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MODELING THE EFFECTS OF VARIABLE ANNUAL FLOW ON RIVER CHANNEL MEANDER MIGRATION PATTERNS, SACRAMENTO RIVER, CALIFORNIA, USA[1]

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ABSTRACT: Flow regulation impacts the ecology of major rivers in various ways, including altering river channel migration patterns. Many current meander migration models employ a constant annual flow or dominant discharge value. To assess how flow regulation alters river function, variable annual flows – based on an empirical relationship between bank erosion rates and cumulative effective stream power – were added into an existing migration model. This enhanced model was used to evaluate the potential geomorphic and ecological consequences of four regulated flow scenarios (i.e., different hydrographs) currently being proposed on the Sacramento River in California. The observed rate of land reworked correlated significantly with observed cumulative effective stream power during seven time increments from 1956 to 1975 ($r^2 = 0.74$, $p = 0.02$). The river was observed to rework 3.0 ha/yr of land (a mean channel migration rate of 7.7 m/yr) with rates ranging from 0.8 ha/yr to 5.1 ha/yr (2.0 to 13.3 m/yr), during the analyzed time periods. Modeled rates of land reworked correlated significantly with observed rates of land reworked for the variable flow model ($r^2 = 0.78$, $p = 0.009$). The meander migration scenario modeling predicted a difference of 1 to 8 percent between the four flow management scenarios and the base scenario.

(KEY TERMS: fluvial processes; geomorphology; riparian ecology; GIS; bank erosion; meander migration; water management.)

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INTRODUCTION

Altering flow regimes impacts many ecological functions on major rivers (Abramovitz, 1996), including aquatic and riparian ecosystems (National Research Council, 2002; Tockner and Stanford, 2002; Postel and Richter, 2003). One of the primary processes influencing riparian ecosystems on large alluvial rivers is river meander migration. Channel migration is critical for establishing and maintaining natural riparian, oxbow lake, and riverine ecosystems (Hupp and Osterkamp, 1996; Scott *et al.,* 1996; Ward *et al.,* 2002). Water diversion and river flow management have detrimental effects on riparian habitat (Johnson *et al.,* 1976; Merritt and Cooper, 2000). Research suggests that current flow regulation practices, which focus primarily on flood control and water delivery, can be modified to help maintain dynamic riparian ecosystem processes while providing necessary water deliveries and flood control (Poff *et al.,* 1997).

Flow regulation affects riparian habitat by controlling the magnitude, timing, and duration of inundations over the adjacent floodplain (Poff *et al.,* 1997). Research has shown that linkages between floodplain and aquatic systems help maintain species diversity and increase productivity (Junk *et al.,* 1989). Artificially lowered river flows disconnect floodplains from adjacent ecosystems by limiting overbank flooding. Within floodplain rivers, flood waters are the medium through which resources are exchanged between terrestrial and aquatic systems. Flood waters also generate ephemeral habitat for fauna in stream ecosystems (Bayley and Li, 1992). Limiting floodplain inundation

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patterns has the potential to harm valued fish populations (Gutreuter *et al.,* 1999; Limm and Marchetti, 2003). Despite great interest in developing alternative flow regulation protocols for various purposes, little research has focused on the potential to create riparian habitat creation by encouraging meander migration.

Channel migration processes create the characteristics important for natural riparian ecological communities (Bradley and Smith, 1986). These processes create and maintain a natural range of heterogeneity within the riparian habitat landscape mosaic (Naiman *et al.,* 1993). The depositional side of a continuously migrating channel forms a natural nursery site for riparian forests (McBride and Strahan, 1984; Wood, 2003). These sites are necessary to recruit key riparian species such as cottonwoods and willows. Forest ecosystems mature relatively rapidly; for example, within 100 to 300 years they can transition to upland ecosystems (Sands and Howe, 1977). Without channel migration, riparian communities would no longer form, and existing communities would progress into late seral upland communities (Johnson *et al.,* 1976; Fremier, 2003).

To fully consider the environmental and societal constraints on river systems, more effective ways are needed to plan and manage the impacts of river flow management (CALFED, 2000). Any analysis of the effects of river flow management on riparian forest habitat integrity should consider the temporal and spatial dynamics of influential processes such as river meandering, channel cutoff, and overland flooding.

River managers are increasingly required to balance flood concerns and water supply agendas with the needs of the environment (NEPA, 1970; SRCA, 1998; USACE, 2002; Golet *et al.,* 2003). Analyzing the geomorphic and ecological effects of river flow management can be difficult because it must integrate both hydrogeomorphic and ecological response models. Aspects of this comprehensive analysis have been simulated with river meander migration models (e.g., Larsen, 1995; Larsen and Greco, 2002), two-dimensional flood analysis models (e.g., HEC-RAS, 2003), and vegetation succession models (Richter and Richter, 2000). Management and research efforts have focused on the effects of flow restoration (CALFED, 2000). Studies in conservation research journals have tended to report on how flow regulation affects river processes such as sediment transport and recruitment (Poff *et al.,* 1997; Richter and Richter, 2000). However, none has quantified how proposed alternative flow management scenarios will affect the quantity of land reworked through meander migration.

Meander migration modeling has proved useful for considering management alternatives on large rivers such as the Sacramento (Larsen and Greco, 2002; Golet *et al.,* 2003; Larsen *et al.,* 2006b) and predicting the patterns of meander migration development (e.g., Howard, 1992, 1996; Larsen, 1995; Sun *et al.,* 2001). Because many past meander migration modeling efforts have assumed a constant flow rate, they have not been able to assess geomorphic responses to river flow management changes (e.g., Larsen and Greco, 2002). Previous studies (Larsen *et al.,* 2002; Larsen and Greco, 2002) used the two-year recurrence interval flow as the characteristic discharge to represent the integrated effects of a range of flows. The rationale is similar to that used in traditional geomorphic analyses that relate channel form and processes to the bankfull or dominant discharge (Wolman and Leopold, 1957; Wolman and Miller, 1959). Accordingly, the model used for those studies did not simulate the effects of particular flow events but instead produced estimates of long term erosion or channel migration rates. Assuming a single, continuously acting characteristic discharge that produces continuous and gradual erosion is a useful simplification (Howard, 1992) when the goal is to predict long term channel migration. However, using a constant flow rate does not reveal differences in migration patterns due to flows that change from year to year. Consequently, this approach does not reveal the spatial vegetation patterns that result from variable flow rates.

