PREDICTING MODES AND MAGNITUDE OF RIVER CHANNEL MIGRATION AND CHUTE CUTOFF BASED ON BEND GEOMETRY, SACRAMENTO RIVER, CALIFORNIA, USA.

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ABSTRACT

Channel centerlines were mapped on a 160 km meandering alluvial reach of the central Sacramento River, California (from Red Bluff to Colusa) from historic topographic maps (1904) and aerial photographs (in 6 time periods between1937 and 1997). Centerlines were broken into individual segments (one bend of a two-bend meander sequence) and analyzed in a GIS for sinuosity, wave-length, radius of curvature and bend entrance angle. The mean meander shape was observed with average river sinuosity of 1.38 (related to a down valley axis), and the following average values for sinuous bends: half wavelength 1185 m (4.7 channel widths), radius of curvature 699 m (2.8 widths), and bend entrance angle 73 degrees.

Temporal changes in channel centerlines and bend geometry were tracked over the 93-year time interval. By intersecting sequential channel centerlines, modes and magnitudes of lateral channel change over time were measured. Bend movement was classified as progressive migration, chute cutoff and "partial cutoff". An average of 94% of channel length moved via progressive migration at a rate of 4.7 ± 0.5 m y^{-1}, 5% of the total channel length moved laterally via chute cutoff at a rate of 22.1 ± 3.3 m y^{-1} versus and the remaining 1% of channel length migrated via partial cutoff at an a rate of 13.0 ± 2.8 m y^{-1}.

The river channel length, beginning and ending in the same valley location, remained relatively constant from 1904 to 1997. This suggests that river length lost due to cut-off has been approximately made up for by progressive migration over the study period, but that the formation of high sinuosity bends susceptible to future cut-off may be on the decline.

The data show that geometric parameters can serve as a predictive indicator for modes (progressive migration, chute cutoff and partial cutoff) of channel change. Bends that experienced chute cutoff displayed an average sinuosity of 1.97 ± 0.1, an average radius of curvature of 2.1 ± 0.2 channel widths, and an average entrance angle of 111 ± 7 degrees, as opposed to average values for bends migrating progressively of 1.31 ± 0.01, 2.8 ± 0.1, and 66 ± 1 degrees (respectively). This suggests that the likelihood of a bend being prone to progressive migration versus chute cutoff on the Sacramento River may be estimated based on centerline geometry alone for a range of channel slopes typical of the meandering portion of the Sacramento River.

INTRODUCTION

River channel meander migration and cutoff processes drive the planform morphology and habitat attributes of floodplain rivers. Measuring and planning for channel change are some of the most important challenges for managing a meandering river corridor (Golet et al. 2006). These dynamic processes benefit ecosystem health. At the same time, conflict between natural river meander dynamics and infrastructure protection has led to the placement of channel riprap and groins to limit channel dynamics. Whether the goal is to promote channel dynamics for ecosystem health or to enhance channel stability, knowledge of the natural dynamics of river channel migration is critical. Studying long-term large-scale dynamics on a river over the scale of a century provides an important opportunity to quantify fundamental processes. In this study, maps of roughly 100 years of detailed river channel locations of the Upper Sacramento River (Figure 1) were used to analyze river channel changes. Documenting historical patterns provides a better understanding of the forces driving river channel migration.

Centerline morphology, migration, and cutoff

Sequential measurements of river bend planform geometry provide a way to quantify the morphology of a river and to study the changes in channel planform shape over time (e.g. Hickin and Nanson 1984, Hooke 1984, Gurnell 1997). Channel curvature is assumed to be related to the spatial distribution and the magnitude of channel migration (Hooke and Harvey 1983, Johannesson and Parker 1989, Furbish 1991, Larsen 1995). Empirically testing relationships between the patterns of the meandering channel and the channel geometry (Howard and Hemberger 1991)is key to predicting patterns of channel movement based on shape. Research efforts have linked the shape of river meander bends with the movement of bends. Hooke examined the shapes of meander bends and related subsequent movement with characteristic shapes. A recent model for predicting rates of meander migration was based on bend shape (Lagasse et al. 2004). More complex physically-based models use the planform shape in predicting the hydrodynamics (velocity patterns) that are directly related to bank erosion (Ikeda et al. 1981, Darby and Thorne 1996b, Langendoen et al. 2001, Darby et al. 2002). Large scale pattern changes on alluvial (self-formed) meandering rivers help inform both qualitative geomorphic theories and physically-based models that tend to “scale-up” from micro-scale processes (i.e. sediment transport.) Broad large-scale studies can help to identify thresholds for migration processes (i.e. distinguish between geometries that will evolve by cutoff versus by other processes), but it is likely that these relationships will need to be studies in individual case studies to identify the range of natural variation.

Channels move progressively and by cutoff processes. Both modes of channel change have been shown to be important in ecosystem health; both processes also pose challenges to planning, particularly with respect to land use and infrastructure placement. Three categories are used here to describe modes of channel migration observed on the Sacramento River: progressive migration, chute cutoff, and partial cutoff.

Progressive Migration

Progressive migration is lateral change that occurs via a continual but gradual process of bank erosion. Migration proceeds via erosion of the outside (concave in planform) bank and deposition of eroded material on bars located on the inside (convex in planform) bank (Lewin 1977, Ikeda et al. 1981, Knighton 1998). Under equilibrium conditions, rates of bank erosion and bar deposition are assumed equal. However in non-equilibrium cases where bar aggradation is accelerated, erosion may also be accelerated on the opposite bank, a hypothesis sometimes termed "bar push" (Personal communication Dietrich 2001). The mechanism of bank retreat when fine-grained floodplain deposits are underlain by a coarser gravel-cobble layer, as is common in this case, is usually the undermining of floodplain materials due to the concentration of shear forces causing erosion at the bank toe (Darby and Thorne 1996a, Micheli 2002). Forces acting at the bank toe may be expected to increase with flow depth up to an effective maximum at bankfull.

The rate of progressive migration is generally assumed to increase with centerline curvature up to some threshold (Hickin 1983). Numerical models of progressive migration estimate that the maximum rate of bank erosion will coincide with the location of the peak differential between mean and near-bank velocities, generally lagging somewhat behind the location of peak channel curvature in the latter half of a meander bend (Ikeda et al. 1981, Furbish 1991). Over time, progressive migration may increase the sinuosity and/or cause the downstream translation of a meander bend, but empirical observations show this is not always the case on the Sacramento River, since in some cases (perhaps due to influences that are outside the channel) progressive migration has been observed to actually straighten the channel over time (Micheli 2000).

Chute and Partial Cutoffs

The majority of observed cutoffs on the Sacramento River occur via chute cutoff, a channel avulsion that occurs when overbank flows are sufficient to concentrate shear stresses to a degree capable of carving a new channel across the floodplain (Hooke 1984, 1995, Micheli and Larsen In prep.). This study examines the hypothesis that chute cutoffs form where the centerline has reached a threshold geometry (in terms of radius of curvature, sinuosity, and entrance angle). A related hypothesis not discussed here is that cutoff occurs only when extended periods of overbank flow provide sufficient stream power to excavate a channel across the floodplain.

