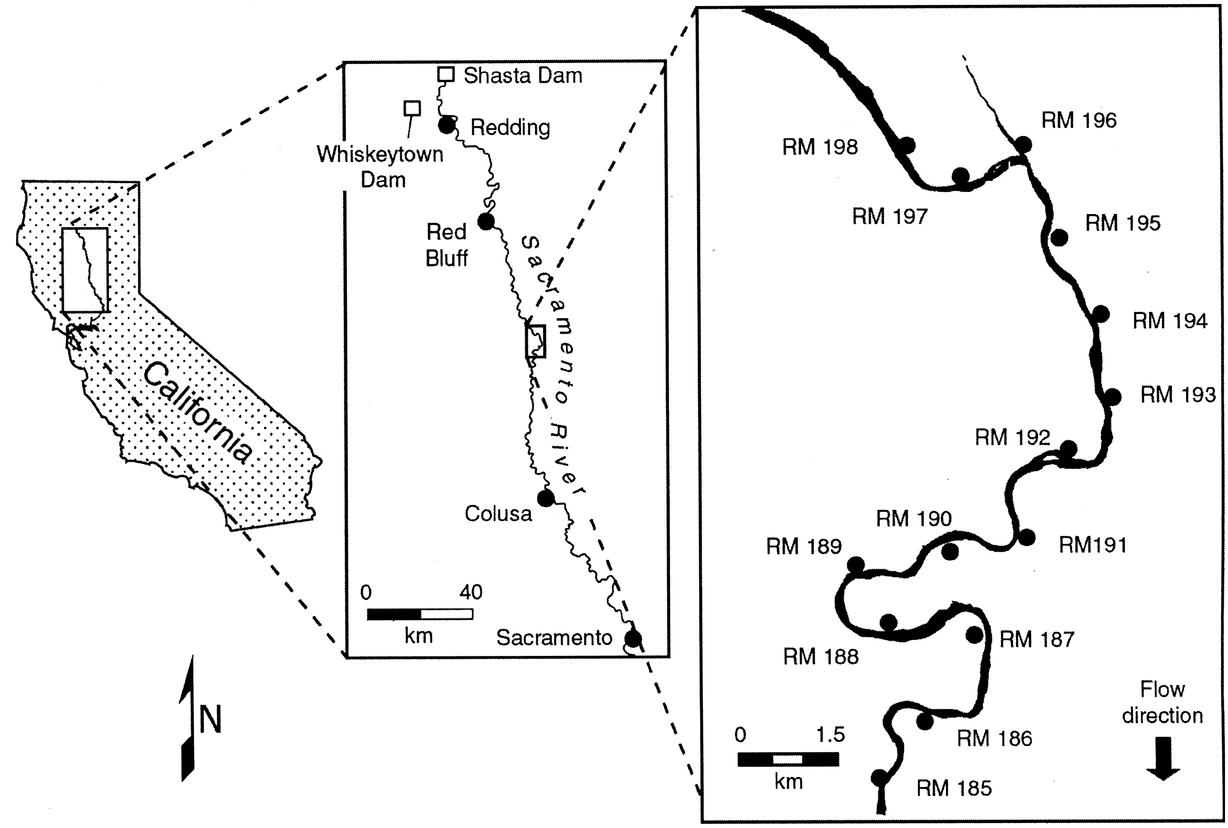

Figure 1. Location within California of the Sacramento River and the study reach.

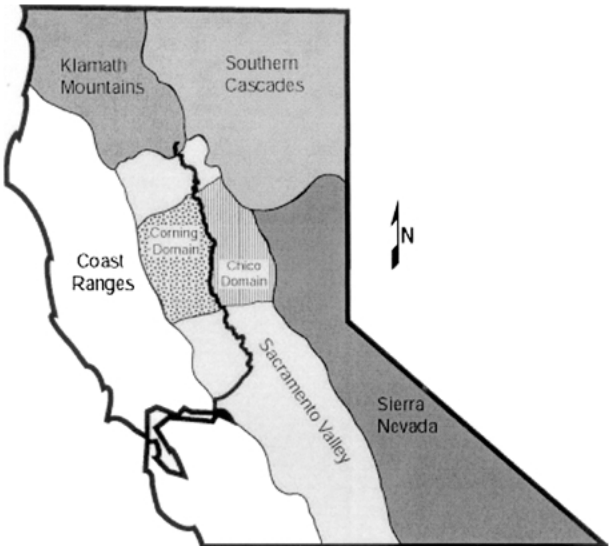

Figure 2. Tectonic units of the Sacramento River watershed.

of Pliocene recent extrusive volcanic activity, located northeast of the river in the Southern Cascades. There are also areas Pliocene–Pleistocene alluvium and fluvial deposits found in the Sacramento Valley, the Corning Domain, and the Chico Domain through which the river flows. The composition of sediments deposited into the Sacramento River from creeks is directly related to the surrounding tectonic units. For example, the bedload of Pine Creek, which meets the Sacramento River at RM 196 in our study area (Figure 1) and drains from the east, is 89% volcanic clasts (Robertson 1987).

The depositional units primarily responsible for limiting channel migration in the study reach are the Pleistocene-age fluvial (terrace) deposits of the Riverbank (Qr) and Modesto formations (Qm) (Figure 3). These terrace deposits typically consist of 1–3 m of dark gray to red fine sand and silt overlying 1.5–2 m of poorly sorted gravel (CDWR 1994). The Riverbank Formation is light red in color and consists of gravel, sand, silt, and clay. Soil formation in this unit displays a B-horizon and local hardpan (CDWR 1994). The Modesto Formation is younger than the Riverbank Formation and contains the youngest terrace with a pedogenic B-horizon (CDWR 1994). This unit is usually less than 2.5 m thick and is composed of gravel, sand, silt, and clay (CDWR 1994). The Riverbank and Modesto formations are generally erosion resistant;

