Meander cutoff and the controls on the production of oxbow lakes

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ABSTRACT

Using satellite images archived by Google Earth™, we measured channel and oxbow-lake characteristics of 30 large meandering rivers to identify the controls on the production of oxbow lakes by meander cutoff. Cutoff produced lognormal distributions of lake lengths within the studied reaches, and the geometric mean lake length of each population correlated positively and exponentially with sinuosity, due to more highly sinuous reaches being comprised of longer meanders and to cutoff removing longer segments of more sinuous channels. We successfully predicted the size-frequency distributions of lakes stored within the floodplains of five freely meandering reaches using only channel sinuosity and an assumption of the variance about the geometric mean lake length, a variable that did not significantly vary between the studied reaches. While the river's sinuosity remains steady, the temporal rate of cutoff can be estimated using channel sinuosity, the fraction by which cutoff reduces channel length, and the rate at which the reach lengthens by meander growth.

Keywords: oxbow lakes, meander, floodplains, sinuosity, meandering.

INTRODUCTION

The growth and cutoff of meanders are important in the construction of the meandering river's floodplain (Wolman and Leopold, 1957; Mertes et al., 1996) and its alluvial architecture (Allen, 1965; Bridge et al., 1986). Oxbow lakes are the products of meander cutoff, and their occurrence and sedimentary deposits influence rates of meander migration (Hudson and Kesel, 2000), the width of the meander belt (Allen, 1965; Howard, 1996; Sun et al., 1996), the hydrogeological characteristics of alluvial reservoirs (Richardson et al., 1987), and the diversity of floodplain habitat (Ward, 1998). Despite their importance, little is known of the manner by which the meandering river populates the floodplain with oxbow lakes. For instance, cutoff maintains the river's sinuosity over the long term by removing segments of channel and storing those segments in the floodplain (Howard and Knutson, 1984; Camporeale et al., 2005), but it was not previously clear what determined the lengths of those removed segments, the size-frequency distribution of oxbow lakes that result, or the volume of lakes and sediment accommodation space that exist at any one time. In his pioneering study, Stølum (1998) found that the cumulative size-frequency distribution of Amazonian and model-generated oxbow lakes could be fit by a power function, and he argued, as a result, that the shape of the distribution was due to the inherent nature of the meandering river to organize itself into a critical state, a hypothesis first introduced by Stølum (1996) and founded on the theory of self-organized criticality (Bak et al., 1987). Stølum's (1998) findings were based on three rivers with a sinuosity greater than 2.5.

Without widespread observations, the development of a theory that explains the role of meandering in floodplain evolution has lagged behind the considerable progress made toward a theoretical description of the meandering process. As a result, meandering evolution models have typically focused only on a narrow set of conditions in which cutoff occurs, producing highly sinuous planforms not commonly observed in nature. In order to augment existing observations to include a variety of meandering planforms and to identify the controls on the production of oxbow lakes, we have assembled measurements of meanders and oxbow lakes across a range of lowland floodplain environments using satellite images archived by Google Earth™. From these measurements, we have determined that the cutoff process produces a characteristic and predictable size-frequency distribution of oxbow lakes. We then demonstrated that this insight allows for predictions of the temporal rate of cutoff under a condition of steady time-averaged channel sinuosity. Our results will aid efforts to improve theoretical understanding of the full range of meandering behavior and provide an added means for quantifying the development of the floodplain environment.

METHODS

Due to the variable resolution of satellite images stored in the Google Earth™ database, we chose 30 meandering reaches with a minimum channel width of 100 m so that we could confidently measure their spatial attributes (see the GSA Data Repository[1]). We ensured that the selected reaches varied geographically and were located in wide valleys, such that their meandering behavior was not affected by encounters with valley margins. For each reach, we measured the bankfull channel width at a minimum of ten locations along straight segments as the distance perpendicular to the channel between vegetated banks and sinuosity as the ratio of channel length to valley length. We distinguished the contribution to total sinuosity made by the segmented lines joining inflections that may not parallel the valley and separately measured this inflection sinuosity as the ratio of the total length of the segmented lines to valley length. We measured the lengths of meanders within each reach as the channel distance between inflections. We then identified a minimum of 20 oxbow lakes in each floodplain and measured their lengths, including both open water and recently terrestrialized segments. In total, 911 lakes were measured among the 30 reaches. We normalized each meander- and lake-length measure by the average bankfull width of the active channel in the reach.

