地形　第 31 巻第 2 号
155-170 頁　（2010）

Transactions, Japanese Geomorphological Union
31-2, p. 155-170 (2010)

The Role of Sediment Transport and Sediment Supply in the Evolution of River Channel and Floodplain Complexity

Thomas DUNNE[1], José A. CONSTANTINE[2] and Michael B. SINGER[3]

Abstract

River channel and floodplain complexity, including the diversity of river bends, pool depths, oxbow lakes, scroll bars, and related features, is generated by the tendency of river channels to migrate laterally. The primary driver of this migration is the flow field, which molds the sediment of the channel boundary and is in turn altered by the gradient, curvature, and bar forms of the channel. However, the rate and texture of the sediment supply, determined by the topography, lithology, climate, and vegetation cover of the drainage basin, play important roles in affecting the resultant rates of bank erosion, bend growth, and form of floodplain erosion that generate sinuosity and oxbow lake production. We illustrate this point with examples of our recent studies of channel mobility and floodplain erosion and sedimentation. The supply of bed material to a reach accelerates point bar growth that increases the cross-channel acceleration of flow and intensifies bank erosion. The vulnerability of floodplain surfaces to chute incision, which depends on point bar growth, floodplain texture, floodplain gradient, and vegetation cover, limits channel sinuosity and alters the average rate and length of oxbow lakes. The form and rate of sedimentation in oxbow lakes and thus the length of time they survive as open water bodies before filling depends on the initial diversion angle of the cutoff (and therefore, on average, the sinuosity of the channel), and the relative supplies of bed material and wash load.

Key words: *point bar, bank erosion, channel migration, oxbow lakes*

Introduction

The large-scale morphological complexity of single-thread alluvial channels and their floodplains results from the tendency of channels to move laterally (Howard, 1992; 1996), although significant complexity can be added when flow fields are disrupted by large woody debris complexes (Triska, 1984; Abbe and Montgomery, 1996), as well as neotectonic effects and local runoff (Mertes et al., 1996; Dunne et al., 1998) Not

Received and accepted: February 10, 2010

[1] Bren School of Environmental Science and Management, University of California, Santa Barbara, California 93106, USA
[2] School of Earth and Ocean Sciences, Cardiff University, Cardiff CF10 3YE, United Kingdom
[3] School of Geography and Geosciences, University of Saint Andrews, Fife, Scotland, KY169AL, United Kingdom

surprisingly, most early theoretical and process-based studies of river channel morphology concentrated on simple, regular channel forms in both the laboratory and the field (e.g. Rozovskii, 1961; Yen, 1970; Engelund, 1974; Hooke, 1975; Kikkawa et al., 1976; Bridge, 1977; Odgaard, 1981; Langbein and Leopold, 1966; Dietrich et al., 1979; Dietrich and Smith, 1983). Hooke (2003) traced the history of theoretical studies of river meandering from the analysis of regular, steady-state forms to a focus on the inherent instability of river bends (e.g. Furbish, 1991) and their irregularity (e.g. Speight, 1966). Emphasis on the evolution of bends had been growing since the 1970s, after early laboratory experiments and field observations led Leopold and Wolman (1957) to develop a conceptual model of the role of bar development in forcing channel migration, and Keller (1972) elaborated qualitatively on the trajectory of bar and pool formation as stream reaches "evolve at different rates at different times and new straight or meandering reaches are constantly being created, maintained, or destroyed ⋯." (Keller, 1972, p. 1533). There followed quantitative field studies of channel migration by Lewin (1972), Hickin and Nanson (1975), Odgaard (1987), Hasegawa (1989), and Hooke (1995) among many others.

The ability of theories to address river migration quantitatively began with the work of Ikeda et al. (1981), Howard and Knutson (1984), and Johannesson and Parker (1989), who concentrated on the role of channel curvature driving the flow field to erode the concave outer banks of meanders. These theories were then used in simulation models to investigate the long-term evolution of river bend trains and the complexity that they introduce into floodplain morphology and sedimentology (Howard, 1992, 1996; Stølum, 1998).

Only recently have sediment transport and sedimentation in river bends been taken into account formally in models of channel evolution and floodplain construction. Doing so requires the addition of considerable complexity to channel models, involving computation of flow in two dimensions (e.g. Duan (2001)) or three (Shimizu et al., 1990; Fischer-Antze et al., 2008), and a relationship between bed shear stress and sediment transport rate to mold the bed and alter the flow field and the near-bank shear stress. For example, Duan and Julien (2005) coupled a vertically averaged model of flow to the Meyer-Peter sediment transport formula to calculate bedload and suspended load transport and the erosion of banks The local rate of bank erosion depends on the longitudinal gradient of sediment transport, strength of secondary flow, and the collapse of bank material resulting from bed elevation changes at the base of the bank. Darby et al. (2002) developed a similar model, except that the rate of erosion of the cohesive bank was driven directly by excess shear stress at the base of the bank and subsequent mass failure, the timing of which was affected by pore pressure in the riparian ground water.

To the best of our knowledge, the role of sediment supply as an external driver of the processes of bar building, flow field distortion, and bank erosion has not been systematically studied. There are two scales (not entirely independent of one another) at which the relationship between sediment supply and bar building require study. The first scale is that of the river-basin sediment budget at which certain reaches accumulate bed-material sediment while other reaches are in a steady state or undergo a net loss of sediment. The second scale is within a river bend where processes of sediment redistribution and bend molding are strongly influenced by the evolving curvature of the channel and its relationship to channel cross-sectional asymmetry.

Bend lengthening is an important driver of channel and floodplain complexity and irregularity, especially where secondary bars and pools develop in straighter reaches as they lengthen and gradient diminishes (Keller, 1972). The changes referred to above occur through erosion entirely within the channel. They lead to bend lengthening, increased sinuosity, and eventually to "neck cutoff" where two bends approach one another so closely that the narrow land between them is breached by collapse or overflow, creating a shorter path for the channel flow (Figure 1a). The main flow then abandons a short stretch of channel (typically, but not always, about 0.5–1 meander wavelength), which is partly isolated from the main channel but still inundated by groundwater seepage and occasional river overflow so that an "oxbow lake" becomes a long-lived feature of the floodplain topography. This set of features evolves where the probability of new channel formation through incision into the floodplain surface is low, and channel bend erosion is confined to the channel for long enough to develop a high sinuosity. Although we know of no systematic survey of the conditions limiting floodplain incision, it seems likely that it would be favored by low valley gradients, cohesive floodplain sediment, and dense, or at least erosion-resistant, floodplain vegetation. In other valley floodplains, overbank flow can erode both the bank and the floodplain surface, incising a new path, called a "chute cutoff", in the floodplain sediments (Figure 1b), again abandoning a reach of channel, and creating an oxbow lake. We hypothesize that chute cutoffs occurring with sufficient frequency to limit the sinuosity to values between 1.0 and 1.5, for example, would be favored by relatively steep valley gradients and sparse vegetation.