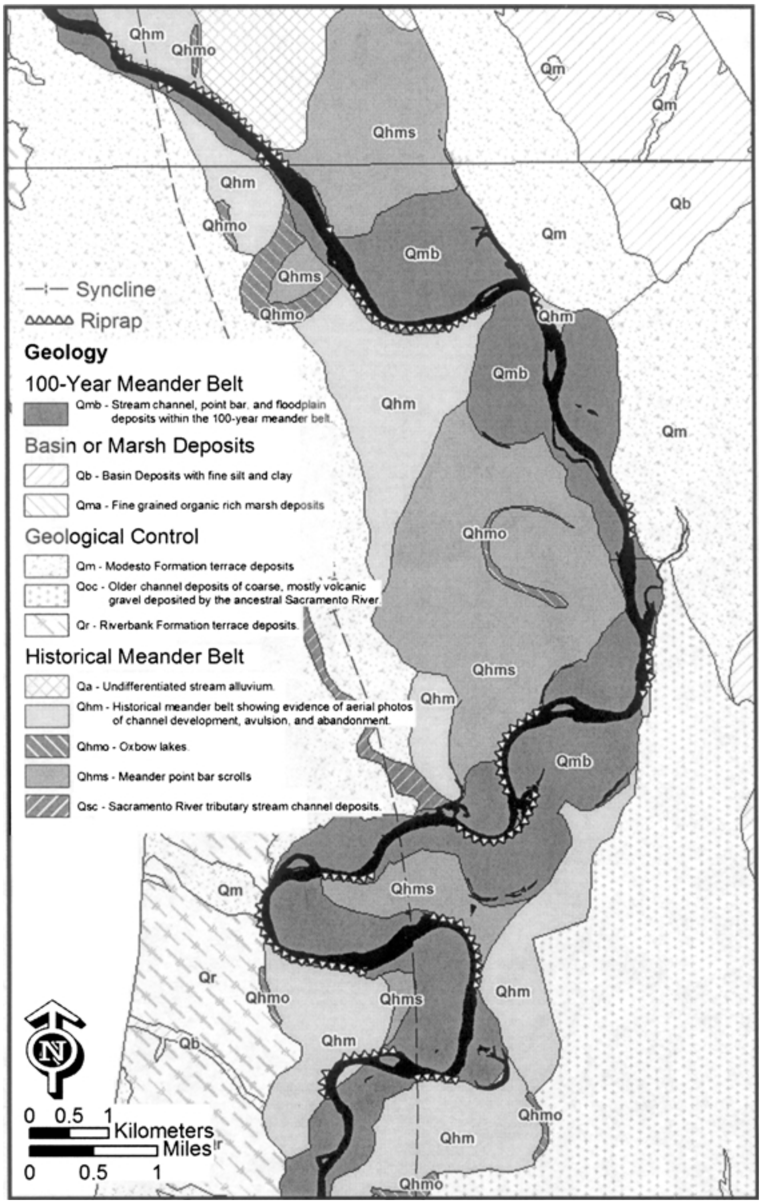

Figure 3. Geomorphic erosion zone map of the Sacramento River and study reach. Gray areas represent erodible geomorphic deposit types. (Data from the California Department of Water Resources.)

when exposed on bends, these formations can inhibit bank erosion and channel migration (Fischer 1994). In the study reach, the west side of the river in the vicinity of RM 194 (Figure 1) is constrained by the Modesto Formation (Figure 3). The erosion potential described by this geologic information, in connection with model calibration, was used to develop the erosion-potential grid described below.

The river is partially free to migrate between Red Bluff and Colusa. Records of recent (roughly 100 years) channel dynamics exist for this stretch of river, providing excellent opportunities to validate models and use simulations to evaluate setback constraint scenarios. We located our study reach at RM 184–201 (Figure 1) to investigate the effect of riprap versus setback constraint due to the availability of historic river movement records and high interest from river managers.

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 (Water Engineering &

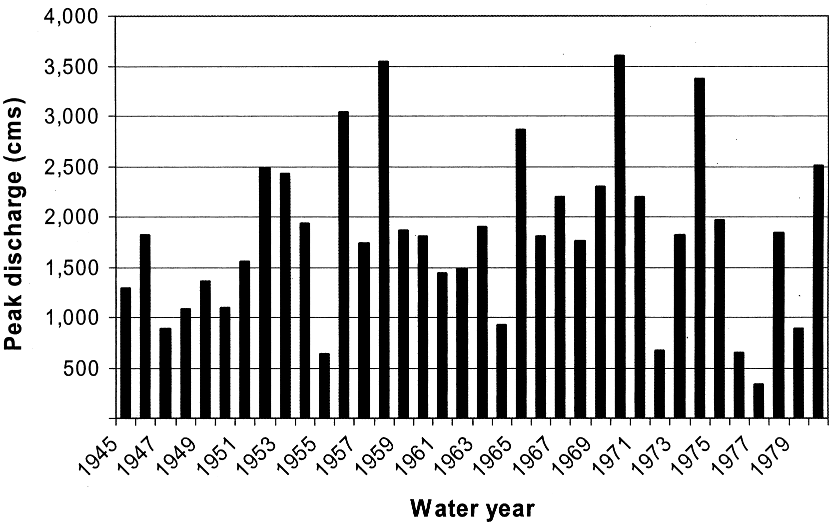

Figure 4. Peak annual flow 1945–1980, USGS gauge number 11383800, Hamilton City gauge.

Technology 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 184–201 (Water Engineering and Technology 1988). The channel banks are composed of sand and gravel, with isolated patches of erosion-resistant rock types. Heights of the eroding bank measured from the thalweg to the top of the bank from RM 199 to RM 186 are fairly uniform, averaging between 6 and 7 m. The lower layer is 2–4 m deep and composed of gravel with a mean average diameter (D_{50}) of 25 mm (minimum: 12.5 mm; maximum: 34 mm) (California Department of Water Resources 1995). Overlying silt and sand floodplain deposits are generally less than half sand and more than half silt and clay, with a mixture D_{50} of less than 0.5 mm (WET 1988).

Study Area: Hydrologic Setting

The man-made structures that have most affected the Sacramento River's hydrology in the last 60 years are Shasta Dam, located at RM 312, and a number of flood control structures. These allow overflow into catchment basins at specified flows and were installed as part of the federal flood control project of the Sacramento River. The hydrologic history of the Sacramento River within the study reach can be illustrated by the flow records recorded by a US Geological Survey (USGS) river gauge (US Department of Agriculture 2001). The USGS Hamilton City gauge (number 11383800) is located at approximately RM 199, near the top of the study reach. Daily flows were recorded from 21 April 1945 through 30 September 1980. Figure 4 shows a plot of annual peak flows. The data showed the 2-year return flow to be approximately 2270 cm. This discharge value was used to model the meander migration.

Study Area: Environmental Setting

The Sacramento River is the largest and arguably the most important river for water supply in California. Before European settlement in the early 1800s, a wide swath of riparian forest lay along the Sacramento River (Water Engineering and Technology 1988). The first type of land converted to agriculture was rimland, or lands adjacent to the river but at a higher elevation than the tule swamp and overflow lands in the basins. By 1871, almost all of this area had come under private ownership and was in the process of being converted for agriculture (Buer and others 1989). The floodplains were also progressively converted from riparian forest and tule swamp to farmland, primarily fruit and nut orchards. By 1989, 98% of the original riparian forest was gone (Sacramento River Advisory Council 1998).

