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RIVER CHANNEL CUTOFF DYNAMICS, SACRAMENTO RIVER, CALIFORNIA, USA

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ABSTRACT

We measured patterns of river channel migration and cutoff between 1904 and 1997 on a 160 km meandering alluvial reach of the Sacramento River by intersecting a sequential set of river channel centrelines mapped from a field survey and aerial photography. We identified approximate dates and locations of cutoffs and quantified cutoff dimensions. Twenty-seven chute and 11 partial cutoffs occurred over this 93-year time interval, with an average of one cutoff approximately every 2.5 years or 0.0029 cutoffs per kilometre per year. The average rate of lateral channel change was over the study period was $5.5 \pm 0.6\,\mathrm{m\,year^{-1}}$ (approximately 0.02 channel widths per year) due to progressive migration and cutoff combined. An average of 5% of the total channel length moved laterally via chute cutoff at a rate of $22.1 \pm 3.3\,\mathrm{m\,year^{-1}}$ versus 94% of channel length that moved via progressive migration at a rate of $4.7 \pm 0.5\,\mathrm{m\,year^{-1}}$. The remaining 1% of channel length migrated via partial cutoff at a rate of $13.0 \pm 2.8\,\mathrm{m\,year^{-1}}$. Although channel cutoff was less predominant mode of channel change than progressive migration in terms of channel length, an average of 20% of the total floodplain area change between successive centrelines was attributable to cutoffs. Peak cutoff frequency was concentrated temporally between 1964 and 1987 and was also spatially clustered in specific active sub-reaches along the valley axis over the entire study period.

We hypothesize that the probability of channel cutoff is a function of both channel geometry and discharge. 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 $111 \pm 7^\circ$, as opposed to average values for bends migrating progressively of 1.31 ± 0.01, 2.8 ± 0.1 and $66 \pm 1^\circ$, respectively. The sinuosity of Sacramento River bends experiencing chute cutoff appears to have been consistently declining from 2.25 ± 0.35 channel widths in 1904 to 1.54 ± 0.23 channel widths in 1987. We hypothesize that this trend may be due in part to the influence of land-use changes, such as the conversion of riparian forest to agriculture, on the 'erodibility' of bank and floodplain materials. For the post-dam flow regime (1937 on), cutoff frequency was significantly correlated with an estimate of cumulative overbank flow. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: river meanders; cutoff; channel migration; bank erosion; riparian vegetation

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INTRODUCTION

Processes of river channel meander migration and cutoff drive changes in channel morphology, sediment load and habitat attributes of alluvial floodplain rivers. Predicting and planning for river cutoff in a manner that balances ecological function, flood protection and water supply is one of the greatest challenges in managing today's meandering river corridors. Studying century-scale centreline dynamics of a big river provides an important opportunity to detect change over time and to quantify processes fundamental to channel cutoff.

Empirical channel change studies can help to refine our understanding of forces driving river channel cutoff and improve models for predicting future river migration patterns. These tools are central to evaluate the ecological and land-use planning implications of future river management alternatives. We used a series of maps of the central Sacramento River spanning 93 years to analyse rates and modes of river channel cutoff (see Figure 1 for site location). In this paper we focus on the dynamics of river channel cutoff, while a companion paper will focus on interactions between progressive migration and cutoff and net impacts on bend and centreline geometry.

We use three categories to describe modes of channel migration observed on the Sacramento River in this study reach: progressive migration, chute cutoff and partial cutoff (Figure 2) (Hooke, 1984, 1995a,b; Fares and Herbertson, 1990). Neck cutoffs, which result from a bend increasing sinuosity and decreasing radius of curvature until it essentially double backs upon itself via progressive migration, did not occur on the Sacramento River over this period of study. However, historic channel configurations preserved in the floodplain provide evidence for higher-sinuosity cutoffs in the past (Robertson, 1987). The

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Figure 1. The central Sacramento River study reach

occurrence of neck cutoffs prior to European settlement or under a different climatic regime cannot be ruled out, particularly in the lower section of the study reach.

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, 1995a,b). If a floodplain 'chute' erodes a secondary channel linking approximately the upstream and downstream inflection points of a bend, the chute may grow, short circuit the former meander path and become the primary channel (Gay *et al*., 1998). Field observations of chute cutoff suggest that there may be a threshold overbank flow required to scour a preliminary shallow chute of sufficient length (sometimes termed a 'probe channel', e.g. Fares and Herbertson, 1990) to reach the downstream end of the bend. The bulk of chute channel excavation, a process of enlarging the chute to the point where it can capture the river's entire flow, is hypothesized to evolve via upstream migration of a knickpoint (Gay *et al*., 1998).

A chute cutoff can ultimately produce an oxbow lake once sediment deposition closes off the entrance and exit of the

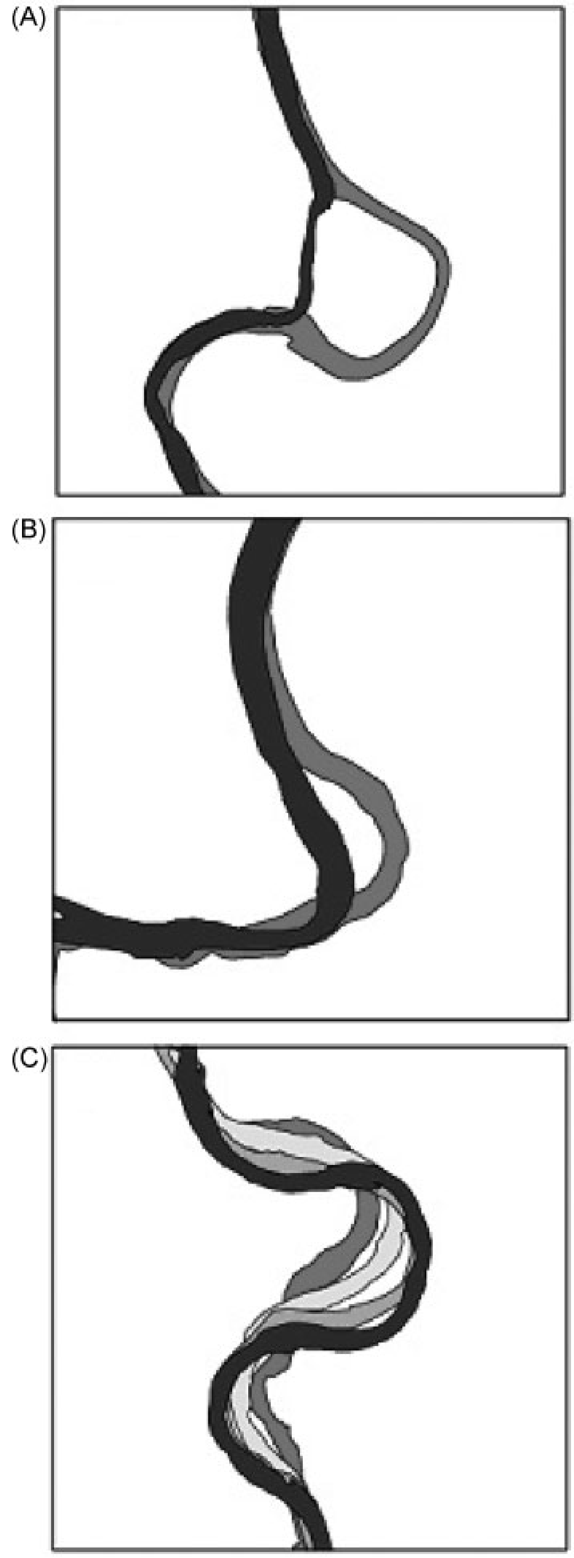

Figure 2. Modes of channel migration. (A) Chute cutoff: excavation of a secondary channel across the floodplain approximately linking upstream and downstream inflection points that ultimately captures the river's entire flow. (B) Partial cutoff: channel avulsion that affects only a portion of a bend and may create a persistent mid-channel bar. (C) Progressive migration: downstream migration of a meander due to a gradual process of bank erosion

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cutoff meander bend, a process that has been observed to occur in a matter of years on the Sacramento River (Morken and Kondolf, 2003). Over time, floodplain deposition of fine sediments may fill an oxbow lake yet leave a discernible trace of the former channel alignment in aerial photography due to distinctive soil and vegetation characteristics (Greco and Alford, 2003a,b).