The partial cutoff category describes episodes of channel avulsion that affect only a portion of a meander bend (Fares and Herbertson 1990).

Analysis of Centerline Geometry

One hypothesis about the relationship between progressive migration and cut-off is that progressive processes generally adds sinuosity to meander bends while cut-off processes reduce sinuosity and reset the cycle of bend generation. Thus, maintaining a constant centerline sinuosity over time may imply an approximate balance between rates of lateral migration due to progressive migration versus cut-off. However, other field studies of rivers in the western US have indicated that disturbances that decrease the effective cohesion of floodplain and bank materials can serve to accelerate bank migration rate in a manner that effectively straightens the channel centerline and resulting in longer, less sinuous bends, as observed on Nevada’s Lower Truckee River (Micheli 2000). The geometry of meander bends of the whole river were examined in order to track any potential changes over time and to test for correlations between bend geometry related to modes and magnitudes of channel change. Here, 93 years of bend shape data are used to distinguish between geometries (sinuosity, wave-length, curvature, and entrance angle) that will evolve by progressive migration versus by cutoff processes.

SITE DESCRIPTION

Location

The Sacramento River (Figure 1) is the largest river in the state of California and drains an area of 2,305,100 ha, more than half of the total drainage area of the San Francisco Bay. Collecting precipitation and snowmelt runoff from the western slopes of the Sierra Nevada, the eastern slopes of the Coast Range, and the southern Trinity and Klamath ranges, the river drains 17 percent of the land in California and flows from north to south with a length of about 483 km, ultimately discharging into the Pacific Ocean by way of San Francisco Bay.

The length of the river has been measured using various reference systems, of which the most common one is a set of “river mile” (RM) markers established by the U.S. Army Corps of Engineers (USACOE) in 1964. According to this system, the river extends from the confluence of the Sacramento and San Joaquin Rivers (RM 0) at the San Francisco Bay to near Shasta Dam (about RM 312) (Figure 1). The lower half of the river (from San Francisco Bay to the town of Colusa at RM 143) is limited by artificially installed channel constraints, while the upper half, from Colusa to Red Bluff (RM 143-244), is relatively free to meander, though riprap has been installed on this reach in the second half of this century. Our study was located in this upper half that is relatively free to migrate.

Geologic setting

The Sacramento River flows south through the Sacramento Valley over sedimentary rocks and recent alluvium. The Sacramento Valley is a structurally controlled basin between the Cascade and Sierra Nevada Mountains to the east and the Coast Ranges of California to the west (Harwood and Helley 1987).

Four major tectonic units comprise the Sacramento River watershed: 1) the Great Valley sedimentary sequence, located in the Coast Range; 2) the Franciscan formation, also part of the Coast Range; 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 of Pliocene-Recent extrusive volcanic activity, located to the northeast of the river in the Southern Cascades. There are also areas of 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 that are deposited into the Sacramento River from creeks is directly related to the surrounding tectonic units (Robertson 1987).

The reach between Red Bluff and Colusa (i.e. from RM 244 to RM 143) 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 and 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 typically composed of sand and gravel with isolated patches of erosion-resistant rocks of Modesto or Riverbank formation. Between RM 240 and RM 185, the average bank height from thalweg to top of the bank varies from 2 to 8 m with the mean of 4 m (CDWR 1994).

The Pliocene-Pleistocene deposits comprising the banks and floodplain of the Sacramento River are variable in terms of bank "erodibility." Erodibility refers to the relative resistance of bank materials to lateral migration and can be expressed as a coefficient for use in numeric meander models (Johannesson and Parker 1989, Larsen 1995, Micheli et al. 2004). Channel banks are typically composed of sand and gravel with isolated patches of erosion-resistant bedrock of the Modesto or Riverbank formations, terrace deposits typically consisting 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 Modesto formation is younger than the Riverbank formation and is usually less than 2.5 m thick and composed of gravel, sand, silt, and clay (CDWR 1994). Where Riverbank and Modesto are exposed, reduced rates of bank erosion and channel migration have been observed (Fischer 1994, Larsen and Greco 2002).

METHODS

Quantifying River Geometry over Time Using GIS techniques

Observing changes in channel centerline data over time is a tested method of quantifying transitions in river geometry and measuring the lateral movement of a river channel over time (e.g.Brice 1977, MacDonald et al. 1991, Gurnell et al. 1994, Brewer and Lewin 1998, Dietrich et al. 1999, Larsen et al. 2002, Micheli et al. 2004). Performing these analyses using Geographic Information System (GIS) tools allows for automating measurements promptly, archiving results efficiently, and specifying a repeatable protocol.

Digitizing channel centerlines

Channel centerlines used in this study were derived from historic channel bank locations (banklines) (Greco and Alford 2003a, b). Using georeferenced aerial photos, planform maps showing channel locations were digitized into a geographic information system (GIS) database. A detailed description of the channel mapping process can be found in Greco and Plant (2003) and Greco et al. (2003). Channel bank lines were mapped on clear acetate layered over the aerial photographs. The banklines were then scanned, vectorized, and projected into real-world coordinates using ArcGIS software (ESRI 2003) with control points derived from USGS orthophoto quadrangles. From these geo-referenced line files, lateral-change polygons were generated by intersecting the centerline for each pair of sequential time steps.

The bankline data spanning from 1904 to 1997 were obtained from two types of map sources, USGS topographic maps (1:68,500) for 1904 banklines and aerial photography scaled primarily at a scale of 1:10,000 or larger for the remaining years. Where possible, similar discharge magnitudes were used for plotting banklines from which channel centerlines were determined. In doing so, the apparent changes of bank locations due to flow variation instead of channel migration were minimized. (For example, a river at flood stage will appear wider and less sinuous than when it is contained within low-flow channel banks). Most air photo surveys were taken during discharges ranging between 57 cms (2000 cfs) and 85 cms (3000 cfs), which were significantly lower than the estimated "bankfull" discharge 2265 cms (i.e. 80,000 cfs). Since low-flow centerlines tend to track channel thalwegs, these centerlines tend to reflect the location of the high velocity core at higher flows which corresponds with the magnitude of shear stresses occurring on the banks.

Channel centerlines were subsequently digitized on-screen in ArcView by estimating the location of the line midway between banklines. Because our objective was a single strand centerline, occasional reaches split by bars or islands were mapped as a single channel. In these locations, mid-channel bars were ignored if their widths were less than the average channel width at a straight reach, and if the bar appeared that it would be inundated at flows approximating bankfull. If mid-channel bar widths were wider than the average channel width, the widest strand of the split channel was assumed to be dominant and the centerline was mapped down the center of that strand.