Current vegetation patterns are typical of riparian areas in the large, alluvial river systems of the western United States. New floodplains are created by point-bar deposition and channel abandonment. Point bars along sinuous reaches remain predominantly gravel due to seasonal flooding, with strips of vegetation growing parallel to the channel. Vegetation colonizing less active areas along the bar include Fremont cottonwood (*Populus fremontii*) and various willow species (*Salix* spp.). Figure 5 shows the vegetation patterns after flow regulation. The geographic information system (GIS) layer was created using aerial photographs

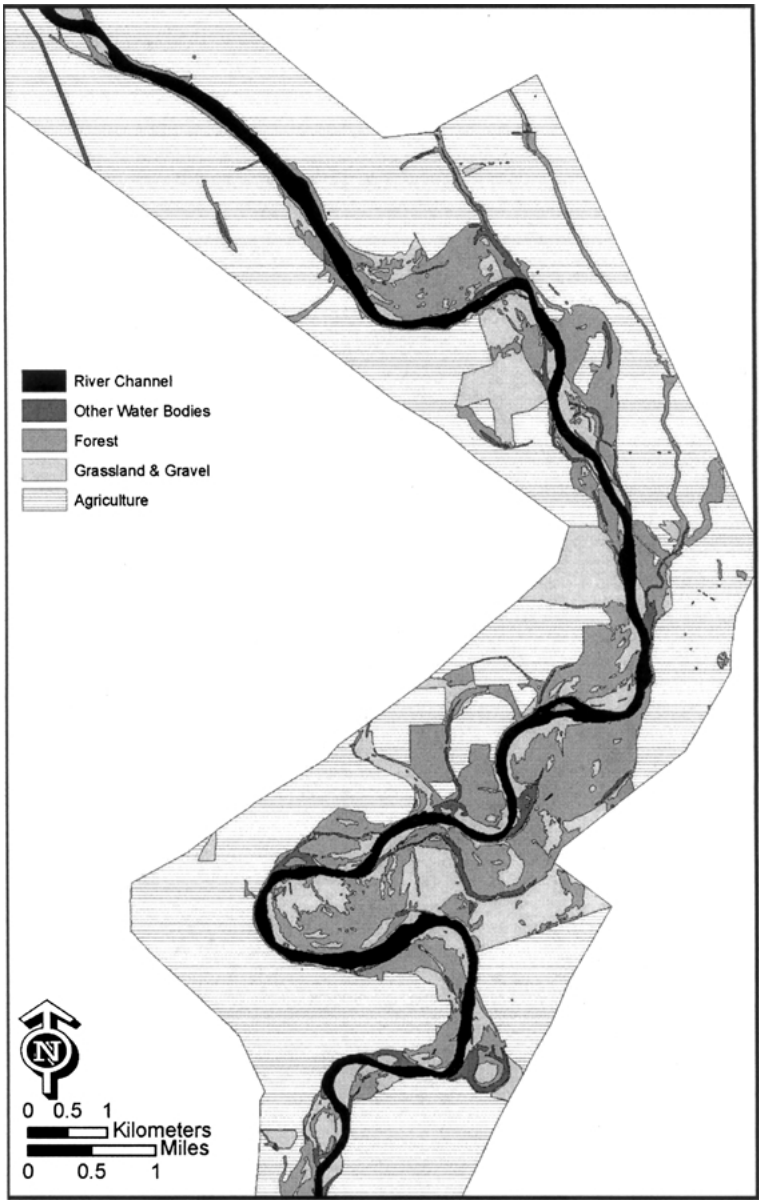

Figure 5. Land-cover types of the Sacramento River and study reach digitized from aerial photography depicting natural land-cover types (e.g., mixed riparian forest, gravel bars, and grasslands) and agricultural lands. (Data obtained from the Landscape Analysis and Systems Research Laboratory at the University of California, Davis.)

taken in 1997, the first year after one of the largest post-dam-flow years (Greco and Alford 2003).

Micheli and others (2004) compared the migration of the Sacramento River for 50 years before and after the completion of Shasta Dam and found that despite flow regulation, overall bank migration rates and erodibility increased approximately 50%, as riparian floodplains were progressively converted to agriculture. In addition, agricultural floodplains were found to be 80–150% more erodible than riparian forest floodplains in the absence of bank constraint (Micheli and others 2004). Brice (1977) maintained that riparian vegetation promotes higher sinuosity because it can inhibit chute cutoffs; therefore, clearing trees would result in river straightening and a change in channel form. Even a narrow fringe of riparian vegetation has been known to deflect the flow of a river and prevent rapid bank erosion (Brice 1977). Also, riparian vegetation on the inside of the meander loop inhibits downstream migration of the meander loop, helping to prevent cutoffs (Brice 1977). Micheli and others (2004) note that bank strength can be increased by root reinforcements by mature riparian stands. Channel roughness is also higher for reaches bordering riparian forest than reaches bordering agriculture (Micheli and others 2004), although this effect might be influenced by larger scales of channel roughness like form roughness and sinuosity roughness.

The reduced flows following dam construction allowed agricultural development in most downstream locations up to the edge of the river channel. Sinuosity and migration rate are not thought to have decreased, as concomitant land clearing for agriculture most likely increased the erodibility of the bank (Micheli and others 2004). Reduction in sediment flows due to Shasta Dam might have decreased point-bar formation and thereby channel migration rates; however, it is unclear how large a role sediment, bank erodibility, and flow regulation have played in altering the channel planform over the last 62 years.

Meander Migration Model

The meander migration model used in this study and variations of it have been used to predict and analyze the channel migration of a wide range of rivers, including 16 in Minnesota (Johannesson and Parker 1985; MacDonald and others 1991), the Genesee River in New York (Beck and others 1984), the Mississippi River (Larsen 1995), and a reach of the Sacramento River (Larsen 1995; Larsen and Greco 2002). Johannesson and Parker (1989) used the model to predict wavelengths of meandering rivers, with results comparing favorably to laboratory and field data. Pizzuto and Mecklenberg (1989) confirmed the relationship between migration rates and velocities 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. Another version of the model was used to examine conditions affecting meander initiation and growth (Sun and others 2001). Because this meander migration model was successfully used to simulate migration on the Sacramento River (Larsen 1995; Larsen and Greco 2002) and because Sacramento River conditions fall within the range of conditions tested by previous applications, we expected the model to work well for our Sacramento River study reach.