Stølum (1998) used simulations of the long-term evolution of trains of river bends and a rule for neck cutoff development as sinuosity increased to propose that the monotonic increase in sinuosity and asymmetry is eventually balanced by censoring of bends, producing stable populations of bend and oxbow lake lengths. Constantine and Dunne (2008) elaborated on this principle with a survey of 30 large, lowland rivers on various continents, showing that the cutoff process produces a characteristic and predictable size-frequency distribution of oxbow lakes the mean of which depends on the sinuosity of the river. Assumption that the average sinuosity remains constant over time then allows a calculation of the frequency of cutoff from a calculation of bend lengthening that was based on the Sun et al. (1996) modification of the Johannesson and Parker (1989) method.

The significance of the cutoff process, and especially the conditions under which chute cutoffs can censor bends before they become sinuous enough to evolve mainly by

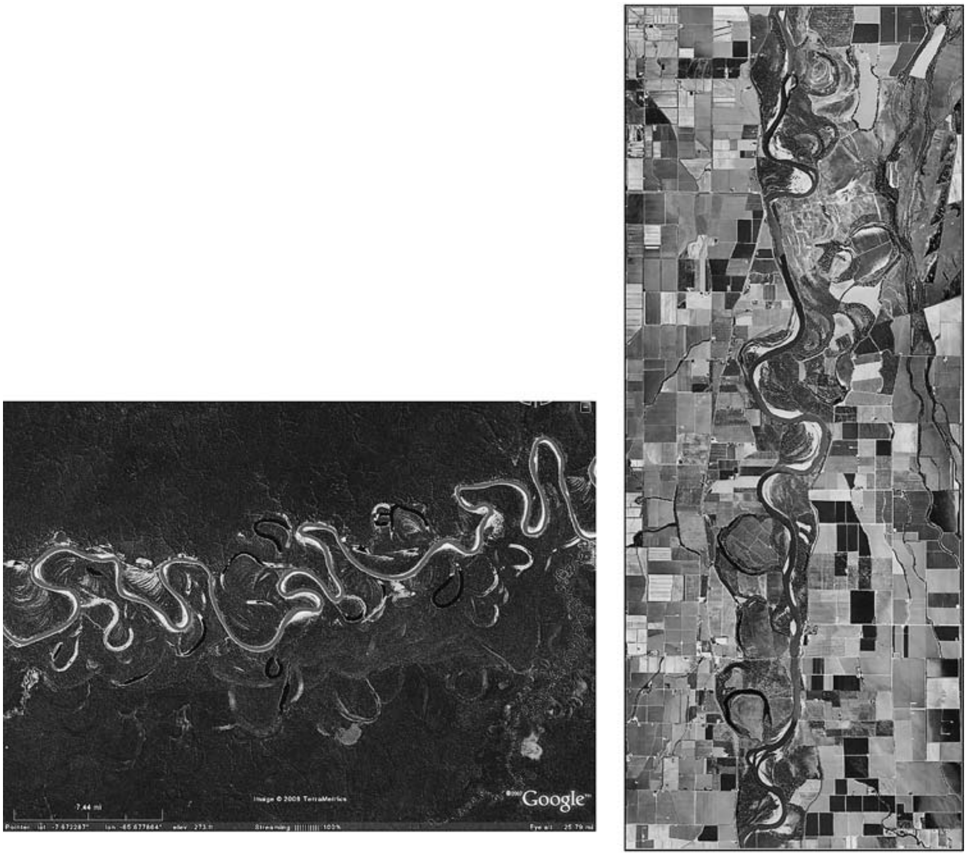

Figure 1. (a) Google Earth™ image of the Purus River, a tributary of the Amazon in Brazil, with a sinuosity of 2.75 and abundance evidence of recent and imminent oxbow lake generation by neck cutoff. (b) Aerial photographic mosaic of the gravel bed reach of the Sacramento River, California with a sinuosity of 1.35 and evidence of oxbow lakes produced mainly by chute cutoff. Image courtesy of the California Department of Water Resources.

neck cutoff, thus becomes a crucial process governing the production of floodplain complexity. Slingerland and Smith (1998, 2004) were the first researchers to address the conditions required for avulsions to occur from a meandering river. They proposed that the process is driven by cross-valley gradients that develop as a result of floodplain sedimentation being faster within a meander belt than in the distal, flood basin. During a sufficiently high overbank flood, flow down this gradient will scour a crevasse channel, and the depth of this initial incision, together with the bed-material grain size (sand) of the crevasse, and the ratio of crevasse slope to main channel slope, will determine whether the crevasse heals, or erodes to the depth of the main channel, or evolves to a stable intermediate depth.

Once an oxbow lake is formed, the rate and pattern of sedimentation along its length continues to influence the topographic and hydrologic complexity of the floodplain for decades to centuries and the sedimentology and hydrogeology of the floodplain for millennia. Field observations and measurements by Fisk (1947), Li et al. (2007), Hooke (1995), Shields and Abt (1989), and Piégay et al. (2002) among others have led to interpretations that the angle by which the new chute diverges from the original channel controls the pattern of sedimentation and thus the rate of filling with coarse and fine sediment and the longevity of the lake as open water.

