Evaluating River Restoration Design Using a Meander Migration Model on the Trinity River, California

Alex Young
Eric Larsen
Evan Girvetz
Alex Fremier

UC Davis Department of Environmental Design

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Abstract

River restoration designs are increasingly focused on rehabilitating natural river processes, such as channel migration, to maintain functioning riparian and riverine habitats. Often restoration design is done without a quantitative analysis of the potential geomorphic evolution of the restored features. A quantitative model of lateral channel movement allows managers and others to forecast potential changes in meander migration rates, both locally and downstream, of a local rehabilitation of the channel.

A rehabilitation effort is underway to help restore natural processes on the Trinity River, California, USA, after the construction of two dams in the early 1960s. An increased flow schedule (mimicking a natural flow regime), gravel augmentation and mechanical rehabilitation are being used to create a scaled-down river that simulates pre-dam ecosystem processes such as sediment transport, and flood water inundation as the foundation to fishery recovery. One of the objectives of the increased flows is to increase channel migration in an effort to increase channel complexity and provide increased habitat quality for smolt production.

A meander migration simulation model was used to assess the potential effectiveness for increasing meander migration of rehabilitation projects on the Trinity River. Comparisons were made of future migration patterns under different rehabilitation scenarios - with and without mechanical rehabilitation, and with and without an increased flow schedule. The proposed increase in flow resulted in little change to lateral bank migration rates. This reflects the fact that, although flows were increased, the total stream power was not increased significantly. The difference in area reworked and migration rate of rehabilitated floodplains was apparent in 5 out of the 13 sites; average channel bank migration rates in those 5 sites increased from 0.20 m/yr to 0.45 m/yr. With rehabilitation, average migration rates of all 13 sites increase from 0.27 m/yr to 0.39 m/yr., Influences of rehabilitation on the channel bank migration rate were classified in three different ways: 1) rehabilitation resulted in increased migration rates only at the bend where the rehabilitation was performed (4 of 13 sites); 2) rehabilitation resulted in increased migration both locally and downstream (3 of 13 sites); 3)rehabilitation resulted in increased migration rates at the next downstream bend (4 of n sites); 4) rehabilitation resulted in no change to migration rates (2 of 13 sites).

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Introduction

Alluvial rivers provide vital functions to natural ecosystems and human societies (Constanza et al. 1997, Trush et al. 2000). However, dams have altered the natural flow regime on rivers throughout the world resulting in ecological impacts to the natural ecosystems which depend on natural fluvial processes (Poff et al. 1997). Some flow alterations have virtually halted natural river processes, such as river channel floodplain reworking that creates and maintains a complex landscape habitat mosaic in riparian ecosystems over long periods of time (Naiman et al. 1993), (Lytle and Poff 2004). Recently, there has been a focus on using natural fluvial processes such as natural bed load transport and channel migration to maintain fish habitat, meander bend evolution, and a natural flow regime to maintain and restore riparian landscapes (Richter et al. 1996, Poff 1997, CALFED 2000); (US Department of Agriculture 2001).

One of the primary processes driving the reworking of land on alluvial rivers is river meander migration (Hughes 1997). Alluvial rivers have a tendency to migrate laterally (Johannesson & Parker 1989), eroding outside banks and depositing point bars on the inside bank. This process recruits new alluvium and reworks the channel bed surface. Channel migration of a meandering river is therefore an important process in developing point bars, recruiting gravel from bank erosion, and the natural reworking of the bed surface.

River channel restoration and rehabilitation schemes are increasingly designed to restore the natural processes in order to reestablish ecosystem functions (Richter and Richter 2000). Such designs have many advantages, including the possibility of being self-sustaining. In many cases, re-establishing natural processes requires mechanical manipulation to “reset the system.” A crude analogy is to the healing process in humans; a doctor does not “cause” the healing of a broken bone; healing is a natural process of the body. However, a doctor may be required to “set the bone” in order for the healing processes to take place in a manner that will result in an on-going system that is optimum. Restoring natural river processes often requires “setting the bone” through mechanical means in order to restore self-sustaining natural processes. Yet this is only the first step. On a highly regulated river such as the many rivers in the western US, sediment and flow management are also required to increase the effectiveness of the mechanical rehabilitation and maintain the restored processes.

Mechanical manipulations are common in riparian restoration and rehabilitation design and implementation. However, such rehabilitation designs often are planned and implemented without regard to the hydrodynamics of the associated river. These rehabilitation designs would benefit from proscriptive methods to check their effectiveness before the rehabilitation is implemented, through analytical methods of simulating results. Using proper analysis one can better predict the potential impacts—both positive and negative—of a particular rehabilitation design.

Since planform channel bend geometry and its evolution is predictable based on the underlying hydraulics in alluvial river systems (i.e. meander migration modeling), a landscape-level planning approach in alluvial river systems has been effectively considered and applied to assess the effect of various erosion and flood control management scenarios. In particular, a meander migration model has been effectively used to estimate results of channel manipulations (Larsen et al 2005d) and for assessing the effect of human infrastructure projects (e.g. bridges, pumps, and bank revetment) on actively migrating alluvial rivers (Larsen et al. in press).

Although this model has been effectively used for assessing the effect of erosion and flood management, it has never been used to assess the potential impacts of river rehabilitation or restoration projects. In this case a meander migration model is used to assess the impacts of a rehabilitation design before the rehabilitation measures are applied on the ground. This meander migration model can be used to assess two important aspects of a riparian rehabilitation design. First, it can be used to determine if the channel migration patterns predicted by the model match the intended ecological goal of the rehabilitation design. Secondly, this model can evaluate if the rehabilitation design increases the danger to existing infrastructure. Through a better understanding of predicted channel migration tendencies, channel rehabilitation design can be evaluated. The model can predict both local and downstream effects of rehabilitation design, and evaluate risks to downstream structures.

This paper describes an evaluation of rehabilitation plans using results from a meander migration model (Larsen and Greco 2002, Golet et al. In Press): on the Trinity River, California, USA. This evaluation offers concrete and realistic examples of how managers can use a model of channel migration to consider the effectiveness of rehabilitation design in relation to the natural processes affected by channel migration. By considering changes in river meander migration, demands for protecting infrastructure can also be evaluated while promoting natural processes.

History

Construction of two dams for the Trinity River Division (TRD) of the Central Valley Project in the early 1960s cut off large winter and spring flows resulting in major changes in the 111 miles between Lewiston Dam and the Klamath River. Trinity Dam was completed in 1962, followed by Lewiston Dam in 1964. Built as a storage and diversion facility for hydro-electric power, it was thought that water could be diverted for agricultural use in the Central Valley with little or no impact on fish. Soon after closure, Lewiston Dam began diverting an average of 88% or 1,234,000 acre ft of Trinity River flows to the Sacramento River for agricultural use in the San Joaquin valley. As a result of the restricted flows, releases into the Trinity River ranged from 150-250 cfs year-round for nearly 10 years. Within a few years of completion, the dams had severely impacted fish and riparian habitat downstream (US Fish & Wildlife Service & Hoopa Valley Tribe 1999).

Beginning in the mid 1970s, some efforts were made to increase flows. In 1984 congress enacted a Management Act to restore fish and wildlife populations. This act was renewed in 1996 and was intended in part to restore Hoopa and Yurok Tribal fisheries to sustainable levels (US Fish & Wildlife Service & Hoopa Valley Tribe 1999). When the TRD was authorized in 1955, part of the congressional act stipulated that the US Secretary of the Interior "…adopt appropriate measures to ensure the preservation and propagation of fish and wildlife (US Fish & Wildlife Service & Hoopa Valley Tribe 1999)." To determine how to restore fisheries resources on the Trinity River, US Fish and Wildlife Service launched the Trinity River Flow Evaluation (TRFE) study. The resulting report provides recommendations for the rehabilitation of fisheries resources. It was determined that rather than attempting to predict the specific flow needs of individual species, a channel maintenance approach was necessary to conserve the fluvial geomorphic processes that maintain a dynamic channel form, presumably capable of supporting all native aquatic species.

Post-dam channel form has changed in the absence of large geomorphic flows, resulting in the recruitment of woody vegetation on the floodplain and the subsequent formation of riparian berms. These riparian berms change the cross-section channel geometry from a trapezoidal shape with a sloping floodplain to one with near vertical banks, channelizing the flow and increasing flow velocities. Much of the summer and winter base flows are made up from tributaries to the Trinity River between Lewiston and the Klamath River. These tributaries however cannot make up for the loss of snowmelt and winter storm event flows that contribute to large-scale geomorphic flows.

The Record of Decision (ROD) documents the US Secretary of the Interior's decision and recommendations for the recovery and improvement of fish populations on the Trinity River. Based on nearly 20 years of scientific investigation, the ROD recommends a plan to replicate some of the conditions associated with an unbound river at a smaller scale (Trush et al. 2000). ROD flow schedules are based on the following Water Years : Critically Dry, Dry, Normal, Wet, and Extremely Wet (US Fish & Wildlife Service & Hoopa Valley Tribe 1999). The Magnitude of dam releases are dependent on the total amount of water calculated for each water year class and each class has a specific target rehabilitation strategy associated with it.. Only in the very wettest of years will the ROD flows focus on overbank, and geomorphic flows. The magnitude and duration of scheduled dam releases range from a peak release of 1,500 cfs for 36 days in a critically dry year, to 11,000 cfs for 5 days in an extremely wet year. Dam releases are limited to a maximum of 13,750 cfs (389 cms) due to spillway capacity and infrastructure.

ROD flows are paired with mechanical rehabilitation of the floodplain and gravel augmentation to reset the river's natural processes. The rehabilitation designs are aimed at eliminating riparian berms and increasing scour on the floodplain during higher ROD flows. It is expected that a meandering channel would help scour and redeposit pointbars in a regenerative pattern eliminating the need for mechanical maintenance. Thus meander migration is essential to a dynamic regenerative river system.

Methods

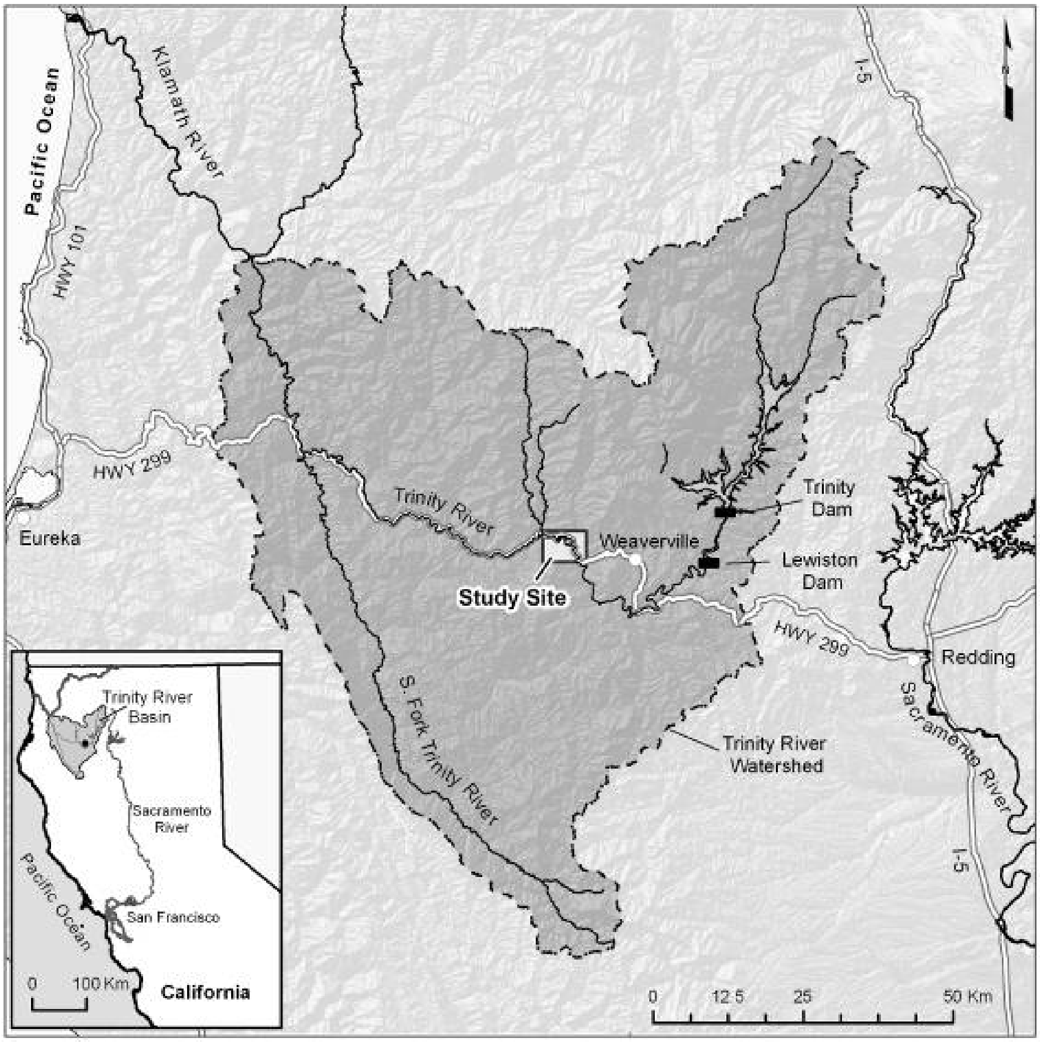


Figure 1. Trinity River Basin and study site:
The focus area is approximately six river miles along State Highway 299 between Junction City and the North Fork Trinity (highlighted in the center of the map).