Analyzing geometric properties of centerlines

A suite of geometric attributes were measured on each of the channel centerlines in our study. A mathematical algorithm was used to calculate curvature values every 0.25 channel widths (approximately every 60 meters) along centerlines for each year (e.g. Johannesson and Parker 1989). An ArcView script was used to analyze the curvature for identifying inflection points (where curvature changes sign). Initially, the entire length of a centerline was broken into “segments” strictly defined as a section between two mathematically identified inflection points. Second, small segments (less than 2 channel widths) were manually merged with their neighbors to form channel segments were greater than 2 channel widths. In this way, the entire river length was composed of the sum of the segments.

Once the segments were identified, attributes were measured using the ArcView script. Half wavelength ($\lambda/2$) is defined as the straight-line distance between the two inflection points of a bend, and sinuosity is defined as the ratio of the curved arc of a channel bend to the half wavelength (Figure 3).The entrance angle (θ) was defined as the angle between the line connecting inflection points of a segment and a tangent to the channel at the upstream inflection point (Figure 3). The mean radius of curvature was defined to be the mean of the sum of curvature values at every node (every 0.25 channel widths) between the two inflection points defining a segment. Segments that had sinuosity equal to or less than 1.1 were designated as straight channel sections (Wolman and Leopold 1957) and not included in the analysis of individual “bends.”

In fluvial geomorphology, channel features such as wavelength and curvature can be effectively normalized by channel width as a non-dimensional parameter to facilitate the comparison with rivers of different scales. In the study reach, a mean bankfull width (W) of 250 m was used to normalize the half wave-length and radius of curvature of these Sacramento River bends, producing the dimensionless mean wavelength ($\lambda/2W$), and dimensionless mean radius of curvature (R/W). This width was a mean average width taken from the Corps of Engineers HEC-RAS (Hydrologic Engineering Center - River Analysis System 2003) model of the Sacramento River. Previous studies of the Sacramento River used characteristic widths ranging from 235 m to 360 m (Larsen and Greco 2002, Larsen et al. 2006c). An analysis of trend in width as a function of river mile or as a function of time was not done. The analysis of the changes of the river geometry over time would require data on width over time, which is not available for the study reach.

Parameters were measured for all segments, and separated into categories. Chute and partial cutoffs were identified from channel planforms (Figure 2) (Micheli and Larsen In prep.) In addition, bends that did not experience cutoff but had similar sinuosity to the ones that experienced cutoff (sinuosity > 1.85) were classified into a separate class (table 3).

For a comparison of channel length and sinuosity in different years, a "clipped" channel length was established (Table 1). This was done because channel centerlines in each of the 7 years for the complete study did not begin and end at exactly the same location. The modified channel lengths were measured from "clipped segments" that began and ended at the same locations (when projected onto the valley axis that is described below). For this length, the associated clipped valley length was 104 km. The clipped length was used for comparisons of channel length and sinuosity between years.

The sinuosity of the whole channel reach was calculated in two ways, bend-by-bend, and by valley length, both of which used "clipped lengths". For the sinuosity measured "bend-by bend" the sum of the arc length along the channel was divided by the sum of the straight line lengths between inflection points. The sinuosity was also measured as the quotient of the arc length of the channel divided by the valley length. Because the valley length was less sinuous (therefore shorter) than the sum of the straight lines between inflection points, the sinuosity measured using the valley length is greater than the bend-by-bend derived sinuosity.

Linking bend geometry to subsequent channel movement: progressive migration versus chute cut-off

Superimposing a temporal sequence of centerlines derived from channel planform maps is a common approach to detecting patterns of lateral channel change, including progressive migration and river channel cutoffs (e.g. Brice 1977, MacDonald et al. 1991, Gurnell et al. 1994, Gurnell 1997, Brewer and Lewin 1998, Dietrich et al. 1999, Larsen et al. 2002, Larsen et al. 2004, Micheli et al. 2004). Chute cutoff, partial cutoff, and progressive migration are described in Micheli and Larsen (In prep.)

The "lateral change polygons" were categorized, based on an inspection of the aerial photography used to map channel centerlines, as one of four categories: progressive migration, channel cutoff (both chute and partial), and stable "high sinuosity" bends. The geometric attributes of bends in each of these categories were tabulated and graphed for each time period (Figure 5.)

Lateral change polygons were created by intersecting sequential channel centerlines and used to calculate rates of lateral channel change based on the methodology of Larsen et al. (2002) and Micheli et al. (2004). Lateral migration was measured by mapping sequential channel centerlines in an ArcInfo software environment and by quantifying the change in location of a channel centerline over time using a unit called the 'eroded-area polygon'. An eroded-area polygon is created by intersecting two channel centerlines mapped at two different points in time (Larsen et al. 2002, Micheli et al. 2004). This approach is similar to that applied by MacDonald et al. (1991) to a set of Minnesota streams. ArcInfo calculates the area and perimeter of the eroded polygon, from which the 'average distance migrated perpendicular to the channel centerline' was calculated. The lateral migration distance is equal to the polygon area divided by the average stream length for the polygon (with average stream length equal to one-half of the polygon perimeter).With the aid of a GIS, this eroded-area polygon method may be easier to reproduce than alternative methods such as Hickin orthogonal mapping (Hickin and Nanson 1975, Hickin 1984).

For progressive migration, this method tends to provide a conservative estimate of migration because migration polygons measured in this manner often do not capture the entire area of reworked floodplain. This error may be reduced by reducing the length of time interval between photo sets. For cutoffs, this method provides an estimate of the extent of the lateral change of the channel. In the case of progressive migration, the lateral change is also an estimate of the area reworked; for cutoffs, it is not.

RESULTS

Total segments

The historical planform change of the study reach was analyzed by using seven (clipped) channel centerlines dated between 1904 and 1997. Figure 4 shows the extent of the reach and the centerlines for 1904 and 1997. There were 706 separate segments identified from all seven years of clipped centerlines (Table 1). Of these segments, 398 were bends with sinuosity greater than1.1 (308 were segments with sinuosity less than or equal to 1.1).

Sinuosity

The sinuosity of the whole channel reach when measured over the “clipped” channel length, and using the valley axis as the datum, ranged from a low of 1.36 to a high of 1.41 with a mean of 1.38 (Table 1). The segment average sinuosity (in each year) ranged from a low of 1.24 to a high of 1.28, with a mean average of 1.26 (Table 1). The clipped channel length ranged over time from 141 to 147 km with a mean length of 143 km. The length of the sum of the individual straight segments (sinuosity < 1.1) varied from 38 to 50 km with a mean length of 46 km (Table 1). The percentage of stream length that was straight (<1.1 sinuosity) was roughly one-third.

The number of rare highly sinuous bends (sinuosity greater than 2.5) has been steadily declining over time. In 1904 there were four bends with sinuosity greater than 2.5; since 1978, there has been only one (Table 1.) This suggests that river length lost due to cut-off has been approximately made up for by progressive migration over the study period, but that the formation of high sinuosity bends susceptible to future cut-off may be on the decline.