This paper introduces a method to incorporate a variable flow pattern into a meander migration model based on a relation between bank erosion rates and effective stream power (Larsen *et al.,* 2006a). Previous applications of the migration model (Larsen *et al.,* 2002; Larsen and Greco, 2002) have used a characteristic discharge estimate that over the long term represents the integrated effects of the variable flow regime. The results of the variable flow method are then used to quantify potential impacts on riparian communities from Sites Reservoir, which the California Department of Water Resources (CDWR) may install west of the Sacramento River between Colusa and Red Bluff (Figure 1). The CDWR has proposed four flow management scenarios that would divert different amounts of water from the Sacramento River depending on reservoir operation protocols. These management scenarios are factored into the variable flow meander migration model to determine how river meander migration patterns could be affected. The river channel meander patterns are simulated for a 4 km reach of the Sacramento River. The area of floodplain reworked each year is then predicted by the modeled river migration. Although resulting vegetation patterns are not explicitly modeled, the model illustrates the potential impacts of these scenarios through altered channel migration patterns.

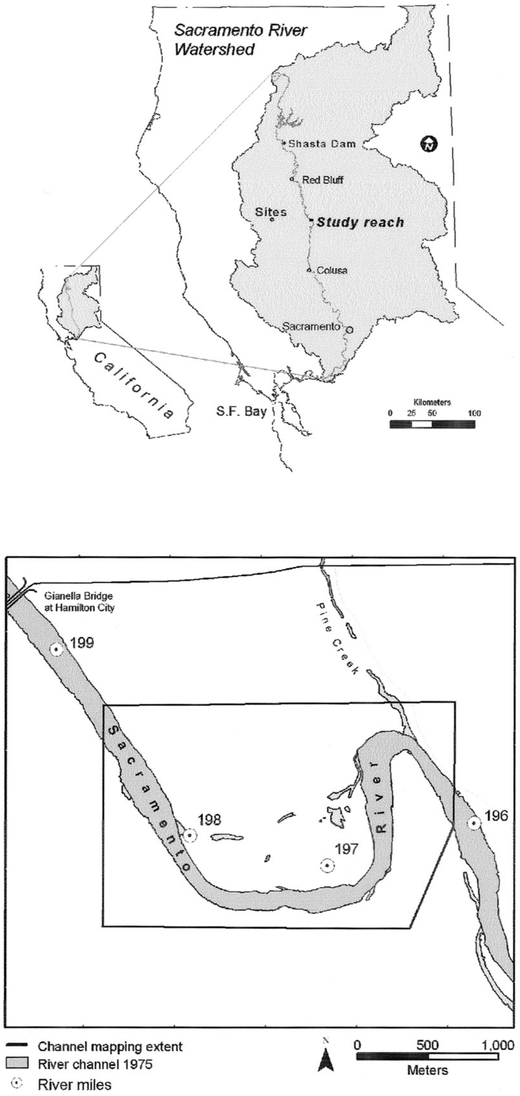

Figure 1. Sacramento River Watershed and Study Site in Northeastern California, USA. The study site for this project is located on the meandering sector of the Sacramento River between river miles 196 and 199 at the confluence with Pine Creek.

MATERIALS AND METHODS

Study Area

The Sacramento River in north-central California, USA, flows south through the Sacramento Valley (Figure 1) over sedimentary rocks and recent alluvium. The Sacramento Valley, 96 km wide and 418 km long, is a structurally controlled basin lying between the Cascade and Sierra Nevada Mountains to the east and the Coast Ranges of California to the west (Harwood and Helley, 1987). The total drainage area of the river is 6.8 by 104 km^2, more than half of the total drainage area of San Francisco Bay on the west coast of California. Further river reach detail is available in Larsen *et al.* (2006a).

The main sources of water for the Sacramento River's hydrologic system come from seasonal precipitation and snow melt. The major man made structures that have affected the Sacramento River's hydrology in the past 60 years are Shasta Dam, located 312 river miles upstream from the river's confluence with San Francisco Bay (RM 312), and a number of flood control structures. These structures permit overflow at specified flows into overflow catchment basins installed as part of the Sacramento River federal flood control project. Flow regulation changed the hydrograph primarily in two ways: (1) winter peak flows were limited in order to decrease downstream flooding and increase water storage, and (2) summer base flows were increased for agricultural irrigation in the dry season (CALFED, 2000).

Flow Regulation Scenarios

The study reach is between RM 196 and RM 199 (Figure 1). The reach was chosen because ample data exist for historic channel dynamics and because it was a site of interest to local river managers. Larsen *et al.* (2006a) contains a more detailed description of the Pine Creek study site. Four daily flow management scenarios and a base scenario were simulated using the computer program CalSim II as part of the CDWR North of Delta Off-Stream Storage (NODOS) project (CDWR, 2003). These simulations estimate the daily river flows that would have occurred between 1921 and 1994 under different water management scenarios, based on actual river flows. The base hydrograph simulates river flows that would have occurred with the dams and diversions currently in place. Scenarios 4a, 5b, 6, and 7 simulate flows that would have occurred if a new NODOS reservoir had diverted water from this sector of the river.

The scenarios differ in the total amount and temporal patterns of water diversion. Over the entire period studied, Scenario 5b diverted the most water, while Scenario 7 diverted the least. For individual years, which have different hydrographs, the amount of water diverted by each scenario depended on the total amount of water flowing down the river. Each of the four flow scenarios was characterized during a low flow (1964), a medium flow (1963), and a high flow (1974). For each of these characteristic years, the annual hydrograph showing daily discharges was plotted for each of the four scenarios plus the base (Figure 2). For low flow years, Scenario 5b diverts the most water, while Scenario 6 diverts the least (Figure 2). In medium flow years, however, Scenario 6 diverts the most water, while Scenario 7 diverts the least (Figure 2). In high flow years, Scenario 4a diverts the most water, and Scenarios 6 and 7 divert the least (Figure 2).

