MODELING REVETMENT REMOVAL AND IMPLICATIONS FOR MEANDER MIGRATION OF SELECTED BENDS RIVER MILES 222 TO 179 OF THE SACRAMENTO RIVER

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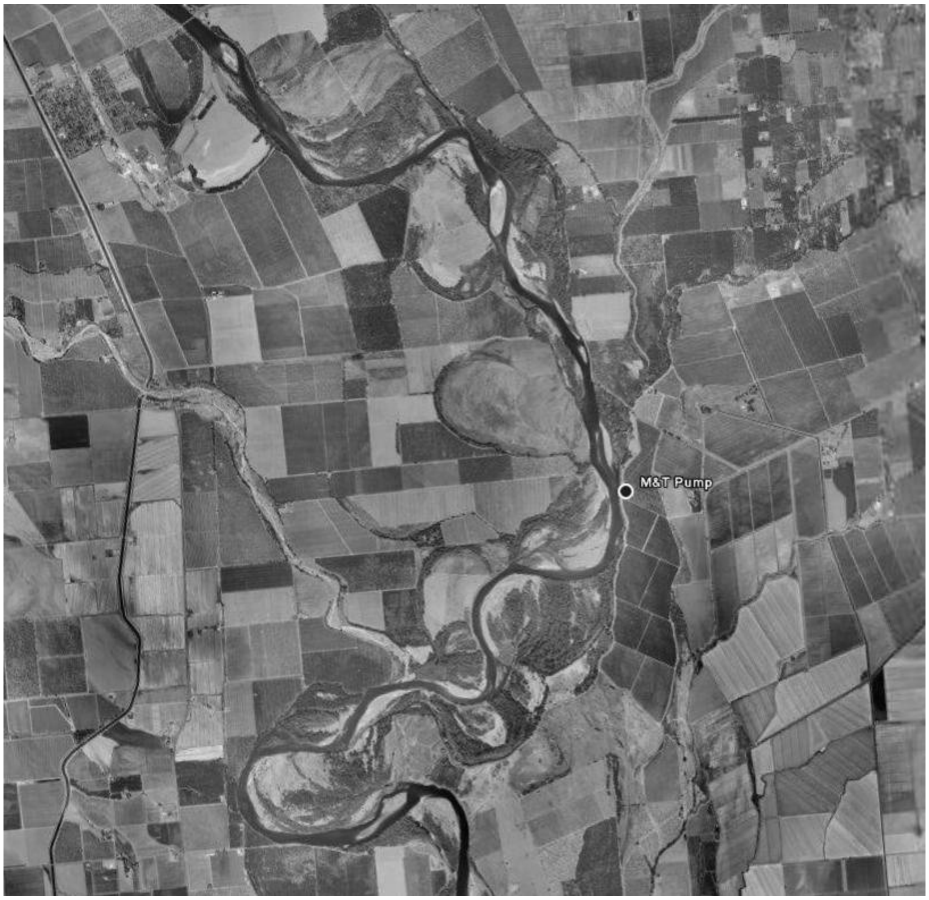

FINAL TECHNICAL REPORT FOR DUCKS UNLIMITED
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EXECUTIVE SUMMARY

This report describes analyses to study the meander migration patterns 50 years into the future when revetment is removed on selected bends of the Sacramento River between River Miles (RM) 222 and 179. Previous studies have been done to document the channel dynamics near the location of the M&T pumping plant near RM 192 (Larsen and Cui 2004, Larsen 2005b, a, 2006). The current report describes modeling that can be used to understand the patterns of migration at individual bends on a bend-by-bend basis, and to compare the extent of migration when revetment is removed and when it is in place.

The modeled scenarios simulate meander migration patterns from a 2004 river planform to 50 years in the future. The simulation scenarios utilize calibration, a spatially variable erosion field, and a variable hydrograph. River bends were identified where existing revetment exists and could possibly be removed. Modeling was performed that first simulated the future migration with the revetment in place, and then simulated the migration with the revetment removed.

The details of modeling techniques, the background on the meander migration model, and key assumptions are not repeated in this report and can be found in previous reports (Larsen and Cui 2004, Larsen 2005b, a). The current study incorporated a variable flow algorithm that relates yearly migration rates to the observed (or modeled) flow in that year. The modeled migration was performed from simulated water year (WY) 2005 to 2054. These simulated future flows were taken from recorded historical flows for WY 1939 to WY 1988 from three different gauges on the Sacramento River. In addition a prototype model for channel cutoff was used to assess the potential for chute cutoff when revetment was removed.

For the purposes of calibration and modeling, the river was broken into three segments and a total of nine modeling scenarios are described as shown in the following table, where the “R” and “L” refer to left or right when looking downstream.

Reach name	Modeled bends					
Woodson Bridge	220-222R	216-217L				
Hamilton City	197-198R	191-192R	186R	186.5L	191.5L	197.5R
Ord Ferry	179R					

For each of the nine scenarios, maps were produced that show the migration patterns 50 years into the future, with channel locations at 5-yr increments. When the nine sites are considered as a whole, two of the sites have limited increase in migration when revetment is removed, and one site experiences cutoff. Migration of the bend at RM 196L is limited by the natural restraint to the east. Migration of the bend at RM 186R is modeled to move away from the revetment. The bend at RM 179R cuts off when the revetment is removed. At the remaining six sites, revetment removal results in significant increases in area reworked. At some sites, there is also some change in the pattern and quantity of area reworked in the bend immediately downstream. These findings, when considered in relation to other criterion, will help consider the benefits, in terms of channel migration and area reworked, to be gained when revetment removal is considered for mitigation or for other purposes, at the selected sites on the Sacramento River.

1.0 INTRODUCTION

This report describes analyses to study the meander migration patterns 50 years into the future of selected bends of the Sacramento River between River Miles (RM) 222 and 179. Previous studies have been done to document the channel dynamics near the location of the M&T pumping plant near RM 192 (Larsen and Cui 2004, Larsen 2005b, a). The current report describes modeling at individual bends that can be used to understand the patterns of migration on a bend by bend basis, and to compare rates of migration between different bends.

The previous studies analyzed the meander migration dynamics 50 years into the future starting with a channel location in 1997 (using data existing at that time) and reported migration tendencies with a simulation of proposed groins in place (an eight dyke groin field). Subsequent work used new data, consisting of a 2004 channel centerline, and also simulated migration for 50 years into the future with and without simulation of the placement of the eight dyke groin field, and with a newly proposed nine dyke groin field. The current study incorporated a variable flow algorithm (Larsen et al. 2006a, Larsen et al. 2006b, Larsen 2007) that relates yearly migration rates to the observed (or modeled) flow in that year.

Simulation of future meander migration shows tendencies of the river dynamics at the scale of approximately a meander bend or meander wavelength. Mathematical modeling of geomorphic processes such as meander migration can provide information about tendencies. Although such modeling can be accurate in predicting migration patterns, simulations are not expected to produce precise point-by-point predictions of future channel locations. For this reason, analyses results show patterns of meander migration, and can be effectively used to compare patterns at different sites. In this study, the modeling is used to compare migration rates at a number of individual bends. Such information can be used to consider effectiveness of mitigation by estimating the amount of land reworked that would result from various mitigation actions such as revetment removal.

The modeled scenarios simulate meander migration patterns from the 2004 river planform to 50 years in the future. The simulation scenarios utilize calibration and use a spatially variable erosion field and a variable hydrograph. River bends were identified where existing revetment exists and could possibly be removed. Modeling was performed that first simulated the future migration with the revetment in place, and then simulated the migration with the revetment removed.

2.0 METHODS

2.1 Site Description

The individual bends of the Sacramento River that were modeled were located from River Mile 222 to RM 179. This long reach of river was broken up into 3 segments based on geomorphic similarities (Figure 1). The three reaches were then individually calibrated so that the hydraulic (channel dimensions) and hydrologic (flow) characteristics were calibrated for that segment (Larsen 2007).