Bend geometry properties of channel centerlines

The analyses of geometric parameters for individual bends was done using the clipped channel lengths. When bends inside the “clipped” area were measured, 398 separate bends were analyzed (Table 2) with the following results. Between 1904 and 1997, the average half wavelength ($\lambda/2$) varied from a low of 1077±70 to a high of 1257±66 m (4.3+/-0.3 widths to 5.0±0.3 widths) with a mean of 1185±25 m (4.7±0.1 widths). The mean sinuosity (M/L) of individual bends in each time period varied from 1.38±0.04 to 1.45±0.05 with a mean of 1.43±0.02. The mean radius of curvature (R) varied from 627±40 m to 767±40 m (2.5±0.2 widths to 3.1±0.2 widths) with the mean of 699±14 m (2.8±0.1 widths). The entrance angle θ varied from 69±3 degrees to 78±4 degrees with a mean of 73±1 degrees (Table 2). The average bend sinuosity remained essentially constant during the entire period and the other three geometric attributes varied only slightly over time (figure 5). In general, the average geometric properties of all sinuous bends did not change significantly for roughly 100 years.

Geometric attributes of cutoff versus progressively migrating bends

Geometric attributes of delineated meander bends provide a basis for correlating channel centerline geometry to subsequent modes of channel change (Table 3). Bends that experienced chute cutoff displayed an average sinuosity of 1.97 ± 0.1, an average radius of curvature of 2.1 ± 0.2 channel widths, an average half-wavelength of 3.7 ± 0.4 channel widths, and an average entrance angle of 111 ± 7 degrees, as opposed to average values for bends migrating progressively of 1.31 ± 0.01, 2.8 ± 0.1, 4.7 ± 0.1 and 66 ± 1 degrees (respectively). The typical geometry of bends that migrated via chute cutoff is found to be distinctively different from bends that migrated progressively in terms of sinuosity (50% higher), radius of curvature (29% smaller), wavelength (21% shorter), and entrance angle (68% higher). The average sinuosity of chute cutoff bends was also 40% higher than the average bend sinuosity (1.43 ± 0.10) of partial cutoffs. A comparison of partial cutoffs and progressive migration bends reveals no significant difference in half wavelength, but differences of 9% lower sinuosity, 18% higher radius of curvature, and 17% lower entrance angles for progressive migration bends (Table 3). Thus, average bend geometries show clear distinctions between chute cutoff and progressive migration bends, with partial cutoffs occurring at intermediate values that are still distinctive from progressive migration in terms of sinuosity, radius of curvature, and entrance angle.

Comparing the average planform geometry of cutoff bends with high-sinuosity bends (sinuosity > 1.85 channel widths) that remained stable (i.e. no cutoff) over each time interval provides a starting point for evaluating the usefulness of centerline data for predicting the likelihood of potential cutoff (Table 3). Stable bends in excess of 1.85 sinuosity displayed an average sinuosity (2.2 ± 0.1) just slightly higher than that of chute cutoffs, so a sinuosity threshold alone is not a good indicator of cutoff likelihood. Stable sinuous bends also displayed similar values for wavelength compared to both chute and partial cutoffs. The average mean entrance angle for chute cutoffs and stable sinuous bends were essentially equal (111 ± 7 and 112 ± 4 degrees, respectively), and significantly higher than that measured for partial cutoff bends (77 ± 9 degrees). However, the dimensionless mean radius of curvature (R/w) for chute cutoffs (2.1 ± 0.2) was consistently lower than that measured for stable sinuous bends (2.5 ± 0.1).

Figure 6 shows how average bend geometries for cutoffs versus progressive migration and stable sinuous bends varied over time by plotting average values for each time interval (Table 3). Except for an anomalously high dimensionless mean half wavelength ($\lambda/2w$) for a single partial cutoff in the first time period (1904-1937), cutoffs display consistently shorter wavelengths than progressive migration bends, with stable high sinuosity bends generally intermediate between cutoffs and progressive bends. A similar trend is evident for dimensionless radius of curvature. Entrance angles are consistently higher for stable sinuous bends that progressive migration bends, with chute cutoff values wavering between these two data sets in the range of 71 to 124 degrees. The data show a dip in average half wavelength, radius of curvature, and entrance angle for the two time intervals between 1952 and 1978 for both types of cutoffs, coinciding with periods of greatest cutoff activity. One observation is a trend towards increasing radius of curvature and wavelength for both chute cutoffs and progressive migration bends since the mid 1960s.

A comparison of extent and rate of lateral channel change via cutoff versus progressive migration

The majority of lateral channel change on the Sacramento River has occurred via progressive migration rather than channel cutoff. While an average of 94% of the total stream length migrated via progressive migration, 5% migrated via chute cutoff and only 1% migrated via partial cutoff (Table 4). However, the rate of floodplain area reworked by progressive migration (0.617 ± 0.07 km^2 y^{-1}) was only 4.4 times greater than the rate of floodplain area cutoff (0.14 ± 0.02 km^2 y^{-1}). The greater ratio of floodplain affected by cutoff is because per unit stream length migrated, cutoff results in much larger increments of lateral change than progressive migration, with chute cutoffs creating on average 22.1 ± 3.3 m y^{-1} lateral change versus average progressive migration rates of 4.7 ± 0.5 m y^{-1} over the same period (Table 4). However, trends in progressive migration drive average migration rates for the whole river, with an average lateral migration rate of 5.5 ± 0.6 m y^{-1} for progressive migration and cutoff combined.

Temporal trends in rates of progressive migration versus cutoff are displayed in Figure 7. In general, trends towards increased or decreased migration rates between successive time-steps via progressive migration and cutoff are synchronized. However, the average lateral migration rate per unit stream length is not well correlated, since two time-steps (1952 to 1964 and 1964 to 1978) showed inverse trends for progressive migration versus cutoff (with cutoff rates increasing in the earlier time step while progressive migration rates declined, and vice versa for the latter). Figure 7B shows a trend towards increasing rates of lateral migration attributable to cutoff over this time period. Thus, while the linear extent of river experiencing cutoff decreased over the study period, the average rate of lateral change per cutoff event has increased.

DISCUSSION

Water diversion, flow regulation, and flow thresholds: impact on migration rates

Water diversion and flow regulation of the Sacramento River channel over time has influenced channel migration rates and the area of floodplain reworked. Water diversions reduce the amount of stream power acting on the channel banks, while flow regulations redistribute large fluctuating winter flows to constant low flows during the summer and fall months. This water is held behind the dam and let out during the dry months. These summer flows tend not to cause significant migration (Buer 2005). For this reason, one can consider there to be a “threshold” of flow magnitude below which there is effectively no migration. It is difficult to separate the effect of water diversion and flow regulation; however, it is clear that flow regulation has had a significant impact on migration rates through the annual redistribution of flows. As a greater percentage of flows are below the threshold for migration, migration rates may be reduced.

