MODELING MEANDER MIGRATION FOR ASSESSING IMPACTS AND BENEFITS OF CHANNEL MANAGEMENT SCENARIOS, MIDDLE SACRAMENTO RIVER, CALIFORNIA

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OVERVIEW

The Sacramento River Bank Protection Project Interagency Working Group (SRBPP IWG) is in a pivotal planning position to help with integrated long term plans for the future of the SRBPP. Future plans would benefit from having informed quantitative methods that can be used to assess impacts and benefits of different possible management scenarios. In order to compare different scenarios, one must first determine 1) what examples are to be compared, and 2) what methods are to be used to compare examples.

One method of comparison is to use a "baseline" as the standard against which alternative scenarios are compared. Starting with the baseline, quantitative methods are necessary to evaluate alternative scenarios compared to the baseline. The quantitative methods presented in this report provide one means for this "comparison with baseline" conceptual approach.

First, a **baseline** serves as the "gold standard" against which all other scenarios are compared. Because effective planning requires effective methods of evaluating possible scenarios, a well-defined quantifiable baseline provides a target to which alternatives may be compared.

Second, to evaluate the alternative scenarios, repeatable quantitative measures are useful. In this report, **quantitative measures** of river channel **meander migration** and **floodplain area reworked** are used to represent potential ecosystem impacts and benefits. Based on the meander migration patterns and the resulting area reworked, bank swallow habitat and vegetation establishment may also be modeled. Therefore the three quantitative metrics that can be directly derived from meander migration modeling are 1) area reworked, 2) bank swallow habitat, and 3) vegetation establishment patterns.

The Sacramento River Bank Protection Project considers site-specific project sites. What is important to consider is that these sites are located in a larger ecological system. In the case of meander migration, local changes to the river channel configuration will not only have local impacts, but will also have upstream and downstream impacts. The methods described in this report can be used to evaluate larger system implications of local management actions. In addition, meander migration modeling provides for a "**dynamic baseline**" rather than a static one. That is to say that migration modeling can provide what the river patterns would be in the future if conditions were not altered, against which, river patterns with altered conditions may be compared.

The cutoff simulation at RM 172 is of special interest because it provides an alternative management solution to continued repairs on the outside of the bend in question. The cutoff alternative is likely to provide more ecological benefit, and to be less expensive than "fixing" the bank.

In this study, the meander migration model was used to forecast bank swallow habitat at a single location on the river, RM 182. Based on ecological studies of bank swallow habitat characteristics, the "bank swallow" component of the meander migration model forecasts the quantity of good, medium and poor habitat for a simulated hydrograph of yearly flows decades into the future. This prototype shows how the meander migration model may be used in coordination with the bank swallow habitat model to evaluate the impacts and benefits of different bank management actions. Additionally, a "bank shear stress model," performed at the

RM 85 site, which provides a quick and easy method to illustrate the stresses on the existing levees, has potential utility for stakeholder communication and discussion.

The meander migration modeling can also be usefully coordinated with other types of models. For example, the meander migration model has recently been used as an integrated component of the USACE Standard Assessment Methodology (SAM). In addition, it would be valuable to simultaneously use USACE HEC-EFM with the meander migration (with riparian vegetation establishment and bank swallow habitat components) to evaluate different metrics for the impacts to the same site. One method would be to establish baseline (ideal) conditions, to which different management scenarios can be compared utilizing the different metrics that are available in each different model.

EXECUTIVE SUMMARY

This technical report describes a meander migration model applied to evaluating the impacts and benefits of different channel management scenarios on five selected sites of the Sacramento River. This report also interprets model results by quantifying the area of land reworked, and explores implications of the model results for channel management of the Sacramento River.

This study was guided by the Sacramento River Bank Protection Project Interagency Work Group (SRBBP IWG) with funding from the US Army Engineer Research and Development Center (ERDC). Key objectives of this study were to (1) select sites along the Sacramento River that would represent a range of possible management options, (2) apply the meander migration model to the sites selected by SRBBP IWG and, (3) evaluate channel migration patterns resulting from different management actions. This report documents the work done to accomplish the modeling tasks and the results of those tasks.

A total of twelve different scenarios were modeled distributed among the five different river segments. Model scenarios included various bank revetment scenarios (with existing revetment and with selected revetment removed) a prototype of a bank swallow habitat model, and, in one case, a simulated cutoff. The modeled migration was performed for fifty years into the future (except in the bank swallow and cutoff scenarios). Future flow conditions were assumed to be similar to the current flow regime.

There was one simulated cutoff, near River Mile (RM) 172, which resulted from simulating over-bank flows. The cutoff simulation is of interest because it is a viable alternative, which would provide substantial ecological benefit, and may be less expensive, to continuing to repair the erosion occurring on the outside of the bend in this location.

Historical data were used to test the feasibility of a bank swallow model. Observed data at RM 182 were then used to develop a model for bank swallow habitat which incorporates the rate of meander migration. The model was then checked by comparison with other observed data and shown to produce good results. As a prototype test, a scenario was modeled into the future to predict potential habitat quality.

A metric was defined which quantifies the land that is reworked by meander migration, and is called “area reworked.” One task of the study was to determine the magnitude of changes in the area reworked attributable to various management scenarios. The area reworked was calculated for each different scenario, and comparisons revealed differences in scenario results.

The ability to quantify the area reworked due to different revetment management actions provides a quantitative method to compare the impacts and benefits of these different river management scenarios. This ability provides one quantitative measurement in considering different management schemes. This will aid in considering trade-offs or mitigation for revetment changes proposed on the river. The area reworked also is an indication of the riparian vegetation benefits and impacts, and can be used, in coordination with a vegetation establishment model, to quantify the recruitment and succession of various riparian species.

At RM 212, the Kopta Slough site, the modeling shows that the “avulsion scenario” achieves over twice as much area reworked as the current conditions with restraint. It is expected that the avulsion scenario over longer time periods would show even more area reworked per year

because it begins as a lower sinuosity channel, and as the sinuosity increases, the migration rate will increase.

At RM 191 there are two scenarios that are important to compare. One has two different bank restraints removed; the other has only one of the two bank restraints removed. Both have very similar resulting area reworked. This suggests that a management action with only one location of bank restraint removed would get almost as much benefit as the scenario with two removed.

At RM 182, which is the bank swallow model prototype site, quantities of bank swallow habitat were predicted 40 years into the future, and suitable habitat was ranked as good, intermediate, and poor. This test modeling of bank swallow habitat is a pioneering approach in utilizing river meander migration modeling to model the potential habitat for bank swallows, and has major implications for use in considering management related to bank restraints.

At RM 172L (a USACE rock repair site) the modeling exercise shows an alternative method to rocking the bank, which is currently described as needing repair. The cutoff not only solves the problem of the pressure on the bank, but it also allows for ecosystem regeneration through floodplain creation and reworking. The analysis also shows the quantity of floodplain regenerated by this method. The yearly rate of floodplain regeneration would also increase beyond the years of the simulated model because the sinuosity of the channel would increase.

At the RM 80-85 Segment (USACE fish studies site) two models of different management actions, and a third, which is a prototype “bank shear stress” model, were performed. The management actions are currently conceptual. First, a 50 year scenario with the north levee removed showed three main areas of potential dynamic channel migration. A second scenario where a new channel was established across the floodplain, with 50 years of migration, provides an example of a management action that would reintroduce natural processes of floodplain creation. Other ecosystem processes that would be reintroduced include dynamic channel migration, creation of new floodplain surfaces, habitat for heterogeneous age vegetation establishment, floodplain overbank flows (providing habitat for fish,) and potential bank swallow habitat. Finally, a “bank shear stress model” provides a quick and easy method to estimate and illustrate the stresses on the existing levees, using the meander migration model. This methodology has potential utility for increasing stakeholder understanding, communication, and discussion.

1.0 INTRODUCTION

Large alluvial rivers have a tendency to migrate laterally over time. Meander migration, consisting of bank erosion on the outside bank of curved channels and point bar and flood plain building on the inside bank, is a key process for many important ecosystem functions (Malanson 1993). Examples include 1) vegetative establishment for the riparian forest, 2) floodplain creation through progressive meander migration, 3) habitat creation (i.e., bank erosion for swallow habitat), and 4) the creation of off-channel habitats (e.g., oxbow lakes, side channels, and sloughs) by progressive migration and cutoff processes.

The meander migration process is a function of flow, channel form, and bank characteristics. All of these have been altered on the Sacramento River, through the construction of Shasta Dam, channel restraints like revetment and levees, and the land-use changes like the transition from riparian forest to agricultural lands. To develop effective strategies for channel management (like bank constraint) while considering possible conservation and restoration of key ecosystem functions, it is key to understand the role that meander migration plays in these functions. Furthermore, it is critical to understand how the changes channel form and bank erosion characteristics will alter the physical processes of channel migration.

This study is a component of a study for the US Army Corps of Engineers, which is being led by the Sacramento River Bank Protection Project Interagency Work Group (SRBBP IWG) with funding from the US Army Engineer Research and Development Center ERDC. Key objectives of this study were to (1) select sites along the Sacramento River that represent a range of possible management options, (2) apply the meander migration model to the sites selected by SRBBP IWG and, (3) evaluate channel migration patterns resulting from different management actions. This report documents work done to accomplish the modeling tasks and the results of those tasks. The meander migration study is one of several efforts to address project goals by documenting how ecological functions are related to different management actions.

The meander migration study in particular was designed to satisfy three main objectives:

Objective 1. Choose sites which represent a range of management actions
Objective 2. Apply the meander migration model to the sites selected by SRBBP IWG
Objective 3. Evaluate channel migration patterns resulting from management actions (bank protection management at key sites)

Through previous research efforts, a predictive meander migration model has been developed and applied to segments of the Sacramento River. The model calculates channel migration using a simplified form of equations for fluid flow and sediment transport developed by (Johannesson and Parker 1989)

Study Area: River Segments Modeled

This section describes the locations of the Sacramento River where the meander migration model was applied. The choice of locations was based in part on discussions with members of the SRBPP IWG, which includes representatives of the US Fish and Wildlife Service (USFWS), the California Department of Fish and Game (DFG), the California Department of Water Resources (CDWR), USACE, and others. The team decided to model migration with different management scenarios from RM (River Mile) 84 to RM 222.

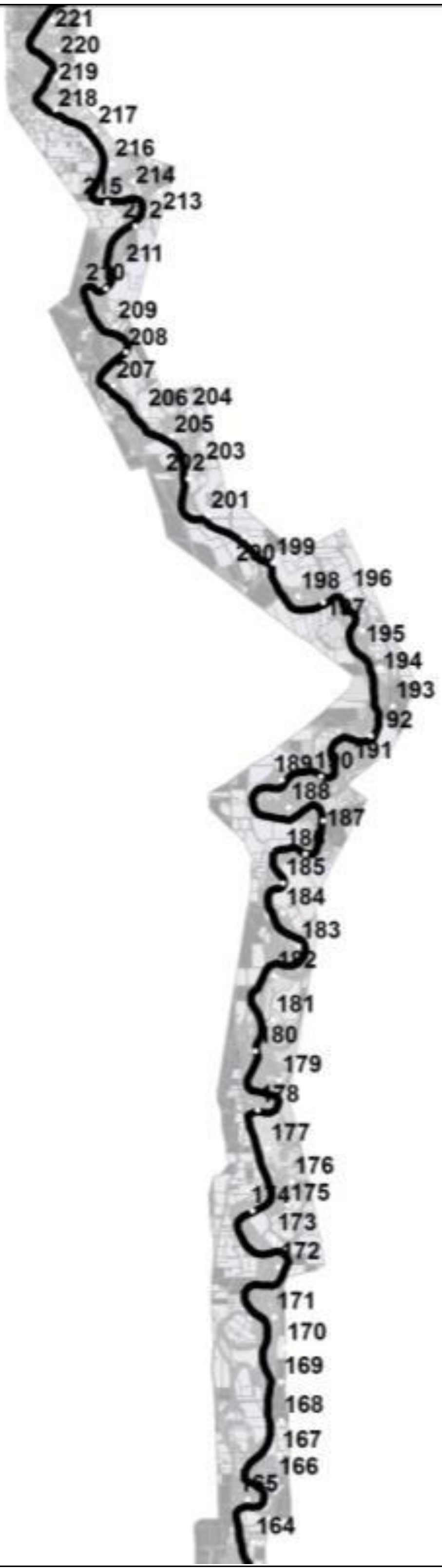

Figure 1 Middle Sacramento River Study (Upper segments not including RM 84)

RM 219-221 Kopta Slough Segment

This segment is near Woodson Bridge State Recreation Area, which is an area of interest for protecting portions of the riparian forest in the Recreation Area. Management actions which can influence protecting the riparian forest were modeled. Three modeling scenarios were performed.

1. A no action alternative, simulated 50 years into the future (with existing infrastructure/conditions).
2. A rock removal scenario, with rock removed on river right upstream, other existing rock/palisades accounted for, and new rock around the bridge abutment simulated 50 years.
3. A constructed channel scenario that reconnects Kopta slough simulated 50 years. We have used the constructed channel alignment in the hydraulic modeling as a surrogate for the river having cut-off on its own.

RM 191-192 Phelan Island Segment

Based on recommendations from the SRBPP Working Group, three scenarios were chosen to be modeled.

1. A no action alternative, simulated 50 years into the future (with existing infrastructure/conditions).
2. A rock removal scenario, with rock removed at two locations simulated 50 years.
3. A rock removal scenario, with rock removed at only one location simulated 50 years.

RM 182 Bank Swallow Site

River Mile 182 was chosen based on the availability of historic data relating to bank swallow populations.

1. First, a historical study was performed in which observed data at RM 182 were used to develop a model, which includes the rate of meander migration, for bank swallow habitat.
2. The model was then checked by comparison with data and shown to produce good results.
3. As a prototype test, a scenario was modeled into the future to predict potential habitat quality at this site 40 years into the future.

RM 172L Segment (USACE rock repair site)

This location was chosen because there is pressure on the outside of the bend, and repairs are suggested.

1. A no action alternative, 50 years into the future (with existing infrastructure/conditions).
2. A levee set-back scenario 50 years into the future
3. A simulated cutoff scenario, with cutoff occurring 20 years into the future, and 50 years of subsequent migration after that.

RM 80-85 Segment (USACE fish studies site)

1. A scenario at 50 years into the future with the north levee removed.
2. A channel realignment scenario where a new channel was established across the floodplain, and 50 year migration into the future is modeled.

3. A prototype “bank stress mapping” that uses the meander migration model to indicate areas of relative bank stress.

2.0 METHODS

2.1 Fundamental Principles and Assumptions

The model has been developed and used extensively on the Sacramento River (Larsen, Schladow et al. 1997, Larsen and Greco 2002, Golet, Roberts et al. 2004, Larsen 2004, Micheli, Kirchner et al. 2004, Larsen 2005, Larsen 2006, Larsen, Girvetz et al. 2006, Larsen, Girvetz et al. 2007, Micheli and Larsen 2011). This section describes the assumptions and relationships used in the erosion field of the model (e.g., the combination of soil and vegetative cover information into a spatial field representing the erosion potential).

Heterogeneous Erodibility Surface
A heterogeneous erosion surface was created using the geographic information system (GIS) ArcGIS and imported into the river meander migration model. The erodibility surface is developed by spatially combining a GIS dataset of geology with a GIS dataset of landcover, as described below.

Values in the merged dataset represent erodibility potential based on both land cover and geologic data. This dataset, or erodibility surface, is then imported into the migration model with areas of natural vegetation being given one value of erodibility, while agricultural lands are given another value, and geologically constrained areas were given a value of zero. These values are consistent with erosion rates observed on the Sacramento River (Larsen and Greco 2002, Micheli, Kirchner et al. 2004).

2.2 Model Calibration

To calibrate the erodibility coefficient to observed conditions, simulations require a calibration process that employs a heterogeneous bank erodibility surface. The calibration period for this study used historic channel position data and flow records primarily from 1952 and 1976 (post dam and pre major channel constraints). Model parameters were adjusted until model erosions rates matched the observed erosion rates between these time periods. The same parameters were then used for each model run of each scenario

Calibration: Data Input
Hydraulic input parameters are given in Table 1 and bed sediment parameter are given in Table 2. Hydraulic values were taken from HEC-RAS runs for the Sacramento River from the USACOE and a California Department of Water Resources (CDWR) study (USACE 2002). Averages taken from every quarter mile of the HEC RAS output were developed for the following river segments: 201-222 (WB or Woodson Bridge), 185 to 201 (HC or Hamilton City), and 170 to 185 (OF or Ord Ferry), and were then applied to the selected sites within those reaches. The data for river Mile 85 were estimated from data from DWR (Pers. Comm).

Table 1 Hydrologic and channel input values for migration model

River Segment	Q Channel (cms)	E. Gl Slope m/m	Top Width Chan (m)	Hydr Depth (m)
WB	2200	0.00045	218	5.01
HC	2181	0.00033	232	5.07
OF	2180	0.0003	277	4.91
RM 85	800	0.00008	90	7.00

D_{50} or median particle size of the bed surface material (Table 2) was taken from an analysis of two sources: (Water Engineering and Technology 1988) and unpublished data from Singer (Singer In preparation). For RM 85, the values were set to 18 mm. Although this is a crude estimate, the model output is not sensitive to bed particle size in a way that would change the pattern of the results for this study.

Table 2 D50 particle size of the bed surface material

Particle sizes (mm) D_{50}					
		RM 170-185	RM 185-201	RM 201-222	RM 85
Singer		18	20	25	NA
WETS/DWR		16	20	26	NA
Used in this study		18	20	25	18

The output of the migration model depends on local hydraulic conditions through the hydraulic and geomorphic input variables, as well as the empirically determined erosion coefficient. In addition, the model uses calibrated values to conceptually simulate cutoff processes (Avery, Micheli et al. 2003). To calibrate the model at most of the sites, the channel planform centerlines from 1952 and 1976 were used, 2 years for which centerlines could be accurately delineated from digitized aerial photos, and a time period during which the existing bank restraints were minimum or relatively easy to identify. The calibration process consists of adjusting the erosion, hydraulic, and cutoff parameters in the meander migration model until the simulated migration from 1952 to 1976 closely matches the observed migration during the same time period. The erosion potential field is thus altered by calibrating the migration between the two time periods. The regions outside the calibration are assigned erosion potentials based on the land-cover type from the GIS coverage. For example, if a riparian area in the calibrated area had a calibrated value of 250, the riparian areas in the GIS coverage were also assigned this value. In addition, the values for different land cover types established in the calibration were subsequently used for predictions.

Cutoff Simulation

A cutoff simulation was used at the RM 172 site to account for bend cutoff due to high flows during large storms. Cutoffs can be simulated by an automated routine in the meander migration code. Individual bends were delineated by first calculating the local curvature along the centerline at points spaced approximately a half-channel width apart, using an algorithm to calculate local curvature (Johannesson and Parker 1985). A change in the sign of the curvature is an inflection point and can indicate a new bend. To account for small changes in the direction of curvature for a compound bend, the moving average of curvature for each point was calculated as the mean of the five adjacent upstream and downstream points. Starting from upstream, points were designated as part of a single bend until five consecutive points occur with the moving average of curvature in the opposite direction. These five points are considered the beginning of the next bend. All subsequent points are designated as part of this bend until five points in a row with a curvature in the opposite direction occur. These, in turn, constitute the beginning of the next bend. This procedure was repeated until all bends were identified and assigned a number. Bends were re-delineated each year after the channel centerline was moved by the meander migration model.