We have recently made some progress in understanding each of the processes generating floodplain complexity referred to above, particularly as they relate to the magnitude and texture of the sediment supply, and we discuss them in the following order:

(i) effects of sediment supply on the form and rate of bank erosion and channel migration
(ii) conditions that promote cutoff channels and oxbow lakes
(iii) the pattern and rate of sedimentation in oxbow lakes

Effects of sediment supply on form and rate of bank erosion and channel migration

We hypothesized that sediment supply and in-channel sedimentation rate could affect the rate of bank erosion and channel migration by causing point bar growth and thereby increasing the cross-stream advection of momentum, and accelerating flow at the base of the outer bank. In order to test this hypothesis, we used the flow and sediment transport model FLUVIAL-12 (Chang, 1988a, b) to calculate channel cross sections at intervals around a curved reach of the gravel bedded Sacramento River, California. The model represents bank retreat as being driven by the balance between the supply of bed material from upstream, the erodibility of the bank materials themselves, and the sediment transport capacity of flow at the base of the outer, concave bank. Previous calculations (Constantine, 2006) had demonstrated that the model predicted the general pattern of bank erosion and bar growth in the Sacramento River for an 8-year period for which aerial photographs were available to map channel migration. Since for the current purpose we were not interested in predictions for a particular time period, we simulated channel change during 10,950 days (30 years) of bankfull discharge (1850 m^3 s^{-1}) and sediment transport calculated with an equation that we had calibrated with various datasets from gravel bedded rivers (Singer and Dunne, 2004). The grain size distribution of the sediment supply to the upper end of the reach was the same as that of the bed material in the reach and the lower half of the river bank. We estimated a representative sediment supply rate that would equilibrate with the channel by connecting a long channel ramp with the measured bed-material grain size to the upper end of the model domain and adjusting the gradient of the ramp until the calculated sediment supply entering the model domain established an approximately steady sediment transport rate through the model reach.

Figure 2a shows the cross-section evolution and bank migration predicted by

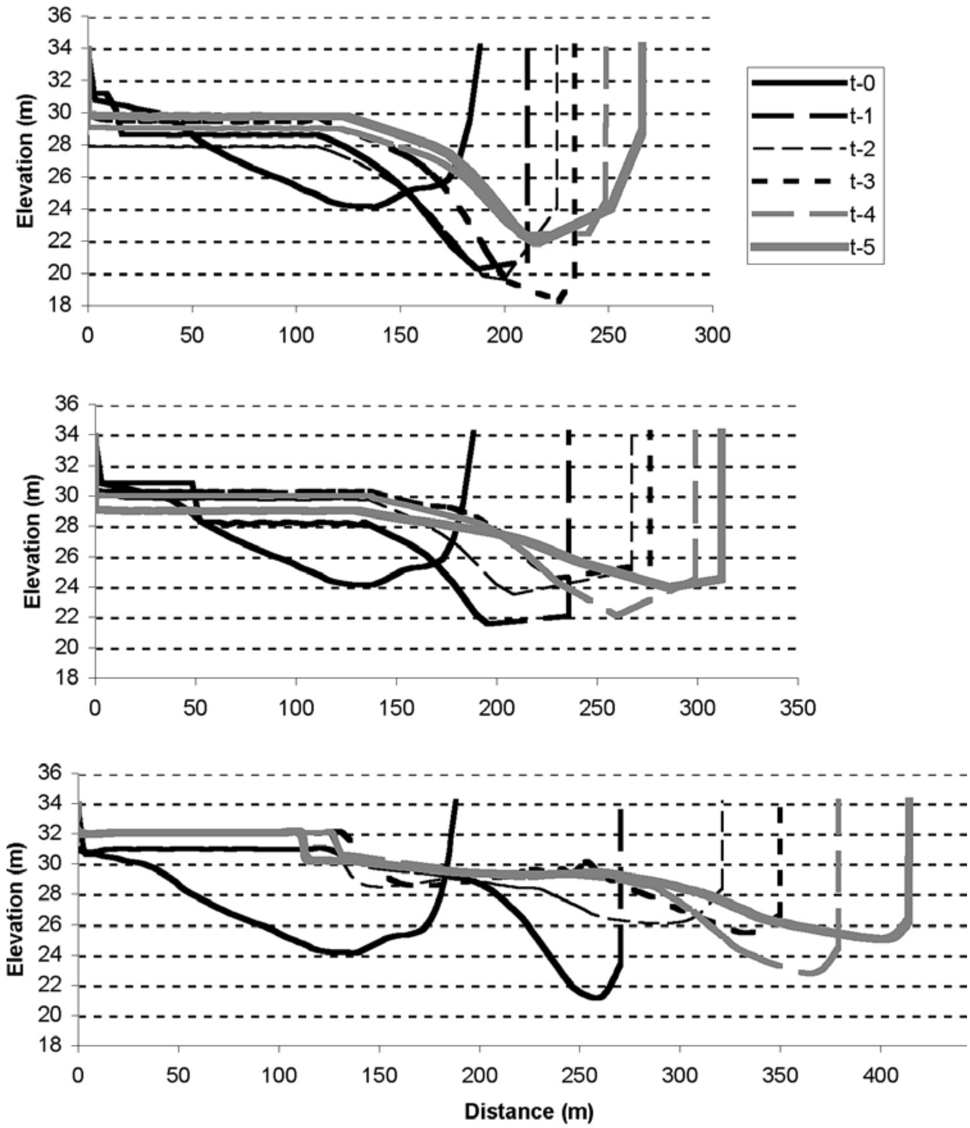

Figure 2. Initial cross section (t-0) and FLUVIAL-12 predictions of bank erosion and bar growth at five equally spaced times over 30 years of constant bankfull discharge at the apex of a bend in the Sacramento River, California. The first two panels show predictions for the bed-material supply rate that is estimated to be in equilibrium with the current initial bed topography, but (a) shows results for a bank erodibility coefficient of 0.2 and (b) for 0.4. Panel (c) shows predicted evolution for a bank erodibility coefficient of 0.4 and a sediment supply rate that is 125% of the current equilibrium rate. The computed annual bank retreat rates, scaled approximately by the average number of days of bankfull flow per year (~4), are (a) 4 m/yr, (b) 6.5 m/yr, and (c) 11 m/yr.

FLUVIAL-12, for a bend apex (the cross section of greatest curvature) with a representative average sediment supply from upstream and a low bank erodibility coefficient of 0.2 in the FLUVIAL-12 model (indicating high resistance to erosion). Figure 2b shows the same bend and sediment supply with a higher erodibility coefficient of 0.4 (low resistance), equal to the one that Constantine (2006) found to most closely match the recent history of the Sacramento River in this reach. When the bank erodibility is low, bed material transport keeps the pool deep but the bank at the axis of the bend retreats only slowly. With the same sediment supply from upstream and a higher bank erodibility, the bank retreats more rapidly and the pool becomes shallower because the combined sediment supply from upstream and from the rapidly retreating bank balances the transport capacity of the flow at the base of the bank while the flow depth there is relatively low. On the other hand, as shown in Figure 2c if the bank erodibility is maintained at a value of 0.4 and the sediment supply increases from the initial representative rate to 125% of that rate, some of the extra sediment accumulates as a higher point bar in the reach, diverting water towards the outer bank and increasing the vertically averaged flow velocity at the base of the bank. The sediment transport capacity then increases at the base of the bank and accelerates its retreat.

