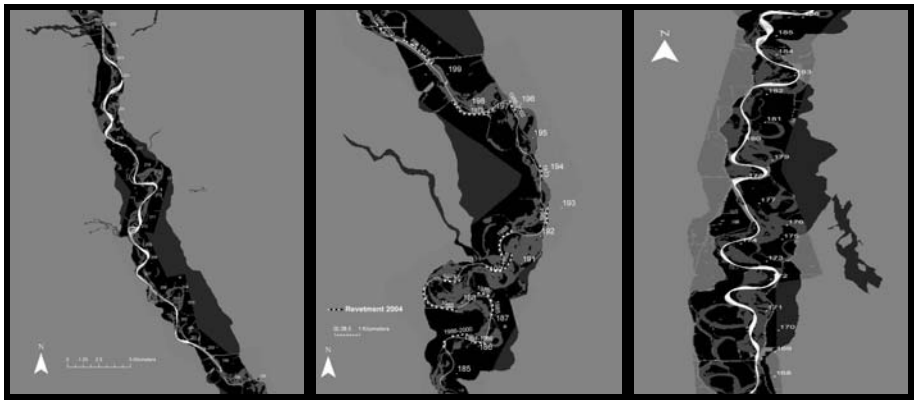

# Sacramento River Ecological Flows Study: Meander Migration Modeling Final Report

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October 2007

Suggested citation:

E. W. Larsen. 2007. Sacramento River Ecological Flows Study: Meander Migration Modeling Final Report. Prepared for The Nature Conservancy, Chico, CA by Eric W. Larsen, Davis, CA.

## Table of Contents

**List of figures**

## List of tables

## EXECUTIVE SUMMARY

This report describes the current version of a meander migration model developed by Eric Larsen, data used as model input, management scenarios used for the model runs, application of the meander migration model to the study reaches used for this study, and model results. The significant difference between the application of the model in this project compared to previous applications is the integration of a variable flow regime. Previous applications of the model assumed a single representative flow. This report interprets model results by showing area of land reworked and migration rates, and explores implications of the model results for management of the Sacramento River. This report documents work done to accomplish the modeling tasks and the results of those tasks.

The Sacramento River meander migration study is a component of the Sacramento River Ecological Flows Study, which is being led by The Nature Conservancy (TNC) with funding from the CALFED Ecosystem Restoration Program (CALFED grant ERP-02D-P61). Key objectives of the meander migration study were to (1) incorporate a variable hydrograph component into the meander migration modeling procedure, and (2) evaluate channel migration patterns resulting from management actions (bank protection removal at key sites and changing river flow rates due to the construction of water storage facilities).

Eighteen (18) different scenarios were modeled, comprised of three river segments, three flow scenarios, and two bank revetment scenarios (one with existing revetment and one with selected revetment removed.) The modeled migration was performed from simulated water year (WY) 2005 to 2059. The "base" flow was taken from recorded historical flows for WY 1939 to WY 1993 from three different gauges on the Sacramento River. Synthetic flows were provided to represent two other flow scenarios: NODOS (the proposed North of Delta Offstream Storage facility, or Sites Reservoir) and Shasta (the proposed 18.5 ft height increase for Shasta Dam). The meander migration output data show the centerline evolution, the area reworked, the migration rate for simulated migration from 2005 to 2059, and (in one case) the length of abandoned channel due to a predicted channel chute-cutoff.

One task of the study was to determine the magnitude of changes in area reworked attributable to changes in flow. When magnitudes of the total area reworked are compared for the three flow scenarios, the area reworked for the NODOS and Shasta flow scenarios varies from 90% to 100%, measured as a percentage of area reworked for the base flow scenario.

When magnitudes of cumulative effective stream power are compared for the three flow scenarios, the stream power for the NODOS and Shasta flows varies from 84% to 90% measured as a percentage of the stream power at base flow. Stream power is related to the magnitude of area reworked. The table below presents an example from the Woodson Bridge segment: the area reworked in the NODOS case is 95% of the area reworked in the base case, and the stream power for the NODOS case is 90% of the stream power in the base case.

There is a correlation between cumulative effective stream power and area reworked, but the correlation is not one-to-one. That is because factors other than flow and stream power influence the patterns of area reworked. Those factors include the channel planform and patterns of channel revetment.

NODOS flows over the modeling time period are smaller in magnitude than base flows. Accordingly the total area reworked in all three segments cumulatively between WY 2005 and WY 2059 decreases by 375,000 square meters ($m^2$) when NODOS flows are used for modeling area reworked. This is a decrease in 5% of the total area reworked when compared with the total area reworked by base flows in the same time and extent with revetment in place. For Shasta flows, the corresponding decrease is 425,000 $m^2$ (6%).

When a total of four revetment removal scenarios were modeled in the three segments, the area reworked between WY 2005 and WY 2059 increased by 575,000 $m^2$. This is an increase in 8% in total area reworked in the same time and full extent of all three segments with revetment in place. Note that the revetment removal scenario at Ord Ferry resulted in a slight decrease in area reworked, although it provided the immediate benefit of creating a length of abandoned channel. Excluding the Ord Ferry revetment removal, there was a total increase in 600,000 $m^2$ (8%) of area reworked by revetment removal in three locations combined.

For the channel migration simulations performed for this report, there was one simulated cutoff, near River Mile 179, which resulted from removing bank revetment. The length of abandoned channel created by that cutoff was about 2500 meters. Channel migration rates decreased subsequent to cutoff due to decreased channel length and decreased sinuosity.

The ability to quantify the area reworked due to flow changes and also due to revetment removal provides a quantitative method to compare the impacts of these different river management scenarios. This ability is useful in considering trade-offs or mitigation for flow or revetment changes proposed on the river. The results suggest that revetment impacts in very limited areas (three individual bends) are comparable (larger in magnitude but of a similar *order* of magnitude) to the effects of flow regulations (as defined in this study) over the entire three segments combined.

# 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 the 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 in flow, channel form, and bank erosion characteristics will alter the physical processes of channel migration.

This report presents the results of the Sacramento River meander migration study, a component of the Sacramento River Ecological Flows Study administered by The Nature Conservancy (TNC) with funding from the California Bay-Delta Authority's Ecosystem Restoration Program (CALFED grant ERP-02D0P61). The Sacramento River Ecological Flows Study was designed to help identify how management of key elements of the river's natural conditions can help promote a healthy ecosystem while simultaneously providing for human needs. The meander migration study is one of several efforts to address project goals by documenting how habitats in the riparian corridor have been affected by anthropogenic activity.

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

Objective 1. Incorporate a variable hydrograph component to the meander migration modeling procedure, and
Objective 2. Evaluate channel migration patterns resulting from management actions (bank protection removal at key sites and the construction of water storage facilities).

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). Previous versions of the model predicted meander migration as a function of a single, representative, geomorphically effective discharge; however, the model has been upgraded to assess the effects of a variable hydrograph on meander migration rates, thereby reflecting more realistic conditions in which meander migration occurs. In this report, “previous versions of the meander migration model” refers to all versions of the meander migration model that use a single, representative, geomorphically effective discharge, and “current, upgraded version of the meander migration model” refers to the version of the meander migration model that uses a variable hydrograph.

To help improve our understanding of how future flow scenarios may affect meander migration rates in the middle Sacramento River, with attendant effects on the formation of vertical cutbanks and off-channel habitats (e.g., oxbow lakes), Stillwater Sciences engaged the services of Eric Larsen to perform a number of tasks. This report describes the activities undertaken and results obtained in those tasks.

## 1.1 Study Area: River Segments Modeled

This section describes the segments of the Sacramento River where the current version of the meander migration was applied for meander migration modeling. The choice of segments was based in part on discussions with other members of the Sacramento River Ecological Flows Study team. The team decided to model migration with different flow scenarios from RM 170 to RM 222, separated into three distinct separate segments of roughly equal length (Figure 1). Beginning and ending points for each segment were altered depending on geomorphic characteristics of each segment.

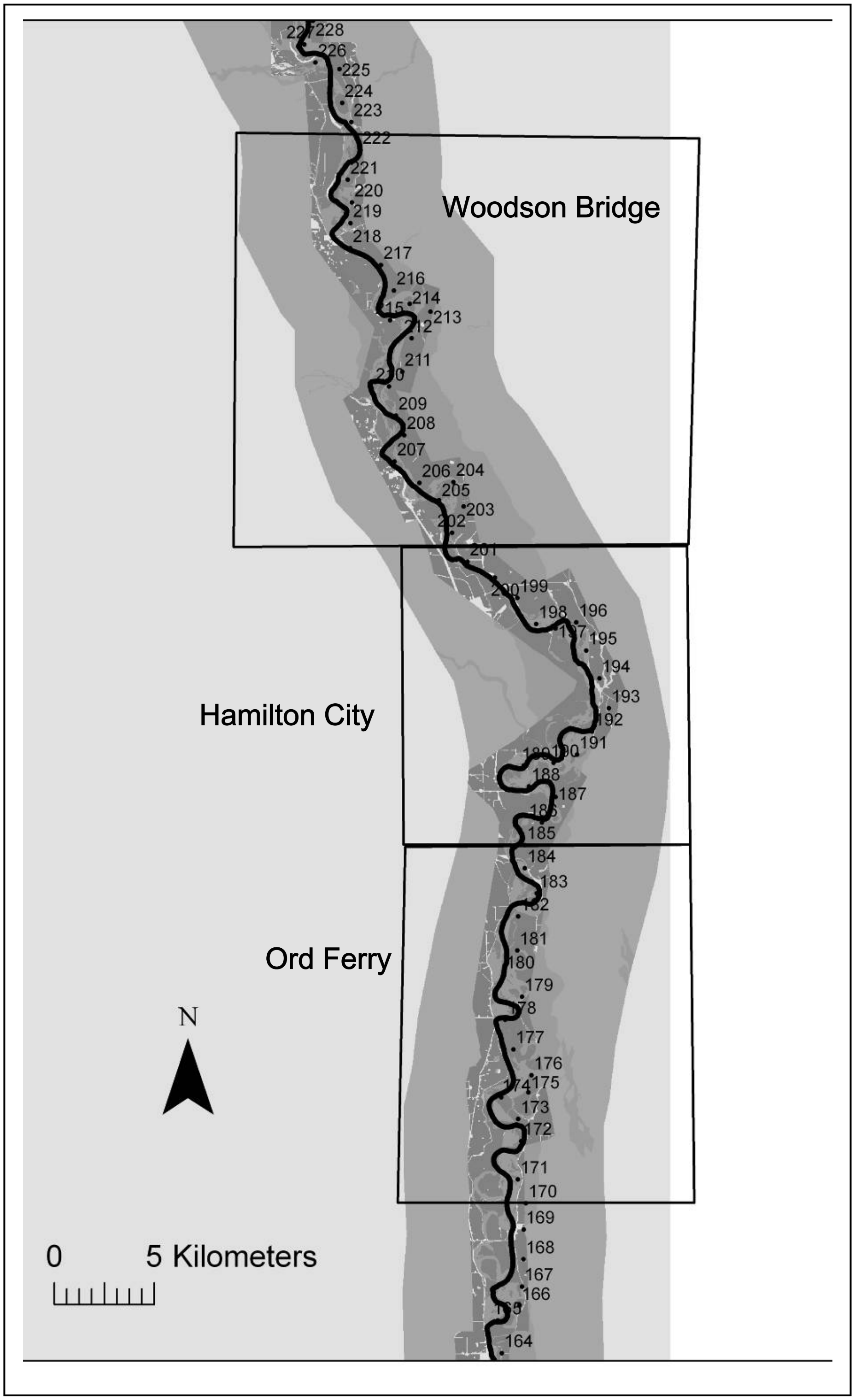

Figure 1 Sacramento River Study segments

### 1.1.1 RM 170-185: Ord Ferry Segment

This segment includes an area of potential cutoff modeling in the vicinity of RM 172 (Cui 2005). It also includes a series of individual meander bends (RM 171-176) that have similar sinuosity and radius of curvature and thus provides an effective comparison with typical meander bend sequences in other environments. Extending the modeling up to RM 185 extends this segment up to the beginning of the next study segment, providing continuous modeling from RM 170 to RM 222.

### 1.1.2 RM 185-201: Hamilton City Segment

This section of the river includes a series of bends that approximate classical "meander bend sequences" (i.e. RM 189– 192). These are good areas to study and model as they provide a series of bends (rather than single isolated bends) that are of similar curvature and wavelength and therefore make a sequence of similar bends (Leopold et al. 1964). Such classic bends provide a comparison with other areas, which are less typical. In addition, some of these bends, which are now restrained, have been suggested for mitigation sites, where bank revetment could be removed in mitigation for installing revetment in other places. Simulations here, with different flow scenarios, help inform future management actions.

Previous studies have been done in this segment. One study documents the historical changes in the segment (Larsen et al. 2002), and includes studies of morphology that is important for migration (i.e. curvature and sinuosity), calculation of historical areas of land reworked, and channel migration rates of the segment as a whole. This study also includes some simulations of future migration with an estimate of the changes in the morphology, the patterns of area reworked, and the migration rates. The model was calibrated with a spatially variable erosion field that was determined by calibration, but did not incorporate spatially variable erosion values based on GIS input of geology and vegetation. That model did not have the latest information on riprap and other installed bank revetment, and did not use variable flows.

There have been other studies in this area (Larsen 2004a, Larsen et al. 2004, Larsen 2005b, Golet et al. 2006, Larsen 2006, Larsen et al. 2006c) Some of these other studies have used a spatially varied erosion field, and limited information on bank restraint, but did not incorporate variable flows or updated bank revetment information.

### 1.1.3 RM 201-222: Woodson Bridge Segment

This segment includes Woodson Bridge State Recreation Area, which is an area of interest for possible removal of bank protection. Former modeling in the vicinity of Woodson Bridge did not use a spatially varied erosion field, did not incorporate variable flows, nor did it use updated bank revetment information.

# 2.0 METHODS

## 2.1 Fundamental Principles, Core Equations, and Assumptions

### 2.1.1 Principles and Core Equations

The underlying hypothesis is that the bank migration rate, in a specified time interval, is linearly related to the sum of the cumulative effective stream power in the same time interval.

In cases where hydraulic forces alter the stream (processes ranging from sediment transport to bed rock river formation), researchers have used stream power to represent the forces moving sediment (e.g. (Leopold et al. 1964, Begin 1981, Hickin and Nanson 1984, Sklar and Dietrich 2004). Leopold et al. 1964, based on the work of Bagnold 1960, argue from a mechanical standpoint that stream power represents "the rate of doing work ... by the flowing water." Available stream power, as defined by Leopold et al. (1964 p. 178) is:

$$\Omega = \gamma QS \qquad [1]$$

Stream power ($\Omega$, kg m/s$^3$) is a rate of potential energy expenditure per unit length of channel, calculated as the product of discharge (Q, m$^3$/s), slope (S, m/m), and the specific weight of water ($\gamma$, kg/m$^2$s$^2$). Equation 1 can be manipulated to express stream power as the product of bed shear stress times the mean streamwise velocity multiplied by width:

$$\Omega = \tau \ u \ w \qquad [2]$$

where $\tau$ (kg/ms$^2$) is the bed shear stress, u (m/s) is the velocity, and w (m) is the width of the channel. In this form, stream power is represented as a force (bed shear stress) times a velocity times a scale of the channel size (width).

Stream power (used as a surrogate for the sum of the flow forces acting on a specific segment of stream bank over a designated time period), can be related to bank erosion rates. Stream power can be calculated from surface stream flow records collected at various sites along the Sacramento River by the USGS and other organizations.

A threshold discharge ($Q_{\text{lower threshold}}$) below which erosion is negligible can be assumed. An upper threshold discharge ($Q_{\text{top of bank}}$) where the water flowing out of the channel theoretically no longer exerts force on the bank itself can also be assumed. Based on the results of an analysis to determine those thresholds (or a decision to ignore the thresholds based on the results of an analysis that shows that they are not significant), the instantaneous effective stream power ($\Omega_e$) can be calculated as:

$$\Omega_e = 0 \ \text{ if } Q <= Q_{\text{lower threshold}}, \qquad [3]$$
$$\Omega_e = \gamma SQ - \gamma SQ_{\text{lower threshold}} \quad \text{if } Q_{\text{lower threshold}} < Q < Q_{\text{top of bank}} \qquad [4]$$
$$\Omega_e = \gamma SQ_{\text{top of bank}} - \gamma SQ_{\text{lower threshold}} \quad \text{if } Q >= Q_{\text{top of bank}} \qquad [5]$$

where Q (m$^3$/s) is the mean daily flow rate at a site, estimated from available gauging records and S is water surface slope . The *cumulative* effective stream power ($\Omega_{ce}$) is then calculated by summing over the seconds in each measurement time interval:

$$\Omega_{ce} = \sum \Omega_e \qquad [6]$$

The basic assumption of this procedure is that the magnitude of bank migration, when flows that are below or above the thresholds are excluded, in a specified time interval is linearly related to the sum of the cumulative effective stream power in the same time interval.

Although previous versions of the meander migration model have been successfully used to assess planning issues (Larsen et al. 2002, Larsen and Greco 2002), those applications have employed a constant flow rate. A method to incorporate a daily flow hydrograph as the basis of modeling meander migration rates as a function of variable flow rates (current, upgraded version of the meander migration model) has been developed (Larsen et al. 2006a).

It has been shown that there is a simple linear regression that correlates the cumulative effective stream power, above a lower threshold, with rates of bank erosion at sites on the middle Sacramento River in California (CALFED 2000, Fremier 2003, Larsen et al. 2006a, Larsen et al. 2006b). This principle can be used to incorporate the effects of a variable flow into the meander migration model and can be used to scale the amount of river movement.

Annual power can be calculated by summing the daily stream power above a lower flow threshold during a given year (starting October 1). This assumes the river channel does not move when flows are less than the erosion threshold, and that the distance the river channel will move increases linearly as the stream power increases (Fremier 2003, Larsen unpublished data, Larsen et al. 2006a, Larsen et al. 2006b). A relative measure of stream power, *scaled annual cumulative effective stream power* ($\Pi_i$), can be calculated by the following formula:

$$\Pi_i = \frac{P_i}{\overline{P}_{calib}} \qquad [7]$$

where $P_i$ is the stream power for a given year *i*, and $\overline{P}_{calib}$ is the mean annual cumulative effective stream power for the calibration period.

### 2.1.2 Assumptions and Relationships Used in the Model

This section is a description of the assumptions and relationships used in the current version of the model (e.g., the combination of soil and vegetative cover information into an erosion surface).

#### 2.1.2.1 Heterogeneous Erodibility Surface

A heterogeneous erosion surface can be created using the geographic information system (GIS) ArcGIS 8.3 (ESRI 2003) and imported into the river meander migration model. The erodibility surface is developed by spatially combining a GIS dataset of geology, described above, with a GIS dataset of landcover, also described above.

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 et al. 2002, Micheli et al. 2004).

#### 2.1.2.2 Variable Hydrograph

This is a description of the use of a variable hydrograph in the model.

The scaled annual cumulative effective stream power (described in the section on scientific principles above) was directly incorporated into the meander migration model by multiplying $\Pi_i$ by the migration distance for each year based on a constant rate flow. Thus, during water years with half the average stream power ($\Pi = 0.5$), the model will simulate half as much migration as it would have for an average year, while in water years with three times the average cumulative annual stream power ($\Pi = 3$), the model will simulate three times as much migration as an average year.

Once a model run has been calibrated with a variable flow and heterogeneous erosion surface, the simulation capabilities of the meander migration model can be used to simulate river meandering under different daily hydrograph scenarios. Modelers can therefore simulate how the river would have moved in the past under a flow regime different from the one that occurred, and forecast how the river might migrate under different potential future management scenarios (Larsen et al. 2006a, Larsen et al. 2007).

## 2.2 Model Calibration

### 2.2.1 Calibration Input

Hydraulic input parameters are given in Tables 1 and 2, and are taken from HEC RAS runs for the Sacramento River from the USACOE and California Department of Water Resources (CDWR) Comp Study (USACOE 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).

**Table 1 Hydrologic and channel input values for migration model**

| River Segment | Q Channel | E.G. Slope | Top W Chnl | Hydr Depth |
|---|---|---|---|---|
| | (cms) | (m/m) | (m) | (m) |
| | | | | |
| WB | 2200 | 0.000445 | 218 | 5.01 |
| HC | 2181 | 0.000332 | 232 | 5.07 |
| OF | 2180 | 0.000297 | 277 | 4.91 |

$D_{50}$ 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).

**Table 2 D50 particle size of the bed surface material**

| Particle sizes (mm) | | | |
|---|---|---|---|
| | **D50** | | |
| | RM170-185 | RM185-201 | RM201-222 |
| Singer | 18 | 20 | 25 |
| WETS/DWR | 16 | 20 | 26 |
| Used in this study | 18 | 20 | 25 |

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 et al. 2003). To calibrate the model, 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 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 established 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.

#### 2.2.1.1 Cutoff Simulation

A cutoff simulation was used to account for bend cutoffs due to high flows during large storms. 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 model cutoffs, discrete single bends were analyzed for sinuosity to determine their cutoff potentials. The sinuosity of each bend was 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 of 1.8 was considered the threshold at which bends were allowed to cut off. This is a value that was established through calibration and from considering previous studies (Avery et al. 2003). The starting point of the cutoff was located at a calibrated distance (typically one-quarter of the bend upstream from the cutoff bend) and the ending point was established from calibration (e.g.: 10% along the length of the downstream bend.) Finally, the cutoff was simulated only if the straight line between the start and end points did not include revetment, levees, or geologic constraints to erosion. If the cutoff conditions were met, the river channel centerline points of the cutoff bend were simulated in a straight line between the start and end points.

### 2.2.2 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 really 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.

**Table 3 Model parameters for calibration and prediction runs**

| | Ord Ferry Calibration runs | Ord Ferry Prediction runs | Hamilton City Calibration runs | Hamilton City Prediction runs | Woodson Bridge Calibration runs | Woodson Bridge Prediction runs |
|---|---|---|---|---|---|---|
| **Erosion coefficients (Fd values)** | | | | | | |
| Non-erodible | 5,000-10,000 | 5,000-10,000 | 5,000-10,000 | 5,000-10,000 | 5,000-10,000 | 5,000-10,000 |
| Agricultural | 85 | 85 | 85 | 85 | 85 | 85 |
| Intermediate | 150 | 150 | 150 | 150 | 150 | 150 |
| Riparian | 250 | 250 | 250 | 250 | 250 | 250 |
| | Upst bend 45 | - | | | | |
| | FD= 20 near Llano Seco bend 20, restrained from cutoff; non-erodible | FD= 20 near Llano Seco bend | - | - | FD= 888 to restrain downstream limb of large loop mid-segment | FD= 888 to restrain downstream limb of large loop mid-segment |
| | Downst 25, non-erodible | - | - | - | - | - |
| Erosion field file (with revetment) | e0_veg_geo_rr_52b_OF_85_150_250_v6.asc | georrveg97ex_85_150_250a.asc | e0_veg_geo_rr_52b_calib_final.asc | georrveg97ex_85_150_250_final_run_all_rr.asc | e0_veg_geo_rr_52b_85_150_250_upres888.asc | georrveg97ex_85_150_250_4000atbend.asc |
| Erosion field file (removed revetment) | n/a | georrveg97ex_85_150_250a_wout_RM179rr.asc | n/a | georrveg97ex_85_150_250_wout_RM1901_2&197_8rr.asc | n/a | georrveg97ex_85_150_250_worr_rm221_4000atbend.asc |
| **Centerline properties** | SacRM OF | SacRM OF | SacR HC 1952 | SacRM HC | SacRM WB | SacRM WB |
| | UTM Z10 NAD 83 | UTM Z10 NAD 83 | UTM Z10 NAD 83 | UTM Z10 NAD 83 | UTM Z10 NAD 83 | UTM Z10 NAD 83 |
| | 1952 Start Channel | 2004 Start Year | 1952 Start Channel | 2004 Start Year | 1952 Start Channel | 2004 Start Year |
| | 1976 End Channel file written 26-May-2007 10:38:12 | 2060 Prediction file written 26-May-2007 10:52:01 | 1976 End Channel file written 27-May-2007 12:23:46 | 2060 Prediction file written 27-May-2007 13:31:18 | 1976 End Channel file written 26-May-2007 20:47:05 | 2060 Prediction |
| | Meander version: Meander 7.3.5: | Meander version: Meander 7.3.5: | Meander version: Meander 7.3.5: | Meander version: Meander 7.3.5: | Meander version: Meander 7.3.5: | Meander version: Meander 7.3.5: |
| **Flow Parameters** | | | | | | |
| Q (cms) | 2180 | 2180 | 2181 | 2181 | 2200 | 2200 |
| H (depth) (m) | 4.91 m | 4.91 m | 5.07 m | 5.07 m | 5.01 m | 5.01 m |
| B (width) | 277 m | 277 m | 232 m | 232 m | 218 m | 218 m |
| S (slope) (m/m) | 0.000297 | 0.000297 | 0.000332 | 0.000332 | 0.00045 | 0.00045 |
| Ds (mm) | 18 mm | 18 mm | 20 mm | 20 mm | 25 mm | 25 mm |
| Flow LowerThresh (cms) | 425 | 425 | 425 | 425 | 425 | 425 |
| Flow UpperThresh (cms) | 30000 | 30000 | 30000 | 30000 | 30000 | 30000 |
| Variable flow record used | Butte City Historic WY 1953-1976 | Butte City: Historic, NODOS, Shasta WY 1939-1994 | Hamilton City Historic WY 1953-1976 | Hamilton City: Historic, NODOS, Shasta WY 1939-1994 | Vina Historic WY 1953-1976 | Vina: Historic, NODOS (synthetic) , Shasta WY 1939-1994 |
| **Computational Parameters** | | | | | | |
| dyr | 1 | 1 | 1 | 1 | 1 | 1 |
| C_max | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Spacing | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Smoothing | 3 | 3 | 3 | 3 | 3 | 3 |
| Eo_Spacing | 1 | 1 | 1 | 1 | 1 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Cf_scale | 2 | 2 | 1.5 | 1.5 | 2 | 2 |
| Calc_uf | 1 | 1 | 1 | 1 | 1 | 1 |
| Check_curve | 1 | 1 | 1 | 1 | 1 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Cutoff Parameters** | | | | | | |
| Sinu Thresh | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| Recur. Int. | 2 | 2 | 2 | 2 | 2 | 2 |
| Cutoff Routine | 1 | 1 | 1 | 1 | 1 | 1 |
| | | | | Upstream Cut Fact = 0.25 | | |
| | | | | Downstream Cut Factor = 0.1 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Erosion Algorithm Parameters** | | | | | | |
| a--Eo | 1 | 1 | 1 | 1 | 1 | 1 |
| b--Depth | 0 | 0 | 0 | 0 | 0 | 0 |
| d--Erosion | 1 | 1 | 1 | 1 | 1 | 1 |

## 2.2.3 Calibrations: Centerline Agreement

### 2.2.3.1 Woodson Bridge Segment

Calibration in the Woodson Bridge segment (Figure 2) was performed starting with the observed 1952 and 1976 channel centerlines. The light solid line is the 1952 observed channel centerline; the bold solid line is the 1976 observed channel centerline; the dashed line is the 1976 modeled channel centerline. The agreement between the observed and simulated 1976 channel was visually assessed as adequate. 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 et al. 2006c).

