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Examining the physical meaning of the bank erosion coefficient used in meander migration modeling

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ABSTRACT

Widely used models of meander evolution relate migration rate to vertically averaged near-bank velocity through the use of a coefficient of bank erosion (E). In applications to floodplain management problems, E is typically determined through calibration to historical planform changes, and thus its physical meaning remains unclear. This study attempts to clarify the extent to which E depends on measurable physical characteristics of the channel boundary materials using data from the Sacramento River, California, USA. Bend-average values of E were calculated from measured long-term migration rates and computed near-bank velocities. In the field, unvegetated bank material resistance to fluvial shear (k) was measured for four cohesive and noncohesive bank types using a jet-test device. At a small set of bends for which both E and k were obtained, we discovered that variability in k explains much of the variability in E. The form of this relationship suggests that when modeling long-term meander migration of large rivers, E depends largely on bank material properties. This finding opens up the possibility that E may be estimated directly from field data, enabling prediction of meander migration rates for systems where historical data are unavailable or controlling conditions have changed. Another implication is that vegetation plays a limited role in affecting long-term meander migration rates of large rivers like the Sacramento River. These hypotheses require further testing with data sets from other large rivers.

1. Introduction

Physically based meander migration models developed from the theory of Ikeda et al. (1981) and Johannesson and Parker (1989) have been used to investigate the long-term (i.e., decades to thousands of years) evolution of meandering river planform (Stølum, 1998; Sun et al., 2001a,b) and floodplain morphology (Howard, 1992; Sun et al., 1996). Shorter term (i.e., decades to years) river responses to management decisions have also been predicted (Larsen and Greco, 2002; Larsen et al., 2006). In these models, the rate of meander migration (M) is predicted from the equation

$$M = E \cdot u_b' \tag{1}$$

where E is a coefficient of bank erosion and u_b' is the difference between the depth-averaged near-bank velocity and the cross-sectionally averaged velocity (Ikeda et al., 1981). Field studies by Pizzuto and Meckelnburg (1989) provided evidence in support of a linear relationship between M and u_b', which reflects the magnitude of the shear forces acting on the bank. In predictions using Eq. (1), the coefficient E is typically determined through calibration to historical planform changes (e.g., Larsen and Greco, 2002); therefore, the meaning of E and the extent to which it depends on physical characteristics of the channel or the bank material remain unclear. Researchers generally agree that E reflects the geotechnical properties of the bank material (Hasegawa, 1989; Wallick et al., 2006) and the effects of vegetation on near-bank flow and bank strength (Odgaard, 1987; Pizzuto and Meckelnburg, 1989; Micheli and Kirchner, 2002a; Micheli et al., 2004). The coefficient may also vary with other channel characteristics such as bank height and local channel slope (Hasegawa, 1989), local channel width (Larsen, 1995; Wallick et al., 2006), and the availability of sediment for deposition on point bars (Ikeda et al., 1981).

Other models have been developed in which bank migration results from intermittent bank collapse in response to a slope-stability criterion instead of depending on calibration to link flow conditions in the channel to the rate of erosion at the bank (Nagata et al., 2000; Darby et al., 2002). Despite this benefit, mechanistic models of bank erosion face the limitation that they are specific to a particular type of bank material or failure mechanism. For example, the model of Darby et al. (2002) predicted the rate of bank retreat via planar failure. Although planar failures are common at steep river banks (Thorne,

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1982), other types of failures are frequently observed in the field. Failures may be rotational where bank material is cohesive (e.g., Brunsden and Kesel, 1973) or cantilever where banks are stratified (Thorne and Tovey, 1981). The occurrence of failure in these cases is driven by the fluvial removal of sediment at the base of the bank. As a result of this natural variability in river bank type, failure, and sediment removal processes, mechanistic approaches are not as broadly applicable as the linear approach in Eq. (1).

The purpose of this study is to make progress toward developing the capability to estimate E from field measurements of bank material properties. The ability to define E without calibration is particularly useful for understanding the rate-limiting controls on bank migration and for predicting migration of rivers for which historical planform data are unavailable or flow and bank conditions have recently changed. One of the hindrances to doing this in the past was the lack of a quantitative field method to measure directly the erodibility of both cohesive and noncohesive banks. This limitation is addressed here by using a recently developed jet-test apparatus and test procedure (Hanson, 1990; Hanson et al., 2002; Hanson and Cook, 2004). The procedure was designed to measure the erosion resistance of both cohesive and noncohesive banks by subjecting the bank material *in situ* to a realistic fluvial shear rather than use a penetrometer or shear vane or other geotechnical index of resistance to collapse. During the course of the test, a known shear stress is applied to the bank *in situ* through a submerged jet apparatus, and the erosion rate of the bank is measured. The relationship between the applied stress and the erosion rate is used to determine the critical shear stress and an erodibility coefficient k that describes bank material resistance to erosion by fluvial shear.