We hypothesize that chute cutoffs form where the centreline has reached a threshold geometry (in terms of radius of curvature, sinuosity and entrance angle) and only when extended periods of overbank flow provide sufficient stream power to excavate a channel across the floodplain. We propose that absent floodplain variations in soil cohesion or surface roughness, overbank flows would tend to concentrate along the steepest path along the valley axis approximately linking the upstream and downstream inflection points defining a bend.

The partial cutoff category describes episodes of channel avulsion that affect only a portion of a meander bend (Fares and Herbertson, 1990). On the Sacramento River, partial cutoffs often result in the formation of a mid-channel island or bar that may result in a double-threaded channel centreline and remain a persistent feature for some time. While related to chute cutoffs in terms of their reliance on floods for formation, we analysed partial cutoffs separately because they seemed mechanistically distinctive. While a chute cutoff essentially re-sets the process of bend formation via a drastic reduction in bend sinuosity, partial cutoffs modify only a portion of a bend, often eliminating a ‘lobed’ section, i.e. cutting off only a short section of the meander typically distinguished by a tighter radius of curvature locally compared to the bend as a whole.

As opposed to progressive migration, cutoff events are distinctly episodic and cause major changes in channel centreline alignment via rare flood events. While progressive migration may occur over a range of flows and is estimated to reach a peak rate during periods of bankfull discharge (Ikeda *et al*., 1981; Johannesson and Parker, 1989), we hypothesize that cutoff processes on the Sacramento River require overbank flow, with the risk of cutoff increasing with the magnitude and duration of floodplain inundation.

Hooke (2004) provides a comprehensive review of research to date on cutoff formation and contrasts a range of hypotheses to explain ‘clustered’ occurrences of cutoff on the River Bollin, UK. Qualitative models relating meander migration to cutoff potential based on empirical observations (Keller, 1972; Brice, 1977; Hickin, 1983; Nanson and Hickin, 1986) provide a starting point for analysis. While a number of numeric models can describe meander migration and neck cutoff via progressive mechanisms (Howard and Knutson, 1984; Johannesson and Parker, 1989; Stolum, 1998), only a handful tackle the mechanics of episodic chute or partial cutoff (e.g. Fares and Herbertson, 1990; Constantine and Dunne, 2008). The process of chute excavation via knickpoint migration initiated at the downstream end of an incipient chute remains to be mechanistically analysed in detail (Gay *et al*., 1998; Cui pers. comm., 2004).

One challenge in modelling channel cutoff is that progressive migration and cutoff are integrally related (Hooke, 1995a,b). Progressive migration creates the bend geometry that renders a bend prone to cutoff, generally by increasing channel sinuosity, reducing the radius of curvature and increasing the entrance angle (Ikeda, *et al*., 1981; Howard and Knutson, 1984). The mechanics of chute cutoff arise out of interactions between channel and floodplain flows during peak floods, interactions which remain poorly defined mechanistically. After cutoff, rapid adjustments to the new channel alignment will generally accelerate progressive migration upstream and downstream of the cutoff bend until a new relatively stable planform is established (Hooke, 1995a,b). These processes are just beginning to be more accurately measured using remote data sources which will provide opportunities to compare equilibrium- versus chaos-based hypotheses of channel change (Lewis and Lewin, 1983; Erskine *et al*., 1992; Hooke and Redmond, 1992; Piegay *et al*., 2000; Phillips, 2003; Hooke, 2004).

Some have hypothesized that the channel dynamics of the Sacramento River may have been damped due to piecemeal efforts to constrain the channel and due to the reduced magnitude and duration of winter peak flows as a result of storage at the dam at lake Shasta upstream constructed in the early 1940s (CDWR, 1994). Conversely, anecdotal observations suggest that clearing riparian forest from the floodplain for agricultural purposes may make it easier for a bend to cutoff (Cepello pers. comm., 2000; Fremier, 2007; Constantine and Dunne, 2008). Others voice concern that if cutoffs are decreasing in frequency and in magnitude, this creates a risk of losing valuable ecological habitats such as oxbow lakes, over time (Morken and Kondolf, 2003). Our aim was to collect data to begin to shed light on some of these questions.

SETTING

The Sacramento River is the largest river in the state of California and collects 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 (Figure 1). The $6.8 \times 10^4\,\mathrm{km}^2$ Sacramento River watershed comprises 17% of the area of state of California and more than half of the total drainage area of the San Francisco Bay estuary. The river channel is approximately 480 km long flowing from north to south and

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ultimately discharging into the Pacific Ocean via the San Francisco Bay. The Sacramento River Valley is roughly 100 km wide and 400 km long and comprised primarily of sedimentary rocks and recent alluvium, a structurally controlled basin created by the Cascade and Sierra Nevada Mountains to the east and the Coast Ranges of California to the west (Harwood and Helley, 1987). The meander belt of the Sacramento River is dominated by Pliocene–Pleistocene alluvium and fluvial deposits classified as the Chico Domain (WET, 1988; Harvey, 1989; Singer, 2008). The most common set of landmarks used to refer to stations along the Sacramento River is a set of 'river mile' (RM) markers established by the US Army Corps of Engineers (USACE) based on the 1964 channel river alignment, with RM 0 set at the confluence of the Sacramento and San Joaquin Rivers at San Francisco Bay to RM 312 near Shasta Dam (Figure 1). Since the channel alignment has changed significantly since 1964, these markers no longer accurately measure meaningful distances along the present channel centreline but provide a locally well-known system for referencing channel locations. In order to provide a spatial coordinate system to more accurately locate lateral channel change measurements over time for this study, we established a calibrated valley axis running along the active meander belt downstream from Shasta Dam to Colusa.

The central reach of the Sacramento River ranging between the towns of Colusa and Red Bluff (RM 143–244) is predominantly unconstrained (Schumm and Harvey, 1986). The reach downstream ranging from Colusa to San Francisco Bay (RM 0–43) is confined by channel levees. The reach upstream of Red Bluff is geologically constrained before the impoundment at Shasta Dam (RM 244–312). Our study focusses on the reach located between approximately RM 145 and 242, corresponding to valley axis 78–182 km (Figure 1). Although local landowners and the USACOE began to install rip-rap on short sub-reaches starting in the 1950s, the majority of the study reach remains free to migrate.

The study reach is primarily a single-thread sinuous channel. The slope, averaged over a minimum of 5 km, ranges from 0.0002 to 0.0007 (WET, 1988). The riverbed material is primarily sand and gravel with a median grain size that ranges from 5 to 35 mm in the reach ranging from RM 184 to 201 (WET, 1988). The composition of deposited sediments in the Sacramento River from tributary creeks is directly related to the surrounding tectonic units (Robertson, 1987). The average height from thalweg to the top of the bank averages 4 m and varies from 2 to 8 m. The average bankfull channel width is approximately 250 m (CDWR, 1994).

The flood history of the Sacramento River is illustrated by the record measured at US Geological Survey (USGS) Bend Bridge gage (Number 11377100) located near the town of Red Bluff (RM 244) (Figure 2). A frequency analysis of annual peak flows between 1903 and 2002 shows that the 2-year return flow was reduced from approximately 3090 to 2150 $m^3 s^{-1}$ after construction of the dam at Shasta Lake in the early 1940s (Figure 3). Today, the former 2-year return flow now corresponds to what was formerly (pre-dam) a 1.5 return-interval (estimated bankfull) flow. Other major man-made influences include a number of flood control structures diverting excess flow into overflow catchment basins during peak floods. The flood peak of record was 7140 $m^3 s^{-1}$ and occurred in 1904 (WET, 1988, 1990).