The insight that arises from these computations is that the grain-size composition and magnitude of the sediment supply from upstream, as well as the local erodibility of bank materials, are vital to the rate at which river bends grow and their channels migrate. Where the supply from the drainage basin is large and coarse enough to create point bars, the growth of the bars, which is strongly influenced by the sediment supply, will increase the cross-stream transfer of high-velocity water beyond that driven by the centrifugal acceleration associated with the bend's curvature, and will therefore accelerate bank erosion on the outer concave bank.

Cutoff channels and oxbow lake formation

Lowland rivers have a range of gradients from about $1\text{–}5\times10^{-5}$ in channels in silt and fine sandy bed material, such as the Lower Amazon of Brazil (Dunne et al., 1998) and the Beni River of E. Bolivia (Aalto et al., 2003), to at least 5×10^{-4} in gravel-bed rivers such as the Sacramento River of central California. Low-gradient floodplains that have dense vegetation covers, such as many floodplains in the wet tropics, can resist erosion by overbank flow and erosion of the floodplain occurs only through the undermining of the channel banks. As suggested by the results described in the previous section, this rate of migration will be lowest in rivers with low bed material supplies, as is the case of Amazon tributaries draining the Guyana and Brazilian shields. These are the conditions envisioned by the models of Ikeda et al. (1981) and other researchers who emphasized the role of flow alone in driving bank erosion. Howard (1992, 1996), Stølum (1998), and Sun et al. (1996) have shown that a simulation of channel bend evolution and migration based solely on the within-channel bank erosion mechanism proposed by Ikeda et al. (1981) will produce an increasingly sinuous channel pattern until neck cutoff occurs. A high overbank discharge does not appear to be necessary for this process, although neck cutoff during overbank flow is not precluded. The population of residual lakes isolated by the neck cutoff process will then have relatively high sinuosity, similar to that of the main channel. Figure 1a shows an example of this kind of floodplain, developed in the central Amazon basin under conditions of low gradients and thickly vegetated floodplains.

By contrast, on floodplains with relatively high gradients (more than 10 times greater than those referred to above in the Amazon basin) and thinner vegetation overbank flow has more opportunities for incising a new channel into the floodplain surface (Figure 2b) by the process of chute cutoff. Constantine et al. (2009a) analyzed examples of this process over a 56-year period documented by aerial photographs. The new channel forms when rapid flow near the outside of bends with a maximum curvature of ~0.005 (in the case of the Sacramento River) leaves the channel at the location of the curvature maximum. Bank erosion contributes to this process by progressively increasing the channel curvature. However, before the sinuosity attains a value of more than ~1.5, chute cutoff occurs and reduces the channel sinuosity locally. The sequence of events by which overbank flow leaving the channel with high velocity extends a trough across the floodplain to create a chute is illustrated by the sequence of images in Figure 3.

A two-dimensional flow model of a reach of the Sacramento River floodplain demonstrated that when overbank flow occurs, the highest flow velocities and boundary shear stresses on the floodplain generally occur at local maxima in channel curvature or where the channel most greatly turns from the downstream flow path (Constantine et

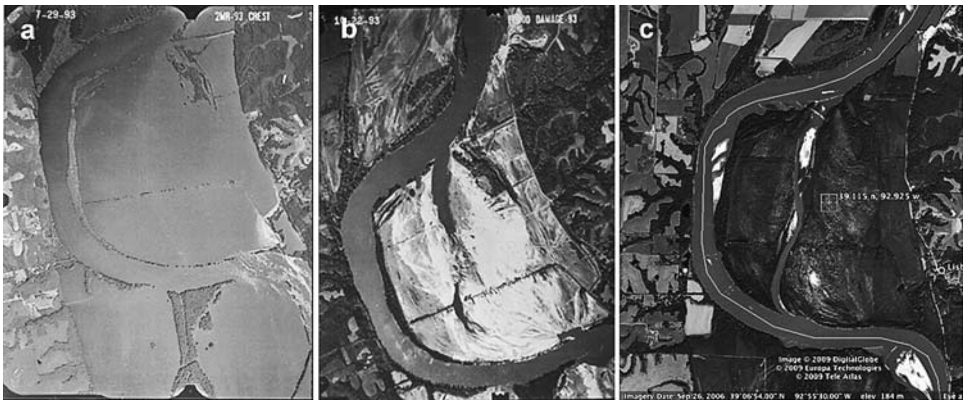

Figure 3. Sequence of events in the development of a chute cutoff channel on the Missouri River from (a) the overbank flood of July, 1993 to (b) the embayment incised into the concave bank and floodplain that was visible by October, 1993, and (c) to the fully developed chute cutoff shown in the Google Earth™ image from September, 2006 at lat. 39.115°N, long. 92.925°. The chute had been modified by dredging and flow-training structures since its formation.

al., 2009a). At these locations, the uppermost increment of the channel flow is no longer steered by the riverbank but instead enters the floodplain, flowing in a direction that closely parallels the channel immediately upstream of the overbanking location and that is also roughly parallel to the valley slope. Constantine et al. (2009a) analyzed the conditions on the floodplain surface which can affect whether the flow is competent to erode a substrate of sandy sediment as it leaves the channel. Observations on air photographs on the Sacramento and other lowland rivers (e.g. Figure 3) before large floods had indicated that these sites where the flow leaves the channel frequently localize the initiation and elongation of a trough that grows eventually into a full chute cutoff.

Constantine et al (2009a) then used a method of calculating flow velocity and the boundary shear stress on the underlying floodplain surface that had been developed by Smith (2004) for flow through uniformly spaced cylinders penetrating the water surface. The results suggest, for example, that overbank flow entering a sandy floodplain with a gradient like that of the Sacramento ($\sim 3.3\times10^{-4}$ in one of the reaches for which we made computations) decreases its velocity because of the reduction in flow depth and the increase in frictional energy loss due to the vegetation. The energy loss continues to increase as the water stage rises because the deeper flow encounters a larger cross-sectional area of plant stems. The extraction of momentum from the flow decreases the boundary shear stress available for transporting sediment on the underlying floodplain surface. Constantine et al. (2009) measured *in situ* the critical value of the shear stress required to initiate erosion and sediment transport on such a sandy surface and on other floodplain sediments along the Sacramento River. Only seven measurements of critical shear stress were possible because of access limitations, and they varied from 0.01–0.03 Pa for clay-rich soils, to 0.01–0.1 Pa for sand, to 1.6–2.8 Pa for sandy gravel, and 3.9 Pa for weathered terrace gravel, indicating another important control of sediment transport and sedimentation on the channel migration process.

