Controls on the alluviation of oxbow lakes by bed-material load along the Sacramento River, California

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Associate Editor: Steve Rice

ABSTRACT

Differences in the nature and quantity of sediment filling oxbow lakes have significant implications for the evolution of meandering rivers and the development of floodplains, influencing rates of meander migration and the valley width over which migration takes place. In an effort to identify the controls on the alluviation of oxbow lakes by coarse bed material, this study examined the sedimentary records stored within oxbow lakes of the Sacramento River of California, USA, and found that the volume of gravel in storage correlated negatively with the diversion angle separating flow between the river channel and the entrance into each lake. A method was devised for estimating the original channel bathymetry of the studied lakes and for modelling the hydraulic and sediment-transport effects of the diversion angle within channels recently abandoned by meander cut-off. The diversion angle determines the width of a flow separation within the abandoned-channel entrance, reducing the discharge diverted from the river channel and thus limiting the ability of the abandoned channel to transport bed material. Aggradation rates are faster within entrances to abandoned channels with high diversion angles, resulting in the rapid isolation of lakes that store only a small volume of coarse-grained sediment. Aggradation rates are slower within channel entrances where diversion angles are low, resulting in the slow transitioning of such channels into oxbow lakes with a larger and more extensive accumulation of coarse-grained sediment. These findings compare well with observations in other natural settings and the mechanism which is described for the control of the diversion may explain why some oxbow lakes remain as open-water environments for centuries, whereas others are filled completely within decades of cut-off.

Keywords Alluviation, floodplains, meander cut-off, oxbow lake, sedimentation.

INTRODUCTION

Oxbow lakes are some of the most widespread and distinctive landforms within the lowland floodplain environment. Their form and persistence in the landscape, as well as their influence on alluvial architecture, hydrogeology and channel migration, are determined in part by the...
manner in which they are filled by sediment. Lakes filled mainly by silts and clays function as important sinks for suspended load (Aalto et al., 2008; Lauer & Parker, 2008), and form sediment lenses that slow the migration of meanders (Hudson & Kesel, 2000) and limit the width of the meander belt (Allen, 1965). The deposition of silts and clays also determines the importance of oxbow lakes as sinks for contaminants that adsorb efficiently to the finest fractions of sediment in suspension (Marron, 1992; Lukashev, 1993; Costa et al., 2006). Oxbow lakes increase the topographic, hydrological and habitat diversity of the floodplain (Castella et al., 1984; Bornette et al., 1998; Ward, 1998) and the rate at which they transition from lentic to terrestrial habitat is controlled by how quickly they are filled by sediment (Piégay et al., 2000). Although the alluviation of oxbow lakes has been observed in natural settings (Fisk, 1947; Hooke, 1995; Li et al., 2007) and generalized by means of rules in planform evolution models (e.g. Howard, 1992; Sun et al., 1996), no quantitative theory has been formulated to explain how oxbow lakes are filled because the controls on the process have not been studied widely nor interpreted physically.

Fisk (1947) provided a qualitative model of oxbow alluviation based on observations along the Lower Mississippi River, USA. Fisk reported that the alluviation of a channel being abandoned by meander cut-off is determined first by its diversion angle, the angle between the approaching active-channel flow and the abandoned-channel entrance (Fig. 1). Fisk proposed that abandoned channels with high diversion angles quickly lose their ability to transmit bed material, resulting in rapid aggradation of the entrance and the formation of an oxbow lake in which the fill is dominated by fine-grained sediment delivered during floods. By contrast, abandoned channels with low diversion angles sustain the ability to transmit both wash load and bed-material load from the active channel, slowly transitioning into oxbow lakes with a much larger representation of coarse-grained sediment. Observations of oxbow alluviation by Bridge et al. (1986) and Hooke (1995) are consistent with the Fisk model, and Shields & Abt (1989) found that differences in diversion angle and sediment load statistically explained over 90% of the variability in rates of bed-material aggradation between artificially formed lakes of the Lower Mississippi River. The reason that the diversion angle is a control has not been understood, however, because its effects on bed-material transport have not been analysed mechanistically.

Here, a mechanistic explanation is proposed for the control of the diversion angle on the morphological response of the abandoned channel to cut-off. The effects of the diversion angle on bed-material transport are due to its control on the development of a flow separation within the entrance to the abandoned channel, which affects the volume of flow being diverted and the boundary shear stress conditions within the channel entrance. This analysis, based on the sedimentary records stored within oxbow lakes of the Sacramento River of California, USA, supports the generality of the Fisk (1947) model and provides a mechanistic framework from which a physically based model of oxbow alluviation can be constructed. The present work also provides an additional means for explaining the diverse sedimentary records that make up the alluvial architecture of the floodplain environment.

**PHYSICAL SETTING**

The Sacramento River produces an average annual discharge of 350 m$^3$ sec$^{-1}$ (US Geological Survey [USGS] gauge 11377100) from precipitation that ranges between 50 and 178 cm year$^{-1}$ (Buer, 1994). The river flows within a tectonically produced valley and its 68 000 km$^2$
watershed drains portions of the crystalline Sierra Nevada and Klamath Mountains, the sedimentary formations of the Great Valley and Coast Ranges, and the southern end of the volcanic Cascades and Modoc Plateau (Norris & Webb, 1976). The hydrograph includes an important snowmelt component from higher elevations and spring flow from the volcanic terrain near Mount Shasta and Mount Lassen, but channel-altering floods usually occur in response to large winter rainstorms and rapid melting of the Sierra Nevada snow pack. Channel-altering floods have been regulated since 1945 by several large dams, the effect of which has reduced the two and 10 year annual maximum discharges at river kilometre 240 from 3300 and 5800 m$^3$ sec$^{-1}$ to 2100 and 3800 m$^3$ sec$^{-1}$ (USGS gauge 11377100). Samples of bed material retrieved from the river include a wide range of grain-sizes, from silt and clay up to 128 mm particles, although the representation of particles finer than 0.5 mm is typically only a few per cent (Singer, 2008; figure 2). Long-term average bed-load transport along the study reach varies from 0.1 to 1.0 Mt year$^{-1}$ (Singer & Dunne, 2004). Suspended load, mostly finer than 0.06 mm, averages 12 Mt year$^{-1}$ (USGS gauge 11389500), but some evidence suggests that sediment concentrations have declined slowly since flow regulation (Wright & Schoellhamer, 2004).

