Appendix 8
Fluvial Geomorphology and Riparian Habitat

Line items and numbers identified or noted as “No Action Alternative” represent the “Existing Conditions/No Project/No Action Condition” (described in Chapter 2 Alternatives Analysis). Table numbering may not be consecutive for all appendixes.

Contents

Appendix 8A
Sedimentation and River Hydraulics Modeling

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Channel Migration Analysis of NODOS

RECLAMATION
Managing Water in the West

Technical Report No. SRH-2011-21

Sacramento River Migration Analysis of NODOS Alternatives

Mid Pacific Region
NODOS Investigation Report

U.S. Department of the Interior
Bureau of Reclamation

July 2011

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation’s natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Sedimentation and River Hydraulics Group, 86-68240

Technical Report No. SRH-2011-21

Sacramento River Migration Analysis of NODOS Alternatives

Mid Pacific Region
NODOS Investigation Report

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The authors would like to thank Koll Buer of the California Department of Water Resource who provided review comments and descriptions of channel morphology. The authors would also like to express their gratitude to coworker David Varyu who provided insight, inputs, and reviewed this report.

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1 Introduction

The Sedimentation and River Hydraulics Group at the Technical Service Center (TSC) of the Bureau of Reclamation has been tasked, at the request of the Mid Pacific Regional Office, to provide analysis to support the North of Delta Off-Stream Storage (NODOS) Administrative Draft Environmental Impact Report/Study (ADEIR/S) and Feasibility Study (FS). This report provides results of channel migration in two spatial scales: a short reach near the New Delevan Pipeline and a long reach from Red Bluff to Colusa (Figure 1-1). The downstream end (bottom in the figure) of the stream is Colusa, which is not shown in the Figure.

CH2MILL (2011) developed model simulations for the NODOS ADEIR/S and FS. The modeling simulations that were completed were labeled as:

- Existing Conditions
- No Action Alternative
- NODOS Alternative A
- NODOS Alternative B
- NODOS Alternative C

These flows were used as input to the analyses presented in this report.

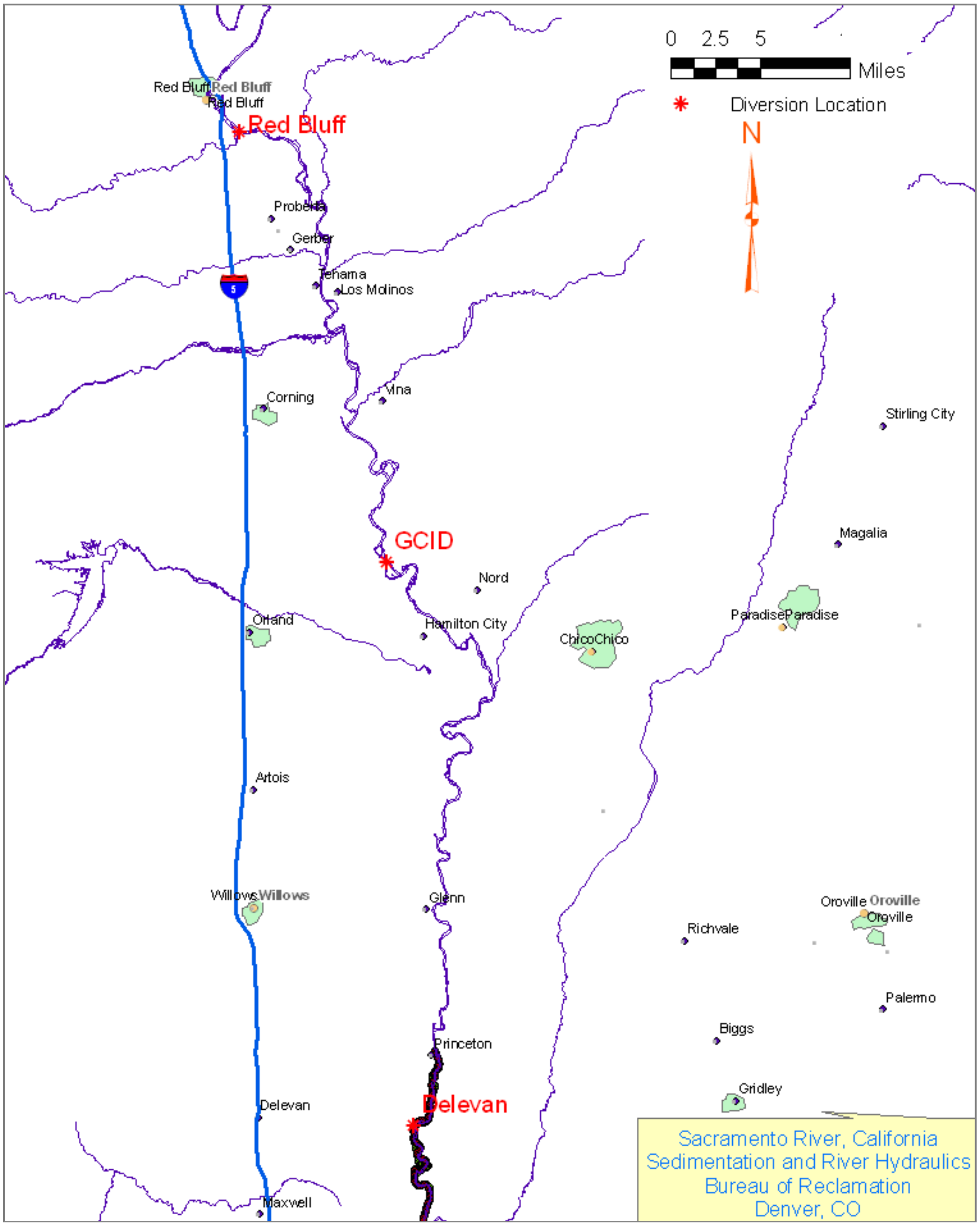


Figure 1-1. Site map of the Sacramento River between Red Bluff and Colusa

2 Model Description

SRH-Meander (Sedimentation and River Hydraulics – Meander, Greimann and Huang, 2007) is a computer model that simulates the bed topography, flow field, and bank erosion rate in curved channel with an erodible bed. In each time step, SRH-Meander first calculates the flow field based on the standard step method, normal depth method, or a user input rating curve. It then computes the channel bank erosion rate. Finally the channel alignment is updated with the erosion rate, followed by a channel cutoff if needed. The model can be used to predict the channel migration in meandering rivers.

SRH-Meander uses the meander method first proposed by Johannesson and Parker (1989). It is a re-derivation of the analysis by Engelund (1974). The basic idea behind these analyses is to write the flow variables as a sum of two parts. The first part is the solution to the case of flow in a straight channel. The second part is equal to the deviation from the straight channel solution for the case of a slightly curved channel. The deviation is assumed to be linearly related to the maximum curvature of the channel. These perturbed flow variables are substituted into the 3D flow equations. The equations are then simplified and grouped into the terms responsible for the straight channel solution and those due to the channel curvature. The equations become ordinary differential equations and can be solve analytically or through relatively simple numerical methods. The sediment transport is assumed to be a function of the local velocity and shear stress.

Sun at al. (2001a, b) improved Johannesson and Parker‟s (1989) linearization theory to calculate bank erosion in river meanders by incorporating multiple-size sediment transport equation. Johannesson and Parker (1989) assume the bank erosion rates are related to the near-bank depth-averaged flow velocity, which is calculated by a small perturbation approach. The near bank depth-averaged flow velocity is decomposed into two parts: the component characterized by local curvature forcing (e.g. point bars) and the component characterized by the free system (e.g. alternate bars).

SRH-Meander adopted the Sun at al. (2001a, b) method which incorporates multiple-size sediment transport equation. More information on SRH-Meander can be found in Greimann and Huang (2007).

3 Channel Migration Near New Delevan Pipeline

SRH-Meander will be used to predict the channel migration during the alternatives evaluation process. As such, a calibration to historic meander rates was completed because “it is not possible to determine the erodibility coefficients a priori, based on bank properties, presence of vegetation, etc.” for real rivers without “calibrating the erodibility coefficients on field observations” (Crosato, 2007). The meander channel model extends 12.5 miles from RM 164 to RM 151.5 as presented in Figure 3-1

The historical gage record at USGS Gage 11389000 (Sacramento River at Butte City, California) was used for model calibration and verification. This gage (RM 168.5) is located about 10 miles upstream of the Delevan new pipeline; however, the available data were for a period prior to June 30, 1995. A bias correction method was used to create the missing data from 7/1/ 1995 to 10/1/2009 via USGS Gage 11377100 (Sacramento River above Bend Bridge near Red Bluff, California) by using a common period from 10/1/1976 to 6/30/1995. The period used for model calibration was from 10/1/1976 to 9/30/1999. The period from 9/30/1999 to 10/1/2009 was used for model verification.

USRDOM was used to simulate flows under the existing operations (Existing) and the proposed NODOS program alternatives: No Action, Alternative A, Alternative B, and Alternative C (CH2MHILL, 2011). The simulated flows were used in SRH-M to predict future channel meandering. The simulated flows

The daily flows from 10/1/1980 to 9/30/2000 were used to predict twenty years of channel meander from 10/1/2010 to 9/30/2030.

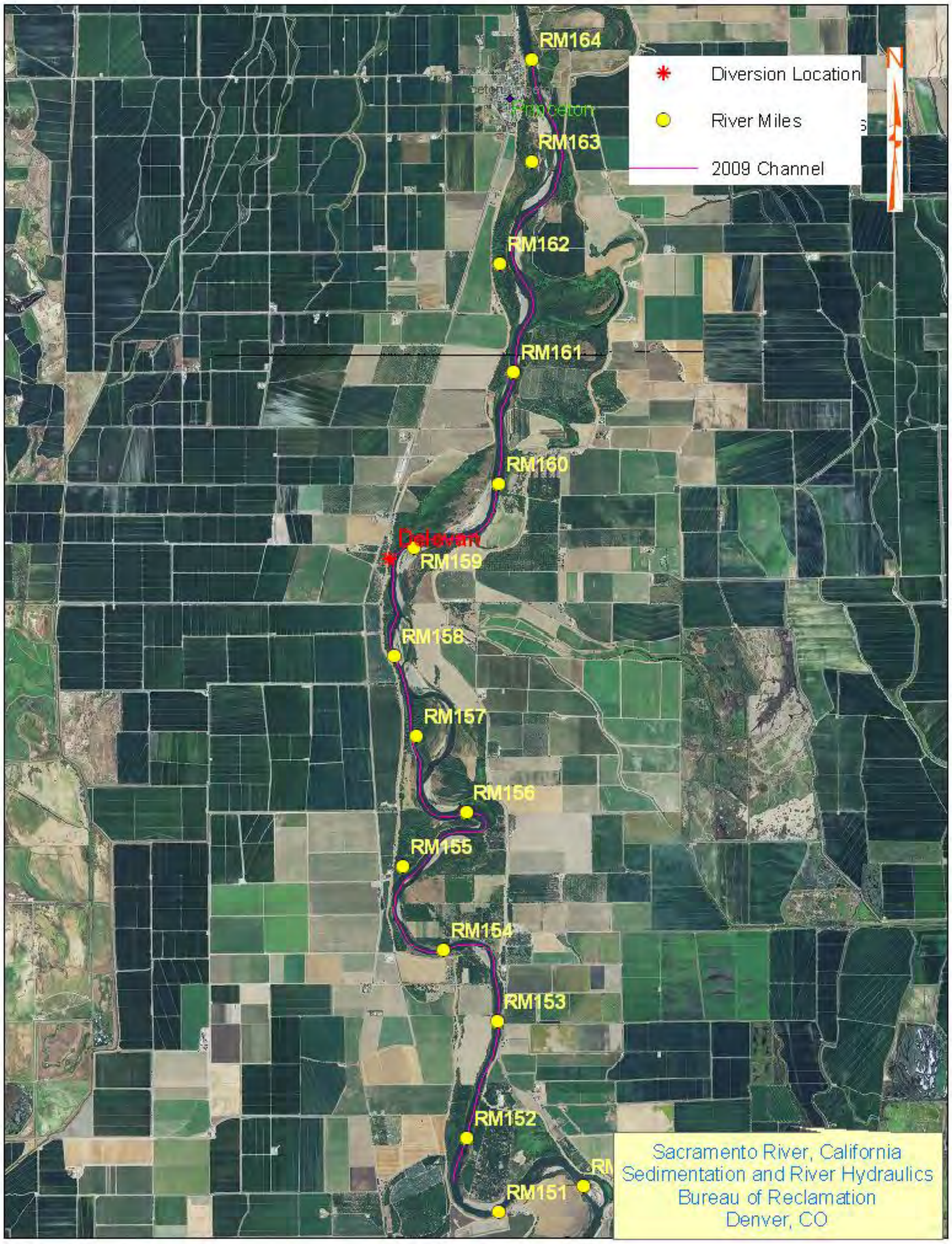


Figure 3-1. Meander channel model study area with 2009 aerial photo

3.1 Data Pre-Processing

No modifications were made to the flow data as described in the previous section. However, a filter is present in SRH-Meander so that flow data that may not affect river meandering can be excluded. For instance, it is generally accepted that base flows do not cause changes in channel morphology. However, due to the linear nature of the computer model, these base flows yield a calculated meander length, however minor. Conversely, when flows of a river exceed the carrying capacity of a channel, the excess flow spills out on to the floodplain, and the flood waters have little effect on channel-forming processes. Without an imposed upper bound on the flow rates, the rate of bank erosion would increase linearly as the flow rate increases. Thus, an upper and lower limit was applied to the input flow data set. Based on the flow hydrograph and the results of the RAS model, lower and upper limits of 35,000 and 90,000 cfs, respectively, were used for the Sacramento River. When the flow is less than the lower limit, the channel migration is neglected. When the flow is larger than the upper limit, the channel migration is considered not increasing.

The HEC-RAS model associated with the 2002 US Army Corps of Engineers (USACE) study was used to derive cross-sectional and profile geometry parameter values. Rather than assume a cross-sectional shape and associated descriptive parameters (e.g., side slope and bottom width for a trapezoidal cross-section) to represent the river, a more generic approach was taken. The HEC-RAS model was run multiple times using a series of steady flow rates. Average hydraulic parameters were calculated for the study reach. The geometry parameters were tabulated into a format which the SRH-Meander model can interpret. Thus, a table was created with flow rates from 35,000 to 90,000 cfs along with associated average values for velocity, friction slope, hydraulic depth, top width, and hydraulic radius. The friction slope parameter was used for profile geometry considerations in lieu of assuming that the bed slope approximates the energy slope. SRH-Meander model linearly interpolates hydraulic parameters for flow rates between the tabulated values.