However, the dominant control of floodplain surface erodibility appeared to be vegetation type and density. Where the riparian vegetation consists of shrubs (with a stem diameter of ~0.5 cm) the Smith (2004) model predicts that flow is only competent to transport sand if the ratio of plant stem spacing to stem diameter exceeds ~35–40 (interpolated between curve values in the left-hand panel of Figure 4). Greater densities of shrub stems would protect against incision of a chute. Similar calculations for a floodplain covered with trees with a trunk diameter of 0.35 m showed that an average trunk spacing denser than 1.75 m would be required to resist chute incision (Constantine et al., 2009a, Figure 14). Such a density is not widely observed for mature floodplain trees with large canopies. The right-hand panel of Figure 4 shows that a floodplain with a gradient of 5×10^{-5} (similar to Amazon tributaries) would be protected by shrubs stems spaced up to 50 cm apart (100×0.5 cm).

The results imply that sandy floodplains with gradients like that of the Sacramento with mature forest canopies would frequently be incised by chute cutoffs if it were not for the stabilizing effect of smaller, dense plant covers and possibly other small woody fragments such as fallen branches. Thus, the penetration of light to the forest floor, aided by disruption of the forest canopy by overbank flooding, frequent collapse of large branches, and plant strategies such as shade tolerance or early sprouting before deciduous canopies have leafed out would all contribute to the growth of dense shrub layers and floodplain resistance. Frequent grazing or burning of the floodplain vegetation, and especially cultivation, would favor incision. On the other hand, if the critical shear stress values measured by Constantine et al. (2009) for sandy gravel are used in the

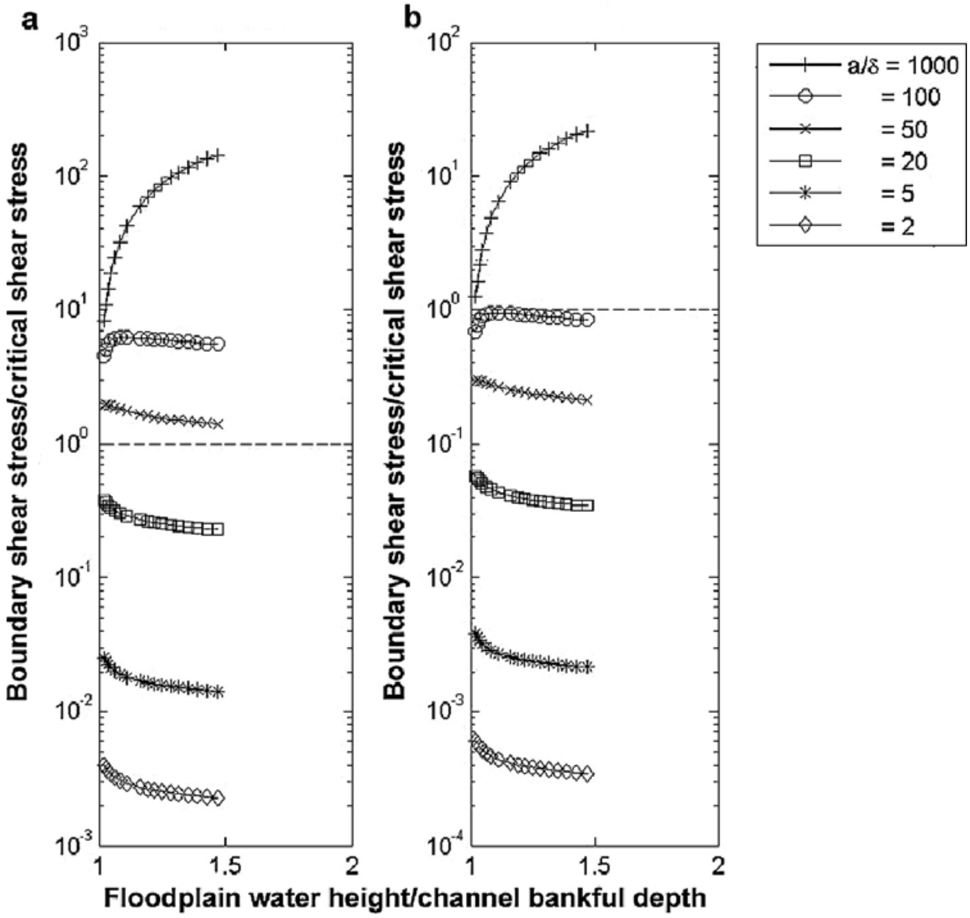

Figure 4. Ratio of the boundary shear stress on the floodplain surface relative to the critical shear stress required to erode 0.13 mm sand for a range of inundation depths and for six values of stem spacing (a) for a shrub stem diameter (δ) of 0.5 cm. In the left-hand diagram the floodplain slope is 3.3×10^{-4} (similar to the Sacramento in its gravel-bed reach) and a spacing (a/δ) smaller than about 35–40 times the stem diameter would preclude floodplain incision. The right-hand diagram indicates results for a floodplain slope of 5×10^{-5} (similar to rivers in the Amazon lowland) where a shrub spacing as low as 100 times the shrub stem diameter would protect the floodplain against incision.

calculation, they indicate that even sparse vegetation covers are sufficient to stabilize steep gravelly floodplains against channelized incision, reflecting yet another influence of the catchment sediment budget on floodplain morphology.