The numeric model for predicting river meander migration (Johannesson and Parker 1989; Larsen 1995) is based on relationships for the sediment transport and fluid flow. The model calculates how an alluvial river channel moves over timescales of years to decades. It assumes that the local bank erosion rate is proportional to a local velocity factor such that

$$M = E_0 * u_b \tag{1}$$

where M is the bank erosion rate (in m/year), E_0 is a dimensionless bank erodibility coefficient of the order of 10^{-8}, and u_b (m/s) 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_0 are described in Larsen and Greco (2002) (see below for more details). Higher E_0 values result in greater erosion potential. Although the model analytically calculates the velocity field in some detail, it represents bank erodibility by an empirically estimated coefficient (Larsen and Greco 2002). The simulations reported here use this dimensionless bank erodibility coefficient as it varies throughout the erosion field.

The crux of the model as applied here is the calculation of the velocity field. The analytic solution for the velocity results from the simultaneous solutions of six partial differential equations representing fluid flow and bedload transport. Together, these processes determine channel behavior (Johannesson and Parker 1989). The downstream and cross-stream conservation of momentum (processes 1 and 2) are expressed using a version of the shallow-water equations. Downstream bedload transport (process 3) calculations are based on Engelund and Hansen (1967), and cross-stream bedload transport (process 4) is related to downstream transport using a relation derived by Ikeda and others (1981) that is well described in Parker and Andrews (1985). The conservation of fluid and sediment mass (processes 5 and 6) are 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 natural variable 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 (e.g., Howard 1992). The rationale is the same as that used in traditional geomorphic analyses relating channel form and processes to the bankfull or dominant discharge (Wolman and Miller 1959). For this study, we have chosen the 2-year recurrence-interval flow as the characteristic discharge. Accordingly, the model is not intended to simulate the effects of particular flow events but to produce estimates of long-term rates of erosion or channel migration. Assuming that a single, continuously acting characteristic discharge 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 the calibration and prediction errors that can be introduced by these discrete events, we used time periods that were as long as possible (50-year intervals). Nonetheless, inaccuracies might have arisen from assuming that bank erosion is a continuous process. For example, Shasta Dam has altered historic patterns of high-flow events, which tend to cause the most erosion on the Sacramento River. Even if the dam did not alter the average flow rate, the reduction in peak flows might affect long-term erosion rates.

Meander Migration Model: Heterogeneous Erodibility Surface

A heterogeneous erosion surface, which was used in conjunction with model calibration, was developed by spatially combining GIS datasets of geology, land cover and riprap. The geology surface dataset was obtained from the CDWR (California Department of Water Resources 1995) (Figure 3). The geology dataset was used to determine areas that were not erodible, sometimes called areas of geologic constraint. Constrained areas included Qr (Riverbank formation), Qm (Modesto formation), and Qoc (old channel deposits). These represent nonerodible areas based on their soil properties. The vegetation dataset, used to distinguish between agricultural and riparian land cover, was derived from aerial photography taken in 1997 (Greco and Alford 2003). The effect of riprap was simulated by modifying the erosion potential grid, using a GIS riprap dataset from the CDWR (Figure 3). The riprap was buffered by a half-channel width and combined with the erosion potential grid (Environmental Systems Research Institute 2004); areas within the buffered riprap were given an erosion potential value of zero (i.e., nonerodible). Each dataset has not been formally ground-truthed to our knowledge; however, the spatial error was presumed to be well within range of the precision used in the meander migration model considering the cell size of the erosion field. All datasets were converted to a 30-m grid based on erodibility potential.

Table 1. Hydraulic input parameters for meander migration model

Flow parameters	Value
Discharge	2265 cm/s
Depth	5.4 m
Width	235 m
Slope	0.00042 m/m
Grain size	25 mm
Manning's number	0.035

Source: Values adapted from Larsen and Greco (2002).

After calibration, areas of natural vegetation were assigned an erosion potential of 100×10^{-8}, and agricultural lands were given a value of 200×10^{-8}. This value corresponds to the midrange of Micheli and others' (2004) findings. They found that agricultural land is 80–50% more erodible than riparian forest land. The erodibility of geologically or riprap constrained areas was set to zero. These values are consistent with published erosion rates observed on the Sacramento River (Larsen and others 2002; Larsen and Greco 2002; Micheli and others 2004), This GIS grid was exported as an ASCII text file and imported into the meander migration MATLAB program and used in conjunction with model calibration.

Meander Migration Model: Input, Calibrating, and Validating

The migration model requires the following six input values, which reflect 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, measured at the characteristic discharge and slope of the reach, is considered 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). Hydraulic input parameters are given in Table 1 and are adapted from Larsen and Greco (2002).

The output of the migration model depends on local hydraulic conditions through the hydraulic and geomorphic input variables, as well as the empirically determined erosion coefficient. In addition, we used empirically estimated values to conceptually simulate cutoff processes (Avery and others 2003). To calibrate the model, we used the channel planform centerlines from 1980 and 1997, 2 years for which centerlines could be accurately delineated from digitized aerial photos. The calibration process consists of adjusting the erosion, hydraulic, and cutoff parameters in the meander migration model until the simulated migration from 1980 to 1997 closely matches the observed migration during the same time period. The erosion potential field is thus established by calibrating the area reworked between the two time periods. The region outside the calibration is assigned erosion potential based on the land-cover type from the GIS coverage. For example, if a riparian area in the calibrated area had a calibrated value of 50, the riparian areas in the GIS coverage were also assigned this value. The GIS was not used as a calibration tool, but as a dataset for land-cover type and channel restraints, both man-made and geologic.

The model was then validated by simulating meander migration for the years 1952 to 1978 using the parameters determined from the calibration procedure. These years were chosen because centerlines could be accurately delineated from digitized aerial photos. Validation accuracy was measured, and the total difference between observed and modeled area worked was less than 10%. Thus, we assume that the differences observed between the scenarios are not due to calibration error, but to differences between the scenarios themselves.

Meander Migration Model: Cutoff Simulation

A cutoff simulation was used to account for bend cutoffs due to high flows during large storms. Bends were delineated by first calculating the local curvature along the centerline at points spaced approximately a half-channel width apart, using an algorithm to calculate local curvature (Johannesson and Parker 1985). A change in the sign of the curvature is an inflection point and can indicate a new bend. To account for small changes in the direction of curvature for a compound bend, the moving average of curvature for each point was calculated as the mean of the five adjacent upstream and downstream points. Starting from upstream, points were designated as part of a single bend until five consecutive points occur with the moving average of curvature in the opposite direction. These five points are considered the beginning of the next bend. All subsequent points are designated as part of this bend until five points in a row with a curvature in the opposite direction occur. These, in turn, constitute the beginning of the next bend. This procedure was repeated until all bends were identified and assigned a number. Bends were redelineated each year after the channel centerline was moved by the meander migration model.