Planform geometry data were extracted from available California Department of Water Resources (CDWR) GIS maps. The SRH-Meander model uses a GIS point file representing the centerline of the river to compute radii of curvature and other parameters which are necessary to estimate the rate of river meander. The CDWR GIS maps contained polygons which depicted the „active‟channel alignments for years 1976 and 1999. Polylines were digitized in ArcGIS to represent the centerline of the 1976 channel and the 1999 channel as shown in Figure 3-2, which are the „starting‟ and „ending‟ conditions to which the model was to be calibrated. The 2009 channel center line was digitized using 2009 aerial photography as a base image. In addition, a valley axis for the 1976 channel was digitized (Figure 3-2) which is used to allow for channel cutoffs. The cutoff ratio is a calibration parameter. When the length of the channel bend divided by the length of the valley for the same bend exceeds the cutoff ratio, the model allows a cutoff to occur.

Model inputs related to channel roughness and bed material size for the calibration were estimated from the USACE study (2002). The USACE study reported Manning roughness coefficients and bed material size information at discrete cross-sections along the Sacramento River. Cross-sections that fell within the model reach were selected, and the reported values were averaged to produce a single roughness and single representative bed material size for each sub-reach. The Manning roughness coefficient used in this study is 0.028. There was very little variation in bed material size according to the USACE study, so these values were not adjusted and not considered calibration parameters. A median bed material size of 14 mm was used.

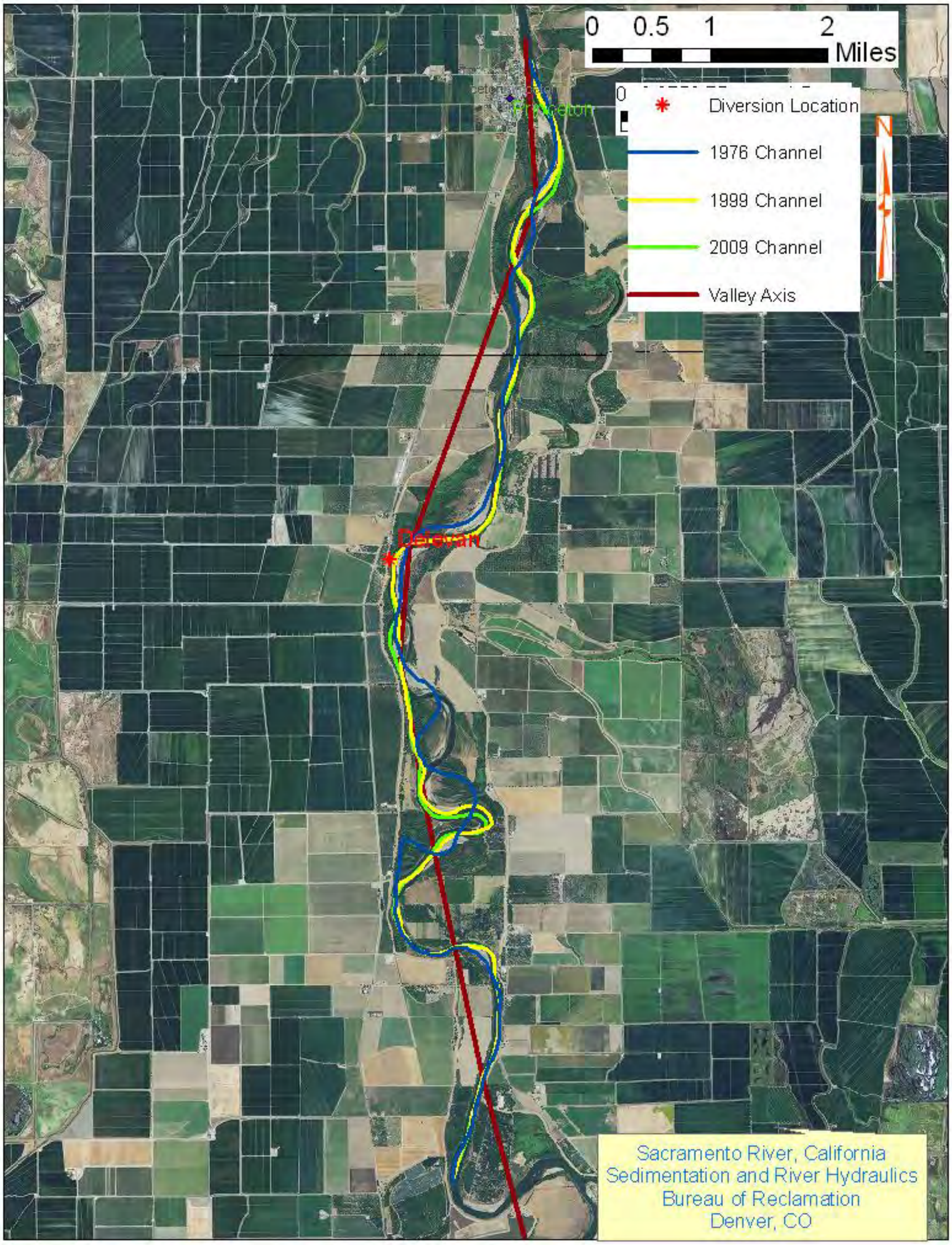


Figure 3-2. Channel center lines in 1976, 1999, and 2009 for model calibration, verification, and prediction

In order to spatially assign erosion coefficients, a series of calibration polygons were created in ArcMap. The polygons mirror the bank segments as identified by the CDWR. In 2005, CDWR conducted an expedition in order to describe the channel banks of the Middle Sacramento River. The erosion polygons were digitized to represent bank properties for bank slope, height, material, geomorphology, and riprap presence, as described by CDWR, and the polygons are small enough for calibration. A total of 87 polygons as displayed in Figure 3-3 was used to represent the bank properties.

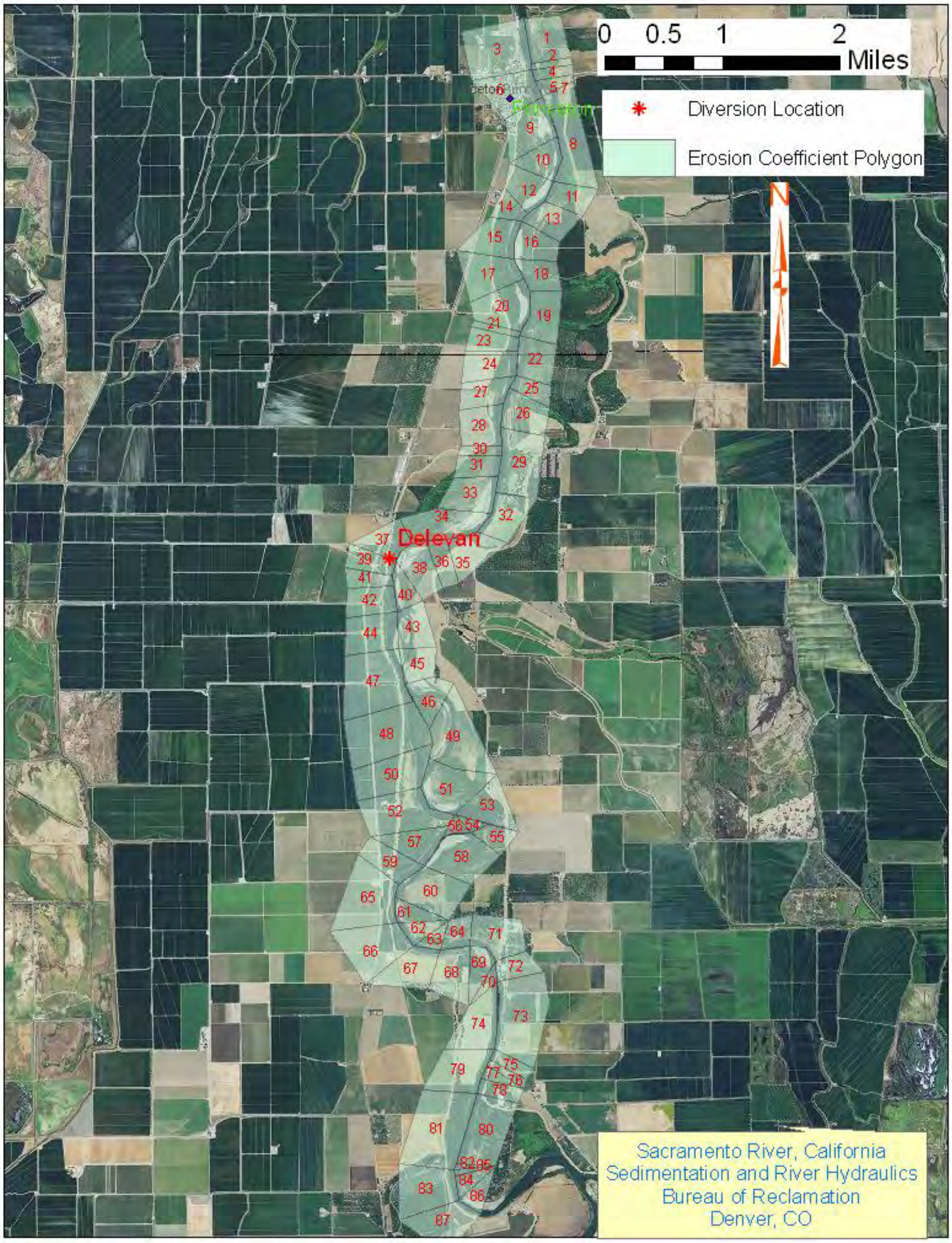


Figure 3-3. Polygons used to represent bank properties

3.2 Model Calibration

Completing the data pre-processing described above resulted in properly formatted data inputs for the SRH-Meander model. The parameters that were changed during calibration (i.e., the calibration parameters) were the cutoff ratio and the erosion coefficients.

Calibration compares the output channel alignment to the actual channel alignment at the end of the time interval being modeled. An iterative approach was taken in calibrating the model. Erosion coefficients were adjusted after an observed model run as necessary until the model output alignment represented the actual channel alignment to a sufficient degree of accuracy.

Table 3-1 presents a summary of the parameters – showing both the calibration parameters as well as those determined before calibration – used during calibration of the SRH-Meander model to the Sacramento River. All of the erosion coefficients are not listed, but rather the minimum, average, and maximum values for each sub-reach are presented.

Figure 3-4 displays the centerlines for the 1976 and 1999 channels, and the SRH-Meander output nodes representing the model output channel centerlines in 1999. The model calculated the 1999 channel fairly well. The channel splits at location marked as “A” in Figure 3-4, and the model does not have the functionality to represent this phenomenon.

Table 3-1. Summary of parameters used during SRH-Meander model calibration

		Model Reach
Pre-determined parameters	**Ave. Channel Width (ft)**	773
	Manning n (-)	0.028
	Ave. Energy Slope (ft/ft)	0.00036
	Bed Material Size (mm)	14
	Number of Polygons	87
Calibration parameters	**Grid Spacing (-)**	0.6
	Cutoff Ratio (-)	3.5
	Min. Erosion Coefficient (-)	1.00E-08
	Ave. Erosion Coefficient (-)	1.72E-05
	Max. Erosion Coefficient (-)	1.00E-04

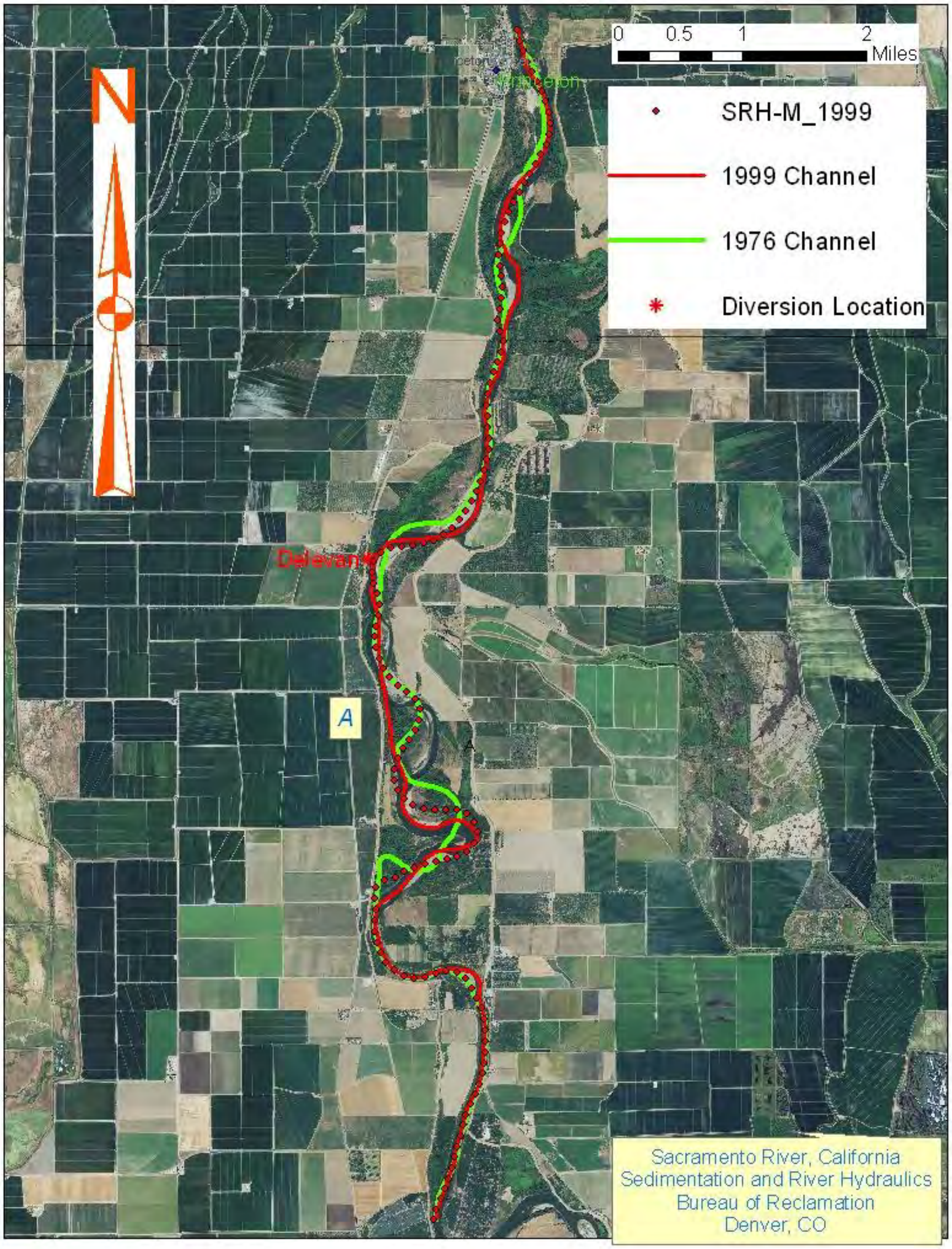


Figure 3-4. Calibration results

3.3 Model Validation and Prediction

The model was verified by using the calibrated model to predict the channel profile in 2009 with initial channel alignment from 1999 photography and flow rate from 1999 to 2009 at the same gage (USGS Gage 11389000, Sacramento River at Butte City, California). The erosion coefficients, the channel roughness, the grid spacing, and all other parameters are kept unchanged. The simulated 2009 channel alignment was compared with field data in 2009. The agreement between the simulated 2009 channel alignment and 2009 field data is fairly good (Figure 3-5), considering the uncertainties associated with the simplification of the model, the bank properties, and the accuracy of the map used to digitize the channel.