Form and rate of sedimentation in oxbow lakes

Some oxbow lakes become isolated from the channel quickly, while in other cases the connection between the channel and the cutoff oxbow may diminish gradually over many years. During this time the intermittent flow and fine sediment supply to the oxbow and therefore its rate and pattern of filling will vary through time as hydraulic connections are diminished and re-established during the annual flow cycle. These characteristics may evolve over time; and the rate of production and extinction of the hydraulic connections provide an important control on the degree to which morphological and hydrologic complexity of the floodplain is maintained. An intriguing aspect of oxbow evolution is that some of them persist as open water bodies for centuries while others are filled with sediment and colonized by terrestrial vegetation within a decade (Piégay et al., 2002). On a regional scale, the rate of filling is likely to be controlled by the river' s sediment supply available for the infilling process. However, even along the same reach of river there are great differences in the lifespan of open-water oxbows. Fisk (1947) proposed a qualitative interpretation of the causes of these differences in the Mississippi floodplain. An oxbow formed with a high diversion angle (the angle between the orientation of the main channel immediately upstream of the breach and that of the

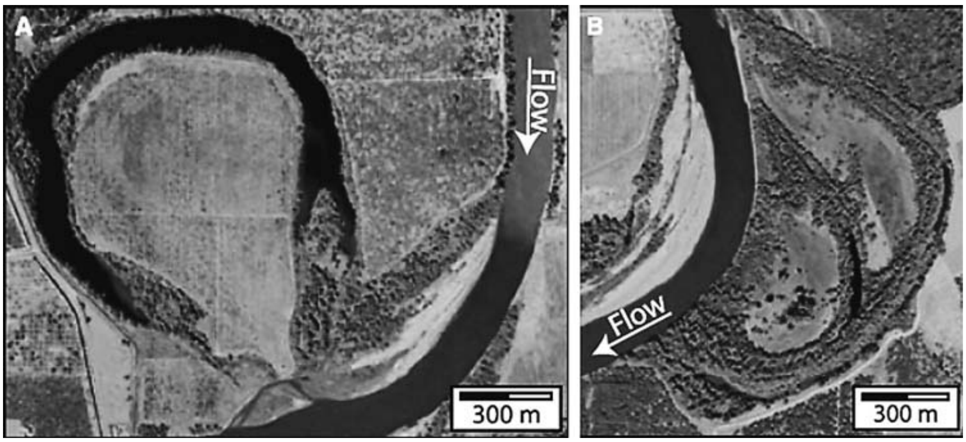

Figure 5. The Sacramento River oxbow shown on the left was formed by neck cutoff (and therefore with two large diversion angles) 134 years before the air photo was taken. The oxbow shown on the right was formed by chute cutoff (and therefore with a lower diversion angle) 18 years before the photo was taken. An aerial photograph taken of the latter site 15 years after cutoff shows active sedimentation on bars along the convex banks throughout the length of the cutoff channel. Source: Constantine et al. (2009b).

abandoned channel reach) becomes plugged quickly with a short ramp of bed material that prevents most sediment-rich flood waters from entering the oxbow except in particularly high floods (Figure 5a). The lake therefore experiences a slow rate of infilling with fine-grained, organic-rich sediment along most of its course. It survives for a long time as an open-water body, sustained by groundwater inflow and rare inflows of river water. By contrast, oxbows formed with a small diversion angle from the original channel (see Figure 5b) continue to allow significant amounts of flow and bed material to enter them and to penetrate far into the oxbow. The suspended and bed sediment are transported throughout the length of the oxbow, rapidly aggrading the bed and bars and narrowing the oxbow channel. Shallowing and narrowing of the channel accelerates colonization by vegetation, which further promotes sedimentation. The rate and pattern of infilling affects therefore affects the evolution of both the aquatic and terrestrial ecosystem of the oxbow.

Constantine et al. (2009b) developed Fisk's (1947) idea with the aid of a mathematical model of how the diversion angle controls the proportion of main-channel flow that is diverted into a cutoff channel. A flow separation zone (labeled e in Figure 6a) develops at the diversion, reducing the effective width of the cutoff channel to μ. The associated reduction in the amount of flow into the oxbow decreases the shear stress and sediment transport capacity available to move sediment along the oxbow. Yet laboratory studies have shown that almost all of the bed material in the main channel is likely to be transported into the channel that is being abandoned by the cross-channel component of flow at the bed. Thus, a sharp decrease in sediment transport capacity in a cutoff with a high diversion angle results in rapid accumulation of a short plug of this bed material close to the entrance of the abandoned channel, raising the channel bed there and precluding further inflow, except during infrequent floods. Where the diversion angle is small, μ and the cutoff channel discharge and the downstream component of boundary shear stress within the abandoned channel remain larger and more of the bed material is transported beyond the separation zone. The entrance aggrades more slowly and most of the bed material spreads along the length of the channel that is being abandoned. Figure 6b shows how the predicted flow per unit width (Q_a) and the downstream component of the bed shear stress (τ_0) immediately downstream of the separation zone diminish as the diversion angle increases. The predicted shear stress was then used to compute the rates at which bed material would accumulate at the entrance to the channel being abandoned or be transported along it. Although extremely simple, the model predicted rapid shutting down of flow and sediment transport along the arm that is being abandoned as the diversion angle increases. Confirmation of the transport of bed material along the channel was provided by borings in 13 cutoffs on the Sacramento River which indicated that the thickness of gravel bed material accumulated at the apices of the bends decreased as the diversion angle increased. The rate of accumulation of fine-grained material over the coarser bed material will also depend on the amount of flow entering that arm that is being abandoned, and the absolute rates of