The present study focused on a 133 km long reach where the channel remains well-connected to the surrounding floodplain, located between the communities of Red Bluff (river kilometre 230) and Princeton (river kilometre 391) (Fig. 2). The study reach was divided into an upper segment and a lower segment (Table 1), based on differences in channel slope. Cross-sections of the study reach were extracted from a 1997 bathymetric survey by the US Army Corps of Engineers (USACE) and used in the Hydrologic Engineering Center’s River Analysis System (HEC-RAS) simulations to establish general flow characteristics for each segment (Table 1). Thirteen oxbow lakes were selected for study based on field accessibility (Table 2). Three of the lakes formed by neck cut-off, which occurs by bank collapse once meanders have migrated into one another (Gagliano & Howard, 1984; Hooke, 1995). The remaining lakes formed by chute cut-off, which results after floods incise a floodplain chute that evolves gradually into the dominant conveyor of river discharge (Hooke, 1995; Gay et al., 1998). The formation and evolution of the 13 lakes was documented by means of 18 sets of digitized aerial photographs spanning the years 1938 to 2004.

**METHODOLOGY**

The onset of abandonment of an oxbow lake was defined as the midpoint of the time between the latest aerial photograph before cut-off (when only a single channel existed) and the earliest aerial photograph after cut-off (when two channels existed, one of which was either still connected to or separated from the
active channel). The cut-off ages of seven of the studied lakes occurred before the present record of historical photographs began (Table 2). A minimum age of five of these lakes was determined using the earliest historical map showing an abandoned channel (Greco & Alford, 2003). The age of Old Packer Lake was based on a basal radiocarbon date from a sediment core reported by Sullivan (1982). The diversion angle (Fig. 1) of each lake (Table 2) was measured using the earliest available aerial photograph after cut-off. The degree of channel shortening by cut-off ($\gamma$) was measured as the ratio of the length of abandoned channel to that of active channel between the lake arms (Table 2), and also with the earliest available aerial photograph after cut-off. The active-channel bankfull width of each lake was determined by measuring the distance perpendicular to the channel between vegetated banks at a minimum of four locations using the latest aerial photograph before cut-off, or the earliest aerial photograph after cut-off if the former was unavailable. The width of the modern lakes similarly was measured with the most recently available aerial photographs.

The thickness of fine-grained material (sand and finer) stored within each of the studied lakes was measured using a soil auger and total station survey (Fig. 3). Although a small amount of fine gravel can occasionally be incorporated, the auger could not penetrate more than a few centimetres into gravel-rich sediment. Between three and five cores were collected at the apex of each lake and sediment was sampled every 10 to 15 cm through one of the cores collected from each of six lakes.

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**Table 1.** Study reach characteristics of the Sacramento River.

<table>
<thead>
<tr>
<th>Reach segment</th>
<th>Upper</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>River kilometres</td>
<td>391 to 311</td>
<td>311 to 258</td>
</tr>
<tr>
<td>Bankfull discharge (m$^3$ sec$^{-1}$)*</td>
<td>1780</td>
<td>1840</td>
</tr>
<tr>
<td>Average bankfull width (m ± 1σ)*</td>
<td>259 (±109)</td>
<td>259 (±60:3)</td>
</tr>
<tr>
<td>Average bankfull pool depth (m ± 1σ)*</td>
<td>9:0 (±2:34)</td>
<td>9:12 (±2:08)</td>
</tr>
<tr>
<td>Cross-sectionally averaged downstream flow velocity (m sec$^{-1}$ ± 1σ)*</td>
<td>1·8 (±0·35)</td>
<td>1·4 (±0·27)</td>
</tr>
<tr>
<td>Average bed slope ($S$)</td>
<td>5·40 $\times 10^{-4}$</td>
<td>3·30 $\times 10^{-4}$</td>
</tr>
<tr>
<td>Average bed material ($d_{50}$)† (mm ± 1σ)</td>
<td>28:6 (±12:8)</td>
<td>13:5 (±10:2)</td>
</tr>
</tbody>
</table>

* Determined from HEC-RAS simulations using Army Corps of Engineers and USGS cross-section data.
† The median particle diameter, $d_{50}$ (Singer, 2008).

**Table 2.** The oxbow lakes of the Sacramento River examined in this study.

<table>
<thead>
<tr>
<th>Lake name</th>
<th>Location (river km)</th>
<th>Cut-off age* (cal yr BP)</th>
<th>Diversion angle† (±3°)</th>
<th>Cut-off ratio ($\gamma$)</th>
<th>Number of cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Barranca</td>
<td>381:2</td>
<td>1976</td>
<td>50</td>
<td>1·2</td>
<td>3</td>
</tr>
<tr>
<td>Ohm</td>
<td>376:7</td>
<td>1976</td>
<td>75</td>
<td>2·4</td>
<td>3</td>
</tr>
<tr>
<td>Rio Vista</td>
<td>342:9</td>
<td>1976</td>
<td>40</td>
<td>3·2</td>
<td>4</td>
</tr>
<tr>
<td>Wilson Landing</td>
<td>326:8</td>
<td>1969</td>
<td>75</td>
<td>2·4</td>
<td>3</td>
</tr>
<tr>
<td>Indian Fishery</td>
<td>314:0</td>
<td>1937</td>
<td>75</td>
<td>3·8</td>
<td>3</td>
</tr>
<tr>
<td>Jenny Lind Bend</td>
<td>314:0</td>
<td>1920‡</td>
<td>50</td>
<td>3·8</td>
<td>4</td>
</tr>
<tr>
<td>Phelan Island</td>
<td>305:9</td>
<td>1870‡</td>
<td>25</td>
<td>3·2</td>
<td>3</td>
</tr>
<tr>
<td>Duck Lake</td>
<td>291:1</td>
<td>Before 1870</td>
<td>110</td>
<td>2·5</td>
<td>3</td>
</tr>
<tr>
<td>Beehive Bend</td>
<td>273:7</td>
<td>1896‡</td>
<td>90</td>
<td>2·8</td>
<td>3</td>
</tr>
<tr>
<td>Young Rasor Slough</td>
<td>271:8</td>
<td>1969</td>
<td>50</td>
<td>1·5</td>
<td>5</td>
</tr>
<tr>
<td>Old Packer Lake</td>
<td>271:1</td>
<td>1176§</td>
<td>80</td>
<td>1·2</td>
<td>3</td>
</tr>
<tr>
<td>Packer Lake</td>
<td>269:2</td>
<td>1870‡</td>
<td>105</td>
<td>14·7</td>
<td>5</td>
</tr>
<tr>
<td>Boggs Bend</td>
<td>259:5</td>
<td>1923‡</td>
<td>85</td>
<td>5·3</td>
<td>4</td>
</tr>
</tbody>
</table>

