MEANDERBELT DYNAMICS OF THE SACRAMENTO RIVER, CALIFORNIA[1]

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Abstract: A 160km-long reach of Sacramento River was studied with the objective of predicting future changes in channel planform and their effects on water-surface elevations. Planform data were used to develop regression relationships between bend radius of curvature (Rc) and both short-term (5 years) and long term (90 years) lateral migration rates (MR) and migration distances (MD). A dimensionless cutoff index (Rc/MD) was developed to predict bend cutoff occurrence. Cutoffs occur when the cutoff index value is between 1.7 and 3.7. Channel planform controls water-surface elevations and bend cutoffs can reduce upstream water-surface elevations by up to 1 meter over a wide range of discharges.

In order to obtain an understanding of the meander dynamics of the Sacramento River, which is a coarse-grained meandering river located in the Great Valley of California, a geomorphic study of a 160km-long reach of the river from Colusa to Red Bluff was undertaken in 1987 (fig. 1). The reach of river between Glenn and Chico Landing (Butte Basin), which is located at the upstream end of the flood-control levees, is of major importance to flood control in the lower Sacramento Valley. The objectives of this study were to see if: (1) an understanding of meander dynamics could be used to predict the rates and locations of within-channel erosion and deposition due to changes in river planform, and (2) the planform of the river has significant effects on overbank flooding and sedimentation.

Point-bar development and concave bank erosion have been the principal concerns of those studying the dynamics of meandering rivers. Figure 2 is a schematic diagram of a reach of a meandering river that defines the terms that are used in this discussion of the dynamics of the Sacramento River. Erosion along the concave bank occurs because of convective acceleration in downstream flow (Henderson 1966), and because of intensification of cross-stream flow. Both are caused by flow convergence which implies that the shape of a meander bend significantly affects bank erosion (Nanson and Hickin 1983). As the radius of curvature of the bend decreases, the channel cross section in the pool zone is constricted laterally because of vertical growth of the point bar (Knighton 1984; Carson 1986). Therefore, lateral migration of the channel and concave bank erosion are dependent on the flow characteristics and the shape of the bend.

The rate of bank retreat is dependent on the resistance to erosion of the concave bank materials (Nanson and Hickin 1986), the duration and magnitude of the flows (Odgaard 1987), the radius of curvature of the bend (Nanson and Hickin 1983, 1986; Odgaard 1987), and the capacity of the flows to transport bed- material sediment (Neill 1984; Nanson and Hickin 1986). Channel migration is a discontinuous process because it is dependent on the occurrence of flood flows (Brice 1977;

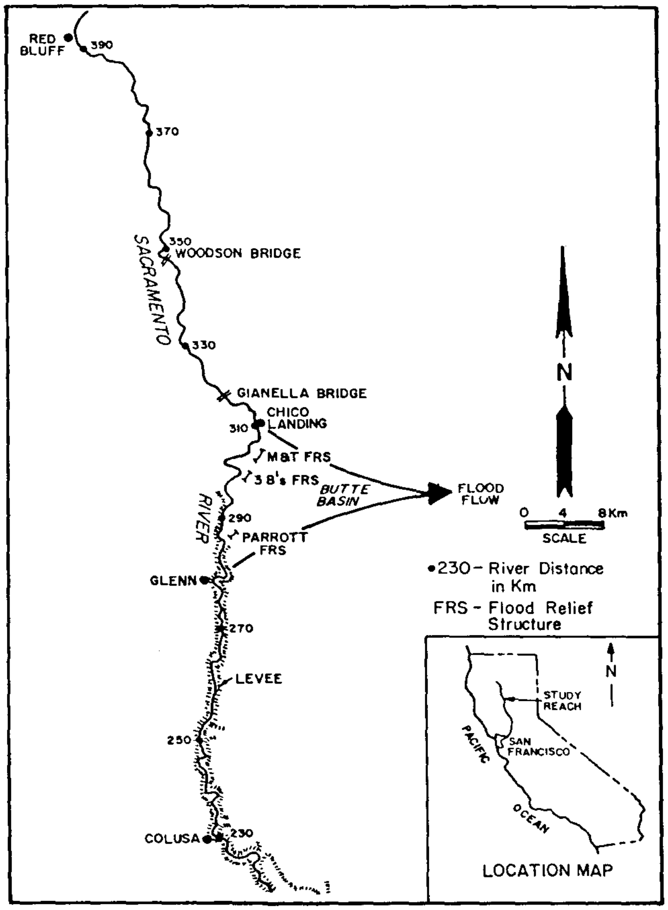

Figure 1 — Location map for study reach of Sacramento River.