This calibration adequately models the cutoff that occurred in the lower part of this river segment.

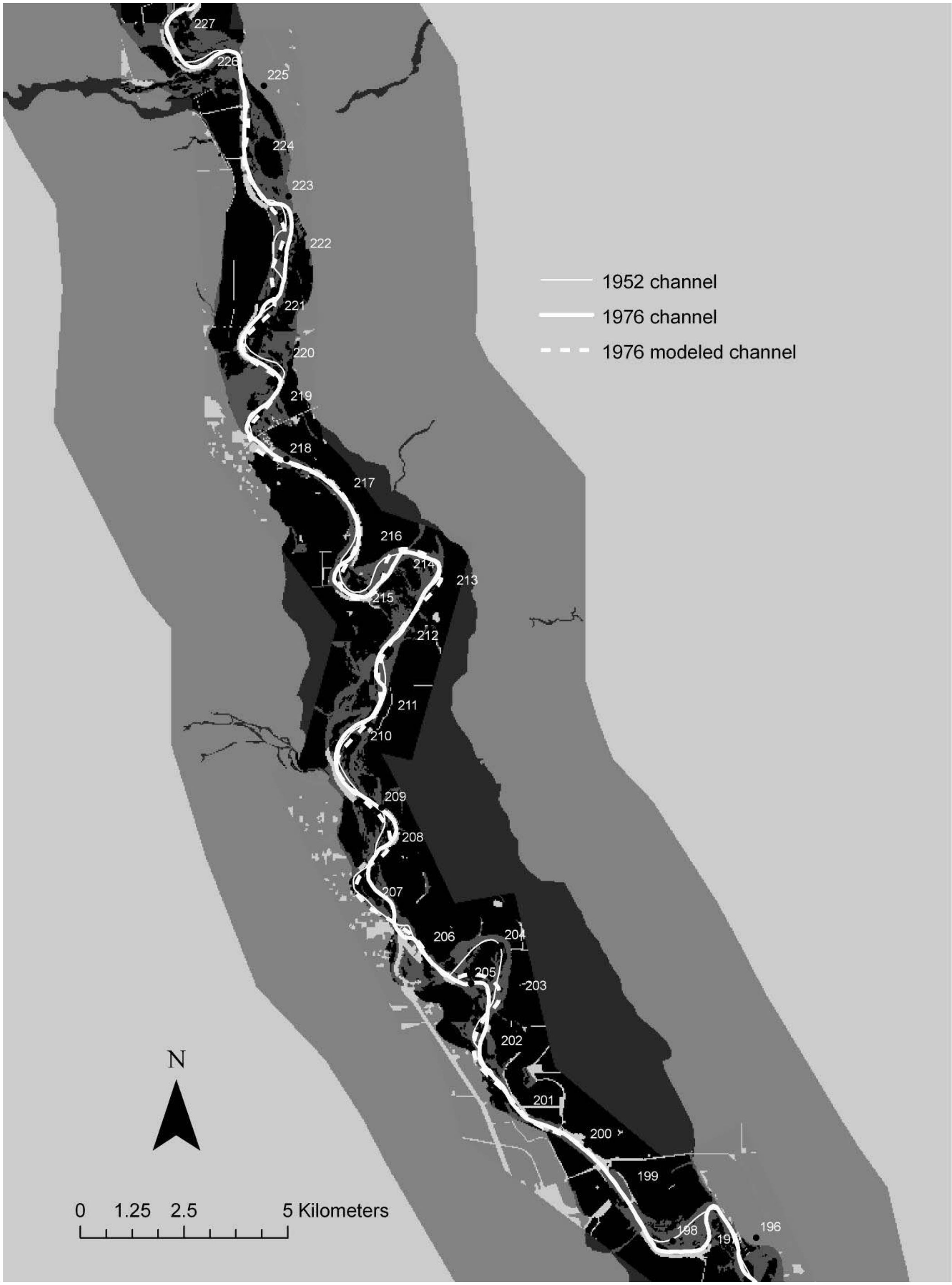

**Figure 2 Calibration Woodson Bridge segment**

#### 2.2.3.2 Hamilton City Segment

Starting with the observed 1952 and 1976 channel centerlines at the Hamilton City segment, calibration was performed (Figure 3).

The light solid line is the 1952 observed channel centerline; the bold solid line is the 1976 observed channel centerline; the dashed line is the 1976 modeled channel centerline. The agreement between the observed and simulated 1976 channel is good in the vicinity of the regular bends upstream from Stony Creek which enters from the west. This is a key place for calibration agreement in order to simulate future migration as it is an area of freely migrating fairly regular meander bends. Agreement in other areas was visually assessed as reasonable.

Note that agreement at Pine Creek in the north is not precise, as there was a "partial" cutoff (Micheli and Larsen In preparation) due to a mid-channel bar formation or island that led to the observed shape, which one would not expect the meander migration model to predict (Fremier, A. K. Personal communication, 2007). Predictive performance of the model would not be compromised by this.

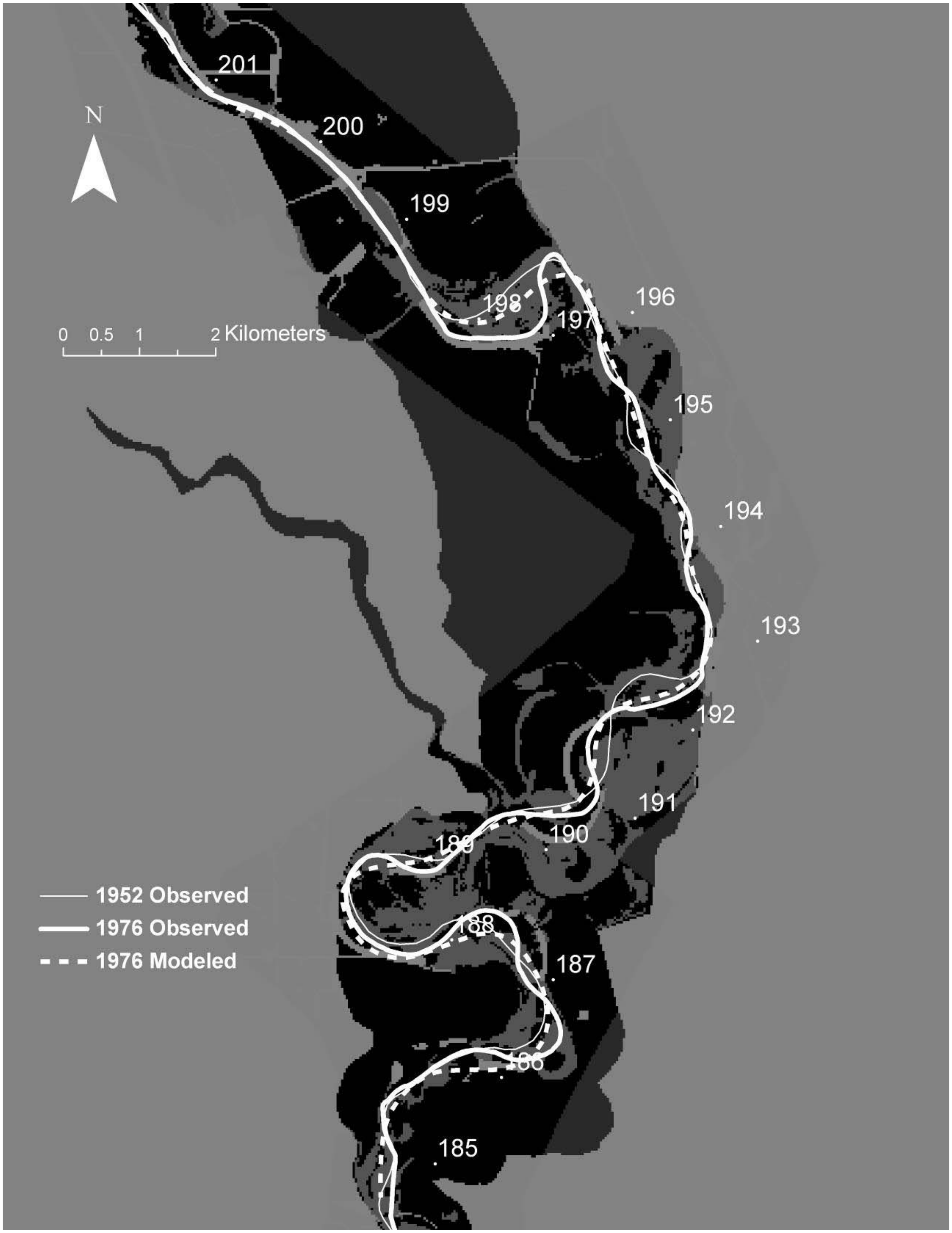

Figure 3 Calibration Hamilton City segment

#### 2.2.3.3 Ord Ferry Segment

Starting with the observed 1952 and 1976 channel centerlines, calibration was done. The light solid line is the 1952 observed channel centerline; the bold solid line is the 1976 observed channel centerline; the dashed line is the 1976 modeled channel centerline. Two areas of known revetment were included.

Areas were adjusted for erosion potential for calibration. The upstream bend was given a value of Fd = 45; the large looping bend in the middle was given a value of Fd = 20 and was restrained from cutting off by inserting a conceptual barrier to cutoff (calibration technique); the downstream bend was given a value of Fd = 25 and was adjusted with some erosion resistant areas.

A chute cutoff occurred in this time period and was simulated with the cutoff routine in the model. This type of cutoff is expected to be able to be predicted by the prototype cutoff routine that was used in modeling.

The agreement between the observed and simulated 1976 channel is good in most of the bends. Agreement in other areas was visually assessed to be acceptable.

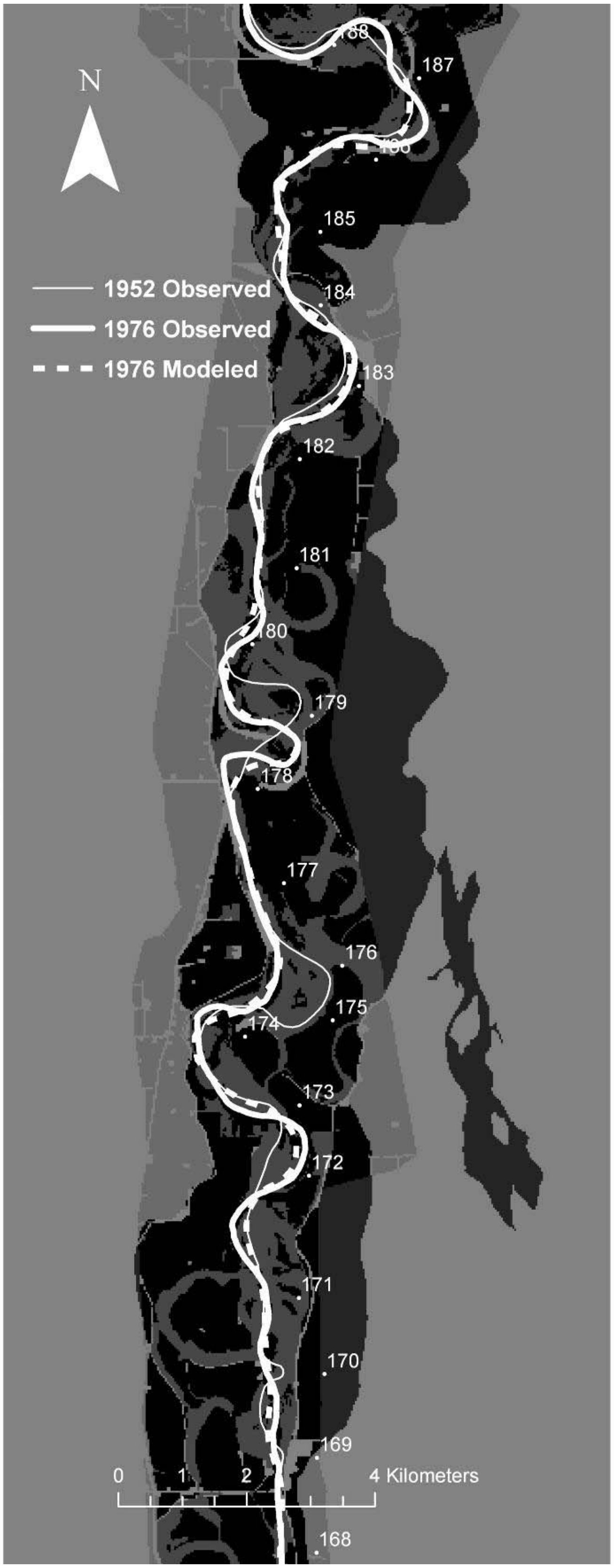

Figure 4 Calibration Ord Ferry segment

### 2.3 Model Input

This section includes a description of the data required as model input (e.g., the discharge records, land cover classification, soil information, etc.) for the current, upgraded version of the model. The hydraulic and geomorphic input that is required for both the previous versions and the upgraded version of the model is also described.

The model requires the following six input values reflecting the hydrology of the watershed and the hydraulic characteristics of the channel: 1) initial channel planform location, 2) characteristic discharge, 3) reach-average median particle size of the bed material, 4) width, 5) depth, and 6) slope. The reach-average width and depth are measured at the characteristic discharge, and slope is the average water surface slope for the reach. Using these data, the model calculates other parameters required to predict channel migration. For a detailed description of the calculation process, see Johannesson and Parker 1989.

#### 2.3.1 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).

Calibration was done using centerlines for 1952 and 1976. Predictions were done starting with a centerline from 2004. The 2004 centerline was developed from bankline drawings by CDWR (CDWR, Henderson, Personal communication, 2006).

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

#### 2.3.2. Daily flow data

Daily discharge data are required for calibration and simulation with the upgraded Meander Migration model. Calibration data can use mean daily flow rates obtained from gauging station records. As an example, when working with simulations at a bend near Pine Creek (RM 196-199) (Fremier 2003, Larsen et al. 2006a) the observed hydrograph for the years 1956 to 1975 was obtained from the California Department of Water Resources Bend Bridge flow gauge (number 11377100, (US Geological Survey 2004).

For the SacEFT model runs, calibration data was taken from historical daily average flow records at three gauges:

**Table 4 Calibration data from historical daily average flow records**

| USGS Discharge Gauge | | Meander Migration Model Segment | | |
|---|---|---|---|---|
| **Name** | **RM** | **Name** | **RM** | **RM** |
| SACRAMENTO R. AT VINA BRIDGE NR VINA CA.[1] | 218 | Vina/Woodson Bridge | 218 | 201 |
| SACRAMENTO R. NR HAMILTON CITY CA. [2] | 199 | Hamilton City | 185 | 201 |
| SACRAMENTO R. AT BUTTE CITY CA. | 168 | Butte City | 170 | 185 |

[1] Two missing data segments at this station (1-Oct-1938 – 12-Apr-1945; 1-Oct-1978 – 30-Sep-2004) interpolated by linear regression of incomplete "SACRAMENTO R A VINA BRIDGE NR VINA CA" *v.* complete "SACRAMENTO R AB BEND BRIDGE NR RED BLUFF CA": (1.2459 x BendBridge – 1364.5) (Yantao Cui, Stillwater Sciences, pers. comm.)

[2] Three missing data segments at this station (1-Oct-1938 – 20-Apr-1945; 15-Jan-1956 – 18-Jun-1956; 3-Oct-1980 – 30-Sep-2004) interpolated by linear regression of incomplete "SACRAMENTO R NR HAMILTON CITY CA" *v.* complete ""SACRAMENTO R AB BEND BRIDGE NR RED BLUFF CA": (1.2047 x BendBridge – 1987.4) (Yantao Cui, Stillwater Sciences, pers. comm.)

Once the calibration was completed, these historical daily flows were then run for the full 56 year period of record for two scenarios of channel confinement: (a) current conditions and (b) revetment removal.

In addition to the historical flow scenario, the Meander Migration Model utilized daily flows taken from two scenarios created by the CALSIM – SRWQM – HEC5Q (USBR-TMS) modeling complex: "Shasta +18.5ft" and "NODOS." The first of these scenarios simulates hydrosystem management under a scenario in which the Shasta dam is raised; the second hydrosystem management using of additional storage at the proposed Sites Reservoir.

Both scenarios are provisional in nature because the daily disaggregation of simulated flow is known to be flawed below Red Bluff Diversion Dam (RM 243). Although they were provided for model testing purposes only, they demonstrate possible contrasts between current conditions and revetment removal. An example simulation is described below.

#### 2.3.2.1 Simulation

One example of simulation input data is CALSIM II data produced by the California Department of Water Resources North of Delta Off-Stream Storage (NODOS) project (California Department of Water Resources 2003). Daily flow management scenarios can be simulated using the computer program CalSim II. These simulations estimate the daily river flows that would have occurred under different water management scenarios, based on actual river flows.

For both the calibration and simulation, daily discharge records are transformed into ".DAT" files with two columns, the daily date, and the mean daily discharge for that day. Table 5 shows the form of the data used. The sample shows the discharges for a few days; the input data set would have this record for a period of years. In the input file, only the digital form of the date is used.

**Table 5 Sample discharge data: input to upgraded model**

| Date | Date (digital format) | Q (cms) |
|---|---|---|
| 10/31/1971 | 26237 | 243 |
| 11/1/1971 | 26238 | 210 |
| 11/2/1971 | 26239 | 207 |
| 11/3/1971 | 26240 | 202 |
| 11/4/1971 | 26241 | 195 |
| 11/5/1971 | 26242 | 187 |
| 11/6/1971 | 26243 | 179 |
| 11/7/1971 | 26244 | 171 |
| 11/8/1971 | 26245 | 159 |
| 11/9/1971 | 26246 | 151 |
| 11/10/1971 | 26247 | 148 |

### 2.3.3 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 from 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.

#### 2.3.3.1 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 5.

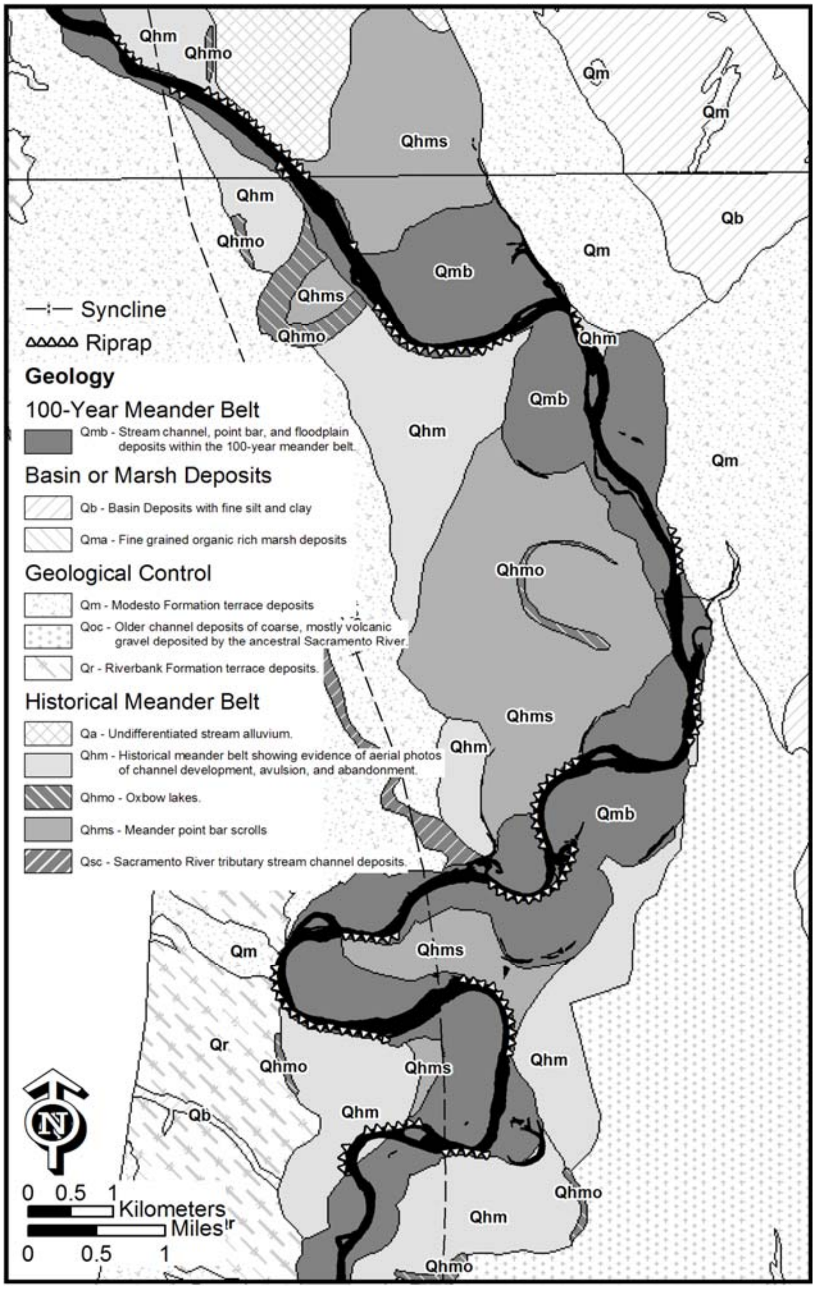

**Figure 5 Geology (soils) coverage map (Larsen et al. 2006c)**

### 2.3.3.2 Vegetation Coverages (1952 and 1976)

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) 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 6.

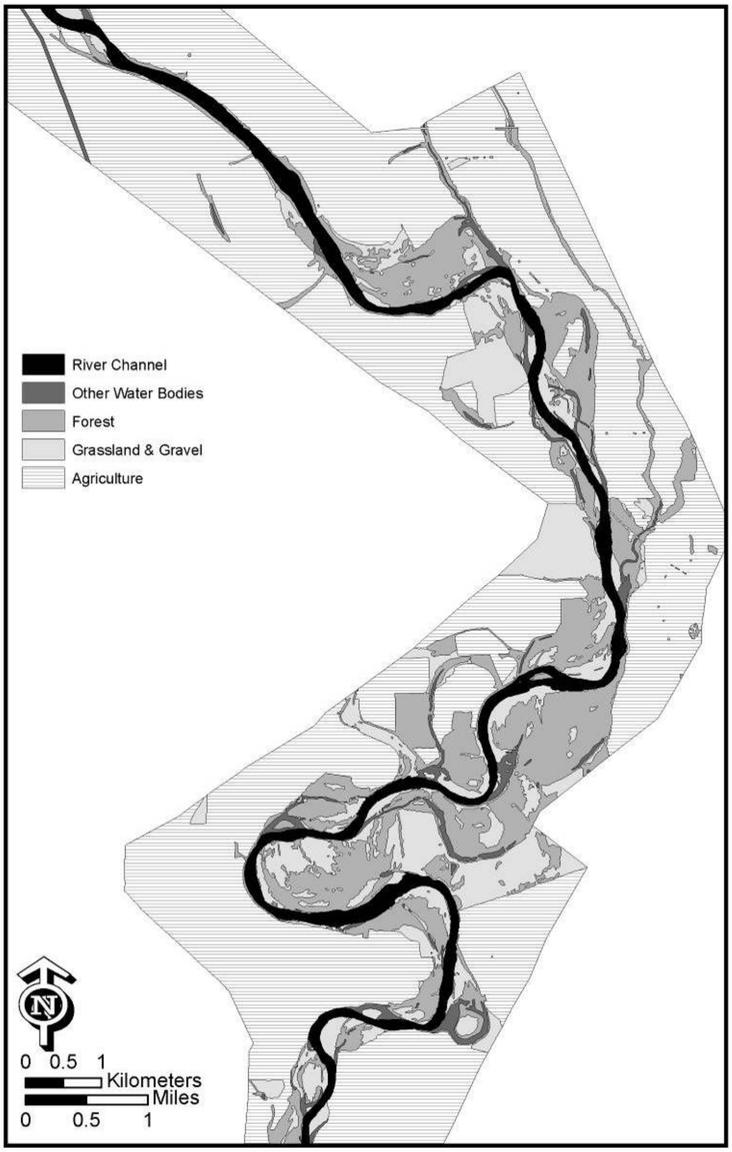

**Figure 6 Land classification coverage map (Larsen et al. 2006c)**

### 2.3.3.3 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, 2006). The revetment was buffered and combined with the erosion potential grid (Environmental Systems Research Institute 2004); areas within the buffered revetment were given an erosion potential value of zero (i.e., non-erodible). Three different revetment scenarios were developed: 1976 existing revetment; 2004 existing revetment; and 2004 existing revetment with site-specific revetment removal (TNC memo) at selected sites. Sites where revetment removal was modeled are located on conservation lands where impacts on private lands and critical infrastructure are not anticipated. Nonetheless, further analyses and additional stakeholder and agency input would be required before any such projects are initiated.

*Woodson Bridge Segment*

For the calibration run from 1952 to 1976 in the Woodson Bridge segment, there were 11 locations that were restrained with reported revetment (Figure 7) 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 (CDWR 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 2005-2059, there were approximately 23 locations of channel restraint (Figure 8), which were incorporated in the heterogeneous erosion field and were set as non-erodible. These 23 were defined in the revetment database (CDWR 2006), and many of the individual “cases” were small segments that ultimately were joined with other individual smaller cases to constitute a continuous revetment installation. Again, installation dates were not given in the database.

For prediction runs, the 2004 revetment coverage was used with the revetment at RM 220-222 (right bank) at Kopta Slough removed.