To automatically model the cutoff, the discrete single bend is analyzed for sinuosity to determine the cutoff potentials. The sinuosity of the bend is calculated by dividing the distance along the channel for a bend by the straight-line distance between the start and end points of the bend. A sinuosity threshold at which the bend was allowed to cut off is estimated based on calibration and from considering previous studies (Avery, Micheli et al. 2003). The starting point of the cutoff is located at a calibrated distance (typically one-quarter of the bend upstream from the cutoff bend) and the ending point is established from calibration (e.g.: 10% along the length of the downstream bend.) Finally, the cutoff is simulated only if the straight line between the start and end points do not include revetment, levees, or geologic constraints to erosion. If the cutoff conditions are met, the river channel centerline points of the cutoff bend are simulated in a straight line between the start and end points.

In addition to the automated procedure, cutoff potential can be estimated and then simulated using a “most probable path” method, which utilizes digital terrain information if it is available. GIS methods are used to estimate the lowest areas in the potential cutoff region, which are often formed by overbank flows.

In this study, both methods were executed, and the most probable path was chosen as the best for simulation.

Channel Centerlines

Channel banklines for calibration were taken from Greco and Alford (2003). These banklines were drawn from aerial photos for the years of calibration. From these, centerlines were drawn down the center of the banklines. For a full description of channel bankline drawing see Greco and Alford (2003).

In most of the calibrations, calibration was done using centerlines for 1952 and 1976. Predictions were done starting with a centerline from 2010. The 2010 centerline was developed from bankline drawings by CDWR (CDWR, Henderson, Personal communication, 2012).

All centerlines were projected in UTM NAD 83 Zone 10 projections for use in GIS analysis.

Heterogeneous Erodibility Surface

A heterogeneous erosion surface, which was used in conjunction with model calibration, was developed by spatially combining GIS datasets of geology, vegetation cover and revetment. All datasets were converted to a 30 meter grid based on erodibility potential. The final erosion values were developed by a calibration process using these data sets. This GIS grid was exported as an ASCII text file and imported into the meander migration MATLAB program and used in conjunction with model calibration.

Geology Coverage

The geology dataset used for creating a heterogeneous land erodibility surface was obtained from the California Department of Water Resources (CDWR 1995). All geology surface types shown on those geology coverages are assumed to be erodible, except for Q_r (Riverbank formation), Q_m (Modesto formation), and Q_{oc} (Old channel deposits) which represent non-erodible areas based on their soil properties; these are sometimes called areas of geologic constraint. An example is shown in Figure 2.

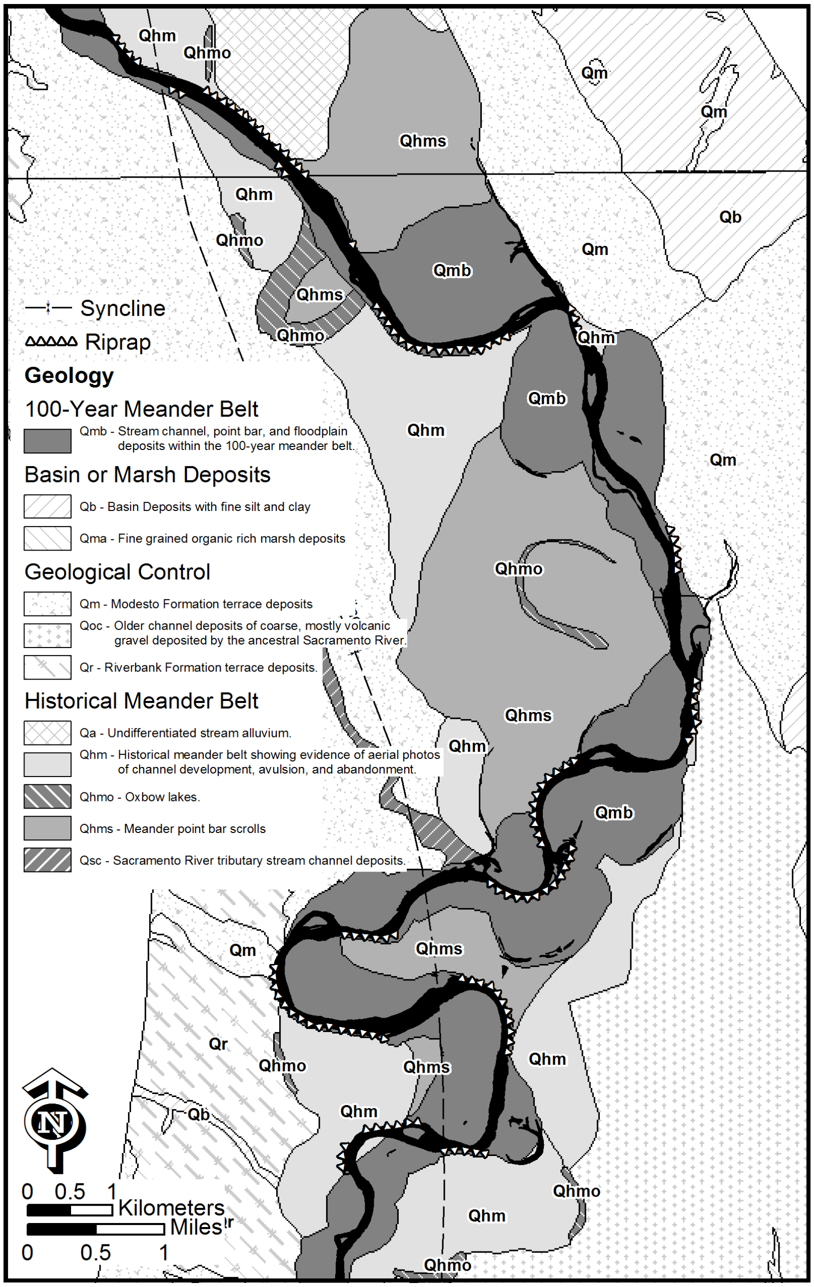

Figure 2 Geology (soils) coverage map (from Larsen et al. 2006c)

Vegetation Coverages

The vegetation dataset, used to distinguish between agricultural and riparian land cover, was derived from aerial photography taken in 1997 (Greco and Alford 2003). For the 1952 coverages, maps from CDWR/McGill were used to digitize vegetation surfaces where the map data were available. Based on the process of calibration, areas of natural vegetation were assigned an erosion potential (Fd in the code) of 250 · 10-8, and agricultural lands were given a value of 85 · 10-8. An example of the Greco and Alford data is shown in Figure 3.

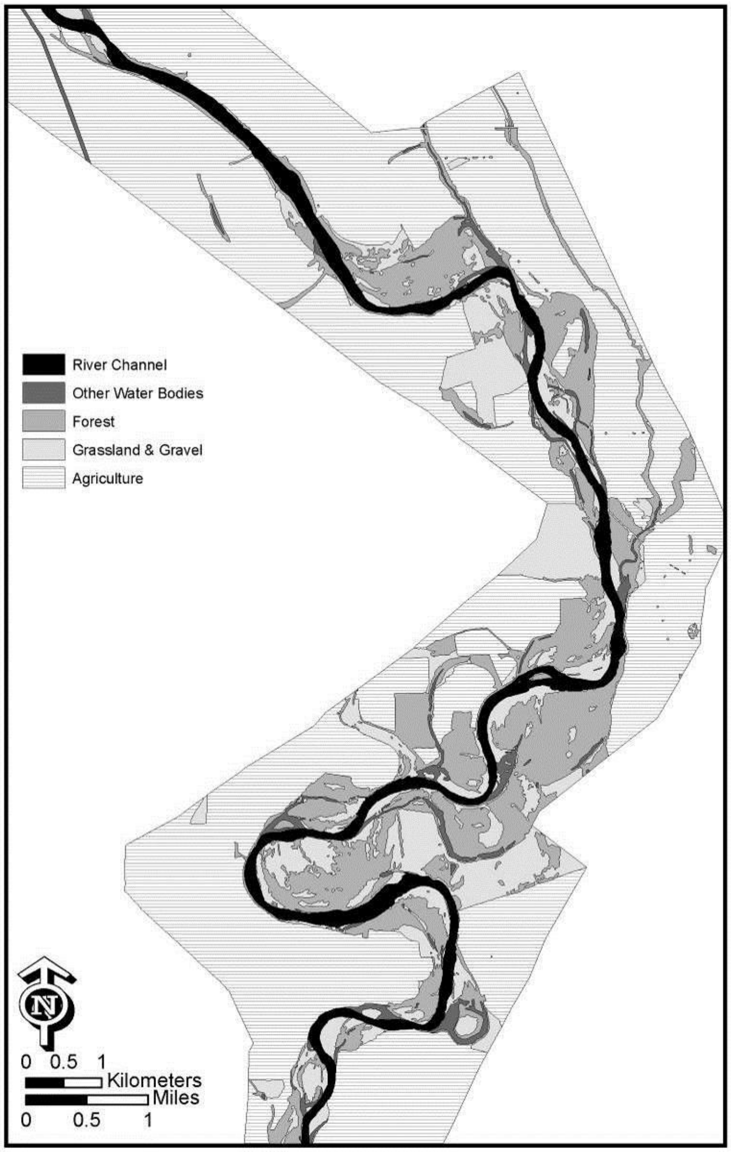

Figure 3 Land classification coverage map (Larsen et al. 2006c)

Revetment Coverages

The effect of revetment was simulated by modifying the erosion potential grid, using a GIS revetment dataset from the CDWR (CDWR, Henderson, Personal communication, 2012). The revetment was buffered and combined with the erosion potential grid (Environmental Systems Research Institute 2010); areas within the buffered revetment were given an erosion potential value of zero (i.e., non-erodible). Three different revetment scenarios were developed: 1976 revetment; 2010 existing revetment; and 2010 existing revetment with site-specific revetment removal at selected sites. Sites where revetment removal was modeled are located on bends that were chosen by the SRBPP IWG. Nonetheless, further analyses and additional stakeholder and agency input would be required before any such projects were initiated.

Calibrations: Centerline Agreement

RM 219-221 Kopta Slough Segment

For the calibration run from 1953 to 1976 in the Kopta Slough segment, there were locations that were restrained with reported revetment (Figure 4) at some time within this time period. The revetment is shown by a dashed black and white line. None of these were given dates in the revetment database provided by CDWR (Henderson 2006). The dates were inferred from observing channel movement from historic centerlines. These were incorporated into the heterogeneous erosion field and were set as non-erodible.

For the predictions with existing revetment, from 2010-2060, the key revetment locations were determined from data from DWR (Henderson, Pers. Com. 2012). Calibration in the Kopta Slough segment (Figure 4) was performed starting with the observed 1953 and 1976 channel centerlines. The blue line is the 1953 observed channel centerline; the yellow line is the 1976 observed channel centerline; the red line is the 1976 modeled channel centerline. The agreement between the observed and simulated 1976 channel was good. Although statistical methods could be used to access calibration agreement with observed migration, those methods can “force” agreement in areas where migration patterns are not controlled by channel planform and internal hydraulics, but by other factors such as anthropogenic changes. Using a visual assessment has proven to be an effective means of calibration (Larsen and Greco 2002), (Larsen, Girvetz et al. 2006).

For prediction runs, the 2010 revetment coverage was used with the revetment at RM 220-222 (right bank) at Kopta Slough removed.

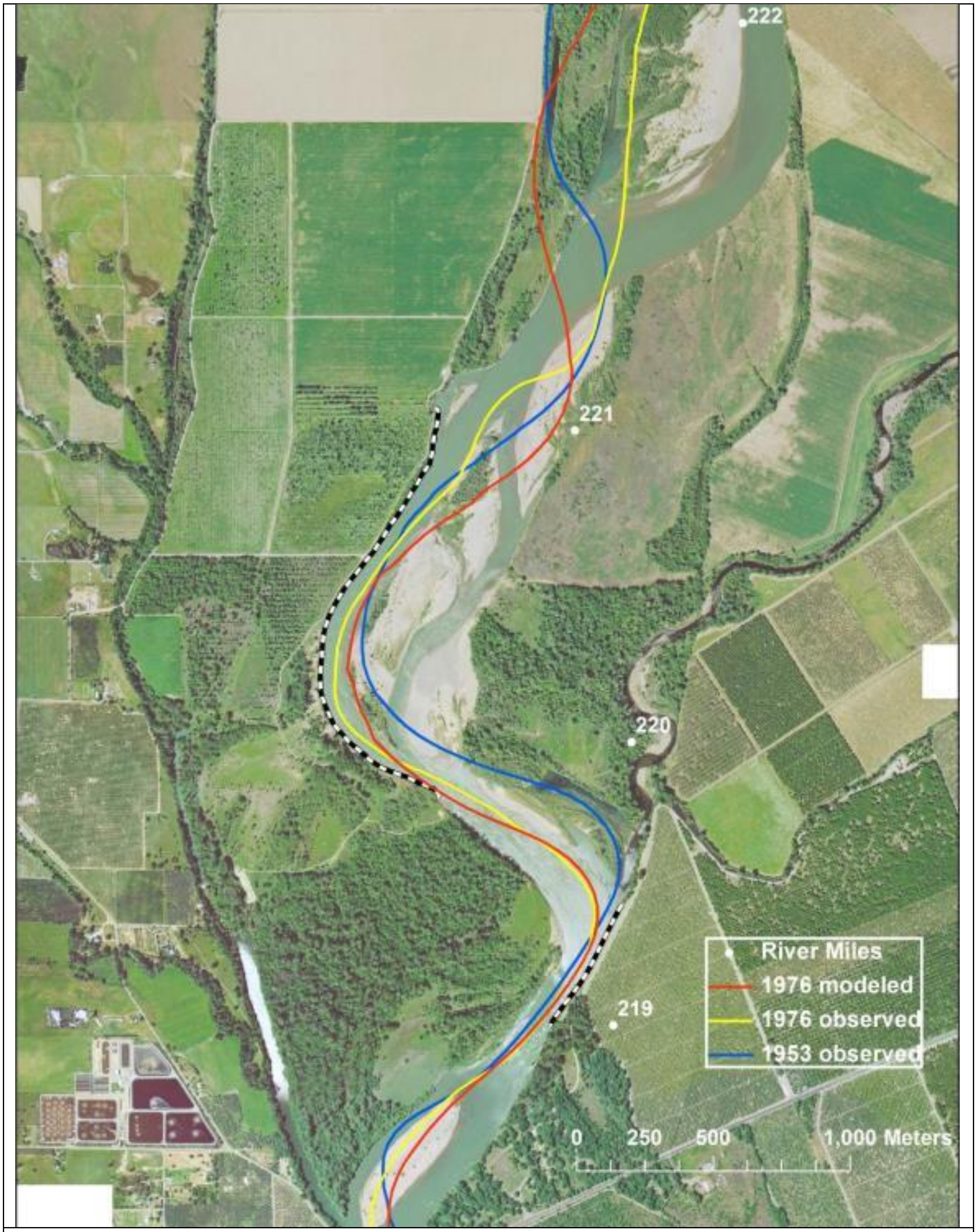

Figure 4 RM 219-221 Kopta Slough segment calibration 1953-1976

RM 191-192 Phelan Island Segment
Starting with the observed 1952 and 1976 channel centerlines at the Hamilton City segment, calibration was performed (Figure 5).

The blue line is the 1952 observed channel centerline; the yellow line is the 1976 observed channel centerline; the red line is the 1976 modeled channel centerline. The agreement between the observed and simulated 1976 channel is good in the vicinity of the area of concern. This is a key place for calibration agreement in order to simulate future migration as it is an area of freely migrating and fairly regular meander bends. Agreement in other areas was also good.

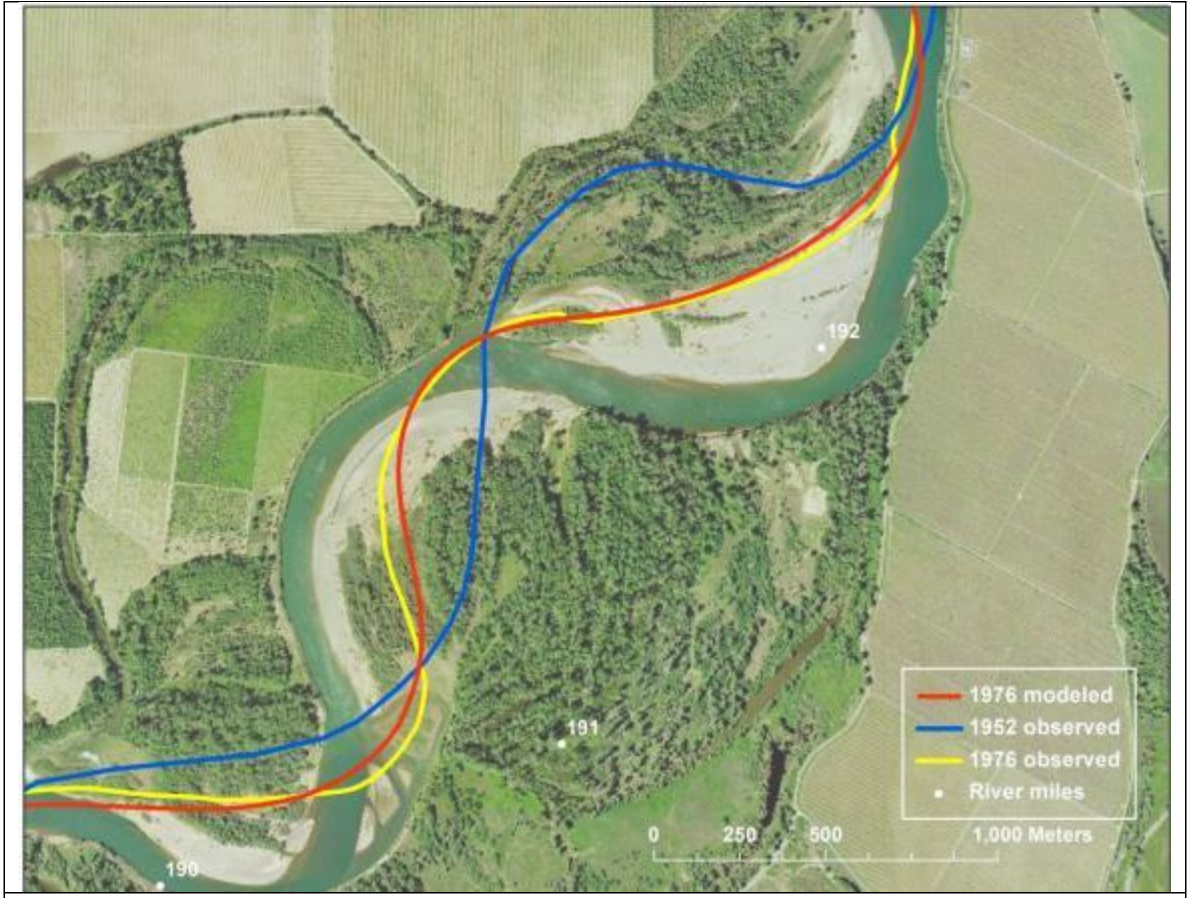

Figure 5 RM 191-192 Phelan Island segment calibration 1952-1976

RM 182 Bank Swallow Site

Because there was no revetment at this bend, more recent data were used for calibration (observed 1976 and 2004 channel centerlines) (Figure 6). The blue line is the 1976 observed channel centerline; the yellow line is the 2004 observed channel centerline; the red line is the 2004 modeled channel centerline. The agreement between the observed and simulated 2004 channel was visually assessed to be acceptable.