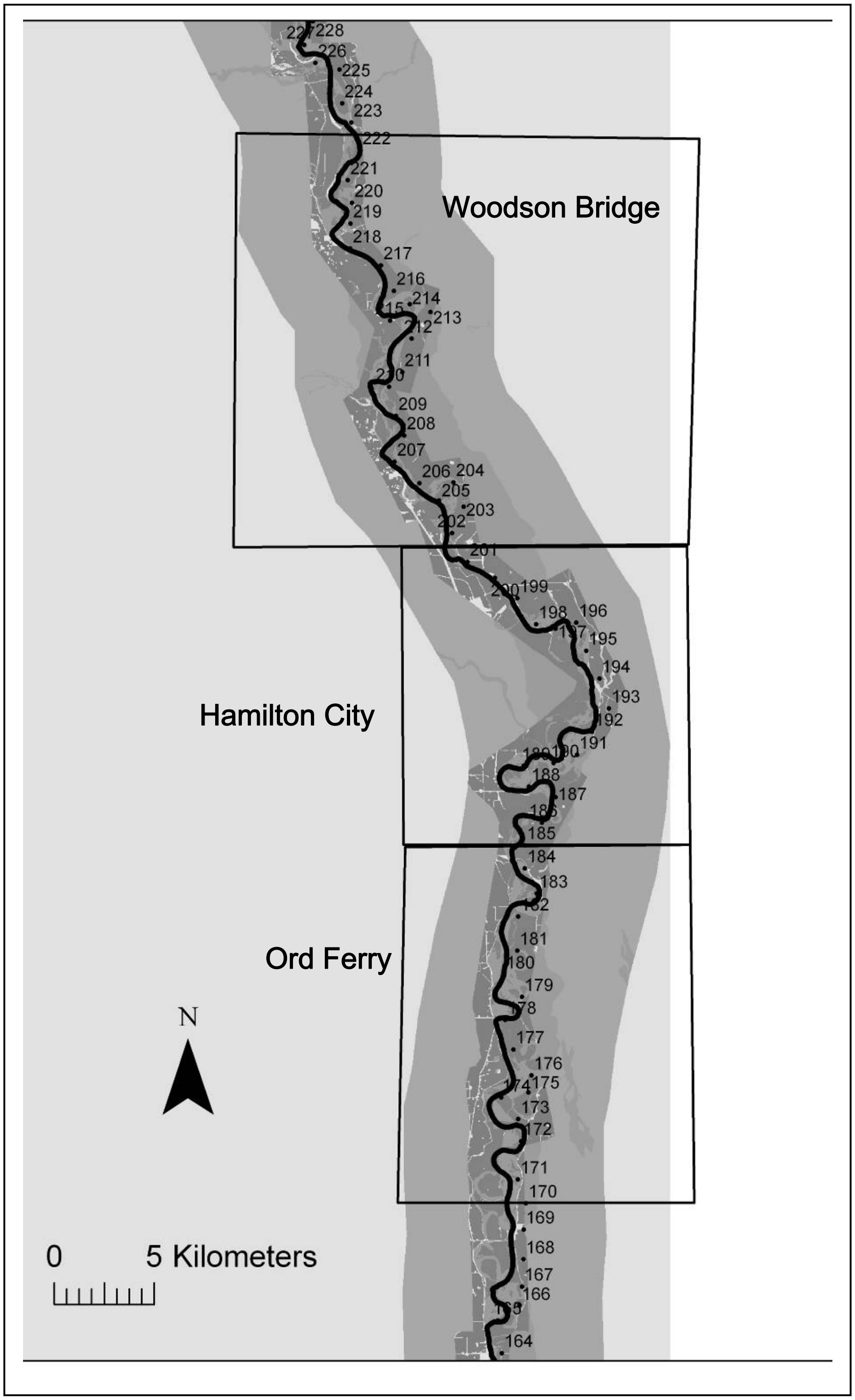

Figure 1 Sacramento River Study segments

2.1.1 Study Area: River Segments Modeled

The segments of the Sacramento River where the meander migration was modeled were based in part on previous studies that identified these segments as distinct separate segments of roughly equal length that had roughly similar geomorphic characteristics.

2.1.2 RM 201-222: Woodson Bridge Segment

This segment includes Woodson Bridge State Recreation Area, which is an area near which there is interest for possible removal of bank protection.

2.1.3 RM 185-201: Hamilton City Segment

This segment of the river includes the location of the M & T pumping plant. Previous studies in this area have been performed (Larsen et al. 2002, Larsen and Cui 2004, Larsen 2005b, a, 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. Although some of the bends modeled in the current study were previously modeled, the meander migration was remodeled for the current study so that the modeling output would be done at similar conditions for all the bends modeled in all three segments in order to ensure similar input conditions for comparing output.

2.1.3 RM 170-185: Ord Ferry Segment

This segment includes an important bend where there is a possibility to remove revetment and allow a cutoff. Cutoff modeling was simulated at this bend.

2.2 Individual bend sites

Eleven individual bend sites were selected by representatives of the USFWS and Duck's Unlimited (Pers. Com. Moroney and Zircle 2007) based on the potential for removing revetment, and the list in Table 1 was provided.

Based on this list, discussions amongst team members resulted in nine sites being chosen to model the effect of removing revetment. Two sites that were North of RM 235 were judged to be outside the area of possible use for mitigation purposes. Although some of these sites have been modeled in previous efforts for the M&T assessment, they were redone using similar methods and comparable conditions and input across all nine sites.

Table 1 Original list of potential bank revetment removal sites
(Maroney and Zircle, Pers Com.)

INITIAL SCREENING & REVIEW FINDINGS - 2/9/07						
POTENTIAL REVETMENT REMOVAL SITES ON THE MIDDLE SACRAMENTO RIVER						
Site No.	**Site Name**	**River Mile**	**Length (meters +/-)**	**Adjoining Landowner**	**Revetment Material**	**Description / Notes**
A	La Barranca	240.5 R	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
B	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
C	Todd Island	237R	2000	USFWS - La Barranca Unit, Sacramento River NWR and BLM Todd Island Unit	Medium Rock	Natural Habitat and currently under restoration
D	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
E	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
F	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
G	English	186R	2500	Private	Large rubble, privately installed	Walnut orchard
H	Dead Man's Reach	186.5 L	1800	USFWS	Large rubble, privately installed	Currently undergoing restoration
I	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
J	M&T Ranch	191.5 L	2000	M&T - Golden State Island	Medium Rock	COE Butte Basin Overflow, Existing savannah habitat
K	TNC	197.5 R	3000	TNC/ J-levee	Medium Rock	Walnut orchard - COE rock - J-levee Project

Table 2 Individual sites modeled

Reach name	Modeled bends					
Woodson Bridge	220-222R	216-217L				
Hamilton City	197-198R	191-192R	186R	186.5L	191.5L	197.5R
Ord Ferry	179R					

2.3 Input variables and Calibration

The study section from RM 222 to 179 was broken into three reaches in order to have a more accurate model at each of the individual sites. Input variables and calibration were adapted to the individual reaches. These data and procedure were used recently in an "ecological flow" study to model the effect of different flows on meander migration patterns (Larsen 2007).

2.3.1 Model Parameters for Calibration and Prediction Runs

Hydraulic input parameters are given in Tables 3 and 4, 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 3 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 3) was taken from an analysis of two sources: (Water Engineering and Technology 1988) and unpublished data from Singer (Singer In preparation).

Table 4 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.

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, 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 as modeling metadata.