In this study, the results of jet tests completed on four different bank material types were compared with E values calculated from historical migration rate data and Eq. (1). To examine the influence of other channel conditions on E, values of the coefficient were also compared with data on land cover, proximity to bank-protection structures, local width-to-depth ratio, local slope, local bank height, local average velocity, bed material grain size, and bed material storage change. Results suggest a strong correlation between E and k, which implies that E may be determined directly from field measurements of bank material resistance to fluvial shear. Such an approach would allow for predictions of meander migration that are independent of past patterns of channel shifting. The correlation between E and k also suggests that bank material properties are the predominant control on long-term meander migration rates of the Sacramento River and perhaps other large rivers with vegetation playing a more limited role. This hypothesis requires further testing with more data from other large rivers.

2. Study area

The Sacramento River drains 68,000 km^2 of northern California, USA. Its basin has a Mediterranean climate characterized by cool, wet winters and warm, dry summers. Average annual precipitation ranges from 50 cm/y on the valley floor to 178 cm/y in the surrounding mountains (California Department of Water Resources, 1994). The study area is an 85 km sinuous portion of the lowland river between Hamilton City (RM 196) and Colusa (RM 144) that exhibits active lateral migration (Fig. 1). As a result of lateral shifting, river mile markers no longer correspond with actual streamwise distance; however, river mile designations are used as longitudinal reference points in this study in accordance with published works by the different researchers and agencies working in the watershed. For this reason, locations are referred to in river miles, whereas all calculations are expressed in metric units.

Peak flows in the Sacramento occur in the winter and spring when the basin receives most of its precipitation and snow melt. The natural hydrograph was altered in 1943 with the closure of Shasta Dam, which had the effect of dampening flood peaks and elevating low summer flows (Singer, 2007). The 2 year flood at the upstream end of the study area is ~2550 m^3/s [U.S. Geological Survey (USGS) gauge 11383800]. Discharge declines downstream as overbank flow is routed to Butte Basin across the floodplain and through Moulton and Colusa weirs where the channel and proximal floodplain are lined by levees (Fig. 1). The 2 year flood at Colusa is 1125 m^3/s. Average bankfull width follows discharge, declining from 340 m near Hamilton City to 150 m at Colusa. Channel slope also declines downstream from 0.0005 near Hamilton City to 0.0002 at Colusa. The channel bed throughout the study area is composed of a poorly sorted mixture of gravel and sand. Gravel dominates the mixture upstream, but sand makes up more than 25% of the bed downstream of RM 160.

Natural river banks in the study area are primarily composed of two types of material: relatively erosion-resistant Quaternary terrace material and younger unconsolidated Holocene alluvium. The Quaternary Riverbank and Modesto Formations form two sets of terraces that border the Holocene meander corridor. The Riverbank Formation, which contains numerous partially cemented and cohesive layers (Smith and Verrill, 1998), is more resistant to erosion. Both the Modesto and the Riverbank Formations are in places underlain by cemented Quaternary and Tertiary deposits. Banks composed of Holocene alluvium typically have a lower layer of noncohesive gravel and sand and an upper layer of silt; grain size and sand content of the gravel base vary widely. Variations within the Holocene alluvium include banks that are mainly sand and lack a gravel base and banks that have a high percentage of clay and represent oxbow lake fill.

The average 50 year meander migration rate in the study area is about 4 m/y, but single-bend rates range from 0 m/y where the river abuts terrace material to 10 m/y at unconstrained bends (Constantine, 2006). Although levees are present in the downstream portion of the study area, they are set back from the river and spaced 0.75 to 2.5 km (~1.0 to 3.3 times meander amplitude) apart (Fig. 1), encompassing both the channel and proximal floodplain and allowing channel shifting to occur. Bank-protection structures, primarily rock revetment and concrete rubble, are present in most reaches and cover about 20% of the bankline in the study area (California Department of Water Resources, 1994). Included in this total are most of the locations downstream of RM 175 where the river abuts a levee and where rock and concrete serve as protection against levee degradation. Only freely migrating bends were included in the analyses conducted for this study.

3. Methods

3.1. Measuring migration rates

Rates of lateral migration for individual bends were measured for the period 1978–2004. This time period was chosen because it captured a number of large erosion events and includes the post-1997 time period for which bed material transport and storage changes were modeled (see Constantine, 2006). Digital copies of aerial photographs taken in May 1978 by the U.S. Department of Agriculture (USDA) (scale 1:40,000) were obtained from the California Department of Water Resources (DWR), Northern District. Orthorectification of the photos was completed in ENVI (Research Systems, Inc.) using USGS orthophoto quadrangles as base photos, a digital elevation model (DEM) from the USGS National Elevation Dataset, and the appropriate USDA camera calibration report. The average horizontal accuracy achieved was 3.5 m (root mean square error). Orthorectified 2004 photos (1.9 m root mean square error) were obtained from AirPhotoUSA.

Thalweg centerlines for 1978 and 2004 were digitized and intersected to define polygons that represent areas of floodplain eroded over the 26 year period. Centerlines were drawn through small mid-channel bars and, in multithreaded segments of the river, were drawn around larger bars and islands, tracing the path of the widest (main) channel. Following a method by Micheli (2000), the average migration rate for