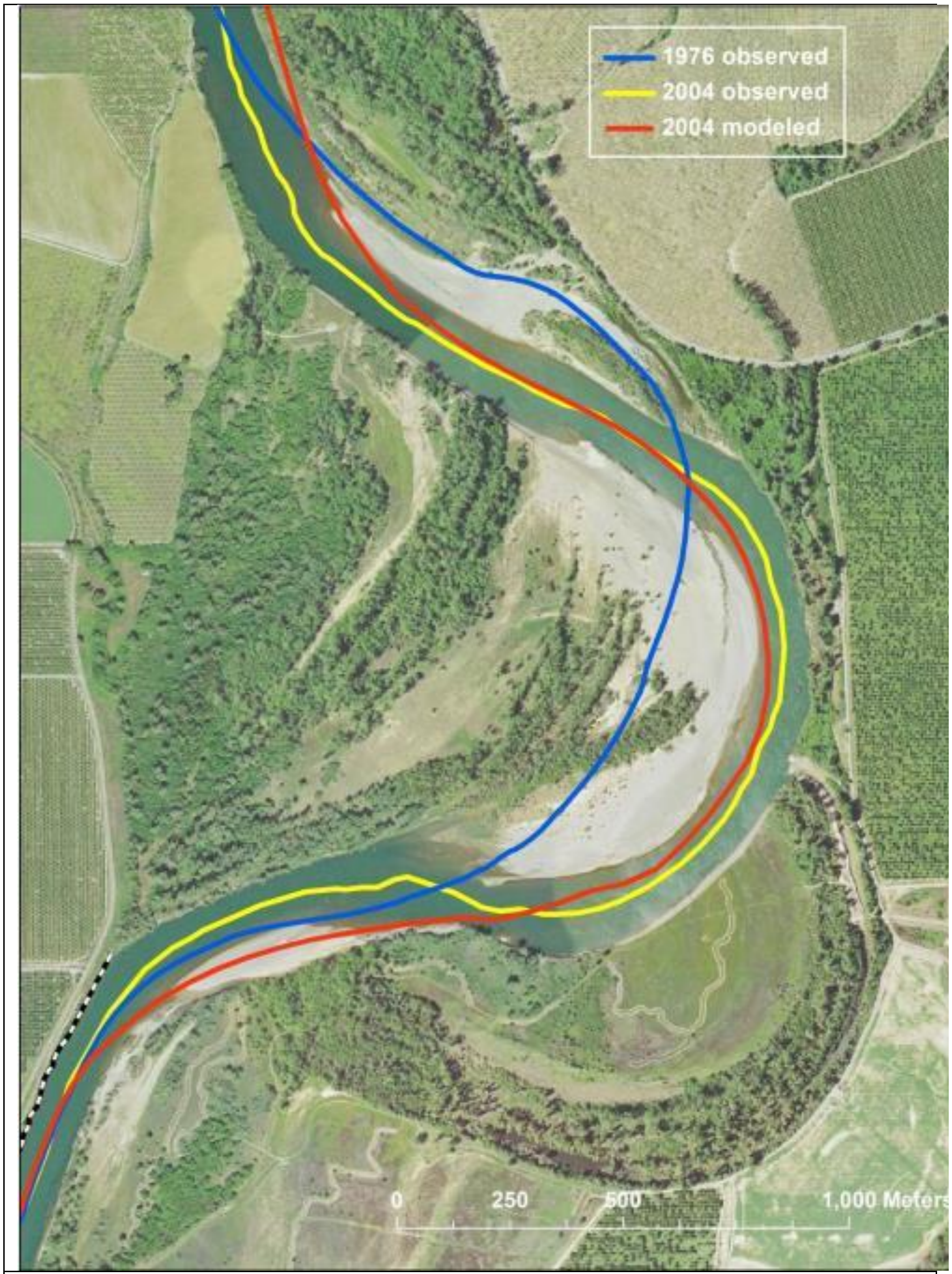

Figure 6 RM 182 Bank Swallow Site calibration

RM 172L Segment (USACE rock repair site)

As in the case for RM 182, there was no revetment at this bend, and more recent data were used for calibration (observed 1976 and 2004 channel centerlines) (Figure 7). The blue line is the 1976 observed channel centerline; the yellow line is the 2004 observed channel centerline; the red line is the 2004 modeled channel centerline. The agreement between the observed and simulated 2004 was visually assessed to be good.

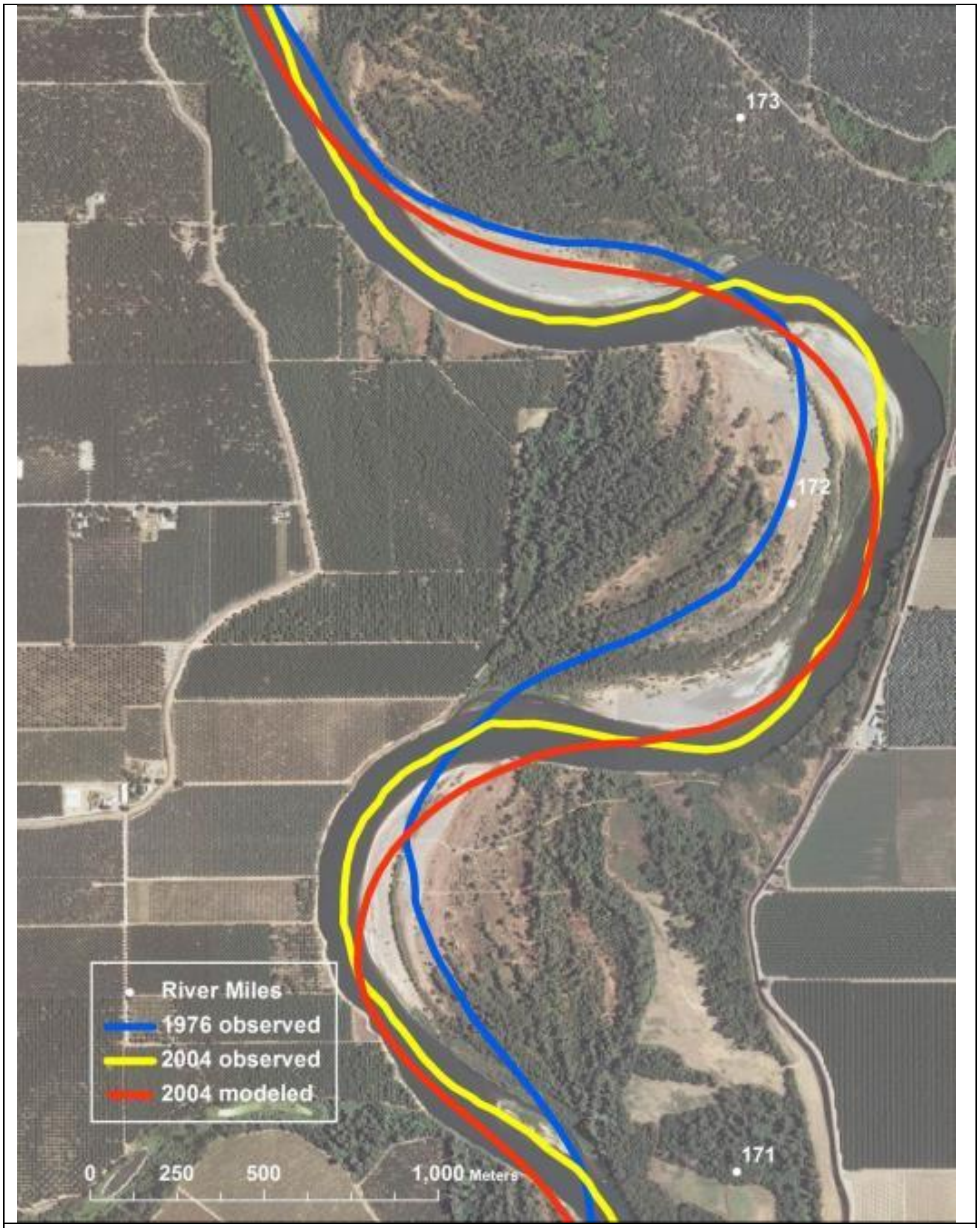

Figure 7 RM 172L Segment (USACE rock repair site) calibration

Cutoff calibration

The meander migration model has the capacity to model cutoffs in at least two ways. The first is based on a hydraulic and geomorphic analysis that matches cutoff occurrence to empirically derived quantities. The second method is to use a “cutoff potential path” derived from digital elevation information of the floodplain that exists between the two limbs of the bend (Figure 8). For this cutoff simulation, the second method was used based on the maps in Figure 8.

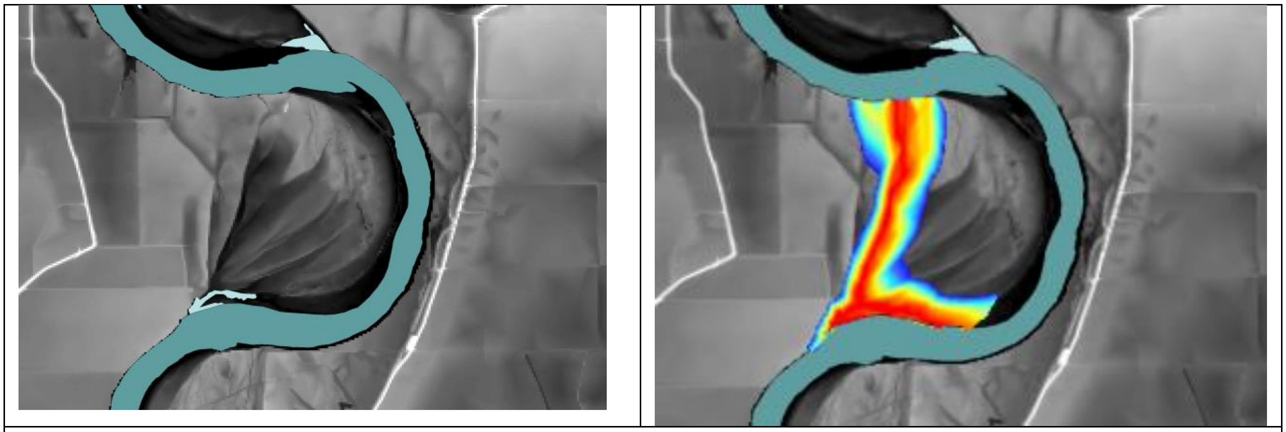

Figure 8 RM 172L Segment (USACE rock repair site) cutoff potential maps

RM 80-85 Segment (USACE fish studies site)
In this location, the channel has been constrained in recent times on both sides by near-bank levees. No channel migration is possible in this situation. Because of this, there is no recent historic data with which to calibrate, and channel migration was not calibrated with historic data. Estimates of bank erodibility were made based on the available data.

2.4 Modeling Scenarios

River Segments Modeled
The Sacramento River from RM 170 to RM 222 was divided into three contiguous segments, for modeling purposes. Four of the five sites fell within these three large segments. A separate segment was used for RM 85. A list of potential sites was provided to the SRBPP IWG by DWR, based on criteria developed by DWR (**Table 3**). From this list, three sites were chosen, and two additional sites were added.

Table 3 Potential revetment removal sites on the middle Sacramento River

POTENTIAL REVETMENT REMOVAL SITES ON THE MIDDLE SACRAMENTO RIVER

Site No.	Site Name	River Mile	Length (meters +/-)	Adjoining Landowner	Revetment Material	Description / Notes	Relevant Meander Analysis	Data Number on Google Earth File
1	La Barranca	240.5R	550	USFWS - La Barranca Unit, Sacramento River NWR	Medium rock	Lower 1/3 of a larger revetment area is adjacent to La Barranca Unit, removal would also take pressure of rock at 240L	A	Reach 2 - 981
2	Kopta Slough	220-222R	1775	State Controller's Trust (TNC is lessee)	Medium rock	Area is being converted to habitat, removal would help redirect erosion from State Recreation Area and County bridge, substantial planning work has occurred	A, B	Reach 2 - 5819
3	Rio Vista	216-217L	1425	USFWS - Rio Vista Unit, Sacramento River NWR	Large rock, privately installed	Rock was installed to protect agriculture, the area is now converted to habitat	A	Reach 2 - 1069, 1183, 4674
4	Brayton	197-198R	600	CDPR, Bidwell-Sac River St Park, Brayton property	Large rubble, privately installed	Rock was installed to protect agriculture, the area is planned to be converted to habitat, consider effect on the road to the east but geologic control should limit meander	A, C	Reach 2 - 2007
5	Phelan island	191-192R	1410	USFWS, Phelan Island Unit and Sac & San Joaquin Drainage Dist.	Medium rock, USACE installed in 1988	Area has been converted to habitat, consider possible Murphy's Slough cutoff / flood relief structure concerns	A, C, E	Reach 3 - 4626
6	Llano Seco Riparian Sanctuary	179R	1300	USFWS, Phelan Island Unit and Sac & San Joaquin Drainage District and small area of private property	Medium rock, USACE installed in 1985 & 87	Rock removal potential identified as part of Lano Seco Riparian Sanctuary planning project as part of a solution to fish screen concerns at Princeton, Codora/ Provident pumping plant at RM 178R	D	Reach 3 - 2805, 1422

Initial screening and review included staff from DWR Northern District, Sacramento River Conservation Area Forum and The Nature Conservancy

Criteria for Revetment Removal Identification

1. Revetment is adjacent to public or conservation ownership land
2. Revetment is not protecting important public infrastructure
3. Revetment removal does not create an obvious flood hazard
4. Revetment is currently limiting meander on lands in the historic meander belt
5. Revetment removal could result in ecosystem benefit: land reworking/creation of riparian habitat, creation of new bank swallow habitat, recruitment of spawning gravel, new shaded riverine aquatic habitat, etc.
5. Revetment removal could help direct meander to protect public infrastructure (if applicable)

Relevant Meander Analysis References

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B. Larsen, Eric, 2002. Modeling Channel Management Impacts on River Migration: A Case Study of Woodson Bridge state Recreation Area, Sacramento River, USA. University of California, Davis, Davis, California.
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D. Larsen, Eric, 2004. Meander Bend Migration near River Mile 178 of the Sacramento River. University of California, Davis, Davis, California.
E. Larsen, Eric, 2005. Future Meander Bend Migration and Floodplain Development Patterns near River Miles 200 to 191 of the Sacramento River. University of California, Davis, Davis, California.

2.5 Number of Scenario Runs

Table 4 Meander migration model scenarios

1	Kopta 220
	With existing restraint
	with restraint removed 2010 -2060
	with planned cutoff
2	Phelan Island 191
	with existing revetment
	with all revetment removed
	with revetment removed upstream
3	RM 182 bank swallow
	future migration 2004-2044
4	RM 172
	existing
	levee removed
	simulated cutoff
5	Rm 85
	north levee removed
	channel realignment
	“bank stress test”

Twelve different scenarios were modeled (Table 4). Calculation of area reworked was done for most of the scenarios, which were shown in bar graphs.

2.6 Area of land Reworked Defined

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 9). 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).

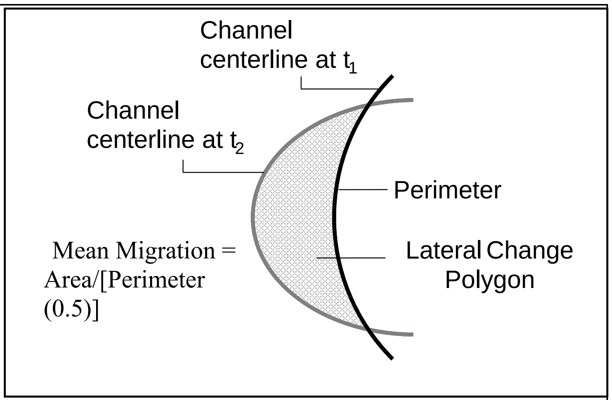


Figure 9 Definition of area reworked polygon

2.9 Limitations and Interpretation of Model Results

This section describes limitations of the meander migration model and caveats regarding the interpretation of expected model results.

Models and Simulations

As with other simulation models (e.g. (Dietrich, Wilson et al. 1993), (Sklar and Dietrich 2004)), the meander migration model is an effective tool to consider patterns of landscape evolution. All large-scale geomorphic models are simulations that estimate future conditions, but they are not intended for precise predictions of small scale site-specific land alterations. For example, one would not expect that a particular point on the landscape would experience *exactly* 15.7 meters (arbitrary example) of bank erosion at a precise spot in a prescribed time interval. Simulations may, however, indicate future patterns, for example, one could simulate that one scenario would result in 35% more land reworked (arbitrary example) than another scenario.

Tributary Influences

Although it has been suggested that bends at or just downstream from stream tributary confluences migrate faster due to sediment input (Constantine and Dunne 2008) analyses of stream power data do not show this pattern (Larsen, Fremier et al. 2006). In a study of bank erosion and stream power (Larsen, Fremier et al. 2006), areas with the highest mean average erosion rates were not found to be located near confluences near tributaries. For example, bank erosion data from RM 196-199, which had the highest rate of bank erosion in a bank erosion study, were measured just *upstream* from the confluence with Pine Creek. A bend near RM 191 is at the direct confluence with a tributary, yet it has not migrated significantly in the past 100 years. Although these data suggest that tributary inflow may not be a large influence on migration rate in some areas, the influence of tributaries is only implicitly modeled in the meander migration model, by means of calibration. Other patterns of migration, such as high migration rates where a bend occurs immediately downstream of long, straight, historically stable reach, are modeled explicitly by the model because they are primarily determined by the flow patterns related to the planform.

3.0 RESULTS AND DISCUSSION

3.1 Model Output

The basic model output consists of predictions of channel centerlines in yearly time steps, which are shown in this report as visual images superimposed on a single map (i.e. Figure 10). From these, area reworked has been calculated.

RM 201-222: RM 219-221 Kopta Slough Segment

Predictions with existing restraint

Three modeling scenarios were performed. The following figures show the channel migration from 2010-2060 in five-year increments.

1. A no action alternative, simulated 50 years into the future (with existing infrastructure/conditions). (Figure 10) For prediction runs, the 2010 revetment coverage was used.
2. A rock removal scenario, with rock removed on river right upstream, other existing rock/palisades accounted for, and new rock around the bridge abutment simulated 50 years. (Figure 11) In this case, the revetment was removed.
3. A constructed channel scenario that reconnects Kopta slough simulated 50 years. We have used the constructed channel alignment in the hydraulic modeling as a surrogate for the river having cut-off on its own.(Figure 12)

The area reworked was calculated in polygons where the channel shifted, and are shown on the maps in Figure 13, and in the table (Table 5).