Table 5 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	2054 Prediction	1976 End Channel	2054 Prediction	1976 End Channel	2054 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, WY 1939-1988	Hamilton City Historic WY 1953-1976	Hamilton City: Historic, WY 1939-1988	Vina Historic WY 1953-1976	Vina: Historic, WY 1939-1988

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

2.3.2 Heterogeneous erosion field

A spatial erodibility surface was developed from GIS data by using a geology layer and a vegetation layer as done in previous studies (Larsen 2005b, a, 2006). The geology surface dataset was obtained from the California Department of Water Resources (CDWR 1995). The vegetation coverage is based on a data set from the LASR lab at UC Davis. All geology surface types were assumed to be erodible, except for Q_r (Riverbank formation shown in black), Q_m (Modesto formation shown in black), and Q_{oc} (Old channel deposits also shown in black) which represent non-erodible areas based on their soil properties, sometimes called areas of geologic constraint. The lighter and darker shadings show agricultural land and forest land respectively. The agricultural land was calibrated to erode roughly twice as fast as forest land. The dataset was converted to a 30 m grid based on erodibility potential. A map representing how certain land use areas erode at different rates was derived from this GIS dataset. This erodibility surface was used as the basis for the calibration and the different simulation scenarios. It was on this basic underlying erosion grid that the bank restraints were placed. In addition, the erosion was modified slightly during the calibration of the model.

2.3.3 Variable flow

An algorithm was developed to use a variable flow hydrograph in performing migration modeling (Larsen et al. 2006a, Larsen et al. 2006b, Larsen 2007).

The scaled annual cumulative effective stream power (Larsen et al. 2006a, Larsen et al. 2006b) was directly incorporated into the meander migration model by multiplying Π_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. It can also be used when modeling cutoffs to identify years when, due to high flows, the channel would be expected to cutoff.

2.3.3.1 Daily flow data

Daily discharge data are required for calibration and simulation with the variable flow 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).

The modeled migration was performed from simulated water year (WY) 2005 to 2054. These simulated future flows were taken from recorded historical flows for WY 1939 to WY 1988 from three different gauges on the Sacramento River.

Table 6 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.	218	Vina/Woodson Bridge	218	201
SACRAMENTO R. NR HAMILTON CITY CA.	199	Hamilton City	185	201
SACRAMENTO R. AT BUTTE CITY CA.	168	Butte City	170	185

Once the calibration was completed, these historical daily flows were then run for the full 50 year period of record for two scenarios of channel confinement: (a) current conditions and (b) revetment removal.

2.3.4 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. This procedure was successfully used in assessing channel restraint set-back on the Sacramento River (Larsen et al. 2006c).

2.3.5 Calibrations: Centerline Agreement

Calibration in the three segments (Figures 2, 3 and 4) 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 assess 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).

The calibrations adequately model cutoffs that occurred in various river segments