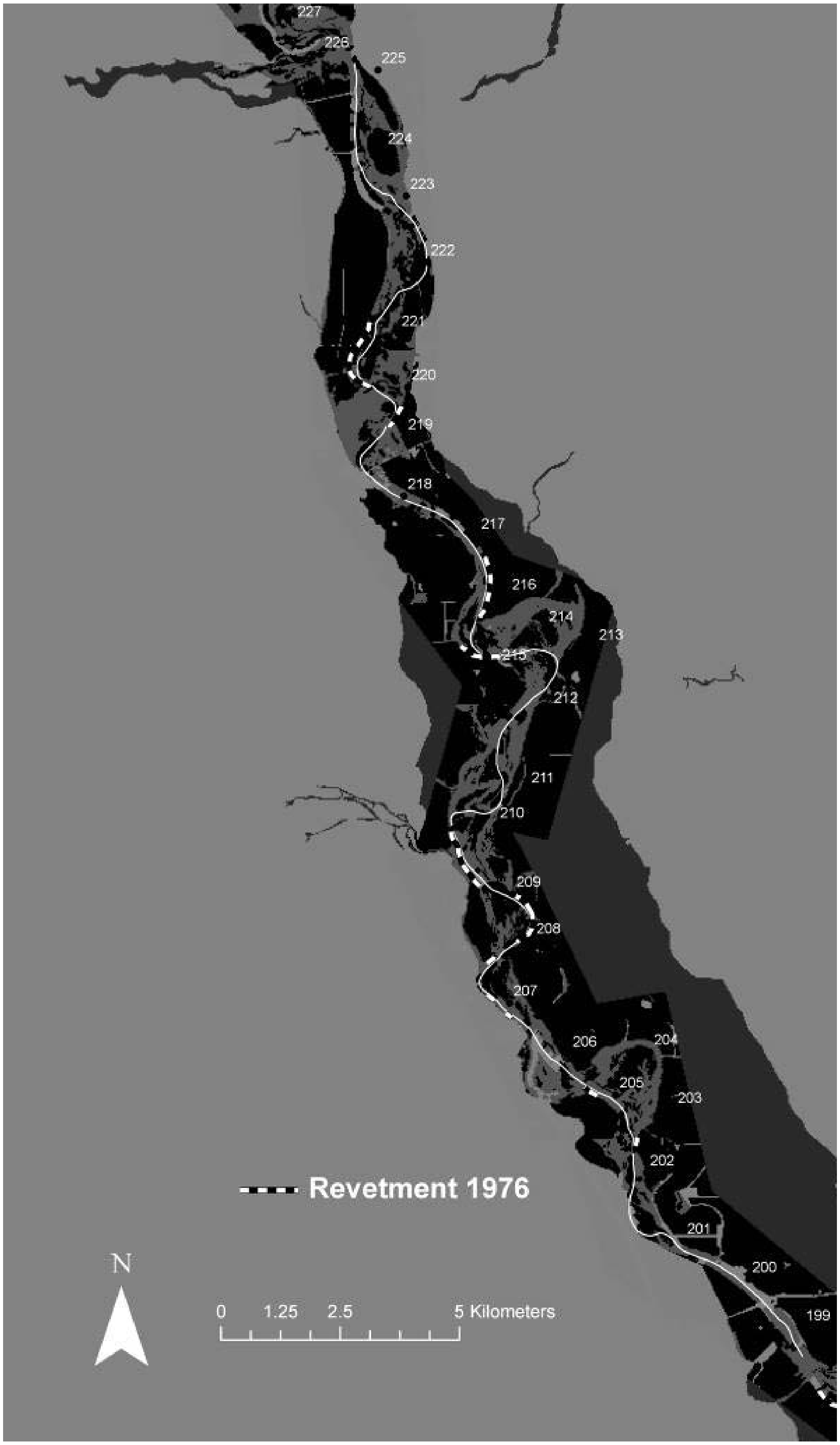

Figure 7 Woodson Bridge segment revetment coverage 1976 (2004 channel)

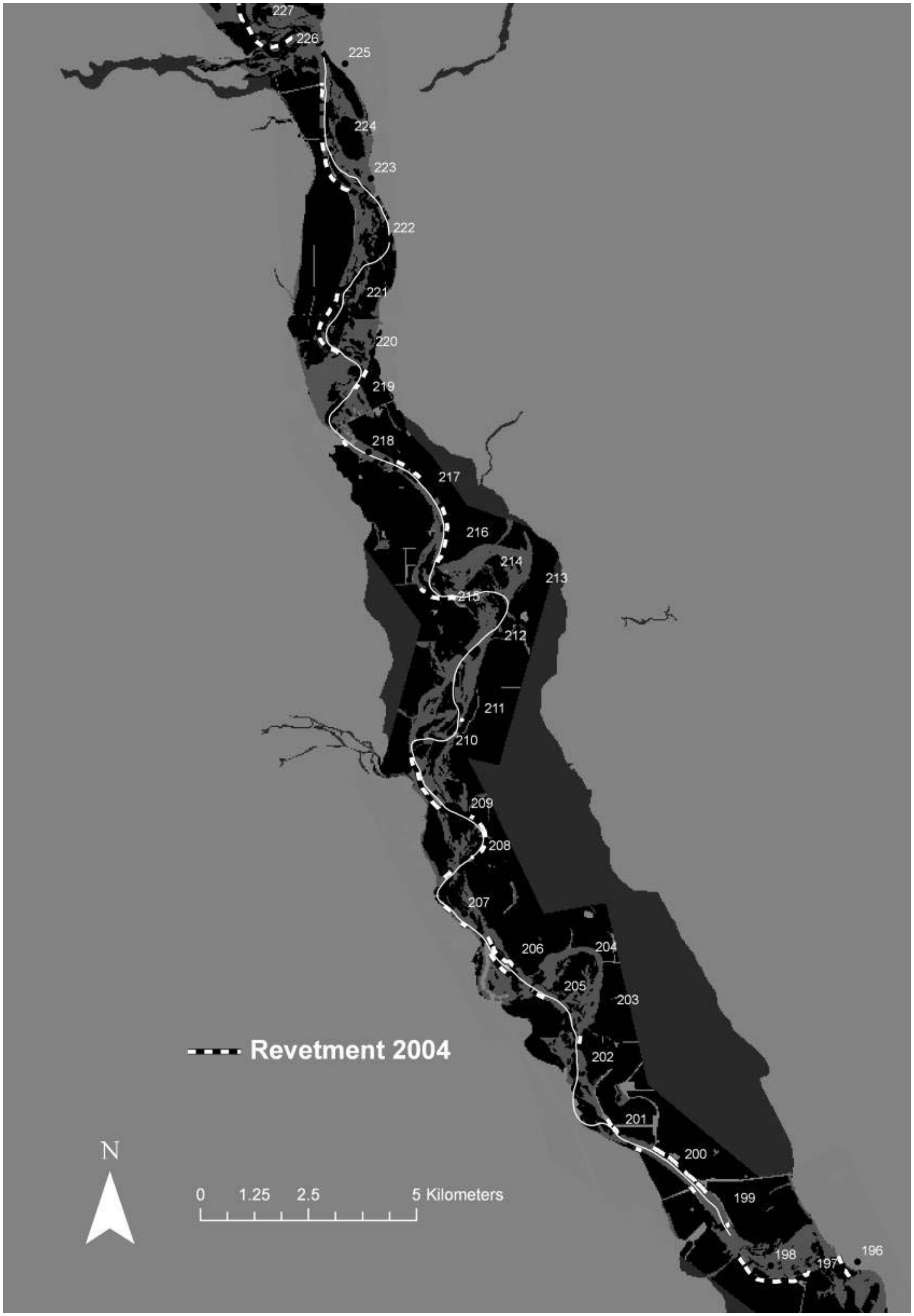

**Figure 8 Woodson Bridge segment revetment coverage 2004 (2004 channel)**

*Hamilton City Segment*

For the calibration run from 1952 to 1976 in the Hamilton City segment, there were four locations that were restrained with reported revetment (Figure 9). These were incorporated into the heterogeneous erosion field for the calibration run and were set as non-erodible.

For the predictions with existing revetment, from 2005-2059, there were 17 locations of channel restraint (Figure 10), which were incorporated in the heterogeneous erosion field and were set as non-erodible. Installation dates were available for all of the revetment work in the Hamilton City segment. These dates were used, when available, to determine if the revetment was in place before 1976 so that it would be modeled in the calibration.

For prediction runs, the 2004 revetment coverage was used with the revetment at RM 197-198 (right bank) and RM 191-192 (right bank) removed.

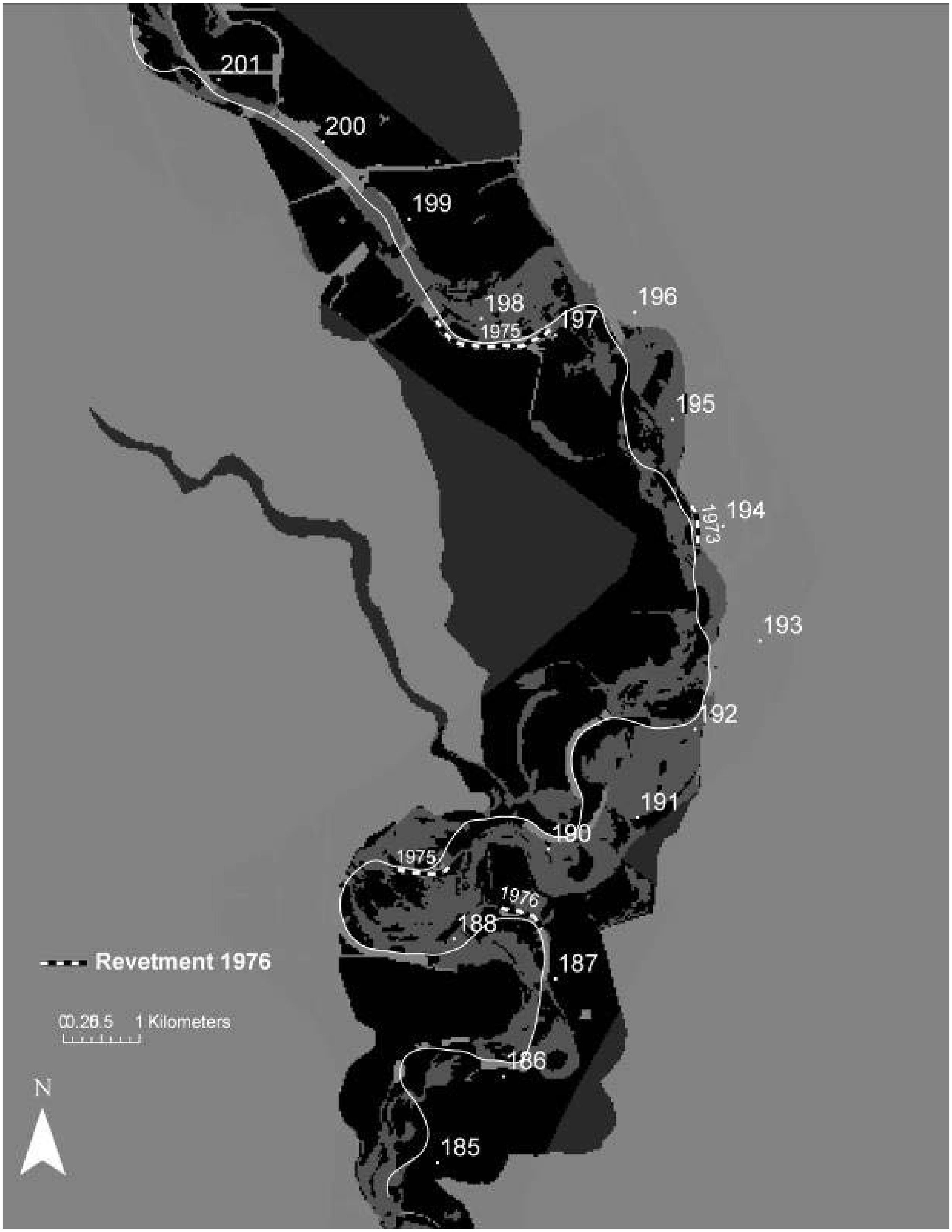

**Figure 9 Hamilton City segment revetment coverage 1976 (1997 channel)**

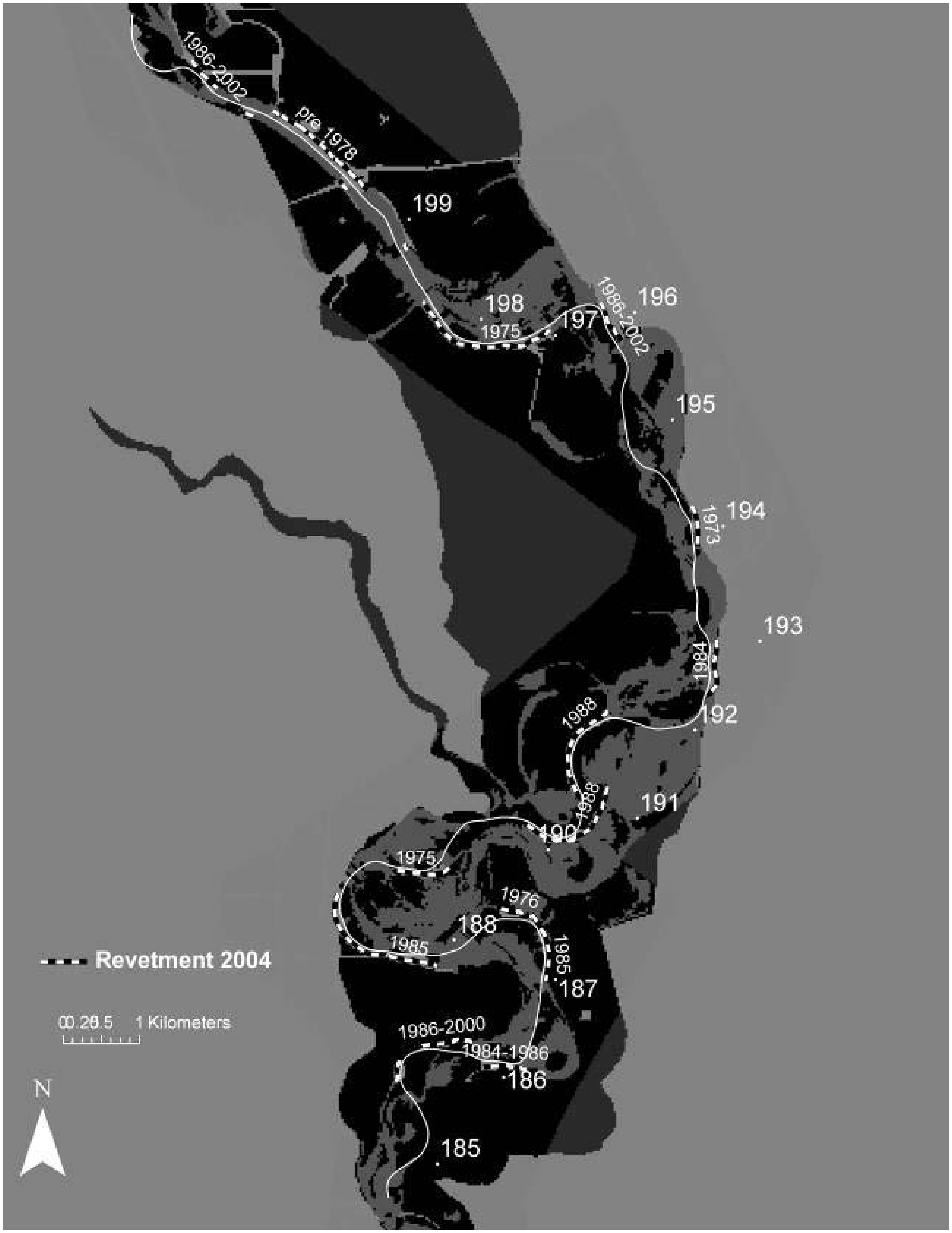

**Figure 10 Hamilton City segment revetment coverage 2004 (1997 channel)**

### *Ord Ferry Segment*

For the calibration run from 1952 to 1976 in the Ord Ferry segment, there were 2 locations that were restrained with reported revetment (Figure 11). These were incorporated into the heterogeneous erosion field for the calibration run and were set as non-erodible.

For the predictions with existing revetment, from 2005-2059, there were 7 locations of channel restraint (Figure 12), which were incorporated in the heterogeneous erosion field for the predictive runs and were set as non-erodible.

For prediction runs, the 2004 revetment coverage was used with the revetment at RM 179 (right bank) at the Llano Seco Riparian Sanctuary removed.

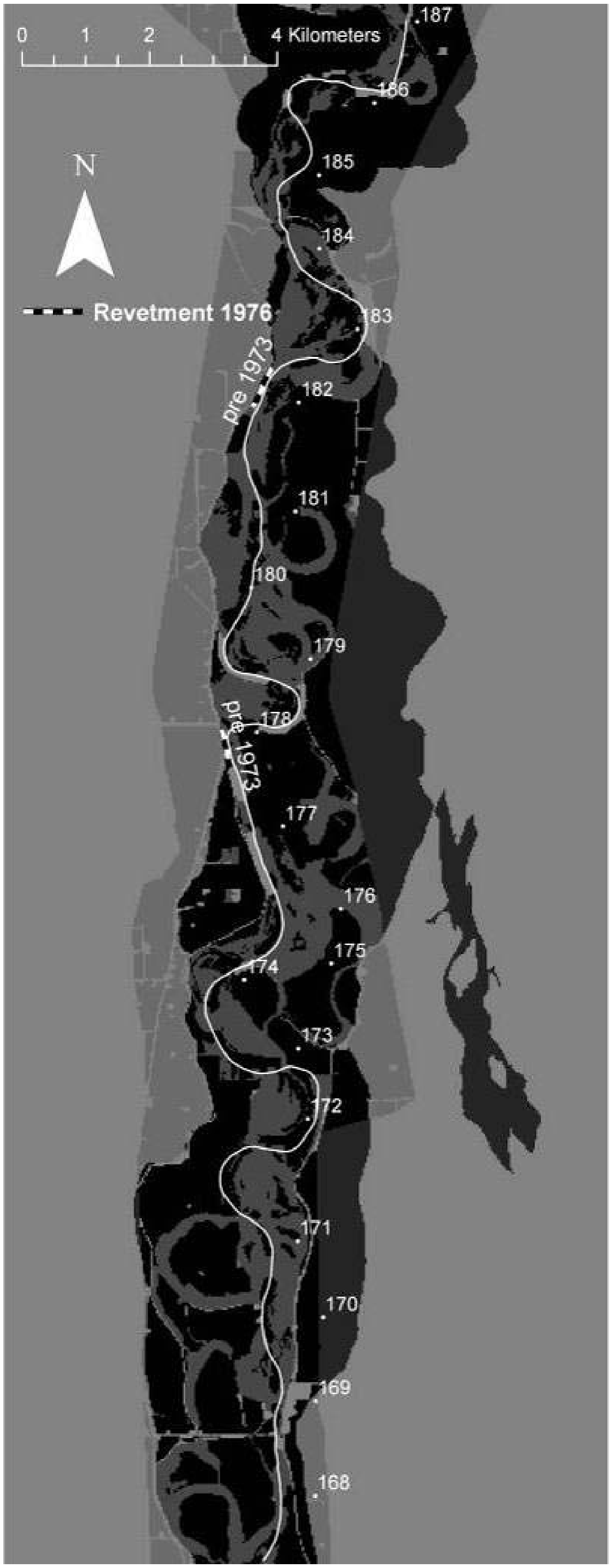

**Figure 11 Ord Ferry segment revetment coverage 1976 (2004 channel)**

## 2.4 Modeling Scenarios

Figure 12 Ord Ferry segment revetment coverage 2004 (2004 channel)

### 2.4.1 River Segments Modeled

The segments of the Sacramento River that were used for meander migration modeling were located from RM 170 to RM 222, separated into three distinct segments, as described in the introduction.

### 2.4.2 Historical and Modeled Flows Used for Meander Migration Modeling[1]

Migration modeling was done for three different flow scenarios, all of which spanned the same time frame: base (historical) flows, NODOS flows, and Shasta +18.5 flows. All flows were provided by the California Department of Water Resources (CDWR) to ESSA technologies.

#### 2.4.2.1 Historical Flows

One goal of the modeling is to compare the ecological performance measures for historical flows across the three segments and two treatments. In this case, it is important to use the Base/Historical discharge for the meander migration simulations, a total of 6 simulations:

$\{\text{Historical}\}_{\text{flows}}$ X $\{\text{Vina, Hamilton, Butte City}\}_{\text{segments}}$ X $\{\text{revetment, no revetment}\}_{\text{treatments}}$

Data from the Vina (also called Woodson Bridge), Hamilton City, and Butte City gauges provided the historical flow data. At issue was uncertainty about the best way to fill in missing data for the modeled NODOS flow at the Vina/Woodson Bridge segment.

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[1] The bulk of this section was originally written by Don Robinson of ESSA technologies: electronic memo of June 22, 2007.

**Table 6 Flow data available from CDWR**

| Segment Name | River Miles | Scenario / Gauge Name | | |
|---|---|---|---|---|
| | | Base / Historical | NODOS | Shasta +18.5 |
| Vina<br>Woodson Bridge | 201 – 222 | VINA | *<not provided in time for analyses>* | VINA[2] |
| Hamilton City | 185 – 201 | HAMILTON | HAMILTON | HAMILTON |
| Butte City<br>Ord Ferry | 170 – 185 | BUTTE CITY | BUTTE CITY | BUTTE CITY |

At each of the 3 study segments (identified in Table 6) there were 3 flow scenarios (base historical, NODOS, and Shasta +18.5) and 2 treatment scenarios (complete revetment removal and no removal), yielding a total of 18 permutations for the Meander Migration model.

### 2.4.2.2 Water Management Scenarios

Two modeled discharge scenarios are part of the SacEFT modeling process: NODOS and Shasta +18.5ft. Of particular concern for migration modeling was the absence of discharge data for the Vina/Woodson Bridge segment for the NODOS scenario.

After discussion (Alexander C., Robinson D., Personal communication, 2007) about ways to combine all the available data *and* provide a plausible NODOS discharge for Vina, it was decided to use the daily relationship between Vina and Hamilton from the Shasta +18.5 scenario to infer a discharge for the NODOS scenario at Vina. This assumes that the Vina- Hamilton link in the Shasta +18.5 scenario can be used to infer a Vina-Hamilton link in the NODOS scenario, given the Vina data in the NODOS scenario. This simple assumed relationship can be expressed as:

$$\frac{VINA_{NODOS,t}}{HAMILTON_{NODOS,t}} = \frac{VINA_{Shasta,t}}{HAMILTON_{Shasta,t}}$$

Rearranging, this becomes:

$$VINA_{NODOS,t} = \left( \frac{VINA_{Shasta,t}}{HAMILTON_{Shasta,t}} \right) \times HAMILTON_{NODOS,t}$$

This we have called the *synthetic* Vina discharge for the NODOS scenario. Although there remains uncertainty about the actual value that would have been reported at Vina

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[2] Following discussions with CDWR modelers (telephone conversation with Chandra Chilmakuri, CH2M Hill, June 8, 2007), it appears that the Woodson Bridge reporting location from the Shasta +18.5 scenario is synonymous with the Vina gauge location. This reporting location is now named VINA in the model database.

for the NODOS scenario, this approach has the benefit of maintaining the temporal correlation with the adjacent NODOS reporting location at Hamilton while incorporating the between-site relationship seen in another SRWQM disaggregation.

**Table 7 SacEFT flow scenarios**

| **Segment Name**[3] | **River Miles** | **Scenario / Gauge Name** | | |
|---|---|---|---|---|
| | | **Base / Historical** | **NODOS** | **Shasta +18.5** |
| Vina Woodson Bridge | 201 – 222 | VINA | $\boldsymbol{VINA_{synth}}$ | VINA |
| Hamilton City | 185 – 201 | HAMILTON | HAMILTON | HAMILTON |
| Butte City (Ord Ferry) | 170 – 185 | BUTTE CITY | BUTTE CITY | BUTTE CITY |

### 2.4.3 Revetment Removal

Six different sites were identified as potential for revetment removal (TNC, Personal communication) as listed in Table 8. Five sites (sites 2-6) fall within the river segments modeled for this report. Simulations were done with four of these sites removed (as described in model input in Section 1). Table 8 includes descriptions of the criteria used to choose the sites, relevant studies related to the sites, and a reference numbers assigned to each site in a related Google Earth file.

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[3] The “Vina” segment is called “Woodson Bridge” in this report; the “Butte City” segment is called “Ord Ferry” in this report.

## Table 8. Potential revetment removal sites on the middle Sacramento River (TNC 2007)

**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**

A. Department of Water Resources, Northern District, 1991, 25 and 50-year erosion projections for the Sacramento River.
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.
C. Larsen, Eric, 2002. The Control and Evolution of Channel Morphology of the Sacramento River: A Case Study of River Miles 201-185. University of California, Davis, Davis, California.
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

There were a total of 18 scenarios that were modeled: these are comprised of three river segments, three flow scenarios, and two bank revetment scenarios (3×3×2=18). The runs are summarized in the following table. File names that were used are shown.

**Table 9. Meander migration scenarios**

With existing revetment

| **Flow** | WB | **HC** | OF |
|---|---|---|---|
| base | ***WB - base – wrr*** | *HC* ***- base – wrr*** | ***OF - base - wrr*** |
| NODOS | ***WB - NODOS - wrr*** | *HC* ***- NODOS - wrr*** | ***OF - NODOS - wrr*** |
| Shasta | ***WB - Shasta - wrr*** | *HC* ***- Shasta - wrr*** | ***OF - Shasta - wrr*** |

Without selected revetment

| **Flow** | WB | **HC** | OF |
|---|---|---|---|
| base | ***WB - base – worr*** | *HC* ***- base – worr*** | ***OF - base - worr*** |
| NODOS | ***WB - NODOS - worr*** | *HC* ***- NODOS - worr*** | ***OF - NODOS - worr*** |
| Shasta | ***WB - Shasta - worr*** | *HC* ***- Shasta - worr*** | ***OF - Shasta - worr*** |

The results were listed by river segment. For each segment (WB: Woodson Bridge, HC: Hamilton City, and OF: Ord Ferry) the report results follow the same pattern. First a map of the channel migration for the *base flow and existing revetment* will be shown. Channel centerlines are shown for every fifth year from modeled year 2005 to 2059. The maps for the NODOS and Shasta flows (which are almost identical to the base flow case) are included in Appendix 2.

Second the effects of *revetment removal* are illustrated by showing the modeled migration in the vicinity of the area where the revetment was removed. The migration for the rest of the segment is almost identical to the base case with existing revetment, and is not shown. The movement for the base, NODOS, and Shasta flows is essentially identical, as the figures in Appendix 3 illustrate.

Third, an image of the extent of the sub-segments that were analyzed is shown. Calculation of area reworked and migration rate is done for individual sub-segments. These were chosen by eye to represent areas that are roughly one bend in extent. The extent was adjusted in some cases to account for river segments that are straight or that did not migrate significantly. In some cases the extents were adjusted to account for area calculation processes.

Fourth, representative graphs of area reworked and migration rate are shown by river sub-segment. For each segment, the data will be shown in two graphs (with all existing revetment and with selected revetment removed). Each sub-segment graph (one for with and one for without revetment) includes data for all three flows.

Fifth, length of "abandoned channel" is described for the one cutoff that occurred in all of the modeling, in the Ord Ferry segment subsequent to revetment removal.

### 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 13). 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).

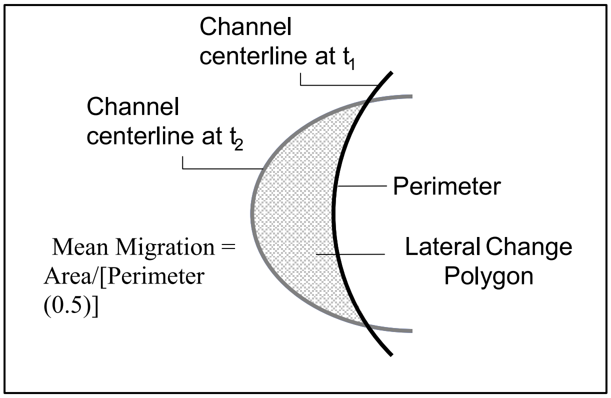


**Figure 13 Definition of area reworked polygon**

### 2.7 Migration Rate Defined

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 (Environmental Systems Research Institute 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:

$$\frac{A_r}{tL} \qquad [8]$$

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 8 calculates the migration rate as a linear distance per time; the rate of land reworked is reported as an area per time, by using Equation 4 without dividing by the length (*L*).