Trinity River Site Description

The Trinity River, located in northwest California, USA flows west/northwest between the Trinity Alps and the Klamath River (Figure 1). The mainstem of the Trinity River is morphologically diverse with both alluvial and bedrock-constrained reaches. Northern California's Mediterranean climate affords dry summers with little or no precipitation followed by wet winters and spring snow melt contributing to high flows in winter into early summer. Historically, large winter flood events were common, followed by a gradual decline in flow from snow melt in the surrounding mountains. These large flows were responsible for much of the geomorphic change in channel form.

Although pre-dam conditions allowed for extensive floodplains and a meandering river channel, today's Trinity River is best described as isolated individual floodplains separated by geologically controlled reaches. The first twenty-five miles of channel below Lewiston is mostly steep narrow valleys & bedrock giving way to less confined reaches that have been heavily impacted by years of mining. Large piles of mine tailings leftover from hydraulic and later dredger mining still act as impediments to river migration. The study site is located in a semi-confined reach approximately 35 miles downstream of Lewiston Dam (Figure 1).

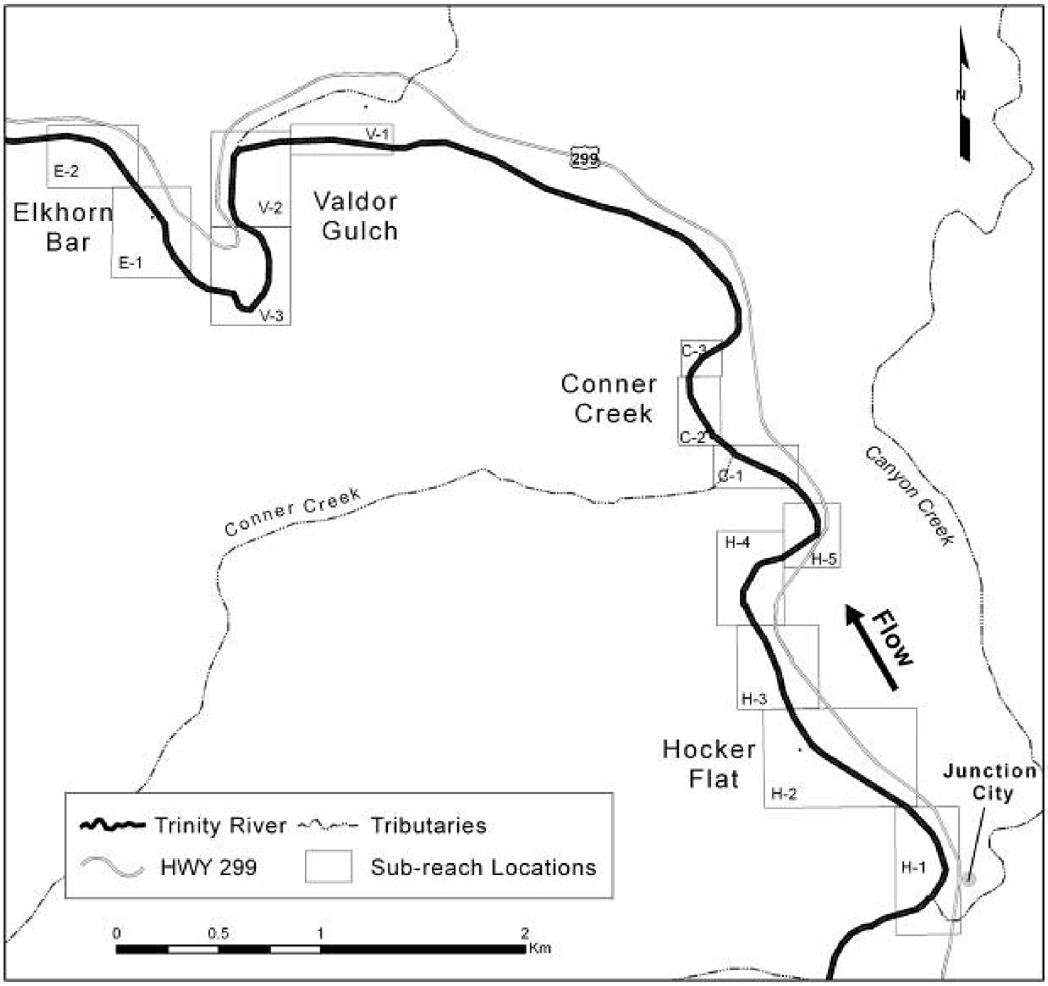


Figure 2. Study site and sub-reach location map.

Study Plan

This study presents a comparison of modeled migration tendencies related to rehabilitation plans at four sites along the Trinity River: Hocker Flat (RM 79-78), Conner Creek (RM 77.3 – 77), Valdor Gulch (RM 75 – 75.6) and Elkhorn (RM 74.3 – 73.5) (Figure 2). These sites were identified as reaches with both historical meander migration and potential for future migration. The meandering sections of this river are ultimately constrained by the geology of the study reaches (bedrock). Therefore, meander migration will not change the overall course of the river but promote regeneration of critical river features. A meander migration model was used to predict future changes in channel location based on a calibration using past flow conditions and observed channel movement from historical aerial photos.

Sub-reaches

The four main study sites were divided into sub-reaches to analyze the channel migration patterns in each sub-reach. Sub-reaches were delineated at channel centerline inflection points (the middle of the straight section, or "cross-over" between meander bends) and intended to separate individual river bends for analysis.

Hocker Flat:

Of the four study sites, Hocker Flat had the most historic channel migration and showed typical alluvial attributes under pre-dam conditions. This site was most easily calibrated in the model as there was significant channel movement from RM 79.2 to RM 78.6 in the 21 years of pre-dam photo record (Figure 3).

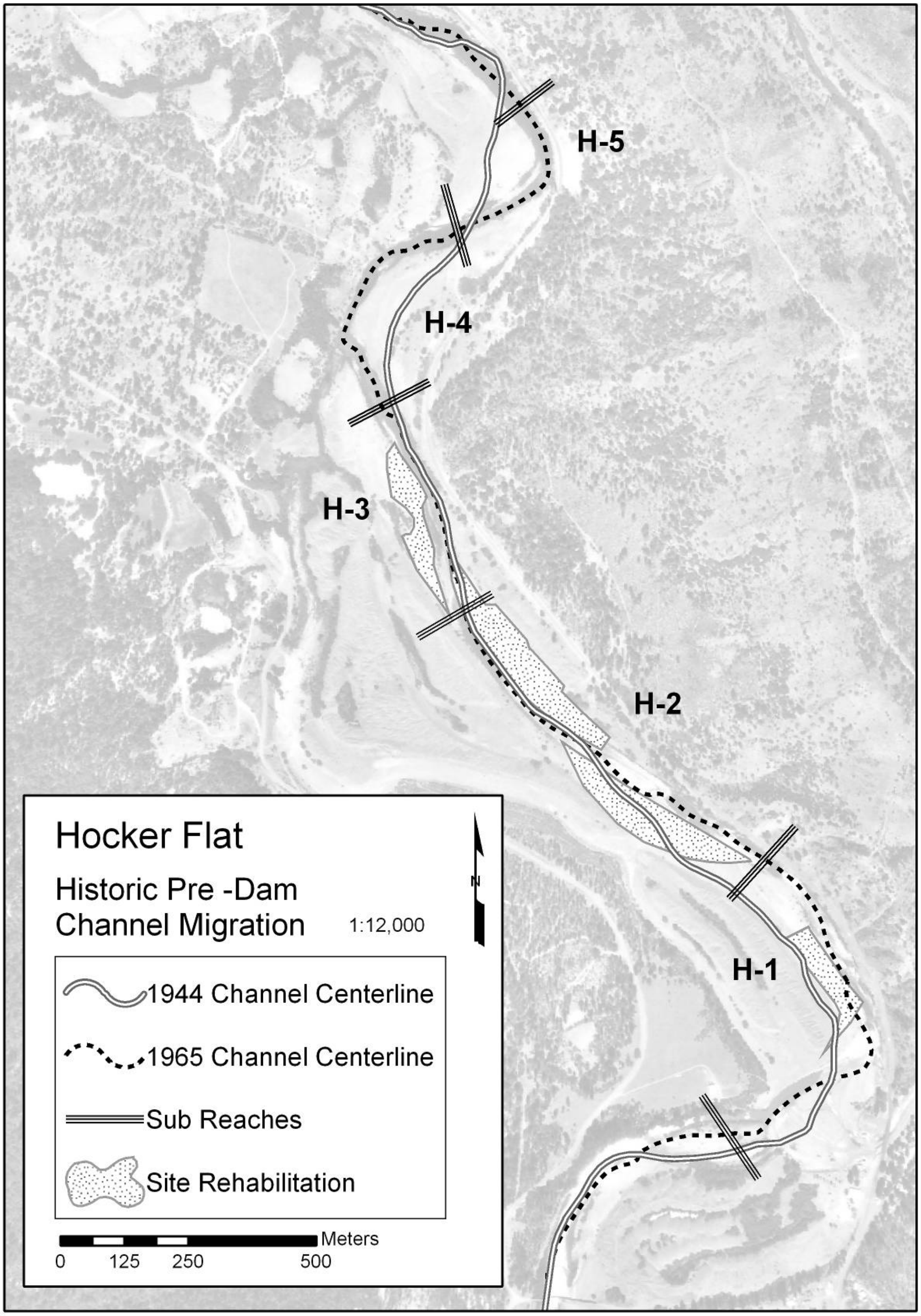


Figure 3. Hocker Flat historic Pre-Dam Channel Migration.

The rehabilitation plans at Hocker Flat extend from RM 79 to about RM 78 and appear to have been designed for the river to meander into the rehabilitated floodplain. This section has been broken down into 5 sub-reaches. Although the channel migrated in the past, it is now geologically controlled on the outside bend of H-1 causing a rather sharp right angle bend as the river runs into bedrock. H-2 is approximately the same length of H-1 (0.4 miles), but is a fairly straight reach that is heavily constrained by riparian berms. H-3 has a fairly small bend that is heavily impacted by riparian berms. It is approximately half the length of the previous sub-reach, and encompasses the furthest downstream rehabilitation at Hocker Flat. H-4 and H-5 are tight, sinuous bends with very high historic channel migration. Although there are no rehabilitation plans at these sub-reaches, they are significant in that they are affected by the upstream rehabilitation effort and have a downstream effect at Conner Creek.