2.3.5.1 Woodson Bridge Segment

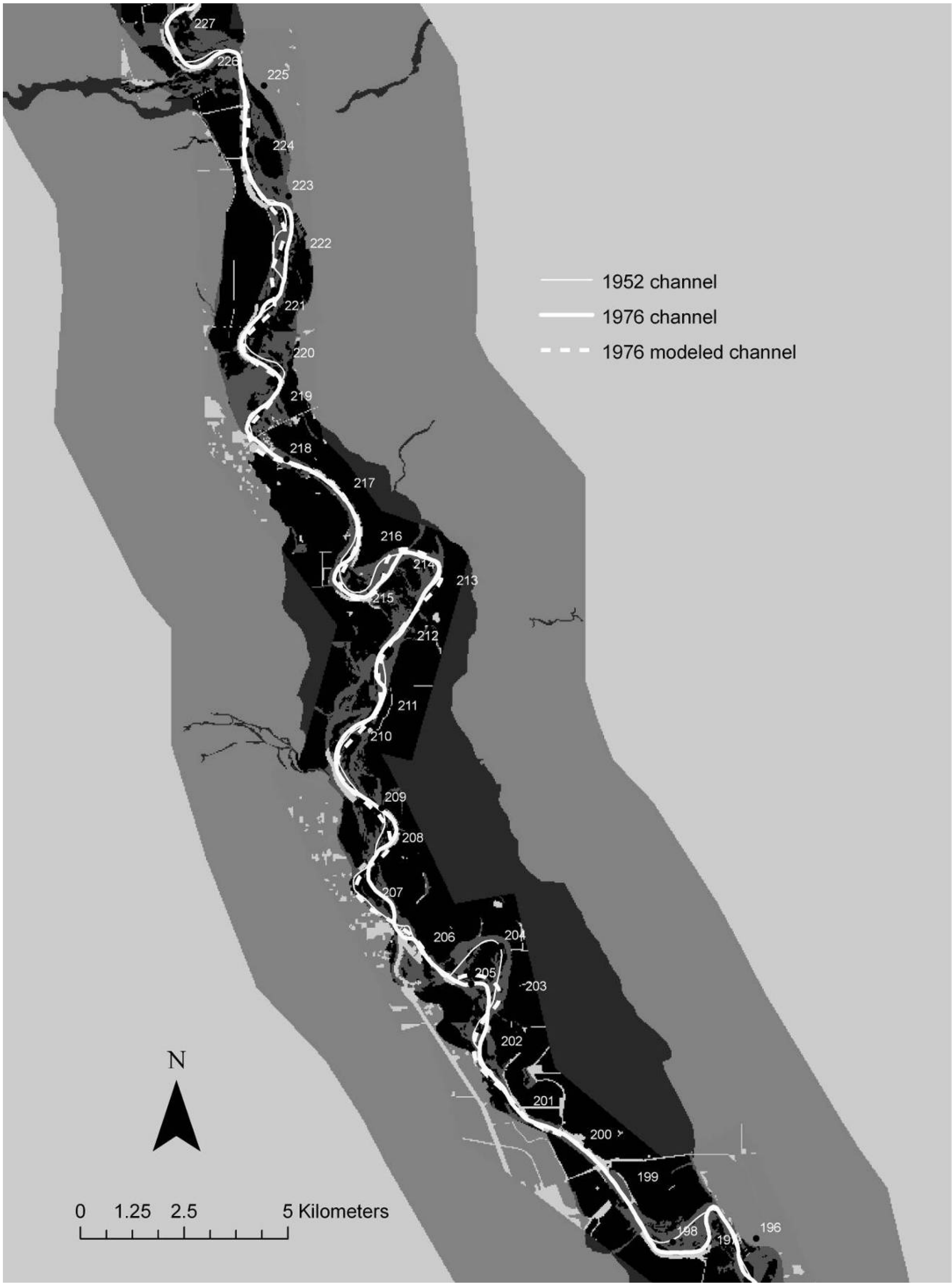

Figure 2 Calibration Woodson Bridge segment

2.3.5.2 Hamilton City Segment

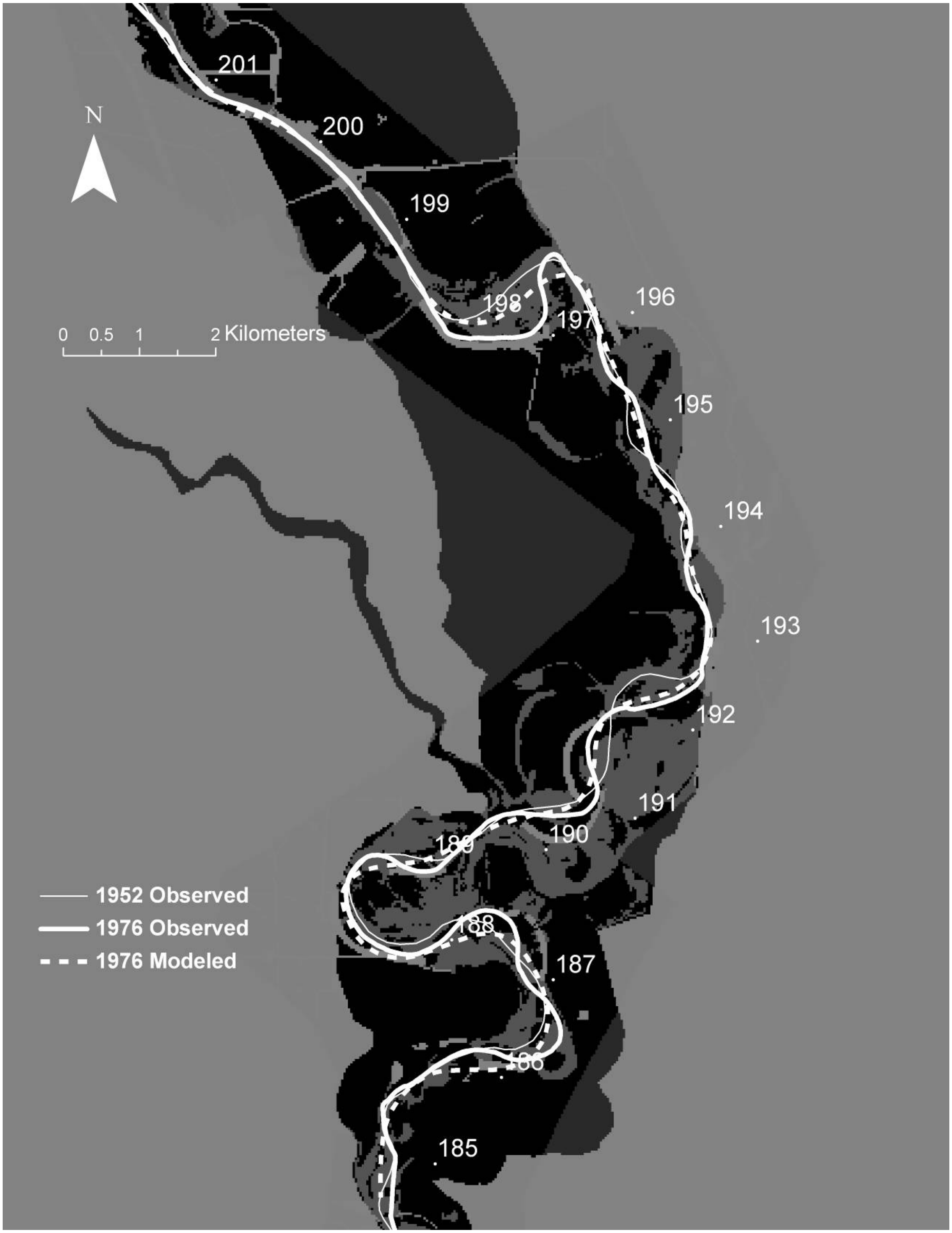

Figure 3 Calibration Hamilton City segment

2.3.5.3 Ord Ferry Segment

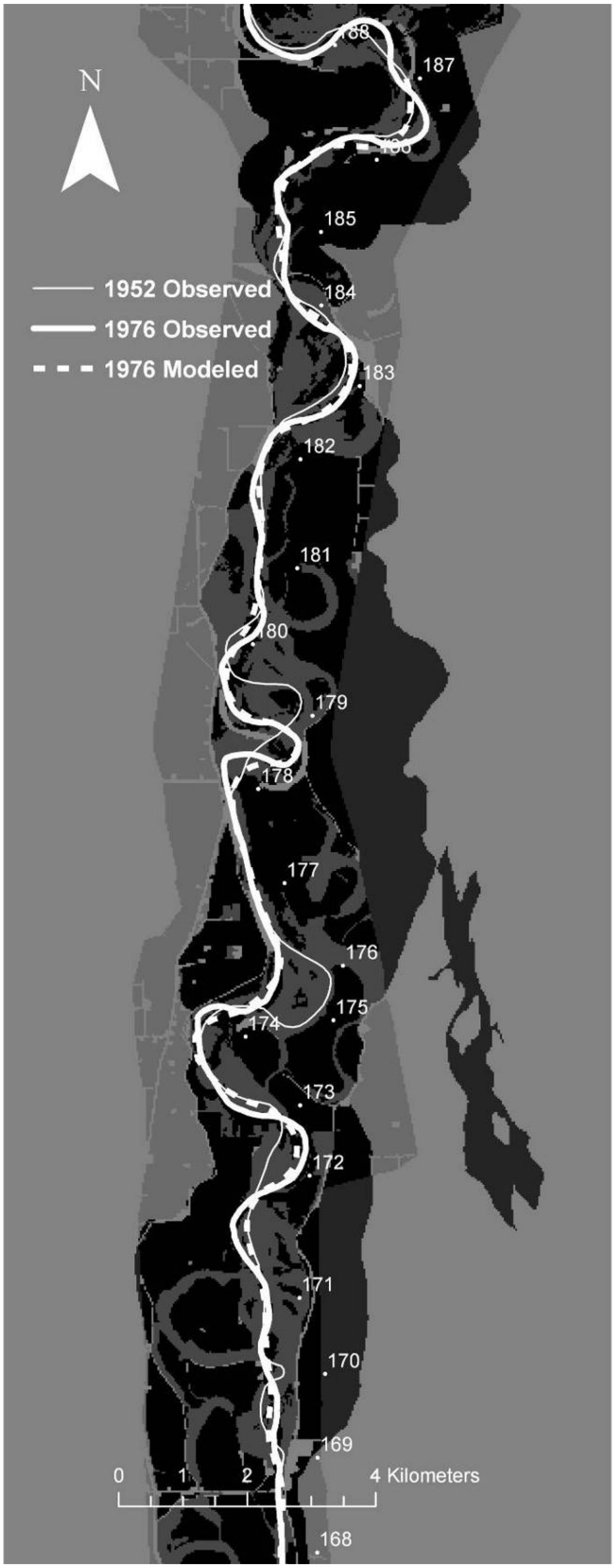

Figure 4 Calibration Ord Ferry segment

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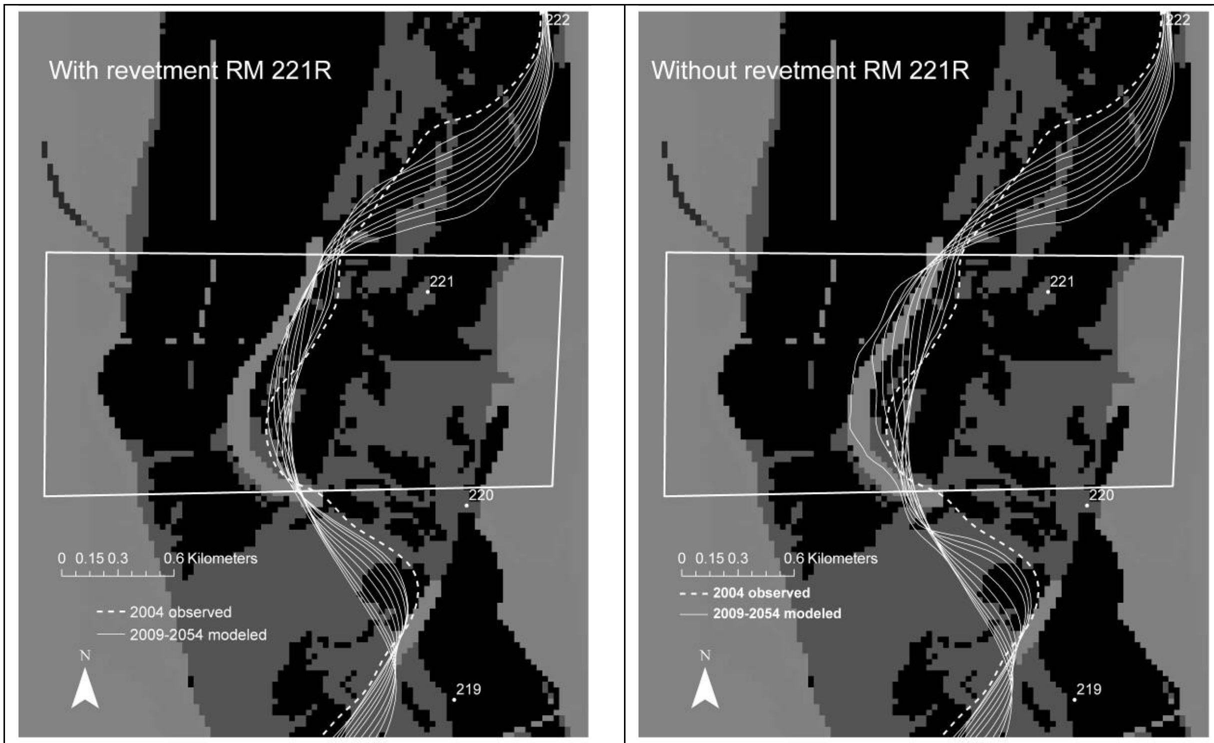
3.0 RESULTS