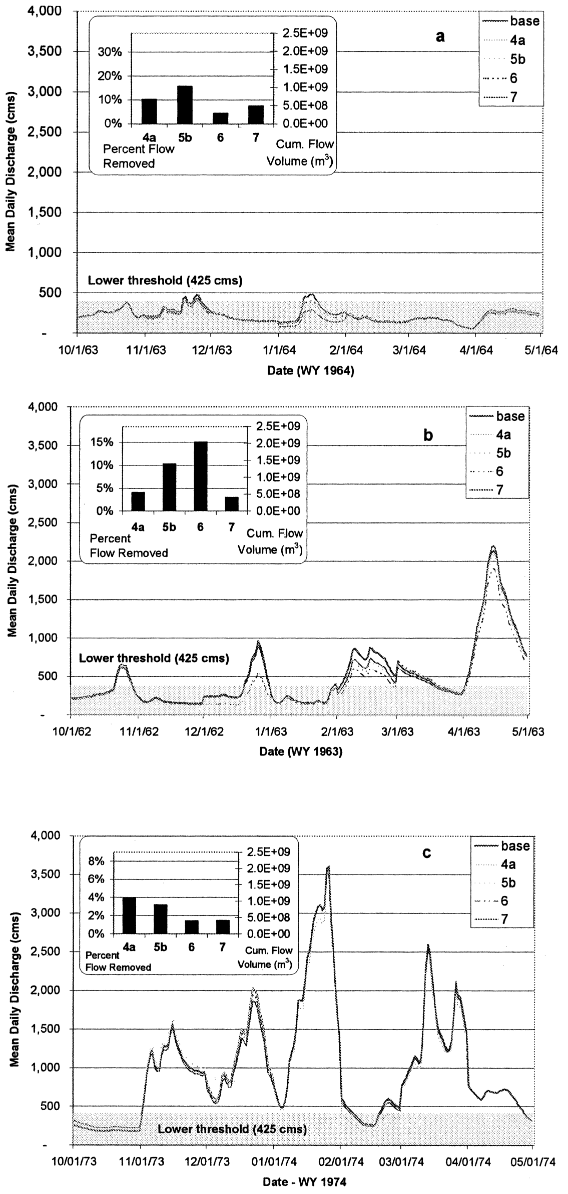

Figure 2. Hydrographs of the Base Flow Scenario and Four Flow Management Scenarios for (a) Low Flow (1964), (b) Median Flow (1963), and (c) High Flow (1974) Water Years During the Study Period (1956-1975). The inset bar graphs show the total amount of water removed annually for each flow management scenario as compared to the base flow scenario.

Meander Migration Model

The meander migration model used in this study and variations thereof have been used to predict and analyze the channel migration of a variety of rivers, including 16 rivers in Minnesota (MacDonald *et al.,* 1991), the Genesee River in New York (Beck *et al.,* 1984), the Mississippi River (Larsen, 1995), and the Sacramento River (Larsen, 1995; Larsen *et al.,* 2002; Larsen and Greco, 2002; Larsen *et al.,* 2006b). Johannesson and Parker (1989) used the model to predict wavelengths of meandering rivers, with results comparable to laboratory and field data. Pizzuto and Meckelnburg (1989) confirmed the relationship between migration rates and velocities assumed by the model. Howard (1992, 1996) used a version of the model to simulate floodplain sedimentation and morphology associated with meander migration. Furbish (1991) has used similar equations to describe the formation of complex meander sequences. A version of the model was used to examine conditions affecting meander initiation and growth (Sun *et al.,* 2001).

The numeric model for predicting river meander migration (Johannesson and Parker, 1989; Larsen, 1995) is based on analytical expressions of sediment transport and fluid flow. This model has been used to calculate how an alluvial river channel moves over time scales of years to decades. The model assumes that the local bank erosion rate is proportional to a local velocity factor such that

$$M = E_o u_b \tag{1}$$

where M is the bank erosion rate (in meters per year), E_o is a dimensionless bank erodibility coefficient of the order 10^{-8}, and u_b (meters per second) is a velocity factor equal to the difference between the velocity near the bank and the reach average velocity (Larsen and Greco, 2002). Higher E_o values result in greater erosion potential. Although the model calculates the velocity field in some detail, it represents bank erodibility by an estimated coefficient (E_o) calibrated to observed data (Larsen and Greco, 2002). To determine the erodibility coefficient, these simulations use a heterogeneous bank erodibility surface, based on observed geology, that varies spatially throughout the erosion field. For a more detailed description of the model as applied to the Sacramento River see Larsen and Greco (2002).

Heterogeneous Erodibility Surface

A heterogeneous erosion surface was created using the geographic information system (GIS) ArcGIS 8.3 (ESRI, 2003) and imported into the river meander migration model. The erodibility surface was developed by combining a GIS dataset of geology with a GIS dataset of land cover. The geology dataset was obtained from CDWR (1995). All geology surface types were assumed to be erodible with the exception of the Riverbank formation, Modesto formation, and Old channel deposits, which have been judged to be non-erodible based on their soil properties (CDWR, 1995). These surface types are sometimes referred to as areas of geologic constraint. These geology data were combined with a GIS land cover dataset of riparian vegetation and agricultural land obtained from the Landscape Analysis and Systems Research Laboratory (LASR), University of California, Davis (Greco and Plant, 2003).

Values in the merged dataset represent erodibility potential based on both land cover and geologic data. This dataset, or erodibility surface, was imported into the migration model. Areas of natural vegetation were given a value of $100 * 10^{-8}$, while agricultural lands were given a value of $200 * 10^{-8}$, and geologically constrained areas were given a value of zero. These values are consistent with erosion rates observed on the Sacramento River (Larsen *et al.,* 2002; Micheli *et al.,* 2004).

Variable Flow Rate

Although the meander migration model used here has been successfully used to assess planning issues, all previous applications have employed a constant flow rate. The method presented here incorporates a daily flow hydrograph to calculate an annual value for stream power. This value is used to model meander migration rates as a function of variable flow rates.