The model captured the amplification and downstream migration of the bends upstream of the new Delevan Pipeline. However, the model did not predict the reduction of the big bend marked as “B”. Theoretically it is difficult to explain why this bend is reduced and it is not clear if this bank was ripraped there, but it is possible since the bend is located close to the levee.

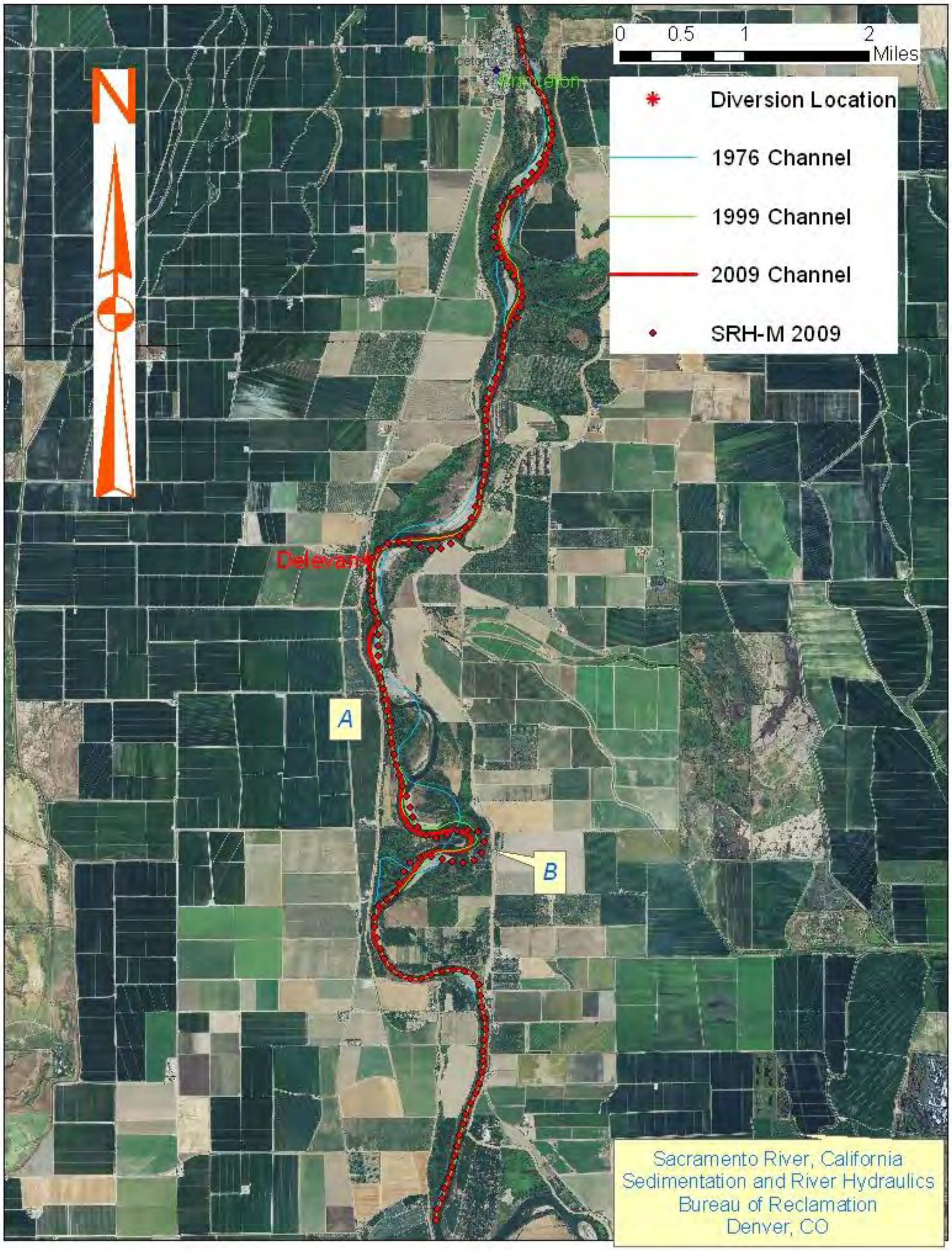


Figure 3-5. Model verification in 2009

Figure 3-6 illustrates the predicted channel alignment in 2030 with flow conditions of Existing, No Action, AltA, AltB, and AltC. There is no noticeable difference in channel alignments between the five flow conditions. Model results show the bend located upstream of the new intake, marked as “C” in Figure 3-6, will continue to migrate downstream unless bank protection is provided. The bend at the new intake, marked as “D”, will continue to migrate to river right. These results indicate that protecting the right river bank near the new intake would be beneficial. A cutoff will occur at the bend located downstream of the diversion, marked as “B”, and the channel will shift to river right. The model indicates bank protection should also be provided downstream of the diversion near location “A” since the river continued to migrate to the right side and the channel is close to the levee.

Figure 3-7 displays the predicted channel alignment in 2030 with bank ripraped at the locations marked as “C” and “D” in Figure 3-6. The bank riprap locations are also illustrated in Figure 3-7. The simulation shows that bank protection at the displayed locations could prevent the bank from migrating in the vicnity of the new intake.

Figure 3-8 compares the 2030 channel alignments near the new intake calculated as the current bank condition versus a ripraped bank. In the 20-year simulation, results show the left bank upstream of the intake will migrate about 650ft to channel left if the bank is not ripraped, and the right bank near the intake will migrate about 300ft to the right if the bank is not ripraped. The bank lines show no difference in channel migration beyond the ripraped bends near the intake.

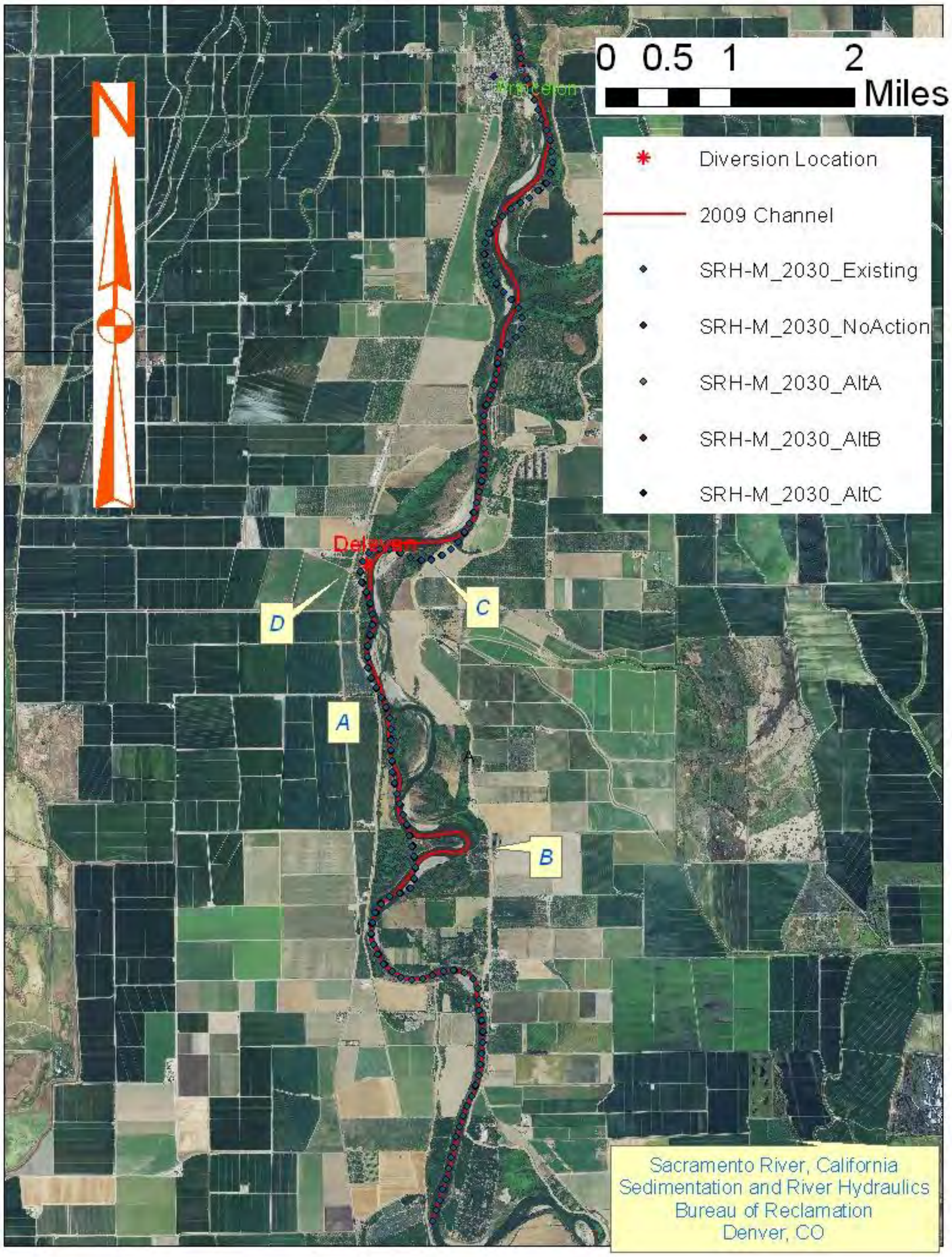


Figure 3-6. Channel alignments predicted in 2030 with hydrological conditions of Existing, NoAction, AltA, AltB, and AltC without riprap along the bank. Results show that there is no noticeable difference in channel alignments between different hydrological conditions.

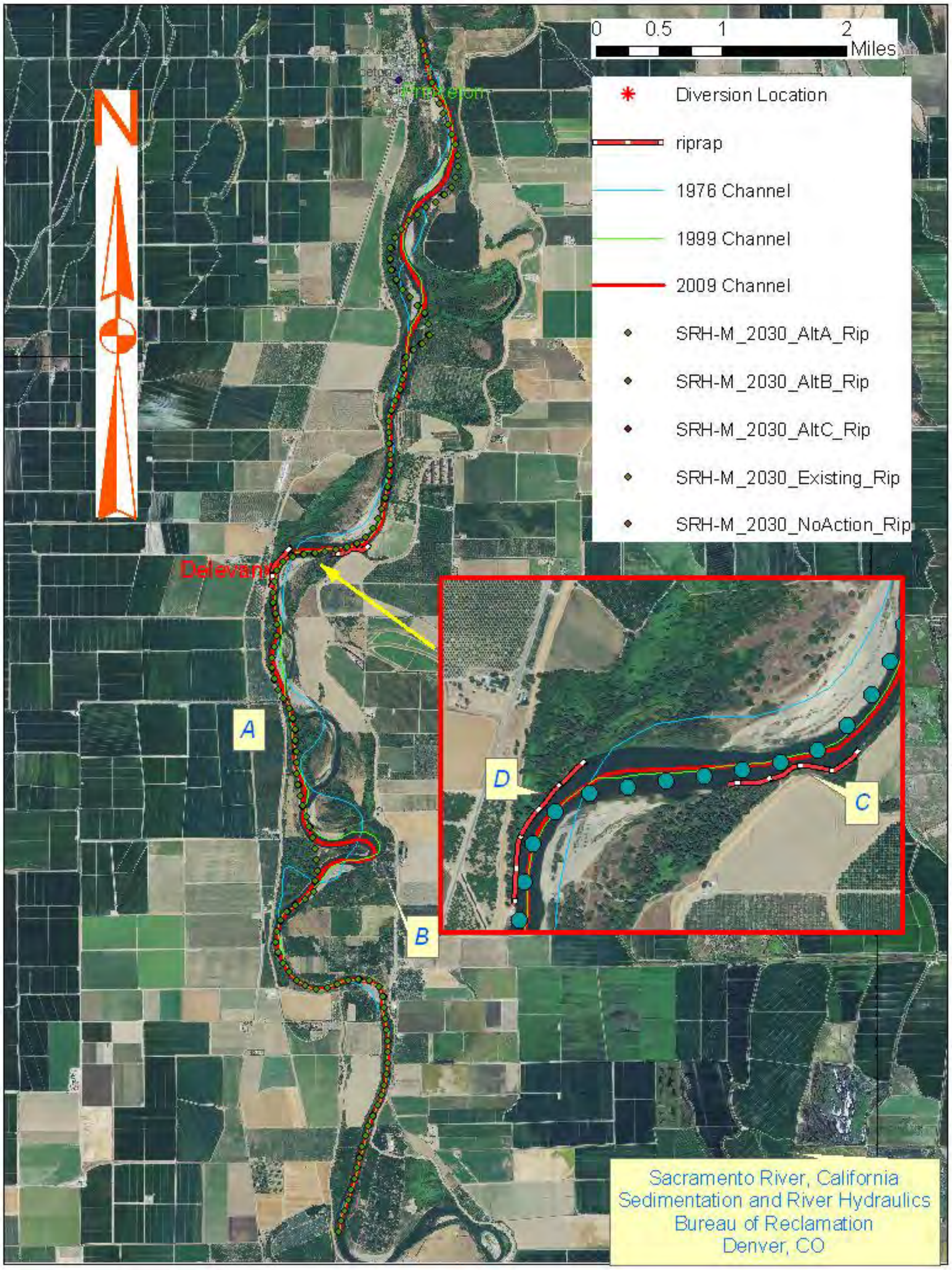


Figure 3-7. Channel alignments predicted in 2030 with hydrological conditions of Existing, NoAction, AltA, AltB, and AltC with bank ripraped near the new intake. Results show that there is no noticeable difference in channel alignments between different flow conditions.