The contributing factors to channel migration patterns are complex. Where flow regulation and channel constraints reduce migration rates, some management actions like vegetation clearing increase it. Isolating the effect on channel migration by type of impact and amount would allow a fuller understanding of migration processes that would benefit environmental assessment and potential restoration/mitigation strategies. In particular, it would be important to identify the locations of channel constraints, and to study the historic migration patterns of individual bends, including the information on whether or not the channel was restrained, and when this occurred.

Removing channel restraint versus changing flow patterns: implications for magnitude of channel migration

Changing flow patterns (volume, peak, duration, and timing) affects the pattern of meander migration. A previous study linked the cumulative excess streampower with the magnitude of bank migration (Larsen et al. 2006b). Using the results of that study, a variable flow model was used to predict the potential effects of water diverted from the Sacramento River by the potential installation of a new reservoir (Larsen et al. 2006a). The study results showed that the potential flow management scenarios resulted in a 1-8 % reduction in land reworked. The magnitude of change in migration rates with diversion scenarios directly reflected the magnitude of changes in stream power.

Although a 1-8% impact is significant, especially considering it would be due to a single water reclamation project, it is considerably less than the impacts of bank protection projects (e.g., rip-rap and groins) on river meander migration patterns. Larsen et al (2006c) found that replacing current bank protection projects on one reach of the Sacramento River with setback levees 300-700 m from the river channel could result in a 370-550% increase in land reworked. Knowing how changes in flow and changes in bank restraint effect channel migration rates allows for effective assessment of environmental impacts and benefits related to management scenarios. For example, land managers would be able to assess how many kilometers of rip-rap would need to be removed at given locations to offset the impact of water management scenarios. Meander migration simulations, used to model the effects of changing flows and channel restraints, are effective in considering mitigation strategies for any actions that impact channel migration.

The effects of land conversion and sediment transport on meander migration rates

Research related to the effect of land conversion on migration rate has shown that the central reach of the Sacramento River tends to migrate more quickly through agricultural land than through riparian forest (Micheli et al. 2004). Removal of riparian forest vegetation appears to accelerate migration rates and increase bank erodibility by 80 to 150%. The overall erodibility of the floodplain tends to correlate with the mean migration rate in the same floodplain. Although bank migration is related to the magnitude of the near-bank velocity, variations in calculated near-bank velocity are generally much less than measured migration rates. Thus, although one needs to consider near-bank velocity variations when considering the relationship between bank erodibility and migration rate, calculation of mean migration rates alone may reflect differences in floodplain erodibility when measured over a suitable length.

It is unclear how variations in sediment transport due to mining, dam installation, and other channel alterations may have influenced historical rates and patterns of meander migration.

It is possible that increased sediment transport rates can increase deposition on point bars which can induce "topographic steering" or a "bar-push" effect (Nelson and Smith 1989) that can increase bend migration rates locally. In areas of decreasing sediment transport, there may be a tendency for less progressive lateral migration and an increased tendency for cutoff (Singer 2006).

Summary of discussion

Migration rates and cutoff tendencies, as measured in this study, are affected by flow variations including the effects of changing frequency, timing and duration of flow. Other influences on bank erosion rates include bank stabilization, land conversion from riparian forests to agriculture, and sediment transport. In detailed studies of site-specific bends, or in restoration or mitigation plans, it may be important to "parse out" the contributions of each of these effects and their relative magnitude. The migration rates and cut-off tendencies reported here for 100 miles of river over almost a full century may serve as a frame of reference for such site-specific considerations.

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Sacramento River Watershed
Shasta Dam
Red Bluff
Study reach
Colusa
Sacramento
California
S.F. Bay
N
Kilometers
0
25
50
100

Figure 1

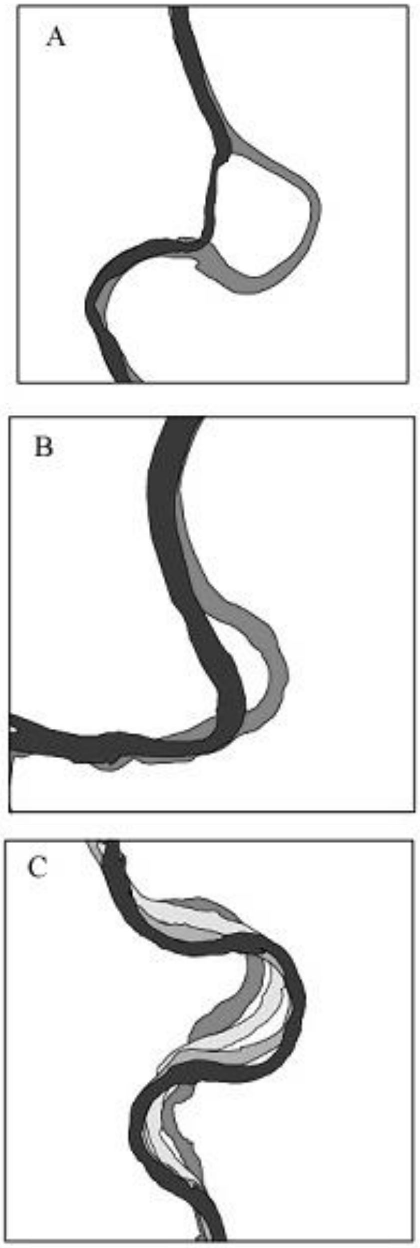

Figure 2

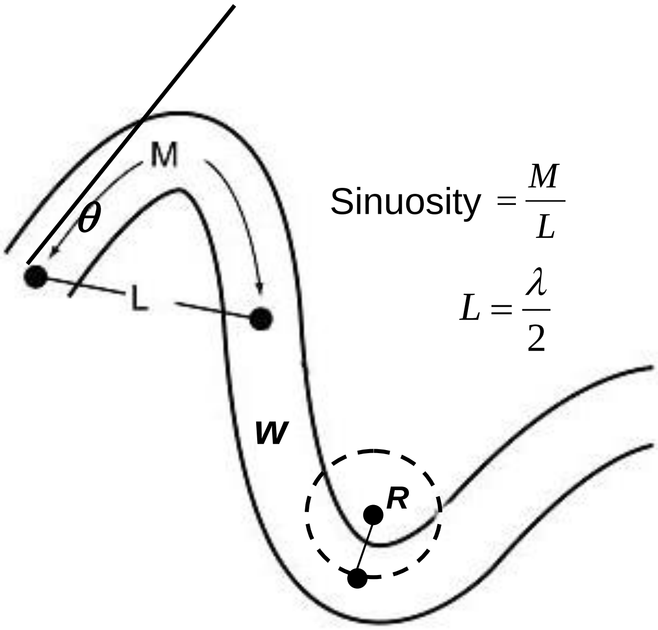

Figure 3
Definition of terms for a single bend. L is the "half wavelength."