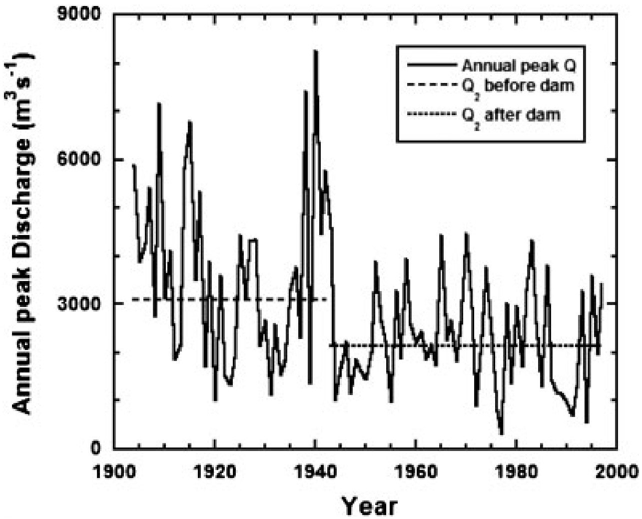

Figure 3. Peak annual discharge measured at the USGS Bend Bridge gage on the Sacramento River. Dashed lines indicate the value of the estimated 2-year return interval flood before and after the closure of Shasta Dam in 1941

METHODS

Observing changes in temporal series of channel centreline data is a tested method of measuring the lateral movement of a river channel over time and identifying bends that migrate either via progressive migration or cutoff (e.g. Brice, 1977; Odgaard, 1987; MacDonald *et al*., 1991; Lawler, 1993; Gurnell *et al*., 1994; Dietrich *et al*., 1999; Micheli and Kirchner, 2002; Constantine *et al*., 2004; Micheli *et al*., 2004). Performing these analyses using Geographic Information System (GIS) tools allows for automating measurements, creating repeatable protocols and sharing results.

Channel centreline analysis

Channel centrelines were derived from a 1904 USGS topographic map (1:68 500) and aerial photography spanning 1937 to 1997 (Greco *et al*., 2003). Channel planform maps were digitized and stored in a GIS database (Greco and Plant, 2003). Scanned aerial photographs (displayed at a scale of 1:10 000) taken during low flow (estimated at

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60–85 $m^3 s^{-1}$) were used to trace the channel banks and thalweg location on-screen in ArcView (ESRI, 2003). In order to consistently map a single-thread centreline, we defined a protocol for occurrences of mid-channel bars: bars were ignored if their widths were less than the average channel width, but for larger bars the larger branch of the split channel was assumed dominant. The spatial uncertainty of mapped features using these techniques is ± 10 m (Greco and Plant, 2003).

Once a channel centreline was digitized and rectified, we defined a set of inflection points to delineate a set of bends. A mathematical algorithm was used to calculate curvature values every 0.25 channel widths (every 62.5 m) along centrelines for each year (Johannesson and Parker, 1989). A preliminary set of inflection points was defined based on nodes where curvature changed sign to segment the centreline into individual arcs. These arcs were then visually inspected and very short segments (less than two channel widths in length) were manually merged with their neighbours either upstream or downstream based on the planform to form a final set of bends for analysis.

We then measured a suite of geometric attributes for each individual bend. The set of bend attributes measured in ArcView are displayed in Figure 4. The meander half-wavelength ($\lambda/2$ or L) equals the straight-line distance between two inflection points. Sinuosity (M/L) equals the ratio of the curved arc length (M) of a channel bend to the half-wavelength (L). The entrance angle (θ) equals the angle between the line connecting bend inflection points and a tangent to the channel at the upstream inflection point. The mean radius of curvature is the numeric average for the bend calculated at nodes located every 0.25 channel widths. We normalized wavelength and curvature measurements by a mean bankfull width (estimated at 250 m) to create non-dimensional parameters to facilitate comparison with rivers of different scales (Larsen and Greco, 2002). For comparison, reach sinuosity was calculated as the total stream length divided by the total valley length measured from the most upstream to most downstream bend.

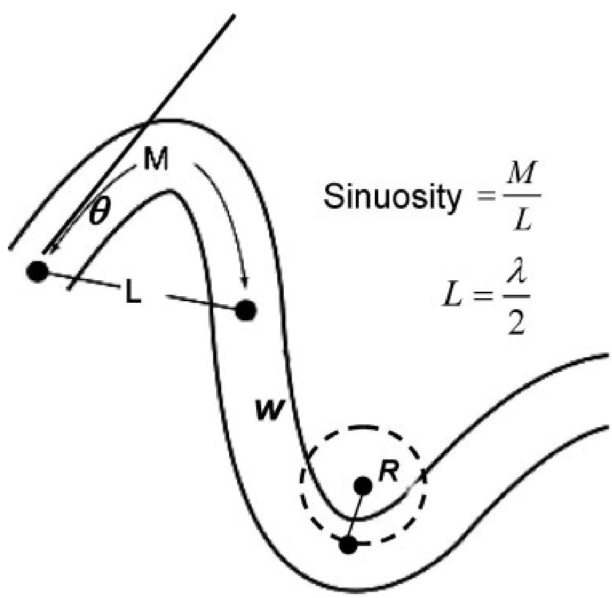

Figure 4. Bend geometry attributes: L equals the straight-line distance between inflection points and is equivalent to the half-wavelength ($\lambda/2$), θ equals the entrance angle defined as the angle between L and a tangent to the centreline measured at the upstream inflection point, w equals the average channel width and R equals the radius of curvature

Measuring magnitudes and rates of channel migration and cutoff

We created a set of 'lateral change polygons' by intersecting successive channel centrelines in order to calculate rates of lateral channel change based on the methodology published in Micheli and Kirchner (2002) and Micheli *et al*. (2004). This approach is similar to those applied by MacDonald *et al*. (1991) in Minnesota, by Constantine *et al*. (2004) on the Sacramento River and Wallick *et al*. (2006) on Oregon's Willamette River. We used an ArcInfo GIS to calculate the area and perimeter of the lateral change polygon. The lateral migration distance perpendicular to the channel centreline over the time interval may be estimated as the polygon area divided by the average stream length for the polygon (where average stream length may be calculated as one-half of the polygon perimeter) (Figure 5). With the aid of GIS this method may be easier to reproduce than alternative methods such as Hickin orthogonal mapping (Hickin and Nanson, 1975). Lateral change polygons were classified as either progressive migration, chute cutoff or partial cutoff based on inspection of the source aerial photography. To distinguish between lateral migration and cutoff we determined whether or not the affected area of floodplain had been 'reworked' via progressive migration using indicators such as the condition of floodplain vegetation, the composition of bar deposits, and where visible, the presence of scroll bars. For progressive migration, the lateral polygon method tends to provide a conservative estimate of 'area reworked' since a lateral change polygon does not account necessarily for the entire area affected by channel migration (depending on the migration path, some 'area reworked' may lie outside the polygon boundary). This uncertainty, which results in a potential underestimation of total floodplain turnover, may be reduced by reducing the length of time interval between photo sets.