Conner Creek:

Directly downstream of Hocker Flat, Conner Creek had moderate historic channel movement across the floodplain but is now somewhat constrained on the outside bend by geologic control (Figure 4). This site has been divided into 3 sub-reaches with the rehabilitation plans contained solely on the inside bend and extending from RM 77.3 to RM 77. It appears that the rehabilitation plans in this case are designed to facilitate floodplain scour at higher flows and not typical meander migration on the outside bend.

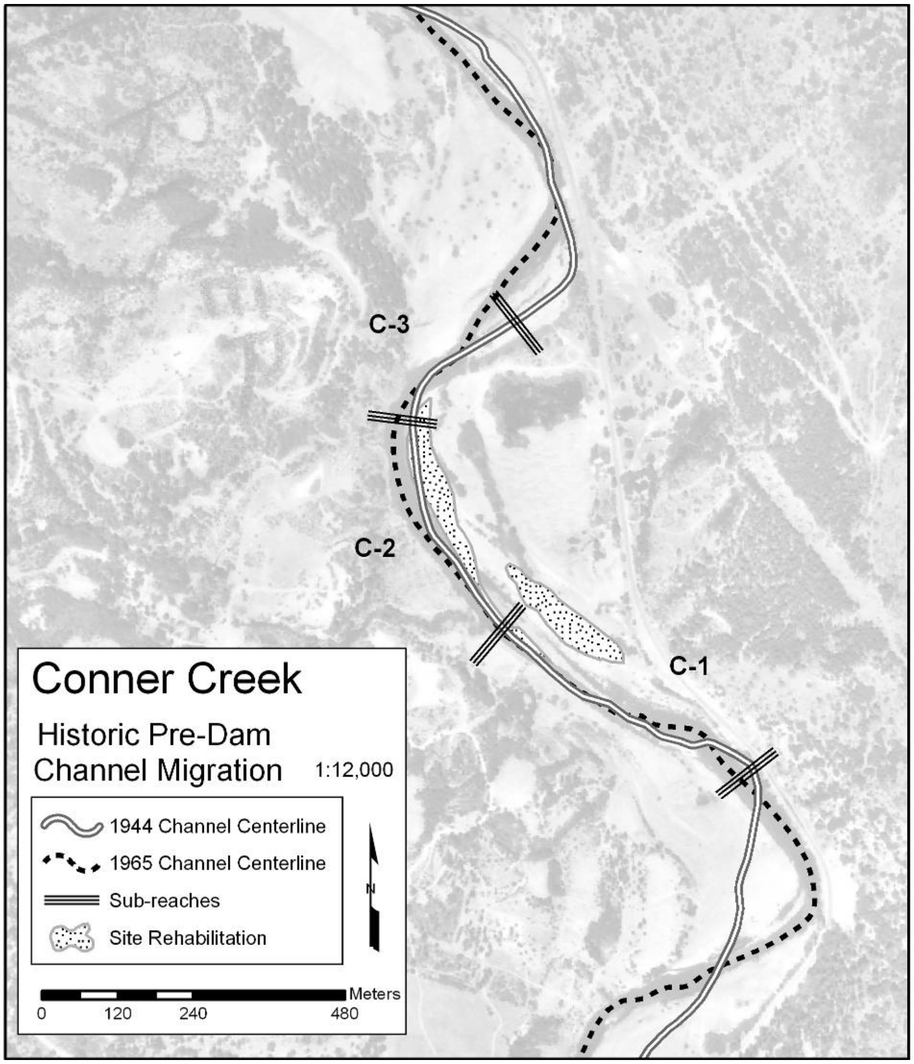


Figure 4. Conner Creek Historic Pre-Dam Channel Migration.

Valdor Gulch:

This reach had limited historic channel migration and therefore presented calibration challenges (Figure 5). At the time of this study, rehabilitation plans at Valdor Gulch (RM 75.6 through RM 75) were preliminary. The site is separated into three sub-reaches. V-1 consists of a portion of the rehabilitation area and a couple of small bends (perhaps smaller than the geomorphic wave length). This is a fairly straight reach that is heavily constrained by riparian berms. The rehabilitation in V-1 appears to be intended to increase scour on the floodplain as it is on the inside of the bend and would not affect typical channel migration on the outside bend. V-2 has a hard right-angle bend held in place by a bedrock cliff where there has been little or no historic channel movement. The rehabilitation plan at this sub-reach calls for removing a piece of the inner bend to soften the corner. V-3 is downstream of the rehabilitation area but is influenced by upstream changes due to the rehabilitation. This sub-reach has a high sinuosity and is constrained by riprap on the outside bend where meander migration is being constrained.

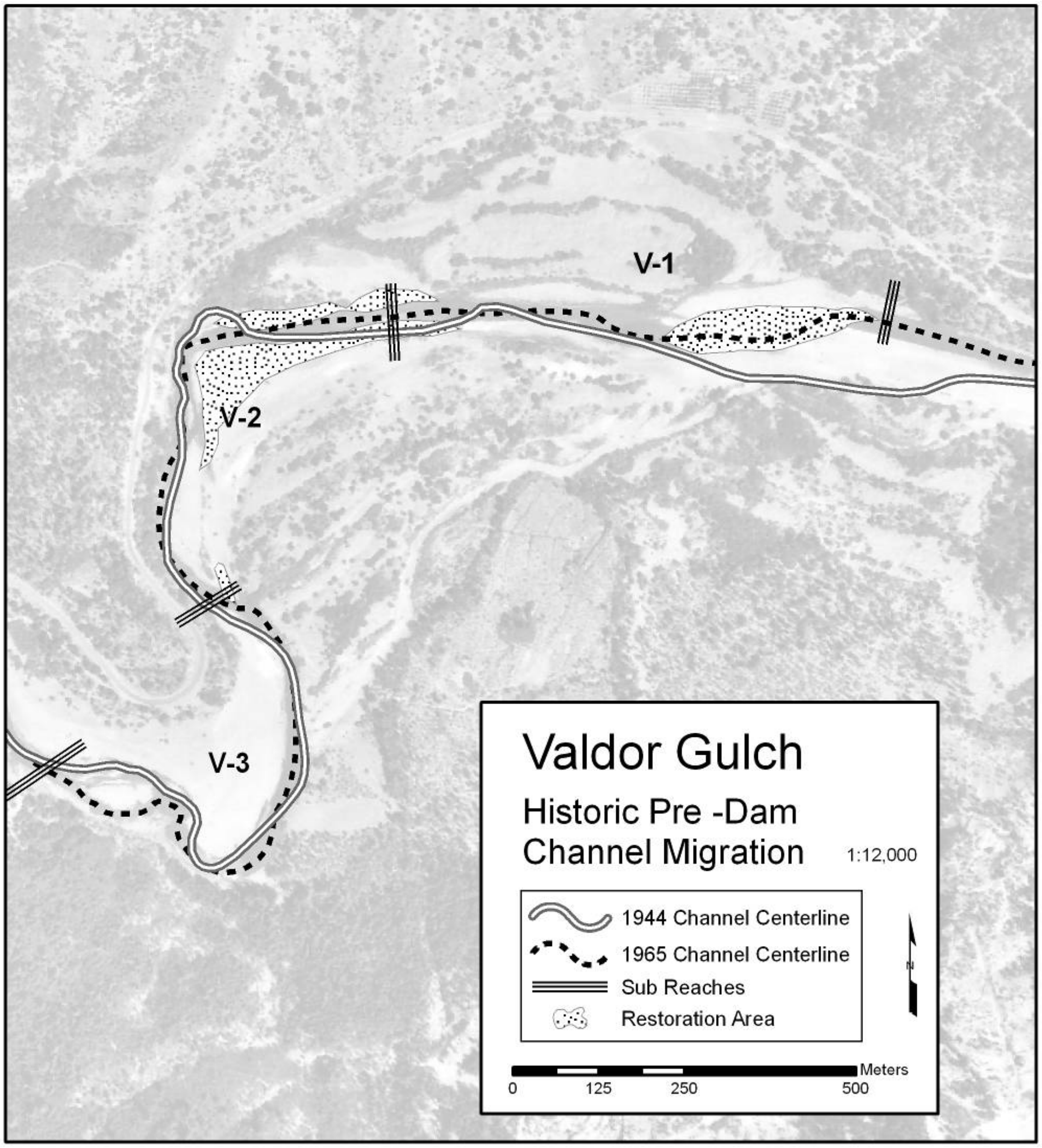


Figure 5 Valdor Gulch Historic Pre-Dam Channel Migration.

Elkhorn:

Historically the Elkhorn reach experienced little channel movement and appears to be controlled mainly by geology with some lesser influences of hydrology (Figure 6). The site has been divided into two sub-reaches. E-1 includes a small area of rehabilitation and tight bend that appears to be geologically controlled. E-2 includes a straight reach followed by a slight bend that is fairly well constrained on the outside. The rehabilitation site is on the floodplain along the straight reach and appears to be designed to relieve pressure on the downstream outside bend.

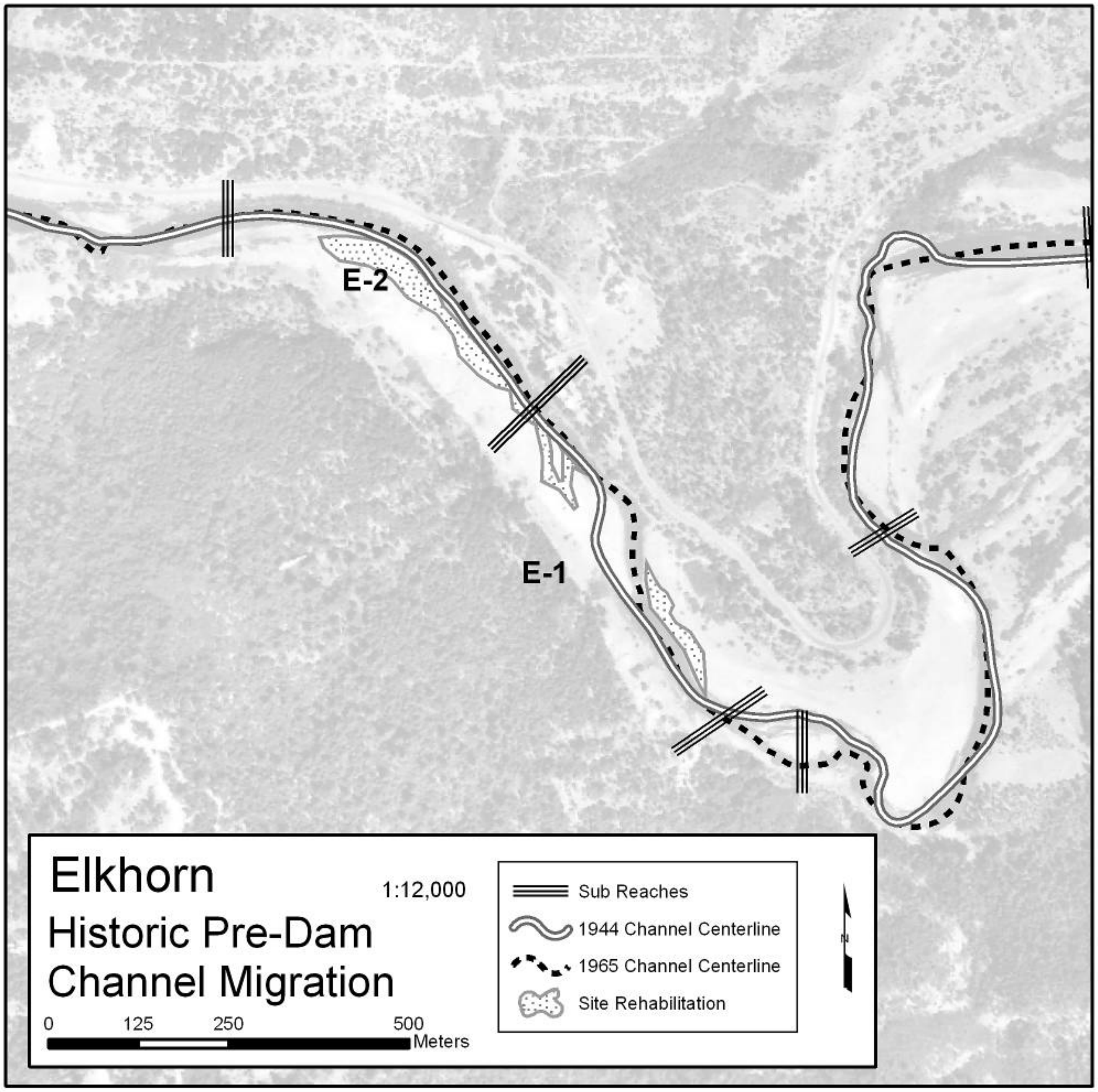


Figure 6 Elkhorn Historic Pre-Dam Channel Migration

GIS Methods

Channel features and centerlines were derived using aerial photos of the Trinity River at several time steps; 1944 and 1965 provide a record of pre-dam river channel locations, while photos from 2000 were used to depict post-dam conditions. The model was calibrated using the pre-dam time period. Because the model is able to predict changes in behavior due to different flow conditions and due to different bank conditions, it is expected that the calibration from pre-dam conditions will be appropriate when applied to post-dam conditions, when the changes in conditions are included in the modeling. "Aerial photos show that the mainstem below Lewiston had morphological features typical of alluvial rivers: therefore, the geomorphologists' knowledge of contemporary alluvial rivers can be applied to the former mainstem channel" (TRFE, p37).