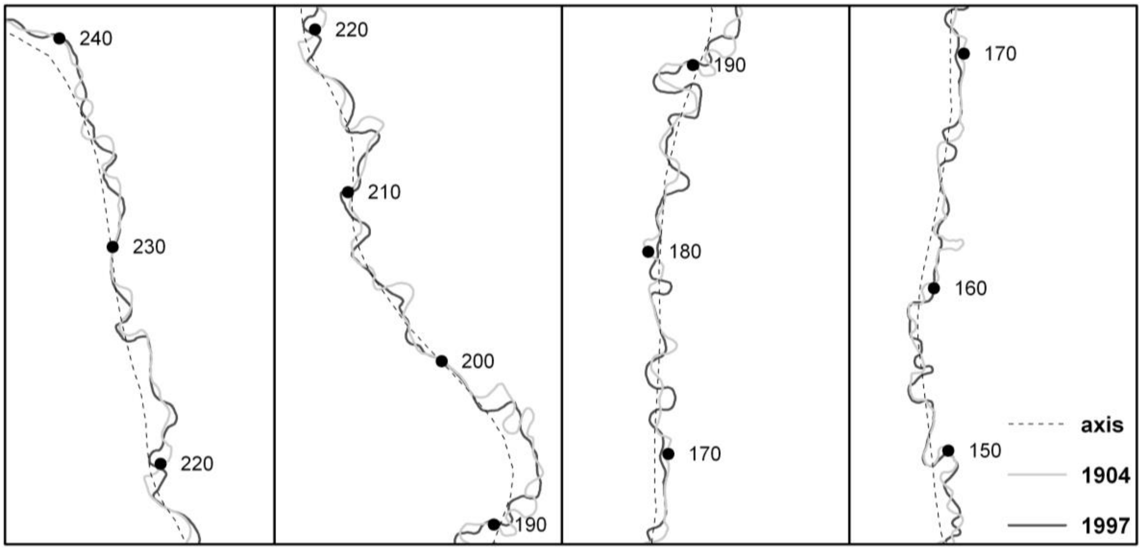

Figure 4
Channel centerlines for 1904 and 1997 from RM 145 to RM 240.

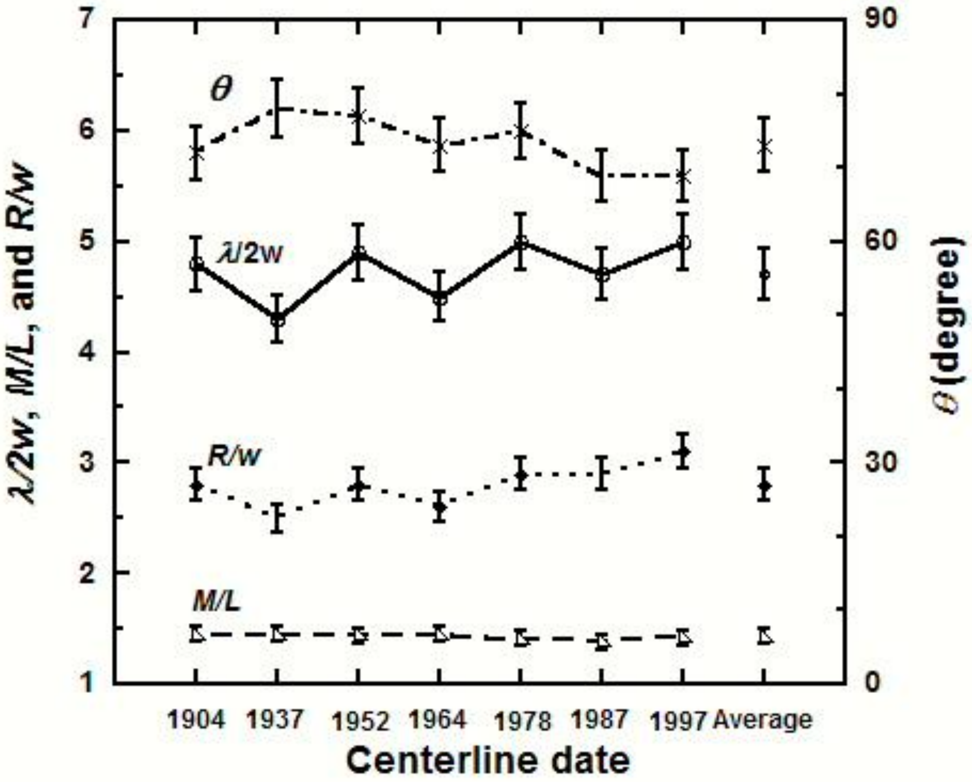
θ
λ/2w
R/w
M/L
7
6
5
4
3
2
1
90
60
30
0
λ/2w, M/L, and R/w
θ (degree)
1904
1937
1952
1964
1978
1987
1997
Average
Centerline date

Figure 5

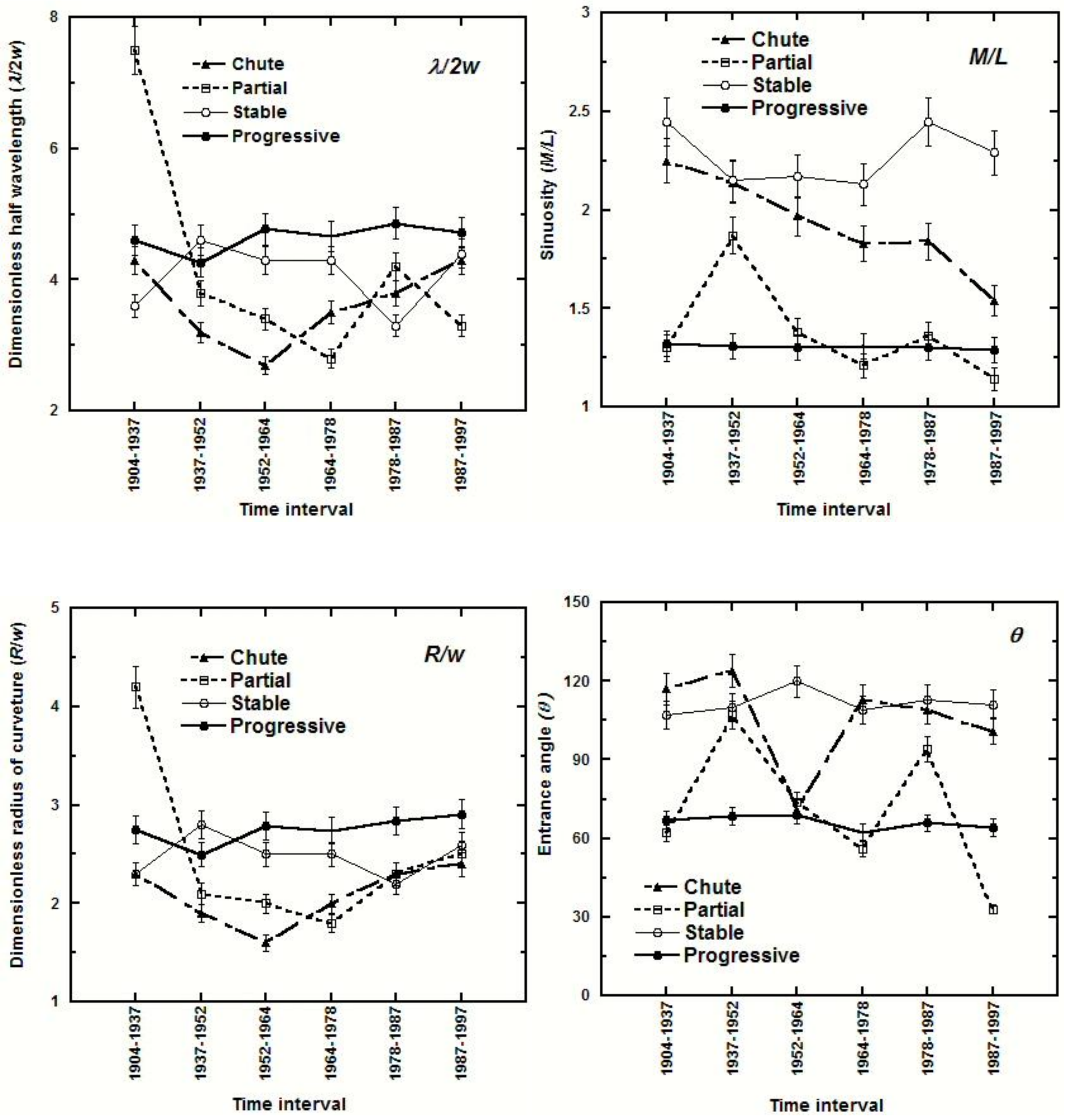
λ/2w
Dimensionless half wavelength (λ/2w)
2
4
6
8
Chute
Partial
Stable
Progressive
M/L
Sinuosity (M/L)
1
1.5
2
2.5
3
R/w
Dimensionless radius of curveture (R/w)
1
2
3
4
5
θ
Entrance angle (θ)
0
30
60
90
120
150
1904-1937
1937-1952
1952-1964
1964-1978
1978-1987
1987-1997
Time interval