Graphs of area reworked and migration rate will have identical shapes, but units and scale differ. Because one segment may have a larger length (for example) than another, only knowing the area reworked does not tell you the relative dynamism of two segments.

When the channel movement is normalized by length, one can compare the rates at which the two segments move.

### 2.8 Length of Newly Abandoned Channel Defined

The length of newly abandoned channel was estimated using a prototype channel cut-off model that has been developed, and was used in conjunction with the meander migration model. Based on empirical studies that have been done to quantify the changes in channel planform shape of the Sacramento River from Colusa to Red Bluff, a threshold geometry for chute cutoff has been investigated and estimated (Avery et al. 2003, Larsen and Micheli In preparation).

The data from those studies show that geometric parameters can serve as a predictive indicator for the geometry that is likely to experience chute cutoff. On a study of about 100 years of channel migration from River Mile 143 to 243 (Colusa to Red Bluff), bends that experienced chute cutoff displayed a characteristic average sinuosity and other geometric characteristics. These findings suggest that the likelihood of a bend being prone to experience chute cutoff on the Sacramento River may be estimated based on centerline geometry for a range of channel slopes typical of the meandering portion of the Sacramento River.

Average and calibrated data were used with the modeling scenarios in the meander migration model to estimate when a channel would be prone to cutoff. The geometric parameters used were a sinuosity of 1.8 and a distance across the meander “neck” of 1200 meters or less. In addition to the geometric parameters, the model tested for the occurrence of “overbank flow” or a 2-yr recurrence interval flow before a cutoff would be simulated. An estimate was made of the upstream location of cutoff and downstream reattachment. The modeled cutoff commenced 0.25 bend lengths upstream from the upstream inflection point (of the cutoff bend) and joined the channel 0.1 bend lengths downstream from the downstream inflection point. Finally, the cutoff was simulated only if the straight line between the start and end points did not include riprap, levees, or geologic constraints to erosion. From this, the length of “abandoned channel” was measured and reported for use in the SacEFT database.

### 2.9 Limitations and Interpretation of Model Results

This section describes limitations of the current, upgraded version of the meander migration model or caveats regarding the interpretation of expected model results.

#### 2.9.1 Models and Simulations

As with other simulation models (e.g. Montgomery and Dietrich 1993, Sklar and Dietrich 2004), the variable flow 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 flow scenario would result in 35% more land reworked (arbitrary example) than another scenario.

### 2.9.2 Streampower

The linear regression relationship that is used between stream power and bank erosion probably does not express the entire relationship between flow rates and bank erosion rates. For example, flow duration may play a role. And although a linear relationship can be effectively used between cumulative effective stream power and erosion, there has been shown a tendency for higher discharges to have proportionally less effect (suggesting a non-linear relationship) (Larsen et al. 2006b). The practical way to deal with this limitation is to do an analysis of a theoretical "upper threshold", above which flows may or may not be excluded from the sum of effective stream power (Larsen et al. 2006b).

Although the migration rates predicted by a variable-flow model significantly correlated with the observed scaled stream power in a very limited study area of RM 196-199 (Larsen et al. 2006a), the correspondence was not exact because stream power is not the only parameter that contributes to bank erosion. Local bank erosion is complex and includes processes that are not directly proportional to flow rates, independent of other factors. For example, bank collapse may occur as a function of rapidly declining flow rates. For this reason, sums of events over a time span (longer than a single event) may be more accurately simulated than smaller-scale time spans like a single flow event.

### 2.9.3 Tributary Influences

Although it has been suggested that bends at or just downstream from stream tributary confluences migrate faster due to sediment input (Constantine et al. 2004), analyses of stream power data do not show this pattern (Larsen et al. 2006a). In a study of bank erosion and stream power (Larsen et al. 2006a), areas with the highest mean average erosion rates are not 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 14). From these, three other types of data have been calculated: 1) area reworked, 2) migration rate, and 3) length of abandoned channel.

### 3.1.1 River Segment Output

#### 3.1.1.1 Woodson Bridge Segment

*Predictions with base flow and existing revetment*

Figure 14 shows the migration in five year increments from 2005 to 2059. The migration patterns using the NODOS and Shasta flows are similar in pattern and are shown in Appendix 2. The total area reworked by each flow scenario is given below.

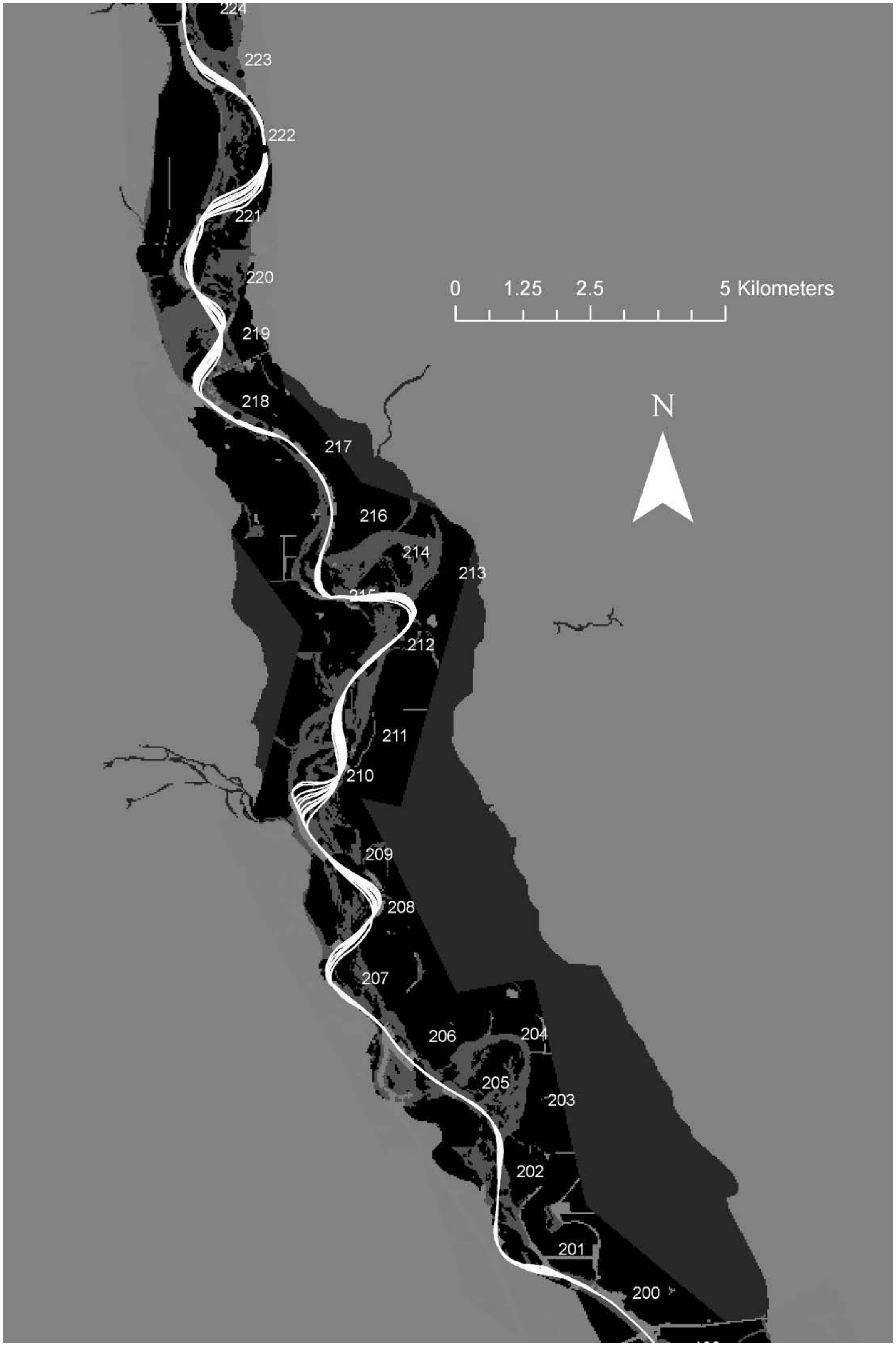
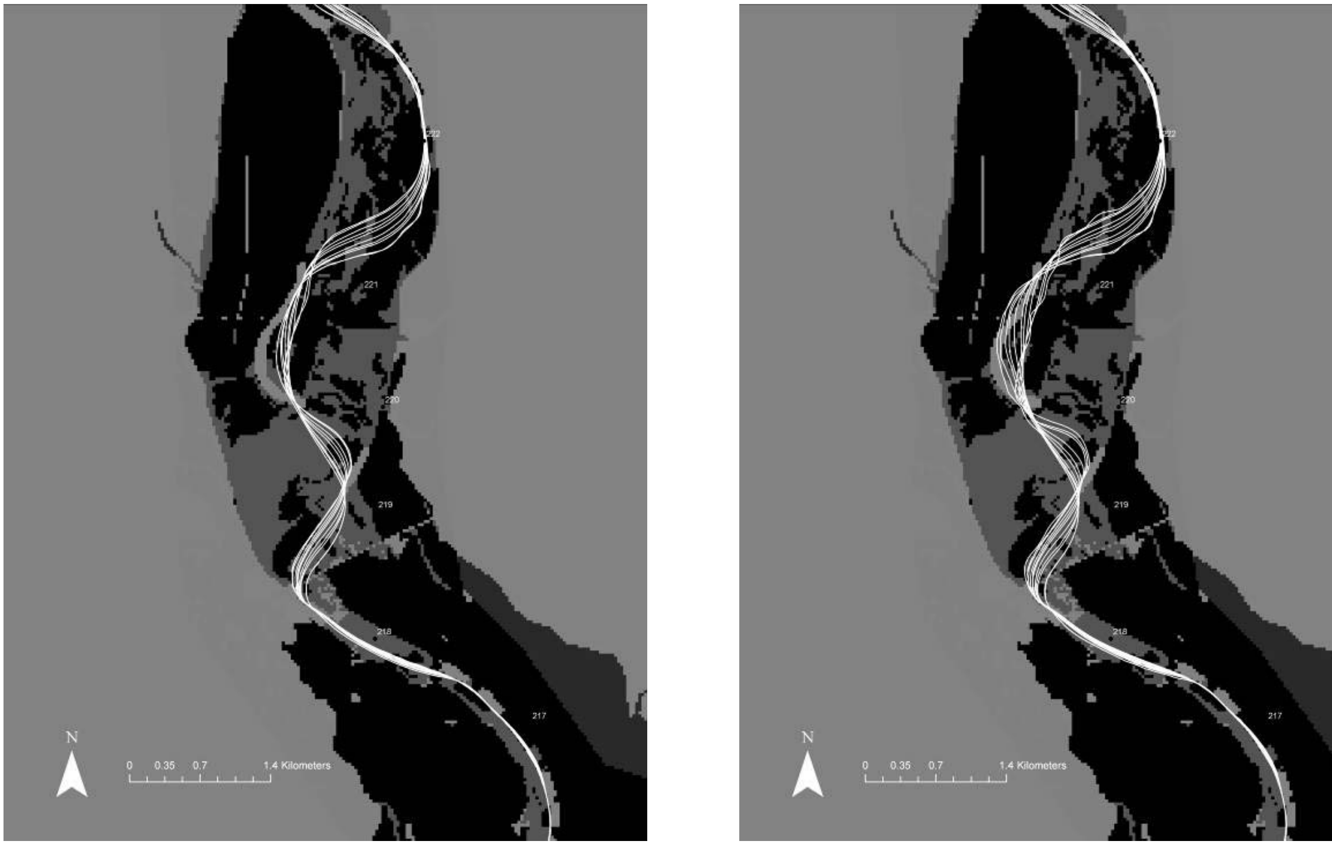


**Figure 14 Woodson Bridge base flow with existing revetment 2005 to 2059**

*Predictions with base flow and revetment removed*

For prediction runs, the 2004 revetment coverage was used with the revetment at RM 220-222 (right bank) at Kopta Slough removed.



(a) (b)

**Figure 15 Woodson Bridge base flow with existing and altered revetment 2005-2059**

Figure 15 shows the channel migration from 2005-2059 in five-year increments a) with the revetment in place and using the base flow hydrograph, and b) with the selected revetment removed and using the base flow hydrograph. The meander migration pattern is similar for the migration at this location with the NODOS and Shasta flows (See Appendix 3). The main difference is the total magnitude of area reworked for each flow scenario, which is shown in table 10.

### *Area reworked and migration rate*

**Table 10. Total area reworked Woodson Bridge segment**

| Total area reworked Woodson Bridge Segment | | | |
|---|---|---|---|
| | Base | Nodos | Shasta |
| With revetment | | | |
| Area ($m^2$) | 2,827,596 | 2,675,392 | 2,606,020 |
| Percent of base | 100% | 95% | 92% |
| Migration rate (m/yr) | 1.36 | 1.29 | 1.26 |
| Percent of base | 100% | 94% | 92% |
| Without revetment | | | |
| Area ($m^2$) | 2,992,761 | 2,805,298 | 2,699,692 |
| Percent of base | 100% | 94% | 90% |
| Migration rate (m/yr) | 1.44 | 1.35 | 1.30 |
| Percent of base | 100% | 94% | 90% |

### *Area reworked by sub-segment*

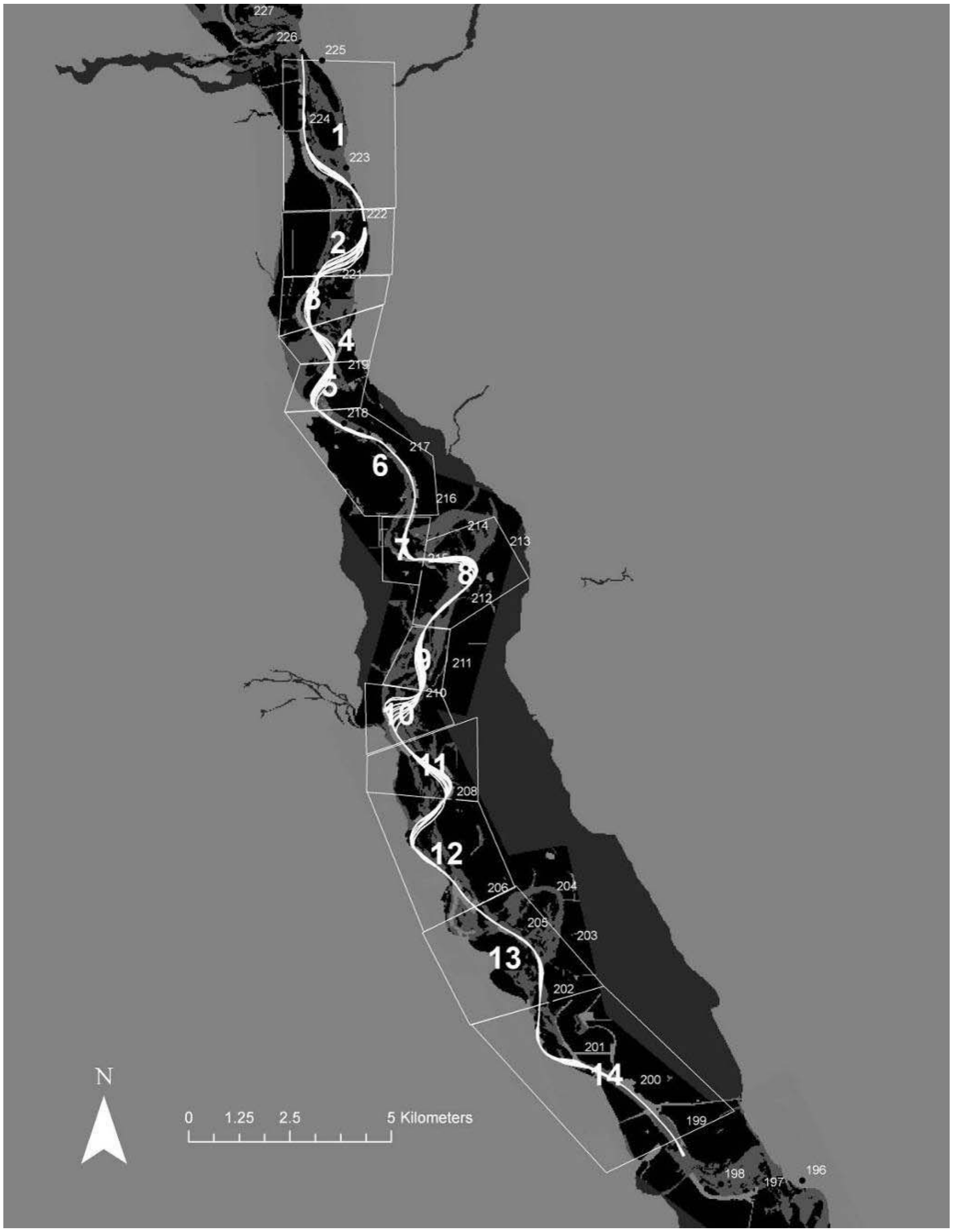


**Figure 16 Woodson Bridge sub-segment extents**

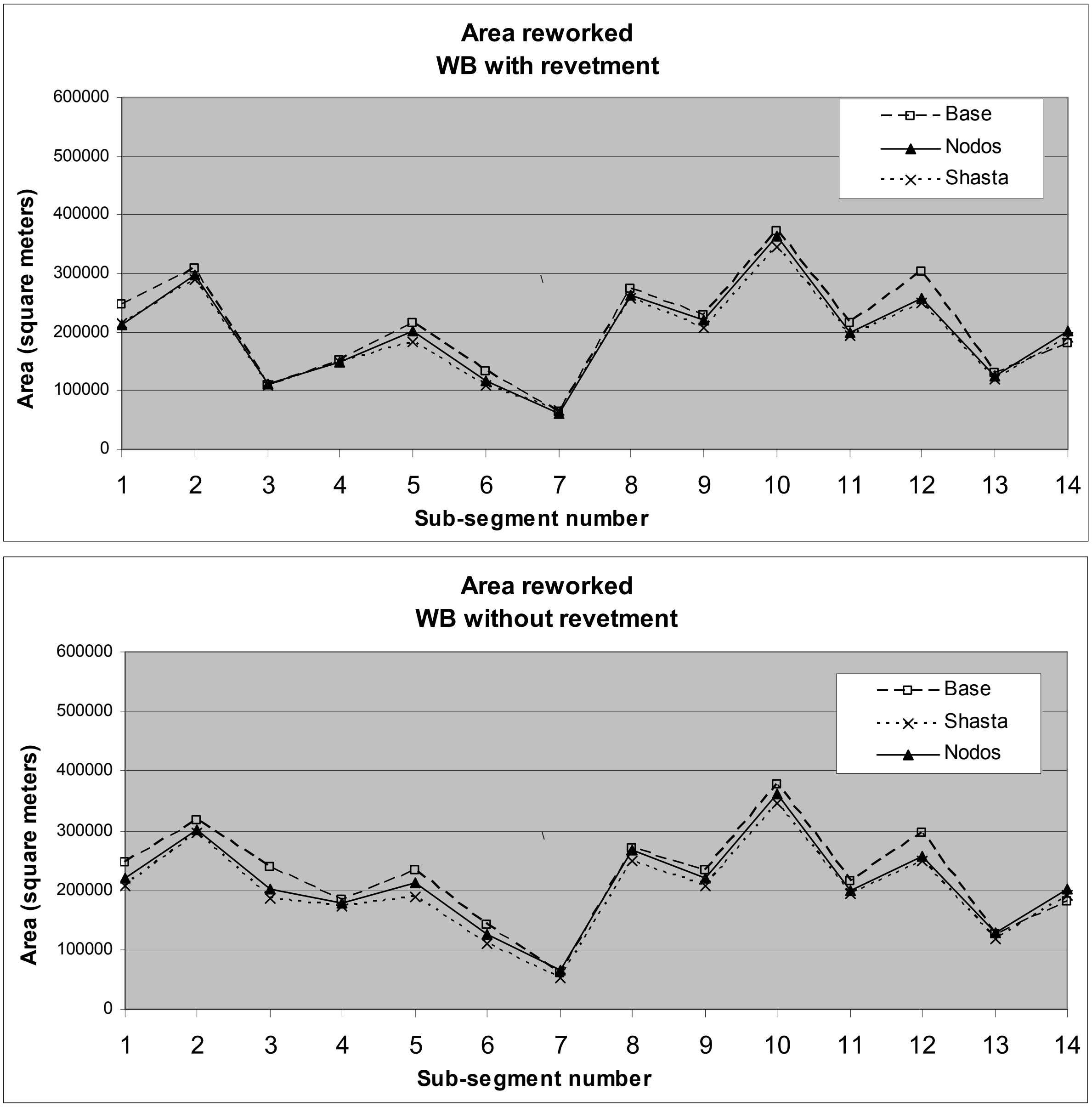


**Figure 17 Woodson Bridge segment area reworked by sub-segment**

Figure 17 shows the cumulative area reworked from 2005 to 2059 on the y-axis. The x-axis consists of the fourteen sub-segment numbers.

The area reworked for each sub-segment tends to differ between the three flow scenarios in the same patterns as shown in the table 10. The base flow tends to have the highest magnitude of area for each sub-segment, with NODOS and Shasta flow scenarios the next largest in that order.

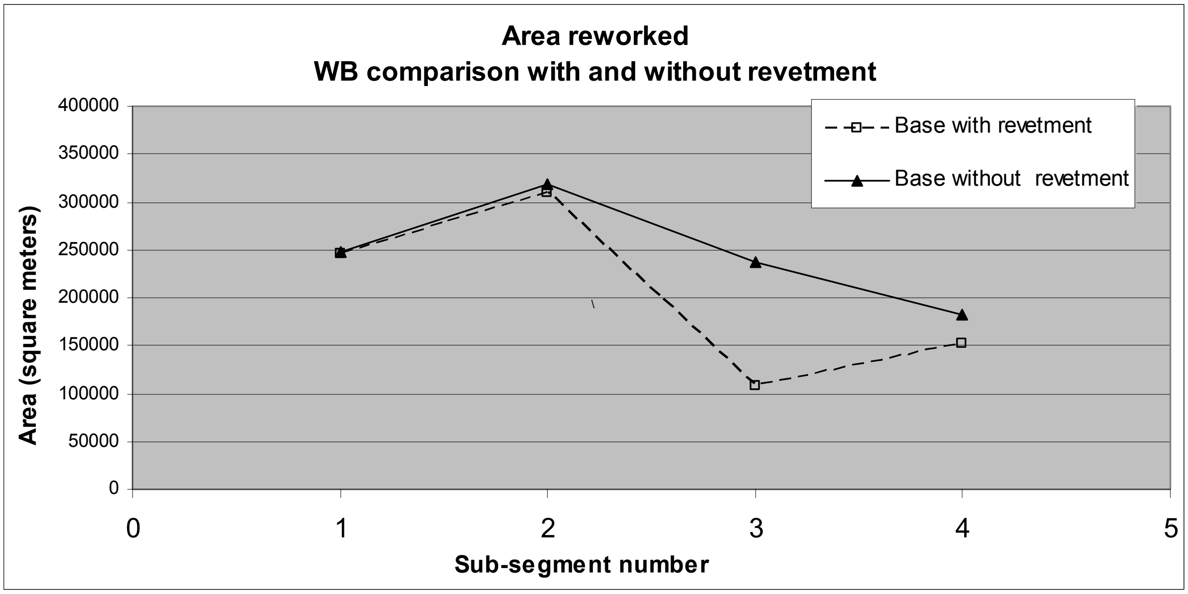


**Figure 18 Woodson Bridge area reworked in the vicinity of sub-segment 3**

Figure 18 shows the comparison of area reworked in the vicinity of sub-segment 3 where the revetment was removed. This figure emphasizes how the area reworked increases for sub-segment 3 when the revetment is not present.

### 3.1.1.2 Hamilton City Segment

*Predictions with base flow and existing revetment*

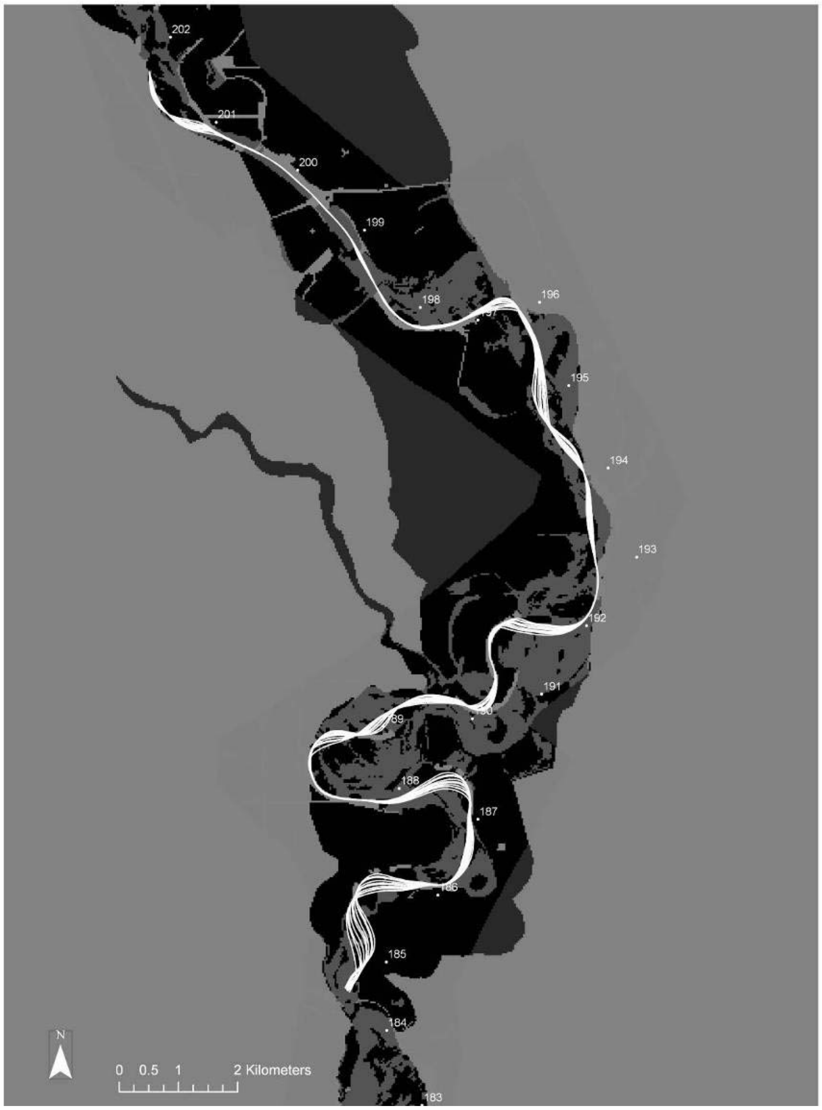
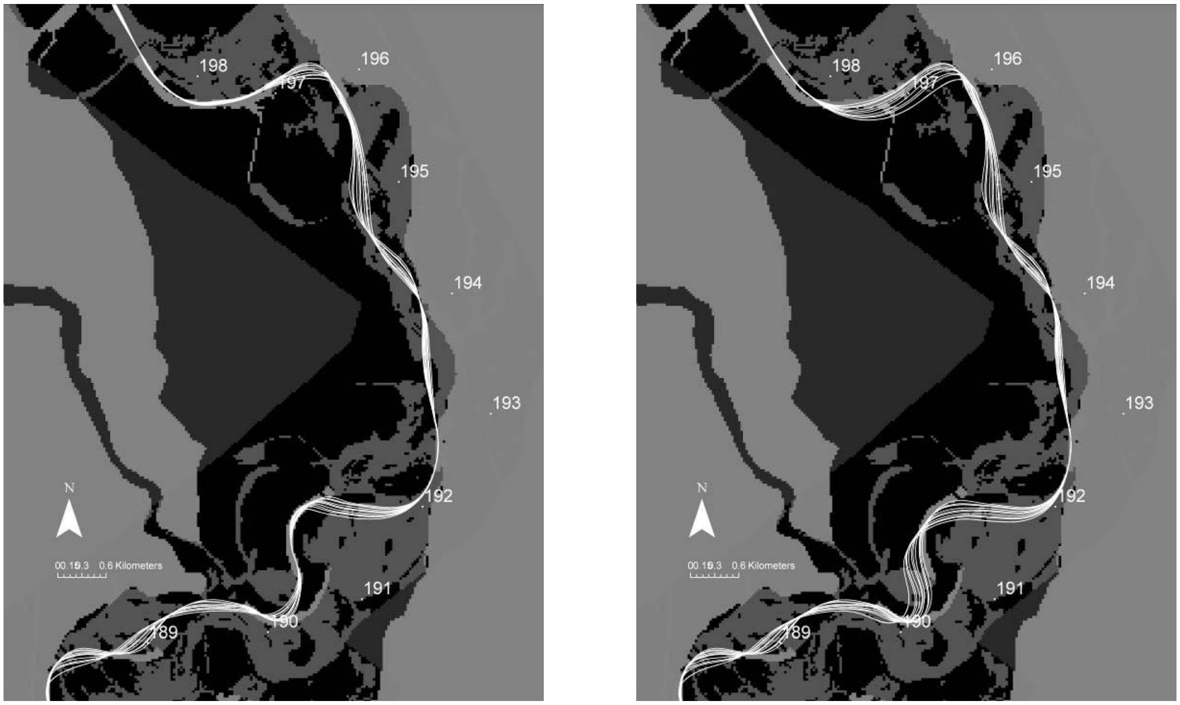


**Figure 19 Hamilton City with base flow with existing revetment**

Figure 19 shows the modeling results for migration from 2005 to 2059 using base flow and the existing revetment. The NODOS and Shasta patterns, which are similar, are shown in Appendix 2.