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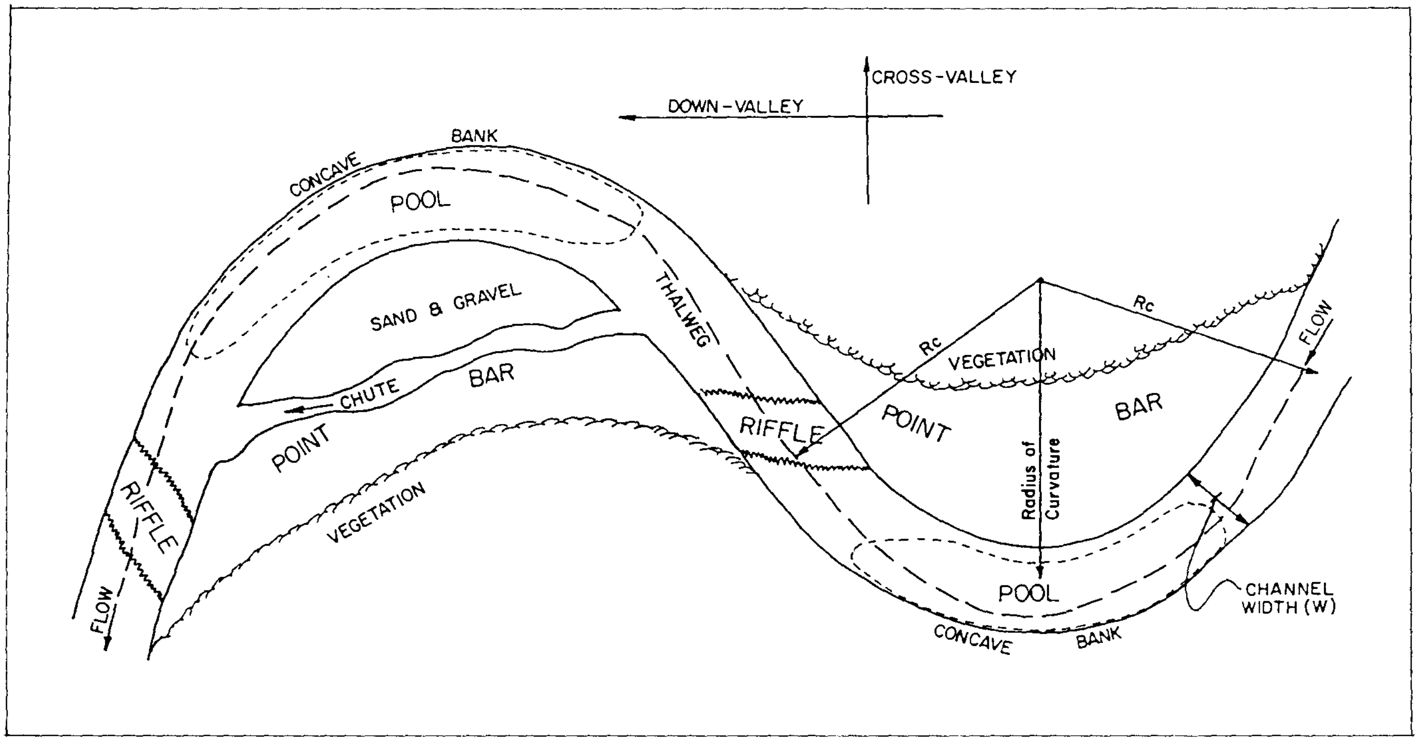

Figure 2— Schematic diagram showing in planform the geomorphic surfaces and features that are associated with meander bends.

Nanson and Hickin 1983). Initially bends migrate in a cross-valley direction (extension) (fig. 2), but eventually bends advance in the down- valley direction (translation) (Brice 1977; Knighton 1984; Leeder and Bridge 1975; Nanson and Hickin 1983, 1986).