* Measured as the midpoint of the time between the latest aerial photograph before cut-off and the earliest aerial photograph after cut-off, unless otherwise noted.
† Measured using the latest aerial photograph preceding meander cut-off or the oldest photograph available.
‡ Date based on the earliest historical map showing the cut-off channel and represents a minimum age.
§ Date based on the radiocarbon measurement reported by Sullivan (1982).
for granulometric analysis. The first-refusal depth, taken as the depth to a gravel surface, was measured at each core location relative to a fixed point at the top of the outer bank near the apex of each lake. The gravel surface could represent either the original main channel surface or the surface of gravelly bed material from the active channel that aggraded the abandoned channel while it was connected hydraulically. A method for estimating the form of the original active channel was needed to calculate the thickness of gravel accumulation beneath this buried surface because bathymetric data from before cutoff are not available. With an estimate of the original channel form, aggradation could then be recognized wherever the first-refusal depth was less than the estimated original channel depth (Fig. 3). In this effort, bathymetry and radii of curvature measured along the modern Sacramento River were used in the following theoretical relation developed by Falcón Ascanio & Kennedy (1983, equation 22), which estimates bankfull depth anywhere along a cross-section based on a momentum balance of flow at the channel bed and the assumption that the transverse bed profile is in equilibrium (i.e. the radial plane forces sum to zero):

\[
\frac{1}{\sqrt{D(\zeta)}} - \frac{1}{\sqrt{D_c}} = \frac{\sqrt{8\theta}}{1 - \lambda} \left( \frac{1}{\sqrt{r(\zeta)}} - \frac{1}{\sqrt{r_c}} \right) \left[ \frac{8S_c r_c \alpha}{fd_{50}(\rho_s - \rho)} \right]^{0.5}
\]

(1)

where \(D\) represents the active-channel bankfull depth at some radial location \(\zeta\) along a transversely oriented cross-section, \(D_c\) represents bankfull depth at the channel centreline, \(\lambda\) represents the porosity of the bed surface, \(\theta\) represents dimensionless boundary shear stress equated to a Shields number of 0.07 from the empirically based estimate of Singer & Dunne (2004), \(f\) represents the Darcy–Weisbach friction factor, \(r\) represents the local radius of curvature at a radial location, \(r_c\) represents the local radius of curvature at the centreline, \(S_c\) represents the downstream bed slope along the centreline, \(\alpha\) represents a boundary shear stress reduction factor equal to 1.0 for this study, \(\rho_s\) represents particle density, \(\rho\) represents fluid density and \(d_{50}\) represents the median particle size of sediment. The variable \(f\) was measured as:

\[\sqrt{\frac{8\theta}{1 - \lambda}} \left( \frac{1}{\sqrt{r(\zeta)}} - \frac{1}{\sqrt{r_c}} \right) \left[ \frac{8S_c r_c \alpha}{fd_{50}(\rho_s - \rho)} \right]^{0.5}\]
where \( g \) represents gravitational acceleration and \( U \) represents the cross-sectionally averaged downstream bankfull flow velocity that was established for both segments using HEC-RAS simulations (Table 1).

Predictions of Eq. 1 were compared with channel cross-sections of the modern Sacramento River extracted from the 1997 bathymetric survey by the USACE. The variable \( r_c \) was determined after a method by Fagherazzi et al. (2004) that uses a cubic spline to measure local curvature at regularly spaced points along a digitized channel centreline, and \( S_c \) was estimated by equating it to the average downstream bed slope, \( S \). Values for variables and constants used in solving Eq. 1 are provided in Tables 1 and 3. The equation was only applied along freely meandering sections of the channel in the study reach away from revetments that might force scour along the outer bank (Thorne, 1992). The presence of mid-channel bars, a function of conditions not directly related to meandering flow (Church & Jones, 1982), can lead to an over-estimate of bankfull volume and cannot be predicted using Eq. 1, and so the equation was only applied at single-threaded sections where such bars are absent.

RESULTS AND DISCUSSION

Observations of morphological change and oxbow alluvium

From the record of aerial photographs, it was observed that some abandoned channels narrowed prior to complete hydraulic disconnection (Fig. 4), presumably because flow and sediment transport through these channels were sufficient to promote bar growth but not bank erosion. Proportional differences in channel width before and after cut-off (\( \Delta w \)) of the studied lakes (based on the difference in the distance between vegetated banks using the latest aerial photograph before cut-off or the earliest after cut-off, if the former was unavailable, and the most recently available photograph) ranged from 5% to 82% and showed no significant correlation with location along the study reach \( (r^2 = 0.34, P > 0.05) \), cut-off age \( (r^2 = 0.27, P > 0.1) \) or the degree of channel shortening by cut-off, \( \chi \) \( (r^2 = 0.41, P > 0.1) \). However, \( \Delta w \) did exhibit a significant and negative correlation \( (P < 0.001) \) with the diversion angle \( (\alpha) \) (Fig. 5), implying that narrowing of the abandoned channel by bar growth was greater in channels with low diversion angles. Due to the incomplete record of aerial photographs, it was difficult to determine accurately when each of the lakes became hydraulically disconnected and so narrowing rates were not measured.

Although coring samples provided a limited estimate of the texture of the gravel surface because only a small sample could be recovered from the impenetrable layer, samples (average dry weight of 130 ± 79 g) retrieved from the gravel surface at the apices of six of the lakes indicate that sediment in the size range of 11 to 22 mm was in motion when the bed rose to the first-refusal depth (Fig. 6). The median particle size of fractions coarser than silt ranged from 0.33 to 10 mm between the samples. The average depth to the gravel surface near the outer bank at the apices of each lake ranged from 5 to 11 m relative to the bank surface. Differences in the average depth to the gravel surface between each lake exhibited no significant correlation with location along the study reach \( (r^2 = 0.31, P > 0.1) \), cut-off age \( (r^2 = 0.31, P > 0.05) \) or \( \chi \) \( (r^2 = 0.05, P > 0.1) \) but did exhibit a significant \( (P < 0.001) \) and positive

### Table 3. Values for variables and constants used in solving equations in the text.

<table>
<thead>
<tr>
<th>Variable or constant</th>
<th>Upper segment</th>
<th>Lower segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average bankfull depth at centreline ( (D_c) ) (m ± 1σ)*</td>
<td>5.45 (±1.37)</td>
<td>6.22 (±1.10)</td>
</tr>
<tr>
<td>Dimensionless boundary shear-stress ( (\theta) )</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Porosity of the bed surface ( (\lambda) )</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Darcy–Weisbach friction factor ( (f) )</td>
<td>0.075</td>
<td>0.085</td>
</tr>
<tr>
<td>Gravitational acceleration ( (g) ) (m sec(^{-2}))</td>
<td>9.81</td>
<td>9.81</td>
</tr>
<tr>
<td>Particle density ( (\rho_p) ) (kg m(^{-3}))</td>
<td>2650</td>
<td>2650</td>
</tr>
<tr>
<td>Fluid density ( (\rho) ) (kg m(^{-3}))</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

* Determined from HEC-RAS simulations using Army Corps of Engineers and USGS cross-section data.

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correlation with $\alpha$ (Fig. 7), implying that lakes with low diversion angles were more greatly filled by gravel.