*Base flow with existing and altered revetment*

For predictions for the revetment removal scenario at Hamilton City (Figure 20), the 2004 revetment coverage was used with the revetment at RM 197-198 (right bank) and RM 191-192 (right bank) removed.



Hamilton City base flow with existing revetment

Hamilton City base flow with the revetment at RM 197-198 (right bank) and RM 191-192 (right bank) removed.

**Figure 20 Hamilton City base flow with existing and altered revetment**

Figure 20 shows the channel migration from 2005-2059 in five-year increments for two cases: (a) with existing revetment using the base flow hydrograph, and (b) with the selected revetment removed and using the base flow hydrograph. The meander migration pattern is similar with the NODOS and Shasta flows (Appendix 3), with the total area reworked and migration rate for each flow scenario shown in the table below.

*Area reworked and migration rate*

**Table 11 Total area reworked in the Hamilton City segment**

| Total area reworked Hamilton City Segment | | | |
|---|---|---|---|
| | Base | Nodos | Shasta |
| With revetment | | | |
| Area ($m^2$) | 2,357,351 | 2,350,742 | 2,345,371 |
| Percent of base | 100% | 100% | 99% |
| Migration rate (m/yr) | 1.46 | 1.46 | 1.46 |
| Percent of base | 100% | 100% | 99% |
| Without revetment | | | |
| Area ($m^2$) | 2,797,267 | 2,715,528 | 2,719,343 |
| Percent of base | 100% | 97% | 97% |
| Migration rate (m/yr) | 1.74 | 1.68 | 1.68 |
| Percent of base | 100% | 97% | 97% |

The area reworked for the Hamilton City segment is shown in Table 11. The migration patterns, the area reworked and the migration rate are very similar.

*Area reworked by sub-segment*

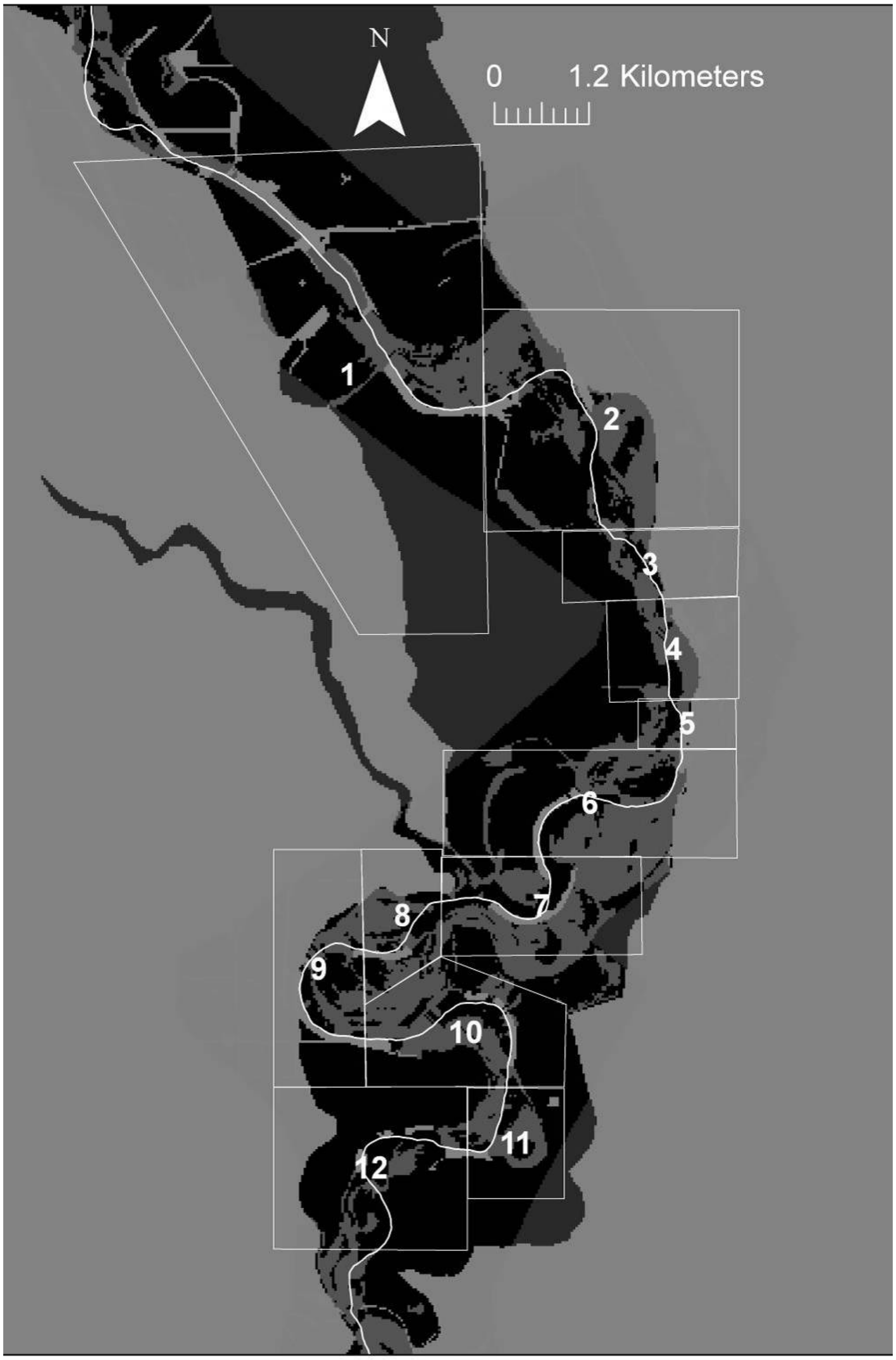


**Figure 21 Hamilton City sub-segment extents**

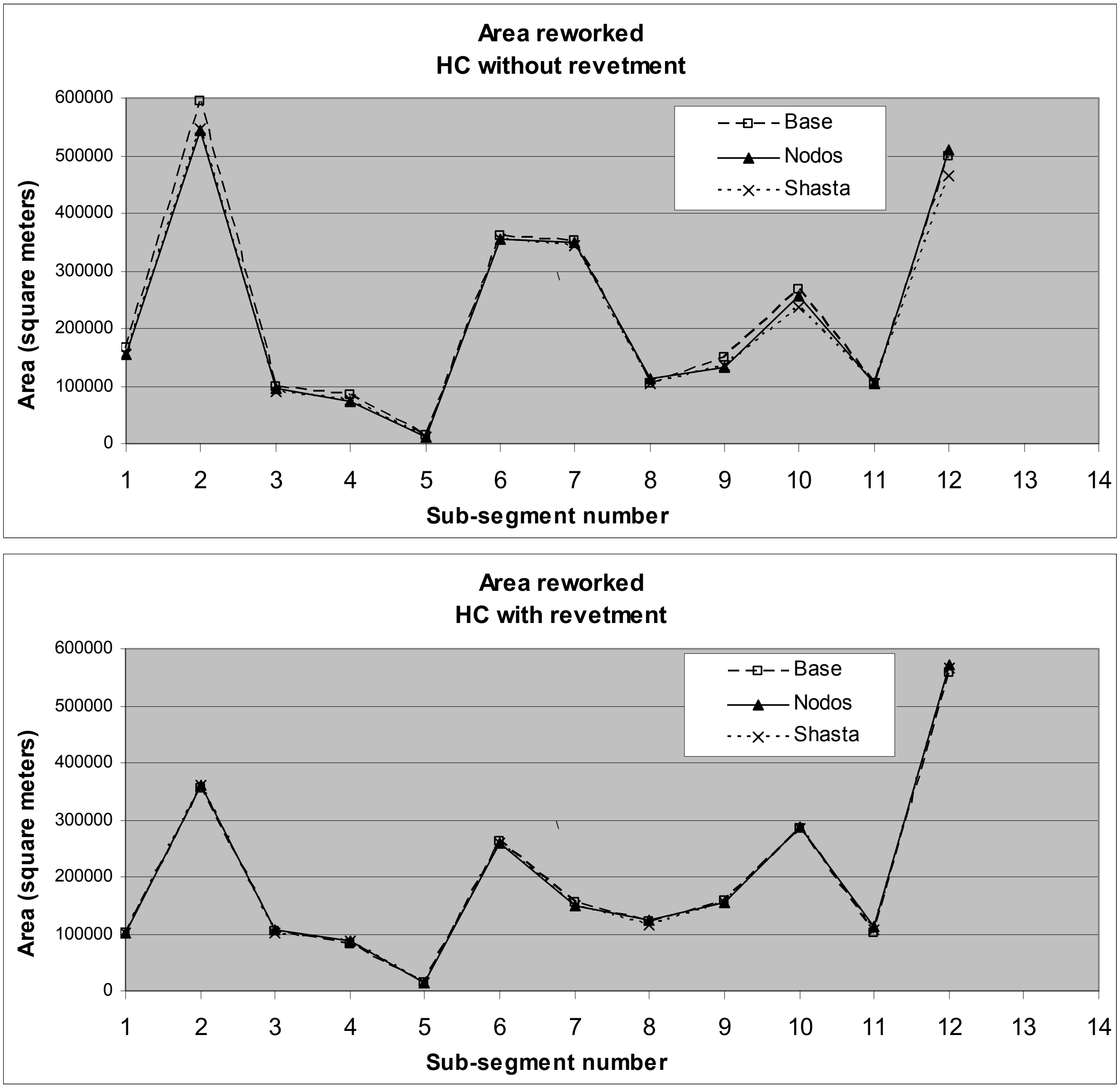


**Figure 22 Hamilton City segment area reworked by sub-segment**

Sub-segments 1&2 and 6&7 are areas where the revetment removal was modeled. Figure 22 shows the difference in area reworked between the scenario without revetment and with revetment. The main differences are the increases in the vicinity of the revetment removal. The increase in area reworked for the areas where the revetment is removed is also shown in Figure 23.

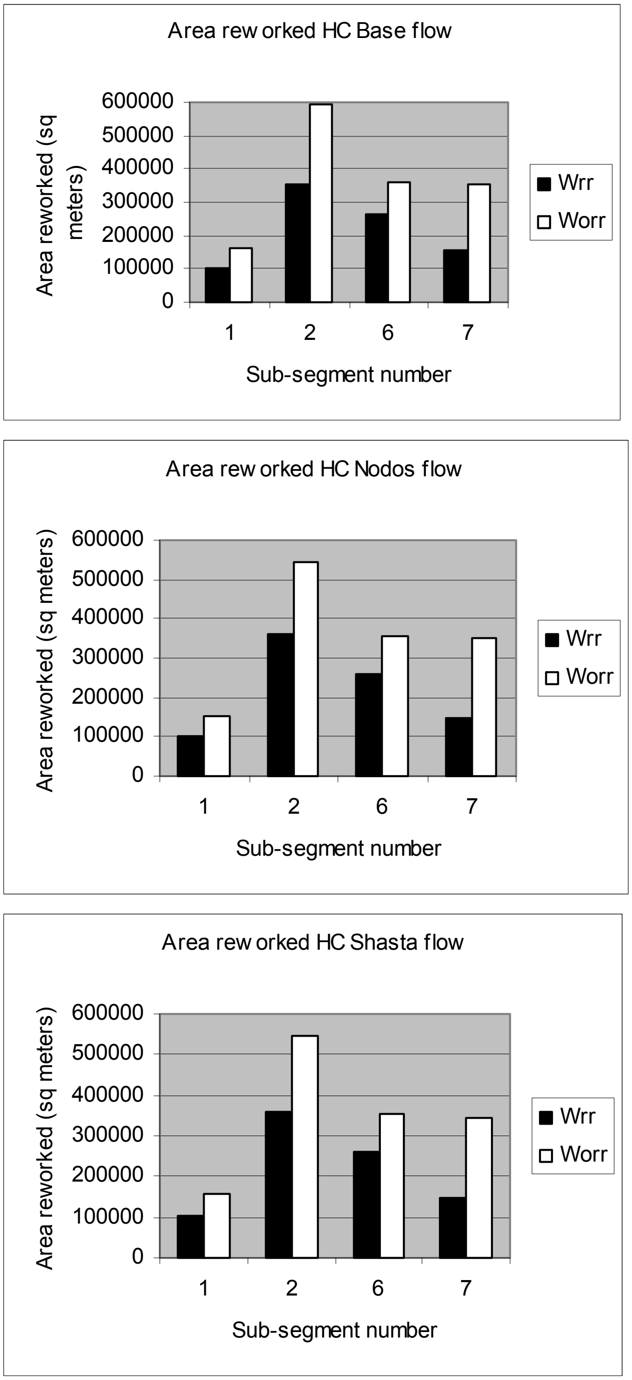


**Figure 23 Increase in area reworked at bends with revetment removed**

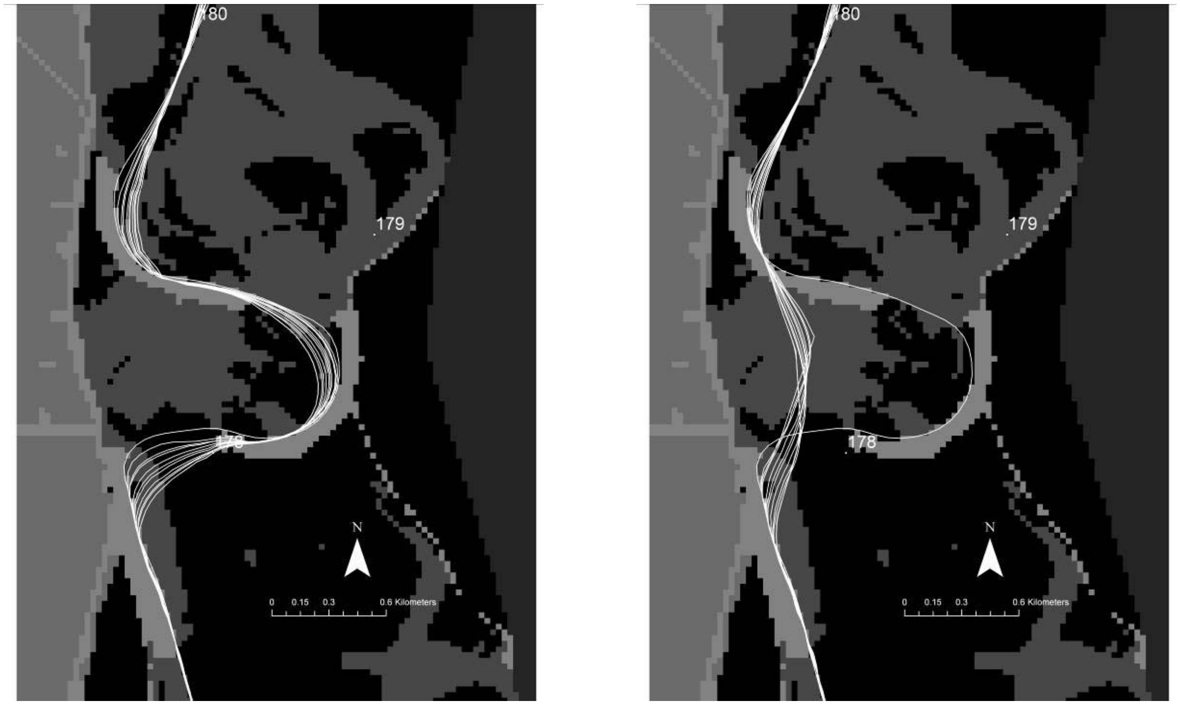
### 3.1.1.3 Ord Ferry Segment

*Predictions with base flow and existing revetment*

**Figure 24 Ord Ferry base flow with existing revetment**

Figure 24 shows the predicted migration from 2005 to 2059 with base flow and existing revetment. The patterns for NODOS and Shasta flows are shown in Appendix 2.

*Predictions with base flow with existing revetment and with revetment removed*



Ord Ferry base flow with existing revetment

Ord Ferry base flow with the revetment at RM 179 (right bank) at the Llano Seco Riparian Sanctuary removed.

**Figure 25 Ord Ferry base flow with existing and altered revetment**

For prediction runs in the Ord Ferry segment, the 2004 revetment coverage was used with the revetment at RM 179 (right bank) at the Llano Seco Riparian Sanctuary removed.

Figure 25 shows the channel migration from 2005-2059 in five-year increments for two cases: (a) with existing revetment using the base flow hydrograph, and (b) with the selected revetment removed and using the base flow hydrograph. The meander migration pattern is similar with the NODOS and Shasta flows (Appendix 3), with the total area reworked and migration rate for each flow scenario shown in the table below.

*Area reworked and migration rate*

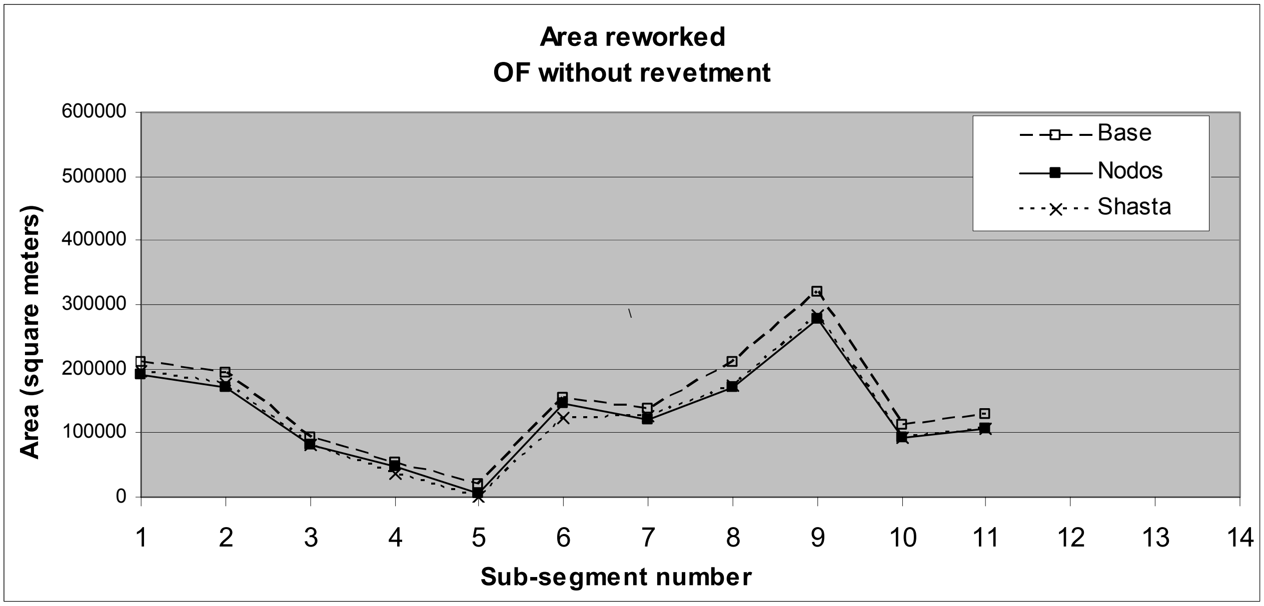
**Table 12 Total area reworked Ord Ferry segment**

| Total area reworked Ord Ferry Segment | | | |
|---|---|---|---|
| | Base | Nodos | Shasta |
| With revetment | | | |
| Area ($m^2$) | 2,204,387 | 1,987,030 | 2,010,988 |
| Percent of base | 100% | 90% | 91% |
| Migration rate (m/yr) | 1.21 | 1.09 | 1.10 |
| Percent of base | 100% | 90% | 91% |
| Without revetment | | | |
| Area ($m^2$) | 2,176,181 | 1,978,602 | 1,982,164 |
| Percent of base | 100% | 91% | 91% |
| Migration rate (m/yr) | 1.21 | 1.10 | 1.10 |
| Percent of base | 100% | 91% | 91% |

Because the river channel alignment returns to a less sinuous planform, the area reworked and migration rate after cutoff (with revetment removed) is essentially the same as the values for the planform with the revetment in place, although the location where the migration occurs is significantly different due to cutoff. The Shasta flows have slightly more effective cumulative stream power, which is reflected in the area reworked and migration rates.

There is less migration in this case when the revetment is removed. The immediate benefit is in the area of abandoned channel that is created with the revetment removed.

Figure 26 Ord Ferry sub-segment extents



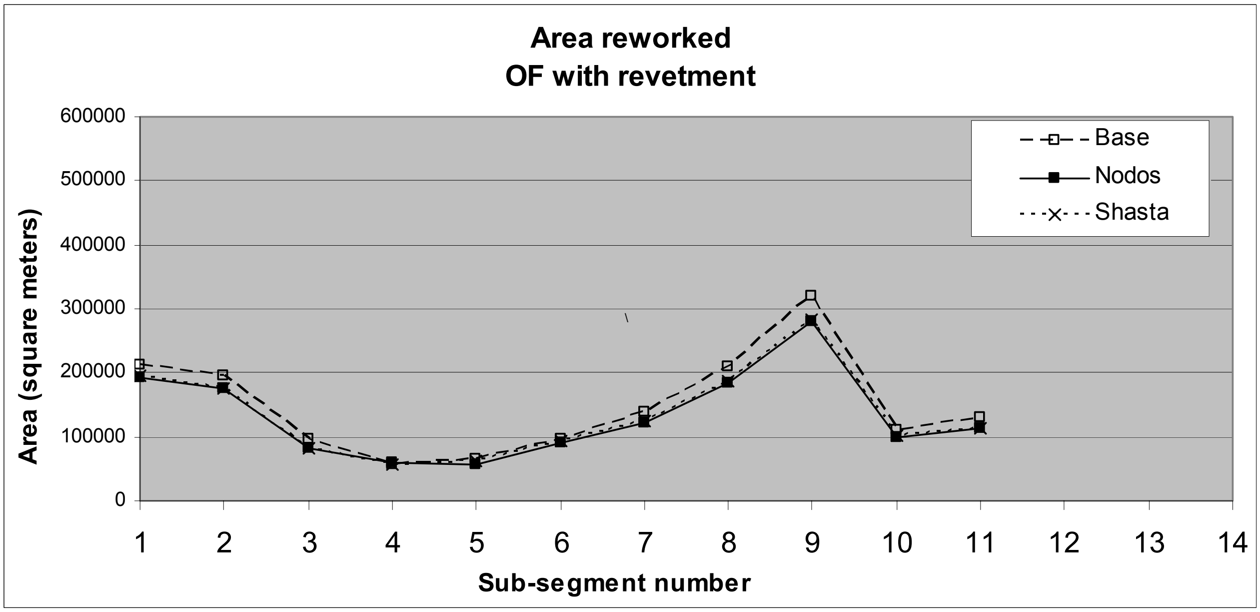


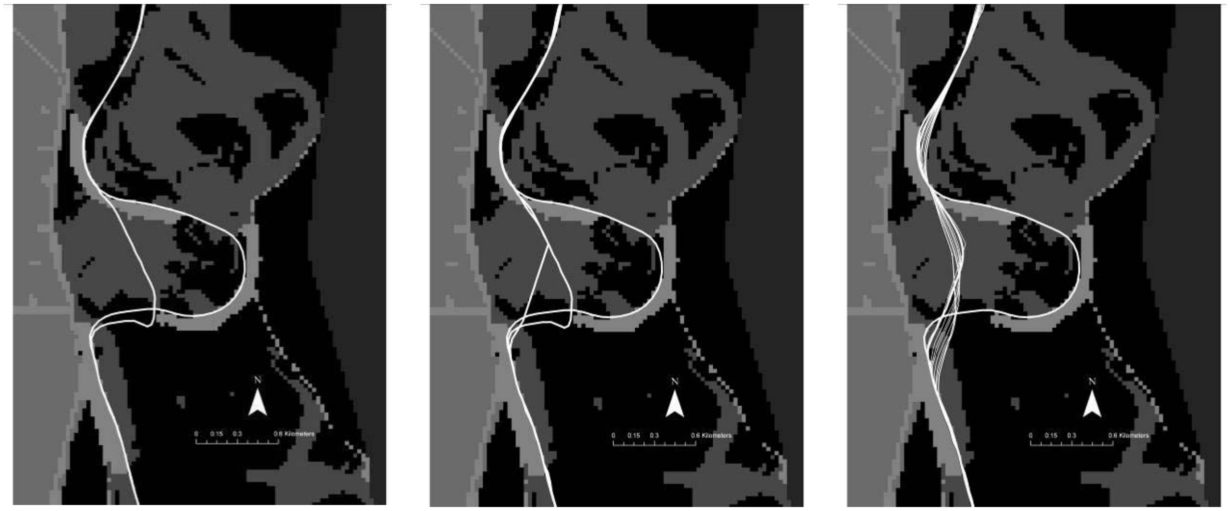
**Figure 27 Ord Ferry segment area reworked by sub-segment**

In the Ord Ferry segment, sub-segment 5 is the location of channel cutoff. The area reworked and migration rate both decrease after cutoff in sub-segment 5. The area reworked increases in sub-segment 6 but decreases in sub-segment 5 when there is no revetment and cutoff occurs. This is discussed in the next section on "Length of Abandoned Channel due to Cutoff" section and also in the "Management Implications" section of this report.