In many cases, researchers have used stream power to represent the hydraulic forces altering the stream (Leopold *et al.,* 1964; Begin, 1981; Hickin and Nanson, 1984). Based on the work of Bagnold (1960), Leopold *et al.* (1964) argue from a mechanical standpoint that stream power represents "the rate of doing work ... by the flowing water." Available stream power, as defined by Langbein (1964) and Leopold *et al.* (1964), is

$$\Omega = \gamma QS \tag{2}$$

Stream power (Ω kg m/sec^3) is a rate of potential energy expenditure per unit length of channel, calculated as the product of discharge (Q m^3/sec), slope (S m/m), and the specific weight of water (γ kg/m^{2}s^2).

A simple linear regression correlates the cumulative effective stream power (above a lower threshold) with rates of bank erosion at sites on the middle Sacramento River in California (Larsen *et al.,* 2006a). This principle was used to incorporate the effects of variable flow into the meander migration model and to scale the amount of river movement. Annual power was calculated by summing the daily stream power above the flow threshold of 425 cms (Larsen *et al.,* 2006a) during a given year (starting October 1). This assumes the river channel does not move when flows are below the erosion threshold (flows above threshold are considered "effective") and that the distance the river channel will move increases linearly with cumulative effective stream power (Fremier, 2003). A relative measure of stream power, *scaled annual cumulative effective stream power* (Π_i), was calculated by the formula

$$\Pi_i = \frac{P_i}{\bar{P}_{calib}} \tag{3}$$

where P_i is the stream power for a given year i, and $\bar{P}_{calib}$ is the mean annual cumulative effective stream power for the calibration period. The scaled annual cumulative effective stream power was incorporated into the meander migration model by multiplying Π_i by the migration distance for each year based on a constant rate flow, which is approximately the bankfull or channel forming flow. Thus, during water years with half the average cumulative effective stream power ($\Pi = 0.5$), the model will simulate half as much migration as it would have for an average year, while in water years with three times the average cumulative effective stream power ($\Pi = 3$), the model will simulate three times as much migration as an average year.

Once calibrated with a variable flow and heterogeneous erosion surface, the model can be used to predict future river meandering under different daily hydrograph scenarios. Researchers can therefore model how the river would have moved in the past under a flow regime different from the one that occurred and forecast how the river might migrate under potential future management scenarios. Because the scaled cumulative annual power used for the calibration run was calculated based on $\bar{P}_{calib}$, the scaled cumulative annual power for the future simulation period is also calculated based on $\bar{P}_{calib}$ using Equation (3) and incorporated into the meander migration code as described above.

Calibration of Model Parameters

The migration model requires the following six input values, which represent the hydrology of the watershed and the hydraulic characteristics of the channel: initial channel planform location; bankfull discharge; reach average width, depth, and slope; and field measured median particle size of the bed material. The reach average width and depth are measured at a characteristic discharge (bankfull), and the slope is the average water surface slope for the reach at the characteristic discharge. Using these input data, the model calculates other parameters required to predict channel migration. For a detailed description of the calculation process see Johannesson and Parker (1989). Hydraulic input parameters are adapted from Larsen and Greco (2002).

The output of the migration model depends on local hydraulic conditions through the hydraulic and geomorphic input variables and the heterogeneous erosion surface. The erosion coefficient is calibrated with a channel planform centerline from two points in time. Here 1956 and 1975 were chosen as years for which centerlines could be accurately defined from digitized aerial photos. The years between 1956 and 1975 were modeled because they occurred after the installation of Shasta Dam (1943) and before the channel was constrained by bank protection (1975). The analysis was stopped at 1975 also to avoid modeling a cutoff event (1978) and to focus this study on the rate of land reworked due to progressive migration. The calibration process consists of adjusting the geomorphic and hydraulic parameters in the simulated migration until the simulated migration from 1956 to 1975 closely matches the observed migration in the same time period.

Calculation of Area of Land Reworked and Migration Rates

The average annual rate of migration is calculated by mapping sequential channel centerlines and then quantifying the change in location of a channel centerline over time (Fremier, 2003). Using an ArcGIS 8.3 programming script (ESRI, 2003), an eroded area polygon is created by intersecting two channel centerlines mapped at two points in time (Larsen *et al.,* 2002; Micheli *et al.,* 2004). The GIS is used to calculate: (1) the area of the polygon between the two centerlines; (2) the average length of the different centerlines forming the polygon; and (3) the time between the two centerline locations of the river. The channel migration rate is then calculated as

$$\frac{A_r}{tL} \tag{4}$$

where A_r is the area reworked for a given polygon, as defined above; L is the average channel length of the two centerlines for a given bend; and t is the time in years that had elapsed between the two channel centerlines (Figure 3). The average centerline length is used to standardize the migration rate for variable bend lengths, resulting in the average rate of migration per year for a given period. A 130 m channel width is assumed for the land reworked analysis; this width is based on an average summer flow because the photographs were taken in summer. Equation (4) calculates the migration rate as a linear distance per time; the rate of land reworked is reported as an area per time by using Equation (4) without dividing by the length (L).

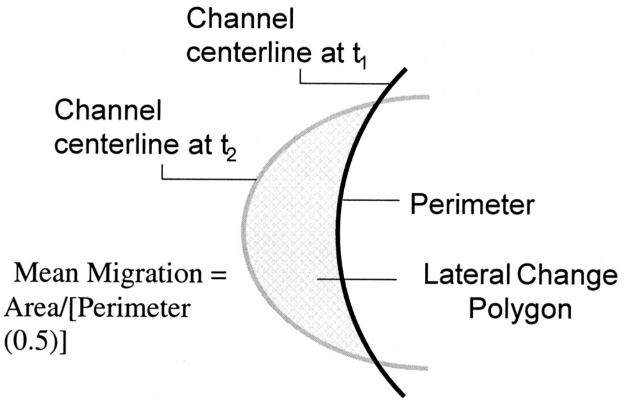

Figure 3. The Area of Land Reworked During a Given Time Period is Calculated by Intersecting Centerlines of Channels From the Beginning and End of the Time Period. The area between the two curves is calculated and called the area of land reworked. The migration rate of the channel is the area divided by the average length of the two channels (i.e., one-half the perimeter of the polygon between the curves).