Meander bends eventually cut off when the radius of curvature decreases below a certain value which is specific to each stream. Reduction of the radius of curvature of a bend causes backwater upstream of the bend, and this is expressed physically as a reduction in the slope of the water surface. Since the sediment transport capacity of the flows is proportional to the slope of the water surface, a reduction in slope reduces the sediment transport capacity of the flows. This causes deposition of sediment in the upstream limb of the bend between the pool and riffle (fig. 2). Deposition of sediment reduces the flow capacity of the channel and this causes flows to be diverted over the point bar (fig. 2). These flows erode the point bar surface and form chutes (Carson, 1986; Lisle, 1986). However, cutoffs can occur as a result of either chute development (Lewis and Lewin 1983; Brice 1977) or neck closure (Fisk 1947). The review of literature suggests that changes in river behavior should be predictable. Any prediction of future behavior is based on past behavior, streams being no exception (Schumm 1984). Implicit in this approach is the assumption that the sequence of hydrologic events (i.e., flood flows) that have controlled the behavior of the river in the past will be repeated.

Channel Migration and Bank Erosion

Data on channel planform (1:12,000) were available from the California Department of Water Resources (DWR) River Atlas (DWR 1984) and 1986 aerial photographs (1:400). Hydrologic records from 1879 were available at the U.S. Geological Survey gaging station at Bend Bridge, which is located upstream of Red Bluff. The planform data were used to construct a data base which could be used to investigate channel migration and bank erosion in the 32km-long reach between Glenn and Chico Landing (fig. 1). Changes in rivers are generally associated with large floods and, therefore, it is important to differentiate between short-term and long-term behavior. Short-term behavior of the river was based on a 5-year period of record between 1981 and 1986 because large magnitude flow events occurred in both 1983 and 1986. Long-term behavior of the river was based on the period of record (1896 to 1986).

Short-Term Migration Rates

Bagnold (1960), Leeder and Bridge (1975) and Nanson and Hickin (1983, 1986) have demonstrated that lateral migration rates of meandering rivers can be correlated with the radius of curvature (Rc) of bends. Migration rates are highest when the radius of curvature to channel width (W) ratio (Rc/W) is about 2.5. Radii of curvature (Rc) and 1981-1986 migration rates (MR) for 11 bends were measured to obtain short-term data on river behavior. Radii of curvature ranged from 381 to 838 meters and migration rates varied from 37 to 10 meters/year. A least- squares regression of the data is:

$$MR = 53.57 - 0.049Rc \ (R^2 = 0.69) \tag{1}$$

Long-Term Migration Rates

In order to determine long-term behavior of the river, radii of curvature and migration rates for the period of record (1896- 1986) were utilized. The radii of curvature were assigned to 9 class intervals that varied by 76-meter increments from 229 to 838 meters. The average channel width in each bend was determined by measurement from the DWR Atlas and the 1986 aerial photographs, and both the migration rate and radius of curvature were divided by the channel width (Nanson and Hickin 1986). The average width of the river in the study reach is 150 meters. The relationship between the radius of curvature-width ratio (Rc/W) and the migration rate-width ratio (MR/W) is shown in figure 3. Also shown in figure 3 are the means and standard errors for the 9 class intervals and the curves which define the upper limits of Nanson and Hickin's (1986) data. The mean migration rates on Sacramento River are close to Nanson and Hickin's maximum values. This suggests that migration rates on Sacramento River are high in comparison with the Canadian sand and gravel streams.

The relationships between the mean migration rates and the radii of curvature were established on logarithmically-transformed data. For the radii of curvature greater than 381 meters (Rc/*W* > 2.5) the least-squares regression is:

$$MR = 6.98 \times 10^{4} Rc^{-1.333} \ (R^2 = 0.83) \tag{2}$$

and for the radii of curvature less than 381 meters (Rc/*W* < 2.5) the least-squares regression is:

$$MR = 2.2 \times 10^{-6} Rc^{2.875} \ (R^2 = 0.94) \tag{3}$$

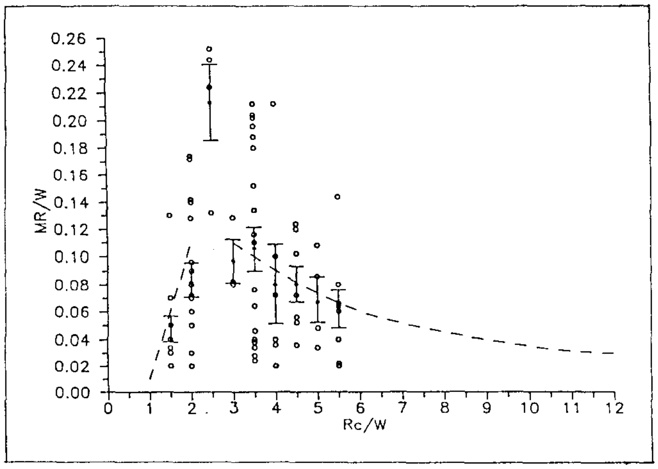

Figure 3— The ratio of migration rate (MR) to channel width (W) plotted against the ratio of radius of curvature (Rc) to width. The asterisks and bars represent the means and standard errors, respectively. The curves are from Nanson and Hickin (1986).