Estimating the form of the original active channel

Three issues became evident after comparing the solutions of Eq. 1 to established cross-sections of the modern Sacramento River. Firstly, the derivation of Eq. 1 is based on the transverse force balance at the channel bed during steady, fully developed flow. Where $D_c r_e^{-1} > 1$, the role of convective acceleration in the force balance can be neglected. Falcón Ascanio & Kennedy (1983) did not specify a $D_c r_e^{-1}$ value above which convective acceleration needs to be considered, but the present study found that Eq. 1 adequately predicts pool depths of the modern Sacramento River only when $D_c r_e^{-1} \leq 1.5\%$ (Fig. 8). Secondly, solutions to the equation are sensitive to channel width; holding all other variables constant, it will predict deeper pools in wider channels. Lastly, the equation predicts pool depths reliably to within ca 2 m, but its prediction of the entire cross-section ignores well-known transverse variations in flow velocity and bed-material composition (see Dietrich et al., 1979; Dietrich & Smith, 1984; Parker & Andrews, 1985; Nelson & Smith, 1989; Dietrich et al., 1979; Dietrich & Smith, 1984; Parker & Andrews, 1985; Nelson & Smith, 1989;
As a result, it overestimates bankfull depths across bars by underestimating the transverse bed slope (Fig. 9). This shortcoming would result in an over-estimate of bankfull volume per unit channel length at a section by as much as 50%.

Given the tendency for Eq. 1 to under-estimate the transverse bed slope, an empirical method was devised to improve predictions of the active-channel surface. It was assumed that the transverse bed slope ($S_r$) was in equilibrium with cross-stream flow and sediment transport and, similar to Odgaard (1982) and Johannesson & Parker (1989), that $S_r$ is spatially constant across a section. Hence, the bankfull depth within any cross-section is:

$$D(\zeta) = D_{\text{max}} - S_r \zeta$$

where, at the outer bank, $\zeta$ is zero and $D_{\text{max}}$ represents the value of $D$ written as a positive number. In the Sacramento River, the transverse super-elevation of the water surface contributes...
only decimetres to bankfull depth and was not considered in estimating transverse bed slope. Thus, the solution for \( S_r \) after Falco´n Ascanio & Kennedy (1983) was written as:

\[
S_r = \frac{\tau_{0r}}{y_b g (1 - \lambda)(\rho_s - \rho)}
\]  

(4)

where \( \tau_{0r} \) represents the transverse component of boundary shear stress at the centreline and \( y_b \) represents the nominal thickness of mobile sediment upon which shear stress and gravity are acting. Using the theoretical relation described by Chang (1988, equation 8.35), the transverse component of boundary shear stress was determined as:

\[
\tau_{0r} = \rho U^2 \left( \frac{1 + m}{2 + m} \right) \frac{D(\zeta)}{r(\zeta)}
\]  

(5)

where \( m \) is defined as:

\[
m = \kappa \left( \frac{8}{\lambda} \right)^{0.5}
\]  

(6)

and \( \kappa \) represents von Karman’s constant. Given the assumption here of a spatially constant transverse bed slope, the ratio of \( D(\zeta) \) to \( r(\zeta) \) in Eq. 5 can be evaluated at the outer bank where \( D(\zeta) \) equals \( D_{\text{max}} \) and \( r(\zeta) \) equals \( r_c + 0.5w_a \), where \( w_a \) represents the width of the abandoned channel.

Karim (1981) and others have argued that, in a sand bedded river, \( y_b \) represents the thickness of the saltating layer envisioned by Einstein (1950) and Abbott & Francis (1977). In a gravel bedded river, the thickness is likely to be associated with the time-averaged fraction of the surface layer that is intermittently in motion when the downslope component of its weight per unit area is balanced against the transverse component of boundary shear stress. Although relationships have been inferred (see Karim, 1981), no theoretical means exists currently to determine \( y_b \) at a section. Consequently, an empirical means was developed here for estimating \( y_b \) and Eq. 4 was rearranged to solve for this variable at 30 cross-sections of the study reach. The transverse bed slope was determined by fitting linear regressions through the bathymetry of point bar cross-sections and the depth was measured at the outer bank directly

Fig. 8. Comparison of measured pool depths of the Sacramento River to predicted measures using Eq. 1. Dark circles represent data points from cross-sections where the ratio of the centreline bankfull depth (\( D_c \)) to local radius of curvature (\( r_c \)) > 1.5%. Open circles represent data points where the ratio ≤1.5%. The shaded region represents the interval ±2 m about the 1:1 regression, shown as a dashed line.

Fig. 9. Bankfull depths based on solutions to Eqs 1 and 8 across the three cross-sections of the Sacramento River, the locations of which are inscribed within each graph. Measured data are based on bathymetric data provided by the US Army Corps of Engineers.
from the bathymetry. Values for the remaining variables and constants were obtained from Tables 1 and 3. As a result, the measure of \( y_b \) correlated negatively and significantly (\( P < 0.01 \)) with the local radius of curvature at the channel centreline \( (r_c) \) (Fig. 10), presumably due to the influence of \( r_c \) on the transverse component of boundary shear stress caused by centrifugal acceleration of the active-channel flow. The regression equation defining the relationship between the variables is:

\[
y_b = 1.4r_c^{-0.77} \quad (7)
\]

and its substitution into Eq. 4 allows Eq. 3 to be rewritten as:

\[
D(z) = D_{\text{max}} - \left[ \frac{r_c^{0.77}U^2}{1.4g(1-\lambda)(r_c+0.5w_a)(\rho_s-\rho)(2+m)} \right] D_{\text{max}} - \frac{\rho}{(1+m)} \quad (8)
\]

Using estimates of \( U \) based on HEC-RAS simulations (Table 1), solutions to Eq. 8 improve predictions of bankfull depth across a section (Fig. 9) to within 20% of the actual active-channel bankfull volume per unit channel length at each of the 30 cross-sections used for the calibration. It is important to note, however, that reconstructing the transverse profile of the channel using the equation assumes that the point bar ends abruptly at the outer bank, which is not true at every section. Furthermore, estimates of bankfull volume within a reach assume that the downstream slope of the water surface does not vary in the downstream direction.

Equation 8 was used to estimate the formerly active-channel bed surface within each of the studied lakes. A channel centreline was digitized within each lake and \( r_c \) was measured as described above at 50 m spaced centreline points. At each centreline location, a transversely oriented cross-section was digitized equal in length to the original active-channel bankfull width, \( w_a \), and \( D_{\text{max}} \) was determined using Eq. 1. Because Eq. 1 tends to over-predict \( D_{\text{max}} \) wherever \( D_c > 1.5\% \), the minimum radius of curvature was defined at the centreline \( (\hat{r}_c) \) that allows for accurate estimates of \( D_{\text{max}} \) as:

\[
\hat{r}_c = \frac{D_c}{w_a} \quad 0.015w_m \quad (9)
\]

where \( w_m \) represents the modern average bankfull width of the study reach. Over-tightened sections were recognized wherever \( \hat{r}_c > r_c \); when the condition was true, \( \hat{r}_c \) was substituted for \( r_c \) in Eq. 1. Next, Eq. 8 was applied to estimate \( D(z) \) every 10 m across the section from the outer bank. It was assumed that the modern conditions of the Sacramento River approximate conditions during the formative history of the studied lakes because the planform characteristics of the river have not changed significantly over the past century (Buer, 1994). Finally, a continuous map was constructed of the active-channel surface within each lake by fitting a regularized spline through the solutions to the equations (Fig. 11). By assuming vertical banks within each of the studied lakes, the spline was used to estimate the active-channel bankfull volume for a reach before it was abandoned by cut-off.