Variable Flow Model Testing

The variable flow algorithm used in the meander migration simulations was tested by comparing the observed rates of meander migration between 1956 and 1975 with rates of migration simulated using a variable flow model as well as a constant flow model (approximately the bankfull or channel forming flow). The time interval chosen included years of high and low flows. Observed centerlines were digitized from aerial photographs for the years 1956, 1962, 1964, 1965, 1968, 1970, 1974, and 1975 (Fremier, 2003) (Figure 4). Maps of land reworked were created from observed channel centerlines, and area reworked per year was calculated for each of the time intervals between successive channel centerlines.

The observed hydrograph for the years 1956 to 1975 was obtained from the CDWR Bend Bridge flow gauge, No. 11377100 (Figure 5) (USGS, 2004). Flow data from the Bend Bridge gauge were used because they comprised the longest temporal discharge record below Shasta Dam and above the study reach. This hydrograph was used with the meander migration model to produce a variable flow model. Values for both annual cumulative effective stream power and

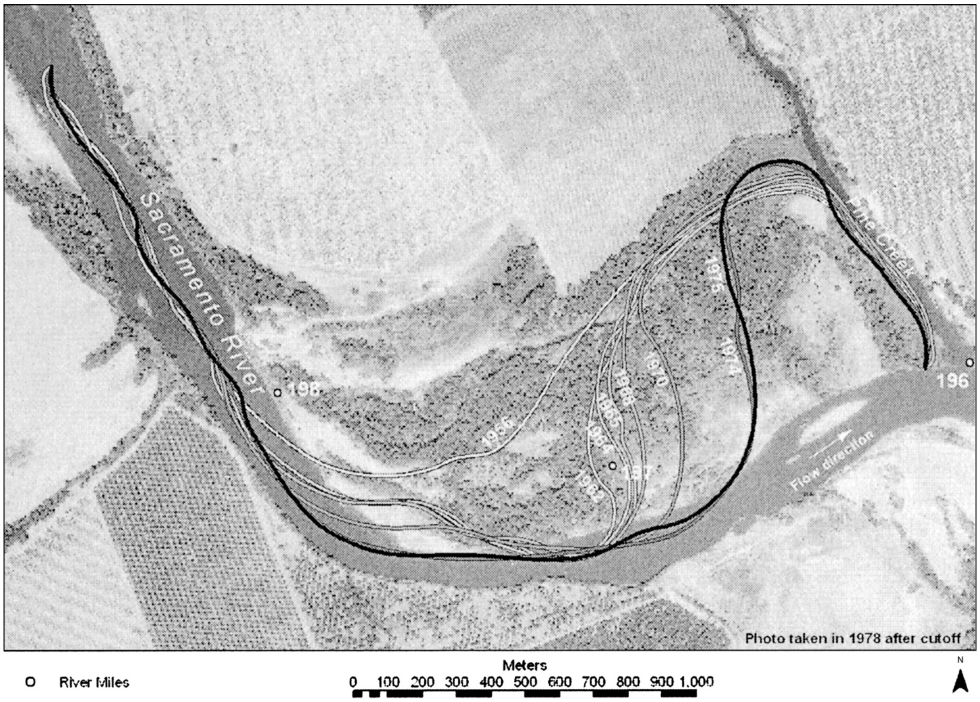

Figure 4. Study Site Aerial Photo, With Observed Centerlines Digitized From Aerial Photographs for the Years 1956, 1962, 1964, 1965, 1968, 1970, 1974, and 1975 (Fremier, 2003).

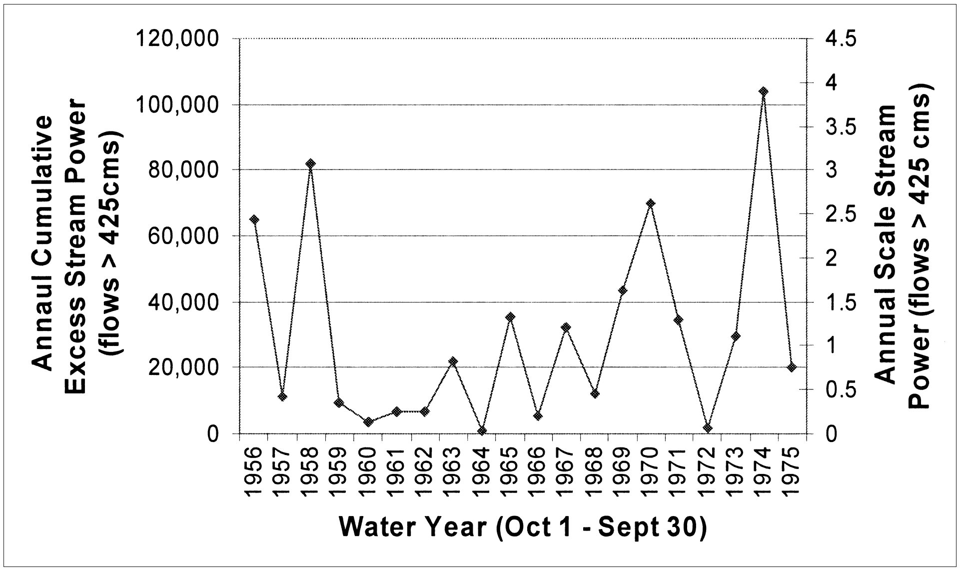

Figure 5. Observed Annual Cumulative Effective Stream Power and Annual Scaled Stream Power for 1956-1975 at the Bend Bridge Gauge Station. A scaled stream power of 1.0 represents the average annual cumulative effective stream power for the study period. A value of 2.0 represents twice the average, while a value of 0.5 represents half the average.

scaled annual cumulative effective stream power (Π_i) were calculated. Channel centerlines were modeled for each of the analysis periods. A map of land reworked per year was then derived from the modeled centerlines using an ArcGIS 8.3 Visual Basic programming script, and a table of area reworked per year was calculated from these maps.