### 3.1.2 Length of Abandoned Channel Due to Cutoff

At the beginning of the model run with no revetment in place near RM 179, there was a cutoff that occurred in sub-segment 5. This was a result of the riprap being removed.

The large loop is the channel centerline in the year 2004. The model shows the first cutoff occurring after the riprap is removed and evolving to the intermediate position between 2005 and 2007 (Figure 28a). The next small cutoff is modeled to occur in 2008, and results in the second line (Figure 28b). From that location, the channel migrates progressively (Figure 28c). The cutoff was modeled as occurring in two phases, the first phase occurred in 2005 (immediately after the riprap was removed), and resulted in 2070 meters of abandoned channel. The second phase occurred within the next two years and added an additional 425 meters of abandoned channel. This two-part cutoff process is the result of modeling, and may not occur in this sequence in an actual cutoff. Results suggest that when the cutoff process is completed, the channel cutoff ultimately leaves about 2500 meters of abandoned channel.



(a) Initial cutoff 2005-2007 (b) Subsequent cutoff in 2008 (c) Progressive migration after 2008

**Figure 28 Cutoff at Ord Ferry RM 179**

## 3.2 Management Implications

It is important to recognize that all findings of this modeling exercise assume that CALSIM II modeled flows utilized as model input accurately reflect the affects of the aforementioned water projects on the flow regime of the Sacramento River. If modeled flows are not accurate, then anticipated changes reported here may be either underestimated or exaggerated.

The following figures illustrate that the flow and stream power are very similar in the three scenarios.

### 3.2.1 Different Flow Scenarios Stream Power, and Area Reworked

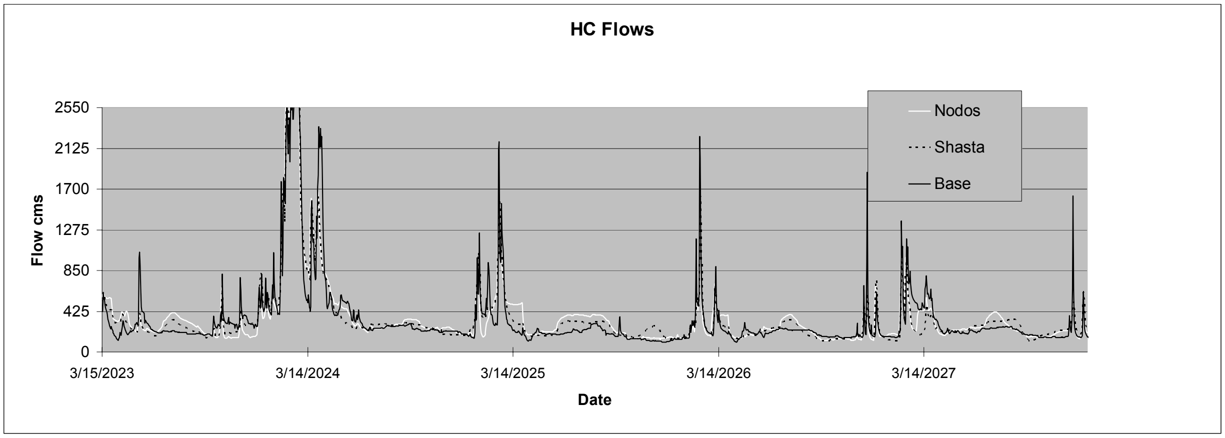


**Figure 29 Representative flow rates in the Hamilton City segment: Base, NODOS, and Shasta flows compared**

The graph above is a sample of the flow data for the Hamilton City segment. The graph shows that there are noticeable differences below 425 cms. 425 cms is the lower threshold for meander migration, and flows below that are not used in modeling. The assumption that flows below this lower threshold are not effective in creating channel migration was tested and validated for the Sacramento River in previous work (Larsen et al. 2006a, Larsen et al. 2006b). Above that line, the base flow is greater, but the NODOS and Shasta flows are similar to each other, and they do not differ greatly from the base flow as characterized by CALSIM II output.

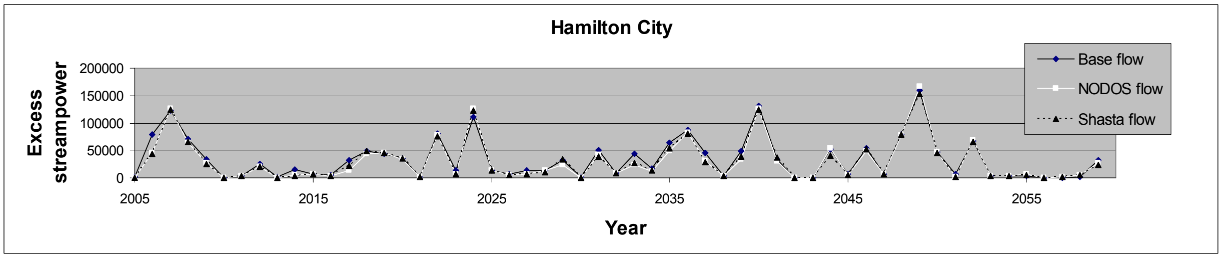


**Figure 30 Effective stream power in the Hamilton City segment: base, NODOS, and Shasta flows compared**

The graph above shows a representative example of the cumulative effective stream power from the Hamilton City record. The (cumulative effective) stream power for the three flows is very similar, and is almost identical for the NODOS and Shasta flows (see also table below). Because meander migration processes are modeled based on stream power, the meander migration patterns (and area reworked) will be similar for the three flow cases as characterized by CALSIM II output. The table shows in more detail the way in which total stream power and area reworked is related for the three different flow scenarios.

**Table 13 Stream power and area reworked compared**

| | Cumulative effective stream power | % of Base | Area reworked (sq meters) | % of Base |
|---|---|---|---|---|
| WBwrr | | | | |
| Base | 2,018,471 | 100% | 2,827,596 | 100% |
| Nodos | 1,811,278 | 90% | 2,675,392 | 95% |
| Shasta | 1,692,951 | 84% | 2,606,020 | 92% |
| | | | | |
| WBworr | | | | |
| Base | 2,018,471 | 100% | 2,992,761 | 100% |
| Nodos | 1,811,278 | 90% | 2,805,298 | 94% |
| Shasta | 1,692,951 | 84% | 2,699,692 | 90% |
| | | | | |
| HCwrr | | | | |
| Base | 1,873,447 | 100% | 2,357,351 | 100% |
| Nodos | 1,676,882 | 90% | 2,350,742 | 100% |
| Shasta | 1,669,165 | 89% | 2,345,371 | 99% |
| | | | | |
| HCworr | | | | |
| Base | 1,873,447 | 100% | 2,797,267 | 100% |
| Nodos | 1,676,882 | 90% | 2,715,528 | 97% |
| Shasta | 1,669,165 | 89% | 2,719,343 | 97% |
| | | | | |
| OFwrr | | | | |
| Base | 2,237,624 | 100% | 2,204,387 | 100% |
| Nodos | 1,890,667 | 84% | 1,987,030 | 90% |
| Shasta | 1,906,702 | 85% | 2,010,988 | 91% |
| | | | | |
| OFworr | | | | |
| Base | 2,237,624 | 100% | 2,176,181 | 100% |
| Nodos | 1,890,667 | 84% | 1,978,602 | 91% |
| Shasta | 1,906,702 | 85% | 1,982,164 | 91% |

When values of cumulative effective stream power are compared for the three flow scenarios, the percent of base (i.e. stream power for NODOS as a percentage of base stream power) varies from 84% to 90%. Area reworked, as a percentage of base area reworked, is always a larger percentage (than the stream power) and varies from 90% to 100%.

There is a correlation between cumulative stream power and area reworked, but the correlation is not one-to-one. That is because factors other than flow and stream power contribute to the patterns of area reworked. Those factors include the channel planform. Given the same flow, there is a certain range of channel curvature and sinuosity for which channel migration rates are greater than other ranges of sinuosity (Larsen 1995). In addition, patterns of channel revetment influence migration rate. For example, there are areas that will migrate in the same pattern, although the flows differ, because the ability to migrate is restrained by revetment.

### 3.2.2 Area Reworked: Effect of Flow Scenarios Compared With Bank Revetment Scenarios

NODOS flows are less than base flows. Accordingly the total area reworked in all three segments between WY 2005 and WY 2059 decreases by 375,000 sq meters when NODOS flows are used (Table 13). This is a decrease in 5% of the total area reworked when compared with the total area reworked by base flows in the same time and extent with revetment in place. For Shasta flows, the corresponding decrease is 425,000 (6%).

When a total of four revetment removal scenarios were modeled in the three segments, the area reworked between WY 2005 and WY 2059 increased by 575,000 sq meters (Table 13). This is an increase in 8% in total area reworked in the same time and extent with revetment in place. Note that the revetment removal scenario at Ord Ferry resulted in a slight decrease in area reworked, although it provided the immediate benefit of creating a certain length of abandoned channel. Another way to view this is that there was 600,000 sq meters (8%) increase in area reworked by revetment removal in three locations.

The ability to quantify the area reworked due to flow changes and also due to revetment removal provides a quantitative method to compare the impacts of these different river management scenarios. This would be useful in order to consider trade offs or mitigation for flow or revetment changes proposed on the river. The results suggest that revetment impacts in very limited areas (three individual bends) are comparable (larger in magnitude but of a similar *order* of magnitude) to the effects of flow regulations (as defined in this study) over the entire three segments combined.

### 3.2.3 Length of Abandoned Channel and Channel Migration after Cutoff

There was one simulated cutoff in the three segments over the modeling time period (2005 to 2059). This cutoff was the result of a simulated revetment removal. There were four revetment removal scenarios in the 50 miles of modeled channel migration. The cutoff at River Mile 179 was the only one that met the criteria for modeled cutoff. There may be other areas, that are currently constrained either by placed revetment or constrained naturally that would cutoff if the constraint were removed. A useful study would be to identify river segments that are currently constrained that would cutoff if not constrained.

The results showed that the cutoff produced about 2500 meters of abandoned channel while reducing the meander migration rate of the segment in question. Considering a reduction of meander migration rates as reducing ecological value, and considering the abandoned channel to be adding ecological value, there is some trade-off in ecological functions when such a cutoff occurs.

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# 5.0 APPENDICES

## Appendix 1. Applications of Previous Versions of the Model to the Sacramento River

The following table identifies the reaches of the Sacramento River where previous versions of the meander migration model have been applied, including a list of relevant reports/manuscripts for each previous model application and brief comments.

**Table 14 Sacramento River reaches where previous versions of model have been applied**

| Reach (RM) | Description | Reference | Comments |
|---|---|---|---|
| 216-224 | Flow Regime Requirements for Habitat Restoration along the Sacramento River between Colusa and Red Bluff | (Kondolf et al. 2000) | Roughly calibrated; no vegetation or geology. |
| 185-201 | The Application of GIS Geomorphology Coverage as Bank Erosion Potential in Meander Migration Modeling | (Kelly 2000) | Senior thesis. Rough study to assess using geology coverage. |
| 193-243 | Predicting Meander Migration of the Sacramento River, Ca.: Comparison of Empirical and Physically-Based Mathematical Modeling Approaches | (Thomas 2001) | Masters. Thesis. Roughly calibrated; no vegetation or geology. |
| 218-222 | Modeling Channel Management Impacts on River Migration: A Case Study of Woodson Bridge State Recreation Area, Sacramento River, California, USA | (Larsen and Greco 2002) | Roughly calibrated; no vegetation or geology. |
| 185-201 | The Controls on and Evolution of Channel Morphology of the Sacramento River: A Case Study of River Miles 201-185 | (Larsen et al. 2002) | TNC study. |
| 216-226 | Using Science to Evaluate Restoration Efforts and Ecosystem Health on the Sacramento River Project, California | (Golet et al. 2003) | Uses results from (Larsen and Greco 2002). |
| 168-170 | Potential Geomorphic Impacts of Bank Stabilization Measures along the Sacramento River near the Butte City Bridge on Route 162 | (Flora 2003) | Master's thesis. |
| 191-200 | Meander Bend and Gravel Bar Migration near River Mile 192.75 of the Sacramento River | (Larsen 2004a) | CBDA/Duck's Unlimited. Focuses on RM 192-194. |
| 177-180 | Meander Bend Migration near River Mile 178 of the Sacramento River | (Larsen 2004b) | CBDA/River Partners. |
| 235-241 | Future Meander Bend Migration and Floodplain Development Patterns near River Mile 241 to 235, Sacramento River | (Larsen 2005a) | CBDA/River Partners. |
| 191-200 | Meander Bend Migration and Floodplain Development Patterns near River Miles 200 to 191 of the Sacramento River | (Larsen 2005b) | CBDA/Duck's Unlimited. Follow up to (Larsen 2004a). Focuses on RM 192-194. |
| 184-202 | Assessing the Effects of Alternative Setback Levee Scenarios Employing a River Meander Migration Model | (Larsen et al. 2006c) | Modeling of theoretical conditions without bank restraint, with setback levees. |
| 185-201 | Assessing Societal Impacts When Planning Restoration of Large Alluvial Rivers: A Case Study of the Sacramento River Project, California | (Golet et al. 2006) | Riprap removal scenarios; three 25-year time steps 75 years into the future. |
| 218-222<br>177-180 | Landscape Level Conservation Planning in Alluvial Riparian Ecosystems: Using Models to Avoid Conflicts between Forests and Infrastructure | (Larsen et al. In Review-a) | Uses results from (Larsen and Greco 2002) and (Larsen 2004b). |
| 191-200 | Future Meander Bend Migration and Floodplain Development Patterns Near River Miles 200 To 191 of the Sacramento River Phase III Memo | (Larsen In review) | CBDA/Duck's Unlimited. Follow up to (Larsen 2004b, Larsen 2005b). Focuses on RM 192-194. |