Figures for each of the nine modeled bends are shown as pairs: the left hand side shows the modeled migration patterns from a 2004 channel centerline to a 2054 centerline with the existing revetment in place. The right hand figure shows the same modeled migration for the same time period, with the revetment removed. The 2004 channel centerline is shown as a bold dashed line. The remaining white lines show the channel migration in 5-year increments.

Following each figure is a brief description of the modeling results illustrated in the figures.

3.1 Woodson Bridge Reach

3.1.1 RM 221R



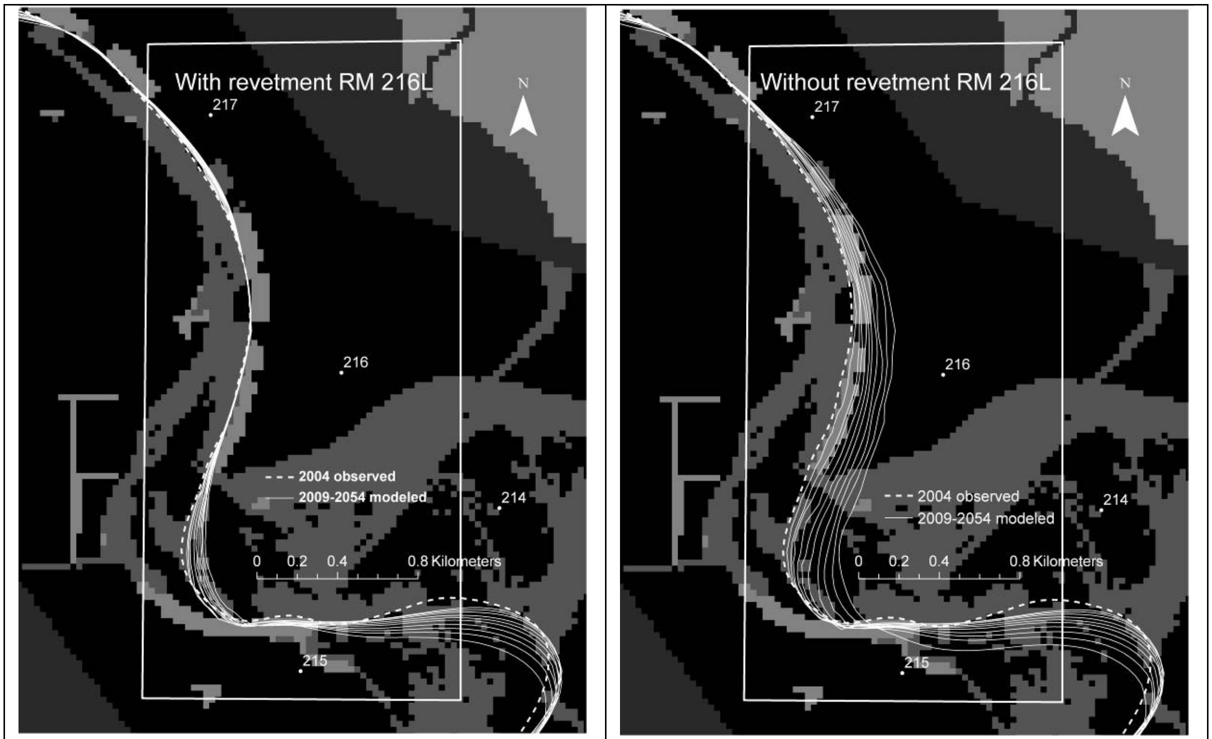
Woodson Bridge Reach with existing revetment at RM 221R

Woodson Bridge Reach without existing revetment at RM 221R

Figure 5 Woodson Bridge Reach revetment at RM 221R

Modeling shows that the removal of the revetment on the western side of the channel (between River Mile 221 and 220) results in more lateral movement to the west. The model shows that removing the revetment also slightly changes the migration patterns directly downstream.

3.1.2 RM 216L



Woodson Bridge Reach with existing revetment at RM 216L

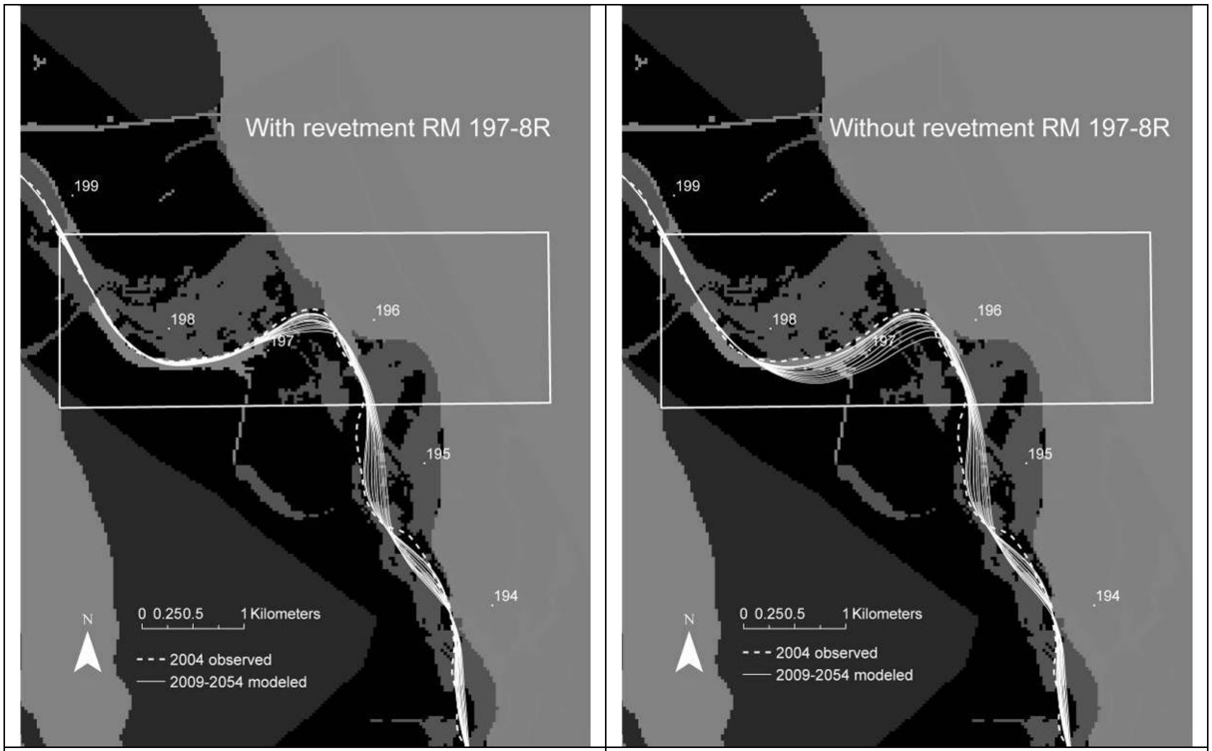
Woodson Bridge Reach without existing revetment at RM 216L

Figure 6 Woodson Bridge Reach revetment at RM 216L

The model shows removing revetment on the east side of the channel results in increased migration to the east. There is only a small amount of change in the migration of the bend immediately downstream to the south.