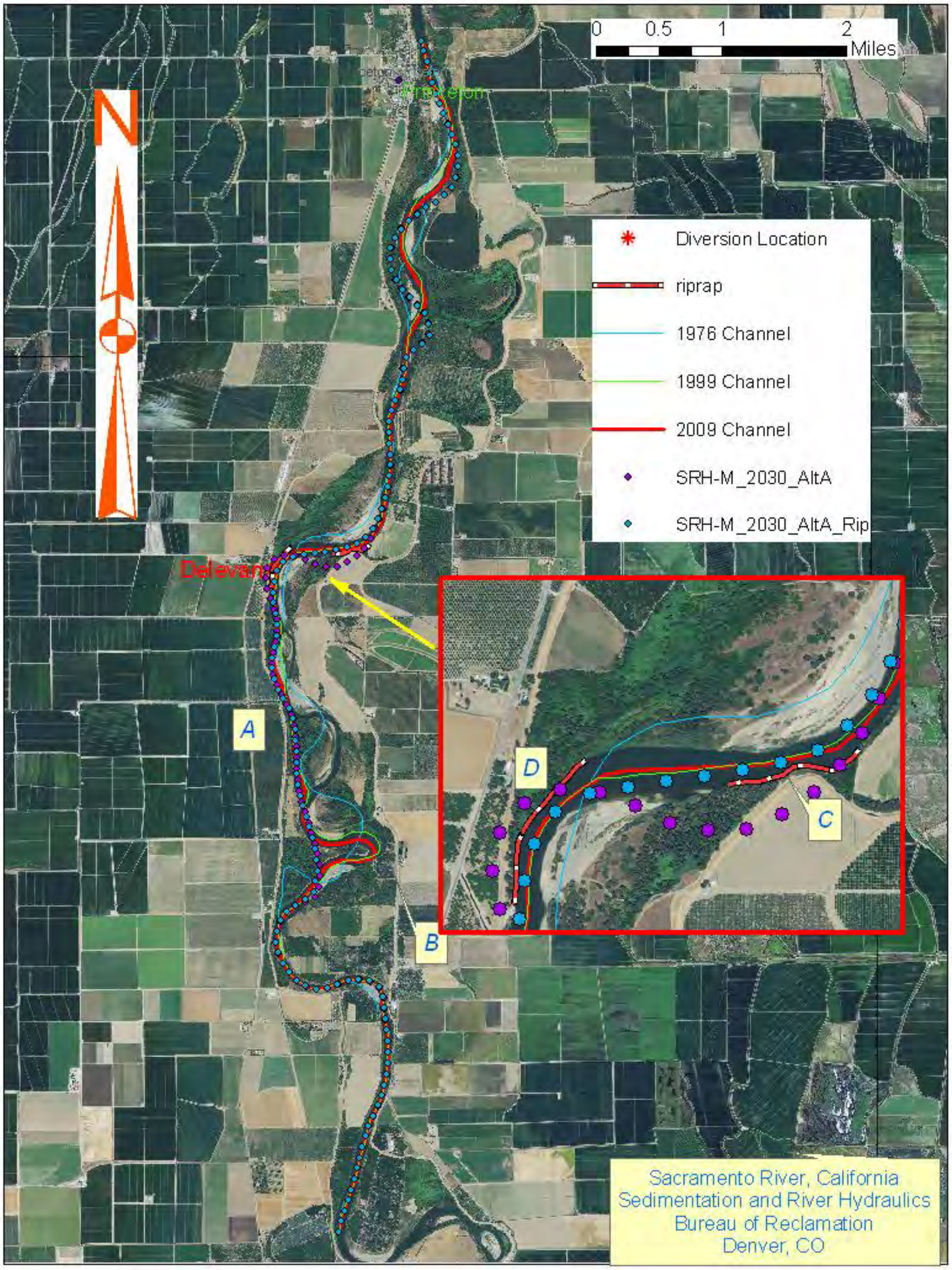


Figure 3-8. Comparison of channel alignments predicted in 2030 under conditions of current bank versus the addition of riprap along the bank (Alternative A only presented for simplicity).

4 Channel Migration from Red Bluff to Colusa

The model extends 101 miles from Red Bluff (RM 243) to Colusa (RM 142) as presented in Figure 1-1. The period of record used for model calibration was from 10/1/1976 to 9/30/1999 and the model is used to predict the channel alignment at 2030.

Flow data from gages operated by the State of California Department of Water Resources (CDWR) were utilized for model calibration. Mean daily flows for the period of record from 10/01/76 to 09/30/99 for CDWR datasets were used. Three CDWR gages are used, including gage „VIN‟ atVina Woodson Bridge (RM 219), gage „NMC‟ at Hamilton City (RM 199.2), and gage „ORD‟ at Ord Ferry (RM 184.2). Some gage flow data are missing in a period of time due to various reasons, and a correlation was built between each gage to calculate the flow data at one gage from the same date at another gage.

Profile and cross-sectional geometry information was taken from a United States Corps of Engineers publication, "Sacramento and San Joaquin River Basins, Comprehensive Study" (U.S. Army Corps of Engineers, 2002). This study produced a HEC-RAS geometry model of the river that was used in this study. River planform geometry was made available by CDWR in the form of aerial photographs and GIS maps consisting of traces of the active channels.

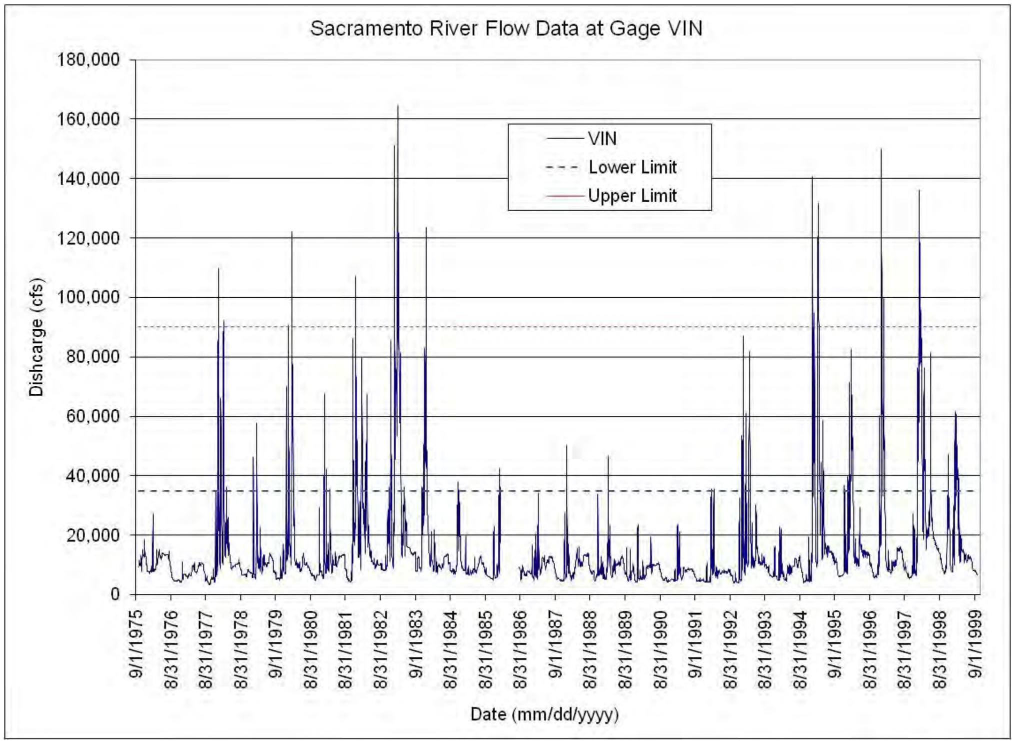
From the 2002 USACOE publication, information on channel roughness, namely Manning‟s roughness coefficient values, was obtained. Also from the study, information on bed material size was gathered and used as input to the model.

The bank erosion rates were not based on available data, but rather were adjusted during the calibration process. During this study a correlation between the calibrated erosion coefficient and existing field data, such as surface geology, vegetation, land use, channel bank information, levee location, riprap linings, etc. were explored.

4.1 Model Calibration

No modifications were made to the existing flow data acquired from CDWR. Missing data are calculated by the correlation between neighbor gages. A filter is present in SRH-Meander so that flow data that may not effect river meandering can be excluded. For instance, it is generally accepted that base flows do not cause changes in channel morphology. However, due to the linear nature of the computer model, these base flows yield a calculated meander length, however minor. Conversely, when flows of a river exceed the carrying capacity of a channel, the excess flow spills out onto the floodplain, and the flood waters have little effect on channel-forming processes. Without an imposed upper bound on the flow rates, the rate of bank erosion would increase linearly as the flow rate increases. Thus, an upper and lower limit was applied to the input flow data set. Based on the flow hydrograph and the results of the RAS model, lower and upper limits of 35,000 and 90,000 cfs, respectively, were used for the Sacramento River.

Flow data from CDWR gage „VIN‟ was used for the reach upstream of Hamilton City, gage data „HMC‟ was used between Hamilton City and Ord Ferry, and gage data „ORD was used downstream of Ord Ferry. SRH-Meandering accepts upstream incoming flow rate and lateral flows. To simulate the different flow rates along the Sacramento River, flow data from gage „VIN‟ was used as incoming flow at Red Bluff. Flow difference between gage „HMC‟ and „VIN‟ was used as lateral flow located at gage station „HMC‟. The flow difference between gage „ORD‟ and „HMC‟ was used as lateral flow located at gage station „ORD‟. Figure 4-1 presents the hydrographs for the gages used, along with the upper and lower limits specified for the model. The limits are only applied to the upstream incoming flow.



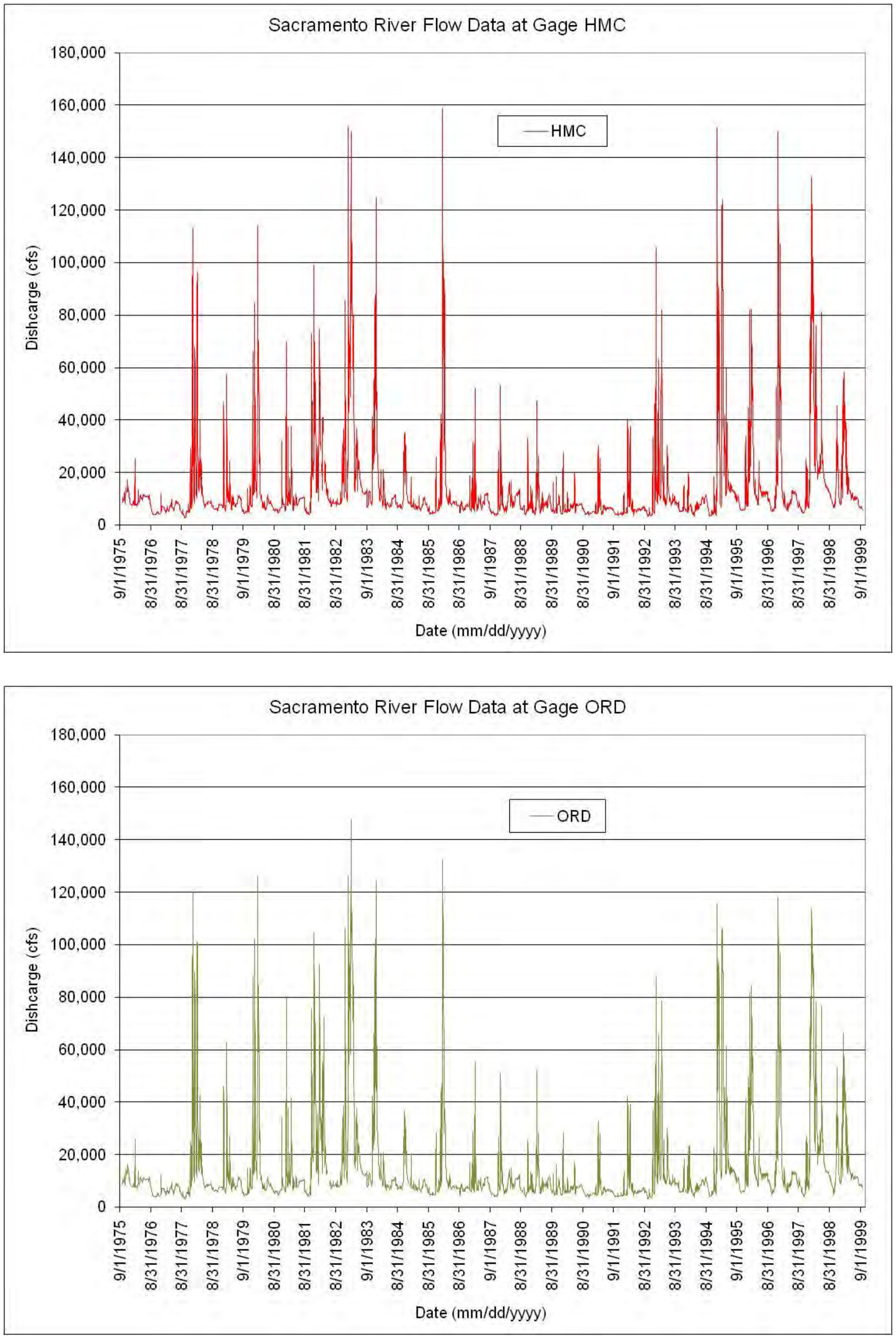


Figure 4-1. Flow hydrograph used for the field calibration (CDWR gages VIN, HMC, and ORD).

Completing the data pre-processing described above resulted in properly formatted data inputs for the SRH-Meander model. The parameters that were changed during calibration (i.e., the calibration parameters) were: the cutoff ratio, the model grid spacing, and the erosion coefficients. The grid spacing is not a parameter reflecting a physical process, but rather a necessary parameter for numerical modeling purposes. It determines the distance between nodes of the modeled centerline, and scales with the reach-averaged channel width.