To model cutoffs, discrete single bends were analyzed for sinuosity to determine their cutoff potentials. The sinuosity of each bend was calculated by dividing the distance along the channel for a bend by the straight-line distance between the start and end points of the bend. A sinuosity of 1.8 was considered the threshold at which bends were allowed to cut off (Avery and others 2003). The starting point of the cutoff was located one-quarter of the bend upstream from the cutoff bend and the ending point was placed one-quarter along the length of the downstream bend. Finally, the cutoff was simulated only if the straight line between the start and end points did not include riprap, levees, or geologic constraints to erosion. If the cutoff conditions were met, the river channel centerline points of the cutoff bend were simulated in a straight line between the start and end points.

Meander Migration Model Predictions

A total of 10 setback constraint scenarios were simulated at 100-m intervals, at distances ranging from 100 m to 1000 m from the channel. Near-bank riprap was assumed to be absent. For each of these scenarios, an erosion potential grid consisting of cells 30 m on a side was created. Areas greater than the setback constraint distance from the river channel were given an erosion potential value of zero, and areas less than the setback constraint distance from the river channel were given the erosion potential value of the heterogeneous erosion surface (described earlier). Each of these 10 erosion potential grids was imported into the meander migration model and 50-year simulations were run. The channel migration model was used to model erosion rates and floodplain creation based on the current riprap scenario and the 10 setback constraint scenarios.

For each scenario, a 100-year forecast (1997–2097) was produced. A map of forecasted floodplain age (Fremier 2003) was created for each scenario. Although channel centerline locations were predicted for each year, the floodplain age map was composed of predicted channels for every fifth year, primarily for graphical clarity. This map denotes which year a given area was last reworked by the migrating channel. The floodplain forecasting algorithm recognizes cutoff events. The cutoff model estimates the location and shape of the abandoned channel after each avulsion event. The area of abandoned channel was considered land reworked. On the Sacramento River, oxbow lakes tend to form within the downstream portion of the abandoned channel. These initially appear as backwaters contiguous to the main stem. Later, they become

Table 2. Forecasted area reworked by channel setback distance

		Setback distance									
	Riprap	100 m	200 m	300 m	400 m	500 m	600 m	700 m	800 m	900 m	1000 m
Area reworked by migration (ha)	137	235	441	648	808	841	845	883	883	883	883
Area reworked by cutoffs (ha)	0	0	0	0	22	119	138	199	199	199	199
Total area reworked (ha)	137	235	441	648	830	960	983	1082	1082	1082	1082
Estimated oxbow lake area (ha)	0	0	0	0	6	30	34	50	50	50	50
Total area reworked (% of riprap scenario)	100	172	322	474	606	701	718	790	790	790	790
% Area reworked by migration	100	100	100	100	97	88	86	82	82	82	82
% Area reworked by cutoff	0	0	0	0	3	12	14	18	18	18	18

separated at low flows when sedimentation occurs at the confluence (i.e., a downstream plug forms). On the Sacramento River between 1938 and 1997, approximately 20–30% of the area within abandoned channels developed into oxbow lakes (Fremier and Greco unpublished data). This value was determined using historical aerial photography of a 100-mile reach at 10–15-year time steps. We assumed that this percentage will remain constant in the future, and we estimated the area of aquatic habitat created per cutoff event as 25% of the abandoned channel area (Table 2). The model also calculated the number of cutoff events per time interval. A grid with cells 10 m on a side was used and a 120-m channel width (approximating the width of a low-flow channel) was assumed for the floodplain age and cutoff channel analysis. The final values of area of land reworked (Table 2) were considered to be the sum of the area reworked by migration and by cutoffs (consisting of the area of the abandoned channels) (Figure 8 and Table 2).

Results

The final simulated channel position, the erosion potential surface, and corresponding floodplain age maps for 4 of the 11 scenarios are shown in Figures 6 and 7. Figure 6 shows the erosion potential and the initial and 100-year predicted channel centerline for four scenarios: with current riprap and 100-, 500-, and 800-m setback. Figure 7 shows "floodplain age" maps for the same scenarios. The current riprap scenario predicted a total of 137 ha being reworked over the 100-year period (Table 2). All 10 setback constraint scenarios resulted in more total area reworked than the current riprap scenario (Figure 8 and Table 2). For constraint distances between 100 and 400 m, the total area reworked increased at an average rate of 180 ha per 100 m of setback distance (Figure 8). The total area reworked changed very little beyond a 500-m setback constraint, and beyond the 700-m setback, the area reworked was constant at 790% of the current riprap scenario (Figure 8 and Table 2). From the 800-m setback and greater, the migration patterns were identical for all scenarios; the constraint had no effect on the river channel meander dynamics within the 100-year period and/or there were geologically constrained areas between the simulated constraint and the river channel.

The river channel migration patterns produced by the scenarios fall into three main categories: (1) complete cutoff restriction, (2) partial cutoff restriction, and (3) no cutoff restriction. Although the names suggest that the processes are entirely related to cutoff dynamics, the progressive migration patterns also differ among categories. For example, the first category includes progressive migration rates that decrease throughout the simulation, whereas the other categories do not. The scenarios with riprap and setbacks of 300 m or less showed complete cutoff restriction because bend cutoffs never occurred within the 100-year prediction. The 400–600-m setback constraint scenarios showed partial cutoff restriction because they did allow some cutoffs, but not the full extent of what could have occurred if the river had been unconstrained (Figure 8). The no-cutoff-restriction scenarios (700-m setback and greater) produced six bend cutoff events (Figure 8); the 400-m setback constraint scenario (partial cutoff restriction) allowed only one cutoff to occur; the 500- and 600-m scenarios (partial cutoff restriction) allowed four to occur (Figure 8).

The temporal patterns of land reworked differed among scenarios, but their patterns could be grouped under the cutoff categories mentioned earlier. For example, complete cutoff restriction scenarios tended to yield higher rates of erosion at the start of the simulation, but these decreased to a relatively low rate by the end of the simulation. In Figure 9, the lines for