RESULTS AND DISCUSSION

The selected reaches range in total sinuosity from 1.19 to 2.26 and in average channel width from 110 m (±30 m) to 830 m (±150 m). The cumulative size-frequency distributions of their lake-length populations are similarly shaped, and their relative position in size-frequency space tends to systematically vary with sinuosity (Fig. 1). The lake-length distributions are nearly all positively skewed, with sample skewness averaging 1.2 ± 0.74. Kolmogorov-Smirnov (KS) tests, Geary tests of skewness, and chi-squared tests cannot reject the null hypothesis that the distributions are consistent with the lognormal model. The geometric mean of each population of lake lengths (L) correlates positively and significantly ($p<0.001$) with the sinuosity (S) of the active channel in the reach, the correlation being best described by an exponential function (Fig. 2). The magnitude of the geometric standard deviation does not vary significantly between the lake populations, ranging from 1.36 to 1.97 (mean = 1.61 ± 0.15) channel widths and does not correlate with sinuosity ($r^2<0.001$).

The cutoff process samples directly from the population of meanders in a reach, and as the meanders of a reach increase in length, longer lakes should subsequently be produced. The 30 populations of meander lengths that make up each of the 30 meandering reaches are log-

[1]GSA Data Repository item 2008009, a description of the reaches, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

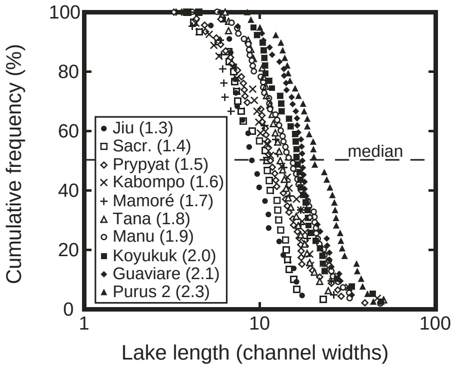

Figure 1. The cumulative size-frequency distributions of oxbow lake lengths. For ease of viewing, the lake-length populations of only 10 of the 30 meandering reaches are shown. The sinuosity of each reach is provided in parentheses beside the reach name. Sacr. denotes the Sacramento River.

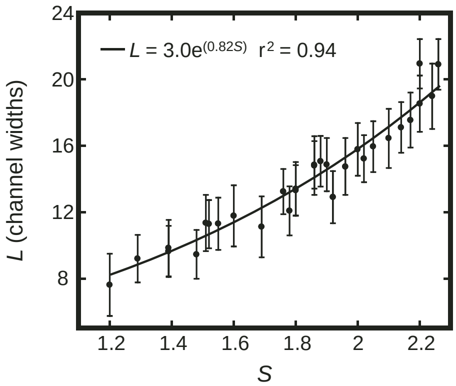

Figure 2. The geometric mean lake length (*L*) of the population of lakes within each of the 30 meandering reaches versus the sinuosity (*S*) of each reach. Error bars represent ±1 geometric standard deviation.

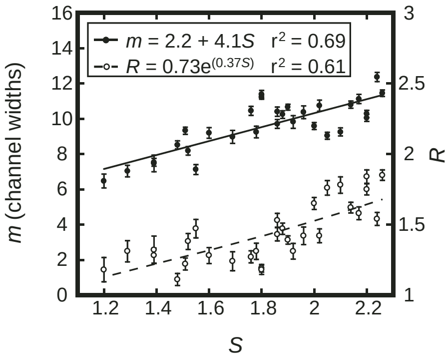

Figure 3. The geometric mean meander length (*m*) and the ratio (*R*) of the geometric-mean lake length to m for each of the 30 meandering reaches versus the sinuosity (*S*) of each reach. Error bars represent ±1 geometric standard error.

normally distributed as determined by KS tests. The geometric mean of each population of meander lengths (m) exhibits a significant ($p<0.001$) and positive linear correlation with sinuosity (Fig. 3), although the resulting regression does not meet the implication of widely published rules about the relationship of meander wavelength to channel width. Many authors have indicated that the wavelengths (λ) of meanders are 7–11 times the bankfull channel width (w) (e.g., Inglis, 1949; Leopold and Wolman, 1960). Using the midpoint of the published range (~9) for this ratio yields a sinuosity of

$$S = \frac{mw}{0.5\lambda}, \tag{1}$$

and

$$m = 4.5S, \tag{2}$$

where, by definition, two meanders comprise a meander wavelength. The higher values of m in Figure 3 caused by a positive intercept are presumably contributed by the sinuosity of the segmented lines joining inflections, for which no theory-based generalization has yet been published. Our values for the inflection sinuosity range from 1.05 to 1.65 as the total sinuosity ranges from 1.19 to 2.26.