# Appendix 2. Predictions with Existing Revetment: NODOS and Shasta Flows

## Woodson Bridge Segment
### NODOS flow

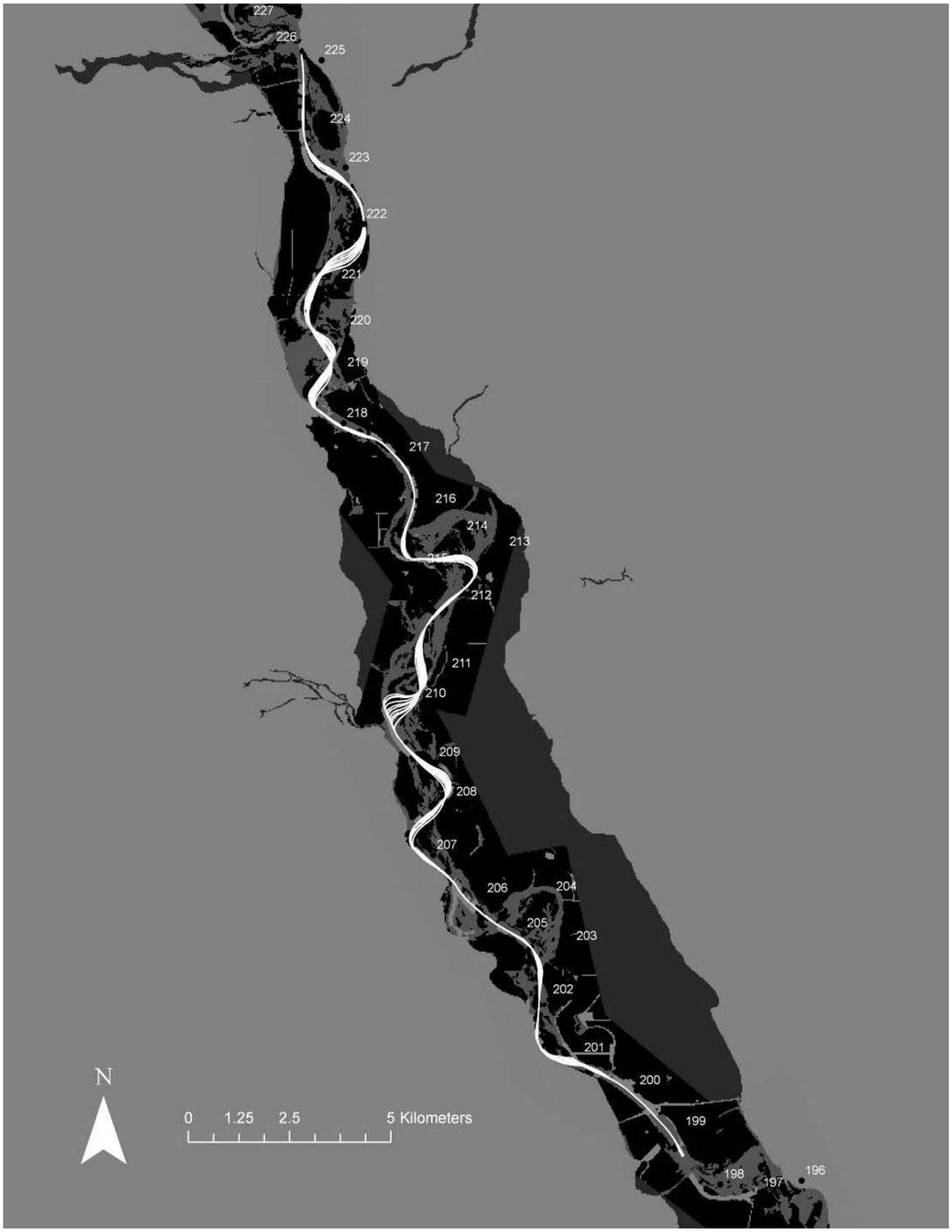


Figure 31 Woodson Bridge segment with NODOS flow and existing revetment

## Shasta flow

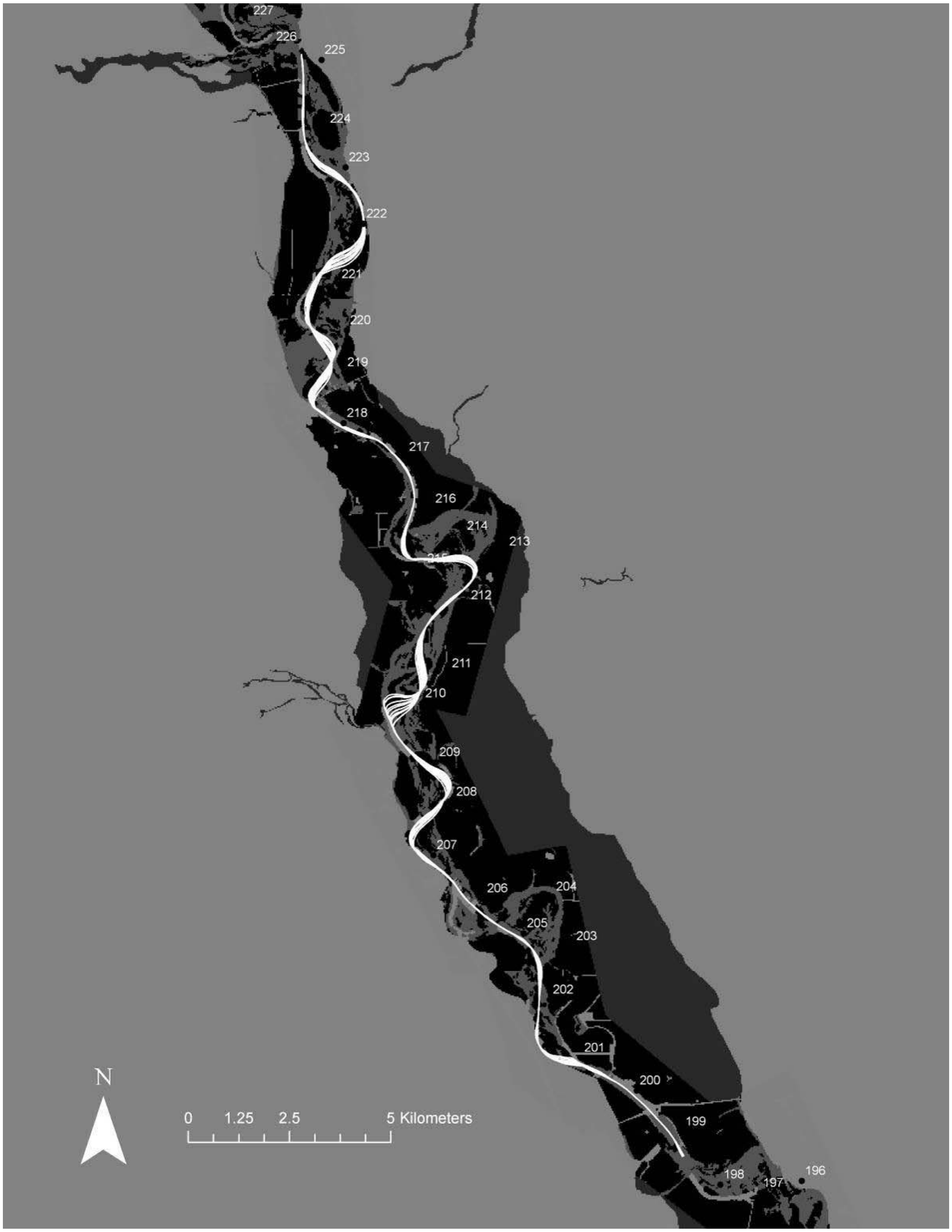


**Figure 32 Woodson Bridge segment with Shasta flow and existing revetment**

## Hamilton City Segment
### NODOS flow

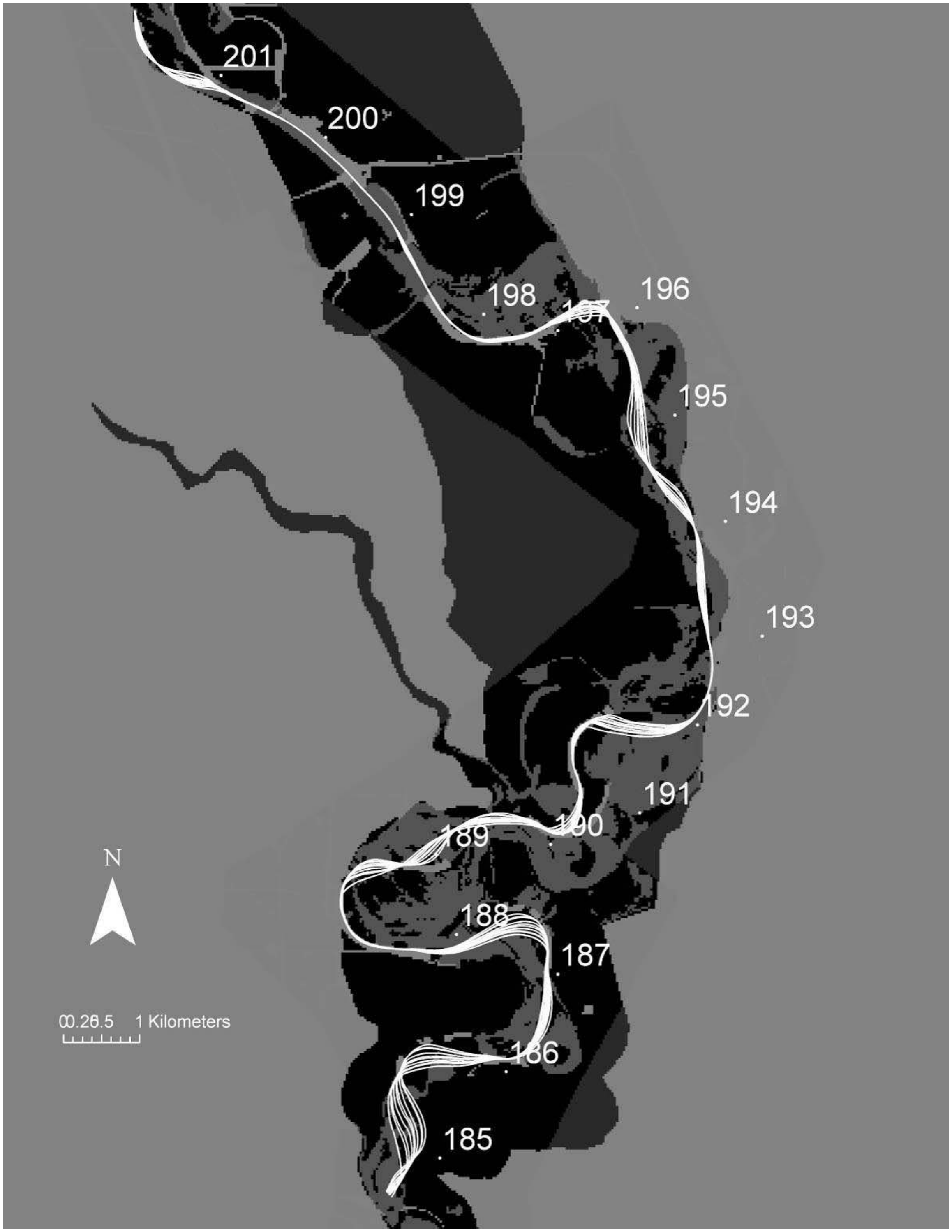


Figure 33 Hamilton City segment with NODOS flow and existing revetment

## Shasta flow

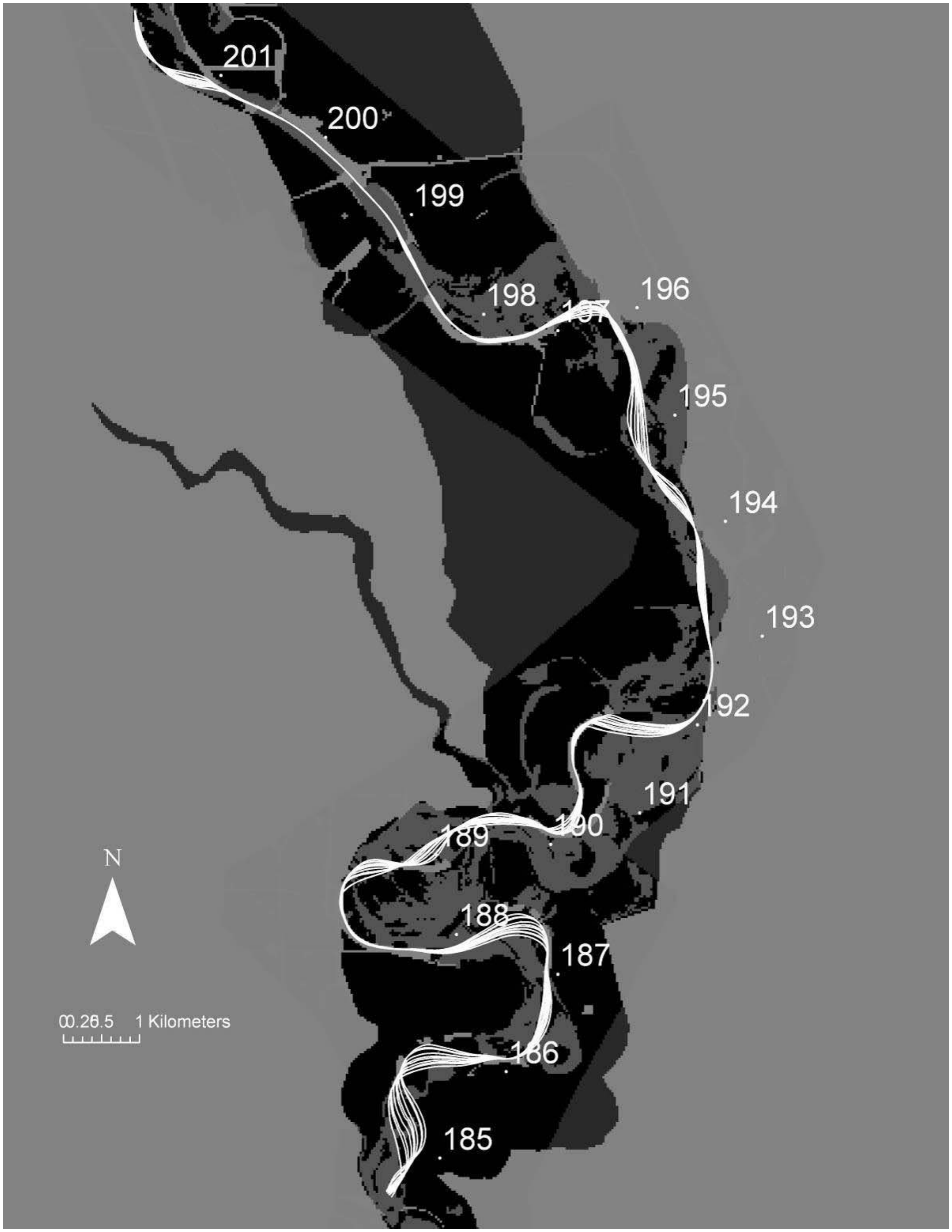


Figure 34 Hamilton City segment with Shasta flow and existing revetment

## Ord Ferry Segment

### NODOS flow

Figure 35 Ord Ferry segment with NODOS flow and existing revetment

## Shasta flow

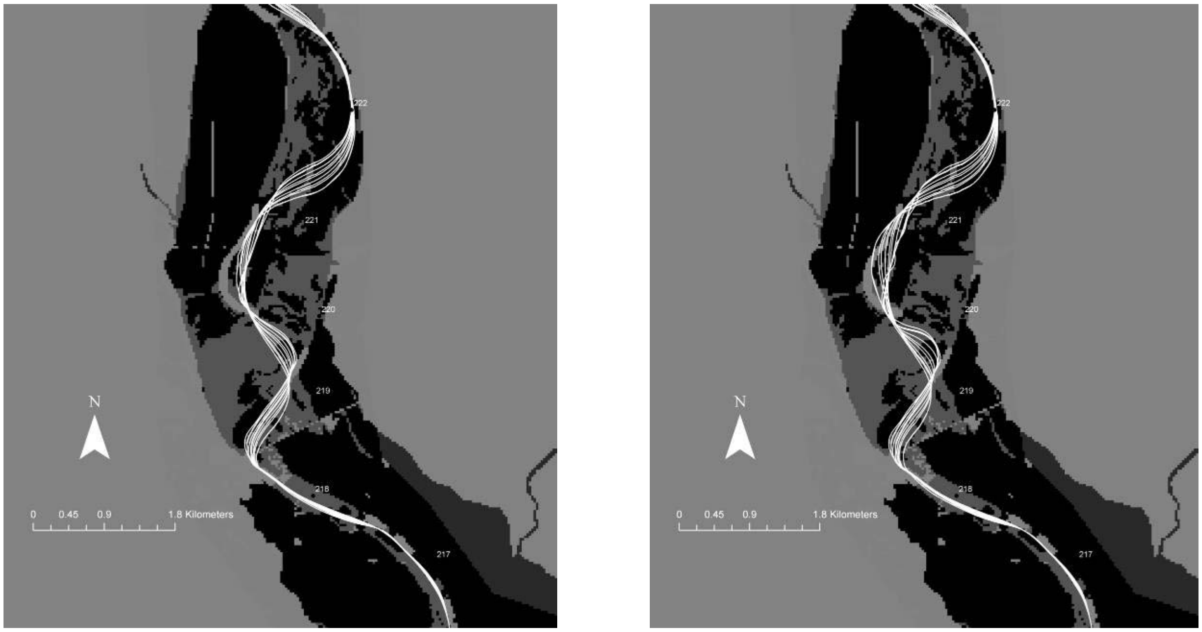
**Figure 36 Ord Ferry segment with Shasta flow and existing revetment**

# Appendix 3. Predictions with Revetment Removed: NODOS and Shasta Flows

## Woodson Bridge Segment

For prediction runs, the 2004 revetment coverage was used with the revetment at RM 220-222 (Right bank) at Kopta Slough removed.

### NODOS flow

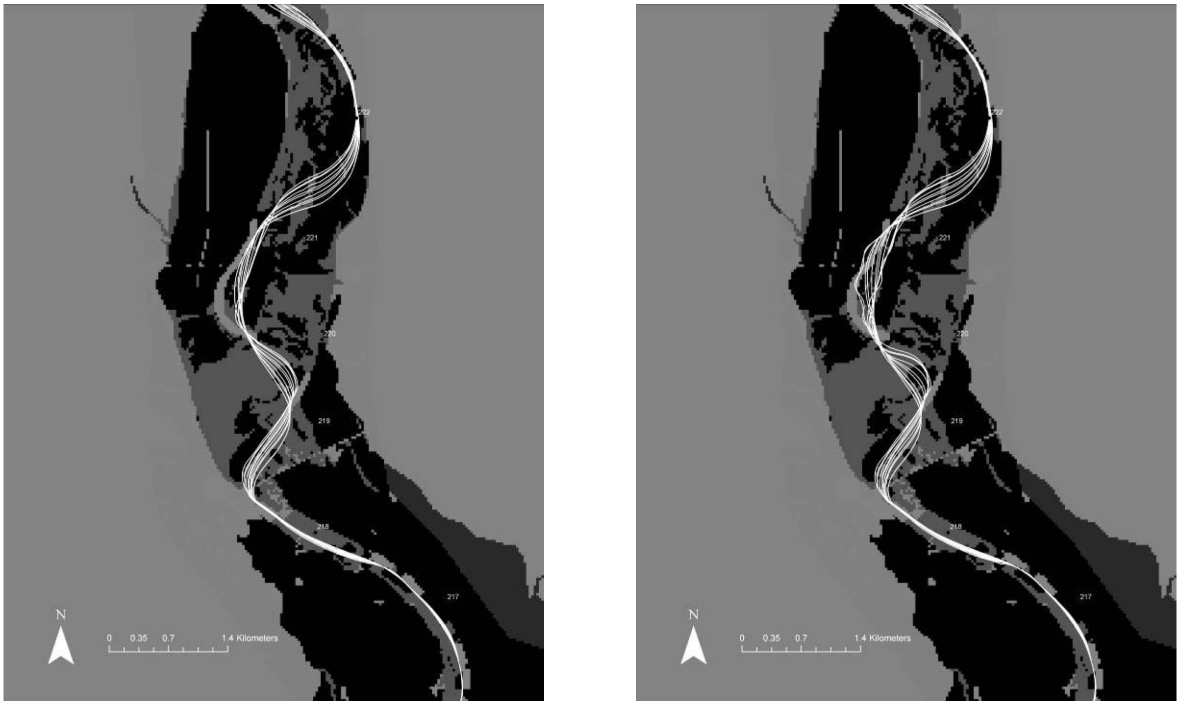


Hamilton City NODOS flow with existing revetment

Hamilton City NODOS flow with the revetment at RM 220-222 (Right bank) at Kopta Slough removed.

**Figure 37 Woodson Bridge segment with Shasta flow and with existing and altered revetment**

## Shasta flow



Woodson Bridge Shasta flow with existing revetment

Woodson Bridge Shasta flow with the revetment at RM 220-222 (Right bank) at Kopta Slough removed.

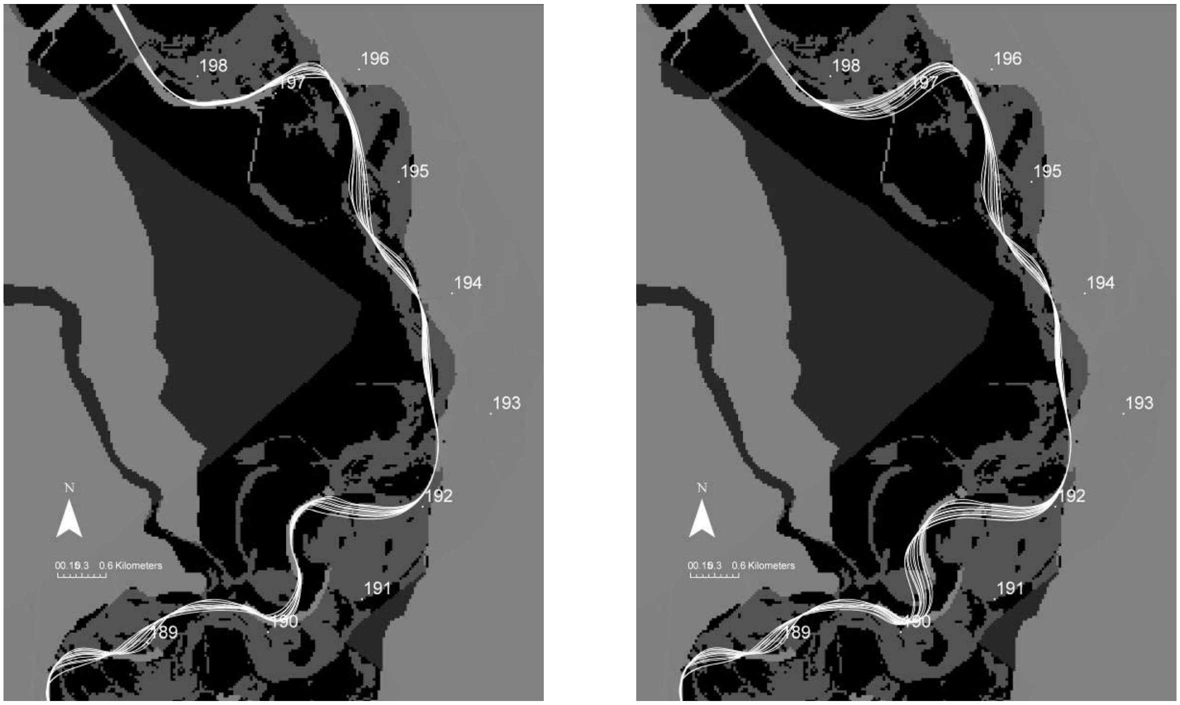
**Figure 38 Woodson Bridge segment with Shasta flow and with existing and altered revetment**

### Hamilton City Segment

For prediction runs at Hamilton City, the 2004 revetment coverage was used with the revetment at RM 197-198 (right bank) and RM 191-192 (right bank) removed.

.

### NODOS flow

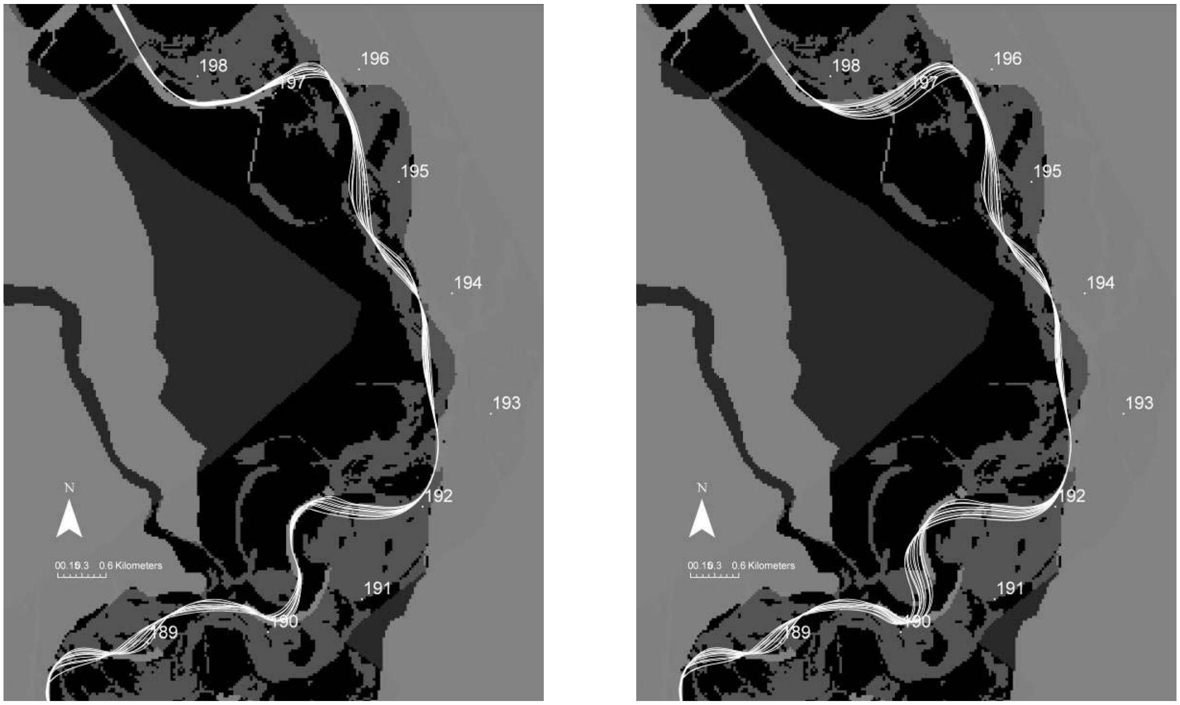


Hamilton City NODOS flow with existing revetment

Hamilton City NODOS flow with the revetment at RM 220-222 (Right bank) at Kopta Slough removed.

**Figure 39 Hamilton City segment with NODOS flow and with existing and altered revetment**

## Shasta flow



Hamilton City Shasta flow with existing revetment

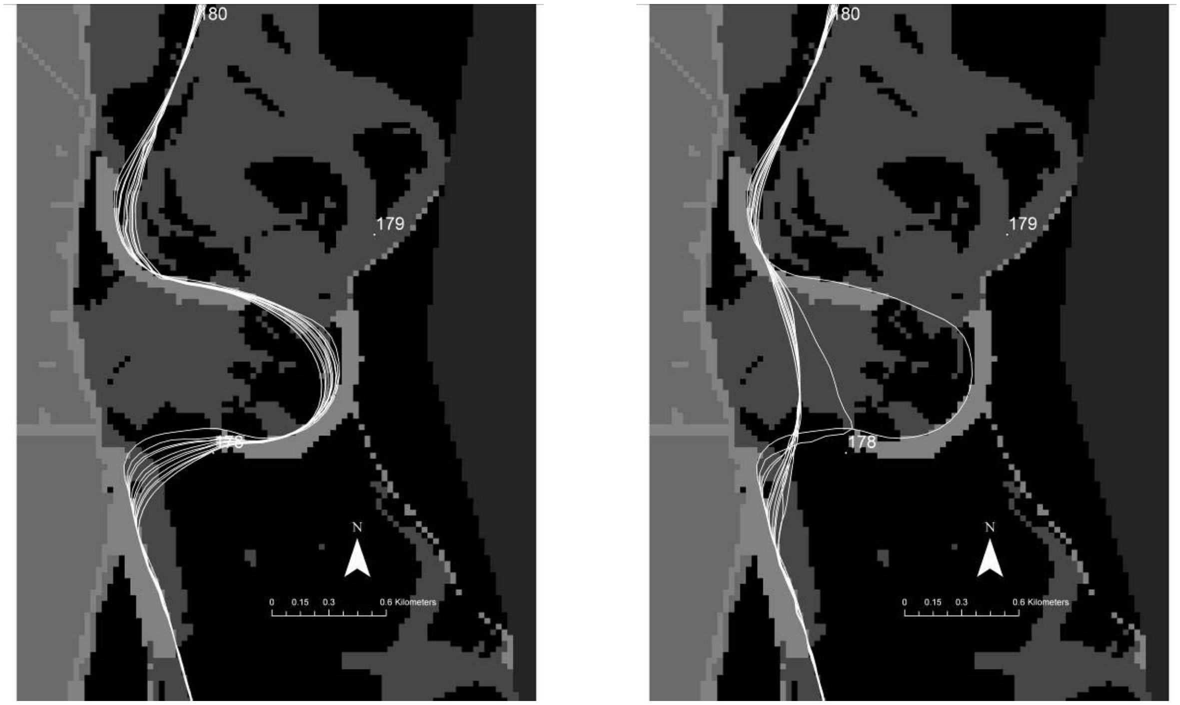
Hamilton City Shasta flow with the revetment at RM 197-198 (Left bank) and RM 191-192 (Right bank) removed.

**Figure 40 Hamilton City segment with Shasta flow and with existing and altered revetment**

## Ord Ferry Segment

For prediction runs in the Ord Ferry segment, the 2004 revetment coverage was used with the revetment at RM 179 (Right bank) at the Llano Seco Riparian Sanctuary removed.

### NODOS flow

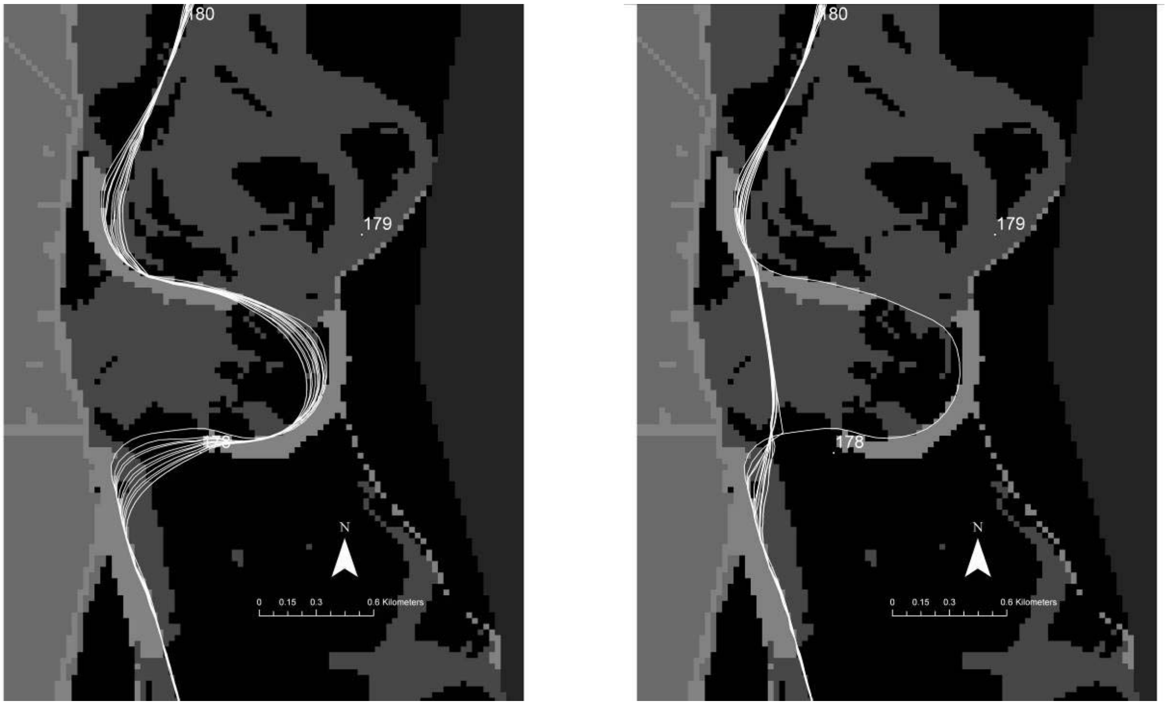


Ord Ferry NODOS flow with existing revetment

Ord Ferry NODOS flow with the revetment at RM 179 (Right bank) at the Llano Seco Riparian Sanctuary removed.

**Figure 41 Ord Ferry segment with NODOS flow and with existing and altered revetment**

## Shasta flow



Ord Ferry  Shasta flow with existing revetment

Ord Ferry Shasta flow with  the revetment at RM 179 (Right bank) at the Llano Seco Riparian Sanctuary removed.

**Figure 42  Ord Ferry segment with Shasta flow and with existing and altered revetment**

# Appendix 5.  Channel Migration Study Plan

### Eric W. Larsen

## Contents

## List of figures

## List of tables

## 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. 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 riprap and levees, and the land-use changes like the transition from riparian forest to agricultural lands. “To develop effective strategies for the 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 in flow, channel form, and bank erosion characteristics will alter the physical processes of channel migration.

“The over-arching goal of this study is to identify different management measures (e.g. hydrograph components, changes in bank protection, and changes in land-use effecting bank characteristics) that can help to conserve and restore” the key ecosystem functions that depend on meander migration.

Through previous research efforts, a predictive meander migration model has been developed and applied to reaches 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). Previous versions of the model predicted meander migration as a function of a single, representative, geomorphically effective discharge; however, the model has been recently upgraded to assess the effects of a variable hydrograph on meander migration rates, thereby reflecting more realistic conditions in which meander migration occurs. For the purposes of this study plan, “previous versions of the meander migration model” refers to all versions of the meander migration model developed by Eric Larsen that use a single, representative, geomorphically effective discharge, and “current, upgraded version of the meander migration model” refers to the version of the meander migration model that uses a variable hydrograph.

To help improve our understanding of how future flow scenarios may affect meander migration rates in the middle Sacramento River, with attendant effects on the formation of vertical cutbanks and off-channel habitats (e.g., oxbow lakes), Stillwater Sciences is engaging the services of Eric Larsen to perform a number of tasks. This study plan is Task 1 of the Scope of Work for Sacramento River Ecological Flows for the sub-consultant list of tasks related to meander migration simulations.

## 1.0 SACRAMENTO RIVER REACHES: APPLICATIONS OF PREVIOUS VERSIONS OF THE MODEL

The following table identifies the reaches of the Sacramento River where previous versions of the meander migration model have been applied, including a list of relevant reports/manuscripts for each previous model application and brief comments.

| Reach (RM) | Description | Reference | Comments |
|---|---|---|---|
| 216-224 | Flow Regime Requirements for Habitat Restoration along the Sacramento River between Colusa and Red Bluff | (Kondolf et al. 2000) | Roughly calibrated; no vegetation or geology. |
| 185-201 | The Application of GIS Geomorphology Coverage as Bank Erosion Potential in Meander Migration Modeling | (Kelly 2000) | Senior thesis. Rough study to assess using geology coverage. |
| 193-243 | Predicting Meander Migration of the Sacramento River, Ca.: Comparison of Empirical and Physically-Based Mathematical Modeling Approaches | (Thomas 2001) | Masters. Thesis. Roughly calibrated; no vegetation or geology. |
| 218-222 | Modeling Channel Management Impacts on River Migration: A Case Study of Woodson Bridge State Recreation Area, Sacramento River, California, USA | (Larsen and Greco 2002) | Roughly calibrated; no vegetation or geology. |
| 185-201 | The Controls on and Evolution of Channel Morphology of the Sacramento River: A Case Study of River Miles 201-185 | (Larsen et al. 2002b) | TNC study. |
| 216-226 | Using Science to Evaluate Restoration Efforts and Ecosystem Health on the Sacramento River Project, California | (Golet et al. 2003) | Uses results from (Larsen and Greco 2002). |
| 168-170 | Potential Geomorphic Impacts of Bank Stabilization Measures along the Sacramento River near the Butte City Bridge on Route 162 | (Flora 2003) | Master's thesis. |
| 191-200 | Meander Bend and Gravel Bar Migration near River Mile 192.75 of the Sacramento River | (Larsen 2004a) | CBDA/Duck's Unlimited. |
| 177-180 | Meander Bend Migration near River Mile 178 of the Sacramento River | (Larsen 2004b) | CBDA/River Partners. |
| 235-241 | Future Meander Bend Migration and Floodplain Development Patterns near River Mile 241 to 235, Sacramento River | (Larsen 2005a) | CBDA/River Partners. |
| 191-200 | Meander Bend Migration and Floodplain Development Patterns near River Miles 200 to 191 of the Sacramento River | (Larsen 2005b) | CBDA/Duck's Unlimited. Follow up to (Larsen 2004a). |
| 184-202 | Assessing the Effects of Alternative Setback Levee Scenarios Employing a River Meander Migration Model | (Larsen et al. 2006) | Modeling of theoretical conditions without bank restraint and setback levees. |
| 185-201 | Assessing Societal Impacts When Planning Restoration of Large Alluvial Rivers: A Case Study of the Sacramento River Project, California | (Golet et al. 2006) | Riprap removal scenarios; three 25-year time steps 75 years into the future. |
| 218-222<br>177-180 | Landscape Level Conservation Planning in Alluvial Riparian Ecosystems: Using Models to Avoid Conflicts between Forests and Infrastructure | (Larsen et al. In Review-a) | Uses results from (Larsen and Greco 2002) and (Larsen 2004b). |
| 191-200 | Future Meander Bend Migration and Floodplain Development Patterns Near River Miles 200 To 191 of the Sacramento River Phase III Memo | (Larsen In review) | CBDA/Duck's Unlimited. Follow up to (Larsen 2004b, Larsen 2005b). |

**Table 15 Sacramento River reaches where previous versions of model have been applied**

## 2.0 Sacramento River reaches: existing agreements with other organizations

The following discussion identifies the reach of the Sacramento River where Eric Larsen has an existing Agreement with DWR (NODOS) to apply previous versions of the meander migration model or the current upgraded version of the meander migration model. In addition, discussions about work, with other organizations (e.g., California Department of Water Resources, United States Bureau of Reclamation, California Bay Delta Authority sponsored projects), but where there is no agreement, are also described.

**DWR (NODOS)**
For a contract with DWR, the modeling of RM 196-199 with variable flow was done with a "virtual Pine Creek", but not applied to a real situation. We modeled the changes in floodplain age patterns that would have occurred with flow operation scenarios (using post 2000 conditions) in the years 1945-1976 at RM 196-199. We are currently continuing this work with a study for DWR/NODOS that links a vegetation model of 6 key riparian species to the migration modeling reported in (Larsen et al. In Review-b).

**DWR (NODOS) and BOR (NODOS) discussions**
I have discussed possible additional simulations for the North of Delta Offstream Storage group, but do not have any existing agreements for this work. Discussions have been with Stacy Ceppelo (DWR Redbluff) and Jim Weiking (DWR Sacramento), and with Blair Greiman (BOR Denver).

Any application of the existing or revised meander migration model for TNC/Stillwater would not be shared in the future with anyone without complete agreement of TNC, Stillwater, and CBDA.