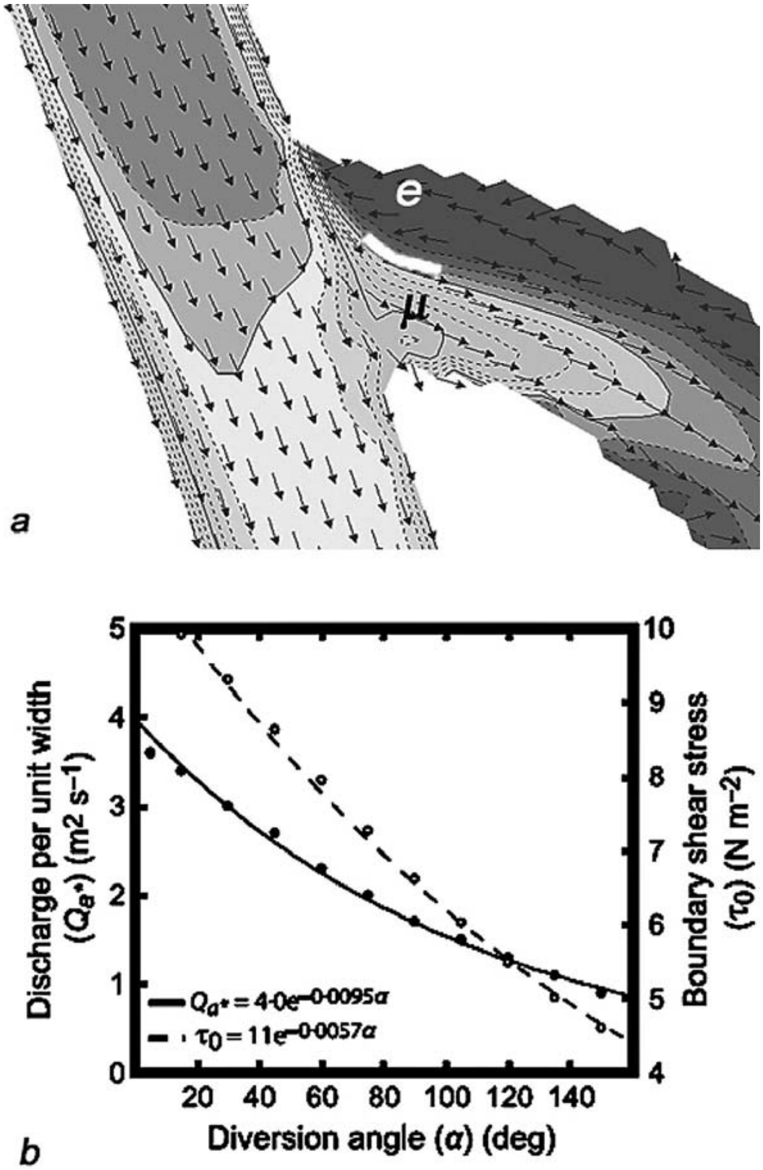

Figure 6. (a) Example of a numerical simulation of a two-dimensional flow field during steady, bankfull flow conditions, using the topography of one bend of the Sacramento River attached to a straight, 170 meter-wide box-shaped diversion reach with a diversion angle of 60". Arrows indicate the vertically averaged velocity. The darkest shading in the curved channel that is being cut off indicates a flow separation zone with both upstream and downstream velocities. The width of this separation zone is indicated by e and it confines the flow entering the channel that is being cut off to the width μ. The width μ decreases from 0.7 to 0.2 of the original main-channel width as the diversion angle increases from 20° to 120°. (b) Computed discharge per unit channel width through the abandoned channel (Q_a) and the downstream component of boundary shear stress within the abandoned channel (τ_0) plotted against diversion angle. Source: Constantine et al. (2009b).

their accumulation will again depend on the magnitude and grain-size composition of the sediment load supplied by the catchment.

Summary

The rate of production of channel and floodplain complexity depends on the rate of bank erosion, channel migration, bend growth, and the creation and filling of cutoff channels by neck cutoff or chute cutoff. Field studies and modeling of these processes emphasizes that sediment supply and grain size play a role in affecting these channel changes in addition to the hydraulic processes that are the usual focus of analysis when channels migrate or otherwise evolve. Sediment supply is determined by drainage basin conditions as well as local channel hydraulics, and therefore the range of channel and floodplain complexity that is sustainable reflects the climatic, tectonic and land use conditions of the region.

Acknowledgements

Candice Constantine, Lee Harrison and Carl Legleiter helped us with data and thoughtful discussions. The research was supported by CALFED grant 4600002659 and the Don J. Easterbrook Award of the Geological Society of America.

References

Aalto, R. E., Maurice-Bourgoin, L., Dunne, T., Montgomery, D. R., Nittrouer, C. A. and Guyot, J-L. (2003) Episodic sediment accumulation on Amazonian floodplains influenced by El Niño/Southern Oscillation: *Nature*, **425**, 493–497.

Abbe, T. B. and Montgomery, D. R. (1996) Interaction of large woody debris, channel hydraulics and habitat formation in large rivers: *Regulated Rivers: Research & Management*, **12**, 201–221.

Bridge, J. S. (1977) Flow, bed topography, grain size and sedimentary structure in bends: A three dimensional model: *Earth Surface Processes*, **2**, 401–416.

Chang, H. H. (1988a) Introduction to FLUVIAL-12: Mathematical model for erodible channels: *In* Fan, S. ed., *Twelve Selected Computer Stream Sedimentation Models Developed in the United States*: Federal Energy Regulatory Commission, Washington, D.C., pp. 353–412.

Chang, H. H. (1988b) *Fluvial Processes in River Engineering*: John Wiley & Sons, Inc., New York, 432 p.

Constantine, C.R. (2006) *Quantifying the Connections between Flow, Bar Deposition, and Meander Migration in Large Gravel-Bed Rivers*: Ph.D. thesis, University of California, Santa Barbara, 191 p.

Constantine, C. R., Dunne, T. and Hanson, G. J. (2009). Examining the physical meaning of the bank erosion coefficient used in meander migration modeling: *Geomorphology*, **106**, 242–252.

Constantine, J. A., and Dunne, T. (2008) Meander Cutoff and the Controls on the Production of Oxbow Lakes: *Geology*, **36**, 23–26.

Constantine, J. A., McLean, S. R. and Dunne, T. (2009a) A mechanism of chute cutoff along large meandering rivers with uniform floodplain topography: *Geological Society of America Bulletin*, **121**, 855–869

Constantine, J. A., Dunne, T., Piégay, H., and Kondolf, G. M. (2009b) Controls on the alluviation of oxbow lakes by bed-material load along the Sacramento River, California: *Sedimentology*, **57**, 389–407.

Darby, S. E., Alabyan, A. M. and Van de Wiel, M. J. (2002) Numerical simulation of bank erosion and channel migration in meandering rivers: *Water Resources Research*, **38**, 1163, doi:10.1029/2001WR000602.

Dietrich, W. E., and Smith, J. D. (1983) Influence of the point bar on flow through curved Channels: *Water Resources Research*, **19**, 1173–1192.

Dietrich, W. E., Smith, J. D. and Dunne, T. (1979) Flow and sediment transport in a sand bedded meander: *Journal of Geology*, **87**, 305–315.

Duan J. G. (2001) Simulation of streambank erosion processes with a two-dimensional numerical model: *In* Harmon R. S. and Doe, W. W. III, eds. *Landscape Erosion and Evolution Modeling*: Kluwer Academic/Plenum Publishers, New York, 389–427.

Duan, J. G., and Julien, P. Y. (2005) Numerical simulation of the inception of channel meandering: *Earth Surf. Process Landforms*, **30**, 1093–1110.

Dunne, T., Mertes, L. A. K., Meade, R. H., Richey, J. E. and Forsberg, B. R. (1998) Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil: *Geological Society of America Bulletin*, **110**, 450–467.

Engelund, F. (1974) Flow and bed topography in channel bends: *J. Hydraulic Div. Am. Soc. Civ. Eng*., **100** (HYll), 1631–1648.