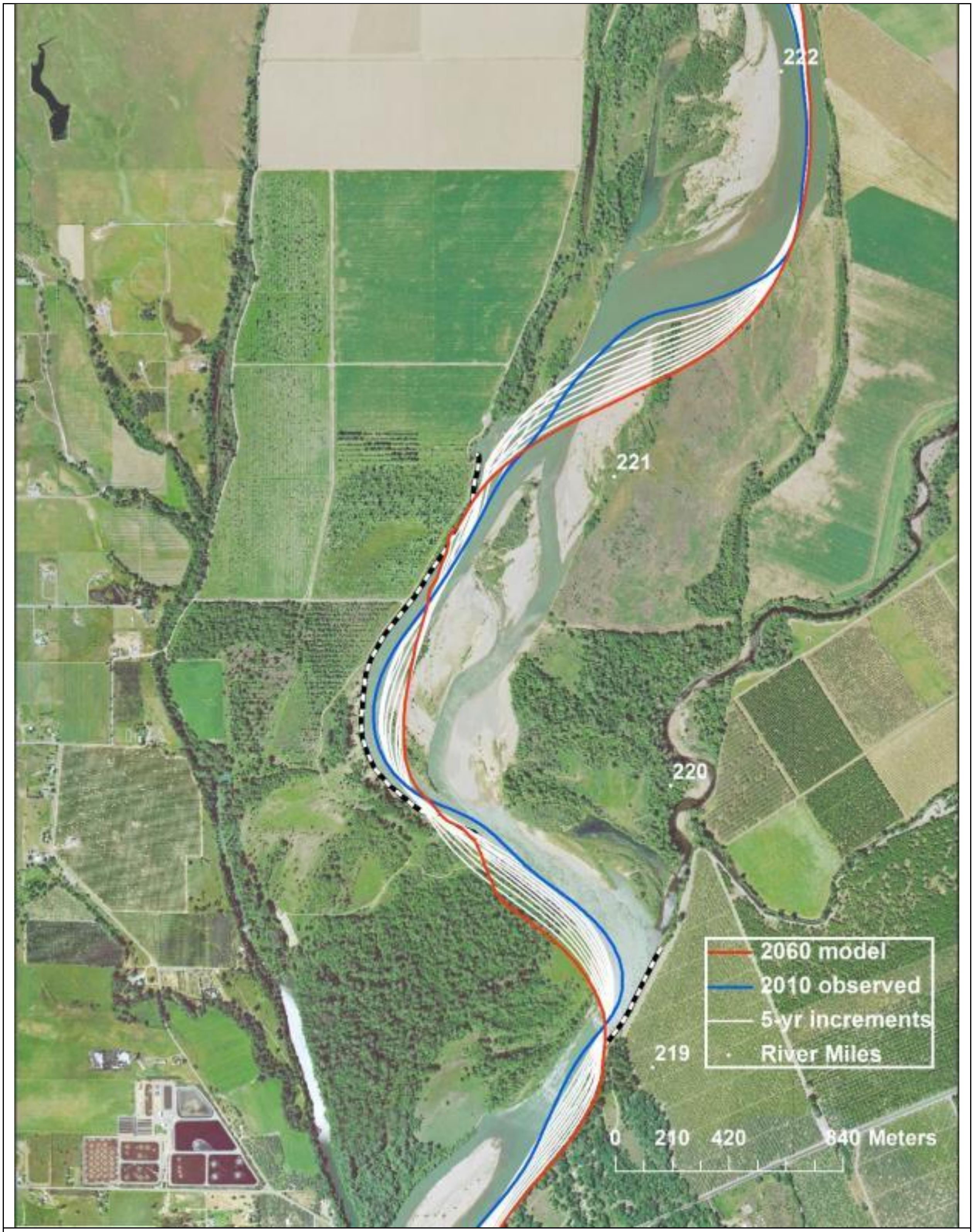


Figure 10 RM 219-221 Kopta Slough RM 221-219 with existing restraint

Predictions with restraint removed

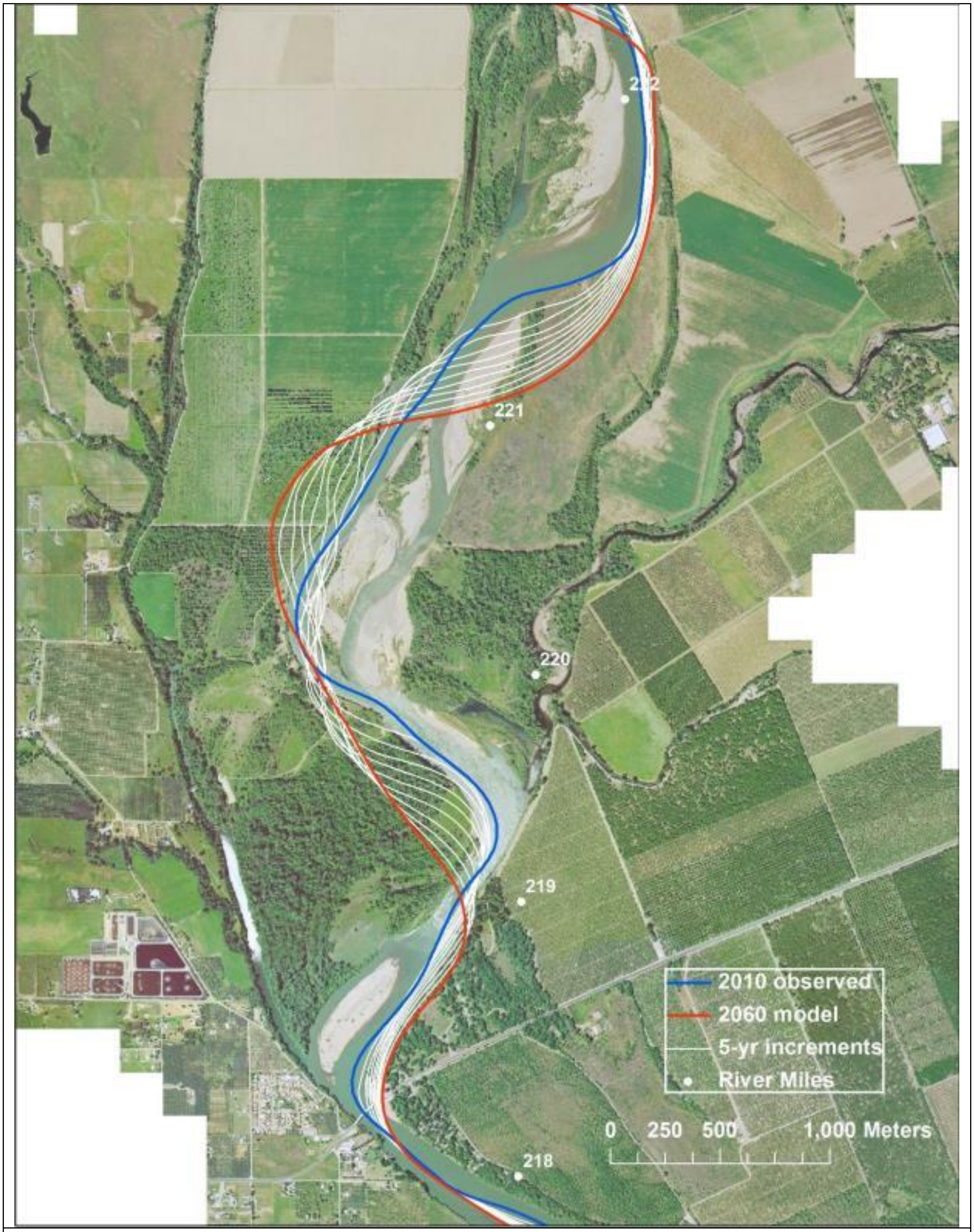


Figure 11 RM 219-221 Kopta Slough with restraint removed 2010 -2060

Predictions with planned cutoff

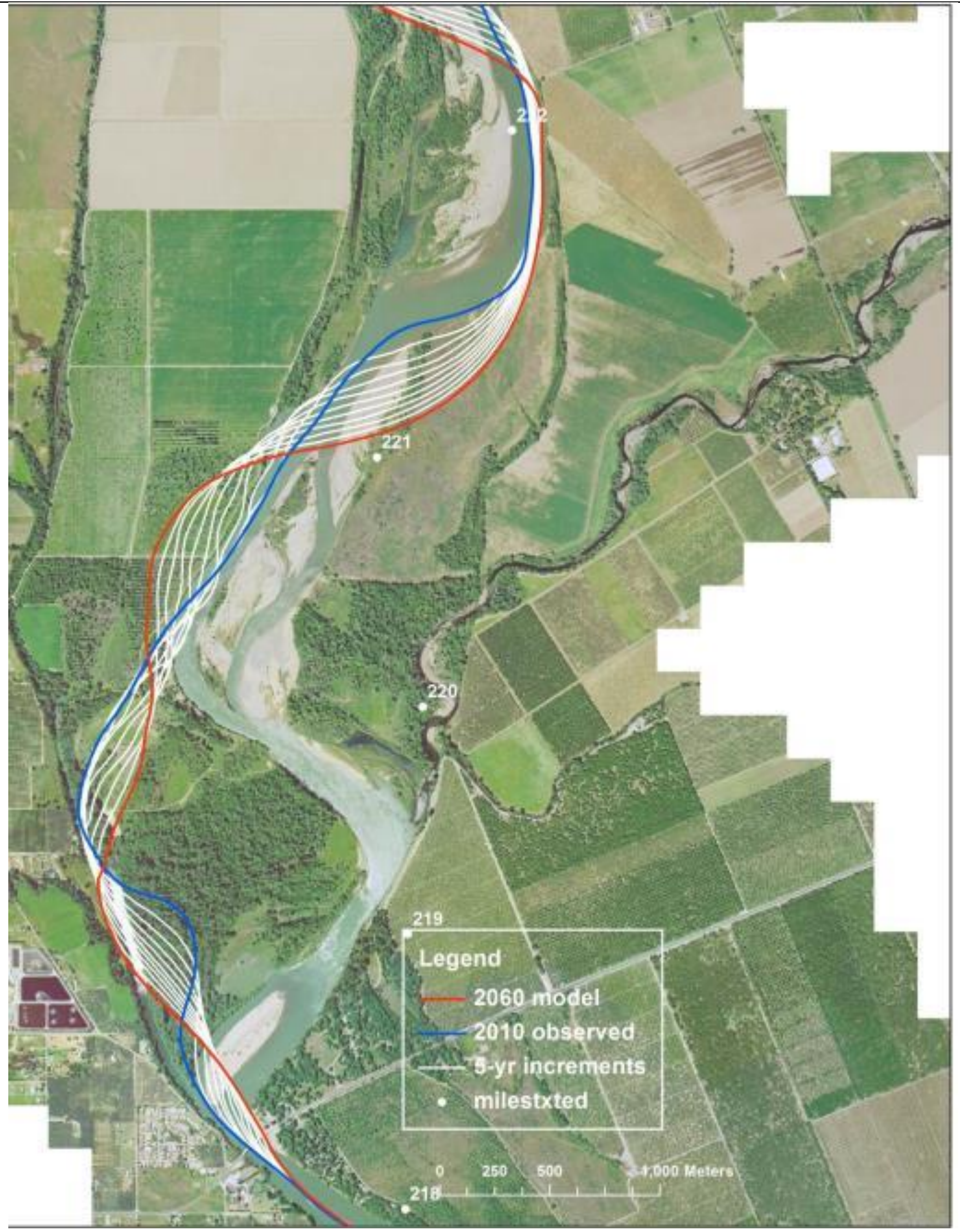


Figure 12 RM 219-221 Kopta Slough with planned cutoff

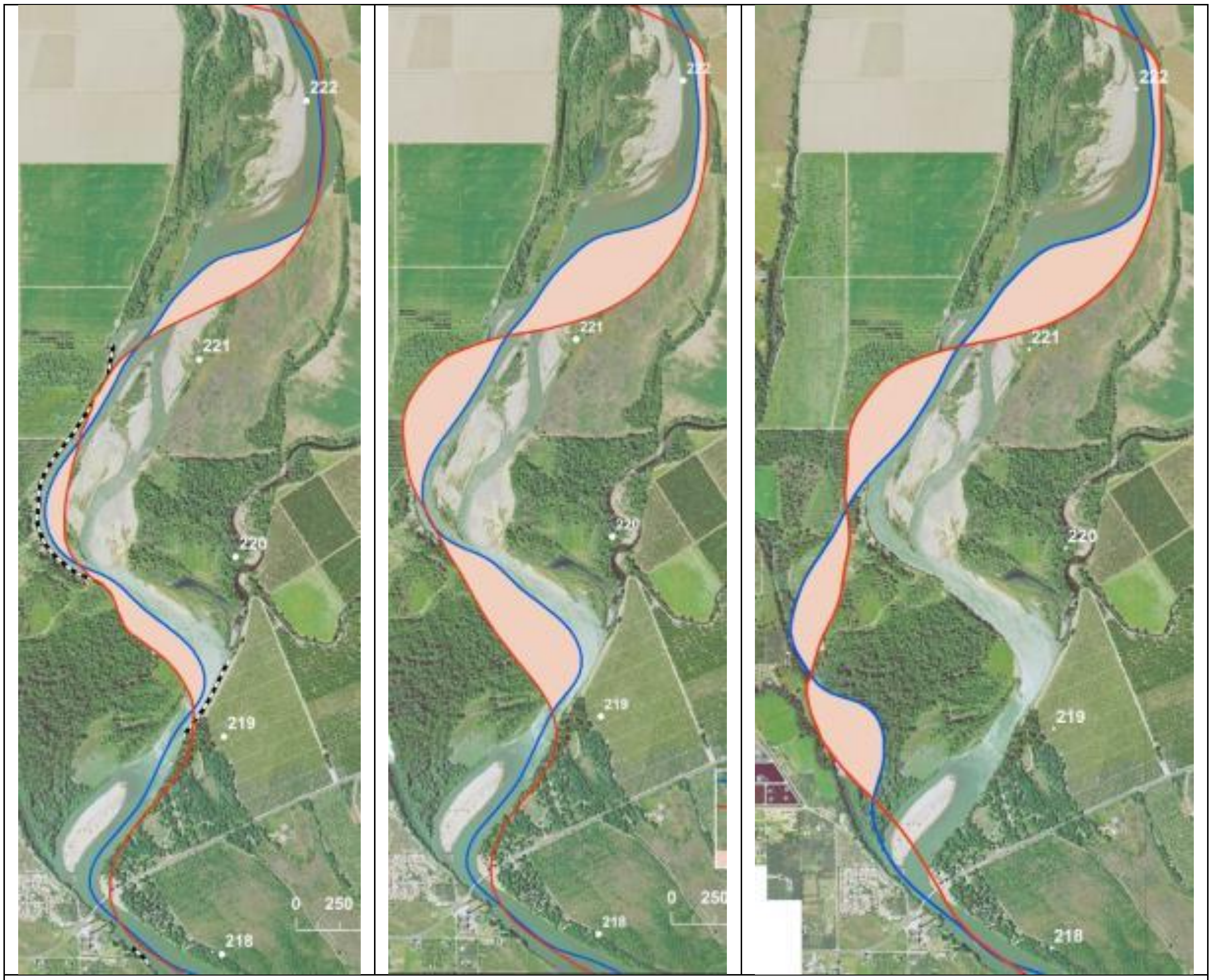


Figure 13 RM 219-221 Kopta Slough area reworked polygons

The total area reworked by each flow scenario is given below.

Area reworked

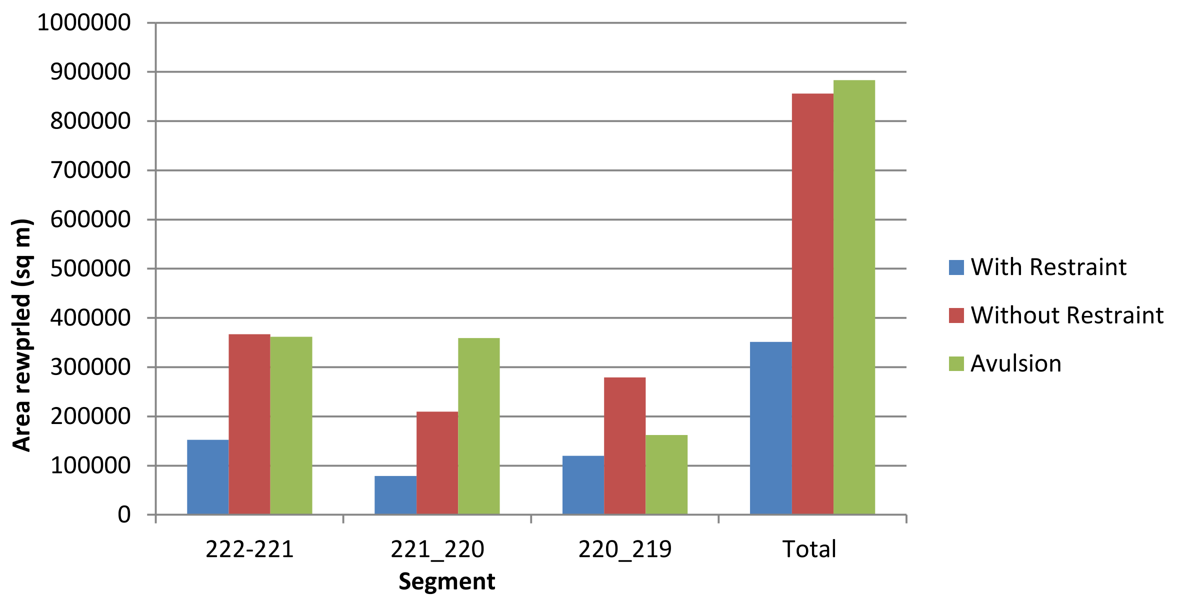


Table 5 Total area reworked RM 219-221 Kopta Slough segment

Discussion
The scenario without any restraints and the avulsion scenario achieve over twice as much area reworked as the current conditions with restraint. It is expected that the avulsion scenario over longer time periods would show more area reworked than the without restrain scenario. This is because it starts as a lower sinuosity channel, and as the sinuosity increases, the migration rate will increase.

RM 191-192 Phelan Island Segment
Three scenarios were modeled.

1. A no action alternative, simulated 50 years into the future (with existing infrastructure/conditions). (Figure 14)
2. A rock removal scenario, with rock removed at two locations simulated 50 years. (Figure 15)
3. A rock removal scenario, with rock removed at only one location simulated 50 years. (Figure 16)

The figures show the modeling results for migration from 2010 to 2060 in 5-year increments.

The area reworked was calculated in polygons where the channel shifted, and are shown on the maps in Figure 17, and in the table (Table 6).