We represented the spatial extent and magnitude of lateral migration via cutoff and progressive migration by projecting the average migration value per lateral change polygon (in metres) onto the down-valley axis. Using this method, a single polygon can be represented with a y-axis value

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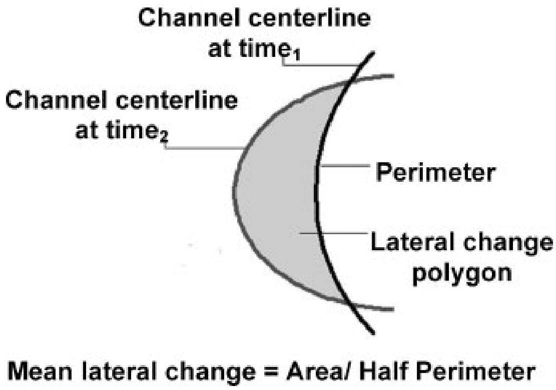

Figure 5. Lateral channel change polygon. Two channel centrelines mapped at different times may be intersected to measure the location and magnitude of lateral channel change over the time interval. Polygon area approximates either floodplain area cutoff or area reworked by progressive migration. The average stream length over the time interval may be estimated as equal to half the polygon perimeter. Average lateral migration per polygon may be estimated as polygon area divided by one half of the polygon perimeter

corresponding to mean lateral migration and a distance along the *x*-axis corresponding to the length of the polygon intersecting the valley axis. Using the results of intersecting only two centrelines, mean migration values appear as a series of steps along the down-valley axis. These plots can be summed to display the cumulative migration measured over the entire period of study. We conducted this analysis of cumulative migration between valley 78 and 182 km to detect patterns of relative stability and instability along the study reach and to compare the magnitude of lateral channel change attributable to cutoff versus progressive migration.

One of our objectives was to link cutoffs to antecedent bend geometry. To achieve this, sets of bends comprising initial channel centrelines were intersected with cutoff polygons to quantify bend geometry prior to cutoff. We isolated a set of high-sinuosity (>1.85) bends for each data set that did not cutoff, to test for geometric differences between cutoff bends and bends with similar centreline geometry that remained stable. For comparison, we also quantified the geometry of bends that migrated via progressive migration. In addition, we digitized the centrelines of oxbow lakes to gather sinuosity and radius of curvature data on the remnants of bends that cutoff prior to the historical record. In the case of oxbows, wavelength and entrance angle measurements were precluded due to the lake of a complete series of bends for analysis, and sinuosity measurements should be considered conservative since some cutoff channel lengths may have been obscured by subsequent channel migration and infilling.

Overbank flow analysis

We characterized overbank flow during study time intervals by quantifying the duration and extent of discharge in excess of estimated ‘bankfull’. Cumulative overbank flow is estimated as the total amount of discharge in excess of estimated bankfull (Q1.5, 2150 $m^3 s^{-1}$) over the time interval of analysis. We estimated this flow volume by analysing mean daily flow data for the Bend Bridge gage (USGS gage 11377100) and isolating days when the average flow rate exceeded the Q1.5. After deducting the Q1.5 from daily flow values, the remaining overbank volume of discharge was estimated for that day. Daily values were summed to estimate cumulative overbank flow annually and for the decade-scale time intervals between successive centreline dates. An average annual overbank flow was then calculated for each time interval by simply dividing the cumulative overbank flow over the time period by the total number of years in the interval. We also calculated the number of days flow went overbank for each time interval. Estimates of cumulative overbank flow provide a simple metric to quantify the net effect of the frequency, duration and magnitude of overbank discharges for the period of record. Alternatively, it would have been possible to calculate cumulative stream power, which has been shown to correlate well with progressive bank erosion on the Sacramento River (Larsen *et al*., 2006), if adequate channel slope data had been available.

RESULTS

Frequency and magnitude of channel cutoff

We identified a total of 27 chute cutoffs and 11 partial cutoffs between 1904 and 1997. Cutoff frequency ranged from a minimum of 0.0013 (1904–1937) to a maximum of 0.0040 (1964–1978 and 1978–1987, respectively) measured in units of number of cutoffs per kilometre per year (No. $km^{-1} year^{-1}$) (Table I). On average, 72% of cutoffs observed were chute rather than partial cutoffs. Cutoff activity was also be quantified as the rate of floodplain area affected, which ranged from a minimum of 0.477 $km^2 year^{-1}$ (1987–1997) to a maximum of 0.888 $km^2 year^{-1}$ (1978–1997) (Table II). Average cutoff size ranged from 0.61 ± 0.10 (1904–1937) to 0.28 ± 0.06 km^2 (1987–1997) (Table II).

The location and magnitude of individual cutoffs is shown in Figure 6, with the *x*-axis representing distance down-valley and the *y*-axis representing the magnitude of lateral channel change attributable to cutoff. The first time interval, 1904–1937, displays the only data available for the period prior to the closure of Shasta dam in 1941. Here we observe seven cutoffs distributed through the study reach, with an average lateral change due to cutoff of 347 ± 32 m. The 1937–1952 data shows a majority of relatively large cutoffs concentrated in the upper reach (above valley 140 km) averaging a lateral change distance of 201 ± 34 m, while next time step (1952–1964) displays a low cutoff frequency

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Table I. Cutoff frequency and area, central Sacramento River, 1904–1997

Time interval	Stream length (km)	Reach sinousity[a]	Number of cutoffs	Partial cutoffs (%)	Chute cutoffs (%)	Average number of cutoffs per year	Average cutoff area (km^2)	Cutoff frequency (No. km^{-1} $year^{-1}$)
1904–1937	167.7	1.41	7	14	86	0.21	0.61 ± 0.10	0.0013
1937–1952	161.0	1.37	9	33	67	0.60	0.31 ± 0.08	0.0037
1952–1964	165.0	1.37	3	33	67	0.25	0.40 ± 0.29	0.0015
1964–1978	164.4	1.36	9	33	67	0.64	0.31 ± 0.12	0.0039
1978–1987	167.2	1.39	6	33	67	0.67	0.35 ± 0.06	0.0040
1987–1997	143.1	1.38	4	25	75	0.40	0.28 ± 0.06	0.0028
Average	156.8	1.38	6.33	29	71	0.46	0.38 ± 0.12	0.0029

[a]Reach sinuosity measured as total stream length divided by total valley axis length for the initial channel centreline for bends located between valley 78 and 102 km.
Values shown ± standard error.

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

Time interval	Average lateral change rate (m $year^{-1}$)	% Length moved via			Rate of floodplain area affected (km^2 $year^{-1}$) via			Lateral migration rate (m $year^{-1}$) via		
		Progressive	Partial cutoff	Chute cutoff	Progressive	Partial cutoff	Chute cutoff	Progressive	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.

(0.0015 km^{-1} $year^{-1}$, Table I) and averaged 241 ± 72 m lateral change, with cutoff activity occurring only below valley 150 km, including the largest cutoff of record, which caused the channel to shift laterally approximately 483 m. Between 1964 and 1978, cutoff activity was observed again throughout this study reach (averaging 212 ± 40 m lateral change), while data for 1978–1987 show cutoffs occurred only above valley 145 km (averaging 247 ± 24 m). In the last time step, 1987–1997, we observed the lowest average lateral change due to cutoff (184 ± 18 m). With a reduction of 47% in average lateral change per cutoff between the first and last time step, there appears a tentative trend towards smaller cutoffs over this study period.

In order to place the spatial distribution of cutoffs in the context of migration patterns on the Sacramento River, we plotted cumulative average lateral channel change versus down-valley distance for the 93-year period of study (Figure 7). Here, cumulative cutoff activity is superimposed on cumulative amounts of progressive migration. Cutoffs at this time and spatial scale appear in clusters, with cutoff activity concentrated in specific sub-reaches, including valley 85–90, 95–100, 120–125 and 132–142 km. We observe that cutoff clusters are frequently located in proximity to zones of peak progressive migration activity. At least six irregularly spaced relatively 'static' sub-reaches emerge in this plot, where no cutoffs occurred and where channel migration has produced less than 200 m total lateral channel change over approximately the last century. Hooke (2007) observed a similar pattern of alternating 'active' and 'static' reaches on the River Dane. Based on a detailed assessment of variations in bank material along the study reach, Constantine *et al*. (2004) hypothesize that static reaches are bound by resistant terrace units that effectively stall the downstream translation of meanders, while active reaches coincide with zones of declining shear stresses and accelerated point bar deposition.