For each of the time intervals, the rate of land reworked (ha/year) for the historically observed data was compared to both the constant flow and variable flow modeled data using a linear regression analysis in JMP 5.1 (SAS Institute, 2003). To compare the migration rates in different time intervals, rates of land reworked were used; these rates were derived by dividing areas of land reworked by the number of years in the interval. This was necessary because the time intervals varied with the availability of the aerial photographs used to derive observed channel centerlines.

Modeling the Effects of Flow Regulation Scenarios

For considering the effects of the different flow scenarios, the base scenario was used to calibrate the meander migration model between known channel centerlines from 1956 and 1975. Calibrating with the base flow scenario rather than the historic flow allowed comparisons among diversion scenarios rather than historic versus current operations. By calibrating observed migration patterns to a simulated hydrograph, a modeling exercise is conducted to show the utility of the model. The modeling exercise is not historical fact, although it uses observed data for the migration patterns. The modeling shows the patterns and scale of changes that would have resulted from the various flow scenarios. Meander migration scenarios were modeled using the variable flow protocol described above and the relationship between cumulative effective stream power and bank erosion, as explained in Larsen *et al.* (2006a). A map of the land area reworked per year was created for each scenario using the ArcGIS programming script described above (Fremier, 2003).

RESULTS

Variable Flow Model Testing

Between 1956 and 1975, the channel was observed from aerial photography to rework land at a mean rate of 3.0 ha/yr (a mean migration rate of 7.7 m/yr), with the channel varying in length from 3.7 to 4.4 km. Rates within time intervals ranged from 0.8 to 5.1 ha/yr (2.0 to 13.3 m/yr) (Table 1). A significant relation between the rate of land reworked and the annual cumulative effective stream power was found for the time intervals analyzed between 1956 and 1975 ($r^2 = 0.74$, $p = 0.02$) (Figure 6).

Figure 7 presents the maps of the modeled patterns of floodplain development for this same period. The variable flow meander migration model predicted that the river would rework land at an average rate of 2.8 ha/yr (channel migration rate of 7.0 m/yr). Rates within intervals varied from 1.4 to 5.3 ha/yr (3.4 to 14.1 m/yr) (Table 1). The constant flow meander migration model predicted an average rate of 2.7 ha/yr (6.7 m/yr) (Table 1) – similar to both the observed and variable flow model rates. Rates within intervals, however, ranged from 1.7 to 3.2 ha/yr, steadily decreasing throughout the period.

TABLE 1. Observed Stream Power, Observed and Modeled Rates of Land Reworked, and Channel Migration Rates for Time Periods of Various Lengths, 1956-1975.

			Rate of Land Reworked (ha/yr)			Channel Migration Rate (m/yr)		
Time Period	**Observed Scaled Stream Power**	**Channel Length (km)**	**Observed From Aerial Photo**	**Modeled With Variable Flow**	**Modeled With Constant Flow**	**Observed From Aerial Photo**	**Modeled With Variable Flow**	**Modeled With Constant Flow**
1956 to 1962	0.7	4.4	3.3	2.4	3.2	7.4	5.4	7.2
1962 to 1964	0.4	4.1	0.8	1.4	2.9	2.0	3.4	7.0
1964 to 1965	1.3	3.8	2.3	3.8	2.8	6.2	10.1	7.3
1965 to 1968	0.6	3.7	1.0	1.6	2.7	2.6	4.3	7.3
1968 to 1970	2.0	3.7	4.9	5.3	2.3	13.1	14.1	6.2
1970 to 1974	1.5	3.8	5.1	3.7	2.2	13.3	9.7	5.9
1974 to 1975	0.7	4.0	1.4	1.5	1.7	3.6	3.7	4.3
Time Weighted Average	1.0	4.0	3.0	2.8	2.7	7.7	7.0	6.7

Note: The stream power was calculated from observed flows at the Bend Bridge gauge station. The table shows the yearly mean in the time interval. The observed rates of land reworked were calculated from aerial photography. The modeled rates of land reworked and channel migration rates were calculated from center lines output from the meander migration model using both a variable and a constant hydrograph.

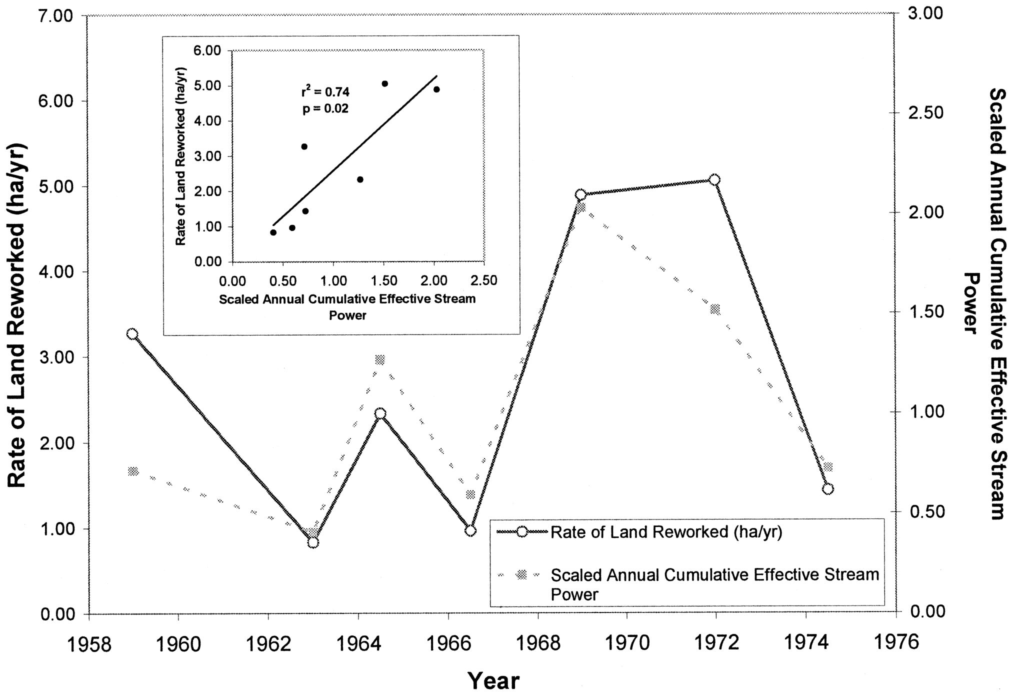

Figure 6. Observed Rates of Land Reworked and Scaled Mean Annual Cumulative Effective Stream Power for Various Time Periods During 1956-1975. Note that time intervals analyzed are for different lengths of time depending on the available aerial photography for digitizing observed channel centerlines. Data points are plotted at the median value for each time interval analyzed. The inset graph shows a regression analysis relating rate of land reworked to the scaled mean annual cumulative effective stream power; the linear regression line is significant ($r^2 = 0.74$, p = 0.02).