The positive correlation between L and sinuosity can be explained by the increased availability to the cutoff process of longer meanders as sinuosity increases, but it cannot explain why an exponential function best describes that correlation. In order to determine how L and m change relative to one another as channels become more sinuous, we divided L by m for each of the 30 reaches, the result revealing a significant ($p<0.001$) and positive correlation between this ratio, R, and sinuosity (Fig. 3). Thus, the lengths of lakes produced by cutoff will increase not only as meanders increase in length, but also because the cutoff process removes progressively longer segments of the channel (ranging from ~1 meander in almost straight channels to 1.7 times the average meander length at the highest sinuosity sampled) as sinuosity increases.

The positive correlation between R and sinuosity may be a function of the cutoff mechanisms operating in a river. In the absence of chute cutoff, which results after floods incise a new channel into the meander floodplain (Gay et al., 1998), meandering evolution models produce highly sinuous planforms wherein neck cutoff, which results after meanders migrate into one another (Gagliano and Howard, 1984), is the only mechanism of channel shortening (e.g., Howard, 1992; Sun et al., 1996; Camporeale et al., 2005). Howard (1996) observed that by allowing chute cutoff to randomly occur in his simulation, the resulting planform became much less sinuous; the more frequent the occurrence of chute cutoff, the more reduced became sinuosity. As the planform is allowed to mature, complex meander forms arise (Parker and Andrews, 1986; Furbish, 1991; Lancaster and Bras, 2002), and so the probability that cutoff will remove segments of channel comprising more than one average meander length should increase while chute cutoff is absent.

The correlation between L and sinuosity and the finding that each of the 30 meandering reaches produced lognormal populations of lake lengths suggest the potential for predicting the size-frequency distribution of oxbow lakes stored within a freely meandering reach using only a measure of its sinuosity and an assumption of the variance about the geometric mean. Implicit in the success of such a prediction is that sinuosity has remained temporally stable over the period in which the lakes of interest were produced. Based on the exponential function that best describes the correlation between L and sinuosity, an estimator ($\hat{L}$) for L is defined as:

$$\hat{L} = 3.0e^{(0.82S)}. \tag{3}$$

The size-frequency distribution of lakes populating a floodplain can then be estimated by substituting $\hat{L}$ for L in the lognormal probability density function of lake lengths. Due to the similarity in the values of geometric standard deviation between the lake-length populations, we applied their average value (0.48) to estimate the standard deviation of lake populations elsewhere.

We used Equation 3 to predict the size-frequency distributions of lake lengths within reaches of five freely meandering rivers. We compared the predictions to the actual lake-length distributions determined by methods outlined above (Table 1). Two-tailed KS tests ($\alpha = 0.05$) cannot reject the null hypothesis that the measured lake lengths within each reach were drawn from a lognormal population in which L was estimated using Equation 3. The result lends support to the ability of the equation, as well as to that of the lognormal model, to predict the size-frequency distribution of lake lengths stored within a freely meandering reach.

The rate of production of oxbow lakes is a function of the temporal rate of cutoff, which, because the typical length of channel removed by the process is defined by L, can be written as:

$$\frac{dn}{dt} = \frac{1}{fL}\left(\frac{dM}{dt} - V\frac{dS}{dt}\right), \tag{4}$$

where the temporal rate of cutoff is denoted by the change in the number of cutoff events (n) over time (t), f is the fractional reduction in channel length for a typical cutoff event and is measured as $(L - l)/L$ where l is the average newly formed channel length between the ends of removed channel segments, M is the length of channel produced by meander growth in

TABLE 1. THE FIVE FREELY MEANDERING REACHES WHOSE OXBOW LAKE SIZE-FREQUENCY DISTRIBUTIONS WERE PREDICTED USING EQUATION 3

River name	Location	Measured lakes (No.)	Sinuosity	L_m* (channel widths)	L_m-L_p† (channel widths)	D§
Moksha	Russia	30	1.33	9.71	0.78	0.20
Oka	Russia	19	1.69	12.4	0.41	0.16
Vichada	Colombia	27	2.03	14.0	–1.85	0.15
Fly	Papua, New Guinea	16	2.05	15.4	–0.71	0.15
Bolshaya Irgiz	Russia	18	3.01	45.8	10.4	0.27