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

By all measures, 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

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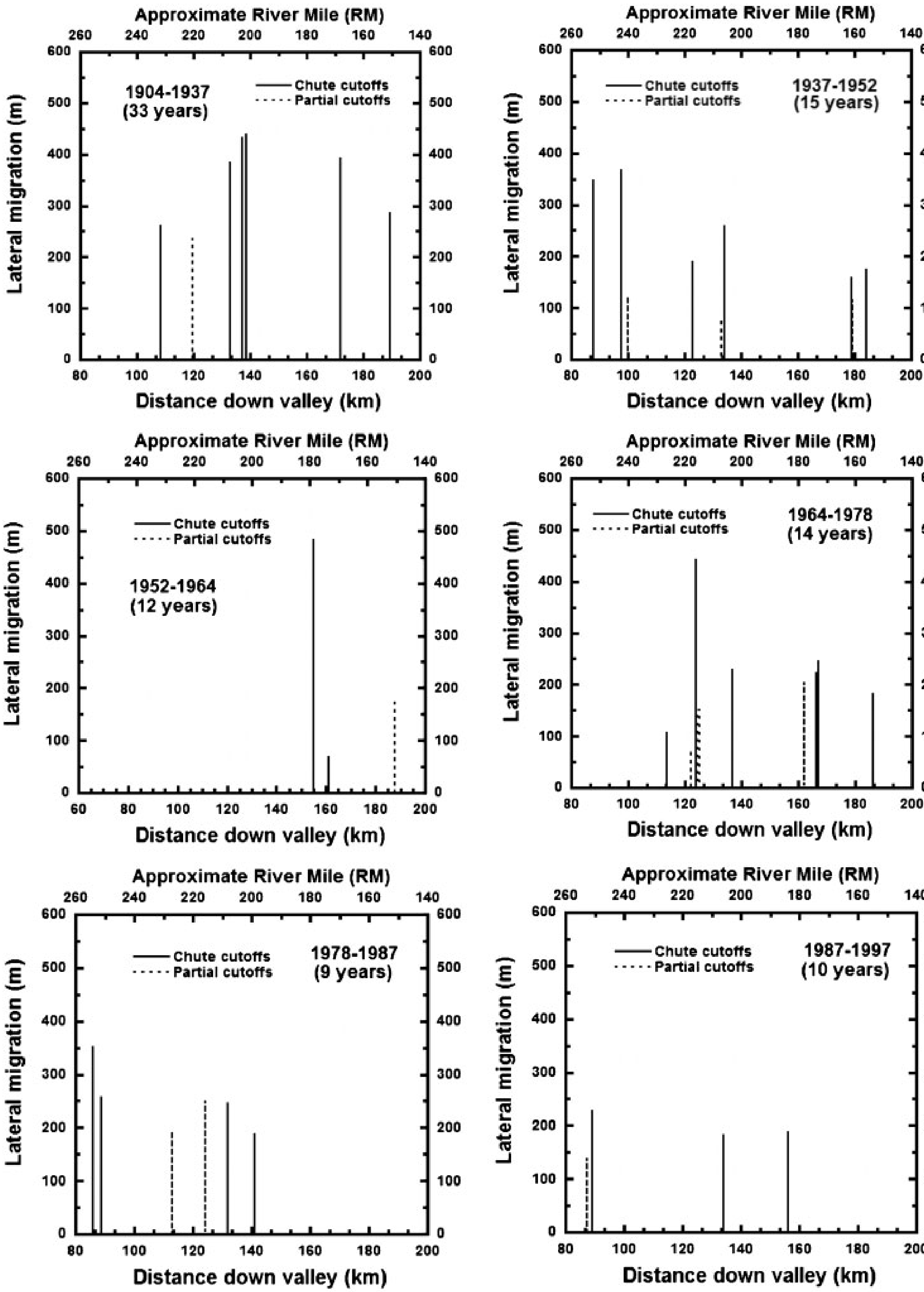

Figure 6. Location and magnitude of cutoffs, Central Sacramento River, 1904–1997

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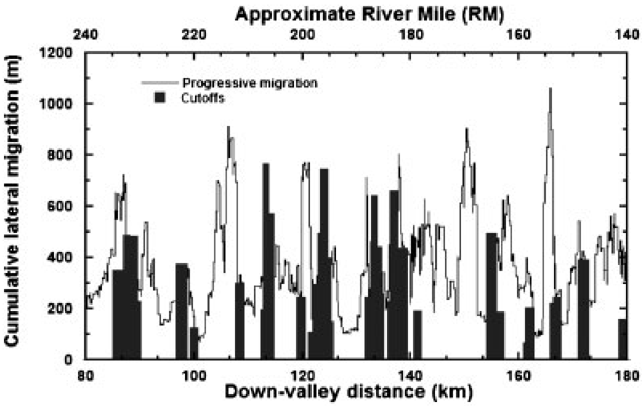

Figure 7. Cumulative lateral channel change due to cutoff versus progressive migration, 1904–1997. Cutoff activity occurs in clusters, and in general, highly mobile reaches (progressive migration and cutoff combined) alternate irregularly with relatively static reaches

migration, 5% migrated via chute cutoff and only 1% migrated via partial cutoff (Table II). However, the rate of floodplain area reworked by progressive migration ($0.617 \pm 0.07\,km^2\,year^{-1}$) was only 4.4 times greater than the rate of floodplain area cutoff ($0.14 \pm 0.02\,km^2\,year^{-1}$). 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 $22.1 \pm 3.3\,m\,year^{-1}$ lateral change versus average progressive migration rates of $4.7 \pm 0.5\,m\,year^{-1}$ over the same period (Table II). However, trends in progressive migration drive average migration rates for the whole river, with an average lateral migration rate of $5.5 \pm 0.6\,m\,year^{-1}$ for progressive migration and cutoff combined.

Temporal trends in rates of progressive migration versus cutoff are displayed in Figure 8. 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 (1952–1964 and 1964–1978) 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 8B 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.

Geometric attributes of cutoff bends

Geometric attributes of delineated meander bends provide a basis for correlating channel centreline geometry to

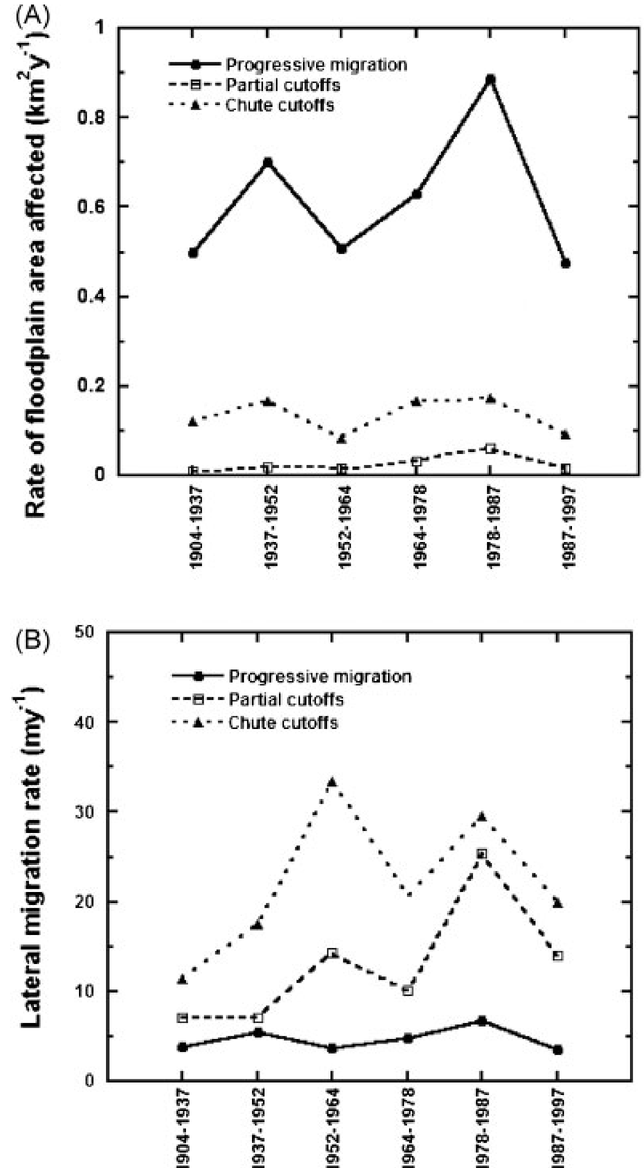

Figure 8. (A) A comparison of floodplain area affected by cutoff (chute and parttial) versus progressive migration for each time interval. (B) A comparision of lateral magration rates generated by cutoff (chute and partial) versus progressive migration for each time interval

subsequent modes of channel change (Table III). 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 $111 \pm 7°$, as opposed to average values for bends migrating progressively of 1.31 ± 0.01, 2.8 ± 0.1, 4.7 ± 0.1 and $66 \pm 1°$, 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)