No channel geometry were input, instead the rating curve table was used to calculate the average flow velocity, channel top width, hydraulic radius, and energy slope at specific flow rate. The rating curve table was obtained by a separate HEC-RAS model with 1976 channel geometry. The rating curve is presented in Table 4-1.

Calibration compares the output channel alignment to the actual channel alignment at the end of the time interval being modeled. An iterative approach was taken in calibrating the model to match the field data. Erosion coefficients were adjusted after an observed model run as necessary until the model output alignment represented the actual channel alignment sufficiently well. The cutoff ratio is also adjusted in each polygon defining the erosion coefficient to reproduce the channel cutoff at specific location.

Table 4-1. Rating Curve

Q m^3/s	Velocity m/s	Friction Slope m/m	depth m	Tw m	Rh m
849.51	1.179	5.786E-04	2.774	271.482	2.758
991.09	1.234	5.626E-04	2.927	284.233	2.910
1132.67	1.285	5.479E-04	3.072	291.911	3.054
1274.26	1.332	5.399E-04	3.216	297.914	3.196
1415.84	1.376	5.360E-04	3.350	303.491	3.330
1557.43	1.401	5.430E-04	3.415	315.194	3.395
1699.01	1.426	5.484E-04	3.507	323.956	3.486
1840.60	1.456	5.529E-04	3.610	331.497	3.588
1982.18	1.485	5.621E-04	3.697	337.876	3.675
2123.76	1.511	5.680E-04	3.795	341.866	3.773
2265.35	1.535	5.659E-04	3.894	350.249	3.870
2406.93	1.561	5.681E-04	3.995	353.004	3.972
2548.52	1.582	5.699E-04	4.085	355.679	4.061
2690.10	1.603	5.709E-04	4.172	358.245	4.147

Table 4-2 presents a summary of the parameters – both calibration parameters as well as those determined before calibration – used during calibration of the SRH-Meander model to the Sacramento River. All of the erosion coefficients are not listed, but rather the minimum, average, and maximum values are presented.

Table 4-2. Summary of parameters used during SRH-Meander model calibration

Pre-determined parameters	**Manning n (-)**	0.032
	Ave. Energy Slope (ft/ft)	0.00056
	Bed Material Size (mm)	14
	Number of Polygons	542
Calibration parameters	**Grid Spacing (-)**	0.6
	Cutoff Ratio (-)	2.3-4.5
	Min. Erosion Coefficient (-)	8.90E-09
	Ave. Erosion Coefficient (-)	2.23E-05
	Max. Erosion Coefficient (-)	1.40E-04

Figure 4-2 through Figure 4-4 display three examples of calibration results – the centerlines for the 1976 and 1999 channels and the simulated SRH-Meander channel centerlines in 1999. The model was calibrated moderately well. The average absolute distance of the model output coordinates to the actual channel centerline was 88.1 feet for the whole reach. These values are small relative to the average channel top widths about 1000 ft. The value of 0.60 for the grid spacing was used and it agrees with the finding of Crosato (2007) for numerical meander models that the "optimal distance between successive grid points had the order of half the channel width".

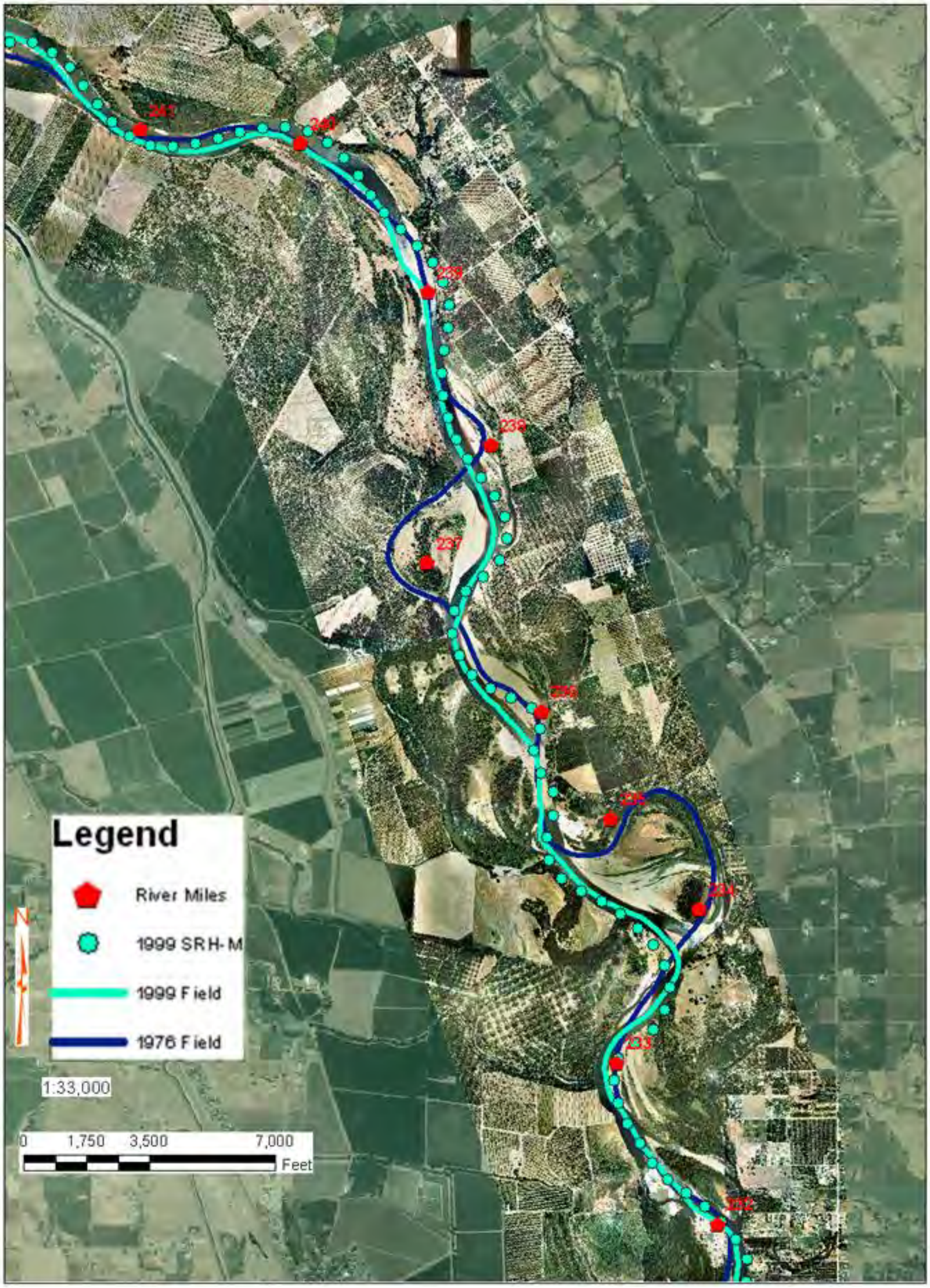


Figure 4-2. Calibration result in location 1.

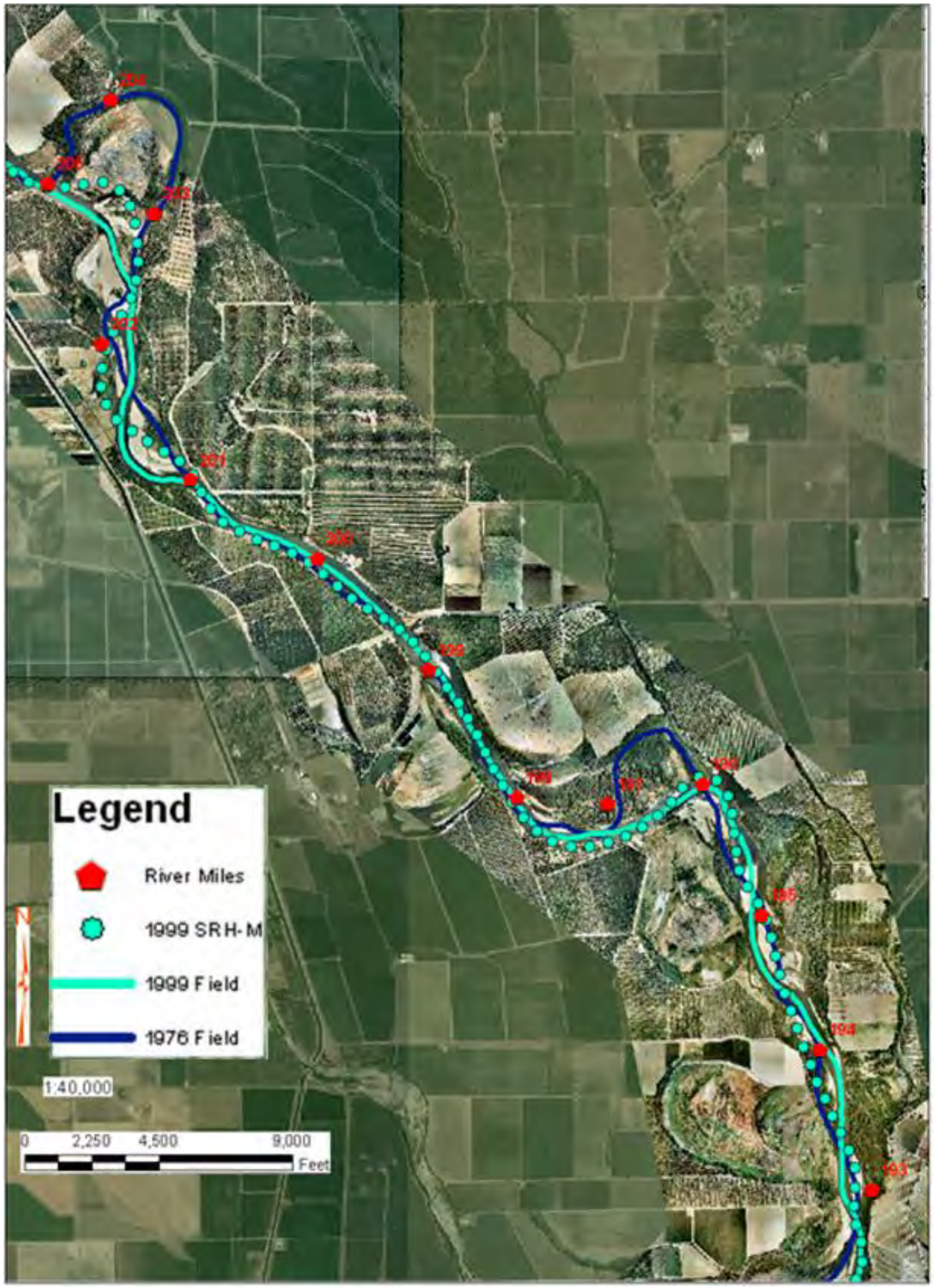


Figure 4-3. Calibration result in Location 2.

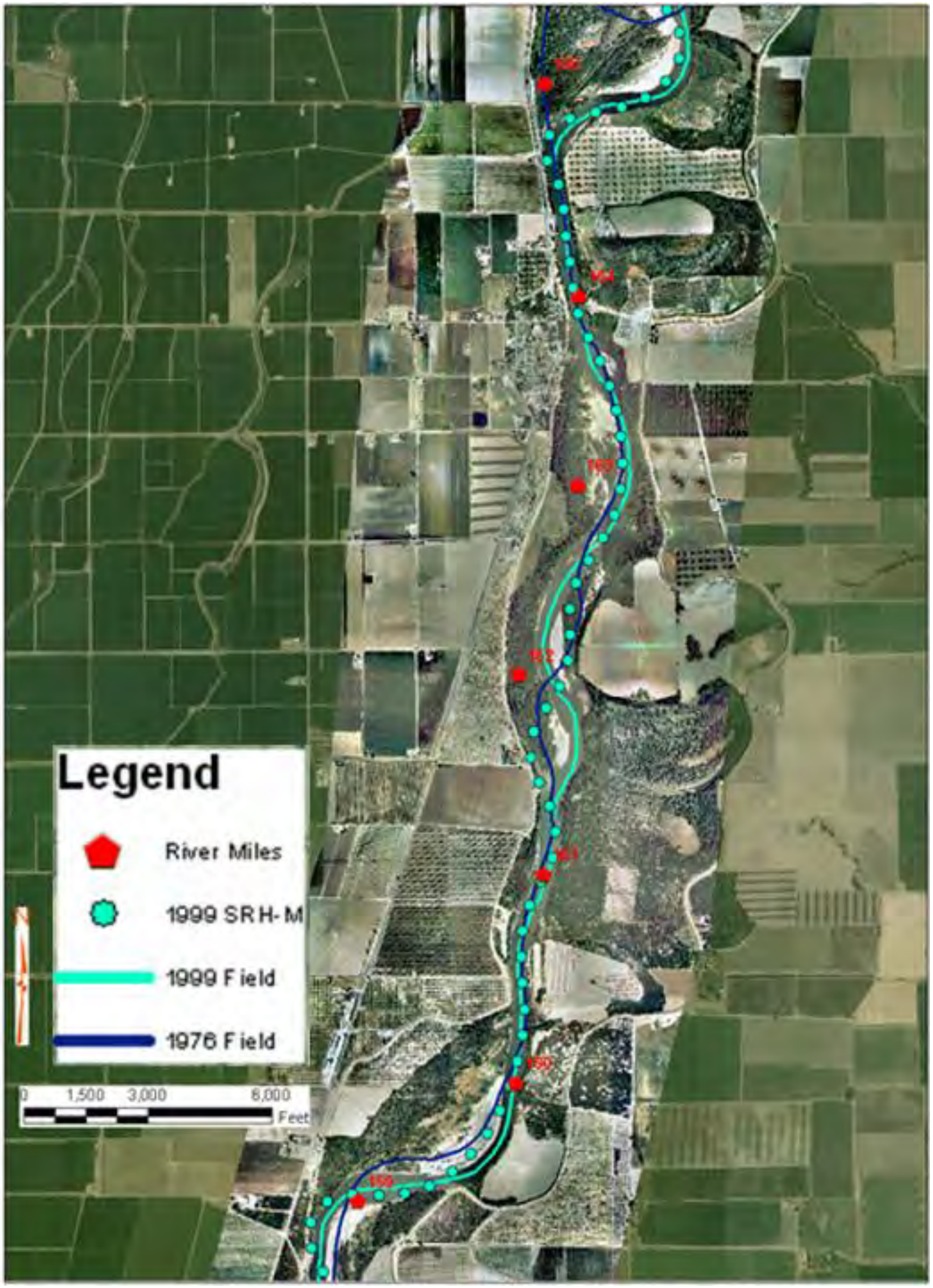


Figure 4-4. Calibration result in location 3.