*The geometric-mean lake length measured (L_m) for the lake population within each reach.
†The difference between L_m and the predicted geometric-mean lake length (L_p) based on Equation (3).
§The Kolmogorov-Smirnov statistic (D) determined by comparing the full measured and predicted lake-length cumulative distributions.

channel-width units, and V is valley length in channel-width units. While channel sinuosity is not adjusting, dS/dt is zero, and by substituting $\hat{L}$ for L, Equation 4 becomes:

$$\frac{dn}{dt} = \frac{e^{(-0.82S)}}{3.0f}\frac{dM}{dt}. \quad (5)$$

If dM/dt is unchanging during a time interval, it can be estimated at any time step within the interval by directly measuring the change in channel length or using a calibrated bank migration model. Planform evolution models that employ the linear theory of meander migration predict migration rates at equidistant points defining locations along a channel centerline and subsequently adjust the planform by moving those points in a direction orthogonal to the centerline (e.g., Parker and Andrews, 1986; Sun et al., 1996). We utilized this method to estimate dM/dt for a reach of the Sacramento River of California (39°14′48.12″ N, 122°00′05.62″ W). The sinuosity of the river has not changed significantly during the past 90 yr (Buer, 1994), satisfying the condition leading to Equation 5 and allowing an assessment of the equation's ability to estimate dn/dt for the reach.

The linear theory of meander migration (Ikeda et al., 1981) states that the bank migration rate (E_j) at any location j along the channel centerline of a meander can be determined as the product of a dimensionless erodibility coefficient (ε) and a near-bank velocity term (ω_j). We used this product to estimate E_j within the study reach of the Sacramento River during bankfull conditions. For the purposes of this study, we treated ε as spatially constant. Values for ε have been reported to range from 1.65×10^{-7} to 2.58×10^{-7} in the Sacramento River (Micheli et al., 2004). We used the following equation developed by Sun et al. (1996, Equation 15) and based on Ikeda et al. (1981) to determine ω_j:

$$\omega_j = \frac{v}{U/\Delta p + 2(U/y)F} \left[-U^2 \frac{\partial c}{\partial p}\bigg|_j + c_j F\left(\frac{U^4}{gy^2} + A\frac{U^2}{y}\right) + \frac{U}{\Delta p}\frac{\omega_{j-1}}{v} \right], \quad (6)$$

TABLE 2. VALUES USED IN SOLVING EQUATION 6

Variable or constant*†	Value
Bankfull channel half-width (v)	105 m
Distance between centerline points (Δp)	100 m
Average bankfull-channel depth (y)	6.7 m
Average channel slope	39.2 cm km^{-1}
Gravitational acceleration (g)	9.81 m s^{-2}
Reach-average downstream velocity (U)	2.0 m s^{-1}
Friction coefficient (F)§	0.0064
Scour factor (A)§	4.13

*Variables relevant only to the study reach within the Sacramento River.
†Channel characteristics are based on U.S. Army Corps of Engineers cross sections.
§The variables F and A were determined after Pizzuto and Meckelnburg (1989).

where v is equal to $w/2$, U is the bankfull, reach-averaged, downstream velocity, Δp is the change in distance between centerline points, y is the average bankfull depth, F is a dimensionless friction coefficient that we assumed is constant, c_j is the local curvature, and A is a scour factor. We determined U using the Manning equation, substituting y for the hydraulic radius and setting the Manning friction coefficient to 0.035 based on previously calibrated hydraulic computations (USACE, 2002). Sun et al. (1996) evaluated the $\partial c/\partial p$ term in Equation 6 as $(c_j - c_{j-1})/\Delta p$. Values used in solving the equation are shown in Table 2.

After orthogonally adjusting channel-centerline locations based on the measures of E_j, we determined that dM/dt for the study reach ranged between 1.42 and 2.21 channel widths yr^{-1} based on the reported range of ε values. We examined eight incidents of cutoff using historical aerial photos of the reach and found that cutoff reduced local channel length on average by half, so we set f equal to 0.5. The integration of Equation 5 (where S = 1.39) over the time span provided an estimate of between 27 and 42 cutoff events for the past 90 yr. Thirty-eight cutoffs were identified in the study reach of the Sacramento River over this time span using historical maps and aerial photos (Avery et al., 2003), lending support to the ability of Equation 5 to predict the temporal rate of cutoff.