Fischer-Antze T., Olsen N. R. B., and Gutknecht D. (2008) Three-dimensional CFD modeling of morphological bed changes in the Danube River: *Water Resources Research*, **44**, W09422, doi:10.1029/2007WR006402.

Fisk, H. N. (1947) *Fine Grained Alluvial Deposits and Their Effects on Mississippi River Activity*: Vols 1 & 2. Mississippi River Commission, Vicksburg, MS.

Furbish, D. J. (1991) Spatial autoregressive structure in meander evolution: *Geological Society of America Bulletin*, **103**, 1576–1589.

Hasegawa, K., (1989) Studies on qualitative and quantitative prediction of meander channel shift: *In* Ikeda S. and Parker, G. eds. *River Meandering*: American Geophysical Union, Water Resources Monograph **12**, Washington, DC, 215–236.

Hickin, E. J. and Nanson, G. (1975) The character of channel migration on the Beatton River, northeast British Columbia, Canada: *Geological Society of America Bulletin*, **86**, 487–94.

Hooke J. M. (1995) River channel adjustment to meander cutoffs on the River Bollin and River Dane, N W England: *Geomorphology*, **14**, 235–53, 1995.

Hooke, J. M. (2003) River meander behaviour and instability: a framework for analysis: *Trans. Inst. Br. Geogr.* NS, **28**, 238–253.

Hooke, R. L. (1975) Distribution of sediment transport and shear stress in a meander bend: *Journal of Geology*, **83**, 543–565.

Howard A. D. (1992) Modelling channel migration and floodplain sedimentation in meandering streams: *In* Carling, P. A. and Petts, G. E., eds. *Lowland Floodplain Rivers*: Wiley, Chichester, UK, 1–41.

Howard, A. D. (1996) Modeling channel evolution and floodplain morphology: *In* Anderson, M.G., Walling, D. E. and Bates, P. D., eds. *Floodplain Processes*: John Wiley and Sons, New York, 15–62.

Howard, A. D. and Knutson, T. R. (1984) Sufficient conditions for river meandering: a simulation approach: *Water Resources Research*, **20**, 1659–1667.

Ikeda, S., Parker, G. and Sawai, K. (1981) Bend theory of river meanders. Part 1. Linear development: *Journal of Fluid Mechanics*, **112**, 363–377.

Johannesson, H., and Parker, G. (1989) Linear theory of river meanders: *In* Ikeda, S. and Parker, G. eds. *River Meandering*. American Geophysical Union, Water Resources Monograph **12**, Washington, D. C., 181–213.

Keller, E. A. (1972) Development of alluvial stream channels: a five-stage model: *Geological Society* *of America Bulletin*, **83**, 1531–1540.

Kikkawa, H., Ikeda, S. and Kitagawa, A. (1976) Flow and bed topography in curved open channels: *J. Hydraulic Div. Am. Soc. Civ. Eng*., **102** (HY9), 1327–1342.

Langbein, W. B. and Leopold, L. B. (1966) River Meanders Theory of Minimum Variance: *U. S. Geological Survey Professional Paper,* **422–H**, 18p.

Leopold, L. B, and Wolman, M. G. (1957) River channel patterns – braided, meandering, and straight: *U. S. Geological Survey Professional Paper,* **282–B**, 85 p.

Lewin, J. (1972) Late-stage meander growth: *Nature-Physical Science*, **240**, 116.

Li, L., Lu, X. and Chen, Z. (2007) River channel change during the last 50 years in the middle Yangtze River, the Jianli reach: *Geomorphology,* **85**, 185–196.

Mertes, L. A. K., Dunne, T. and Martinelli, L. A. (1996) Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil: *Geological Society of America Bulletin*, **108**, 1089–1107.

Odgaard, A. J. (1981) Transverse bedslope in alluvial channel bends: *J. Hydraul. Div. Am. Soc. Civ. Eng.*, **107**, 1677–1694.

Odgaard, A. J. (1987) Streambank erosion along two rivers in Iowa: *Water Resources Research*, **23**, 1225–1236.

Piégay, H., Bornette, G. and Grante, P. (2002) Assessment of silting-up dynamics of eleven cut-off channel plugs on a free-meandering river (Ain River, France): *In* Allison, R. J., ed. *Applied Geomorphology,* John Wiley & Sons, New York, 227–247.

Rozovskii, I. L. (1961) *Flow of Water in Bends of Open Channels* (in Russian), 233 pp., Academy of Sciences of the Ukrainian SSR, Kiev, 1957. (English translation, Israel Program for Scientific Translation, Jerusalem).

Shields, F. D., Jr. and Abt, S. R. (1989) Sediment deposition in cutoff meander bends and implications for effective management: *Regulated Rivers Res. & Management*, **4**, 381–396.

Shimizu, Y., Yamaguchi, H. and Itakura, T. (1990) Three-dimensional computation of flow and bed deformation: *J. Hydraul. Eng., Am. Soc. Civ. Eng*., **116**, 1090–1108.

Singer, M. B., and Dunne, T. (2004) Modeling decadal bed material sediment flux based on stochastic hydrology: *Water Resources Research*, **40**, W03302, doi:10.1029/2003WR002723.

Slingerland, R. and Smith, N. D. (1998) Necessary conditions for a meandering-river avulsion: *Geology,* **26**, 435–438.

Slingerland, R. and Smith, N. D. (2004) River avulsions and their deposits: *Annual Review of Earth and Planetary Science*, **32**, 257–285.

Smith, J. D. (2004) The role of riparian shrubs in preventing floodplain unraveling along the Clark Fork of the Columbia River in Deer Lodge Valley, Montana: *In* Bennett , S. J. and Simon, A., eds. *Riparian Vegetation and Fluvial Geomorphology*: American Geophysical Union, Washington, D. C., 71–85.

Speight, J. G. (1966) Meander spectra of the Angabunga River: *Journal of Hydrology,* **3**, 1–15.

Stølum, H. (1998) Planform geometry and dynamics of meandering rivers: *Geological Society of America Bulletin*, **110**, 1485–1498,

Sun, T., Meakin, P. and Jøssang, T. (1996) A simulation model for meandering rivers: *Water Resources Research*, **32**, 2937–2954.

Triska, F. J. (1984) Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: a historical case study: *Verhandlung Internationale Vereinigung Limnologie*, **22**, 1876–1892.

Yen, C. (1970) Bed topography effect on flow in a meander: *J. Hydraulics Div. Am. Soc. Civ. Eng*., **96**, 57–73.