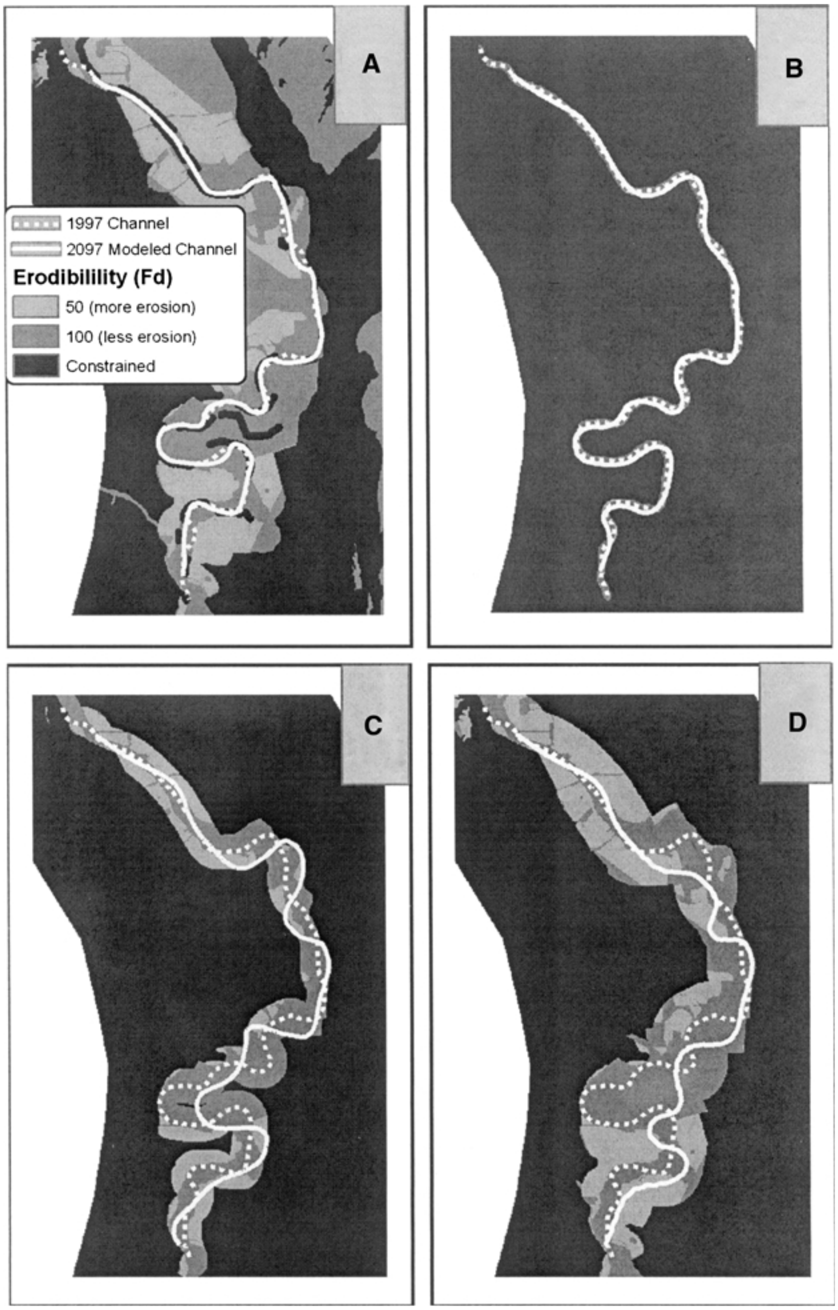

Figure 6. Original river channel (1997) and 100-year forecasted river channel laid over erodibility surface for (**A**) the riprapped scenario, (**B**) the 100-m setback constraint scenario, (**C**) the 500-m setback constraint scenario, and (**D**) the 800-m and greater setback constraint scenarios. The 1997 channel is represented by a dashed line and the final location of the 100-year simulation is represented by a solid white line.

100–300-m setbacks (complete cutoff restriction) tend to have an inverse power relationship with elapsed time, with initially steep declining slopes that level off over time. Scenarios with partial cutoff restriction and no-cutoff restriction tended to have high rates of land reworked throughout the simulation, punctuated with spikes in land reworked caused by cutoff events (Figure 9).

The fully restrained (riprap) scenario had low rates of land reworked for all years, with a maximum rate of land reworked (3 ha/year) at the start of the simulation; this rate decreased for the first 50 years be-

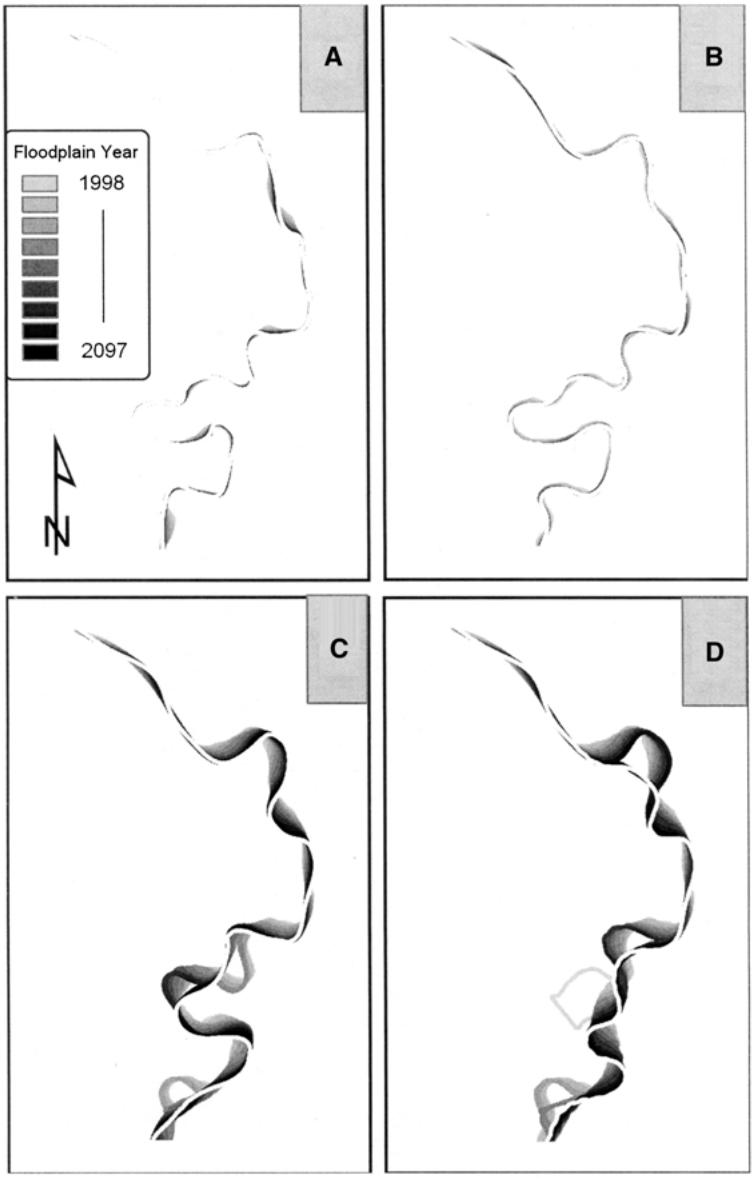

Figure 7. Floodplain year map produced for (**A**) the riprapped scenario, (**B**) the 100-m setback constraint scenario, (**C**) the 500-m setback constraint scenario, and (**D**) the 800-m and greater setback constraint scenarios. Floodplain year refers to the year in which a piece of land was created (i.e., deposited) from river movement.

fore leveling out at less than 1 ha/year (Figure 9). The 100-m setback scenario began with a relatively high erosion rate (10 ha/year; Figure 9), resulting in 20% of the erosion occurring during the first 5 of the 100 years, 75% occurring during the first 35 years, and 90% during the first 65 years (Figure 9). At first, the 100-m setback scenario reworked more land per year than the riprap scenario, but the two scenarios converged upon the same rate of less than 1 ha/year after 40 simulated years. Rates of land reworked were highest during the first 5 years because the river moves approximately 100 m, then is halted by the 100-m setback constraint.