### 3.0 RECOMMENDATIONS FOR REACHES TO APPLY CURRENT MODEL

This section outlines recommendations for reaches of the Sacramento River where the current, upgraded version of the meander migration will be applied as part of the Agreement (Scope of Work). These recommendations are based in part on discussions with other members of the team at the planning session at UC Davis in early December. At that meeting, a map was drafted that showed previous efforts of various kinds along the Redbluff to Colusa reach. A draft proposal of the people in the session at that time, was to model migration with different flow scenarios from RM 170 to RM 222, separated into three distinct separate reaches of roughly equal length. Beginning and ending points for each reach could be altered depending on geomorphic characteristics of each reach.

**RM 170-185**
This reach includes an area of potential cutoff modeling in the vicinity of RM 172 (Cui 2005). It also includes a series of meander bends (RM 171-176) that are typical of meander bends and thus provide effective comparison with typical meander bend

sequences in other environments. Extending the modeling up to RM 185 extends this reach up to the beginning of the next study reach, potentially providing continuous modeling from RM 170 to RM 222.

### RM 185-201

This section of the river includes a series of bends that approximate classical "meander bend sequences" (i.e. RM 189– 192). These are good areas to study and model as they provide a "type" that is relatively easy to understand. Such classic bends provide a backdrop against which other areas, which are less typical, can be compared. In addition, some of these bends, which are now restrained, have been suggested for mitigation sites, where bank restraint could be removed in mitigation for installing restraints in other places. Simulations here, with different flow scenarios, could help inform future management actions.

Previous studies have been done in this reach. One study documents the historical changes in the reach (Larsen et al. 2002b), with studies of morphology that is important for migration (i.e. curvature and sinuosity), calculation of historical areas of land reworked, and channel migration rates. This study also includes some simulations of future migration with an estimate of the changes in the morphology, the patterns of area reworked, and the migration rates. The model was calibrated with a spatially variable erosion field that was determined by calibration, but did not incorporate spatially variable erosion values based on GIS input of geology and vegetation. That model did not have the latest information on riprap and other installed bank restraint, and did not use variable flows.

There have been other studies in this area (Larsen 2004a, Larsen et al. 2004, Larsen 2005b, Golet et al. 2006, Larsen et al. 2006, Larsen In review). Some of these other studies have used a spatially varied erosion field, and limited information on bank restraint, but have not incorporated variable flows or updated bank restraint information.

### RM 201-222

This reach includes Woodson Bridge State Recreation area, which is an area of interest for possible removal of bank protection. Former modeling in the vicinity of Woodson Bridge did not use a spatially varied erosion field, and had limited information on bank restraint. Former modeling did not incorporate variable flows or updated bank restraint information.

## 4.0 SCIENTIFIC PRINCIPLES AND CORE EQUATIONS USED IN THE UPGRADED MODEL

**Cumulative Effective Stream Power** *(Kondolf et al. 2000, Larsen et al. In Review-c)*

The underlying hypothesis is that the bank migration rate, in a specified time interval, is linearly related to the sum of the cumulative effective stream power in the same time interval.

In cases where hydraulic forces alter the stream (processes ranging from sediment transport to bed rock river formation), researchers have used stream power to represent the forces moving sediment (e.g. (Leopold et al. 1964, Begin 1981, Hickin and Nanson 1984, Sklar and Dietrich 2004). (Leopold et al. 1964), based on the work of (Bagnold 1960), argue from a mechanical standpoint that stream power represents "the rate of doing work ... by the flowing water." Available stream power, as defined by Leopold et al. (1964 p. 178) is:

$$\Omega = \gamma QS \qquad [9]$$

Stream power ($\Omega$, kg m/s$^3$) is a rate of potential energy expenditure per unit length of channel, calculated as the product of discharge (Q, m$^3$/s), slope (S, m/m), and the specific weight of water ($\gamma$, kg/m$^2$s$^2$). Equation 1 can be manipulated to express stream power as the product of bed shear stress times the mean streamwise velocity multiplied by width:

$$\Omega = \tau\ u\ w \qquad [10]$$

where $\tau$ (kg/ms$^2$) is the bed shear stress, u (m/s) is the velocity, and w (m) is the width of the channel. In this form, stream power is represented as a force (bed shear stress) times a velocity times a scale of the channel size (width).

Stream power (used as a surrogate for the sum of the flow forces acting on a specific reach of stream bank over a designated time period), can be related to bank erosion rates. Stream power can be calculated from surface stream flow records collected at various sites along the Sacramento River by the USGS and other organizations (Larsen et al. In Review-c).

A threshold discharge ($Q_{\text{lower threshold}}$) below which erosion is negligible can be assumed. An upper threshold discharge ($Q_{\text{top of bank}}$) where the water flowing out of the channel theoretically no longer exerts force on the bank itself can also be assumed. Based on the results of an analysis to determine those thresholds (or a decision to ignore the thresholds based on the results of an analysis that shows that they are not significant), the instantaneous effective stream power ($\Omega_e$) can be calculated as:

$$\Omega_e = 0 \ \text{ if } Q <= Q_{\text{lower threshold}}, \qquad [11]$$
$$\Omega_e = \gamma SQ - \gamma SQ_{\text{lower threshold}} \quad \text{if } Q_{\text{lower threshold}} < Q < Q_{\text{top of bank}} \qquad [12]$$
$$\Omega_e = \gamma SQ_{\text{top of bank}} - \gamma SQ_{\text{lower threshold}} \quad \text{if } Q >= Q_{\text{top of bank}} \qquad [13]$$

where Q (m$^3$/s) is the mean daily flow rate at a site, estimated from available gauging records and S is water surface slope . The *cumulative* effective stream power ($\Omega_{ce}$) is then calculated by summing over the seconds in each measurement time interval:

$$\Omega_{ce} = \sum \Omega_e \qquad [14]$$

The basic assumption of this procedure is that the magnitude of bank migration, when flows that are below or above the thresholds are excluded, in a specified time interval is linearly related to the sum of the cumulative effective stream power in the same time interval.

**Variable Flow Rate** (Larsen et al. In Review-b)
Although previous versions of the meander migration model have been successfully used to assess planning issues (Larsen et al. 2002a, Larsen and Greco 2002), those applications have employed a constant flow rate. A method to incorporate a daily flow hydrograph as the basis of modeling meander migration rates as a function of variable flow rates (current, upgraded version of the meander migration model) has been developed (Larsen et al. In Review-b).

It has been shown that there is a simple linear regression that correlates the cumulative excess stream power, above a lower threshold, with rates of bank erosion at sites on the middle Sacramento River in California (CALFED 2000, Fremier 2003, Larsen et al. In Review-c). This principle can be used to incorporate the effects of a variable flow into the meander migration model and can be used to scale the amount of river movement.

Annual power can be calculated by summing the daily stream power above a lower flow threshold during a given year (starting October 1). This assumes the river channel does not move when flows are less than the erosion threshold, and that the distance the river channel will move increases linearly as the stream power increases (Fremier 2003, Larsen unpublished data, Larsen et al. In Review-c). A relative measure of stream power, *scaled annual cumulative excess stream power* ($\Pi_i$), can be calculated by the following formula:

$$\Pi_i = \frac{P_i}{\overline{P}_{calib}} \qquad [15]$$

where $P_i$ is the stream power for a given year *i*, and $\overline{P}_{calib}$ is the mean annual cumulative excess stream power for the calibration period.

## 5.0 Data required as model input

This section includes a description of the data required as model input (e.g., the discharge records, land cover classification, soil information, etc.) for the current, upgraded version of the model. The hydraulic and geomorphic input that is required for both the previous versions and the upgraded version of the model is also described.

### *Hydraulic and geomorphic input*

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

*Channel planform centerlines.* Centerlines are determined by tracing channel edges from aerial photos and drawing centerlines one half-channel width from the cut-bank (outside of bend) of the channel margin.

***Discharge records***

*Calibration.* For the upgraded model, discharge data are required for calibration, and for simulations. Calibration data can use mean daily flow rates obtained form gauging station records. As an example, when working with simulations at a bend near Pine Creek (RM 196-199) (Fremier 2003, Larsen et al. In Review-b) the observed hydrograph for the years 1956 to 1975 was obtained from the California Department of Water Resources Bend Bridge (number 11377100) flow gauge (US Geological Survey 2004).

*Simulation.* One example of simulation input data is data produced by the California Department of Water Resources North of Delta Off-Stream Storage (NODOS) project (California Department of Water Resources 2003). Daily flow management scenarios can be simulated using the computer program CalSim II. These simulations estimate the daily river flows that would have occurred under different water management scenarios, based on actual river flows.

For both the calibration and simulation, daily discharge records are transformed into ".DAT" files with two columns, the daily date, and the mean daily discharge for that day. Table 2 shows the form of the data used. The sample shows the discharges for a few days; the input data set would have this record for a period of years. In the input file, only the digital form of the date is used.

| Date | Date (digital format) | Q (cms) |
|---|---|---|
| 10/31/1971 | 26237 | 243 |
| 11/1/1971 | 26238 | 210 |
| 11/2/1971 | 26239 | 207 |
| 11/3/1971 | 26240 | 202 |
| 11/4/1971 | 26241 | 195 |
| 11/5/1971 | 26242 | 187 |
| 11/6/1971 | 26243 | 179 |
| 11/7/1971 | 26244 | 171 |
| 11/8/1971 | 26245 | 159 |
| 11/9/1971 | 26246 | 151 |
| 11/10/1971 | 26247 | 148 |

**Table 16 Sample discharge data: input to upgraded model**

## Land cover classification

Land cover classification (Figure 2) is taken from a GIS landcover dataset of riparian vegetation and agricultural land obtained from the Landscape Analysis and Systems Research Laboratory (LASR), University of California, Davis (Greco and Plant 2003).

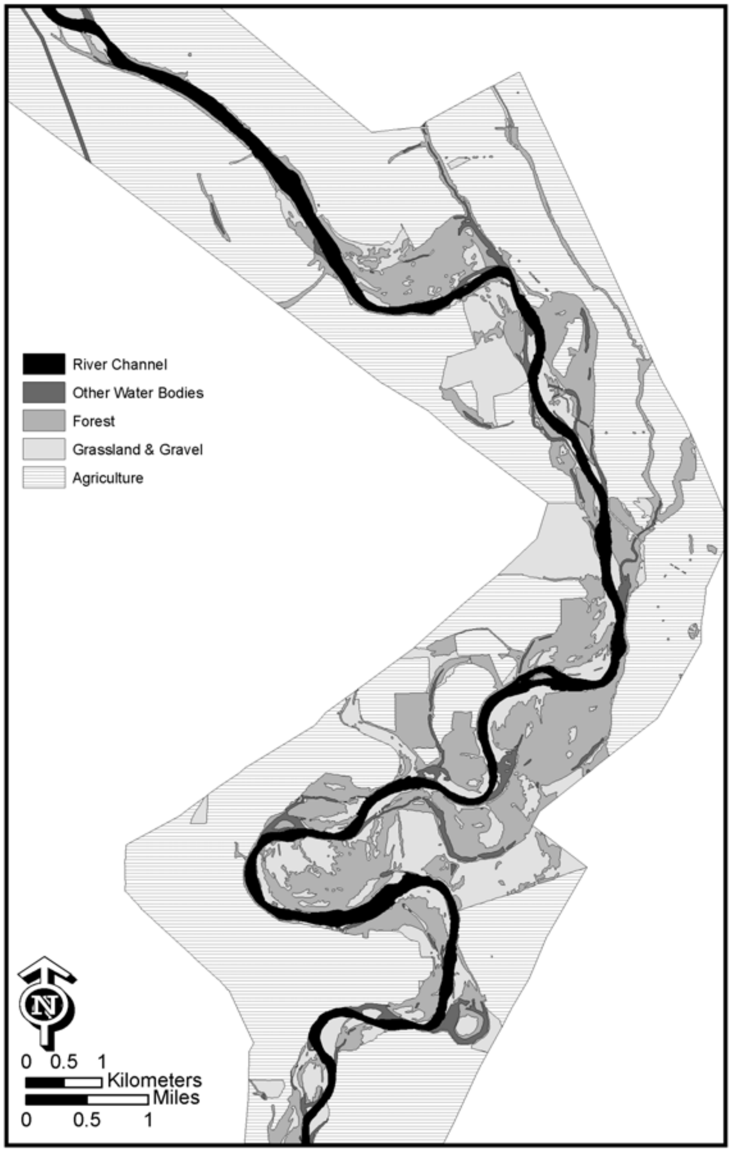


Figure 43 Land classification coverage map (Larsen et al. 2006)

## Geology (soils) coverage

The geology dataset used for creating a heterogeneous land erodibility surface has been 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.

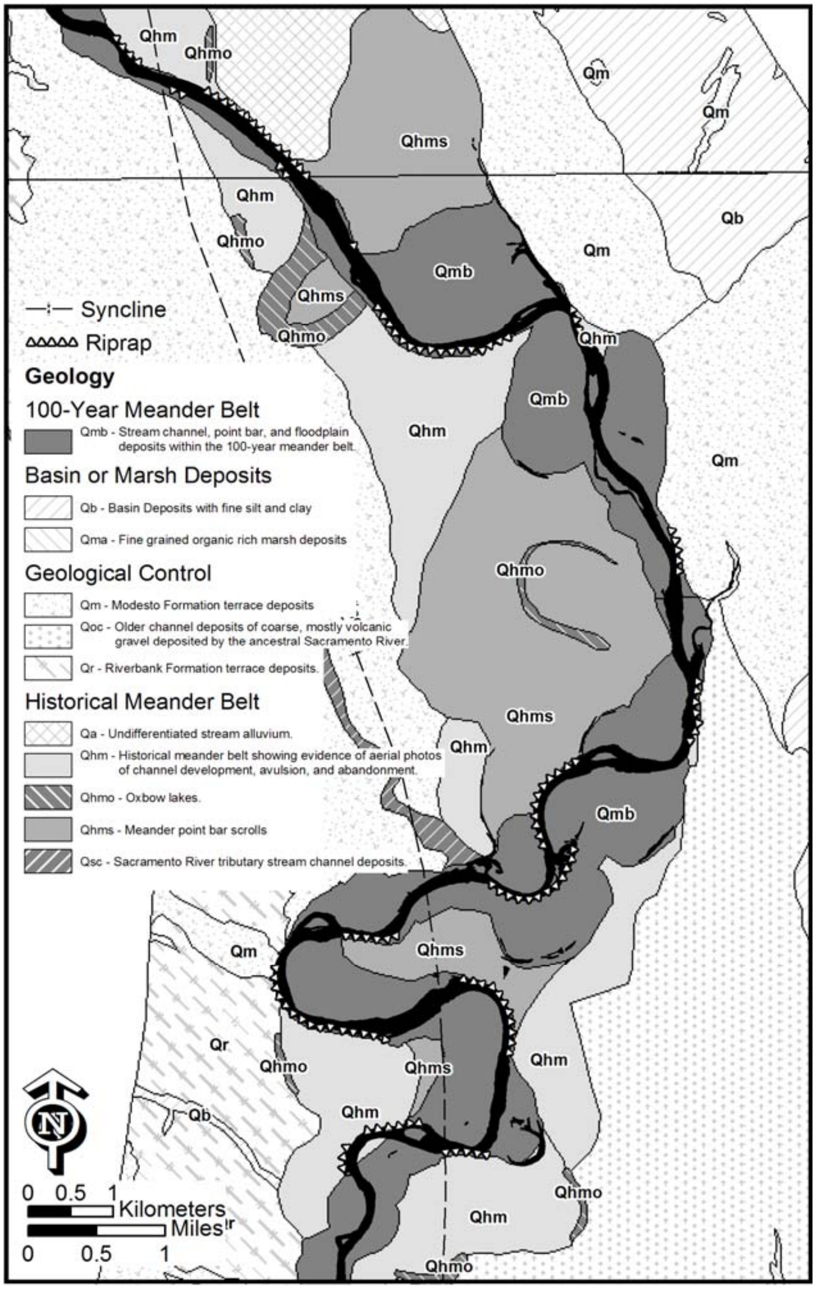


Figure 44 Geology (soils) coverage map (Larsen et al. 2006)

## 6.0 ASSUMPTIONS AND RELATIONSHIPS USED IN THE UPGRADED MODEL

This section is a description of the assumptions and relationships used in the current, upgraded version of the model (e.g., the combination of soil and vegetative cover information into an erosion surface).

### Heterogeneous Erodibility Surface

A heterogeneous erosion surface can be created using the geographic information system (GIS) ArcGIS 8.3 (ESRI 2003) and imported into the river meander migration model. The erodibility surface is developed by spatially combining a GIS dataset of geology, described above, with a GIS dataset of landcover, also described above.

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 et al. 2002a, Micheli et al. 2004).

## 7.0 INCORPORATING A VARIABLE HYDROGRAPH INTO THE UPGRADED MODEL

This is a description of how recent improvements to the current, upgraded version of the meander migration model were achieved (e.g., incorporation of a variable hydrograph).

The scaled annual cumulative excess stream power (described in the section on scientific principles above) was directly incorporated into the meander migration model by multiplying $\Pi_i$ by the migration distance for each year based on a constant rate flow. Thus, during water years with half the average stream power ($\Pi = 0.5$), the model will simulate half as much migration as it would have for an average year, while in water years with three times the average cumulative annual stream power ($\Pi = 3$), the model will simulate three times as much migration as an average year.

Once a model run has been calibrated with a variable flow and heterogeneous erosion surface, the simulation capabilities of the meander migration model can be used to simulate river meandering under different daily hydrograph scenarios. Modelers can therefore simulate how the river would have moved in the past under a flow regime different from the one that occurred, and forecast how the river might migrate under different potential future management scenarios (Larsen et al. In Review-b).

## 8.0 MODEL OUTPUT

This describes the environmental variables or performance metrics for which the meander migration model will produce model output (e.g., meander migration rates, linear feet of bank eroded, area of floodplain reworked, length of newly orphaned channel, etc.)

### 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 3). 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).

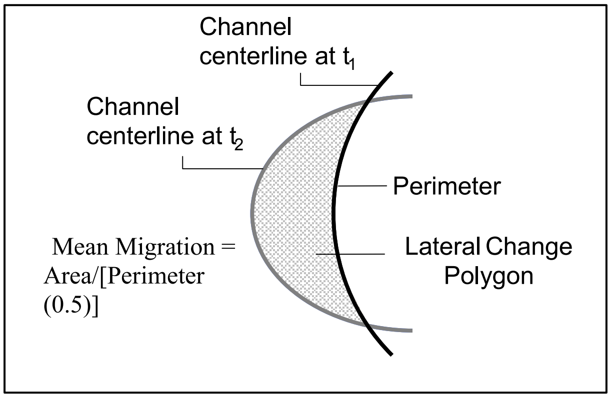


**Figure 45 Definition of area reworked polygon**

An example of the output that is possible is shown in Figure 4. In this example, the area reworked is show two ways for two possible channel configurations, one with channel constraint, and one without.

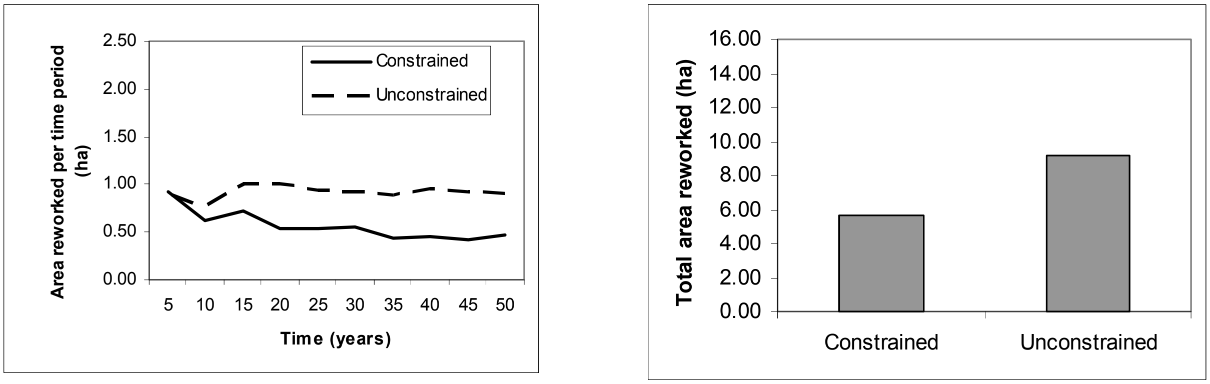


**Figure 46 Example of area of land reworked output at a single bend (Larsen 2005b)**

## 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 (Environmental Systems Research Institute 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:

$$\frac{A_r}{tL} \qquad [16]$$

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 8 calculates the migration rate as a linear distance per time; the rate of land reworked is reported as an area per time, by using Equation 4 without dividing by the length ($L$).

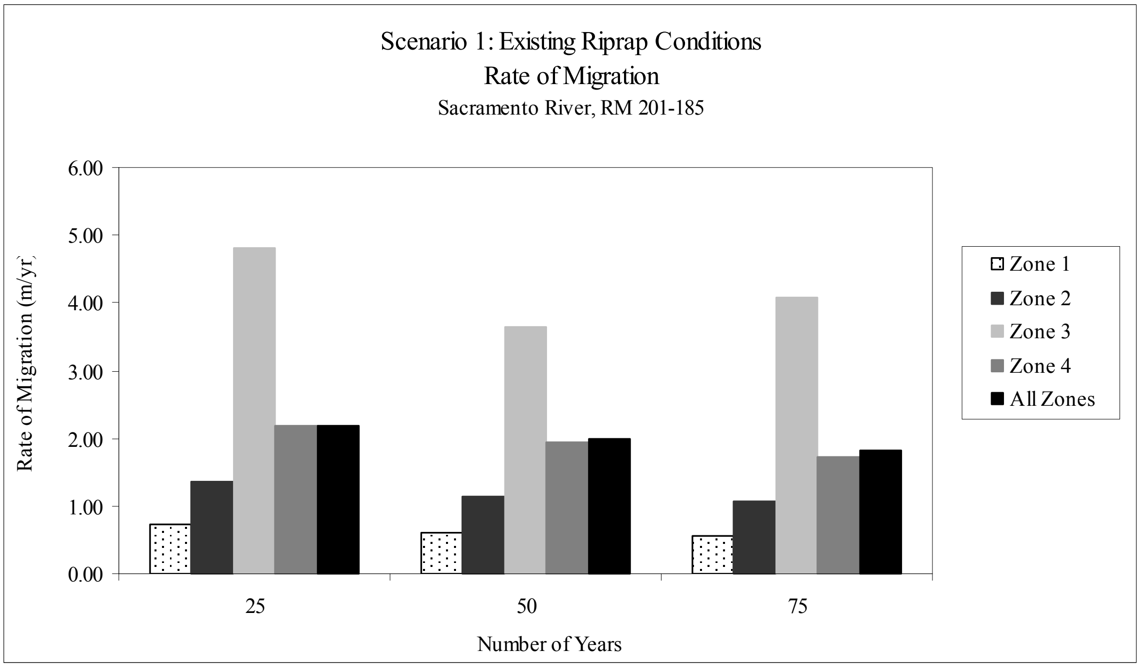


Figure 47 Example of migration rate over time in multiple zones (Larsen et al. 2002b)

***Linear feet of bank eroded***

The linear feet of bank eroded from one time period to another can be estimated in GIS from the polygons that are used in the calculation of the area of land reworked (Figure 3). A first estimate is the length of the arc of channel for time 2 where it is not overlapping with the channel in time 1. A refinement of that would be to buffer both centerlines by a channel width, and then to take the intersection of the outside bank lines for the two time periods and calculate the length of the outside bank of time two.

**Length of newly orphaned channel**

The length of newly orphaned channel can be estimated using a prototype channel cut-off model that has been developed, and can be used in conjunction with the meander migration model. Based on empirical studies that have been done to quantify the changes in channel planform shape of the Sacramento River from Colusa to Red Bluff, a threshold geometry for chute cutoff has been investigated and estimated (Larsen and Micheli In manuscript).

The data from that study show that geometric parameters can serve as a predictive indicator for the geometry that is likely to experience chute cutoff. On a study of about 100 years of channel migration from River Mile 143 to 243 (Colusa to Red Bluff), bends that experienced chute cutoff displayed a characteristic average sinuosity, average radius of curvature, and an average entrance angle. These findings suggest that the likelihood of a bend being prone to experience chute cutoff on the Sacramento River may be estimated based on centerline geometry for a range of channel slopes typical of the meandering portion of the Sacramento River.

These average data will be used with the modeling scenarios, in the meander migration model to estimate when a channel will be prone to cutoff. In addition to the geometric parameters, the model will test for the occurrence of "overbank flow" before a cutoff will be simulated. An estimate will be made of the location of cutoff and downstream reattachment. From this, the length of "orphaned channel" will be measured and reported for use in the SCAEFT database.

## 9.0 LIMITATIONS AND INTERPRETATION OF EXPECTED MODEL RESULTS.

This section describes limitations of the current, upgraded version of the meander migration model or caveats regarding the interpretation of expected model results.

### *Models and simulations*

As with all simulation models, the variable flow 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 say that a particular point on the landscape would experience 15.7 meters (arbitrary example) of bank erosion at a precise spot in a prescribed time interval. Simulations are good to indicate patterns, for example, one could simulate that one flow scenario would result in 35% more land reworked (arbitrary example) than another scenario.

### *Streampower*

The linear regression relationship that is used between stream power and bank erosion probably does not express the entire relationship between flow rates and bank erosion rates. For example, flow duration may play a role. And although a linear relationship can be effectively used between cumulative effective stream power and erosion, there has been shown a tendency for higher discharges to have proportionally less effect (suggesting a non-linear relationship) (Larsen et al. In Review-c). The practical way to deal with this limitation is to do an analysis of a theoretical "upper threshold", above which flows may or may not be excluded from sum of effective stream power (Larsen et al. In Review-c).

Although the migration rates predicted by a variable-flow model significantly correlated with the observed scaled stream power in a very limited study area (RM 196-199 (Larsen et al. In Review-b)), the correspondence was not exact because stream power is not the only parameter that contributes to bank erosion. Local bank erosion is complex and includes processes that are not directly proportional to flow rates, independent of other factors. For example, bank collapse may occur as a function of rapidly declining flow rates. For this reason, sums of events over a time span (longer than a single event) may be more accurately simulated than smaller scale time spans like a single flow event.

### *Tributary influences*

Although it has been suggested that bends at or just downstream from stream tributary confluences migrate faster due to sediment input (Constantine et al. 2004), analyses of stream power data do not show this pattern (Larsen et al. In Review-c). In a study of bank erosion and stream power (Larsen et al. In Review-c) areas with the highest mean average erosion rates are not 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.

***Vegetation and draw down rates***

When considering the relevance of area reworked on the distribution and regeneration of plant species, factors other than area reworked (which can be translated into floodplain age) are important. For example, plant ecologists have found that vegetation recruitment and succession is affected by intra-annual flow patterns, such as spring draw down rates, and stage discharge relationships through the year, especially at low flows and peak flows (Mahoney and Rood 1998, Richter and Richter 2000). Analysis developed from the area reworked by variable flows only accounts for the total amount of area reworked that the river produces in a time interval, not the intra-annual timing of flows.

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