Aerial photos from 1944, 1965, and 2000 - acquired the California Department of Water Resources (DWR) - were georeferenced to 1993 USGS Digital Ortho Quarter Quads (DOQQs) using ArcGIS 8.2 software to create a photomosaic of the study area. Channel banklines and features were digitized on-screen at a scale of 1:1000 by hand-tracing the edges of the banks and mid-channel bars. Centerlines were then located by visually estimating the location of the line midway between channel edges. The meander migration model does not support a split centerline; therefore in the case of a mid-channel bar, where the channel is split, the wider of the two channels was digitized as the dominant channel. Digitized centerlines were cleaned and processed for use with the meander migration model using ArcGIS 8.2 software.

In comparing channels at different time steps it became obvious that there was not much movement in the post-dam channel, and that there were some anomalies in the pattern of channel movement. Since dredger mining occurred in the time period between photosets, it is reasonable to assume that mining caused some of the anomalous movement. Accordingly, the 1944 channel was modified from RM 78.6 to RM 78.1 in order to account for a major channel change. A dredger is visible on the 1944 aerial photo cutting a new channel in the path of the eventual 1965 channel. For this study it was assumed that the dredger excavated the current channel and a modified 1944 centerline was created to reflect the change.

Predictions

Area of land reworked

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 (Figure 7). 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).

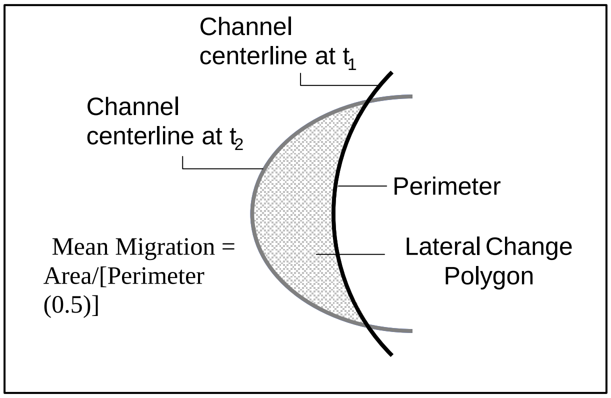


Figure 7 Definition of area reworked polygon

Migration Rate

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 different points in time as shown above (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 period between the two centerline locations of the river. The channel migration rate is then calculated as:

$$\frac{A_r}{tL} \qquad \text{[Equation 1]}$$

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. The average centerline length is used to standardize the migration rate for variable bend lengths, resulting in the average rate of migration per year per length of channel for a given period of time. Equation 1 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 1 without dividing by the length (L). This represents area reworked for a single year; the process is repeated for all modeled channels and aggregated to represent total area reworked. For each prediction scenario, a 50-year forecast (2005-2055) was produced and a map of forecasted floodplain age was created (Fremier 2003). The floodplain age map is composed of predicted channels for every fifth year. This map denotes a prediction of which year a given area will be reworked by the migrating channel. A 10m grid cell size was used, and a 50m channel width was assumed for the floodplain age analysis.

Meander Migration Model

River channel migration models based on mathematical-physical algorithms of sediment transport and water flow can be used to predict future channel migration (e.g.Larsen 1995, Darby et al. 2002). This study uses a simulation model of river meander migration with a geographic erosion surface that incorporates geologic control and areas of erodibility (Johanesson and Parker 1985, Larsen and Greco 2002, Larsen et al. In Review). Because the model is a process-based simulation model, it is calibrated based on observed historical channel locations. The model accommodates changes in input variables and projects the consequences of conditions that have not existed in the past, such as the addition or removal of riparian berms and changing flow conditions. Understanding the dynamics of the river given different management scenarios will provide important information to inform planning decisions. For this study a model for predicting meander migration of alluvial rivers has been modified for use on a highly impacted river that has variable mobility potential. Modeling in this case differs from modeling highly mobile alluvial rivers. In many locations the Trinity River is highly constrained by bedrock and valley walls. However the model can provide insight into the tendencies of the lateral movement and bank erosion of the river in the sections where it is not constrained

A version of this migration model has been used to predict and analyze the Sacramento River (Larsen 1995, Larsen et al. 2002, Larsen and Greco 2002, Larsen et al. In Press). Previously, (Johanesson and Parker 1989) used the model to predict wavelengths of meandering rivers, with results comparable to laboratory and field data. (Pizzuto and Meckelenburg 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. Likewise, a similar 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 (Johanesson 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:

$$M = E_o u_b \qquad \text{[Equation 2]}$$

where M is the bank erosion rate (in meters per year), Eo 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, which varies spatially throughout the erosion field. For a more detailed description of the model, see (Larsen and Greco 2002).

The meander migration model uses a variable-flow protocol which predicts that cumulative effective stream power is proportional to bank erosion (Larsen et al. *in press*). 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^2s^2). The historic flow record was used to calibrate the meander migration model between known channel centerlines from 1944 and 1965.

Variable Erosion Surface Incorporating Rehabilitation Design

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 erosion surface was assembled using a geology surface dataset obtained from McBain & Trush, and a refined version made by DWR, whereby a range of estimated erodibility values were assigned to features based on their estimated erodibility potential. Through multiple calibration runs, erodibility values were reduced to 2 values: non-erodible or erodible. Features such as bedrock and riprap are considered non-erodible for this study while alluvial point bars and floodplains with high observed channel migration are attributed as erodible. Riparian berm features from the geologic map have been removed in the calibration, as they did not form until after the dam was in place.

Calibration

The model was calibrated using observed channel centerlines from 1944 and 1965. Other factors considered in calibration include Discharge (Q), channel width (W), channel depth (H), sediment size (D_{50}), and slope (S). Calibration of the numerical model employs two adjustable parameters; the coefficient of friction (C_f), and empirical bank erodibility coefficient (E_0). C_f is calibrated to match the *pattern* of migration, while E_0 is calibrated to adjust the *magnitude* of migration, in other words, bank erodibility.

In calibration runs, average pre-dam values for the 1.5 year recurrence interval discharge were used. Flow (Q) was estimated at 302 cms. Slope (S) was calculated using HEC-RAS software at 0.002. Bankfull channel width (W) used in calibration was 85 m, channel depth (H) was 1.77 m and sediment size (D50) was 76 mm.

For predictive runs, riparian berms were added to the erosion field and attributed as non-erodible. Rehabilitation site plans provided by DWR and McBain & Trush, were georeferenced, digitized and attributed as erodible surfaces.

Each site was calibrated individually and predictive runs made using four 50-year predictive scenarios: current conditions with no ROD flows, current conditions with ROD flows, site rehabilitation without ROD flows, and ROD flows coupled with rehabilitation.

Table 1 Description of model runs

Name	RE	RO	RR	SQ
Description	Rehabilitation Only, (No ROD)	ROD Only (No Rehabilitation)	ROD & Restoration	Status Quo (No ROD, No Restoration)
Restoration	Yes	No	Yes	No
Hydrograph	No ROD	ROD Flows	ROD Flows	No ROD

Modeling assumed that the riparian berms would not re-establish if the channel were rehabilitated. The migration model is therefore not suited to predict the differences between scenarios RE and RR (rehabilitation and rehabilitation with ROD flows) in the long run. We assume that RE (without ROD) would result in the berms re-establishing on the floodplain. The erosion field of the meander migration model does not allow for a dynamically changing erosion field to automatically “build in” riparian berms over time, or predict where the berms would occur. The model also does not account for the role of large woody debris (LWD) in pointbar formation and channel form complexity.

Hydrograph

Three different synthesized hydrographs were developed for this study; Hydrograph-1 (Figure 8) represents historic pre-dam conditions for calibration of the model. Hydrograph-2 represents a 50-year predictive daily flow schedule based on historic post-dam conditions. Hydrograph-3 represents a flow schedule that incorporates ROD flows into the 50-year predictive plan. Figure 9 shows a comparison of three different synthetic hydrographs (High Low and Average water years) for the study area with and without ROD flows.