Fig. 10. The nominal thickness of the bed that is susceptible to movement \( (y_b) \) as predicted using a method described in the text plotted against the local radius of curvature at the channel centreline \( (r_c) \).

Fig. 11. Map of the original active-channel bankfull depths of Wilson Lake, located at river kilometre 326.8 of the Sacramento River, based on solutions to Eq. 8. The locations of cross-sections for which solutions were obtained are shown as an inset, as well as an aerial photograph of the lake taken in 2004.
Estimates of the gravel thickness at lake apices

Based on the present maps of the active-channel surface, the thickness of gravel stored beneath the three to five sediment cores taken from each lake apex was estimated as the difference between the depth to the gravel surface and the original channel depth beneath each core. The average thickness of stored gravel ranged from 0.5 to 4.1 m and exhibited no significant correlation with location along the study reach ($r^2 = 0.13$, $P > 0.2$), cut-off age ($r^2 = 0.04$, $P > 0.05$) or $\chi$ ($r^2 = 0.06$, $P > 0.2$). As with the average depth to the gravel surface, the average thickness of stored gravel exhibited a significant ($P < 0.01$), but negative, correlation with $\alpha$ (Fig. 12), suggesting that the greater the diversion angle, the smaller the volume of bed material being stored.

The volume of bed material that can accumulate in an abandoned channel is determined by the time period during which it receives sufficient flow to transport gravel from the active channel. The duration of such a competent hydraulic connection depends upon the aggradation rate within the abandoned-channel entrance; the more quickly the bed aggrades within the entrance, the more quickly the abandoned channel becomes disconnected and aggradation by bed-material load stops. Oxbow lakes of the Sacramento River with low values of $\alpha$ contained a smaller thickness of stored bed material at the apex, implying the converse. The present empirical findings are consistent with the Fisk (1947) model and suggest its generality, but the need remains for a mechanistic explanation of the control of $\alpha$ on flow conditions within the entrance to the abandoned channel.

Effect of the diversion angle on diverted discharge

Results from flume studies show that as the diversion angle increases, discharge through the abandoned channel ($Q_a$) decreases (Vanoni, 2006) and a separation zone that exists along the inner bank of the channel entrance (Taylor, 1944; Law & Reynolds, 1966; Neary & Odgaard, 1993) widens (Keshavarzi & Habibi, 2005). By assuming uniform flow conditions and a hydrostatic pressure distribution, Hager (1984) derived a theoretical relation that describes the flow structure as a function of $\alpha$ and $Q_a$. The flow structure within the entrance was characterized first using ratios of the maximum width of the separation zone ($b_1$) and the minimum width of the downstream flow cross-section ($b_2$) to the abandoned-channel width, where $\varepsilon = b_1w_a^{-1}$, $\mu = b_2w_a^{-1}$ and $\varepsilon + \mu = 1$ (Fig. 1). Based on a momentum balance of the flow within the channel entrance, Hager (1984, equation 14) then determined the fractional width of the downstream current ($\mu$) as:

$$\mu = \left(1 + \sqrt{1 + \frac{1}{q^2} - \frac{2\cos(3\alpha/4)}{q}}\right)^{-1}$$  \hspace{1cm} (10)

where $q$ represents the ratio of $Q_a$ to the undivided, active-channel discharge upstream of the flow diversion. Solutions to the equation show that the downstream flow in the channel cross-section narrows with increases in $\alpha$ and widens with increases in $q$ (Fig. 13). Furthermore, $q$ declines with decreases in the fractional width of the downstream current for a given $\alpha$ because a widening separation zone induces increased pressure drag on the diverted flow, thereby reducing discharge through the abandoned channel.

A means was developed here for determining $Q_a$ for any $\alpha$ based on Eq. 10, but first it was necessary to derive an independent measure of $\mu$ because no theoretical relation currently exists to estimate the variable without knowledge of
discharge conditions. To derive this independent measure, simulation experiments were conducted using the Multi-Dimensional Surface Water Modeling System (MD-SWMS) of the US Geological Survey (Nelson et al., 2003) and \( \mu \) was measured over varying values. MD-SWMS provides an interface to several hydrodynamic models. The particular model used in this case was FaSTMECH, which solves the vertically averaged, two-dimensional forms of the conservation of mass and momentum equations and allows for straightforward characterizations of the flow field.

In this simplified analysis of the control of \( \alpha \) on flow conditions, a post-cut-off scenario was modelled in which bankfull averages of width, depth and slope were the same for the active and abandoned channels. Such a scenario exists once the chute has deepened and widened enough to become the dominant conveyor of discharge while changes in the morphology of the abandoned channel were largely absent during chute incision. This scenario is consistent with observations of the cut-off process from aerial photographs of the Sacramento River. The active channel was designed as a straight, rectangular channel, the orientation of which was adjusted relative to a fixed abandoned channel to allow for six separate simulations with different values of \( \alpha \). The original active-channel topography of Duck Lake (denoted DL in Fig. 2), estimated by solutions to Eq. 8, was used as the abandoned-channel topography for the simulations where bankfull averages of width, centreline depth and slope equalled 160 m, 6.2 m and \( 3.3 \times 10^{-4} \), respectively. Roughness was estimated across the study segment using a spatially variable coefficient of drag based on flow depth and lateral eddy viscosity was treated as a constant equal to \( \xi D_c U \), where \( \xi \) represents a dimensionless coefficient of 0.001 for this study. The variable \( \mu \) was then measured as the relative width (where \( \mu = b_2 w_2^{-1} \)) of the zone of compressed, rapid flow being diverted from the main channel.

Results from the simulations (such as the one illustrated in Fig. 14A) show that the downstream flow cross-section narrows with increases in \( \alpha \) (Fig. 14B), yielding a relationship for typical Sacramento River conditions that was used here as the independent measure of \( \mu \):

\[
\mu = 0.94 e^{-0.013\alpha}
\]

(Fig. 13. The fraction (\( \mu \)) that the downstream current in the abandoned-channel entrance makes of the total width plotted against the fraction of total discharge in the abandoned channel (\( q \)) relative to the active-channel discharge upstream of the diversion. The plot is based on solutions to Eq. 10 for varying values of the diversion angle (\( \alpha \)).