Predictions with existing revetment

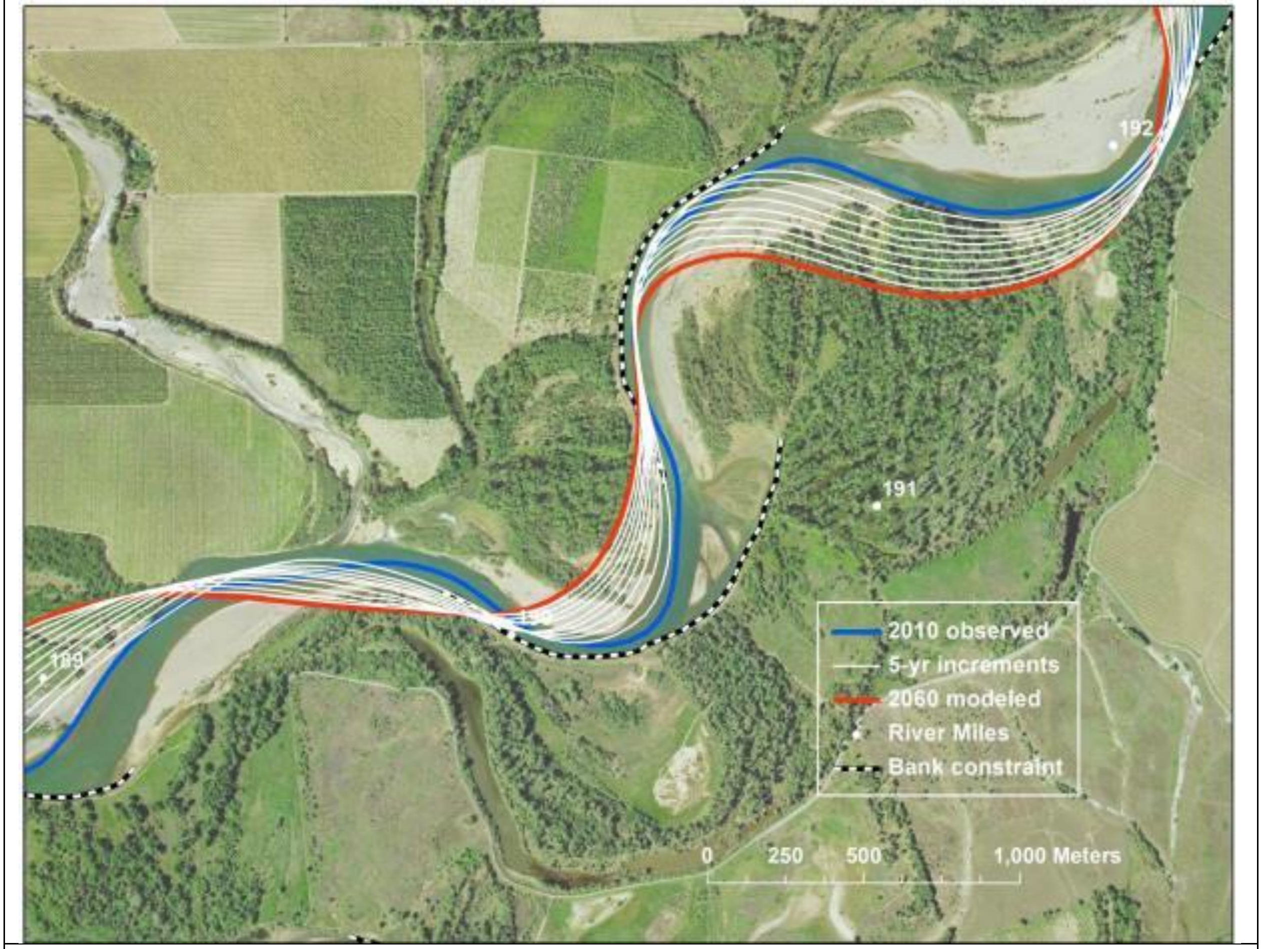


Figure 14 RM 191-192 Phelan Island with existing revetment

Predictions with all revetment removed

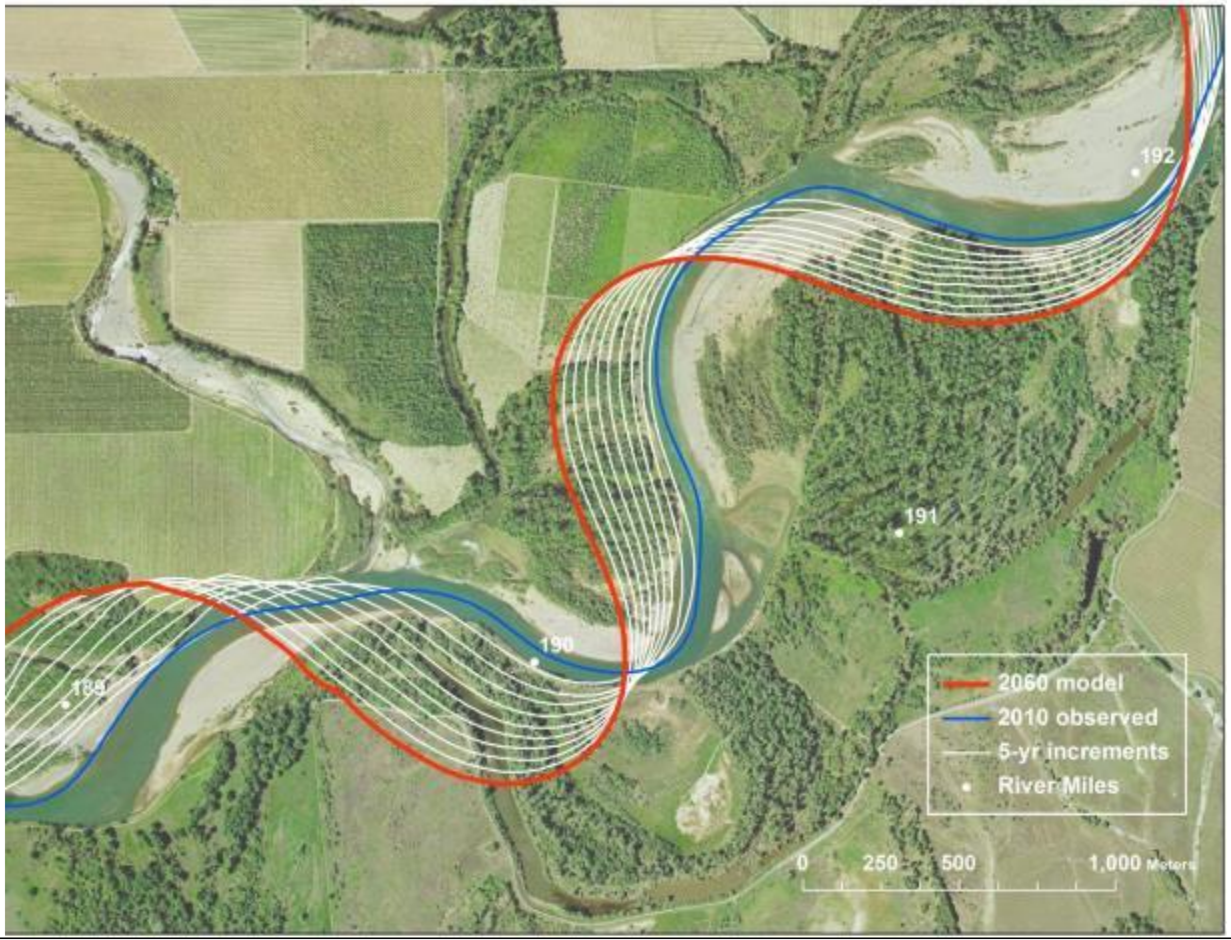


Figure 15 RM 191-192 Phelan Island with all revetment removed

For predictions for the revetment removal scenario (Figure 15), the 2010 revetment was removed.

Predictions with revetment removed upstream

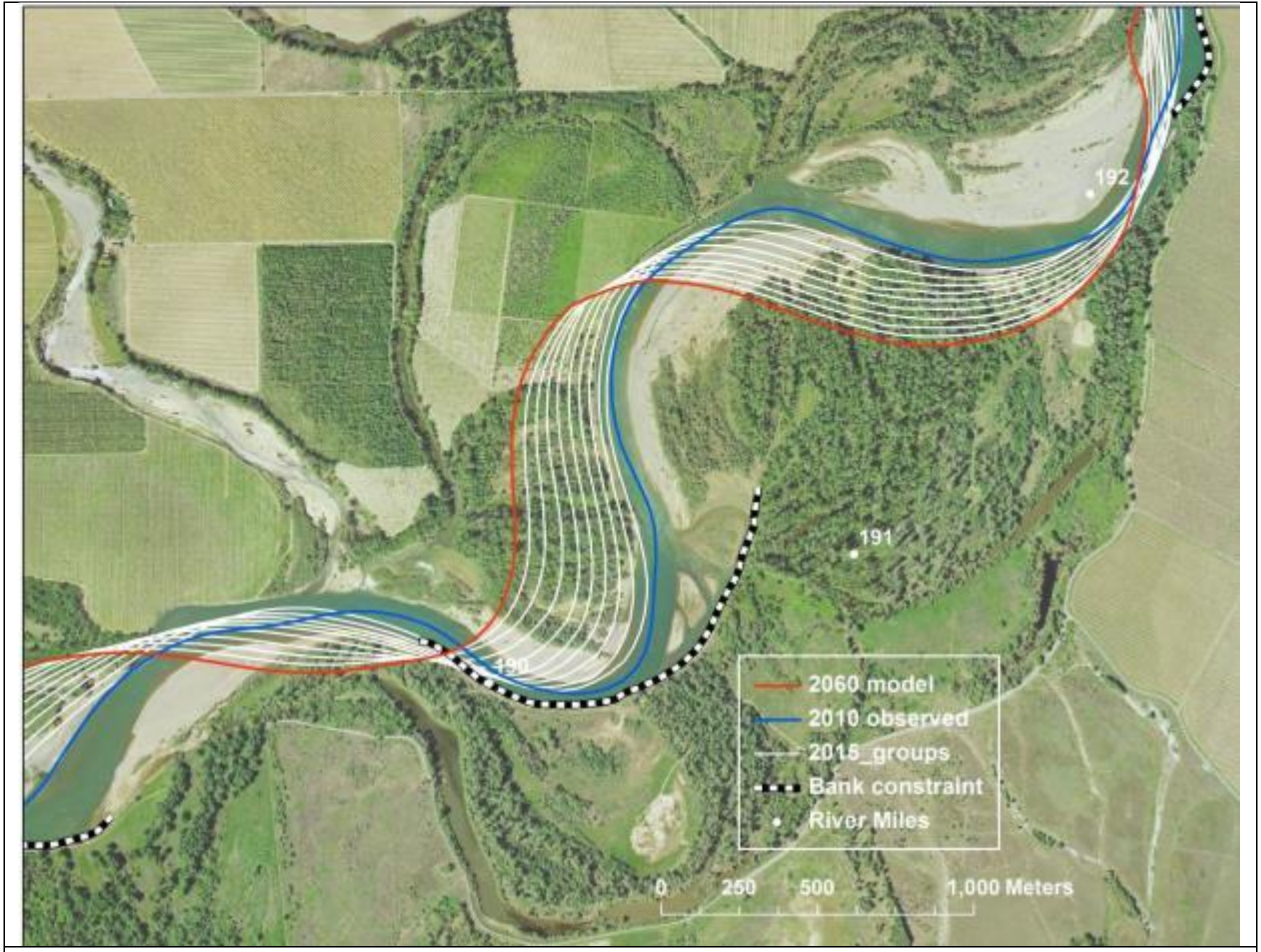


Figure 16 RM 191-192 Phelan Island with revetment removed upstream

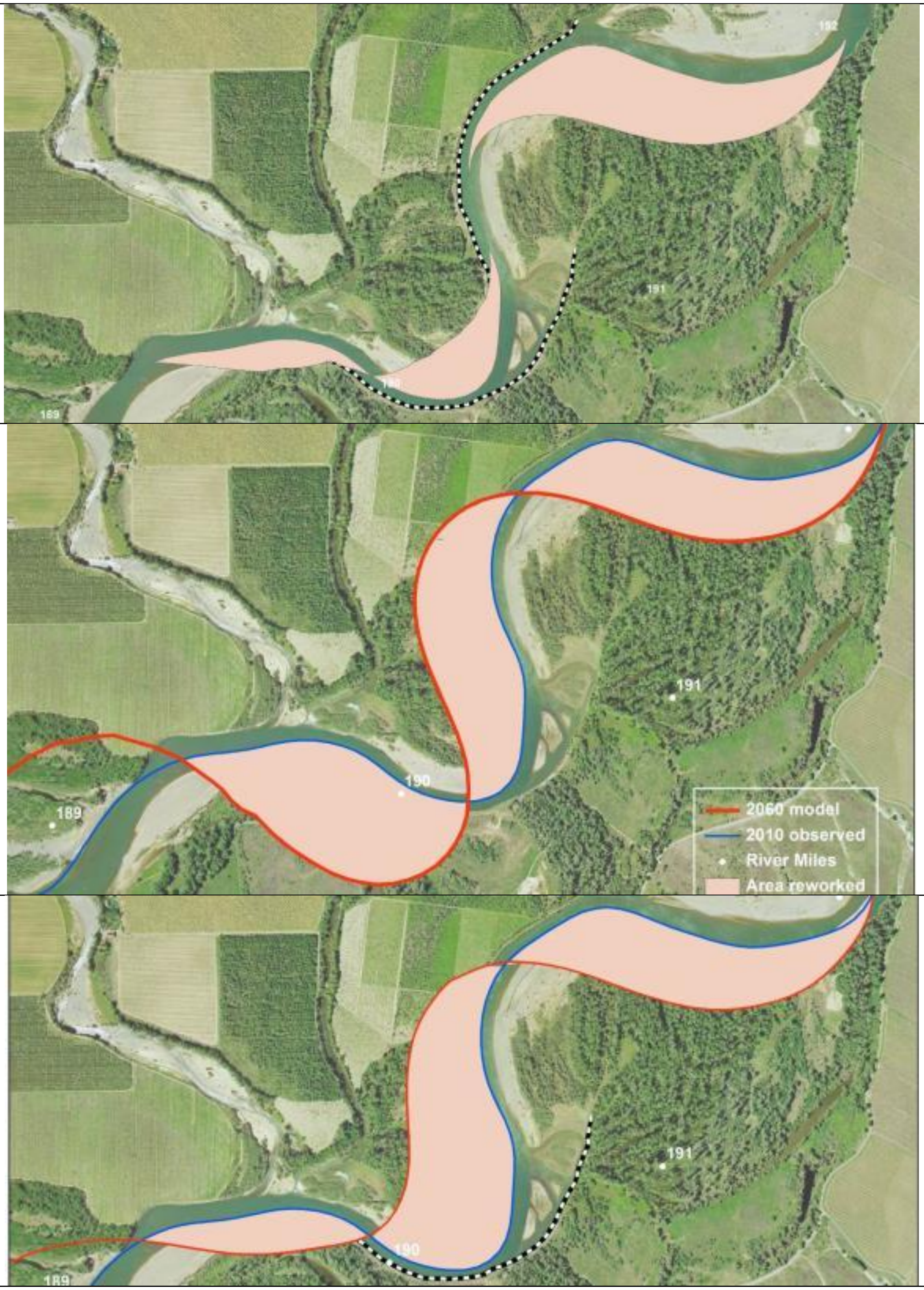


Figure 17 RM 191-192 Phelan Island area reworked polygons for all scenarios

Area reworked and migration rate

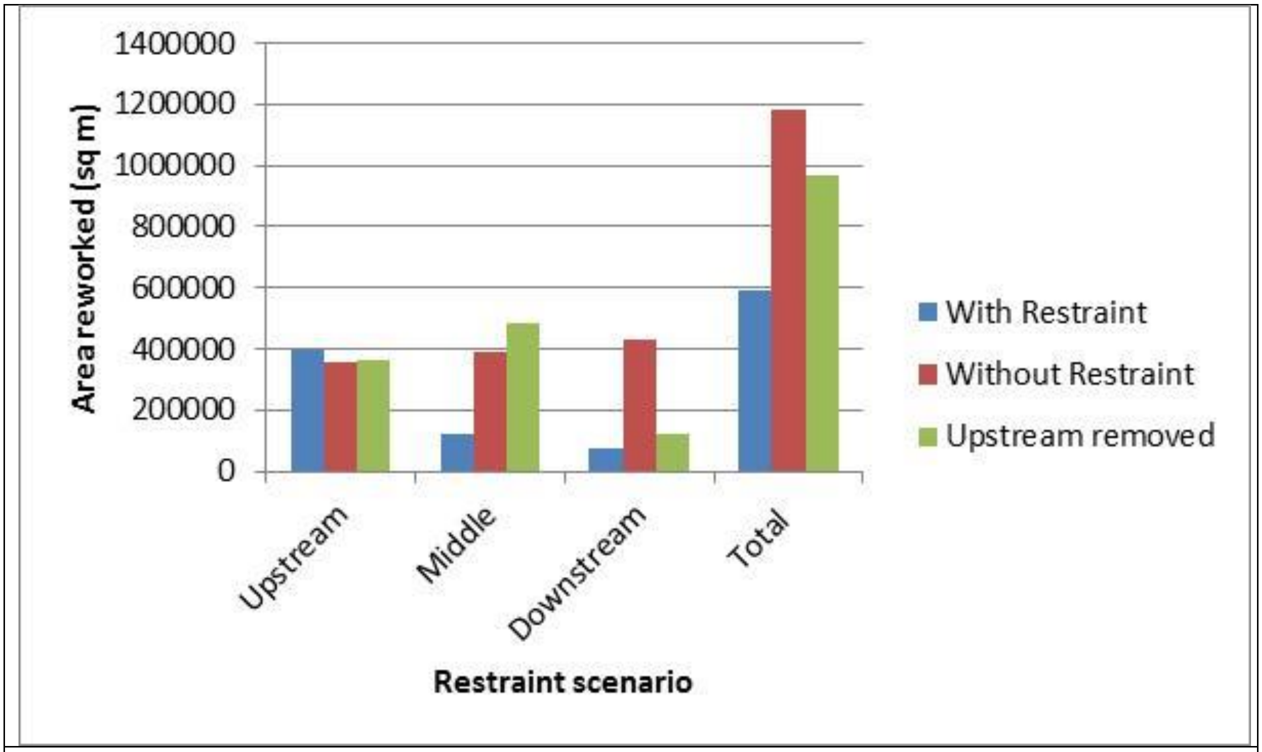


Table 6 Total area reworked RM 191-192 Phelan Island

Discussion

What is of interest here is that the scenario with only one of the two bank restraints removed has almost as much area reworked as the scenario with both bank restraints removed. This suggests that a management action with only one set of bank restraint removed would get almost as much benefit as the scenario with two removed.

RM 182 Bank Swallow Site

Bank swallow model
Frank Paulson of ESSA technologies has worked with the meander migration modeling and developed a simulation of bank swallow habitat. The model utilizes channel migration and other factors to estimate the extent of bank swallow habitat over a range of years. The habitat model is based on burrow reuse. It has been observed that the habitat quality of an existing burrow declines after three years of use, unless the burrows are "refreshed" by bank migration. It has also been observed that bank migration greater than one meter is required to refresh the nests.

In the model, habitat is ranked by the weighted depth over a period of three years. For example, in Figure 18, example B, the bank has eroded more than one meter in one year, and would receive the highest rating factor (green); in example C, the bank has eroded less than a meter in 6 years, and would receive the lowest rating factor (red). Example A is an intermediate case, not ideal, and receives an intermediate rating (yellow).