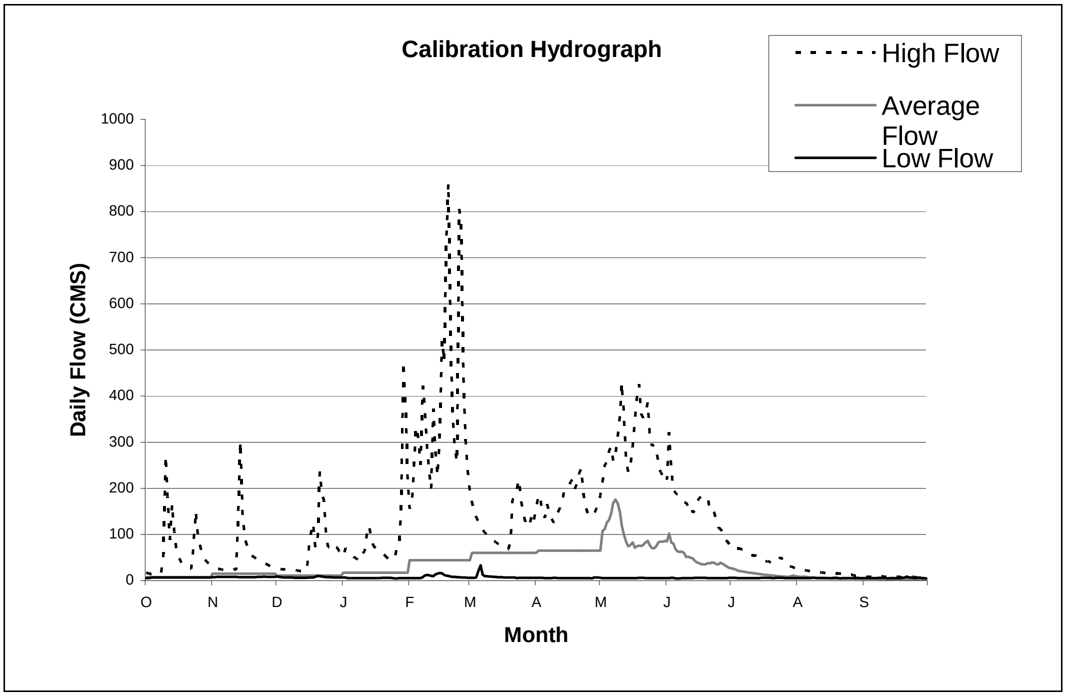
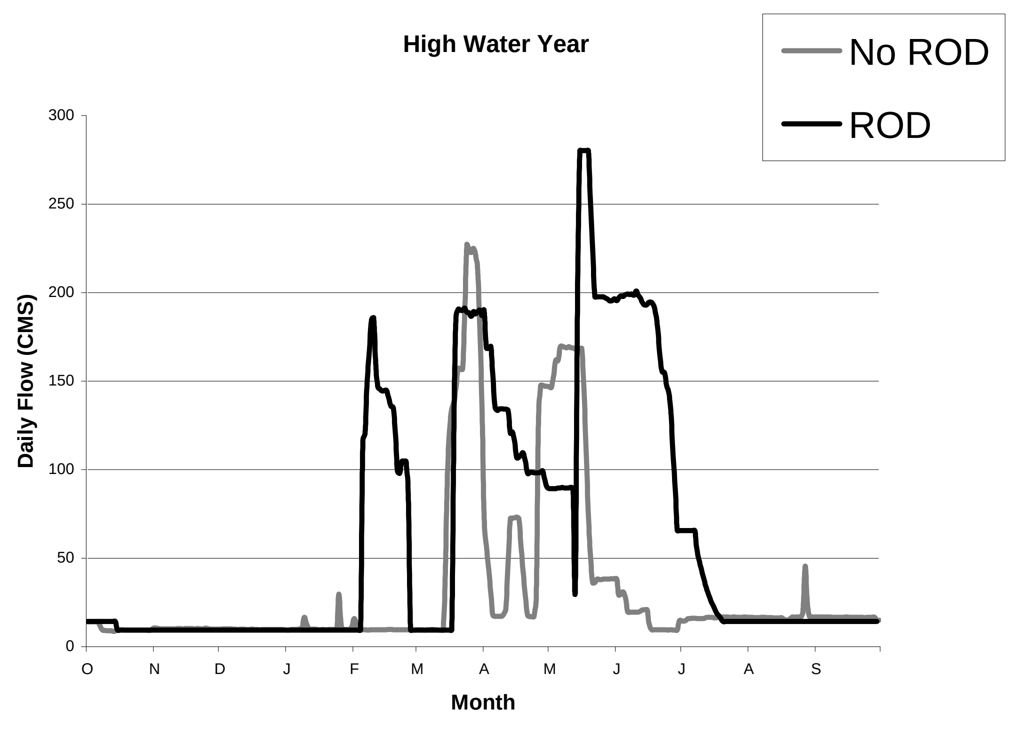
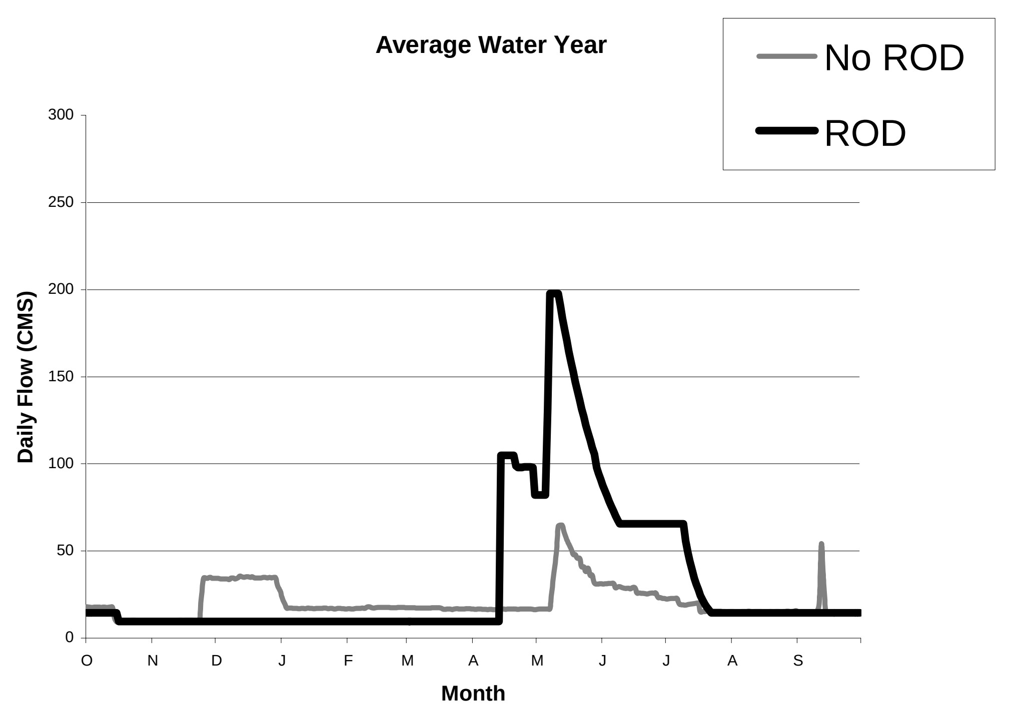


Figure 8 Example of synthesized high, average and low flow water years of the calibration hydrograph.


High Water Year
No ROD
ROD
300
250
200
150
100
50
0
Daily Flow (CMS)
O
N
D
J
F
M
A
M
J
J
A
S
Month


Average Water Year
No ROD
ROD
300
250
200
150
100
50
0
Daily Flow (CMS)
O
N
D
J
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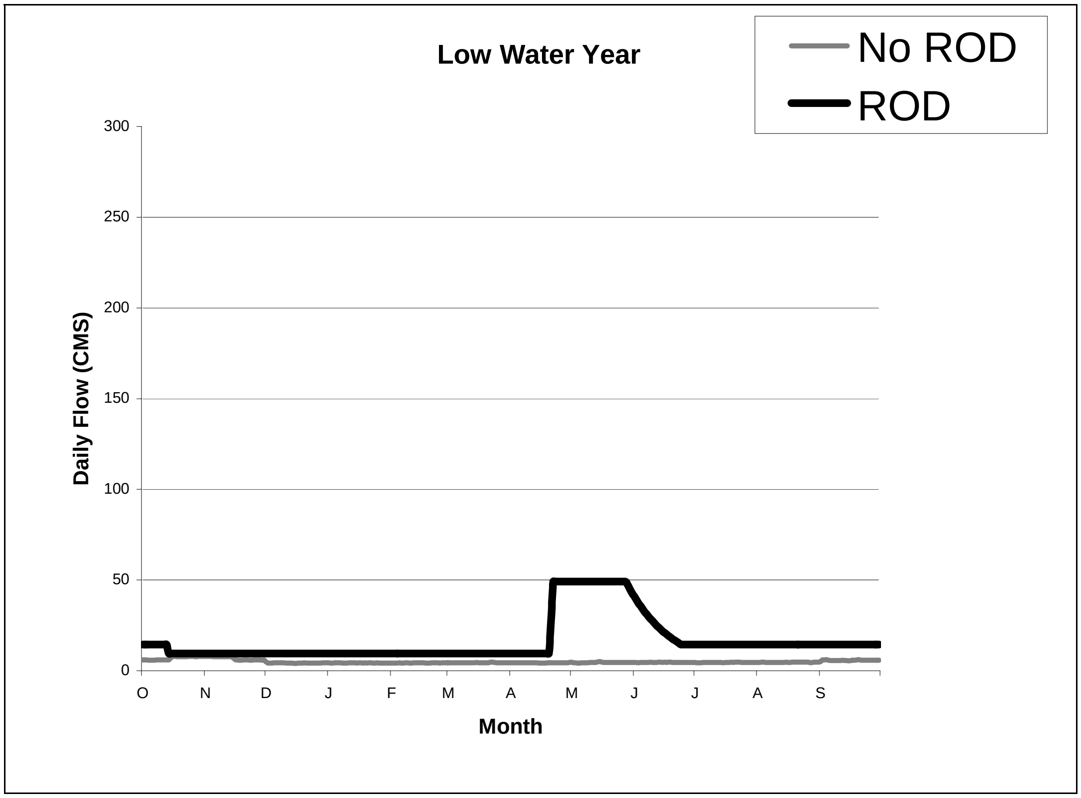

Figure 9 Synthesized prediction daily flow hydrograph without ROD flows for study site adjusted for tributary accretion. Example high flow, average flow and low flow water years

Although flood recurrence estimates exist for the study area, historic daily flow data was not available as no reliable gages existed at the study site until the late 1990s. Therefore a synthesized hydrograph was generated by comparing the daily flow from Douglas City (the nearest upstream gage), for the available pre-dam years (1943-51) and performing a regression analysis against the daily flow at Lewiston to account for tributary accretion at the downstream location. An equation was produced from the regression and applied to the daily flow at Lewiston to create a calibration hydrograph for WY1944-WY1965. The same regression equation was applied the daily flow at Lewiston from 1964-2004, with years 1964-1974 repeated to make up a fifty year simulated hydrograph with no ROD flows.

A simulated ROD flow hydrograph was produced by applying the regression equation for tributary accretion to a schedule of distributed ROD flow conditions at Lewiston. Daily ROD flow values were obtained from the US Bureau of Reclamation Trinity River Flow Schedule. Daily flows were then compared to the post-dam no-ROD hydrograph to determine the frequency of large, emergency dam releases and the post-dam ROD was adjusted to reflect the same frequency and magnitude of these releases.

Table 2 Summary of hydrographs

Summary of hydrographs				
	Name	**Description**	**Years**	**$Q_{1.5}$ (cms)**
Hydrograph-1	Calibration	Historic pre-dam	1944-1965	302
Hydrograph-2	Post Dam	Prediction No ROD	50 Years	240
Hydrograph-3	Post Dam ROD	Prediction with ROD Flows	50 Years	240

Results and Discussion

The four modeled scenarios are summarized in Table 3. The results shown here compare the difference between rehabilitation (RE) and Rehabilitation with ROD flows (RR). The differences between ROD (RO) and non-ROD (SQ) flows were insignificant.

Table 3 Summary of runs

Summary of runs										
Reach	**Scenario description**	**Hydrograph**	**Restoration**	**Erosion field**	**$Q_{1.5}$**	**w**	**d**	**s**	**D_{50}**	**C_f**
Hocker (CA)	Pre Dam	Calibration	No	H-Calib	302cms	85m	1.77m	0.002	76mm	0.75
Hocker (RE)	Prediction	No ROD	Yes	H-Berms-Removed	240cms	60m	1.8m	0.002	85mm	0.75
Hocker (RO)	Prediction	ROD	No	H-Berms	240cms	60m	1.8m	0.002	85mm	0.75
Hocker (RR)	Prediction	ROD	Yes	H-Berms-Removed	240cms	60m	1.8m	0.002	85mm	0.75
Hocker (SQ)	Prediction	No ROD	No	H-Berms	240cms	60m	1.8m	0.002	85mm	0.75
Connor (CA)	Pre Dam	Calibration	No	C-Calib	302cms	85m	1.77m	0.002	76mm	0.75
Connor (RE)	Prediction	No ROD	Yes	C-Berms-Removed	240cms	60m	1.8m	0.002	85mm	0.75
Connor (RO)	Prediction	ROD	No	C-Berms	240cms	60m	1.8m	0.002	85mm	0.75
Connor (RR)	Prediction	ROD	Yes	C-Berms-Removed	240cms	60m	1.8m	0.002	85mm	0.75
Connor (SQ)	Prediction	No ROD	No	C-Berms	240cms	60m	1.8m	0.002	85mm	0.75
Valdor (CA)	Pre Dam	Calibration	No	V-Calib	302cms	85m	1.77m	0.002	76mm	0.5
Valdor (RE)	Prediction	No ROD	Yes	V-Berms-Removed	240cms	60m	1.8m	0.002	85mm	0.5
Valdor (RO)	Prediction	ROD	No	V-Berms	240cms	60m	1.8m	0.002	85mm	0.5
Valdor (RR)	Prediction	ROD	Yes	V-Berms-Removed	240cms	60m	1.8m	0.002	85mm	0.5
Valdor (SQ)	Prediction	No ROD	No	V-Berms	240cms	60m	1.8m	0.002	85mm	0.5
Elkhorn (CA)	Pre Dam	Calibration	No	E-Calib	302cms	85m	1.77m	0.002	76mm	1
Elkhorn (RE)	Prediction	No ROD	Yes	E-Berms-Removed	240cms	60m	1.8m	0.002	85mm	1
Elkhorn (RO)	Prediction	ROD	No	E-Berms	240cms	60m	1.8m	0.002	85mm	1
Elkhorn (RR)	Prediction	ROD	Yes	E-Berms-Removed	240cms	60m	1.8m	0.002	85mm	1
Elkhorn (SQ)	Prediction	No ROD	No	E-Berms	240cms	60m	1.8m	0.002	85mm	1

Table 4 shows migration rates and area reworked by sub-reach. The migration rates reflect the physical process; the area reworked shows the results of that physical process. The migration rates are non-dimensional having been normalized by length and time. The area reworked is dimensional (m^2). Despite these differences the observed patterns are very similar because the time period analyzed is the same (50 years) for all analyses and the lengths of the bends are approximately the same.