The reason for subdividing the data is provided by figure 3. Nanson and Hickin's (1986) curves show that for Rc/W values between 1 and 2.5 there is a direct relationship between MR/W and Rc/W. Conversely, for Rc/W values greater than 2.5 there is an inverse relationship between MR/W and Rc/W.

Brice (1977) considered that most bends on Sacramento River would cutoff by the time that the radius of curvature had reduced to 381 meters. However, a number of low radius of curvature bends (less than 381 meters) are located in the lower part of the study reach near Colusa. This may be due to the fact that the sediments are finer, more cohesive and, therefore, more resistant to erosion.

For a given class interval of radius of curvature between 381 and 838 meters (Rc/*W* > 2.5) the long-term migration rates are lower than short-term rates by 57 to 73 percent. This is consistent with the general observation that large magnitude, low frequency, events significantly effect changes in the river, and that change occurs because of the occurrence of large floods. Further, both the short-term and long-term data indicate that bends with radii of curvature of about 380 meters erode the fastest, but bends with radii of curvature that are either greater or lesser than 380 meters have lower rates of erosion.

Radius of Curvature and Cutoffs

The progressive development of a meander bend to the point where it cuts off is an example of exceeding an intrinsic geomorphic threshold (Schumm 1977). The cumulative frequency distributions of the radii of curvature of bends between Glenn and Chico Landing in 1969, 1981 and 1986 were determined from aerial photographs. The radii of curvature were assigned to 8 equally-spaced class intervals (305 to 838 meters). Between 1969 and 1986 the median radius of curvature declined from 600 to 550 meters. The median radius of curvature for a cutoff is 380 meters, but the range is from 305 to 610 meters. Ninety percent of all cutoffs occur when the radius of curvature is less than 533 meters. The radii of curvature of bends that had cut off since 1908 (10) and pre-1908 meander scars on the floodplain (22) were measured. The radii of curvature of four bends that had cut off following revetment were also measured.

Statistical analyses (t-Tests, 90% probability level) of the cutoff data were conducted. The results indicate that there are no statistically significant differences between the mean radii of curvature values of the floodplain (417 + 98m), post- 1908 (419 + 95m) and revetted (390 + 163m) cutoffs. This can be interpreted as indicating that changes in hydrology and upstream sediment supply due to dam construction and gravel mining (DWR, 1984) have had little effect on the meander dynamics in the Butte Basin reach. This may be due to the fact that the dams have not significantly reduced the peak flows and that sediment supply to this reach has been maintained by within-channel erosion in the reach between Red Bluff and Chico Landing (fig. 1).

A dimensionless cutoff index, which is defined as the ratio of the radius of curvature to the migration distance (Rc/MD) was developed to predict cutoff occurrence. Equation 1 was used to determine the MD values for the cutoff index for both the recent (10) and floodplain (22) cutoffs. With the exception of two floodplain cutoffs, the Rc/MD values were less than 4. The mean and standard deviation for the recent cutoffs were 2.7 and 1.0, respectively and the values for the floodplain cutoffs were 2.6 and 0.9, respectively. Therefore, cutoffs can be expected to occur when the value of the cutoff index (Rc/MD) lies between 1.7 and 3.7.

The cutoff indices for 14 bends between Glenn and Chico Landing were calculated using measured values of MD between 1981 and 1986 (table 1). The data indicate that seven of the bends have Rc/MD values that lie within the range of values that were identified for cutoffs ($1.7 < Rc/MD < 3.7$). Associated with these Rc/MD values for these seven bends are two other characteristics that were identified on the 1986 aerial photographs: (1) the presence of a mid-channel bar in the upstream limb of the bend, and (2) the presence of chutes across the point bar. Therefore, it appears that cutoffs can be predicted on the basis of the value of the cutoff index and the presence of the two ancillary features. This was tested on the bend at river distance 278.4km which had cutoff in 1986. This bend was revetted prior to 1981 and, therefore, no migration of the bend took place between 1981 and 1986. However, the radius of curvature of the bend decreased from 572 meters in 1981 to 343 meters in 1986. The MD value for a radius of curvature of 343 meters (Eq. 1) is 181 meters and, therefore, the cutoff index (Rc/MD) is 1.9. The aerial photographs confirm the presence of both a mid-channel bar in the upstream limb of the bend and the chutes on the point bar.