In general, the SRH-Meander was better at modeling changes in bend amplitude than at modeling bend translation (Figure 4-2). Whether the model predicts translation versus amplification is primarily a function of the channel roughness input parameter combined with the calculated curvature of the centerline. The roughness parameter can only have a single value for the entire model and for the full range of flows used, which may not reflect the actual channel. Calibrating one bend with a given curvature to amplify properly may cause a subsequent bend of similar curvature to not translate as was observed.

Channel cutoff was predicted in the study reach. SRH-Meander simulates the channel cutoffs when the ratio of the length of channel to the length of the valley exceeds a threshold value input by the user. When the channel sinuosity exceeds a limit, the channel has not enough energy to carry the incoming flow and sediment, and the river abandons an existing portion of its length to find a new shorter and steeper path. A straight line is used to link the two points of the channel during the cutoff. After the cutoff, points are redistributed along the channel at equal distances. The model calibration tried to match the simulated channel profile with 1999 field data.

4.2 Model Prediction

The calibrated model was used to predict the channel profile in 2030 with initial channel alignment from 2009 photography, the USRDOM simulated hydrology at difference locations of the Sacramento River. The erosion coefficients, the channel roughness, the grid spacing, the cutoff ratios, and all other parameters are kept unchanged from the calibration model.

USRDOM simulated the flow hydrology at the Sacrament River from 1921 to 2003 with different water managements for river restorations options (named Existing, NoAction, AltA, AltB, and AltC). The simulation provided flow hydrology upstream from Shasta Reservoir to downstream at Colusa, and flow hydrology from tributaries including Antelope Creek, Elder Creek, Miller Creek, Thomas Creek Creek, Deer Creek, Big Chico Creek, and Stony Creek. The hydrology from 10/1/1980 to 9/30/2000 was used to predict channel meander from 2010 to 2030. Flow data from the gage at Red Bluff Diversion Dam (RM 243.0, Control Point 160) was used as upstream incoming flow. Flow rate varies along the over 100 mile reach due to incoming flows from tributaries, distribution of flows into irrigation cannels, and water infiltrations. The Control Points located in this study reaches are CP 175 at Red Bluff Diversion Dam (RM 242.8), CP 170 at Antelope Creek (RM 235.0), CP 165 at Elder Creek and Mill Creek (RM 229.6), CP 162 at Thomas Creek (RM 225.3), CP 160 at Deer Creek(RM 219.5), CP 150 at Glenn-Colusa Canal (GCC) Diversion (RM 206.2),CP 142 at Stone Creek (RM 189.8), CP 140 at Ord Ferry (RM 189.0), CP 135 at Butte City (RM 169.0), and CP 128 at Delevan Pipeline (RM 158.3). Flow rate differences from Control Points are input as lateral inflows/outflows to adjust the varying flow along the river.

Figure 4-5 to Figure 4-7 present the hydrographs at Red Bluff Diversion Dam, GCC Diversion, and the New Delevan Pipeline. The upper and lower limits (section 4.1) are only specified at upstream (Red Bluff) for the model. Only minor differences are displayed along different hydrographs.

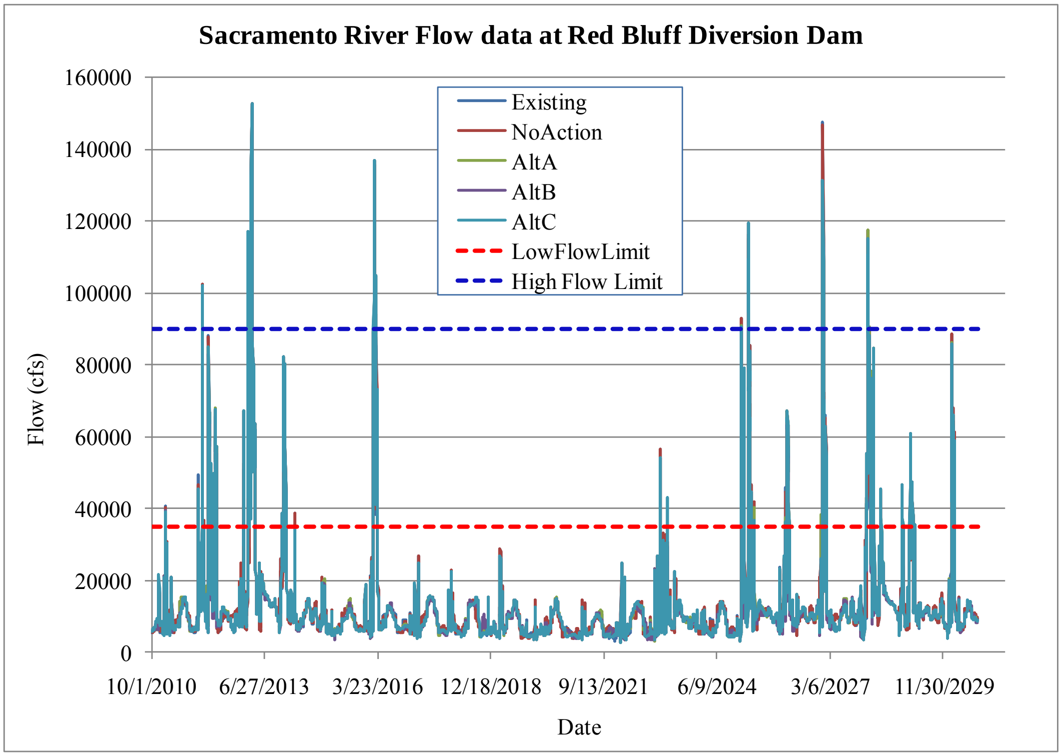


Figure 4-5. Flow hydrograph of Sacramento River at Red Bluff used for future prediction

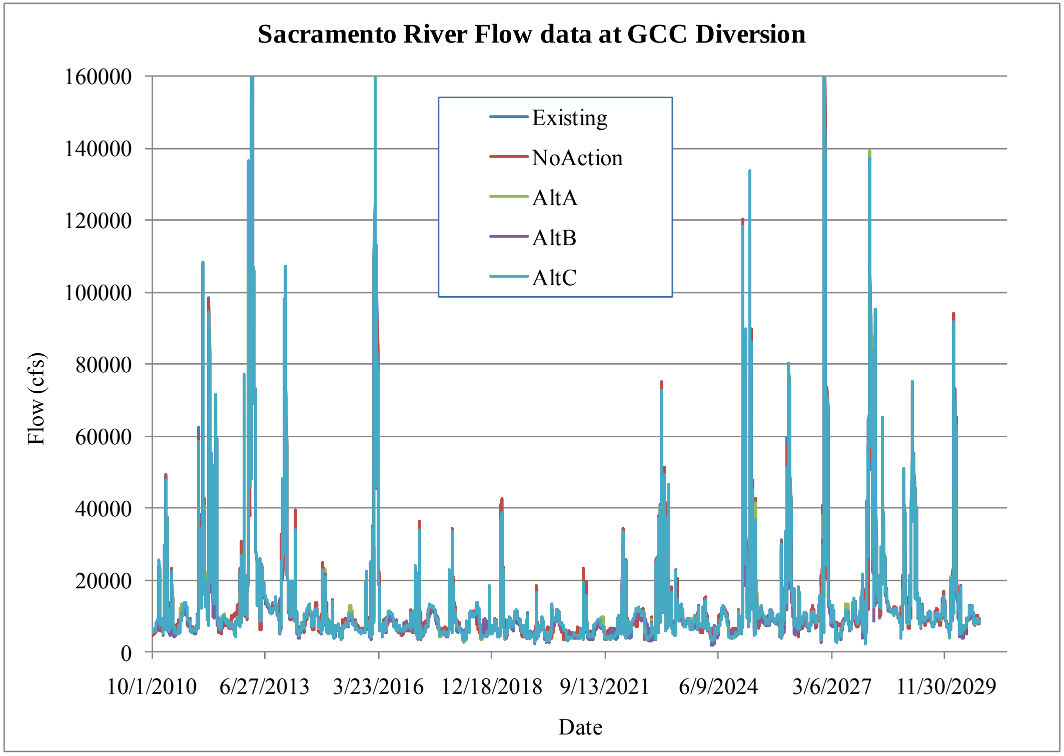


Figure 4-6. Flow hydrograph of Sacramento River at GCC Diversion used for future prediction at GCC Diversion

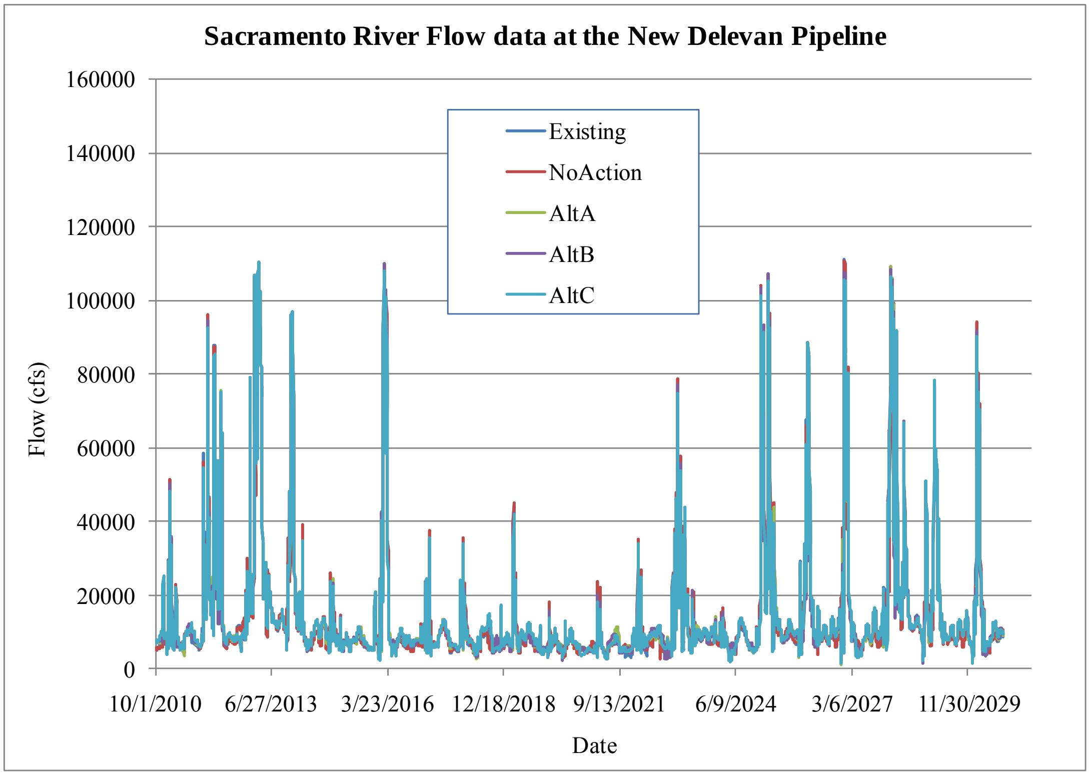


Figure 4-7. Flow hydrograph of Sacramento River at the New Delevan Pipeline used for future prediction .

Flow duration curves under difference alternatives are given in Figure 4-8 to Figure 4-10. Only minor differences exist along difference alternatives. At Red Bluff, AltA, AltB, and AltC conditions have less flows under 10,000 cfs comparing with Existing and NoAction conditions. At GCC diversion, AltA, AltB, and AltC conditions have less flows under 7,000 cfs and between 10,000 and 20,000 cfs comparing with Existing and NoAction conditions. At New Delevan Pipeline, AltA, AltB, and AltC conditions have less flows under 5,000 cfs and between 10,000 and 20,000 cfs, and have more flows between 6,000 to 10,000 cfs comparing with Existing and NoAction conditions.

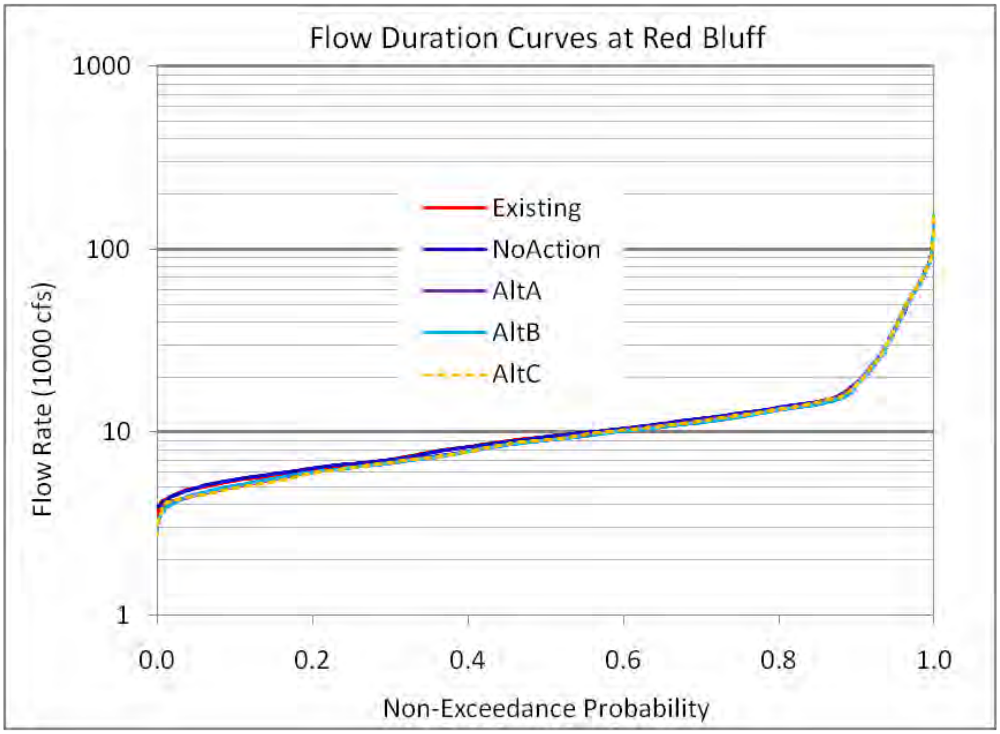


Figure 4-8. Flow Duration Curves at Red Bluff. The flow duration curve is derived from USRDOM results from Oct. 1, 1980 to Sept. 30, 2000.