Fig. 14. (A) Example of MD-SWMS output during steady, bankfull flow conditions, using the estimated topography of Duck Lake and a straight, box channel oriented such that the diversion angle equals 60°. Vectors indicate the vertically averaged, prevailing direction of flow. Shaded regions distinguish velocity zones, the values of which are provided in the legend. The variables \( \mu \) and \( \epsilon \) represent the fractions of the total abandoned-channel width occupied by the downstream flow cross-section and the zone of flow separation. (B) The fraction that the downstream current in the abandoned-channel entrance makes of the total width plotted against diversion angle (\( \alpha \)). Measures of \( \mu \) are based on steady, bankfull flow simulations by MD-SWMS, as shown in (A).
where $\alpha_{deg}$ represents $\alpha$ in units of degrees. Using the quadratic formula, Eq. 10 can be rewritten as the following to solve for $q$, where $0 \leq q \leq 1$:

$$q = \frac{1}{2/[1 - (1/\mu - 1)^2]} [2 \cos(3\alpha/4) - \sqrt{2 \cos(3\alpha/4)^2 - 4[1 - (1/\mu - 1)^2]}}$$

By substituting Eq. 11 into Eq. 12, $q$ can be determined theoretically for any $\alpha$ during conditions of steady, bankfull flow within the Sacramento River. However, when compared with results from the MD-SWMS simulations, Eq. 12 systematically over-predicts abandoned-channel discharge for any $\alpha$ (Fig. 15). The systematic over-prediction of $q$ may have resulted because the pressure gradient through the abandoned-channel entrance was insufficient to force the diversion of a significant portion of the active-channel flow, at least as modelled by MD-SWMS using the present estimates of drag and eddy viscosity. The formation of Eq. 10 assumes uniform flow conditions and that the pressure gradient is affected minimally by head losses through the entrance, thereby being of sufficient magnitude to divert flow from deep within the active channel (Hager, 1984). In addition, Eq. 12 does not consider variations in cross-sectional shape of the entrance and their effects on flow conditions. For instance, a narrow entrance due to the presence of a point bar would reduce the discharge being diverted. Yet, even in spite of the over-prediction, the Hager formula allows for an explanation of the effects of $\alpha$ to be expressed simply in physical terms, and so the linear regression that describes the over-prediction was used to calibrate solutions to Eq. 12. Given that the channel widths of the active and abandoned channels are the same in the post-cut-off scenario, discharge per unit channel width flowing through an abandoned channel ($Q_{av}$) of the Sacramento River was solved as:

$$Q_{av} = Q_{m} (0.047 + 0.51q)$$

where $Q_{av}$ represents the bankfull discharge per unit channel width of the active channel upstream of the diversion, estimated using channel characteristics found in Table 1, and $q$ is obtained from Eqs 11 and 12.

**Effect of the diversion angle on bed-material aggradation**

The downstream transport of bed material is driven by the downstream component of boundary shear stress, and Eq. 13 was used to examine the control of $\alpha$ on this variable within the abandoned channel. The Manning equation was rearranged here to solve for cross-sectionally averaged depth and the boundary shear stress in the abandoned channel ($\tau_{b,a}$) was written as:

$$\tau_{b,a} = \rho g S^{0.7} \left( \frac{nQ_{av}}{c} \right)^{0.6}$$

where $n$ represents the Manning coefficient equal to 0.035 based on previously calibrated hydraulic computations (USACE, 2002) and $c$ represents a coefficient of unity with dimensions of m$^{1/3}$ sec$^{-1}$. Using lower segment values (Table 1) to solve Eqs 13 and 14, it was found that, because of the effect of the diversion angle on abandoned-channel discharge, increases in $\alpha$ cause boundary shear stress to decrease nearly two-fold as $\alpha$ ranges over 0° to 120° (Fig. 16). The findings from this one-dimensional analysis confirm that the ability of the abandoned channel to transmit bed material becomes increasingly compromised by increases in $\alpha$. By determining the width of the separation zone at the inlet, the diversion angle controls the energy losses experienced by the diverted flow and consequently limits discharge and boundary shear stress within the abandoned channel. This sequence of effects provides the mechanism by which $\alpha$ directs the morphological response of the abandoned channel to cut-off. The manner of the response, however, is also a

---

Fig. 15. The ratio of the bankfull discharge within the abandoned channel to the bankfull discharge within the active channel upstream of the diversion as simulated by MD-SWMS ($Q_{m}$) plotted against the same variable, but as predicted using Eq. 12 ($q$).
function of the quantity and nature of bed material being diverted from the active channel.

Lindner (1953) reviewed results from flume studies detailing the effects of channel diversions on the routing of flow and bed load. Holding $\alpha$ constant, Lindner reported that the majority of bed load transported by the channel upstream of the diversion was delivered into the diversion channel by cross-channel, near-bed flow whenever $q \geq 30\%$. Lindner also reported that the proportion of bed load delivered to the diversion was nearly independent of variations in $\alpha$ (>90% of bed load was diverted over a range of $\alpha$ values between 30° and 150°) when the dimensions of the diversion and the active channel were the same and $q = 50\%$. Schoenfliksch, quoted in Vanoni (2006), reported similar results from flume experiments. To explain why the diverted flow transports most of the bed load, Lindner (1953) and Vanoni (2006) both proposed that the faster near-surface flow within the active channel requires a greater cross-channel pressure-gradient force to adjust its course, whereas the slower, bed-material laden, near-bed flow is turned into the diversion within a shorter travel distance. Early in the cut-off process when the shallow depth of the newly incised chute prevents the delivery of bed material into the chute, all of the bed load transported by the active channel will be transmitted into the abandoned channel. According to the flume studies, most of this load will continue into the abandoned channel even after the chute depth approximates that of the active channel, at least until flow through the abandoned channel has been reduced significantly by deposition of diverted bed material.