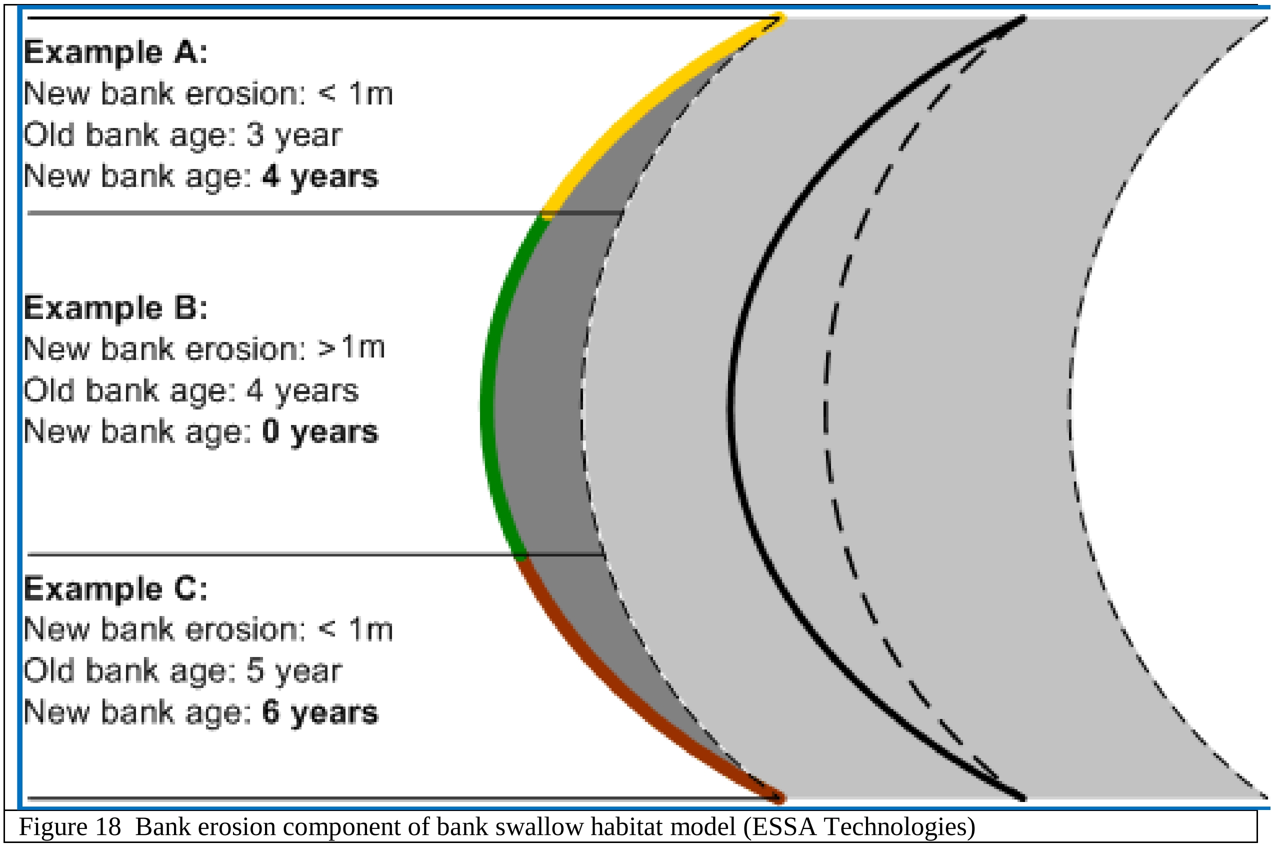


Figure 18 Bank erosion component of bank swallow habitat model (ESSA Technologies)

The model uses a "regression tree" method to assign a colony size for the modeled scenarios. Regression trees find the natural breaks in data. The regression tree shown in Figure 19 is based on habitat quality and the burrows that existed in the previous year. In order to understand how this works, imagine starting at the arrow at the top of the figure. The first question is (which corresponds to the first break point): was the habitat (colony size measured in burrows) last year greater than or equal to 1636? If it was, then you immediately jump to the answer that the current colony size would be 1913. If the habitat last year was less than 1636, you go down the left hand branch to where you ask if the number of burrows last year was greater than or equal to 1233, or less than 1233. Depending on the answer, you follow the appropriate branch to either the resulting number of burrows, or to the next decision branch. In this, way the number of colonies is determined.

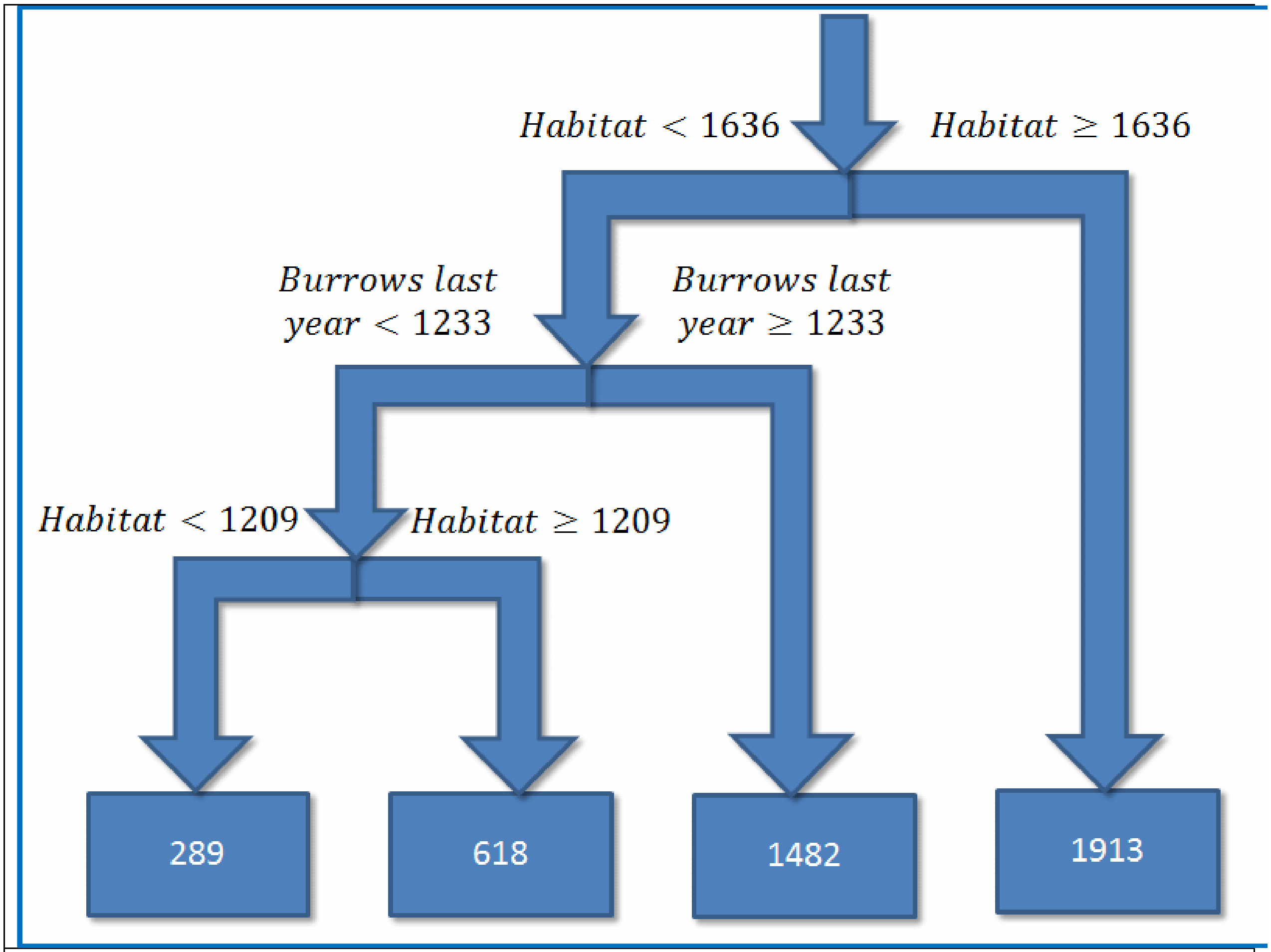


Figure 19 Regression tree component of bank swallow habitat model (ESSA Technologies)

Figure 20 shows the results of a model of bank swallow habitat analysis for historical years at River Mile 182. The model matches the general patterns, but not the extremes. The results of the comparison of modeled and observed support the hypothesis that the population may be correlated with habitat.

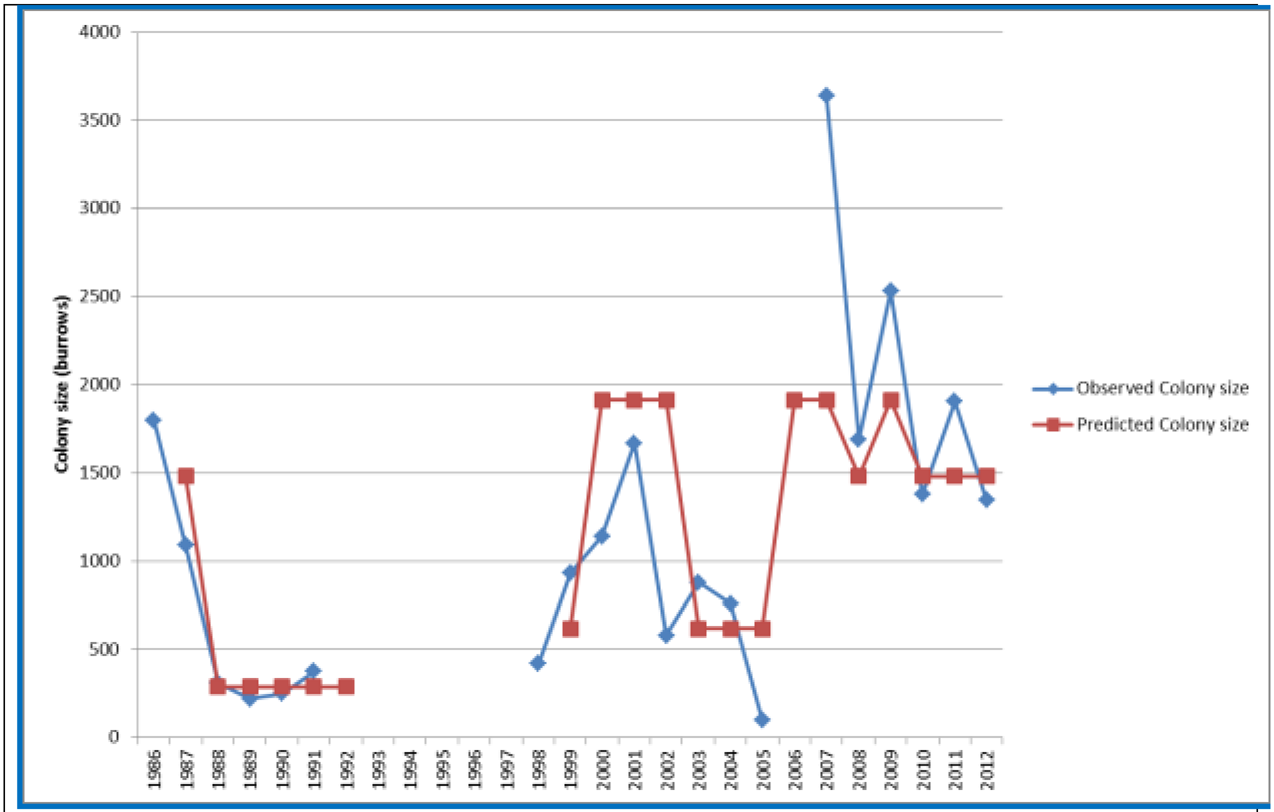


Figure 20 Modeled bank swallow colony size (ESSA Technologies)

The final step in the use of this model was to predict future bank migration patterns at RM 182 (Figure 21), and to use the model described above to evaluate the habitat. Figure 22 shows the results on a yearly basis, giving the suitable habitat in length (meters) in the three categories described above (green = good; red = poor; and yellow = intermediate.)

This test modeling of bank swallow habitat is a pioneering approach in using river meander migration modeling to model the potential habitat for bank swallows, and has major implications for use in considering management related to bank restraints.

Predictions with existing revetment

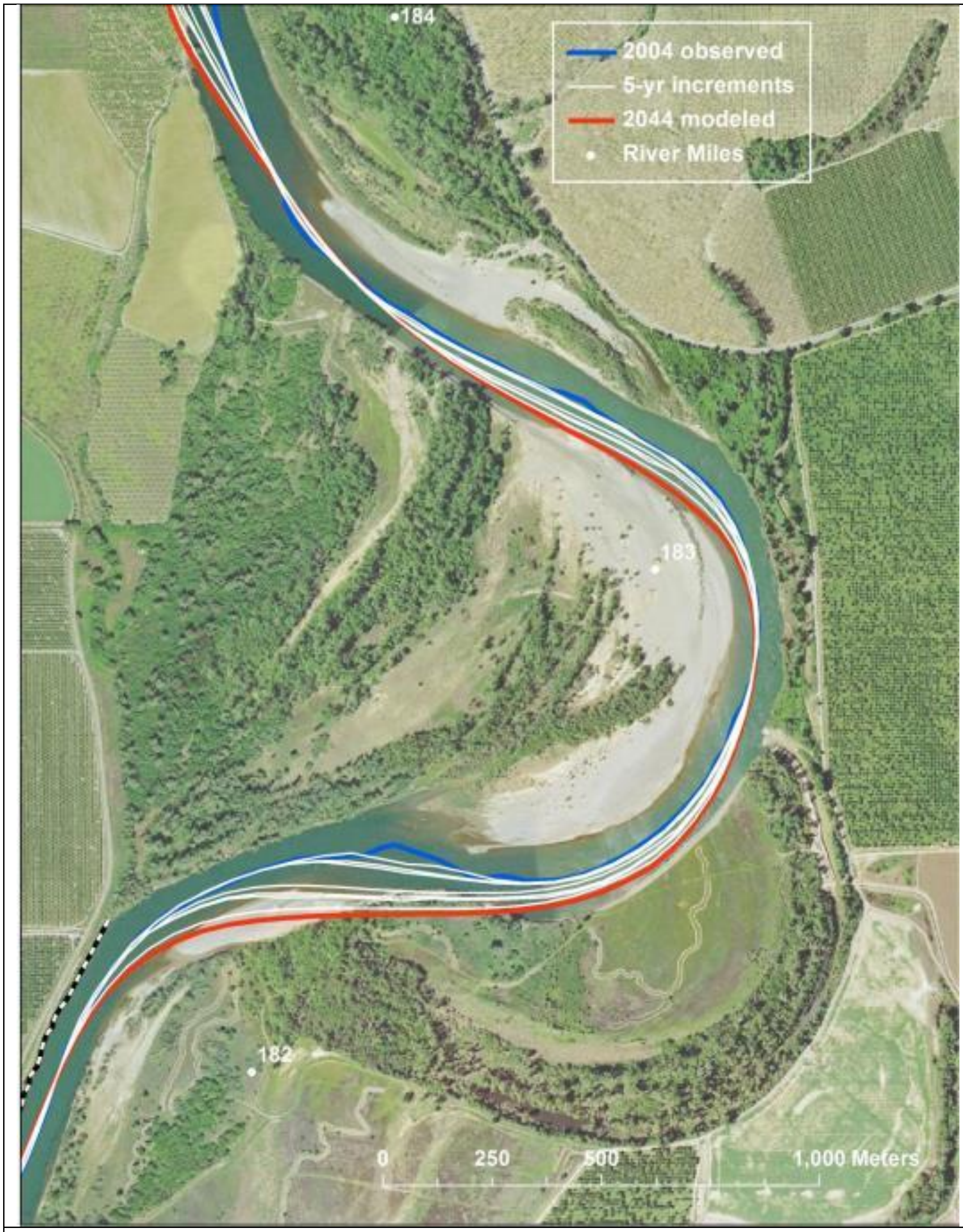


Figure 21 RM 182 Bank Swallow Site migration 25004-2044

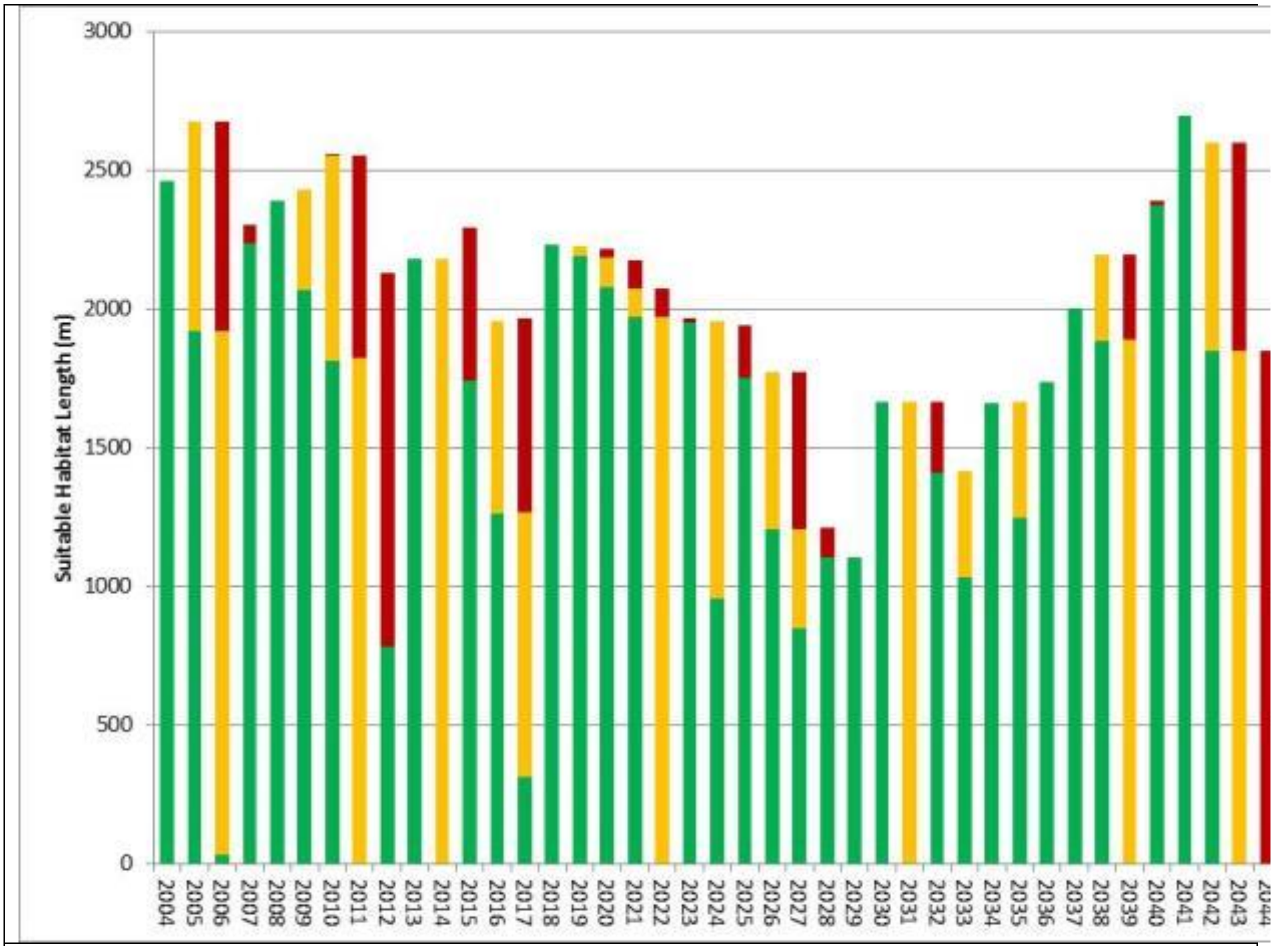


Figure 22 RM 182 Bank Swallow Site tabulation of swallow habitat 2004-2044

RM 172L Segment (USACE rock repair site)

Predictions with existing conditions

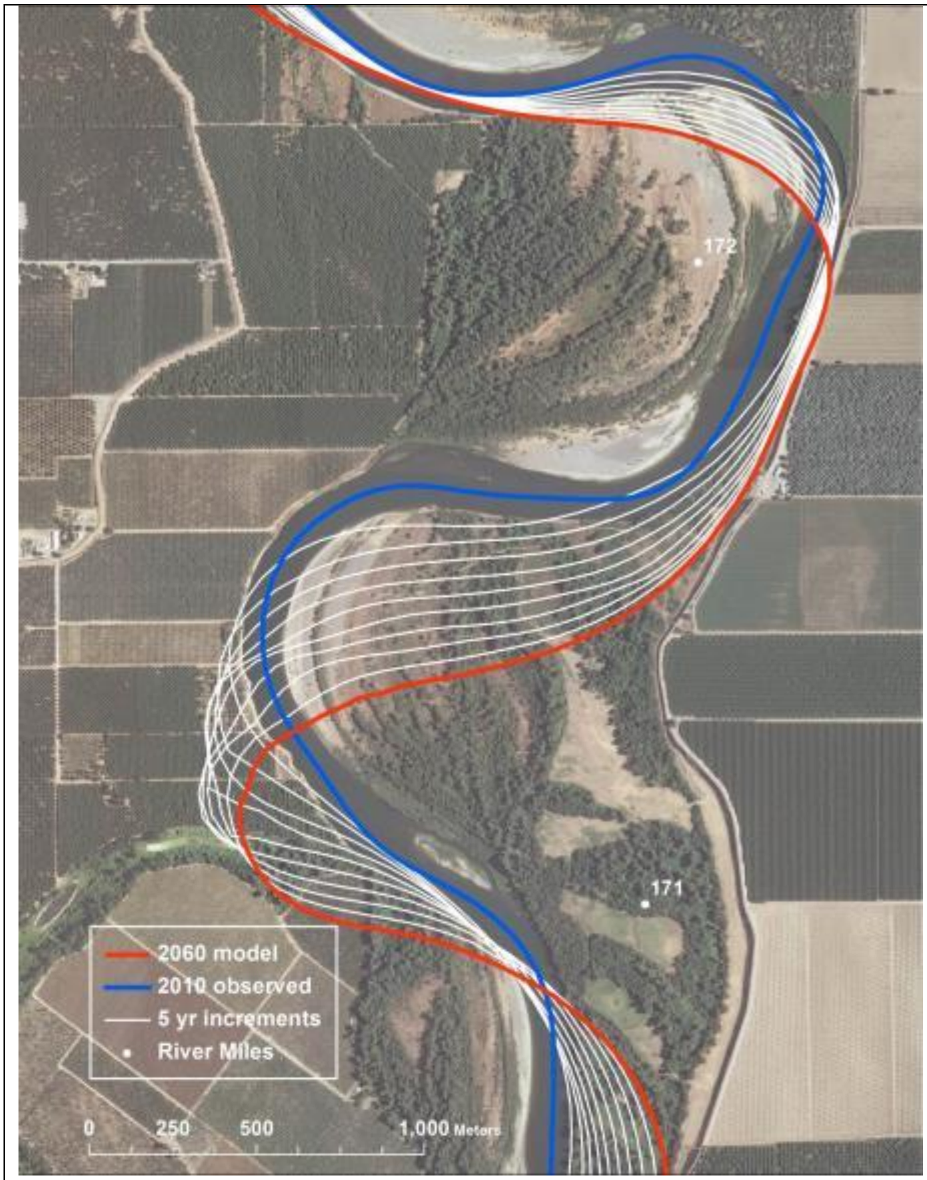


Figure 23 RM 172L Segment Predictions with existing conditions

As in previous output figures, the observed channel centerline for RM 172 at the beginning of the simulation is shown in solid blue and the simulated final channel 50 years later is shown in solid red (Figure 23). The white lines show the channel centerline at 5 year intervals in the intervening time periods.