Figure 6

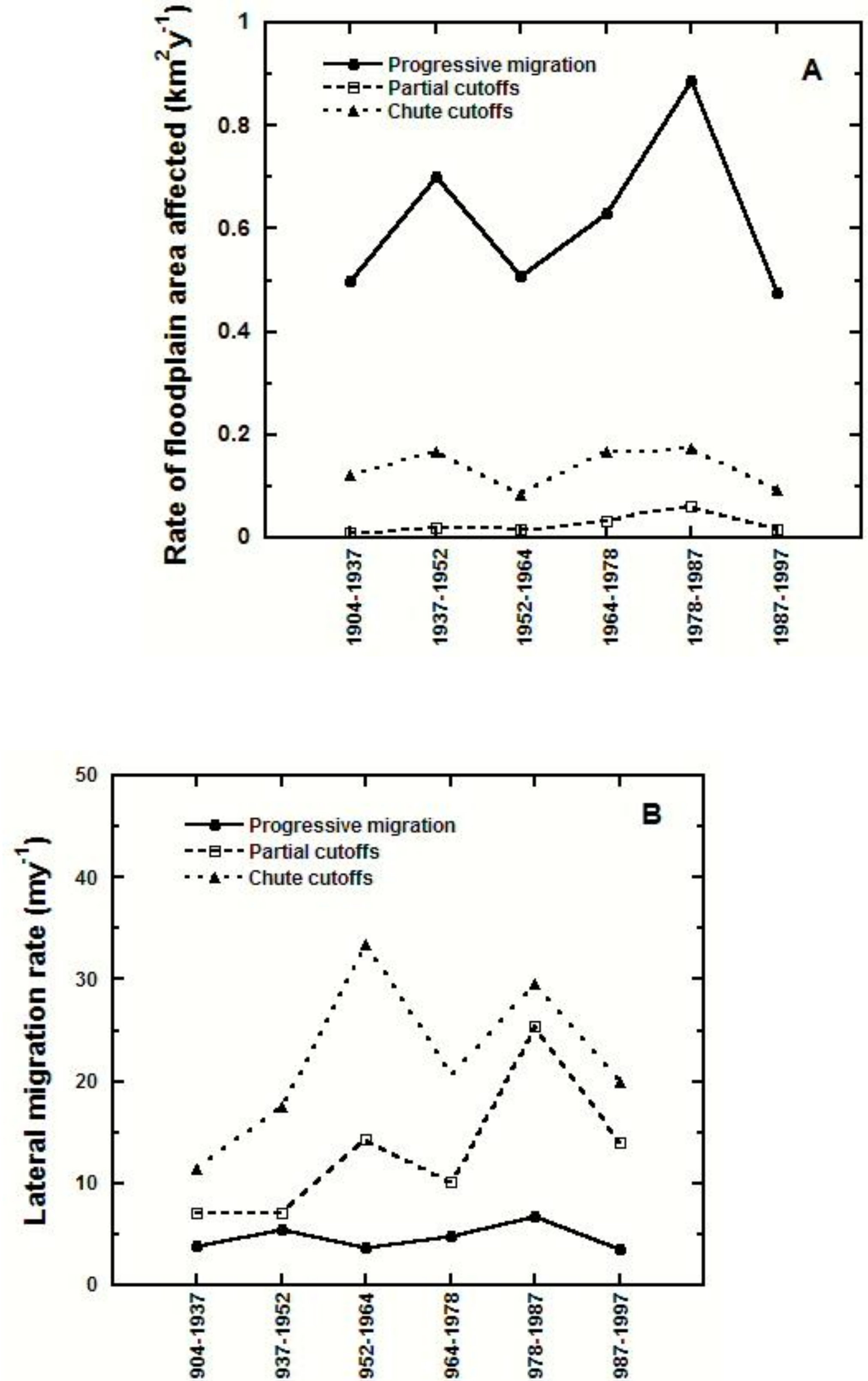
A
Rate of floodplain area affected (km^2y^{-1})
Progressive migration
Partial cutoffs
Chute cutoffs
0
0.2
0.4
0.6
0.8
1
1904-1937
1937-1952
1952-1964
1964-1978
1978-1987
1987-1997
B
Lateral migration rate (my^{-1})
Progressive migration
Partial cutoffs
Chute cutoffs
0
10
20
30
40
50
1904-1937
1937-1952
1952-1964
1964-1978
1978-1987
1987-1997

Figure 7

Table 1. Sinuosity values of all segments measured between valley km 78 and 182 (valley length is constant)