Table 4 Summary of bend area reworked and migration rate

Summary of bend area reworked and migration rate

Reach	Length	Predicted Area Reworked RO (ha)	Predicted Area Reworked RR (ha)	Migration Rate RO (m/yr)	Migration Rate RO (width/yr)	Migration Rate RR (m/yr)	Migration Rate RR (width/yr)	RR-RO (m/yr)	Migration group	Rehabilitation group	Comments
H-1	674	11,589	10,245	0.34	0.006	0.30	0.005	-0.04	N	L	
H-2	824	5,112	10,094	0.12	0.002	0.25	0.004	0.12	L	LO	straght reach -slight effect
H-3	436	4,661	13,943	0.21	0.004	0.64	0.011	0.43	L	LD	typical
H-4	464	9,886	14,567	0.43	0.007	0.63	0.010	0.20	U	LD	inward toward the bar
H-5	347	9,490	8,606	0.55	0.009	0.50	0.008	-0.05	N	D	inward toward the bar
C-1	466	3,860	9,173	0.17	0.003	0.39	0.007	0.23	L	LO	typical
C-2	362	1,685	5,615	0.09	0.002	0.31	0.005	0.22	U	D	
C-3	277	3,222	2,543	0.23	0.004	0.18	0.003	-0.05	N	D	
V-1	510	7,061	7,347	0.28	0.005	0.29	0.005	0.01	N	N	inward toward the bar
V-2	647	5,337	13,313	0.16	0.003	0.41	0.007	0.25	L	LD	inward toward the bar
V-3	727	18,202	16,935	0.50	0.008	0.47	0.008	-0.03	U	U	
E-1	471	8,153	13,575	0.35	0.006	0.58	0.010	0.23	L	LO	anomalous
E-2	575	1,653	1,737	0.06	0.001	0.06	0.001	0.00	N	N	
ave	522	6916	9823	0.27	0.004	0.38	0.006	0.12			
max				0.55	0.009	0.64	0.011	0.43			
min				0.06	0.001	0.06	0.001	-0.05			

Hydrograph

There was no significant difference in total cumulative area reworked between the Rehabilitation only (RE), and ROD & Rehabilitation (RO) scenarios. Similarly the Status Quo (SQ) and ROD Only (RO) are similar in value. This suggests that mechanical rehabilitation is the mechanism enabling meander migration (Figure 10). Although the ROD flows will likely serve a valuable purpose in the maintenance of restoration areas, they do not contribute significantly to channel migration. Total area reworked in SQ is equal to 94.6% of the area reworked in the ROD Only scenario. An even closer match, the RO is equal to 99.6% of ROD & Rehabilitation. Therefore we have eliminated two scenarios from the analysis and focus on the differences between ROD Only (no restoration), and ROD & Rehabilitation.

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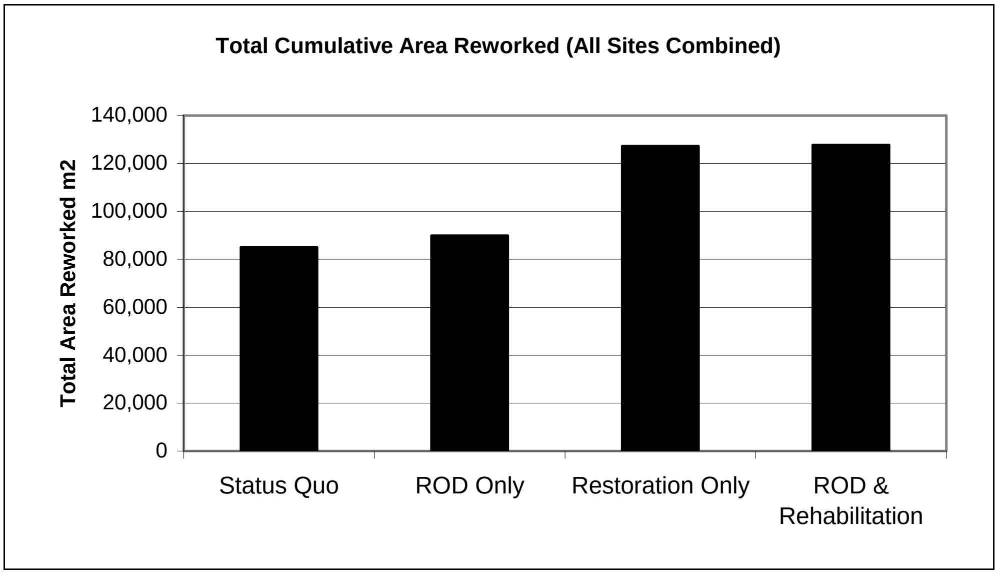

Figure 10 Total Cumulative Area Reworked

Area reworked, migration rate, and the effect of rehabilitation are summarized in Table 4 and Figures 11, 12, and 13. The effects of migration can be separated into three groups (Table 5):

"L": migration due to local rehabilitation (e.g. H-1, H-2, H-3, C-1, V-2, E-1);
"U": migration due to upstream rehabilitation (e.g. H-4, C-2, V-3); and
"N": no outside bend migration due to rehabilitation (e.g. H-5, C-3, V-1, E-2).

Table 5. Effect of Migration

Migration Group	Effect of Migration
L	Due to Local Effect
U	Due to Upstream Rehab.
N	No outside bend migration

Migration Group By Bend		
L	**U**	**N**
H-1	H-4	H-5
H-2	C-2	C-3
H-3	V-3	V-1
C-1		E-2
V-2		
E-1		

When considering the effects on the bends in terms of rehabilitation, there are three different groups (Table 6):

“LO”: rehabilitation has only local effects on migration (H-2, E-1);

“LD”: rehabilitation has both local and downstream effects (H-3, C-1, V-2);

“D”: rehabilitation has no effect on migration, but may have other desired effects – for example relieving pressure and discouraging migration towards the outside bank protecting infrastructure such as Hwy 299 (H-1), (E-2); providing floodplain habitat for Salmonids by promoting scour on the pointbar thus eliminating future riparian berms (C-2 ,C-3, V-1).

Table 6 Effect of Rehabilitation

Rehabilitation Group	**Effect of Rehabilitation**
LO	Local Effect
LD	Local & Downstream Effects
D	Downstream Effects
N	No Local or Downstream Effect

Rehabilitation Group			
LO	**LD**	**D**	**N**
H-1	H-3	H-5	V-1
H-2	H-4	C-2	E-2
C-1	V-2	C-3	
E-1		V-3	

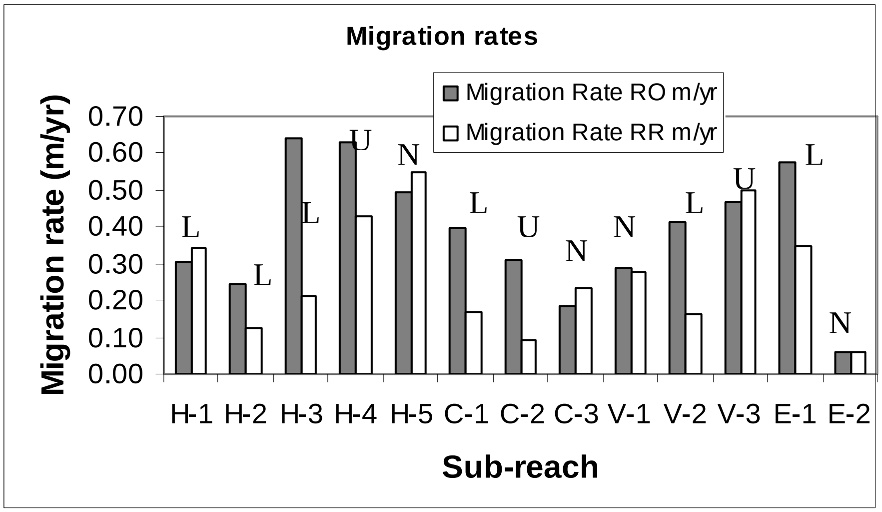

Figure 11 Migration rates for each of the study bends.
(area/length)

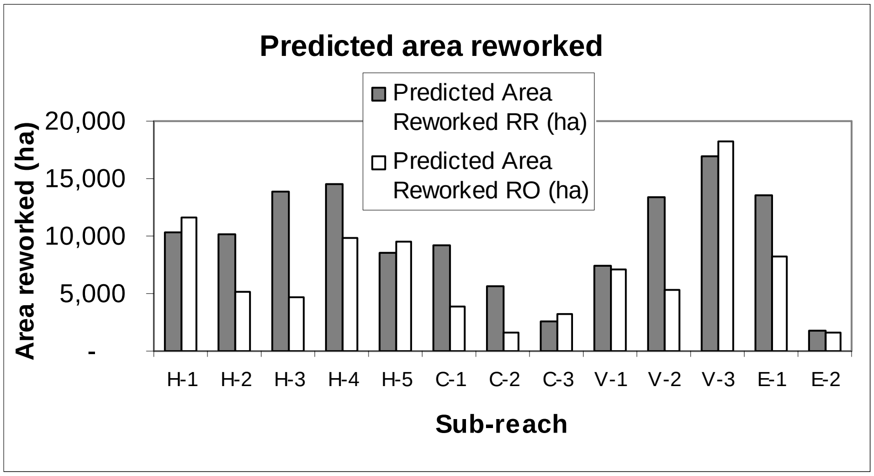

Figure 12 Predicted area reworked

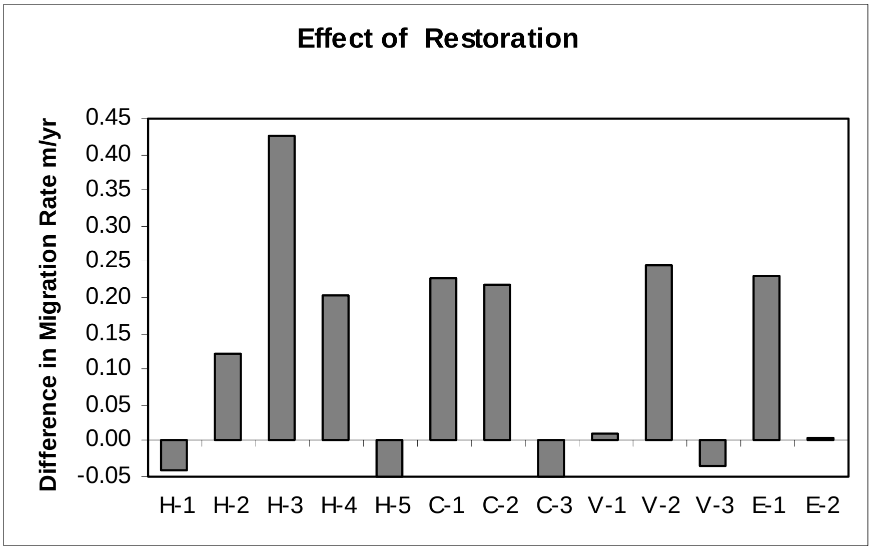

Figure 13 Effect of restoration: the difference in migration rate between the rehabilitation scenario with the ROD flows and the base (ROD flows with no rehabilitation).