To examine the effects of $\alpha$ on the aggradation of the abandoned-channel entrance during bankfull conditions, the Shields formula was utilized to illustrate the impact on sedimentation in a general way even though it is not necessarily the most accurate predictor of absolute rates of bed-material transport. As such, the downstream transport capacity of bed-material load per unit channel width of the active channel ($G_m$) was estimated as:

$$G_m = 10Q_mS\frac{(\tau_{0,m} - \tau_c)}{gd_{50}(\gamma_s/\gamma - 1)^{\frac{3}{2}}}$$  \hspace{0.5cm} (15)

where $\tau_{0,m}$ represents the boundary shear stress in the active channel, $\tau_c$ represents the boundary shear stress required to initiate transport of bed material, $\gamma_s$ and $\gamma$ represent the particle and fluid specific weights, and $Q_m$ and $S$ were based on lower segment characteristics (Table 1); $\tau_{0,m}$ was determined as:

$$\tau_{0,m} = \rho gD_sS$$  \hspace{0.5cm} (16)

and $\tau_c$ as:

$$\tau_c = \frac{g(\gamma - \rho)}{d_{50}}$$  \hspace{0.5cm} (17)

using lower segment characteristics (Table 1). For simplicity, conditions of equal mobility (see Parker et al., 1982) were assumed within the active channel and the fractional transport capacity ($G_{m,d,i}$) was estimated for each size class ($d_i$) making up the active-channel bed as:

$$G_{m,d,i} = p_iG_m$$  \hspace{0.5cm} (18)

where $p_i$, based on bed-material grain-size data collected by Singer (2008) within the lower segment of the Sacramento River, represents the fraction that a particular size class contributes to the total mass in transport. Equation 18 was solved for two distinctly different bulk samples of bed material collected by Singer (2008), the first with a $d_{50}$ of 4.5 mm (geometric sorting coefficient of 6.4) and the second with a $d_{50}$ of 11.6 mm (geometric sorting coefficient of 2.8). It was then assumed that each size class of diverted bed material would be transported within the abandoned channel at a rate proportional to the difference between boundary shear stress and the shear stress required to initiate motion of a particular size class. Thus, the fractional transport capacity per unit channel width of the abandoned channel ($G_{a,d,i}$) was defined after the Shields formula, in which:

\hspace{1cm}
where \( Q_{n} \) and \( \tau_{o} \) were calculated using Eqs 13 and 14. \( S \) was set equal to that of the lower segment, and \( \tau_{c.d.i} \) represents \( \tau_{c} \) for a particular size class, determined by substituting \( d_{i} \) for \( d_{50} \) into Eq. 17. Based on the discussion of Lindner (1953) and Vanoni (2006), the entrance aggradation rate within the abandoned-channel entrance was determined using a mass balance between sediment transport from the active channel and transport down the abandoned channel beyond the separation zone, written as:

\[
\frac{d h}{d t} = - \frac{1}{\rho} \left( \frac{1}{1 - \lambda} \right) \sum_{i=1}^{c} \left( \frac{G_{a.d,i} - G_{m.d,i}}{\Delta s} \right)
\]

where \( d h / d t \) represents the rate of change in bed elevation \( (h) \) with time \( (t) \) in the entrance of the abandoned channel and \( \Delta s \) represents the channel length through the entrance over which aggradation is taking place.

The aggradation of bed material within the abandoned-channel entrance forms a wedge of sediment that gradually disconnects and plugs the channel. Using the most recent aerial photographs of the studied lakes, the lengths of these sediment plugs were measured (as the distance between lake edge and active-channel bank) and it was found that they ranged from 300 to 1800 m, showing no significant correlation with \( z \) \((r^{2} = 0.03, P > 0.1) \) or cut-off age \((r^{2} = 0.15, P > 0.2) \). The development of sediment plugs by overbank deposition has been examined in the field (Citterio & Pieguy, 2000; Pieguy et al., 2002), but very little is known about the process of plug development by bed-material aggradation. It is therefore difficult to ascertain any control of \( z \) on resulting plug lengths without a detailed study of the mechanics of plug formation. Qualitative reasoning suggests that the earliest deposition would be in the separation zone and in the zone immediately down-channel of the separation where the diminished, diverted flow expands across the abandoned channel; headward aggradation should then gradually plug the intake while a gradually decreasing amount of sediment is transported down the abandoned channel. It is clear that there is much about this process to explore by more complete sediment-transport modelling of the supply rates and the local distribution of deposition within the abandoned-channel entrance and the separation zone.

However, in order to focus on the effects of \( z \) on rates of bed-material aggradation, the present study chose to treat the distance over which aggradation occurs as a constant and the average of the measures of plug length, equal to 670 m \((1 \sigma = 150 \text{ m}) \), was used as an estimate of \( \Delta s \). In the application of Eq. 20, solved over a range of \( z \) values, it was further supposed that the bed of the abandoned channel was inaccessible to diverted flow because the volume of bed material diverted from the active channel would shield the bed from erosion, and so only those size classes where \( G_{a.d,i} \leq G_{m.d,i} \) were included in the summation.

Solutions to Eq. 20 illustrate the control of \( z \) on bed-material aggradation within the abandoned-channel entrance (Fig. 17). While aggradation rates increase linearly with \( z \) (by roughly 1.3 fold as \( z \) ranges over 0° to 120°), their magnitudes are clearly a function of bed-material composition. When the bed of the active channel is coarse, the capacity for bed-material transport is low and little sediment is diverted into the abandoned channel, leading to low rates of aggradation regardless of \( z \). When the bed of the active channel is fine, the capacity for bed-material transport is high and a great amount of sediment is diverted into the abandoned channel, leading to high rates of aggradation and a greater sensitivity to \( z \). The findings suggest that, if all other variables are held constant, abandoned channels should become hydraulically disconnected more quickly where the active-channel bed tends to be finer. A morphodynamic model that accounts for spatial variations in \( \tau_{c} \) and \( \tau_{o} \) (Ferguson, 2003), as well as the effects of changes in the nature and quantity of diverted bed material, would allow a

![Fig. 17. The aggradation rate in the abandoned-channel entrance \((d h / d t)\), as determined using Eq. 20, plotted against the diversion angle \((z)\) for two different grain-size distributions of bed-material samples from the lower segment of the Sacramento River (Singer, 2008). The median particle size of each distribution \((d_{50})\) is provided.](image-url)
more precise examination of the control of \( z \) on the morphological evolution of abandoned channels. The development of any such model for use in studying oxbow alluviation should also account for the formation of a sediment plug within the downstream junction of the abandoned and active channel, a process which was not considered here and one that may affect patterns of fine-grained sediment deposition within the oxbow lake (Citterio & Piégay, 2000; Piégay et al., 2000).

**Implications for the development of the floodplain environment**

Given that neck cut-off occurs as the product of meanders that have migrated into one another, the process tends to produce oxbow lakes with larger diversion angles than those produced by chute cut-off. The three lakes that formed by neck cut-off along the Sacramento River (Duck Lake, Beehive Bend and Packer Lake) have the largest diversion angles among the 13 lakes examined, store greater volumes of fine-grained sediment, and have existed as aquatic habitat for over a century (Fig. 18A). Chute cut-off occurs by the incision of a new channel into the floodplain and so produces abandoned channels with a greater range of diversion angles but consistently lower than those produced by neck cut-off. This observation is true along the Sacramento River, and the lakes that formed by this process tend to have greater volumes of stored coarse-grained sediment and in many cases have filled in completely, or become terrestrialized, within decades of cut-off (Fig. 18B). Although a global analysis of typical diversion angles associated with each meander cut-off process is required, that cut-off processes may produce oxbow lakes with characteristically different diversion angles has important implications for the development of the floodplain environment. Meandering rivers dominated by neck cut-off may contain floodplains with a larger volume of sediment accommodation space for storing fine-grained sediment than those rivers dominated by chute cut-off, potentially leading to floodplains with distinct alluvial architecture. The relative frequency of cut-off processes operating along a meandering river is a function of a number of variables that vary systematically with geography, including valley slope, the structure of floodplain vegetation, hydrological regime and sediment loading (Constantine, 2008). Consequently, the geomorphic and sedimentological characteristics of the floodplain should then be systematic functions of the environmental context in which the meandering river is located.