Table 1— Characteristics of bends between Glenn and Chico Landing, Sacramento River.

River Distance (km)	Radius Curvature (Rc) 1986 (m)	Short- term Migration Distance (MD)(m)	Cutoff Index (Rc/MD)	Presence of features 1986 Upstream Bar	Chute	Revetted Bank
307.8	838	49	17.1	No	No	No
306.4	495	152	3.3	Yes	Yes	No
304.8	381	186	2.1	Yes	Yes	No
304.0	229	55	4.2	Yes	Yes	No
303.0	533	21	25.4	No	No	Yes
301.6	572	155	3.7	Yes	Yes	Yes
299.2	572	162	3.5	Yes	Yes	Yes
297.6	533	88	6.0	No	No	No
293.9	838	61	13.7	No	No	No
292.8	572	143	4.0	Yes	Yes	No
288.0	533	149	3.6	Yes	Yes	No
287.2	572	116	4.9	No	Yes	Yes
285.6	381	146	2.6	Yes	Yes	Yes
280.0	686	40	17.2	No	No	No

Channel Planform and Water-Surface Elevations

The reduction in the radius of curvature of a bend increases the hydraulic resistance of the flow, which causes increased backwater upstream of the bend. This is expressed by a reduction in the slope of the water surface upstream of the bend which reduces the conveyance capacity of the channel and, therefore, promotes overbank flows.

In order to demonstrate the effects of channel planform on water-surface elevations, step-backwater runs (HEC-2) were conducted for the reach of river between Gianella Bridge and Woodson Bridge (fig. 1). Gaging stations are located at both bridges, which permits calibration of the water-surface profiles. Discharges of 360, 850 and 1980 (bankfull) cubic meters/s. were routed through cross sections that were surveyed in 1923 and 1987. The HEC-2-derived water-surface elevations were plotted against a straight-line valley distance (projected profile) upstream of Colusa, which is in contrast to the normal practice of using river distance. Since river distance changes through time, the use of a projected profile allows different surveys to be evaluated on a common basis (Harvey and others 1988).

The 1923 and 1987 HEC-2-derived projected water-surface profiles for the three discharges are shown in figure 4. Two bends, located at 66.2 and 76 kilometers above Colusa, cut off between the surveys in 1970 and 1976, respectively. The effects of the planform on upstream water-surface elevations can be seen very clearly in 1923. At the three routed discharges the water-surface elevations increase by about 1 meter upstream of the bends. Following the cutoff at 66.2 km in 1970 the water-surface elevations for the three discharges were reduced by about 1 meter upstream of the bend because the channel downstream was relatively straight and, therefore, did not create any backwater. In contrast, following the cutoff at 76 km in 1976 the water- surface elevation upstream of the bend increased or remained about constant because bends downstream of the cutoff were causing backwater.

The comparative water-surface profiles demonstrate that channel planform and its changes have significant effects on water-surface elevations, but the effects of cutoffs also depend on the planform of the channel downstream of the location of the cutoff. Because of the backwater effects of short radius of curvature bends, overbank flooding and sedimentation will occur more frequently in locations upstream of these types of bends. However, a cutoff may or may not reduce the extent of overbank flooding and sedimentation. The overbank effects of a cutoff will depend on the presence or absence of downstream bends.

Application

The ability to predict changes in river planform is important for managing rivers for erosion and flood control. Prediction of future changes is dependent on understanding the past behavior of the river, but uncertainty in prediction is introduced because of the stochastic nature of flood events which cause the changes. On the Sacramento River the ability to predict future changes is especially important in the Butte Basin reach (fig. 1). The Butte Basin reach is a naturally occurring flood overflow area at the head of the leveed section (fig. 1).