Predictions with levee removed

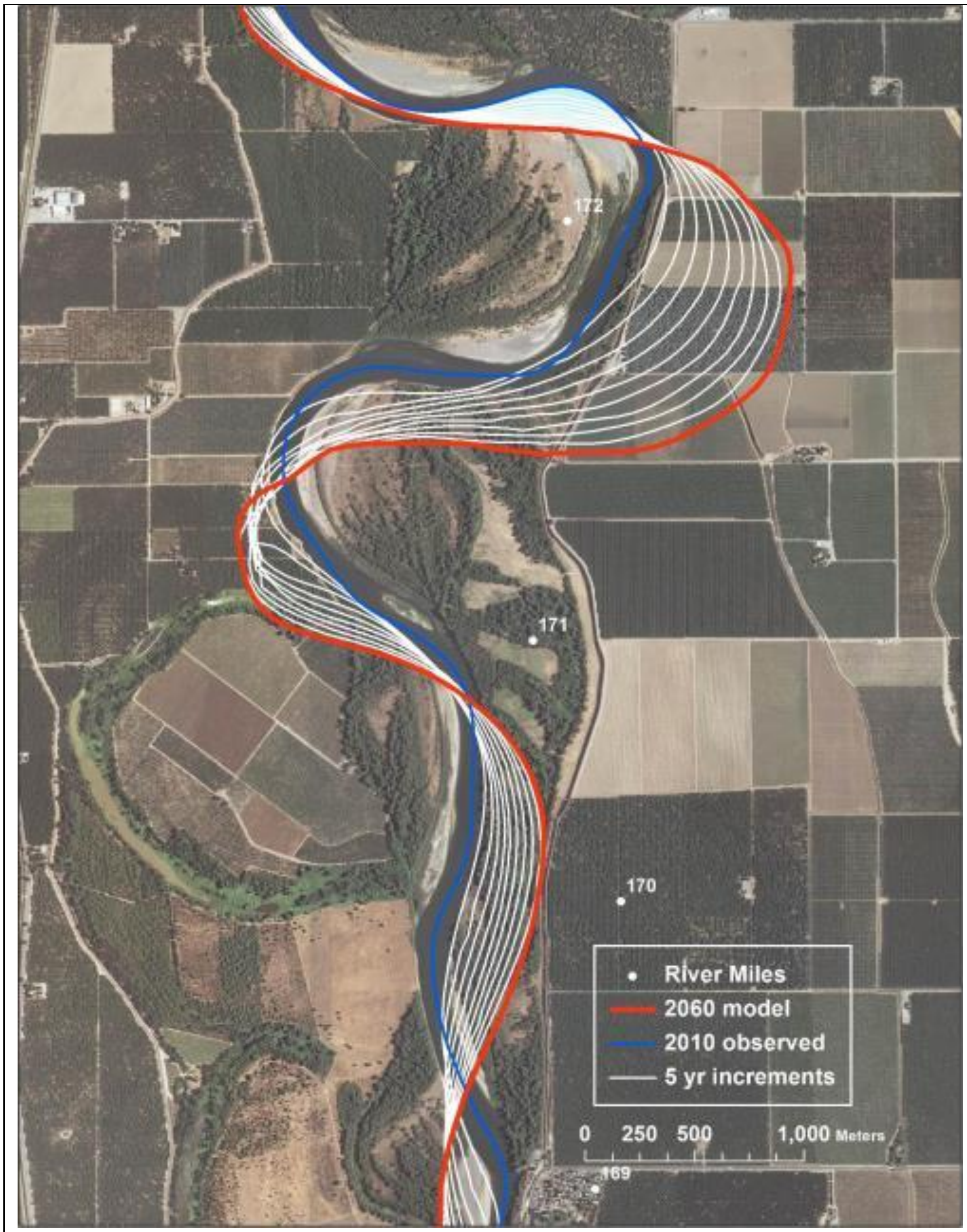


Figure 24 RM 172L Segment (USACE rock repair site) levee removed

Figure 24 shows a simulation, with the same color scheme of a hypothetical situation where the levee is removed. We believe that there is natural hard material underlying the levee (Pers. Com. Buer, Henderson, DWR, 2012), and that that channel would not migrate in this way. The simulation is only for theoretical model demonstration purposes.

Predictions with simulated cutoff

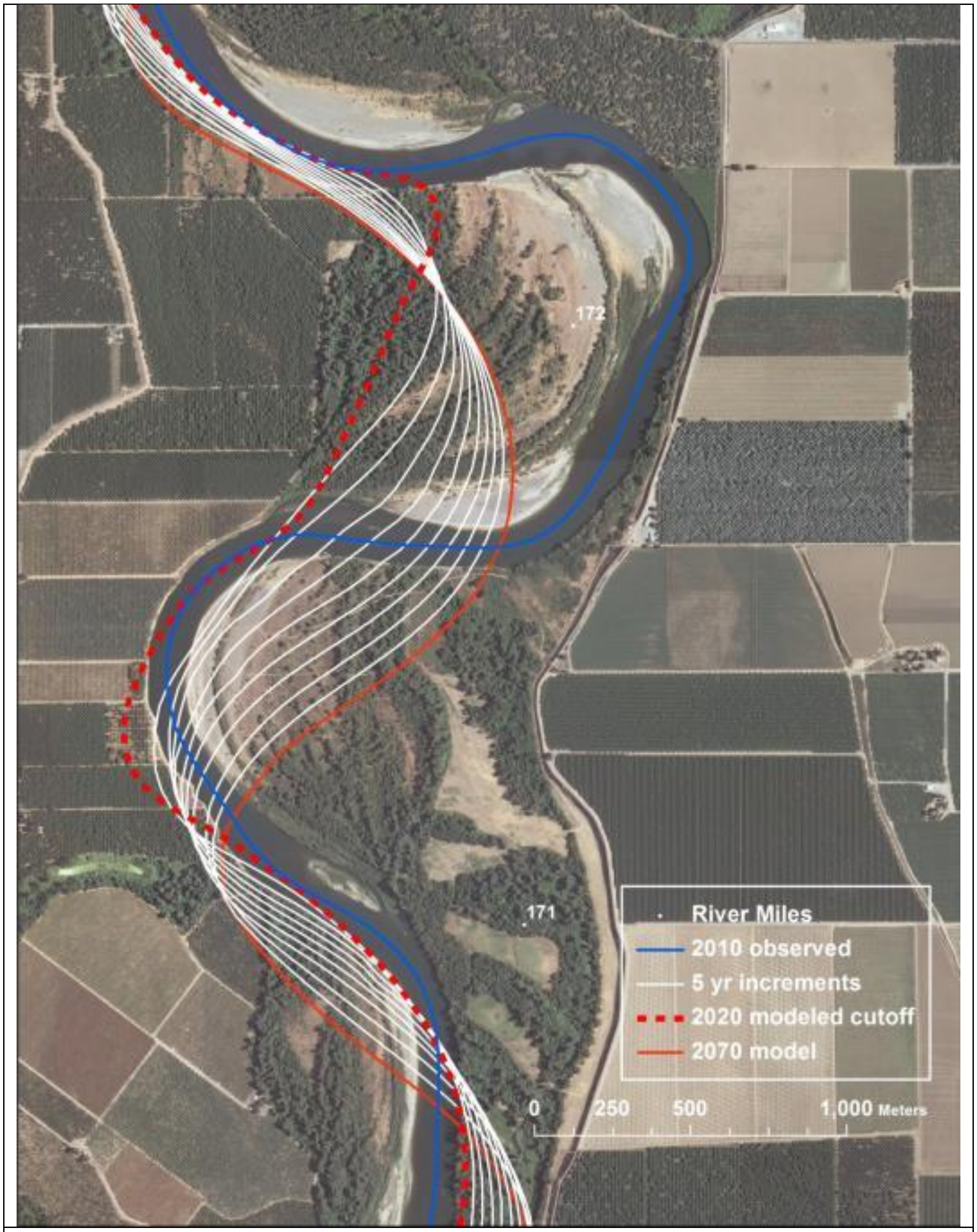
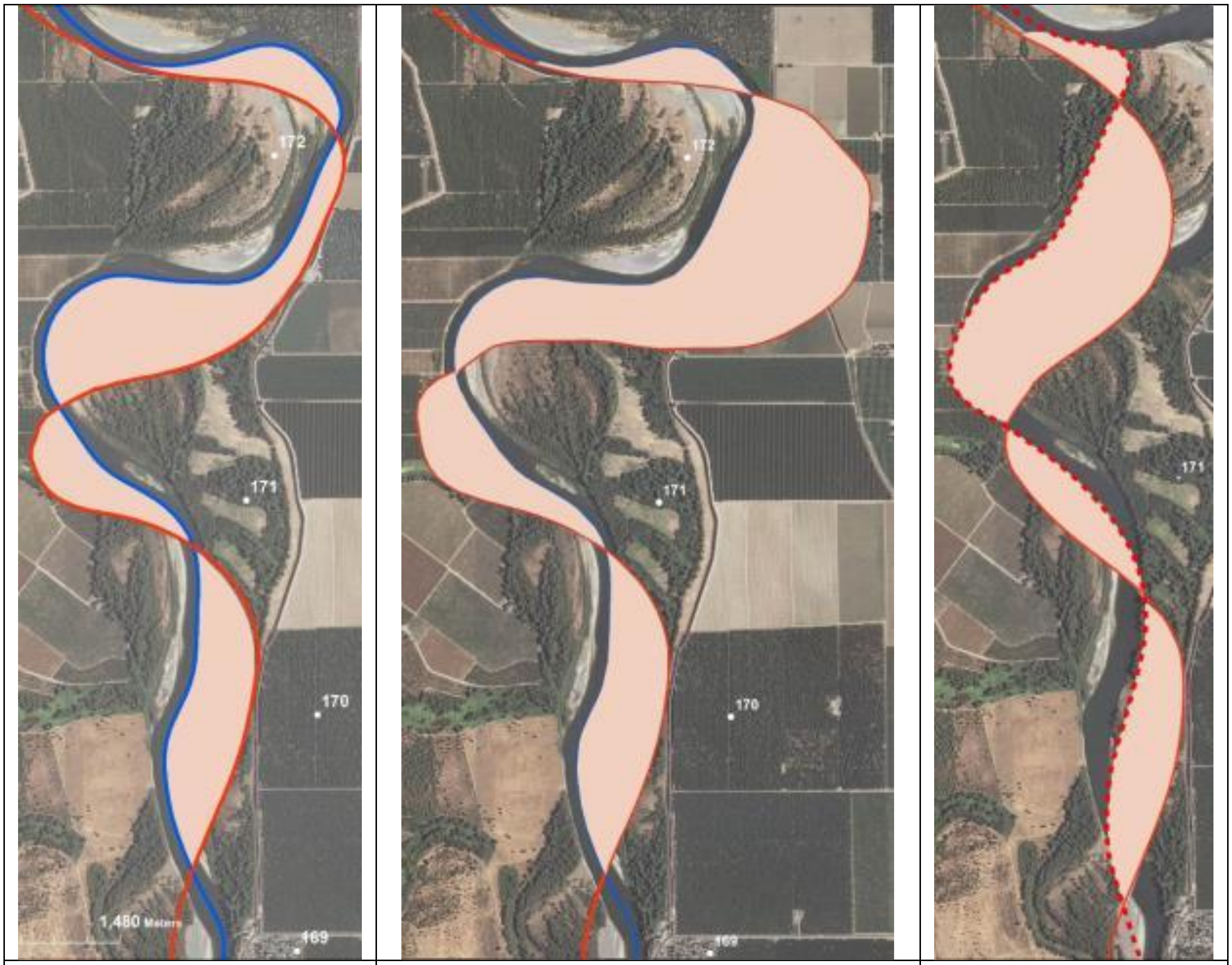


Figure 25 RM 172L Segment (USACE rock repair site) simulated cutoff

Figure 25 shows the results of a simulated cutoff, which was simulated to occur in 2020. The figure shows the subsequent migration pattern 50 years into the future. The white lines show the migration from the 2020 location to the 2070 location.



Existing conditions | Levee removed | Cutoff

Figure 26 RM 172 migration simulation area reworked polygons

Figure 26 and Table 7 show the areas reworked in 50 years by the three different scenarios.

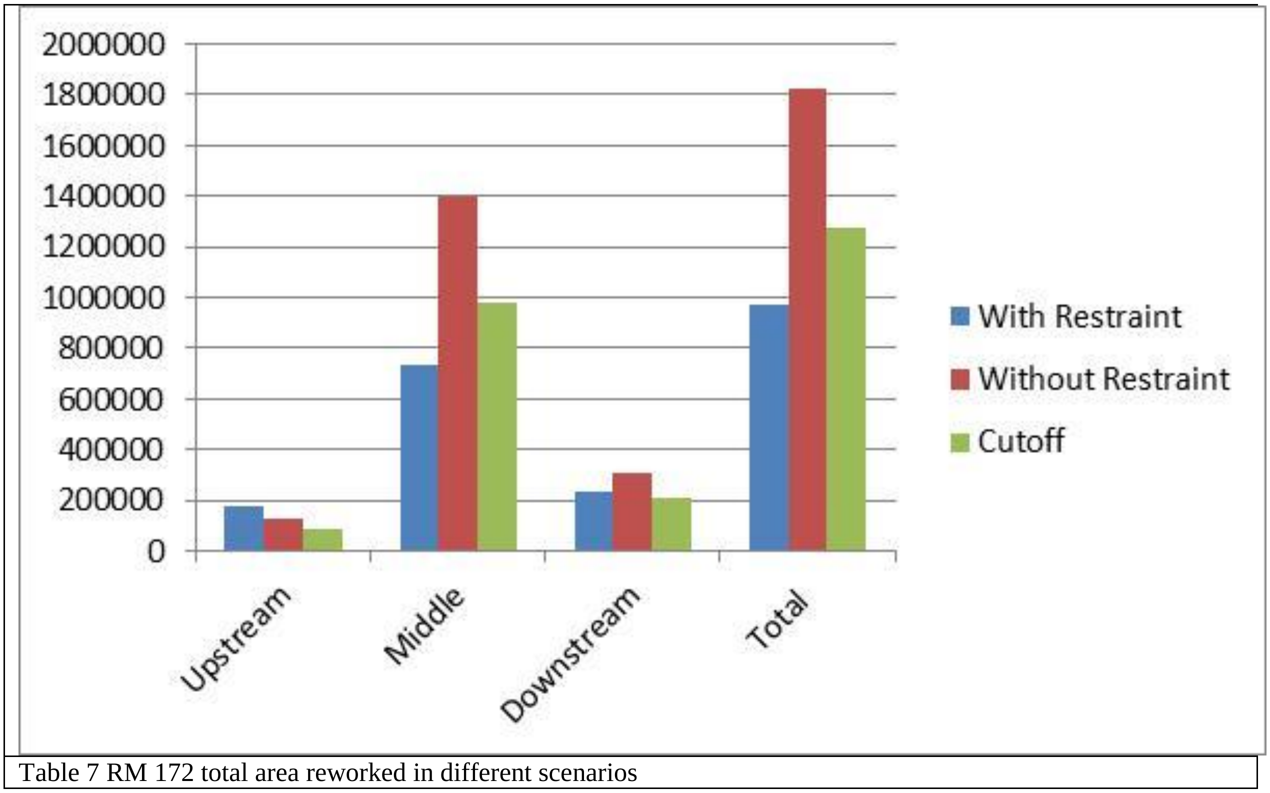


Table 7 RM 172 total area reworked in different scenarios

The scenario without restraint shows the most area reworked. This is only a conceptual scenario to illustrate how the model can work, because the highly resistant bank material at this location would not allow the migration as modeled.

What is important about this modeling exercise is that it shows an alternative method to rocking the bank that is described as needing repair. The cutoff not only solves the problem of the pressure on the bank, it also allows for ecosystem regeneration through floodplain creation and reworking. The analysis also shows the quantity of floodplain regenerated by this method. The yearly rate of floodplain regeneration would also increase beyond the years of the simulated model because the sinuosity of the channel would increase.

RM 80-85 Segment (USACE fish studies site)

The final site is an area where the USACE has done extensive modeling related to fish population. The entire reach that is shown in the figures below is, for almost the entire length, leveed on both sides.

North Levee Removed

In order to show the potential for movement, a scenario at 50 years into the future with the north levee removed was performed (Figure 27). The north levee is the most likely candidate for management actions. The figure shows that there are three main areas of potential dynamic channel migration.