Total areas of land reworked were similar for both the constant flow and variable flow inputs. This is to be expected, as both scenarios were calibrated with the same channel data. That is, each was fitted to the same beginning and ending channel planform. However, the variable flow model predicted different rates of land reworked between years, while the constant-flow model predicted a more uniform rate of land reworked each year (Figure 7). Due to landscape erosion properties and channel characteristics such as curvature, the rate of land reworked for the constant-flow model tended to decrease over time (Table 1).

Rates of land reworked per year from the variable flow model tended to closely mimic the rates of land reworked observed in aerial photographs, while the constant flow model rates showed no relation to the observed rates (Table 1). When the modeled rate of land reworked per year was regressed against the observed rates of land reworked, the variable-flow model showed a significant relation (p = 0.02, r^2 = 0.70) (Figure 8), while the constant-flow did not (p = 0.73, r^2 = 0.03) (Figure 8).

Flow Management Scenarios

The areas of land reworked for a base hydrograph scenario and four potential management hydrograph scenarios using the variable flow meander migration model are presented in Table 2. Scenario 5b resulted in an 8 percent reduction in modeled channel movement compared to the base scenario, which showed the most channel movement. Scenario 7 had the least effect on overall channel movement, resulting in only a 1 percent reduction as compared to the base scenario.

DISCUSSION

River meander migration promotes riparian vegetation recruitment by eroding older floodplain surfaces and depositing younger floodplain surfaces (Hupp and Osterkamp, 1996). Riparian plant species have adapted to this process of land deposition and flood inundation (Lytle and Poff, 2004). To maintain the natural successional dynamics of riparian vegetation communities, new land or newly scoured land must continually be created. However, flood and erosion control measures have severely limited the creation of newly deposited land by reducing meander migration.

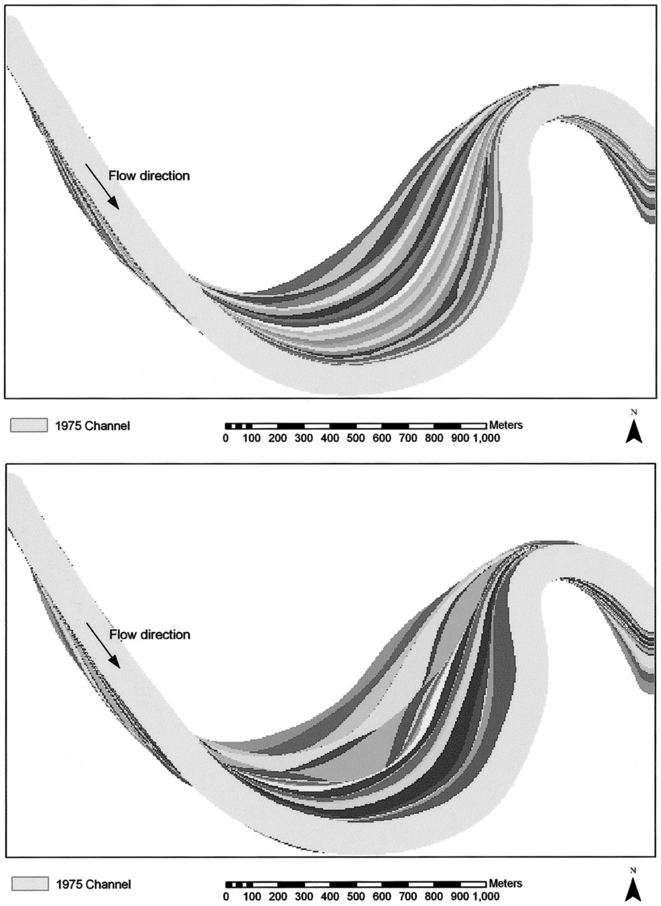

Figure 7. Map of the Modeled Patterns of Land Reworked Derived From Channel Center Lines Produced by the (a) Constant Flow Meander Migration Model and (b) Variable Flow Meander Migration Models. The flow direction is noted by the arrow on the channel in 1975, and river migration tended to occur toward the south and east over this time period.

Using a relationship between flow rate, as characterized by cumulative effective stream power, and river channel migration, a variable flow meander migration model was developed and compared to a constant flow model. The variable flow model was found to more accurately simulate the year-to-year meander migration dynamics, resulting in a more accurate simulation of the spatial pattern of land reworked over time. Both the variable flow and the constant flow models predicted approximately the same total area reworked over the entire 19 years. The variable flow model simulations, however, strongly predicted the observed rates of river meander migration during observed subperiods (one year to six years), while the constant flow model showed no such relation (Figure 8). Although the migration rates predicted by the variable flow model significantly correlated with the observed scaled stream power, the correspondence is not exact because stream power is not the only parameter that contributes to bank erosion. Local bank erosion is complex and includes processes that are not directly proportional to flow rates, independent of other factors. For example, bank collapse may occur as a function of rapidly declining flow rates. Therefore, it is unclear how well this method would work on single flows, specifically single floods.

The variable flow model simulates year-to-year variation in migration, while the constant-flow model can only accurately simulate the total area reworked during the entire analysis period. In addition, the variable flow model is able to simulate the effect of changes to river flows due to water management or other forces (e.g., climate change), while the constant flow model assumes the same river flow each year. The effect of variable river flows on river meander migration has major implications for riparian habitat and water management.