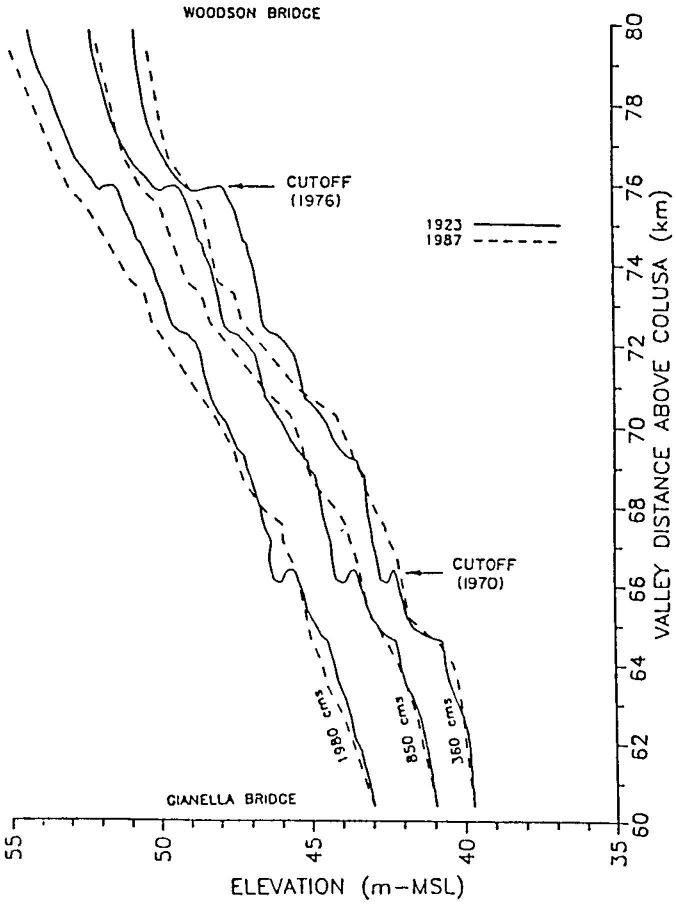

Figure 4 — Projected water-surface profiles for discharges of 360,850 and 1980 cubic meters/s derived from 1923 and 1987 cross sections between Gianella and Woodson Bridges. The solid lines represent the 1923 water-surface profiles and the dashed lines represent the 1987 water-surface profiles. Cutoffs occurred in 1970 at 66.2 km and in 1976 at 76 km.

The design-flood capacity of the leveed reach is 4286 cubic meters/s and, therefore, flows in excess of this discharge must overflow through 3 flood-relief structures (FRS) if the integrity of the levees is to be maintained.

Satisfactory operation of the flood overflows is dependent on the location of the channel with respect to the flood-relief structures, and on the planform of the river downstream of the structures. Therefore, meander migration and bend cutoffs could have serious consequences for flood control on Sacramento River. Successful operation of two of the FRS is currently threatened by potential changes in the bends at 285.6km (Parrott FRS) and 304.8km (M and T FRS). Bank erosion has been prevented by revetment at 285.6km, but the cutoff index is 2.6 (table 1) and both chutes and a mid-channel bar are present. If this bend cuts off, it is highly likely that the water-surface elevation of flood flows in the location of the Parrott FRS will be reduced by about 1 meter because the downstream reach is straight (fig. 4). Continued bank erosion can be expected at 304.8km (M and T FRS) because it is not revetted. The short-term migration rate is 36 meters/yr (Eq. 1), and the long-term rate is 25 meters/yr (Eq. 2). The cutoff index is 2.1 and chutes and a mid-channel bar are present. A cutoff of this bend will not on its own cause reduced water-surface elevations at the M and T FRS because the channel downstream is sinuous and it is causing backwater upstream (fig. 4). However, continued erosion of the concave bank (fig. 2), and down-valley migration of this bend has the potential to cause a neck cut off at the next bend downstream, and therefore, in the longer term overflows through the M and T FRS are threatened.

Conclusions

Lateral channel migration, which involves both point bar deposition and concave bank erosion (fig. 2), can be predicted by meander bend radius of curvature. Long-term rates of channel migration (Eq. 2) vary from 57 to 73 percent of short-term rates (Eq. 1) in bends whose radius of curvature ranges from 381 to 838 meters. Ninety percent of bends cut off when the radius of curvature is less than 533 meters. Bend cutoffs can be expected to occur when the cutoff index values are between 1.7 and 3.7. Meander bend cutoffs can reduce upstream water-surface elevations by up to 1 meter, and therefore, overbank flooding is highly dependent on channel planform changes. The ability to predict changes in river planform and their effects on water-surface elevations provides a rational basis for managing the Sacramento River.

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