Four areas of concern

Hocker Flat

At Hocker Flat, migration rates for the rehabilitated channel with ROD flows ranged from 0.25 to 0.64 m/yr (Figure 14). Bend H-1 has migration rates of about 0.3 for all four cases of management action. The actual movement of H-1 will probably be influenced by a tributary that enters there, and the meander migration simulations should be considered in that light. H-2 is a fairly straight reach that did not migrate much before rehabilitation, but did show minor increased migration when the rehabilitation actions were applied. At H-3 there is a large effect of rehabilitation, with migration rates increasing from 0.21 m/yr without rehabilitation to 0.64 with rehabilitation. Although H-3 is not a high-curvature bend, it experiences the highest migration rate of any of the rehabilitated bends. Due to the overlap with the rehabilitation site , this section has a tendency to migrate faster. H-4 also experiences a relatively large change in migration rate due to the effect of rehabilitation, but this migration is counter to the direction that most bends migrate. At bend H-4, the migration simulation shows the channel moving toward the inside of the bend. There is no rehabilitation activity overlapping with the location of segment H-4; however the rehabilitation activity upstream near H-3 clearly influences H-4. As the channel at H-3 migrates to the west, the channel downstream is affected and moves to the east. This tendency does not translate downstream from H-4 thus there is essentially no effect of rehabilitation at H-5, although the simulations (with and without rehabilitation) show the channel moving to the west, toward the inside of the bend as at bend H-4. The simulations at H-4 and H-5 suggest that the channel will move inward and decrease in curvature, which is counter to typical bend migration (i.e. to move outward and increase in curvature).

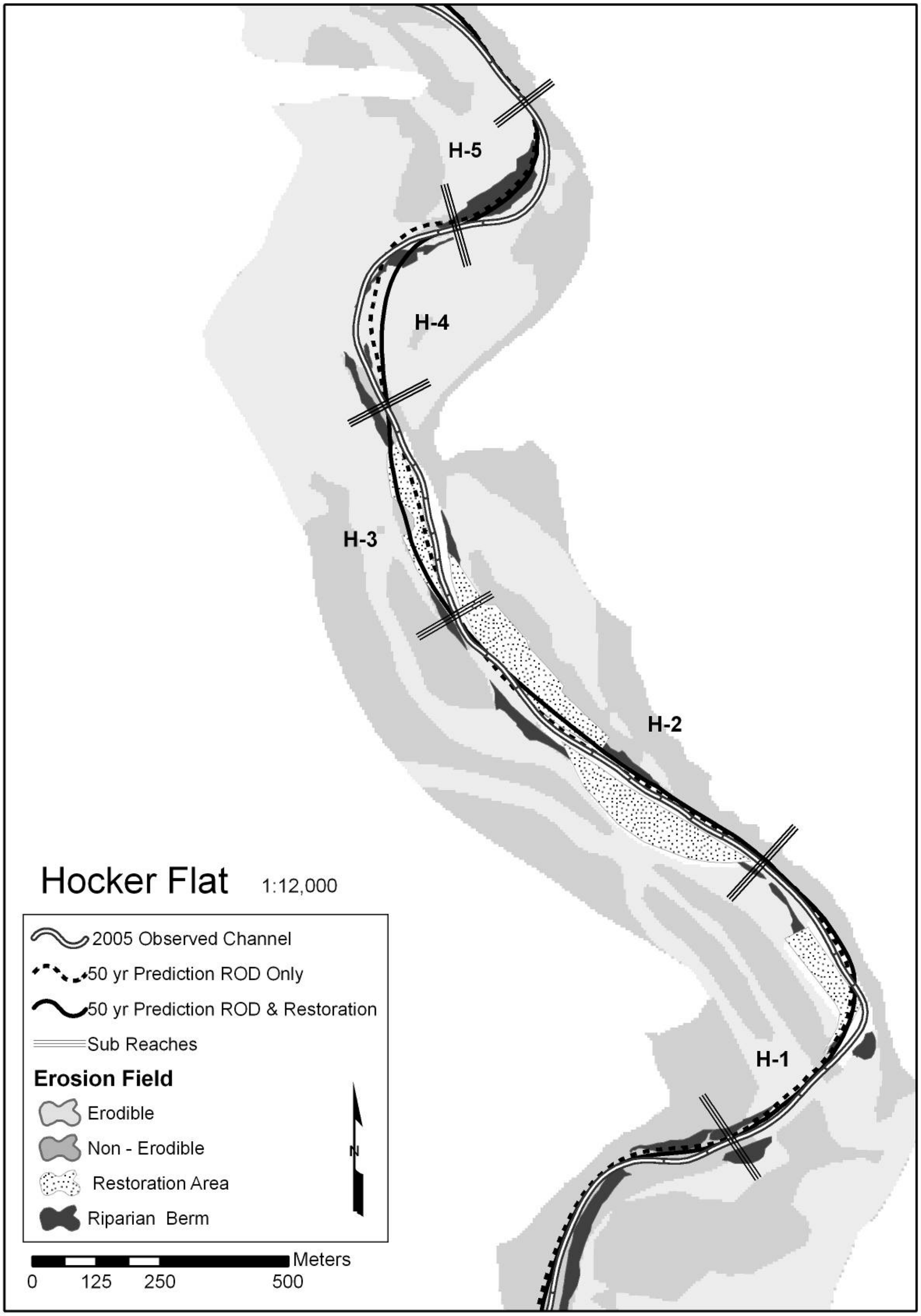

Figure 14 Hocker Flat sub-reach geology, planned rehabilitation, and predicted channel migration The figure includes "Predicted ROD Only" and "Predicted ROD & Restoration" scenarios.

Conner Creek

In the Conner Creek location, (Figure 15) bend C-1 increases in migration rate from 0.17 m/yr to 0.37 m/yr when rehabilitation was simulated. The reason for the increase is not clear. It appears to be due to influence from the upstream bend H-5 combined with some migration into the rehabilitated area near C-1. (Channels on the figures are shown as centerlines. In order to conceptualize the influence of a rehabilitated area, the channel must be imagined to extend a half-channel width on each side of the centerline.) C-2 also increases migration rates under the rehabilitation scenario, but this increase was due to river planform changes from rehabilitation at the upstream bend (C-1) rather than local rehabilitation at C-2. Throughout the Conner Creek site, the river does not meander into the rehabilitation area. Floodplain flows will occur but it is likely that without high ROD flows to scour the floodplain, willows would likely re-inhabit the rehabilitated area. Bend C-3 exhibits no influence of direct rehabilitation with migration rates actually decreasing slightly at that beginning of the bend. This is because there was no rehabilitation applied to C-3, while upstream rehabilitation changes the entrance angle of the river as it enters C-3, causing it to migrate less under the rehabilitated scenario than under current conditions.

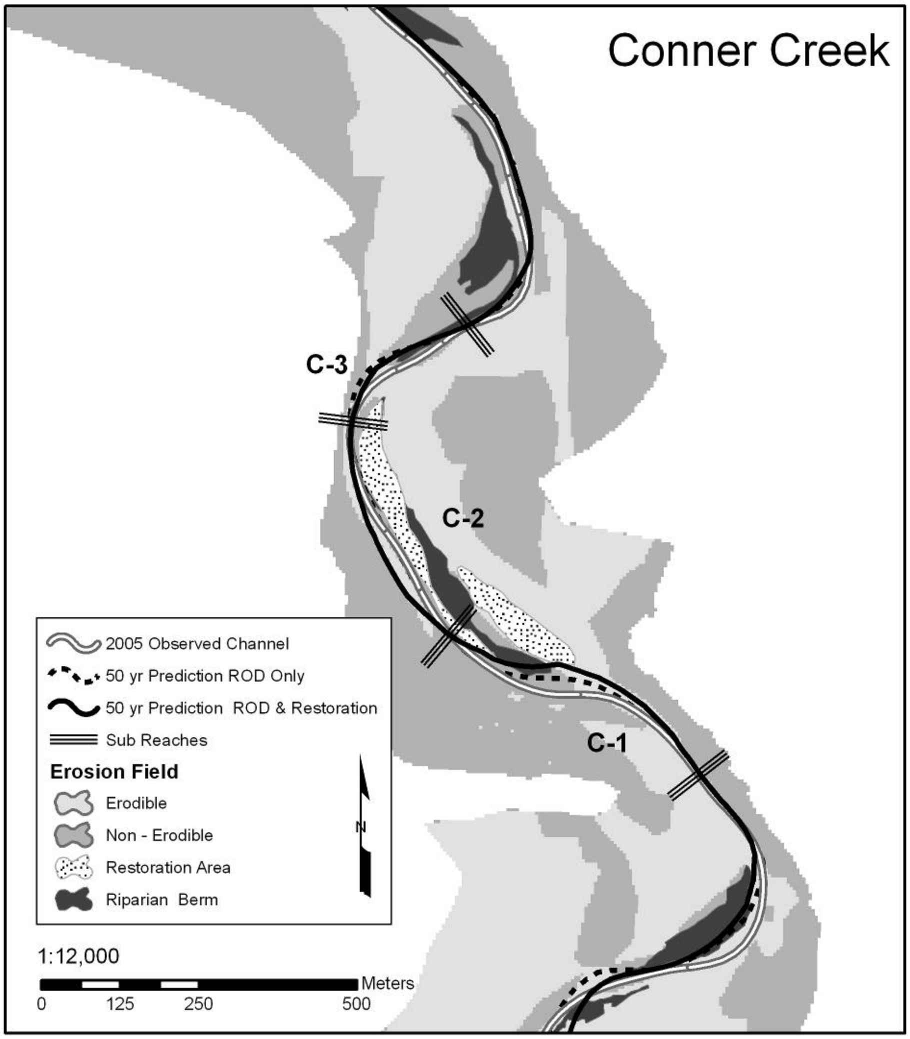

Figure 15 Conner Creek sub-reach geology, planned rehabilitation, and predicted channel migration under "Predicted ROD Only" and "Predicted ROD & Restoration" scenarios.

Valdor Gulch

There was no appreciable change in modeled migration due to restoration at bend V-1 with migration staying constant at 0.29 m/yr (Figure 16). Conversely, V-2 moves into the pointbar on the inside of the bend significantly with rehabilitation. The migration rate at V-2 increased from 0.16 m/yr to 0.41m/yr when the rehabilitation was simulated However, meander migration modeling at site V-2 needs to be interpreted with subjective judgment in order make conclusions regarding the effect of rehabilitation. Meander migration simulations show the river moving in the direction opposite to what we would expect based on flow patterns resulting from channel curvature and the existing geologic control. In essence the channel migration simulation shows the channel cutting across the inside bar. Part of the simulation pattern comes from the fact that the erodibility of the inside of the bend was changed. The changing erosion field is responsible for part of the changed pattern of migration. In addition to this, the meander migration simulation accounts for conservation of meander bend wavelength, and this fact influences this simulation, increasing the tendency to cut across the bar. The simulation may provide insight into where the channel may go. At the same time, site-specific dynamics smaller than the scale of a meander wavelength may ultimately control the migration here, and caution is advised when considering the simulation results.

The modeling in V-1 and V-2 suggests that the meander wavelength of the modeled channel which is calculated based on the magnitude of flow, width, depth (model parameters) is different than the wavelength of many of the small bends that are observed in this area. One of these currently-existing "small bends" is probably determined by a rock outcrop.

In bend V-3, the velocity pattern set up in V-2 propagates downstream and determines the difference in the migration with rehabilitation. This pattern in turn affects the migration patterns in the Elkhorn reach downstream from Valdor gulch. The migration rate at V-3 actually decreased slightly from 0.50 m/yr to 0.47m/yr when the rehabilitation was simulated. Again this is likely due to the velocity pattern set up in V-2.