In the absence of changes in external forcing, the meandering planform will stabilize about an

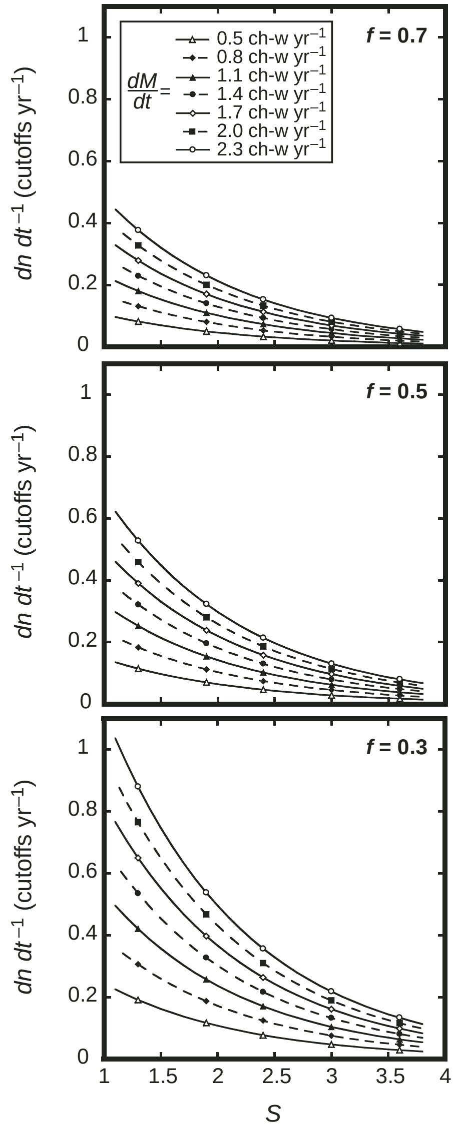

Figure 4. The temporal rate of cutoff (*dn dt*$^{-1}$), as determined using Equation (5) in text, plotted against sinuosity (*S*). Values of *dn dt*$^{-1}$ were calculated for particular values of *f*, or the fraction that a cutoff event reduces meander length (e.g., when *f* equals 0.7, there is a 70% difference between the original meander length and the new meander length). Curves within each graph represent solutions for varying values of reach-lengthening rate (*dM dt*$^{-1}$), in units of channel widths per year (ch-w yr^{-1}).

average sinuosity that fluctuates as the effects of meander growth and cutoff balance each other (Howard and Knutson, 1984; Hooke and Redmond, 1992; Stølum, 1996; Camporeale et al., 2005). During such a condition, solutions to Equation 5 allow for predictions of meandering behavior (Fig. 4). Rivers with rapidly migrating meanders are those that more quickly lengthen, and a high cutoff rate is required for the sinuosity of these rivers to be maintained. Differences in cutoff rates due to varying migration rates lessen with increases in sinuosity for two reasons. For a river to attain high sinuosity, cutoff must be infrequent, because its occurrence, particularly chute cutoff, prevents the elongation of meanders (Howard, 1992, 1996). Moreover, because cutoff removes longer segments of more sinuous rivers, it can occur less often while maintaining a temporally stable sinuosity. The fractional reduction in channel length due to cutoff is an important control on cutoff rate, especially for less sinuous rivers that are rapidly lengthening. Neck cutoff more effectively reduces channel length (Hooke, 1995), and a river dominated by the mechanism can maintain its sinuosity with fewer incidents of cutoff.

CONCLUSIONS

The lengths of channel removed by meander cutoff can be modeled as lognormally distributed random variables whose central tendency scales with sinuosity. The effect of cutoff on the planform can then be generalized because it removes a characteristic length of channel, L. While sinuosity is unchanging, L can be predicted, and the makeup of the floodplain with respect to the population size and length distribution of oxbow lakes can be modeled using Equations 3 and 5. The cutoff mechanisms operating in a river exert important influence on L, and thus on the evolution of the meandering planform. A highly sinuous planform indicates that chute cutoff is nearly absent and that neck cutoff is infrequent. The floodplains of such channels will be populated by longer oxbow lakes than those found along channels whose sinuosity is reduced by frequent occurrences of chute cutoff. The controls on the relative frequency of cutoff mechanisms are not well known, and a more precise understanding of meandering behavior, and thus floodplain development, is contingent on their identification.

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