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Table III. Geometric properties cutoff, stable and progressive migration bends and oxbow lakes (average values shown in bold for each category), Central Sacramento River, 1904–1997

Bend category	Time interval	Number of bends	Dimensionless mean half-channel wavelength ($\lambda/2w$)	Mean sinuosity	Dimensionless mean radius of curvature (R/w)	Mean entrance angle θ (°)
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
Category Average		**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
Category Average		**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
Category Average		**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
Category Average		**54.7**	**4.7 ± 0.1**	**1.31 ± 0.01**	**2.8 ± 0.1**	**66 ± 1**
Oxbow Lakes $N = 32$	1997	n/a	n/a	2.01 ± 0.17	2.2 ± 0.2	n/a

Values shown ± standard error.
n/a, not applicable.

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 III). 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 centreline data for predicting the likelihood of potential cutoff (Table III). 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°, respectively), and significantly higher than that measured for partial cutoff bends (77 ± 9°). 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).

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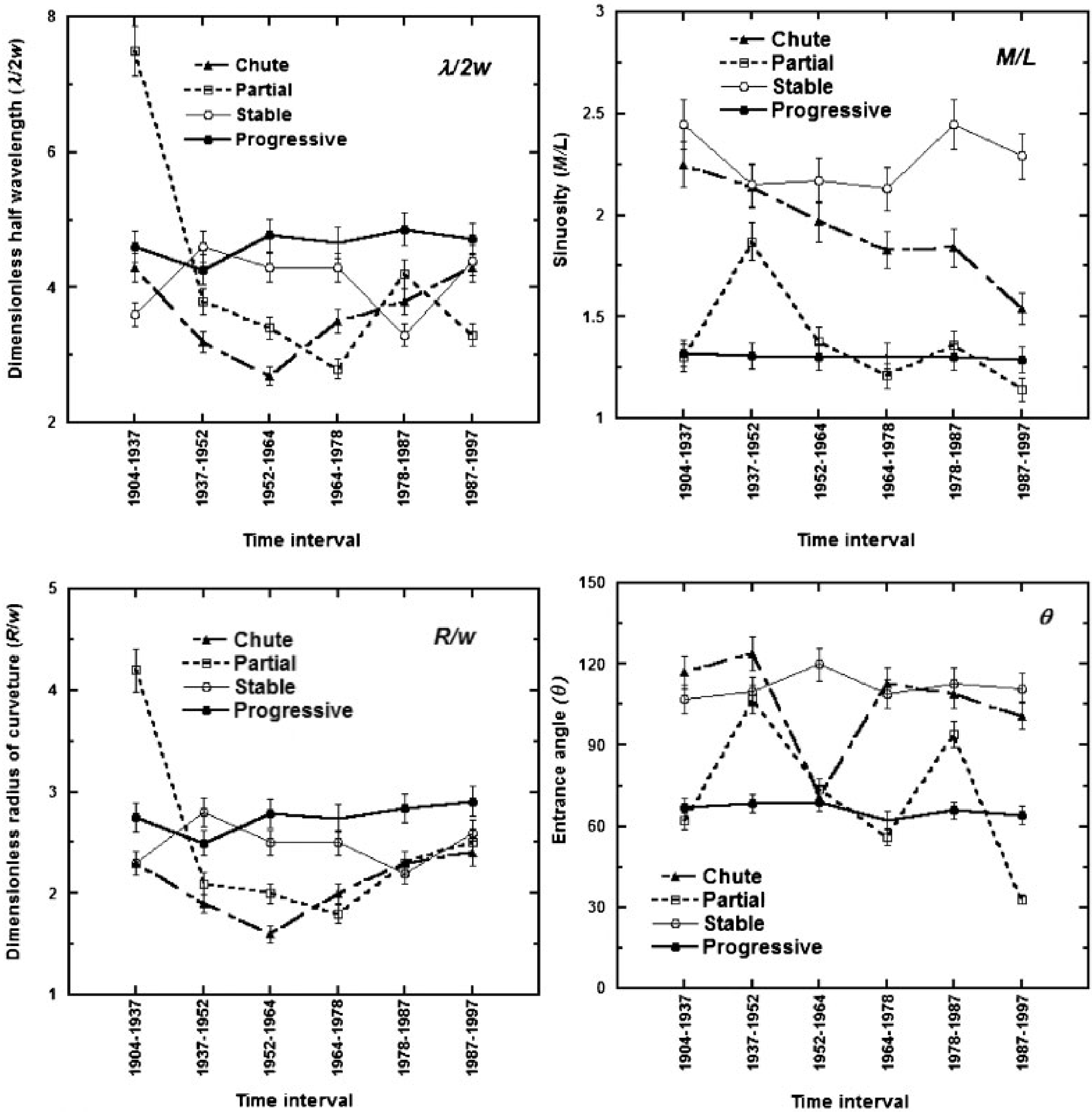

Figure 9. Temporal variation of average bend geometry for cutoffs, progressive migration bends, high-sinuosity (>1.85) stable bends and oxbow lakes

Figure 9 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 III). 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 than progressive migration bends, with chute cutoff values wavering between these two data sets in the range of 71–124°. We observe 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.

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The most striking trend in the temporal data set is a consistent decline in the mean sinuosity (*M*/*L*) of chute cutoffs from 2.3 ± 0.4 (1904–1937) to 1.5 ± 0.2 (1987–1997), amounting to a 35% reduction in the average sinuosity of meanders prone to cutoff. Since 1954, partial cutoff sinuosity has followed a similar trend, with a 42% reduction in bend sinuosity by the 1987 time interval (Table III, Figure 9).

Cutoff frequency versus overbank flow

Measures of cumulative overbank flow and the average annual overbank flow for each time interval is reported in Table IV. Relatively low values occurred in 1952–1964 ($51.5 \times 10^6\,\mathrm{m}^3\,\mathrm{year}^{-1}$) and in 1987–1997 ($68.9 \times 10^6\,\mathrm{m}^3\,\mathrm{year}^{-1}$). Higher values occurred in the remaining four time periods, ranging from 89.5×10^6 (1904–1937) to $115.7 \times 10^6\,\mathrm{m}^3\,\mathrm{year}^{-1}$ (1964–1978) (Table IV).

Figure 10 displays the change over time in the annual average overbank flow for each time period (defined as the total volume of flow in excess of the Q1.5 divided by the number of years in the time interval) and in the frequency of both chute and partial cutoffs per year per kilometre. Examination of Figure 10 indicates that the frequency of both types of cutoff correlate well with annualized cumulative overbank flow. Figure 11 is a scatter-plot of this relationship for chute cutoffs and reveals a linear relationship for the post-Shasta dam era (the time interval 1904–1937 appears as an outlier). The relationship for this linear fit of post-dam conditions may be described by $y = 4\mathrm{E}-05x\ 1\mathrm{E}-05$, where y is cutoff frequency and x is cumulative annual overbank flow. The R^2 value for this relationship equals 0.93.