Year	Total stream length (km)	Number of segments	% stream length > 1.1 bend sinuosity	Sinuosity: with respect to valley axis	Sinuosity: segment average	Maximum segment sinuosity	Sinuosity: □-weighted bend average	Number of segments With M/L > 2.5
1904	146.8	104	69.8	1.41	1.28±0.04	3.34	1.26	4
1937	143.1	103	64.9	1.37	1.28±0.03	2.64	1.27	3
1952	140.8	101	65.6	1.37	1.25±0.03	2.68	1.27	2
1964	141.8	107	73.3	1.36	1.24±0.03	2.82	1.25	2
1978	144.2	101	65.4	1.39	1.24±0.03	3.13	1.24	1
1987	142.2	100	68.5	1.38	1.25±0.03	2.73	1.25	1
1997	141.1	90	68.1	1.36	1.27±0.03	2.73	1.26	1
Average	142.9±0.8	101±2	67.9±0.01	1.38±0.01	1.26	2.87±0.1	1.26±0.00	

Table 2 The geometric properties of sinuous bends (sinuosity > 1.1) measured between valley km 78 and 182

Year	Number of sinuous bends	Half meander wavelength $\lambda/2$ (m)	Dimensionless half meander wavelength ($\lambda/2w$)	Mean Sinuosity (*M/L*)	Mean radius of curvature *R* (m)	Dimensionless mean radius of curvature (*R/w*)	Mean entrance angle θ (degrees)
1904	61	1204±66	4.8±0.3	1.45±0.06	710±38	2.8±0.2	72±3
1937	60	1077±70	4.3±0.3	1.45±0.05	627±40	2.5±0.2	78±4
1952	53	1222±71	4.9±0.3	1.44±0.05	707±38	2.8±0.2	77±4
1964	53	1133±76	4.5±0.3	1.45±0.05	660±40	2.6±0.2	73±4
1978	55	1246±62	5.0±0.2	1.41±0.05	715±33	2.9±0.1	70±4
1987	61	1163±57	4.7±0.2	1.38±0.04	713±36	2.9±0.1	69±4
1997	55	1257±64	5.0±0.3	1.42±0.05	767±40	3.1±0.2	69±3
Total	398	-	-	-	-	-	-
Average	57	1185±25	4.7 ± 0.1	1.43 ± 0.02	699±14	2.8 ± 0.1	73 ± 1

Table 3. Geometric properties cutoff, stable, and progressive migration bends (average values shown in bold for each category), Central Sacramento River, 1904-1997. Values shown ± standard error.

Bend category	Time interval	Number of Bends	Dimensionless mean half channel wavelength (□/2*w*)	Mean Sinuosity	Dimensionless mean radius of curvature (*R*/*w*)	Mean entrance angle □□□(degrees)
Chute cutoffs N=27	1904-1937	6	4.3 ± 1.1	2.25 ± 0.35	2.3 ± 0.4	117 ± 5
	1937-1952	6	3.2 ± 0.5	2.14 ± 0.28	1.9 ± 0.3	124 ± 18
	1952-1964	2	2.7 ± 1.7	1.97 ± 0.13	1.6 ± 1.0	71 ± 9
	1964-1978	6	3.5 ± 0.8	1.83 ± 0.18	2.0 ± 0.4	113 ± 17
	1978-1987	4	3.8 ± 0.2	1.84 ± 0.18	2.3 ± 0.8	110 ± 24
	1987-1997	3	4.3 ± 1.3	1.54 ± 0.23	2.4 ± 0.5	101 ± 20
		4.5	**3.7 ± 0.4**	**1.97 ± 0.1**	**2.1 ± 0.2**	**111 ± 7**
Partial cutoffs N=11	1904-1937	1	7.5	1.3	4.2	62
	1937-1952	3	3.8 ± 1.5	1.87 ± 0.27	2.1 ± 1.0	107 ± 14
	1952-1964	1	3.4	1.38	2	74
	1964-1978	3	2.8 ± 1.0	1.21 ± 0.04	1.8 ± 0.6	56 ± 8
	1978-1987	2	4.2 ± 0.3	1.36 ± 0.09	2.3 ± 0.1	94 ± 8
	1987-1997	1	3.3	1.14	2.5	33
		1.83	**3.8 ± 0.6**	**1.43 ± 0.1**	**2.3 ± 0.3**	**77 ± 9**
Stable high-sinuosity bends (*M*/*L*>1.85) N=35	1904-1937	5	3.6 ± 0.5	2.45 ± 0.20	2.3 ± 0.1	107 ± 13
	1937-1952	6	4.6 ± 0.6	2.15 ± 0.11	2.8 ± 0.5	110 ± 11
	1952-1964	9	4.3 ± 0.5	2.17 ± 0.09	2.5 ± 0.3	120 ± 10
	1964-1978	6	4.3 ± 0.4	2.13 ± 0.14	2.5 ± 0.1	109 ± 6
	1978-1987	4	3.3 ± 0.7	2.45 ± 0.26	2.2 ± 0.4	113 ± 16
	1987-1997	5	4.4 ± 0.8	2.29 ± 0.12	2.6 ± 0.4	111 ± 15
		5.83	**4.1 ± 0.2**	**2.24 ± 0.1**	**2.5 ± 0.1**	**112 ± 4**
Progressive migration bends N=328	1904-1937	60	4.6 ± 0.3	1.32 ± 0.02	2.8 ± 0.2	67 ± 3
	1937-1952	54	4.3 ± 0.3	1.31 ± 0.01	2.5 ± 0.2	69 ± 4
	1952-1964	55	4.8 ± 0.3	1.30 ± 0.02	2.8 ± 0.2	69 ± 4
	1964-1978	50	4.7 ± 0.4	1.31 ± 0.03	2.7 ± 0.2	62 ± 3
	1978-1987	57	4.9 ± 0.3	1.30 ± 0.02	2.8 ± 0.1	66 ± 3
	1987-1997	52	4.7 ± 0.3	1.29 ± 0.02	2.9 ± 0.2	64 ± 3
		54.7	**4.7 ± 0.1**	**1.31 ± 0.01**	**2.8 ± 0.1**	**66 ± 1**

Table 4. A comparison of lateral channel change due to cutoff versus progressive migration

Time Interval	Average lateral change rate (m y^{-1})	% Length moved via			Rate of floodplain area affected (km^2 y^{-1}) via			Lateral migration rate (m y^{-1}) via		
		pro-gressive	partial cutoff	chute cutoff	pro-gressive	partial cutoff	chute cutoff	pro-gressive	partial cutoff	chute cutoff
1904-1937	4.4	92	1	7	0.499	0.009	0.121	3.8	7.1	11.4
1937-1952	6.3	91	2	7	0.703	0.018	0.167	5.5	7.1	17.5
1952-1964	4.4	97	1	2	0.508	0.016	0.085	3.7	14.3	33.5
1964-1978	6.0	92	2	6	0.629	0.032	0.168	4.9	10.1	20.6
1978-1987	8.0	94	2	4	0.888	0.060	0.173	6.7	25.4	29.6
1987-1997	4.2	96	1	3	0.477	0.016	0.095	3.5	14.0	20.0
Average	5.5 ± 0.6	94	1	5	0.617 ± 0.07	0.025 ± 0.008	0.135 ± 0.02	4.7 ± 0.5	13.0 ± 2.8	22.1 ± 3.3

All values shown ± standard error.

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