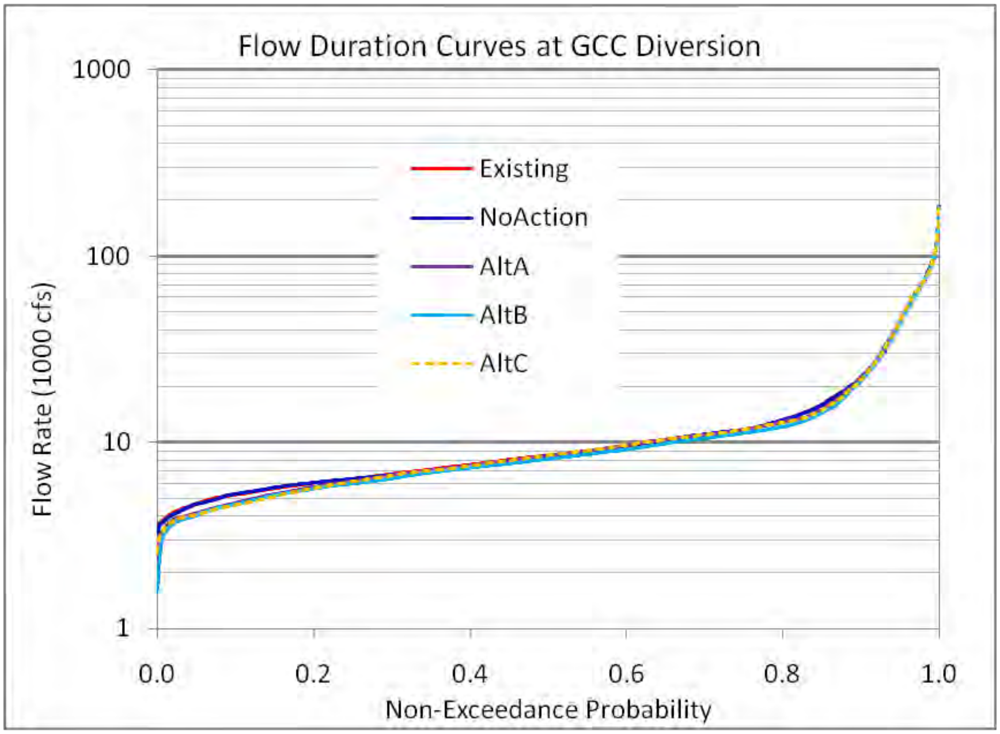


Figure 4-9. Flow Duration Curves at GCC Diversion. The flow duration curve is derived from USRDOM results from Oct. 1, 1980 to Sept. 30, 2000.

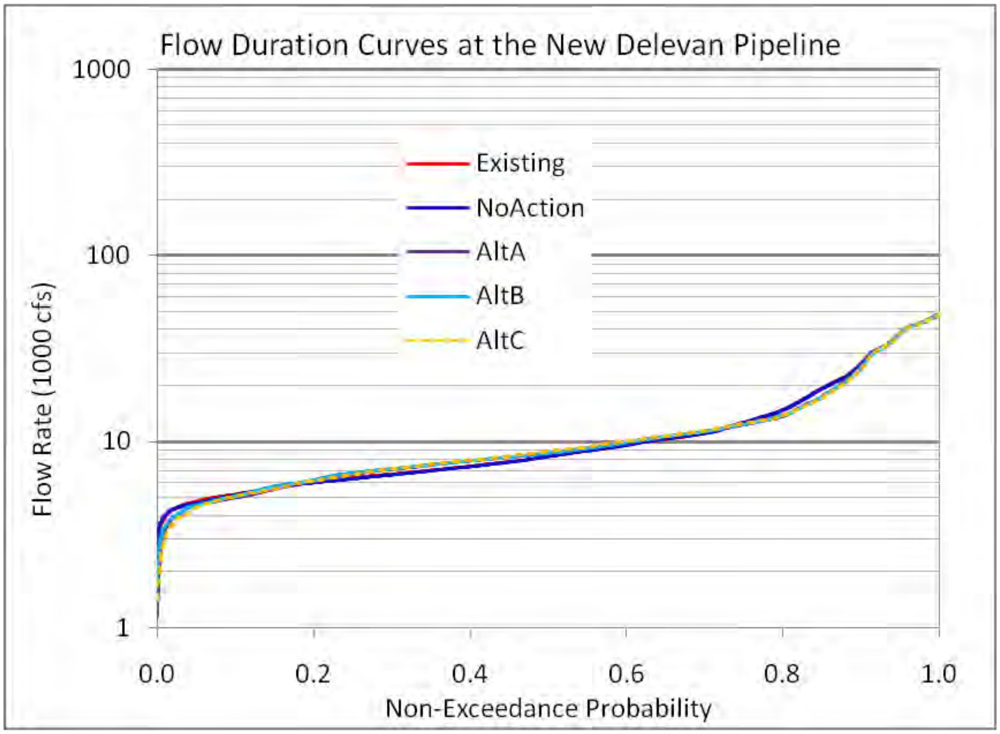


Figure 4-10. Flow Duration Curves at the New Delevan Pipeline. The flow duration curve is derived from USRDOM results from Oct. 1, 1980 to Sept. 30, 2000.

Future channel migration is predicted in two conditions: the current conditions and ripraped conditions. In the current conditions, no modification is made to the calibrated erosion coefficients and the channel will continue to migrate at the same rate as in calibration period from 1976 to 1999. In the ripraped condition, the channel alignment is fixed where the existing bank is ripraped. A DWR 2008 GIS map was provided with updated ripraped banks. In some locations, the channel has encountered geological control (for example at the right bank of Delevan RM 158.5)and is identified as Tehama or Modesto bank. In these cases, the erosion coefficients are set at one order of magnitude lower than the value determined during calibration.

Review comments from Koll Buer (Koll, 2011, personal communication) were incorporated to update channel conditions regarding bank riprap locations and geological controls. At the right bank of RM222, Modesto Formation is exposed along this bank from the mouth of Thomas Creek in the upstream part of the bend, and extending downstream to RM222. From this point on downstream, geologic control continues southward along the boundary between the riparian vegetation and the tan grassy field, continuing to Deer Creek. At the left bank of RM 208, the riprap at the lower end of the bend may have washed out. The 2030 simulation assumes that the riprap will be maintained and it will prevent future channel migrations there. At the right bank of RM201, the bend is mostly geologic control except a floodplain deposit which may be eroded in the future.

Geologic control is exposed upstream, in the center of, and at the downstream end of this bend. At the upstream of the left bank of RM 172, the geologic control follows the levee and road that goes along the bank. This area is still eroding floodplain deposits and will continue to do so until it hits geologic control. At RM191, a cut off will be allowed in the model to show the potential of channel alignment, even though the entire bend is heavily ripraped to keep it from cutting off.

The predicted channel alignment in 2030 is shown in Appendix A. The Sacramento River continues to meander at the same rate. Results show that channel cutoff might happen at the big bend from RM 190 to RM 187 unless the channel bank is enforced at this location.

Accumulated channel migration distances with current conditions are shown in Figure 4-11 to Figure 4-14. Channel migration distance represents the distance that the channel works through in the floodplain. After the channel central alignment is calculated, it is shifted normally to the left and to the right by a distance half of the channel width to obtain the left and right bank, respectively. If any bank point is located outside of a channel envelop, the bank point is inserted into the channel envelop to obtain the new channel envelop. The channel envelope represents the area where the channel has worked through during the simulated duration. After the area of the channel envelop is calculated, it is then divided by the initial channel length to obtain the envelop width. The envelop width subtracted by the initial channel width, which is the same as the initial envelop width, represents the accumulated channel migration distance. Results shows that channel is most active meandering from Stony Creek (RM 190) to Moulton Weir (RM 158.5) and least active from Moulton Weir (RM 158.5) to Colusa Weir (RM 143) for all water management options.

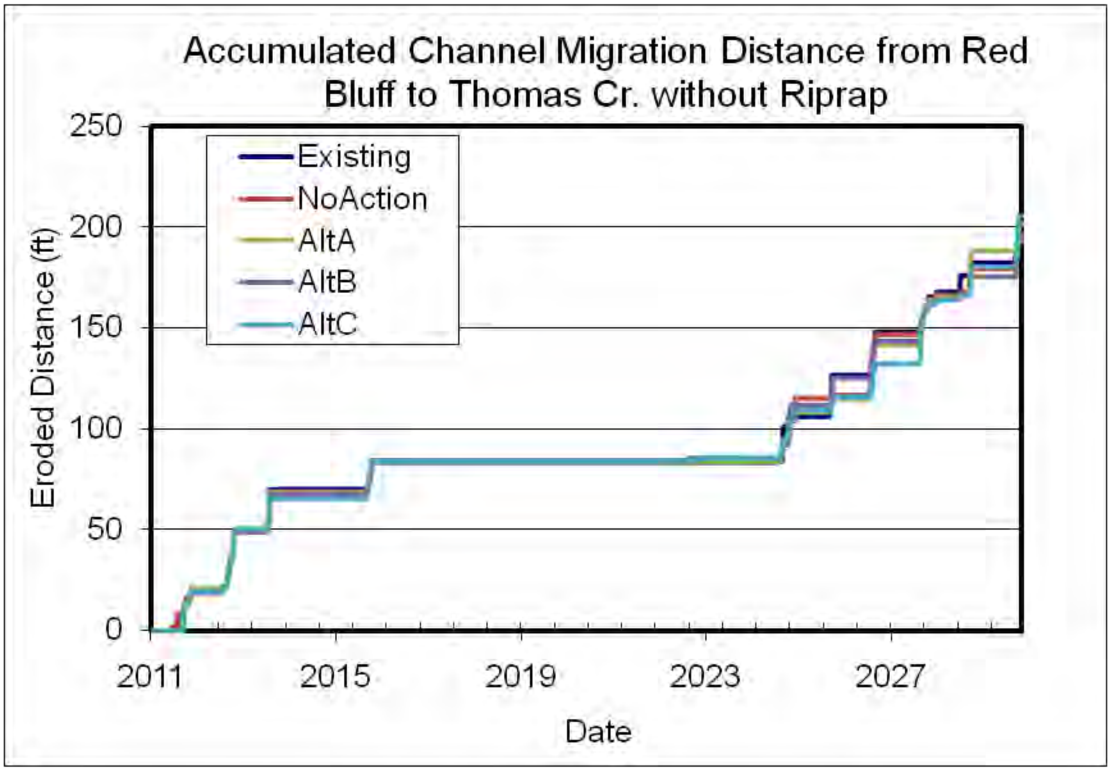


Figure 4-11. Accumulated channel migration distance in reach from Red Bluff Diversion Dam to Thomas Creek with current erosion coefficients

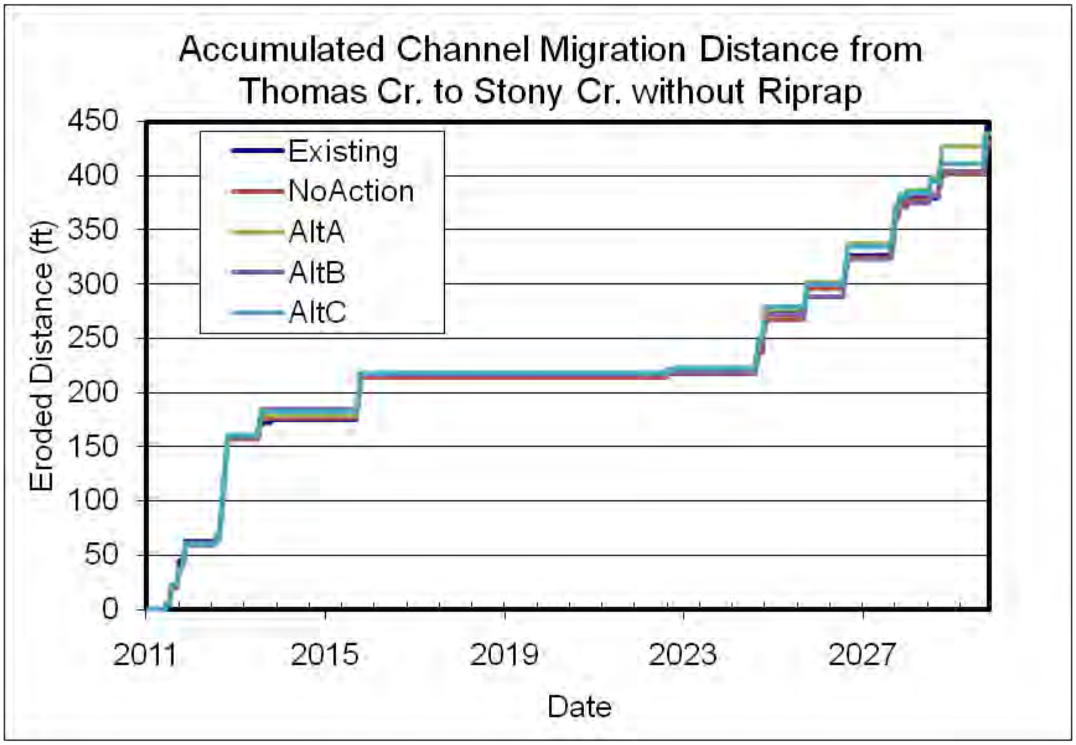


Figure 4-12. Accumulated channel migration distance in reach from Thomas Creek to Stony Creek with current erosion coefficients