3.2 Hamilton City Reach

3.2.1 RM 197-8R



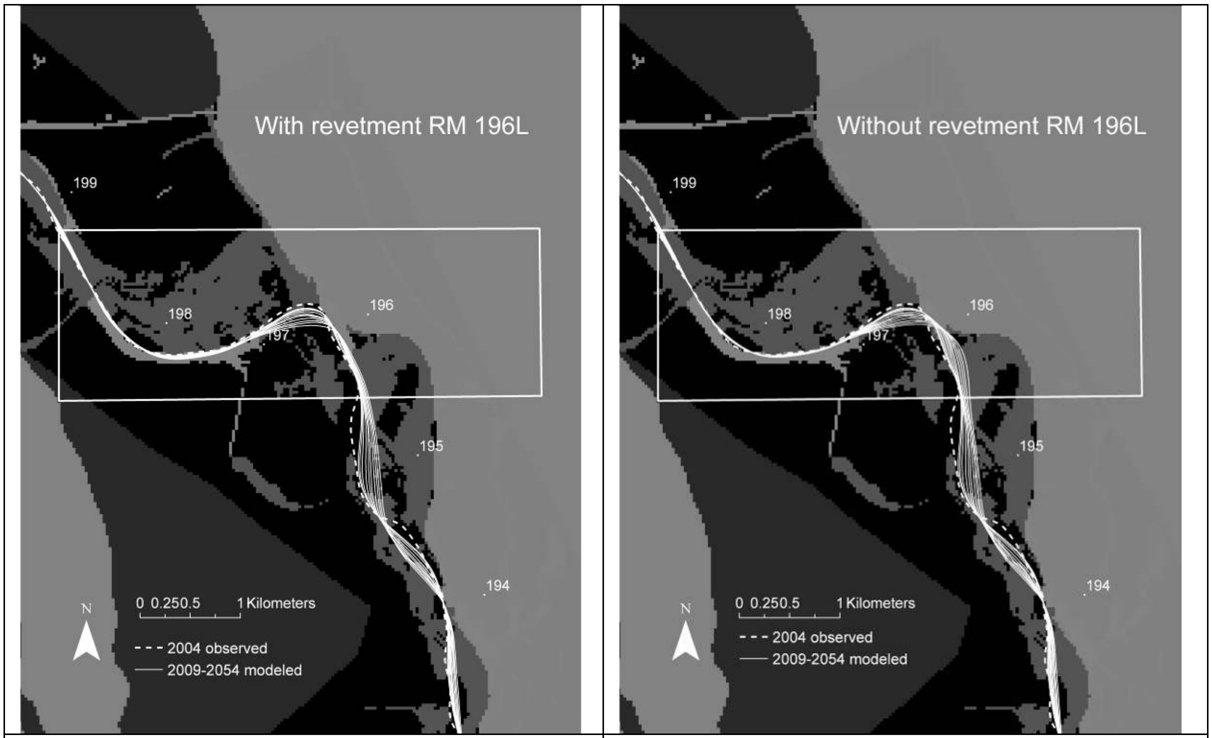
Hamilton City with existing revetment at RM 197-8R

Hamilton City without existing revetment at RM 197-8R

Figure 7 Hamilton City revetment at RM 197-8R

The model shows that removing revetment increases the migration to the south near River Mile 197 in the area where the revetment is removed.

3.2.2 RM 196L



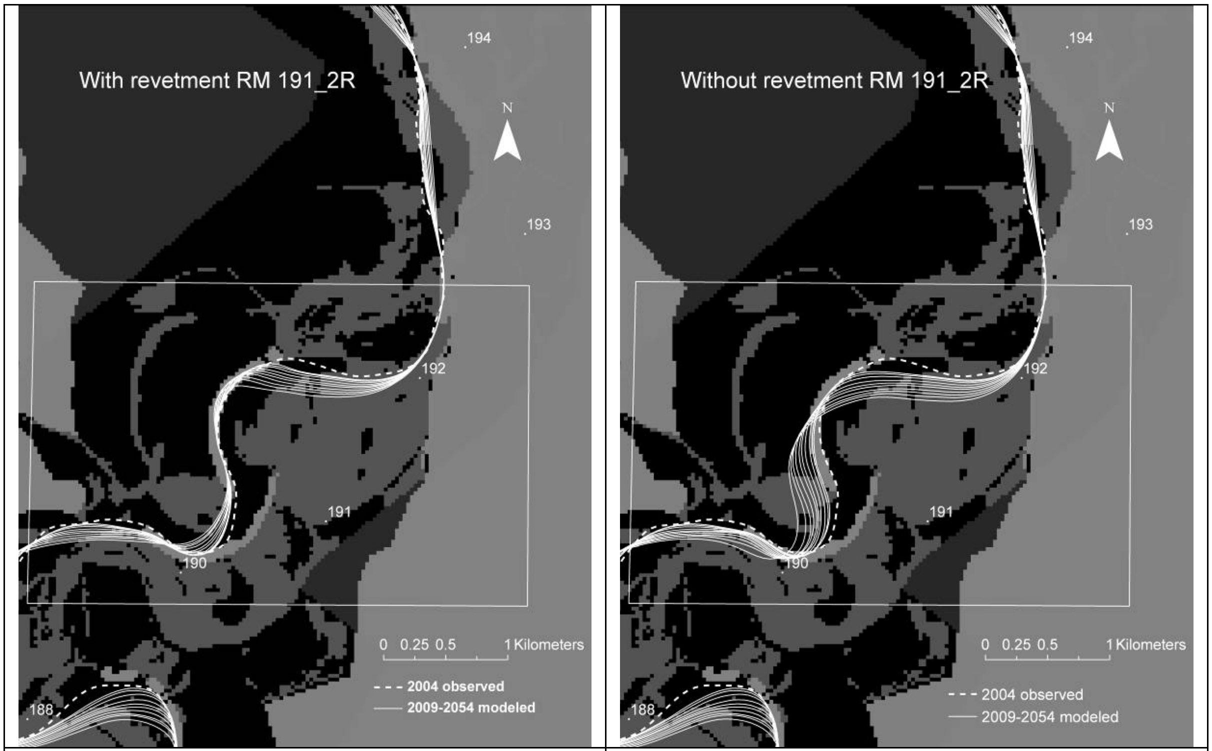
Hamilton City with existing revetment at RM 196L

Hamilton City without existing revetment at RM 196L

Figure 8 Hamilton City revetment at RM 196L

The model shows that there is increased migration to the east in the vicinity where the revetment is removed. The increase is somewhat limited by the natural restraint that occurs because of the erosion-resistant material near River Mile 196 on the east (left hand side of the channel looking downstream).