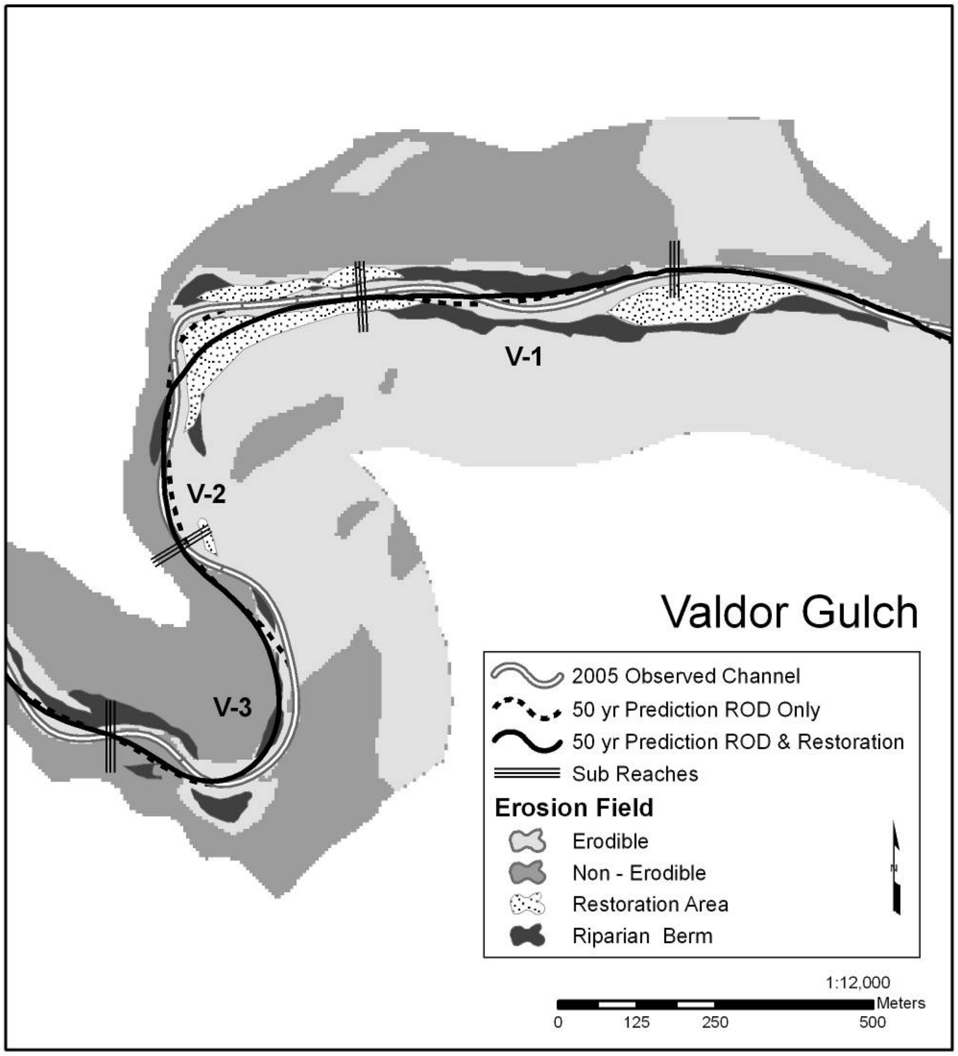

Figure 16 Valdor Gulch sub-reach geology, planned rehabilitation, and predicted channel migration under "Predicted ROD Only" and "Predicted ROD & Restoration" scenarios.

Elkhorn

In the Elkhorn location, bend E-1 is directly downstream of an area that appears exhibit some geologic control and heavy influence of riparian berms. 50 year predictions suggest that the channel will migrate toward a new position to the south west with an increase in migration away from the rehabilitation site. An increase of 0.23 m/yr from 0.35 m/yr to 0.58 m/yr was predicted with the rehabilitation simulated. This is likely due to changes in the channel position from upstream conditions and slight overlap with local rehabilitation activity.

Predictions at E-2 show virtually no migration, even with the rehabilitation action (Figure 17). This is not surprising as this reach has historically been straight, with little meander migration. Furthermore, the slight curvature (planform) would tend toward bank migration to the north east, if it were not restrained. What is not shown in our results is the fact that the rehabilitation design will relieve pressure on the outside bank due to reduced bank height on the south-west side. With larger flows, they will over-top the skimmed bank and result in a reduced water depth on the outside bank. This will reduce bank erosion pressure on the outside bank and scour the inside pointbar, discouraging vegetation recruitment. However, these effects are not reflected in the meander migration modeling and like Valdor Gulch, must be considered subjectively.

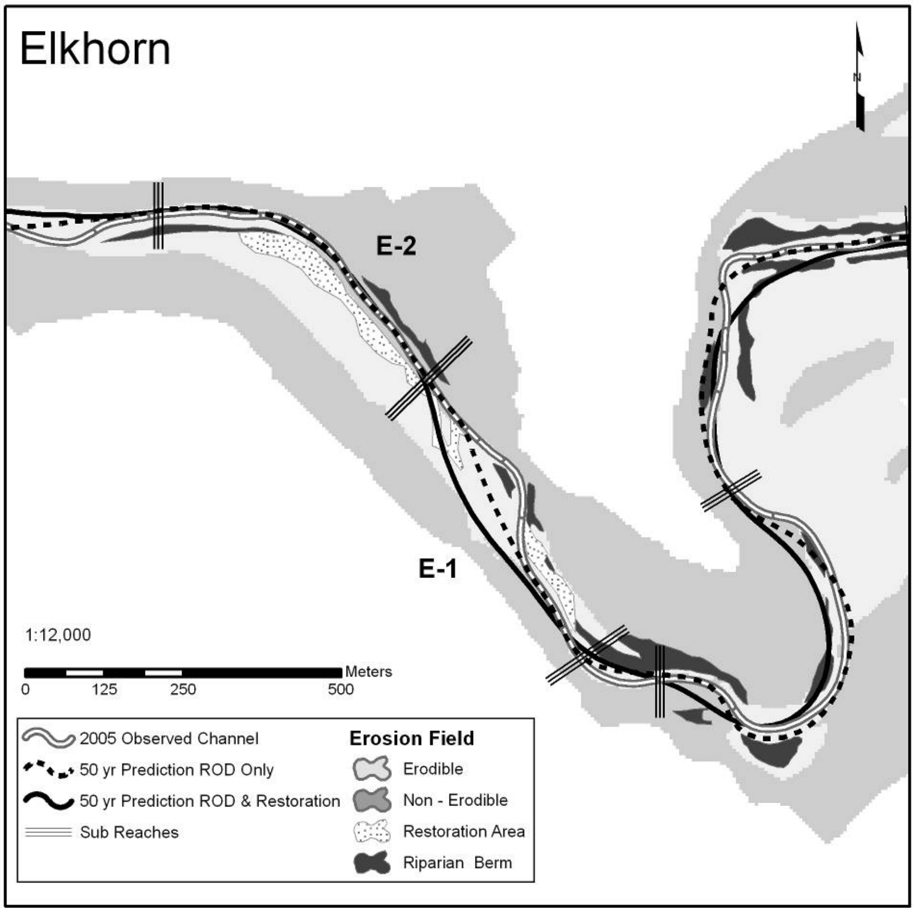

Figure 17 Elkhorn sub-reach geology, planned rehabilitation, and predicted channel migration These are under "Predicted ROD Only" and "Predicted ROD & Restoration" scenarios.

Effect of rehabilitation grouped by migration and rehabilitation pattern

The magnitude of the migration rate or area reworked differs between sites for different reasons, and cannot necessarily be ascribed to the local rehabilitation of each sub-reach. For example, some high values, such as those at C-2, V-2, & H-4 are not related to local rehabilitation, but are related to the influence of change in upstream conditions.

Rehabilitation at Hocker Flat seems to be designed to have the river migrate into the rehabilitation areas (e.g. H-3). This is a classic example of rehabilitation having positive local ecological impacts. However, at the other sites (e.g. C-2, V-1, V-2, E-2) the rehabilitation is designed to relieve erosion pressure on the outside bank by removing the riparian berm on the point bar. This may be effective for reasons different than promoting lateral channel migration on the outside of the bend. For example, at E-2 the rehabilitation seems to be designed to discourage migration toward the outside bank to avoid erosion along HWY 299. In the other cases (C-2, C-3 V-3, H-5,) the rehabilitation tended to have downstream effects. Some sites had both local and downstream effects (H-3, H-4, V-2).

Conclusions

Hydrology

Some aspects of hydrology cannot be addressed by the model and must be addressed in other ways. The influence of tributary creeks cannot be specifically gauged using this particular meander migration model. Therefore some assumptions and subjective judgments have to be made about their influence on the tendencies for channel migration. It is likely in the case of H-1 that there will be some northward migration due to the flow from Canyon Creek that cannot be overtly predicted by the model. Similarly, Conner Creek would likely tend to push northwest on the channel at the downstream end of C-1. However, the extent of influence cannot be measured as it depends on tributary conditions that are not modeled.

The model uses cumulative effective streampower as a measure of erosion capacity. Streampower captures duration, frequency and magnitude of flows which in turn can give a good estimate of which flows will have the greatest geomorphic influence. It is important to note that ROD flows increase the duration of higher flows into the spring to mimic the spring snow melt. They will not be adding to the peak flood stage.

Meander Migration Magnitude and Pattern

The meander migration model was used to assess the potential relationship between the rehabilitation action and the resulting change in the rate of meander migration at the study bend sites. The area reworked indicates the overall ecological benefit of proposed adjustments to the flow regime and floodplain. Meander migration rates are non-dimensionalized by channel length, and give the relative dynamism between sites. They can be used to compare dynamism of large and small sites in way that focuses on the channel dynamics and not on the overall areal extent of the benefit. The ROD flows do not significantly increase the overall lateral bank migration at these particular sites because the change in annual streampower between scenarios is small.

Effect of rehabilitation grouped by migration and rehabilitation pattern

Although in close proximity, the rehabilitation sites discussed here do not share the same conditions and therefore were calibrated individually. Similarly, site-specific differences explain differences in channel dynamics.

At Hocker Flat there was historic channel movement that is typical of a meandering river system. Therefore the calibration at Hocker Flat was fairly precise as it is one of the most alluvial sections of the river, whereas other bends are more geologically controlled. The channel migration tendency of the river appears to match the pattern of the rehabilitation in about 1/3 of the site. Where the river does not match the pattern, there will likely be inundation in the rehabilitated floodplain and subsequent willow recruitment.

Near H-1 the rehabilitation design calls for the river to take on a meandering sequence with a small rock outcrop on the outside bend acting to redirect the flow toward the opposite bank into a sequence of alternate bars in H-2. However, the numerical model operates at the scale of river wavelength, and rock outcroppings may be acting at scales smaller than the river is moving and that are modeled. The model suggests that the rock outcrop will not have an effect on river meander dynamics.

Limitations

The Trinity River is not predominately a classical meandering river but is bedrock controlled in many areas leading to significant lateral restraint; however, there are local areas that migrate laterally. It is in these areas that the model helps to assess the potential effects of rehabilitation. Yet even in these areas the current and potential dynamics are complicated and are not all related to the meandering tendencies of the river. Although we have used a model that is primarily designed for an actively migrating alluvial channel, it is necessary to be careful in applying an alluvial floodplain model only in alluvial floodplain areas.

Observations

- The planform diagrams of future scenarios and tables derived from the meander migration simulations can be used to quantitatively assess the effectiveness of the rehabilitation in increasing lateral channel migration.
- Erosion tendency will not go toward the infrastructure in the area near Elkhorn.
- Where the predicted migration overlaps/coincides with the rehabilitation sites and there is no restraint to migration on the outside of the bend, it indicates that those sites have strong potential for lateral channel migration on the outside of the bend

and associated deposition of point bars (i.e. young floodplains) on the inside of the bends.

- Where predicted migration does not coincide with rehabilitated sites, rehabilitation efforts would at best meet other goals, rather than allowing for bank migration and floodplain deposition. The rehabilitation or scouring of land allows or encourages some lateral bank migration even if it is not in the direction or overlapping the scoured areas. In most of the sites, the mechanical rehabilitation occurs on the floodplain on the inside of the bend, thereby not encouraging direct channel migration on the outside bend.

Acknowledgements

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