**CONCLUSIONS**

Differences in the morphological evolution of oxbow lakes can be explained by differences in flow conditions within their entrances while they remained hydraulically connected to the active channel. Flow diverted into a channel recently abandoned by meander cut-off encounters a separation zone within the channel entrance. The width of the separation zone, and thus the degree to which the diverted flow experiences pressure drag, is controlled by the diversion angle between the approaching active-channel flow and the abandoned-channel.

![Fig. 18. (A) Aerial photograph of Packer Lake, located near river kilometre 269.2, taken in 2004. Packer Lake has existed as aquatic habitat since its formation by neck cut-off in 1870. (B) Aerial photograph of Hartley Island, located near river kilometre 282, taken in 2004. An aerial photograph of Hartley Island taken in 1974 is also shown in Fig. 4. Hartley Island has almost been completely terrestrialized since its formation by chute cut-off in 1956.](image-url)
entrance; the wider this angle, the wider the separation zone. Increased pressure drag on the diverted flow reduces the discharge passing through the channel entrance, thereby reducing boundary shear stress and the bed-material transport capacity of the abandoned channel. As a consequence, the entrances to abandoned channels with high diversion angles rapidly aggrade, and these channels become quickly disconnected from the supply of continuous flow and bed material. By contrast, abandoned channels with low diversion angles sustain the ability to transport bed material and undergo considerable narrowing and filling as bed material that is transported past their entrances becomes gradually deposited along their lengths. Aggradation rates within abandoned-channel entrances are a function of the nature of bed material in transport within the active channel. When the bed of the active channel is fine, bed-material transport rates are high and more material is diverted into the abandoned channel, resulting in faster aggradation rates and a greater sensitivity to variations in diversion angle. Although this study did not observe differences in the morphological evolution of oxbow lakes with respect to channel location, differences between channels may exist where the context of landscape setting is an important control on the nature and quantity of sediment in transport.

ACKNOWLEDGEMENTS

The authors thank Stephen Rice and two anonymous reviewers for critiques that significantly improved the manuscript. The authors are grateful to Stephen McLean, Douglas Burbank, Candice Constantine, Carl Legleiter and Lee Harrison for providing helpful feedback on an earlier draft. Field access was provided by the Sacramento River National Wildlife Refuge and The Nature Conservancy. Aerial photographs of the Sacramento River were provided by the California Department of Water Resources. Field and technical assistance was provided by Julien Levrat, Candice Constantine, Michael Singer, Ryan Luster, Joseph Silveira, Carl Legleiter and Stephen McLean. A Eugene-Cota Robles Fellowship of the University of California provided student support for Constantine. The research was supported by CALFED Grant ERP-02D-P61 and the Don J. Easterbrook Award of the Geological Society of America.

NOTATION

\( x \) Diversion angle
\( z_{\text{avg}} \) Measure of diversion angle in degrees
\( b_1 \) Maximum width of separation zone within abandoned-channel entrance
\( b_2 \) Minimum width of the zone of flow contraction within abandoned-channel entrance
\( c \) Coefficient equal to 1·0 m\(^{1/3}\) sec\(^{-1}\)
\( C_d \) Coefficient of drag
\( \chi \) Fraction that the channel was shortened by meander cut-off
\( d_i \) Particle size class making up channel bed
\( d_{50} \) Median particle size making up channel bed
\( D \) Bankfull depth at a radial location
\( D_{\text{avg}} \) Cross-sectionally averaged bankfull depth
\( D_c \) Bankfull depth at channel centreline
\( D_{\text{max}} \) Maximum bankfull depth
\( e \) Fraction that the separation zone makes of the total width within the abandoned-channel entrance
\( g \) Gravitational acceleration
\( G_{i,d_i} \) Fractional transport capacity of bed-material load per unit channel width of abandoned channel for particular size class
\( G_m \) Downstream transport capacity of bed-material load per unit channel width of active channel
\( G_{m,d_i} \) Fractional transport capacity of bed-material load per unit channel width of active channel for particular size class
\( h \) Bed elevation
\( \gamma \) Fluid specific weight
\( \gamma_s \) Particle specific weight
\( f \) Darcy–Weisbach friction factor
\( \kappa \) von Karman’s constant equal to 0·41
\( \lambda \) Porosity of bed surface
\( m = \kappa \sqrt{8/\tilde{f}} \)
\( \mu \) Fraction that the zone of flow contraction makes of the total width within the abandoned-channel entrance
\( n \) Manning friction coefficient
\( v \) Lateral eddy viscosity
\( p_i \) Fraction that a particular size class of bed material makes of total mass in transport
\( \theta \) Dimensionless boundary shear stress
\( q \) Ratio of the discharge through the abandoned channel to the bankfull discharge carried by the active channel upstream of the diversion
\( Q_a \) Discharge through the abandoned channel
\( Q_{a,c} \) Discharge per unit channel width through the abandoned channel

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Q_{mv} \quad \text{Bankfull discharge per unit channel width within active channel upstream of diversion}

r \quad \text{Local radius of curvature at a radial location}

r_c \quad \text{Local radius of curvature at channel centreline}

\rho \quad \text{Fluid density}

\rho_s \quad \text{Particle density}

s \quad \text{Downstream location along channel bed}

S \quad \text{Average downstream bed slope}

S_c \quad \text{Downstream bed slope along channel centreline}

S_r \quad \text{Transverse bed slope}

\bar{\gamma} \quad \text{Radial location transverse to channel centreline}

t \quad \text{Time}

\tau_c \quad \text{Critical boundary shear stress}

\tau_{0,m} \quad \text{Downstream component of boundary shear stress within active channel}

\tau_{0,a} \quad \text{Downstream component of boundary shear stress within abandoned channel}

\tau_{c,d,l} \quad \text{Critical boundary shear stress for particular size class}

\tau_{tr} \quad \text{Transverse component of boundary shear stress}

U \quad \text{Cross-sectionally averaged downstream bankfull flow velocity}

w_a \quad \text{Active-channel bankfull width}

w_m \quad \text{Modern average width of oxbow lake}

\Delta w \quad \text{Change in channel width before and after cut-off}

\omega \quad \text{Boundary shear stress reduction factor equal to 1−0}

y_b \quad \text{Nominal thickness of mobile sediment within channel bed}

**REFERENCES**


Manuscript received 1 October 2008; revision accepted 14 May 2009.