The 200-m setback constraint scenario reworked almost twice as much total area as the 100-m scenario and more than three times as much area as the riprap scenario during the 100-year period (Table 2). This scenario showed a similar decrease in land reworked rate throughout the simulation, yet appeared to level out around 2 ha/year. Similarly, the rate of erosion for

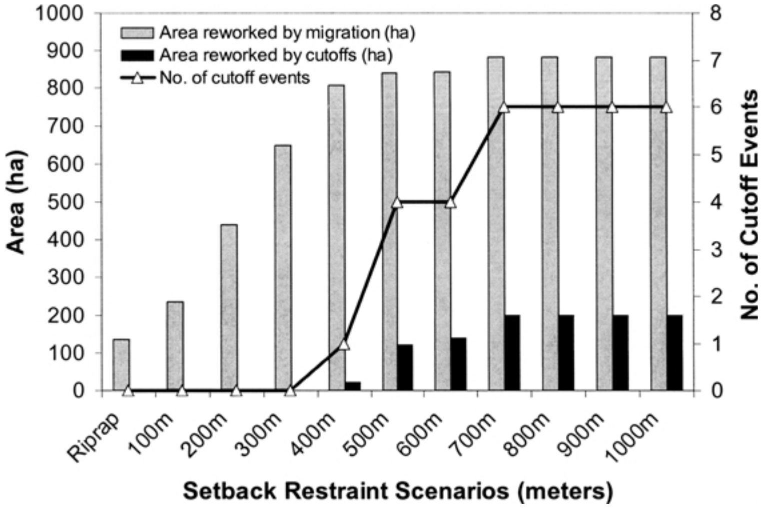

Figure 8. Total area eroded for each of the modeled scenarios. All scenarios greater than 700 m produced identical results. The 100–400-m setback scenario shows a significant linear increase in area reworked.

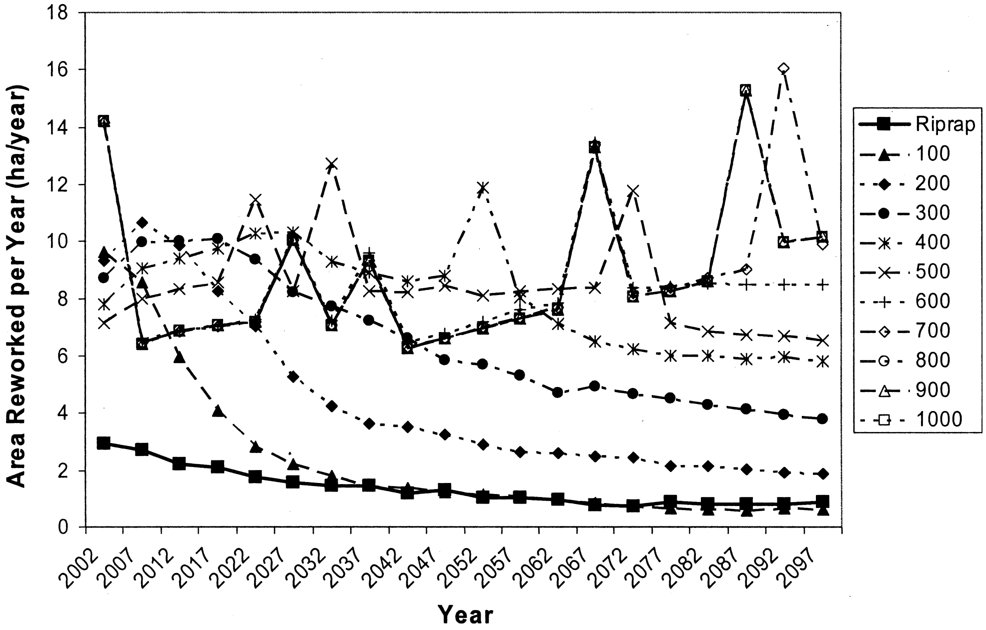

Figure 9. Area eroded per year for each scenario. The complete cutoff constrained scenarios (riprap and 100–300-m setback constraints) decrease as a power function, whereas the partial and no-cutoff constrained scenarios have a fairly constant rate of erosion punctuated by spikes in the area eroded due to cutoff events.

the 300-m setback constraint scenario began around 10 ha/year, decreasing to 4 ha/year by the end of the simulation.

These differences in erosion rates over time directly affect the distribution of floodplain age surfaces in different scenarios. The complete cutoff restriction scenarios produced a higher proportion of floodplains older than 50 years because most of the channel migration occurred during the first half of the simulation. The partial and no-cutoff-restriction scenarios produced floodplains of all ages in fairly equal proportions, with some ages overrepresented due to cutoff events. The area of land deposited per cutoff event was about 3% per cutoff of the total area reworked per scenario (i.e., a total of 3–18% depending on the number of cutoff events). The wet oxbow lake area was estimated (25% of the total abandoned channel area) to be between 6 and 50 ha.

Discussion

Setback levees have been suggested as a means to allow river processes to create and maintain riparian habitat while still providing flood and erosion control constraints. Our results suggest that over a 100-year period, setback constraints would have a positive effect on riparian floodplain habitat. They would allow the river to rework two to eight times as much floodplain area as current riprap conditions allow, and would permit channel cutoff events to occur. In this study, setback constraints placed 500 m or greater from the channel reworked approximately the same amount of land. However, to permit the full range of cutoff dynamics to occur over a 100-year period, restraints should be set back 700 m or greater. Setback constraints placed 300 m or closer would still be better than the current riprap scenario because they would allow for 1.7 to 4.7 times more area reworked, despite the fact that they would not permit cutoff events.