DISCUSSION

Our analysis of Sacramento River channel centrelines reveals at least three important findings. First, bends evolving via chute cutoff, partial cutoff and progressive migration display distinct planform geometries. Based on these results, we can improve forecasts for a potential cutoff based on channel planform. Second, the number of cutoffs, both chute and partial, is significantly correlated with an estimate of cumulative overbank discharge. This correlation suggests that a threshold magnitude and duration of overbank flow may be required to cause a cutoff. Third, the sinuosity of chute cutoffs has been declining consistently since 1904, which we hypothesize may be due to the influence of land-use changes, specifically the conversion of riparian forest to agricultural uses. The reduction in sinuosity of bends prone to chute cutoff may serve to contribute to a trend towards an overall reduction in channel centreline sinuosity over time, although this trend appears barely significant over this period of study. Overall, our results provide evidence that the relationship between cutoff frequency and cumulative overbank flow has shifted significantly, since 1940s, such that less flow appears to be more effective at producing cutoffs on the Sacramento River.

The likelihood of channel cutoff is hypothesized to be a function of channel centreline evolution via progressive migration, which renders a bend ripe for cutoff, and the magnitude and duration of subsequent overbank flow events, which provide the work necessary to excavate a new channel. This hypothesis provides a context for examining the observations listed above.

The usefulness of planform geometry for predicting cutoff

Over this 93-year period, the average bend sinuosity associated with chute cutoff was 2.0 ± 0.1, the average radius of curvature was 2.1 ± 0.1 channel widths and the average entrance angle was approximately 111°. Bends that were similar to this, but which remained stable, displayed similar entrance angles and sinuosity, but were characterized by roughly 20% larger radii of curvature (averaging 2.5 ± 0.1 channel widths). The radius of curvature of a cutoff bend may be considered a surrogate for potential chute path length (with the chute path roughly equivalent to double the radius of curvature). Our results indicate that stable sinuous bends are primarily distinguished by potential

Table IV. Overbank flow, Sacramento River Bend Bridge gage, 1904–1997

Time interval	Total number of cutoffs	Average number of cutoffs per year per km	Peak discharge Q^p (cms)	Date Q^p	No. of days Q1.5 exceeded	Cumulative overbank discharge ($10^6\,\mathrm{m}^3$)	Average annual overbank discharge ($10^6\,\mathrm{m}^3$)
1904–1937	7	0.0013	7136	2/3/09	41	2953	89.5
1937–1952	9	0.0037	8240	2/28/40	17	1488	99.2
1952–1964	3	0.0015	3936	2/19/58	22	618	51.5
1964–1978	9	0.0039	4446	1/24/70	33	1620	115.7
1978–1987	6	0.0040	4304	3/1/83	36	1029	114.3
1987–1997	4	0.0028	3596	3/15/95	18	689	68.9

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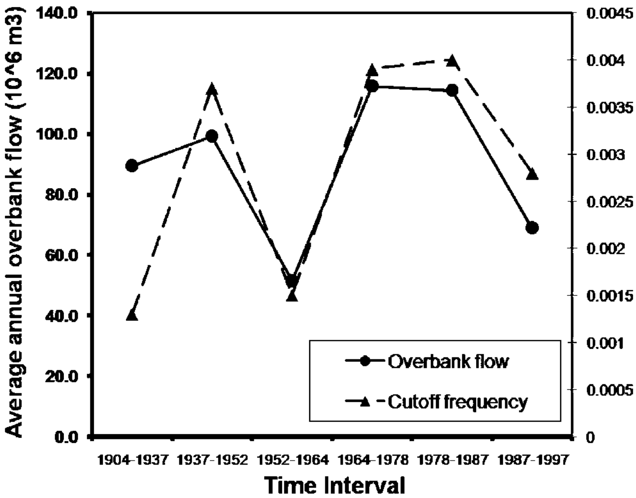

Figure 10. Temporal change in cutoff frequency versus cumulative overbank flow

chute paths that are on average 50 m longer than bends prone to cutoff. This makes sense, since excavation of a longer chute would increase the threshold overbank flow event required to successfully create a cutoff and thus reduce the probability of cutoff.

Given the lack of very high-resolution topographic data for the Sacramento Valley at the initiation of this study, our analysis has been restricted to a two-dimensional centreline analysis. With the advent of higher-resolution floodplain topography, it will be possible to test for the influence of slope on the formation of chute channels, which we predict will result in defining a range of planform geometry thresholds for cutoffs as a function of valley slope and

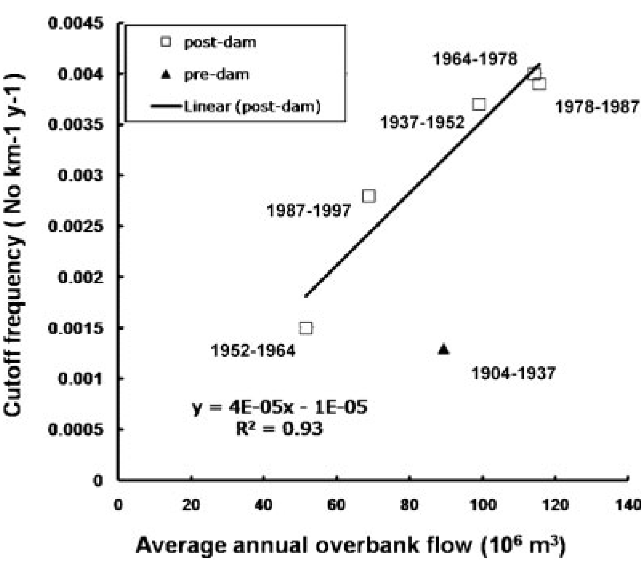

Figure 11. Scatter-plot of cutoff frequency versus average annual cumulative overbank flow

resultant cumulative effective stream power (Larsen *et al.* 2006). Our estimates of cutoff geometry possess some uncertainty since pre-cutoff geometries were often measured up to several years before cutoff actually occurred. Since channel geometry was not measured for the exact year of cutoff, we are likely underestimating threshold cutoff sinuosity and entrance angles and overestimating threshold radii of curvature. Detailed channel cutoff case studies with higher-temporal resolution will provide greater precision in estimating geometric thresholds by analysing aerial photos taken immediately prior to cutoff.

Overbank discharge and cutoff

While bend geometry determines whether or not a bend is ripe for cutoff, the distribution of subsequent stream flows determines *when* cutoff may occur (Hooke, 2008). We hypothesize that the depth of flow will determine how much stream power is available to erode the floodplain surface and thus sets the erosion rate for the chute channel, both during the evolution of a probe into a chute channel via scour and during the subsequent excavation of the chute via upstream knickpoint migration. The duration of flow will control the total amount of erosion available to scour and excavate an incipient chute. Our analysis shows that cutoff frequency is significantly correlated with cumulative discharge above the Q1.5, a rough estimate of the combined effect of magnitude and duration of overbank flows (Figure 11).

Detailed analyses of case studies will be required to better characterize mechanisms of cutoff by overbank flow and to better define site-specific flow thresholds for cutoff. More accurate representations of overbank flow should concentrate on estimating available stream power. The feasibility of stream power calculations will rely again on the availability of very accurate measurements of floodplain slope, which should increase thanks to new tools including laser altimetry.

We observe a distinctly different relationship between overbank flow and cutoff frequency before and after dam installation: while there is a distinctive linear relationship between average annual overbank flow for the post-dam series, the pre-dam data appears on this plot as an outlier (Figure 11). Based on the post-dam relationship between flow and cutoff frequency, we would predict on the order of 175% more cutoff activity in the pre-dam period than actually occurred. This implies that presently less flow is doing more work in terms of cutoff formation, which is reinforced by our measurements of increasing rates of lateral migration per cutoff event over this time period.