3.2.3 RM 191-2R



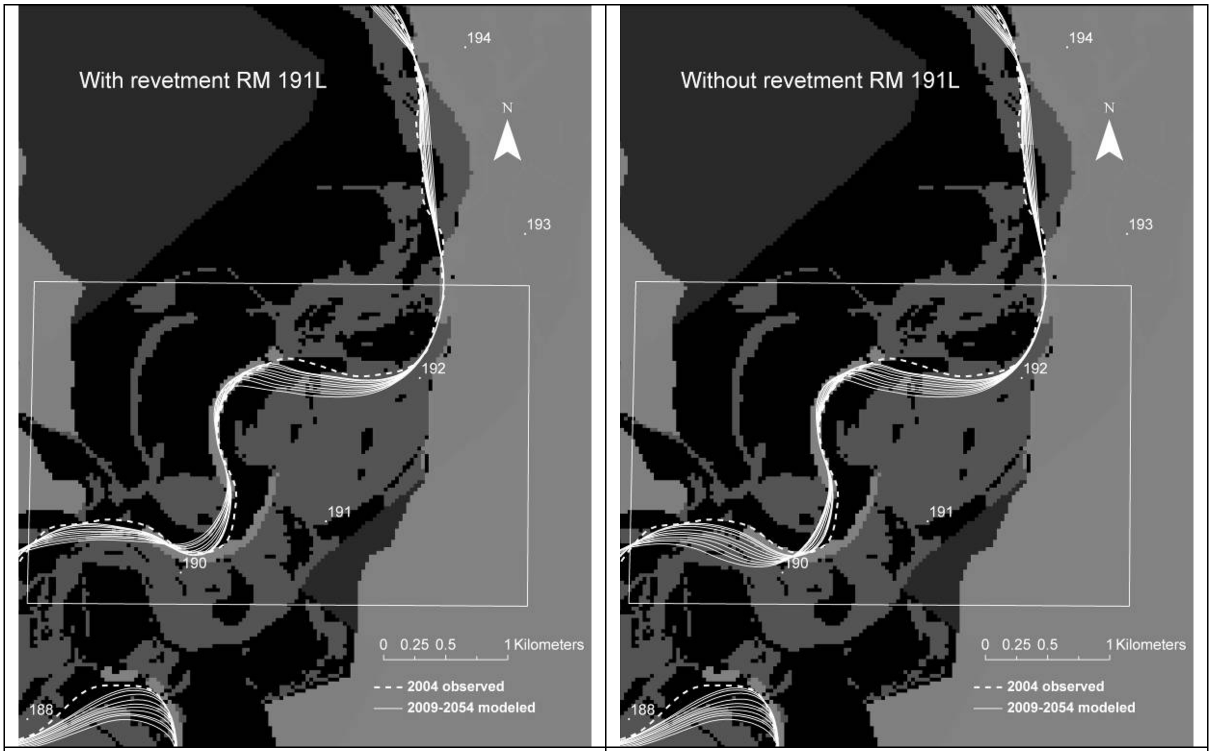
Hamilton City with existing revetment at RM 191-2R

Hamilton City without existing revetment at RM 191-2R

Figure 9 Hamilton City revetment at RM 191-2L

The model shows that the migration increases toward the western side where the revetment is removed in that location. In addition, there is a slight change in the pattern of area reworked in the bend immediately downstream.

3.2.4 RM 191L



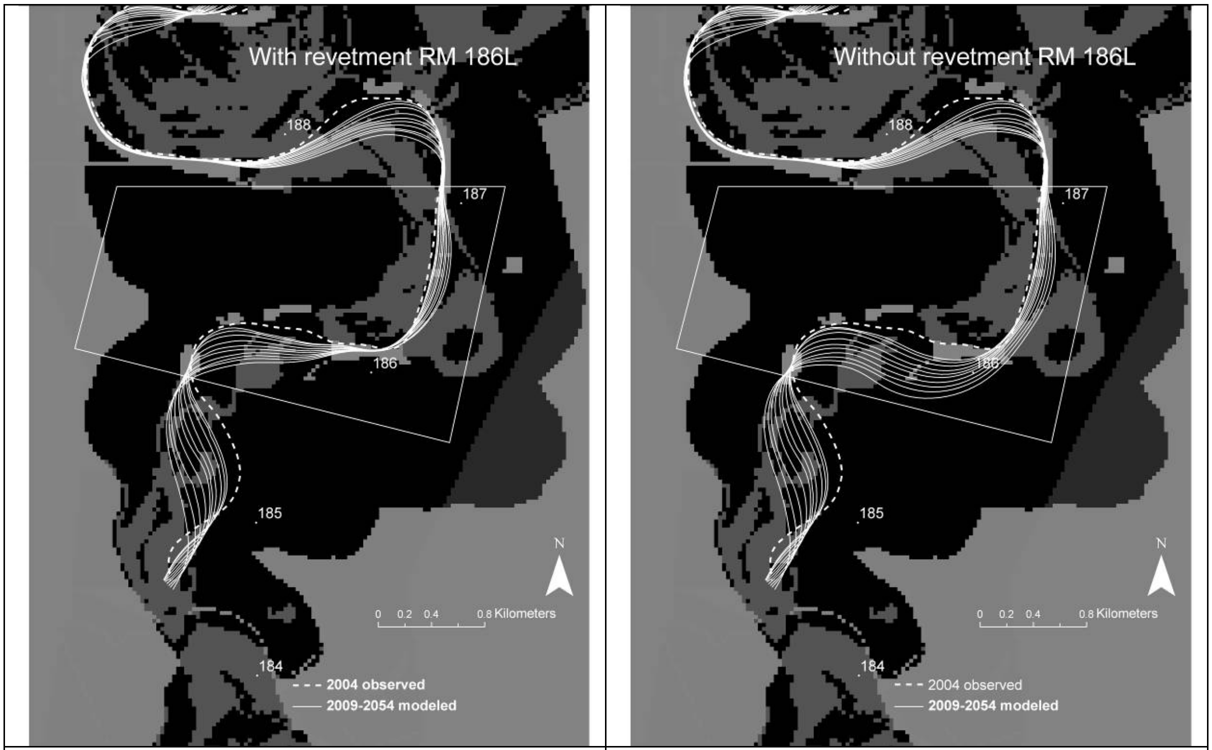
Hamilton City with existing revetment at RM 191L

Hamilton City without existing revetment at RM 191L

Figure 10 Hamilton City revetment at RM 191L

The model shows that the migration increases toward the south (right bank looking downstream) where the revetment is removed.

3.2.5 RM 186L



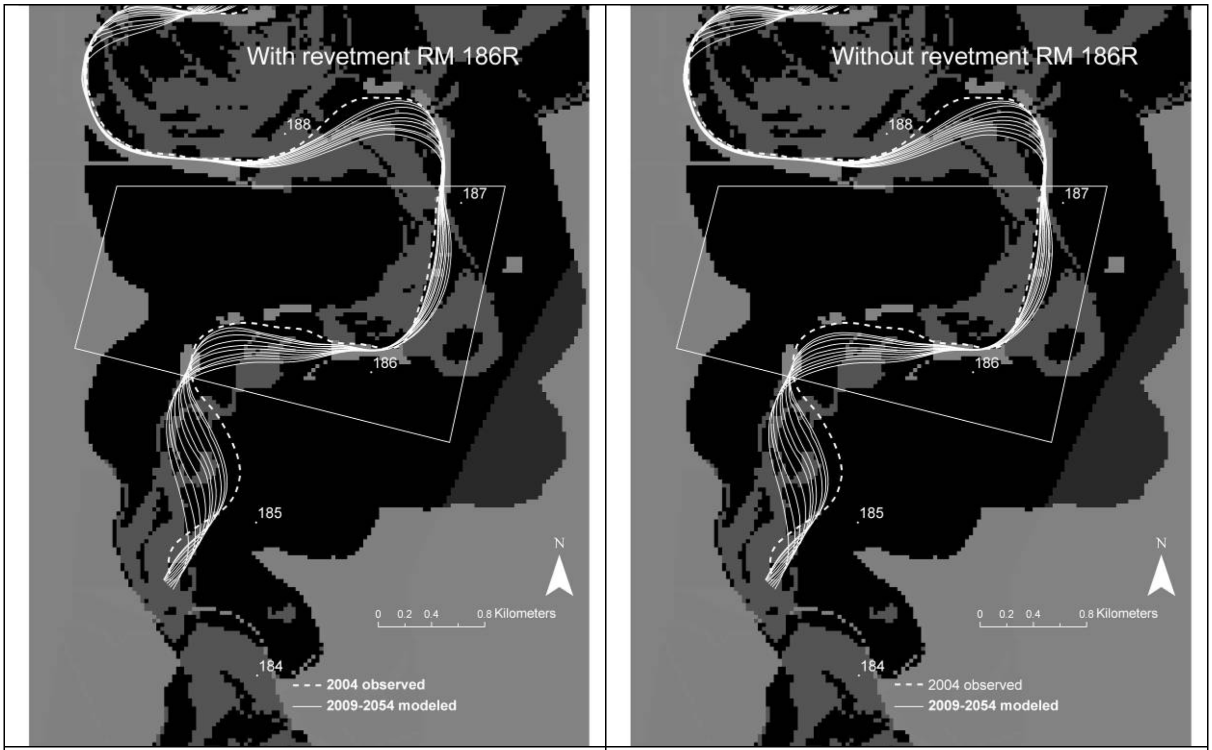
Hamilton City with existing revetment at RM 186L