Migration Patterns with Constraint Setback

The results suggest that the setback constraint scenarios yield three process-related categories of land reworking patterns. The first category allows no cutoffs and only limited progressive migration. Migration rates decline over time as engineered channel constraints halt channel migration. In these scenarios, the amount of land reworked tends to decrease with time as an inverse power relationship after some initial increase in rate. In our study, this occurred for setback constraint scenarios of less than 300 m, or roughly one bankfull channel width (235 m) on either side of the river. Rates of land reworked will decline steadily after the first few years, and cutoffs and oxbow lakes will never be generated. At the other extreme is the category in which the setback distance produces unconstrained migration and cutoff events during and after 100 years from the implementation of setbacks. The scenarios producing unconstrained migration and cutoff were identical, with periodic cutoff events. Our study suggests that this distance is 700 m in our study reach of the Sacramento River, or about three bankfull channel widths.

The scenarios between the lower and upper thresholds (300 and 700 m) allow restricted cutoffs to occur. They rework more land than the completely restricted cutoff scenarios. The rate of land reworked in these scenarios was relatively constant in the 100-year period of modeling, with intermittent spikes representing cutoff events. The graphs of rates reworked had trailing ends that tended to taper slightly. These tapered ends show that the river had migrated up against the setback constraints, resulting in a decrease in the rate of area reworked at the end of the simulation period. For setback distances of less than 400 m, the rate of land reworked declines continuously over the 100 years.

Implications for Management

Information on what will happen to the habitat is necessary to weigh the ecological impacts of various setback scenarios. Point bars and oxbows are particularly important habitat types. The creation of these habitats (which we have represented by the rate of land reworked) differs significantly depending on the category of the constraint setback scenario. Managing for point-bar deposition and development alone would require narrower setbacks than managing for the aquatic habitats created by channel abandonment and oxbow lake formation. For example, although point bars might be created in scenarios that do not allow cutoff events, no new oxbows will be created.

This study found that no additional floodplain was created and no additional cutoffs occurred for setback constraints beyond the 700 m. However, constraints set back further might have additional benefits not directly associated with river meander dynamics. The ecological benefits of wider setbacks would improve exchanges of nutrients, sediment, and woody debris and create additional habitat for fish during large flood events. In addition, constraints set back farther might benefit society by providing increased flood storage (Pinter 2005).

These results for the Sacramento River might appropriately be applied to other rivers; many river processes are scaled by channel width (Leopold and others 1964). Using the channel width corresponding to the bankfull discharge of the river as a scale, the transition from complete cutoff restriction to partial cutoff restriction occurs at slightly more than one channel width. The transition from partial to no-cutoff restriction occurs at about three channel widths. Channel migration dynamics under different setback constraint scenarios depends not only on channel width, a geomorphic scale for a river, but also on some measure of the dominant cutoff dynamics. Channel cutoff dynamics can differ significantly between rivers, depending on what processes dominate (e.g., neck or chute cutoffs). Channel sinuosity has been a typical metric of cutoff dynamics (e.g., Brice 1974, 1977; Hooke 1984). If a sinuosity threshold for a cutoff to occur differs for other rivers, then the scaling of distance from the channel to the setback constraints for other rivers will probably depend on the channel width and some appropriate measure (e.g., cutoff sinuosity threshold) representing the prevailing cutoff dynamic.

Our analysis examines habitat creation over time; it quantifies *rates* of land reworked. In many cases, predictions of management scenarios quantify development of areas of habitat, but neglect the rate of habitat change. In riparian ecosystems, the rate of change is a key component. For example, if one were to examine the land-reworked benefits over the first 10 years of the 100-m setback (cutoff restricted scenario), the amount of land reworked is the same as with the unrestricted scenario. However, after 40 years, the same scenario has a rate of land reworked identical to the riprap scenario. To achieve long-range dynamism, one must consider meander–bend development patterns over longer periods of time. Moreover, sustaining the river's capacity to rework land and create oxbow lakes is just as important as producing large areas of habitat over the long-term management of ecosystems. Therefore, one goal of this research was to present river managers with a spatially explicit framework for making decisions concerning longer design periods in large alluvial river systems.

Model Considerations

The distances and times for channel dynamics to occur are approximations based on a number of estimates. The estimate of the erosion-potential field, the assumptions and approximations related to cutoff dynamics, the assumption of a constant hydrograph (i.e., the flow is modeled as constant), and the use of constant hydraulic input parameters for the reach are all approximations that could be refined. Simulations of future migration also assume that the watershed conditions—such as degree of urbanization and upstream extent of riparian-lined channels—do not change. The absolute numbers in our results would change given different input assumptions, but the pattern of simulation results would probably be similar. This modeling exercise suggests that important areas of geomorphic process change are related to river scale and cutoff dynamic.

Our assumption of a constant hydrograph simplifies the dynamics of floodplain deposition; however, this simplification is not likely to affect the analysis. In another study (Larsen and others in press), we found that the total migration or area reworked with a constant versus a variable hydrograph was not significantly different. By contrast, the ecological differences in a constant and a variable hydrograph, considering vegetation establishment on newly formed surfaces, have been shown to be important (Mahonen and Rood 1998). Research on intra-annual flows has shown that the timing and magnitude of spring flooding in arid and semiarid river systems limits cottonwood establishment (Johnson and others 1976; Mahoney and Rood 1998). It is important to note that we have not modeled these effects. Management would benefit with more complex ecological models of vegetation establishment on newly deposited point bars (e.g., Richter and Richter 2000). Dixon and others (2004) investigate the ecological consequences caused by variable migration patterns to understand how vegetation recruitment on point bars is effected by interannual flow patterns and the prediction of migration under various predicted climate change scenarios.

Conclusions

The ecological integrity of riparian forests depends on the dynamic disturbance regime of natural river flows. Water storage and diversions have decreased peak flows. In conjunction with bank erosion control measures (i.e., riprap), these flows have greatly reduced bank erosion rates over time. The result has been a shift in the riparian forest community toward later successional species (Stromberg 2001) and potentially invasive exotics. Sufficient peak flows are necessary to erode away older floodplains while depositing sediment in areas of riparian forest recruitment. The results of this study can be integrated with vegetation models to determine how setback constraints can influence the future establishment of particular riparian forest vegetation associations (Gergel and others 2002; Fremier 2003).

Although area reworked is important for the general production and maintenance of riparian habitat, cutoff events are equally, if not more, important for the creation of riparian and aquatic habitats. Cutoff events produce oxbow lakes, which are important in the maintenance of a dynamic heterogeneous landscape. Our analyses suggest that riprap and levees setback less than about one to three widths (300–700 m) from the channel would limit the creation of point bars and oxbow lakes and would hinder the establishment and maintenance of the associated vegetation and animal communities within a 100-year time period. Alternatively, if one is managing for point bars alone, the setback need not be as great as when one is managing for more oxbows and aquatic habitat.

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