This variable flow model was used to predict the effects of water diverted from the Sacramento River by the installation of the proposed Sites Reservoir. The study results show that the four potential flow management scenarios proposed for the Sites Reservoir resulted in a 1 to 8 percent reduction in land reworked. The scale of change in migration rates with diversion scenarios reflects the scale of changes in stream power.

Although a decrease of 1 to 8 percent is significant, especially considering it would be caused by only one water reclamation project, it is considerably less than the effects of bank protection projects (e.g., rip-rap and groins) on river meander migration patterns. Larsen *et al.* (2006b) found that replacing current bank protection projects on one reach of the Sacramento River with setback levees 300 to 700 m from the river channel could result in a 370 to 550 percent increase in land reworked. A variable flow meander migration model can tell land managers a variety of useful information such as how many kilometers of rip-rap would need to be removed at given locations to offset the impact of water management scenarios. Removing unnecessary bank protection projects along the Sacramento River could prove to be an effective means to mitigate cumulative migration losses caused by the Sites Reservoir.

The reservoir could offer environmental benefits and impacts beyond the amount of land reworked. This model does not account for cutoff events that create oxbow lake habitat. Also, changes to the intra-annual (within year) timing of water flows could have

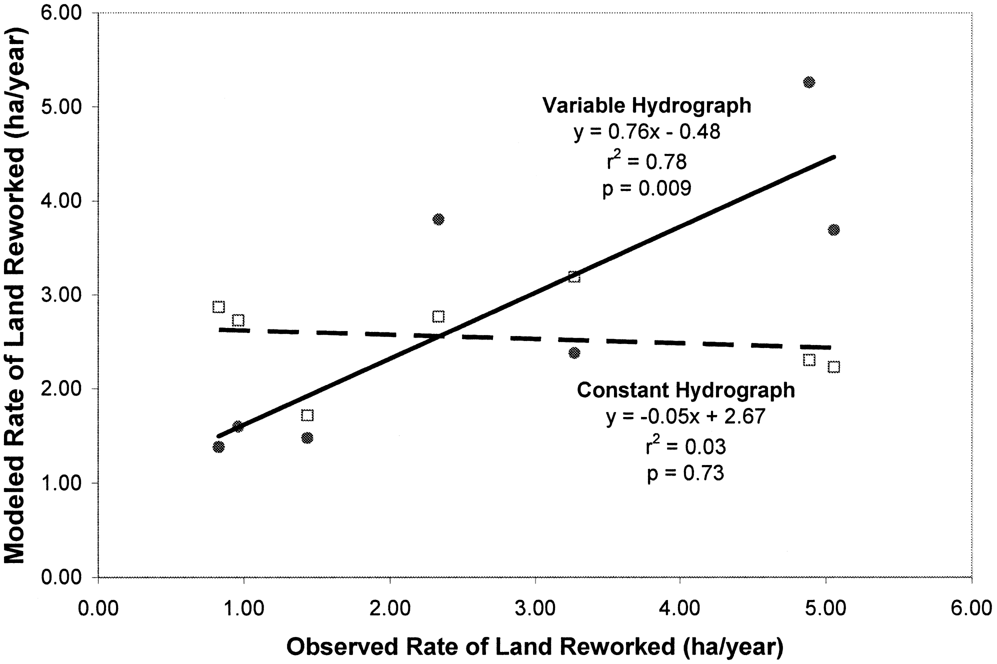

Figure 8. Modeled Rates of Land Reworked Regressed Against the Observed Rate of Land Reworked. The variable flow meander migration model shows a significant relation with the observed rates ($r^2 = 0.78$, $p = 0.009$), while the constant flow model shows no relation to the observed rates ($r^2 = 0.03$, $p = 0.73$).

a large effect on vegetation recruitment and establishment. The annual cumulative effective stream power of flow scenarios is important at the inter-annual (year-to-year) time scale. However, the proposed reservoir could affect other important hydrologic processes driving vegetation succession on an intra-annual time scale (Poff *et al.,* 1997). Plant ecologists have found that vegetation recruitment and succession are affected by intra-annual flow patterns such as spring drawdown rates and stage discharge relationships through the year, especially at low flows and peak flows (Mahoney and Rood, 1998; Poff *et al.,* 1997). The analysis presented here only accounts for the total amount of stream power the river produces each year, not the intra-annual timing of flows.

The results of this work should be integrated with the results of other models to better determine how the integrity of riparian ecosystem processes – such as vegetation recruitment and wildlife habitat formation – might be enhanced and restored by altering river flow management. A more complete assessment of the effects of water diversion could be accomplished by using this model in conjunction with other analysis techniques such as the index of hydrological alteration (IHA) (Richter *et al.,* 1996), which characterizes a hydrologic flow regime over a variety of time scales. In addition, a model of the spatial dynamics of vegetation patterns could be created based on flow patterns (recruitment box) and meander dynamics (disturbance patterns). This tool could be used to better assess how changes in water management affect riparian ecology and restoration.

TABLE 2. Total Modeled Area Reworked During 1956-1975 for the Base Scenario and the Four North of Delta Off-Stream Storage (NODOS) Flow Management Scenarios.

Flow Management Scenario	**Total Area Reworked (ha)**	**Percent of Base Area Reworked (percent)**	**Percent of Base Stream Power (percent)**
Base	46.6	100	100
4a	43.9	94	87
5b	42.8	92	87
6	45.5	97	92
7	46.1	99	91

Note: The percent of area reworked and stream power for each management scenario relative to the base scenario during this same time period are also reported.

In conclusion, this paper presents a novel method for modeling river channel migration that accounts for inter-annual changes in river flows. This is an improvement over previous models that only considered constant river flows. River channel migration simulations of variable flow scenarios can be used to assess rates of river migration and can help water managers assess the effect of water diversion projects on riparian habitat. However, it should be noted that there are other effects on riparian habitat, such as changes to intra-annual flow patterns, and that a broader suite of modeling tools should be used to assess the effect of water diversion on riparian habitat.

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