Influence of anthropogenic disturbance on cutoff processes

Floodplain characteristics may be an important control on probability and rate of cutoff. Agricultural development

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reduced the roughness and the cohesion of floodplain materials due to the removal of approximately 90% of the riparian forest corridor (Buer *et al*., 1989). Micheli *et al*. (2004) compared the erodibility of riparian forest versus agricultural floodplain on the Sacramento River and found that agricultural land erodes via progressive migration roughly twice as fast as riparian forest. One explanation for why cutoff frequency was 175% higher post-dam than pre-dam may be the increased erodibility of the floodplain due to vegetation removal following dam construction and the availability of irrigation. If the river floodplain has become more erodible through riparian vegetation removal in the post-dam era, we hypothesize this effect may facilitate cutoff at lower thresholds of channel sinuosity and lower thresholds of overbank flow. Our field observations of floodplain conditions in remnant areas of riparian forest indicate that undisturbed floodplain surfaces are highly irregular due to woody debris and topographic variation attributable to the preservation of scroll bars and small secondary channels. Therefore, allogenic variations in floodplain materials may influence the path and rate of probe and chute channel formation. Anecdotal evidence drawn from detailed air photo analysis immediately prior to cutoff indicate that even thin strips of riparian forest and fallen woody debris can steer to some degree the upstream location of an incipient cutoff chute (Brice, 1977). We hypothesize that the high roughness created by undisturbed floodplain forests may inhibit the concentration of flow into a single chute channel, and thus effectively raises the threshold of overbank flow required for cutoff. Recent work by Constantine and Dunne (2008) supports this hypothesis: using detailed air photography for a subset of cutoffs reported here, they reported that chutes preferentially formed where riparian forest had been cleared. These authors also conducted hydraulic modelling of floodplain flows and concluded that forming a cutoff chute through dense forest vegetation is 'nearly impossible'. We propose that the best way to further validate this hypothesis is to compare detailed three-dimensional measurements of probe and chute formation patterns (including sites where vegetation is present) against the null hypothesis that absent variations in floodplain cover, the chute would simply form along the steepest path across the meander neck.

The progressive installation of bank protection, a practice initiated in the 1960s that now affects close to 40% of the study reach, would most likely be hypothesized to reduce rates of channel migration (Harvey and Watson, 1989), but this trend is not revealed in our data. In terms of progressive migration, it may be the case that reductions in bank erosion rates for reaches with bank protection are compensated for by more rapid progressive migration occurring in reaches with unprotected banks (e.g. Larsen and Greco, 2002), but this hypothesis merits closer scrutiny. In terms of the impact of bank protection on rates of channel cutoff, we estimate that the installation rip-rap at the upstream end of an incipient chute with the aim of preventing channel cutoff is unlikely to provide long-term protection, since these efforts may be undermined by overbank flow events which may essentially circumvent hardened riverbanks. Since ultimately the excavation of cutoff chutes may proceed from the downstream extent of the chute in the upstream direction, we hypothesize that while bank protection located at the upstream portion of a bend may serve to inhibit formation of an incipient chute for some time, it will not necessarily prevent chute formation should flows succeed in completely inundating the floodplain at some sufficient depth and duration to trigger knickpoint initiation at the downstream extent of a bend.

Anthropogenic impacts on sediment supply may also influence cutoff rates. Anecdotal observations of cutoff events suggest that bed and bar accretion during floods can steer flows onto the floodplain and help to facilitate cutoff (Teisseyre, 1977). Sediment supply on the Sacramento River has been reduced due to both climatic change since the Pleistocene and more recently due to the effect of sediment storage behind dams (Singer and Dunne, 2001). Reduced sediment supply is hypothesized to reduce the 'bar push' available to force progressive migration (Dietrich *et al*., 1999; Singer and Dunne, 2001), resulting in perhaps a potential for increased rates of cutoff (Singer and Dunne, 2001). Recent work by Lauer and Parker (2008) provides a method for using meander migration mapping to better quantify sediment gains and losses associated with overbank scour termed 'floodplain shaving', floodplain deposition and channel extension (migration). Lauer and Parker's finding that 80–90% of material eroded from cut banks is deposited in local point bars (2008) provides a basis for further exploration of the magnitude of 'bar push' acting on a regulated river. We find the question of how anthropogenic alterations to sediment transport dynamics may impact long-term migration patterns on the Sacramento River, and specifically mechanisms of cutoff, to remain open for enquiry.

There is uncertainty inherent in our conclusions about the effect of flow regulation and floodplain conversion to agriculture on cutoff dynamics given that we only have one reliable time interval prior to dam construction to compare to six time intervals after dam construction. A further drawback is that the pre-dam interval (1904–1937) is the longest time period of the series and represents the combined effects of a relatively wet period followed by a relatively dry period. However, given these caveats, the data suggest an increasing susceptibility of the river's floodplain to the formation of cutoffs since the agricultural development of the valley.

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CONCLUSION

We hypothesize that it is easier for overbank flows to excavate chute channels through cleared and levelled agricultural land versus through the rough terrain typical of an undisturbed riparian forest. While flow regulation has reduced the magnitude of overbank flow during peak events, it appears that the reduced erodibility of the floodplain has resulted in making it easier for chute cutoffs to form under the current flow regime. This increased susceptibility to channel cutoff is reflected in a trend for bends to cutoff at progressively lower values for channel sinuosity and higher values for radius of curvature.

Over the last century we observe a slight increase in the length of channel migrating via progressive migration versus cutoff. We also observe a slight trend towards a greater magnitude of stream length migrating via partial versus chute cutoff. While the average area of an individual cutoff has decreased somewhat in the post-dam time steps, cutoff frequency measured as the average number of cutoffs per kilometre per year has been on average higher during the post-dam era than pre-dam. Our data therefore points to a weak trend towards smaller but more frequent cutoffs. We also observe that since agricultural conversion, the magnitude of lateral migration per metre stream length via channel cutoff has roughly doubled, further supporting the hypothesis that riparian vegetation removal may have increased floodplain vulnerability to the effect of cutoffs over this time period.

The concluding hypothesis of this study is that while flow regulation may have reduced the magnitude and duration of overbank floods available to create chute cutoffs, there has been a concurrent reduction in the cohesion and roughness of floodplain materials, such that when overbank floods do occur bends may cutoff at a lower threshold of bend sinuosity and radius of curvature. We suggest that since the pre-dam time period (1904–1937) appears as an outlier on our plot of cutoff frequency versus overbank flow (Figure 11), the effect of anthropogenic disturbance may have been to effectively push the plotted curve up and to the left, causing the river to display higher frequencies of cutoff during smaller overbank flow events. A secondary finding is that there appears also to be a slight trend towards a reduction in the average size of cutoffs in terms of floodplain area and towards a greater frequency of partial cutoffs versus complete chute cutoffs.

If it is easier to cut off sinuous bends and the formation of new sinuous bends is limited by channel stabilization projects, one might expect a reduction in channel sinuosity over the long term. Our data show a small reduction in reach-scale channel sinuosity (on the order of 2%). A longer period of record will be necessary to confidently detect such a trend since reach sinuosity values naturally fluctuate due to 'pulses' of cutoff cluster activity (Constantine *et al*., 2004), with this case characterized by a large pulse of cutoff activity between 1964 and 1987. Presently, we do not observe a statistically significant decrease in average bend sinuosity, but we do observe the progressive elimination of rare high-sinuosity bends.

Detailed mechanistic analyses of individual cutoff cases are needed to quantify relationships between overbank flow shear forces and floodplain characteristics. We propose that a longer period of high-resolution monitoring will be required to confirm if observed trends are progressive or cyclical, in particular to assess if reducing flow and geometric thresholds for cutoff will result in a less sinuous channel over time. In addition, we neglected to address potential impacts of variations in channel cross-section and flood control weirs on cumulative overbank flow: we recommend these factors be addressed at the site-specific scale. However, based on a century-scale 'snapshot', we hypothesize that the conversion of the riparian zone from forest to agriculture may have increased the vulnerability of the floodplain to disturbance to explain how cutoff frequency could have increased during a period of increased flow regulation.

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