Hamilton City without existing revetment at RM 186L

Figure 11 Hamilton City revetment at RM 186L

The model shows that the migration increases to the south where the revetment near River Mile 186 is removed. There is no significant effect on the migration pattern of the bend immediately downstream.

3.2.6 RM 186R



Hamilton City with existing revetment at RM 186R

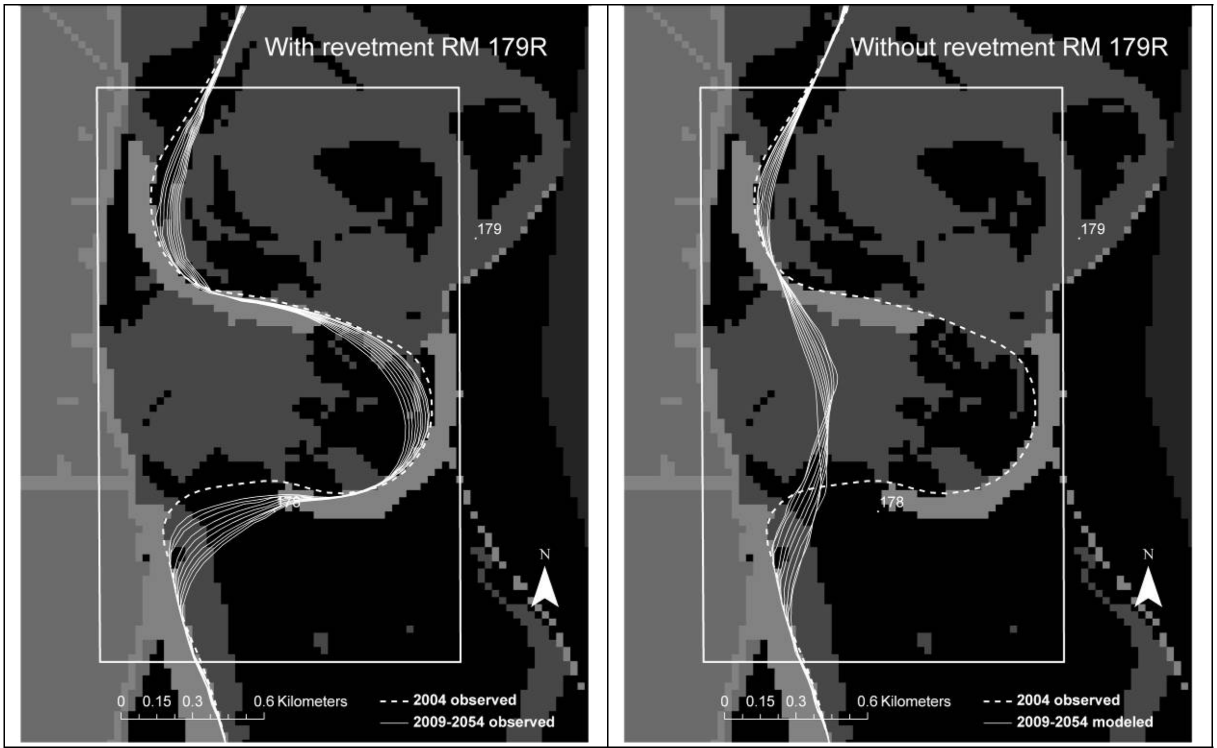
Hamilton City without existing revetment at RM 186R

Figure 12 Hamilton City revetment at RM 186R

The model shows that there is no change in the migration pattern at this location when the revetment is removed. The pattern of migration is to the south away from the revetment that is located to the north of the channel. This revetment is rubble placed by landowners (Pers. Com. Mike Harvey). This pattern of migration is due to the tendency of bends to migrate both in the downstream and cross-stream directions. The apex of the bend (near River Mie 185.5) is moving downstream, and the "outward" migration of the channel is not directed at the revetment but occurs downstream of it.

3.3 Ord Ferry Reach

3.3.1 RM 179R



Ord Ferry Reach with existing revetment at RM 179R

Ord Ferry Reach without existing revetment at RM 179R

Figure 13 Ord Ferry Reach revetment at RM 179R

The model shows that when the revetment is removed at this location, a cut-off occurs. 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.

4.0 DISCUSSION

The river meander migration modeling in this report shows the tendencies of migration patterns of selected bends with and without revetment in place. The migration simulations in this report assume that the flows will be similar to the flows that were observed between WY 1939 and WY 1988, which were used to simulate variable flow conditions.

Migration modeling at all of the selected bends was performed with appropriate site-specific conditions, and was done at all sites with similar hydrologic conditions, over the same time period, using related simulated flows, and using related erosion fields. This procedure was used so that the sites could be compared with each other. Therefore, these simulations can be used for comparing the relative impact of removing revetment at different sites.

In the **Woodson Bridge Reach**, there is increased area reworked of the bends for both bends 221R and 216R when the revetment is removed. For bend 221R, the model shows that removing the revetment also changes the migration patterns directly downstream and decreases the total area reworked (in the downstream bend) when the upstream revetment is removed. For bend 216R, removing revetment increases the local area reworked as well as increases the area reworked for the bend immediately downstream.

In the **Hamilton City Reach**, six bends were modeled. At RM 197-8R the model shows that removing revetment increases the migration to the south near River Mile 197 in the area where the revetment is removed. At RM 196L the model shows that the increase in migration when the revetment is removed is limited by the natural restraint that occurs because of the erosion-resistant material near River Mile 196. The total change in area reworked is comparatively small. At RM 191-2R the model shows that the migration increases toward the western side when the revetment is removed in that location. In addition, there is a slight change in the pattern of area reworked in the bend immediately downstream. At RM 191L the model shows that the migration increases toward the south (right bank looking downstream) where the revetment is removed. At RM 186L the model shows that there is increased migration to the south when the revetment is removed and no effect on the bend immediately downstream. At RM 186R the model shows that there is no change in the migration pattern at this location when the revetment is removed. The pattern of migration is to the south away from the revetment that is located to the north of the channel.

In the **Ord Ferry Reach**, at RM 179R the model shows that when the revetment is removed at this location, a cut-off occurs. 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.

When the nine sites are compared with each other, two of the sites have limited increase in migration when revetment is removed, and one site experiences cutoff. Migration of the bend at RM 196L is limited by the natural restraint to the east. Migration of the bend at RM 186R is modeled to move away from the revetment. The bend at RM 179R cuts off when the revetment is removed. At the remaining six sites, revetment removal results in significant increases in area reworked. At some sites, there is also some change in the pattern and quantity of area reworked in the bend immediately downstream. These findings, when considered together with other criterion, will help consider the benefits, in terms of channel migration and area reworked, to be gained when revetment removal is considered for mitigation or for other purposes, at the selected sites on the Sacramento River.

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