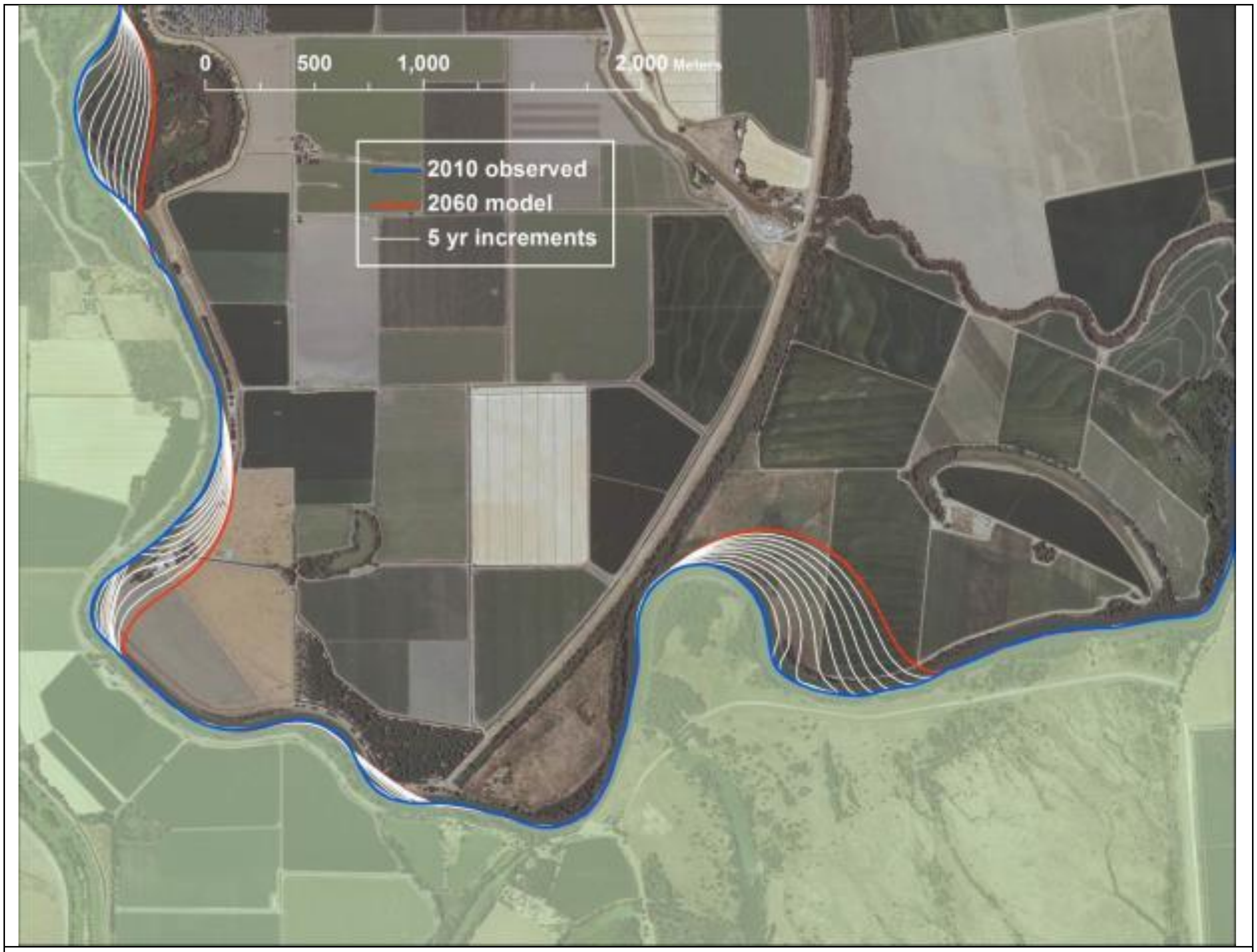


Figure 27 RM 80-85 Segment (USACE fish studies site) north levee removed

Channel Realignment

A scenario where a new channel was established across the floodplain, and 50 year migration into the future is modeled (Figure 28). The initial alignment was established by a subgroup of the SRBPP IWG, including USACE, USFWS, DWR, and UC Davis participants. This scenario provides an example of a management action that would reintroduce natural process of floodplain and ecosystem processes into the system. A whole suite of potential benefits include dynamic channel migration, creation of new floodplain surfaces through deposition, which in turn provides habitat for heterogeneous age vegetation establishment. Floodplain overbank flows could be established, which provide specific habitat values for fish. The natural dynamics in this scenario could also potentially provide bank swallow habitat.

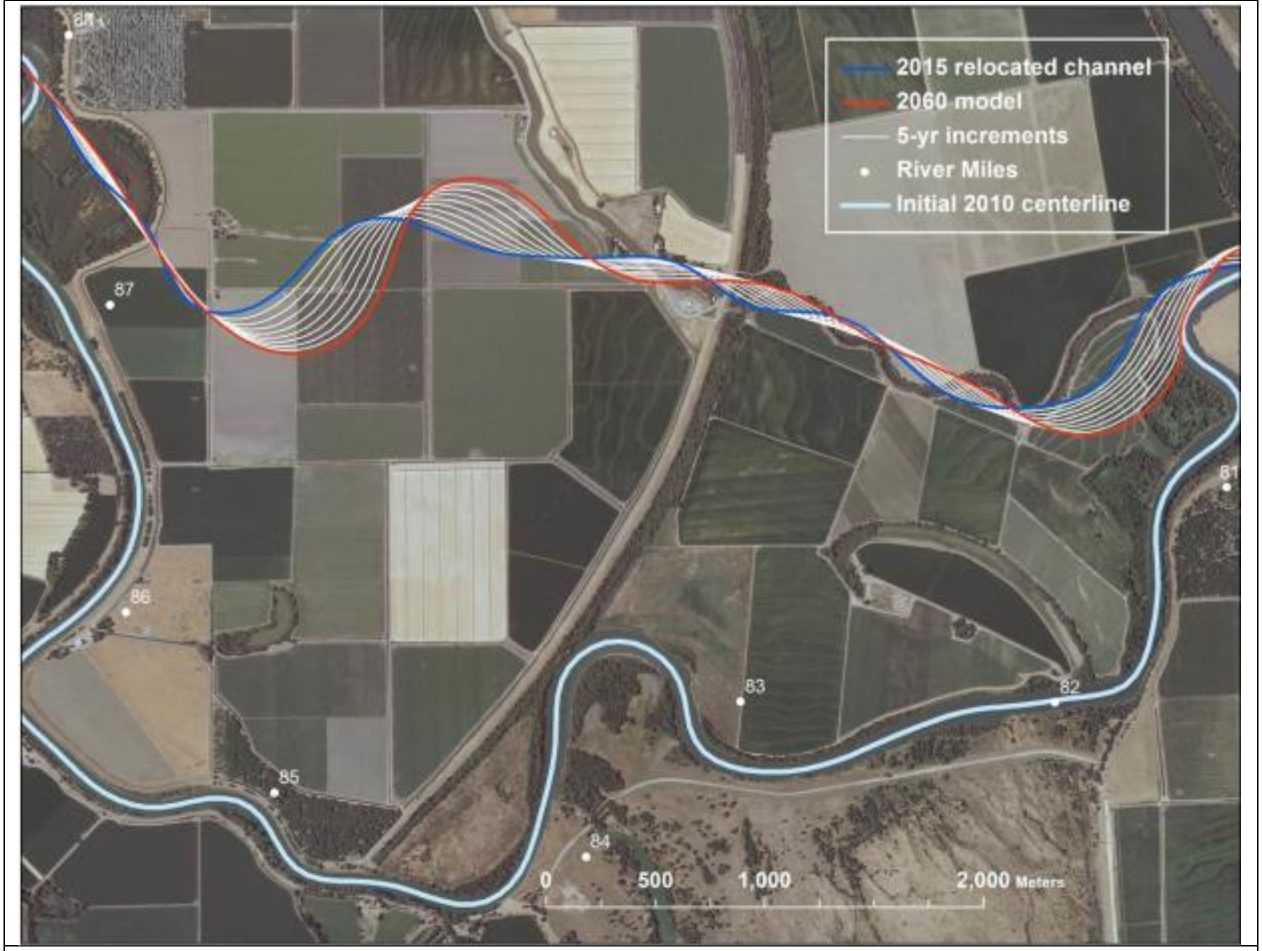


Figure 28 RM 80-85 Segment (USACE fish studies site) new channel

Bank Stress Modeling

A prototype “bank stress mapping” that uses the meander migration model to indicate areas of relative bank stress.

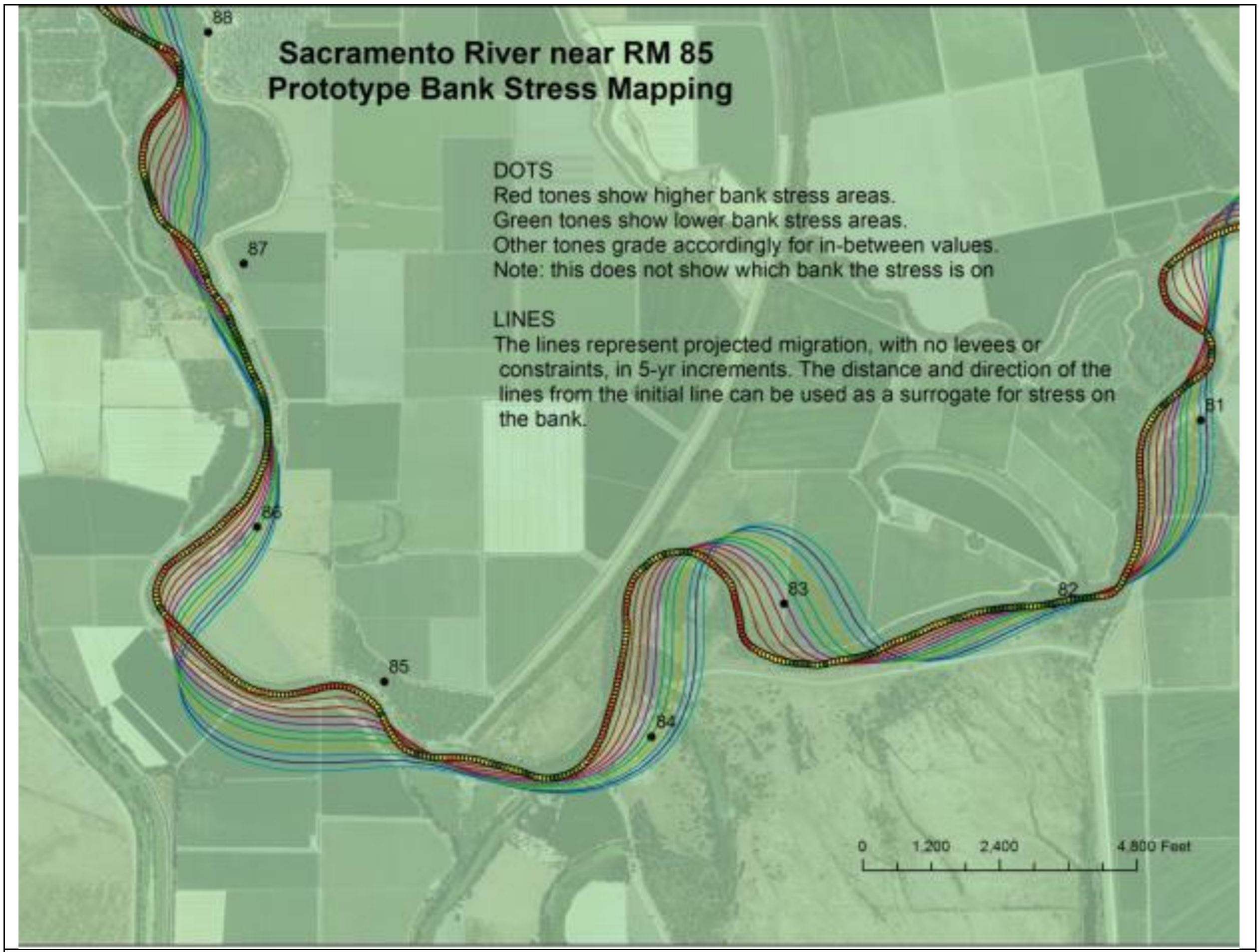


Figure 29 RM 80-85 Segment – prototype bank stress mapping

In conversations with SRBPP IWG, a quick and easy method to illustrate the stresses on the existing levees was desired. Although there are technical analyses available that can calculate stress on the banks, these are not always the best for stakeholder communication and discussion. Figure 29 shows the results of using the meander migration model to estimate the stresses on the existing levees.

An estimate of stress on the banks is shown in two ways: lines and colored dots. The lines represent projected migration, with no levees or constraints, in 5-yr increments. The *distance* of the lines perpendicularly from the initial line can be used as a surrogate for stress on the bank. The dots also represent the estimated stress on the banks. Red tones show higher bank stress areas; green tones show lower bank stress areas. Other tones grade accordingly for in-between values. Note that this method does not show which bank the stress is on.

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Restoration Program, Agreement #ERP-02-PO8-D, Amendment 2. Steering Committee Technical Memorandum., Ducks Unlimited.

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4.0 APPENDICES

Model Parameters for Calibration and Prediction Runs

Some of the model parameters are internal to the model and are recorded as metadata. "Erosion coefficients" are used to establish the erodibility of the erosion surface and are described in other sources (e.g. Larsen and Greco 2002). "Centerline properties" record the projections for geographic data (UTM zone 10 NAD 83), the starting and ending channels for the modeled migration, the date and time of the run, and model version that was used.

"Flow parameters" are derived from acquired data. The discharge, width, depth, slope and particle size were described above. The "Upper threshold" is a value set above which flows may be neglected. It was not used for this modeling, and was technically set at a discharge that was above observed flows. Observed flows did not exceed roughly 9,000 cms. Setting the upper threshold at 30,000 establishes no upper threshold.

"Computational parameters", "cutoff parameters" and "erosion algorithm parameters" are parameters that are internal to the model, and are recorded here as modeling metadata.

RM 222

```
SacRM 1952
Fremier
UTM   NAD   83    zone  10
1952 Start Channel
1976 End Channel
file written 23-Aug-2012 09:40:06
Meander version: Meander 7.3.5: Finalized Code to EWL
D:\07_Meander\Meander7.3.5JN_ERDC_WB_52_76_calib\ERDC_WB_52_76_calib

Erosion field: e0_veg_geo_rr_52b_aug2.asc

FLOW PARAMETERS
Q                 = 2200 cms
H (depth)         = 5.01 m
B (width)         = 218 m
S (slope)         = 0.00045
Ds                = 25 mm
FlowThresh        = 425
Bankfull          = 30000

COMPUTATIONAL PARAMETERS
dyr               = 1
C_max             = 0.6
Spacing           = 0.5
Smoothing         = 3
Eo_Spacing        = 1
Cf_scale          = 3
Calc_uf           = 1
Check_curve       = 1

CUTOFF PARAMETERS
```

```
Sinu Thresh      = 1.8
Recur. Int.      = 2
Cutoff Routine   = 0

BEND PARAMETERS
bend length= 8
straightSin= 0.0005
bendSin    = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo          = 1
b--Depth       = 0
d--Erosion     = 1

HYDRAULIC PARAMETERS
g          = 9.81
fstar      = 1.19
alpha      = 0.077
alphastar  = 0.85
mu         = 0.43
nu         = 1.01e-006
rhos       = 1.65
```

RM 191

```
SacR HC reach 1952
Fremier centerline
UTM Z10 NAD 83
1952 Start Channel
1976 End Channel
file written 14-Aug-2012 13:55:07
Meander version:
D:\07_Meander\Meander7.3.5JN_ERDC_HC_52_76_calib\ERDC_HC_52_76_calib

e0 field: e0_ERDC_52_76_calib_final.asc
      same
as:e0_veg_geo_rr_52b_HC_85_150_250_calib_finalx.5_w131x.8x.8tweak.asc

FLOW PARAMETERS
Q                 = 2181 cms
H (depth)         = 5.07 m
B (width)         = 232 m
S (slope)         = 0.000332
Ds                = 20 mm
FlowThresh        = 425
Bankfull          = 30000

COMPUTATIONAL PARAMETERS
dyr               = 1
C_max             = 0.6
Spacing           = 0.5
Smoothing         = 3
Eo_Spacing        = 1
Cf_scale          = 3
Calc_uf           = 1
Check_curve       = 1

CUTOFF PARAMETERS
Sinu Thresh       = 1.8
Recur. Int.       = 2
Cutoff Routine    = 0

BEND PARAMETERS
bend length= 8
straightSin= 0.0005
bendSin    = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo           = 1
b--Depth        = 0
d--Erosion      = 1

HYDRAULIC PARAMETERS
g           = 9.81
fstar       = 1.19
alpha       = 0.077
alphastar   = 0.85
mu          = 0.43
nu          = 1.01e-006
rhos        = 1.65
```

RM 182

```
OF    SacRM 1976
Greco and   Benninger   centerline
UTM   83    zone  10
1976 Start Channel
2004 End Channel
file written 27-Aug-2012 22:01:04
Meander version: D:\07_Meander\Meander7.3.5JN_ERDC_OFRM182_76_04_calib
Erosion field: ERDC_v7.asc

FLOW PARAMETERS
Q                = 2180 cms
H (depth)        = 4.91 m
B (width)        = 277 m
S (slope)        = 0.000297
Ds               = 18 mm
FlowThresh       = 425
Bankfull         = 20000

COMPUTATIONAL PARAMETERS
dyr              = 1
C_max            = 0.6
Spacing          = 0.5
Smoothing        = 3
Eo_Spacing       = 1
Cf_scale         = 3
Calc_uf          = 1
Check_curve      = 1

CUTOFF PARAMETERS
Sinu Thresh      = 3
Recur. Int.      = 2
Cutoff Routine   = 0

BEND PARAMETERS
bend length= 8
straightSin= 0.0005
bendSin    = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo          = 1
b--Depth       = 0
d--Erosion     = 3
```

RM 172

```
OF    SacRM 1976
Greco and   Benninger   centerline
UTM   83    zone  10
1976 Start Channel
2004 End Channel
file written 27-Aug-2012 21:01:10
Meander version: D:\07_Meander\Meander7.3.5JN_ERDC_OF_76_04_calib
ERDC_v4.asc
e0_1983ERDCaddedv4_458asc

FLOW PARAMETERS
Q                 = 2180 cms
H (depth)         = 4.91 m
B (width)         = 277 m
S (slope)         = 0.000297
Ds                = 18 mm
FlowThresh        = 425
Bankfull          = 20000

COMPUTATIONAL PARAMETERS
dyr               = 1
C_max             = 0.6
Spacing           = 0.5
Smoothing         = 3
Eo_Spacing        = 1
Cf_scale          = 2
Calc_uf           = 1
Check_curve       = 1

CUTOFF PARAMETERS
Sinu Thresh       = 3
Recur. Int.       = 2
Cutoff Routine    = 0

BEND PARAMETERS
bend length= 8
straightSin= 0.0005
bendSin    = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo           = 1
b--Depth        = 0
d--Erosion      = 3
```

RM 85

```
SacRM Rm85
Allison Groom 2010 centerline
Unknown projection
2010 Start Year
2060 Prediction
file written 14-Nov-2012 11:22:38
Meander version: Meander7.3.5JN_ERDC_RM85_BaseFinal_10_60_runs
mergerraster190.asc

FLOW PARAMETERS
Q                = 800 cms
H (depth)        = 7 m
B (width)        = 90 m
S (slope)        = 8e-005
Ds               = 18 mm
FlowThresh       = 425
Bankfull         = 20000

COMPUTATIONAL PARAMETERS
dyr              = 1
C_max            = 0.6
Spacing          = 0.5
Smoothing        = 3
Eo_Spacing       = 1
Cf_scale         = 1
Calc_uf          = 0
Check_curve      = 1

CUTOFF PARAMETERS
Sinu Thresh      = 3
Recur. Int.      = 2
Cutoff Routine   = 0

BEND PARAMETERS
bend length= 8
straightSin= 0.0005
bendSin    = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo          = 1
b--Depth       = 0
d--Erosion     = 3

HYDRAULIC PARAMETERS
g          = 9.81
fstar      = 1.19
alpha      = 0.077
alphastar  = 0.85
mu         = 0.43
nu         = 1.01e-006
rhos       = 1.65
```