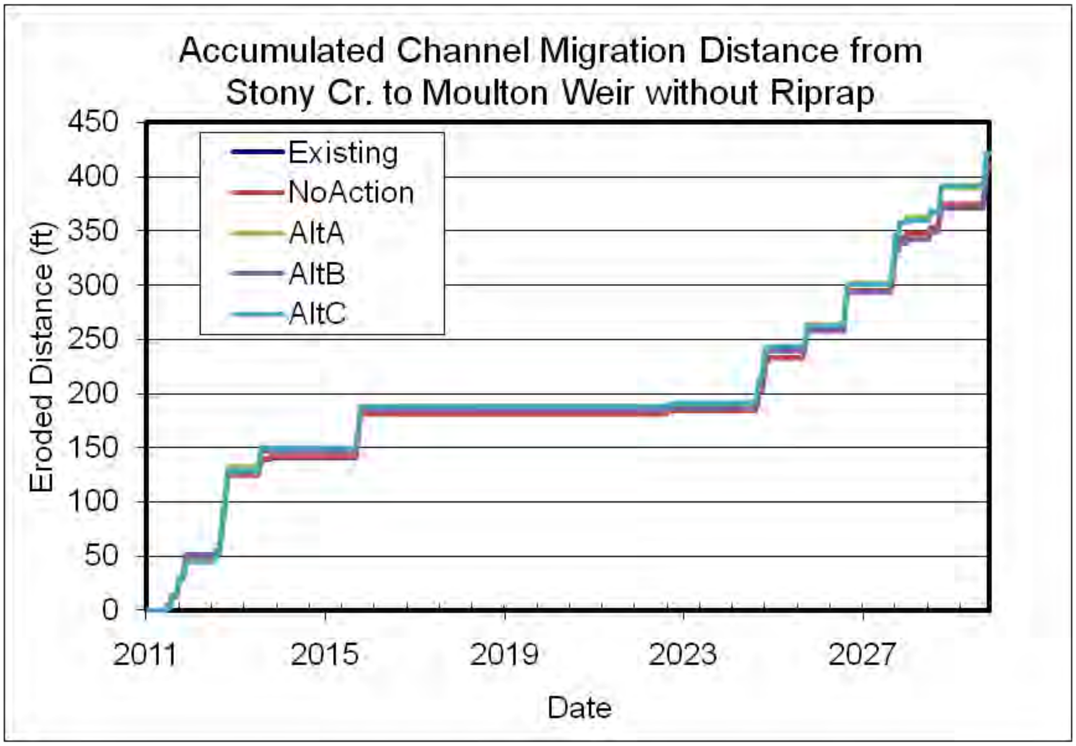


Figure 4-13. Accumulated channel migration distance in reach from Stony Creek to Moulton Weir with current erosion coefficients

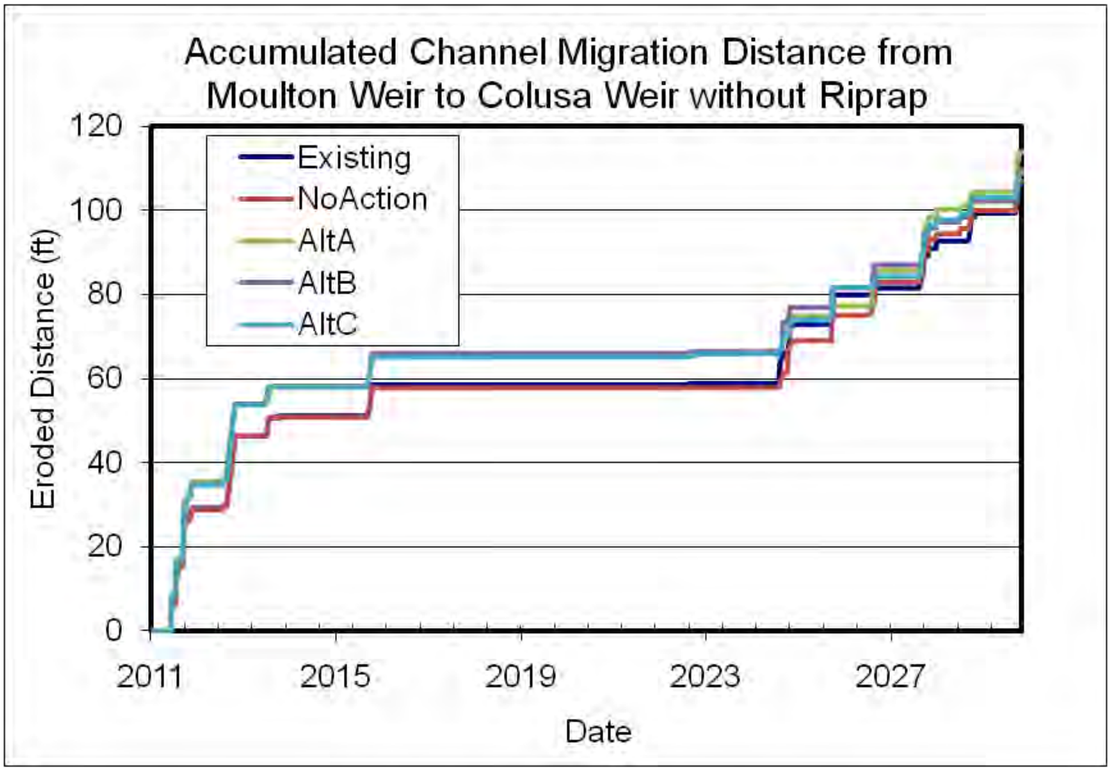


Figure 4-14. Accumulated channel migration distance in reach from Moulton Weir to Colusa Weir with current erosion coefficients

Figure 4-20 and Figure 4-15 shows averaged accumulated channel migration distance for the whole study reach from Red Bluff Diversion Dam (RM 243) to Colusa Weir (142) under the current erosion coefficient condition. AltA and AltC conditions have slightly more meander tendency than other alternatives, but difference is not considered significant considering inherent variability in system.

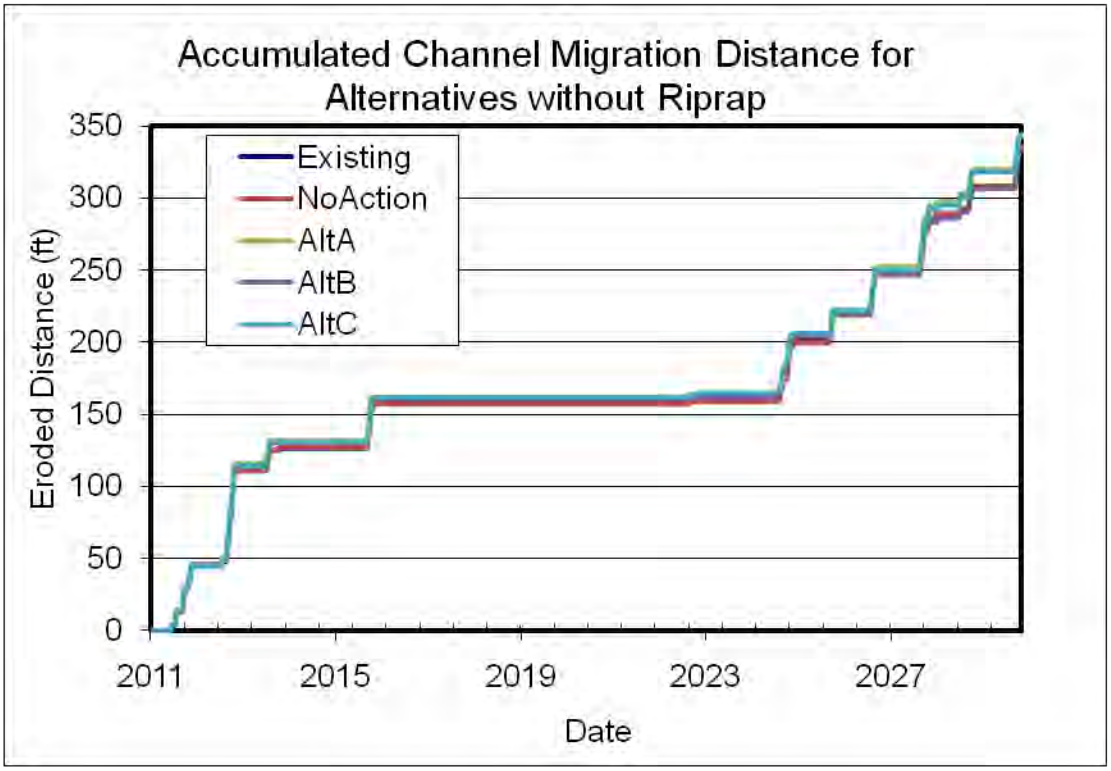


Figure 4-15. Averaged accumulated channel migration distance in the whole reach from Red Bluff Diversion Dam to Colusa Weir with current erosion coefficients

Accumulated channel migration distances with ripraped banks and geological controls are shown in Figure 4-16 to Figure 4-19. The results under this ripraped condition are based on the assumption that the current ripraped banks will be maintained to restrict the channel from any migration and the geological controls will continue to confine the channel at a low migration rate. Compared with results predicted with current erosion coefficients, the averaged channel migration distance reduces with ripraped banks and geological controls. For example, under AltA hydrology, the averaged channel migration distance reduced from 202 ft under the current condition to 139 ft (31% less) under the ripraped bank and geological control condition from Red Bluff Diversion Dam to Thomas Creek. The averaged channel migration distance with ripraped bank and geological control reduces to 218ft (50% less from 439ft) in the reach from Thomas Creek to Stony Creek, 205 ft (51% less from 422ft) in the reach from Stony Creek to Moulton Weir, and 126 ft (11% more from 114ft) in the reach from Moulton Weir to Colusa Weir. Figure 4-20 shows averaged accumulated channel migration distance for the whole study reach from Red Bluff Diversion Dam (RM 243) to Colusa Weir (142) under the riprapped and geologic control condition. AltA and AltC conditions have slightly more meander tendency than other alternatives, but difference is not considered significant considering inherent variability in system.

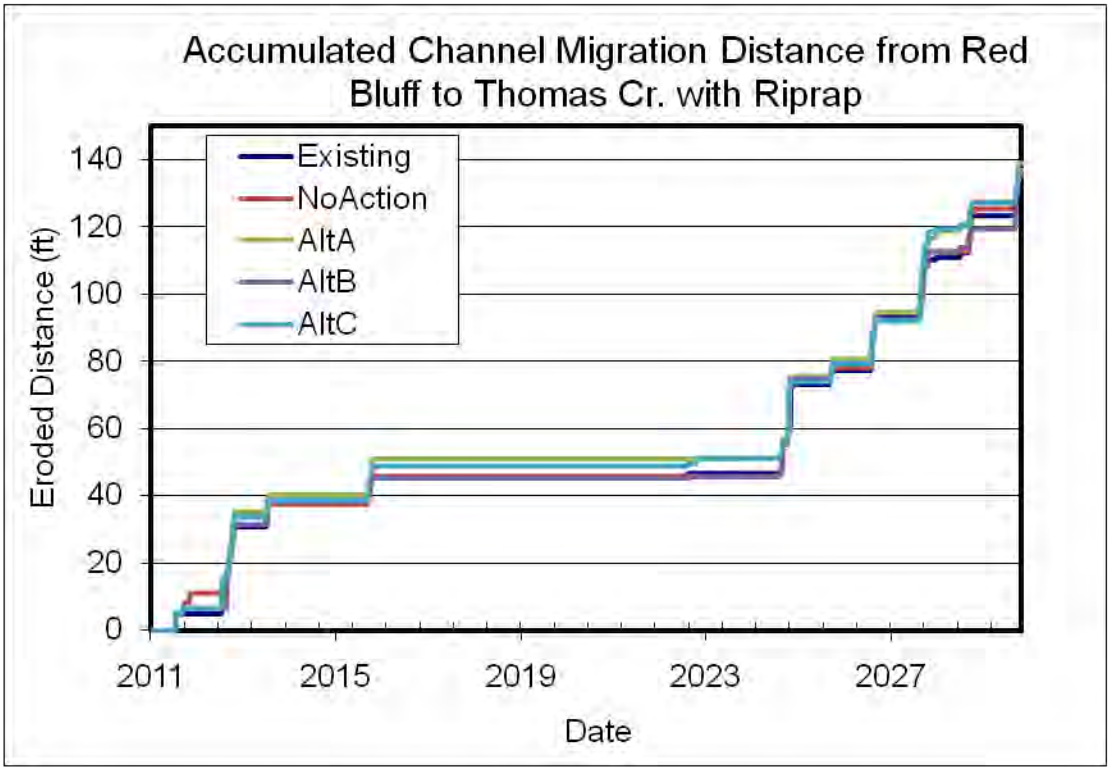


Figure 4-16. Accumulated channel migration distance in reach from Red Bluff Diversion Dam to Thomas Creek with riprap and geologic control

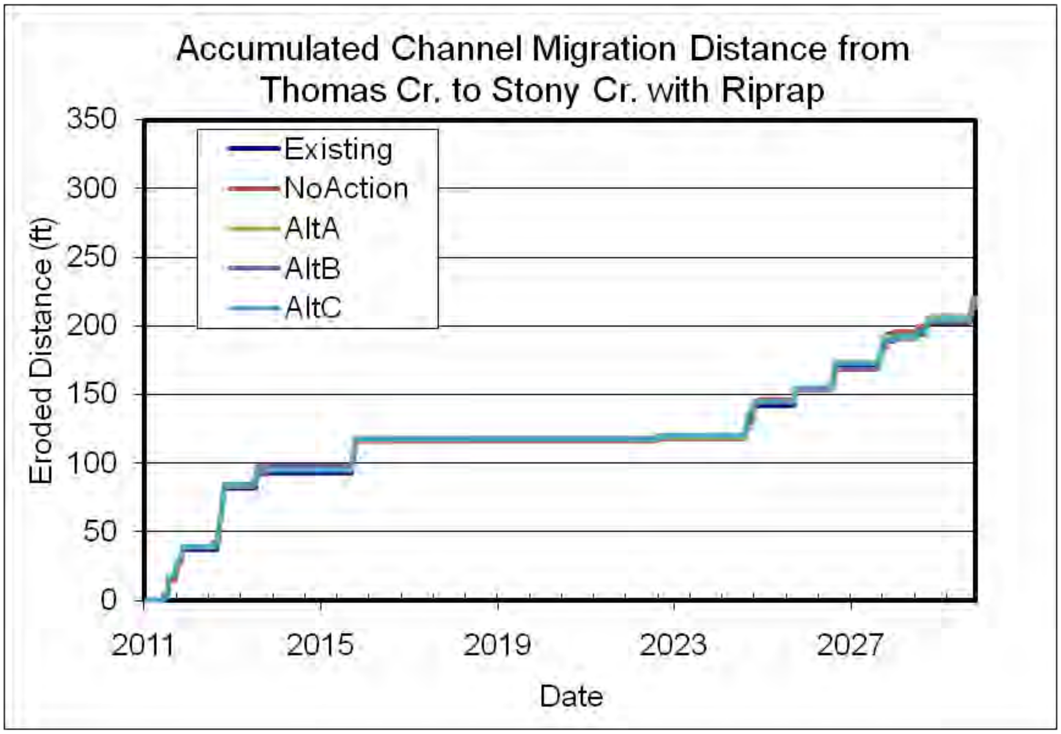


Figure 4-17. Accumulated channel migration distance in reach from Thomas Creek to Stony Creek with riprap and geologic control

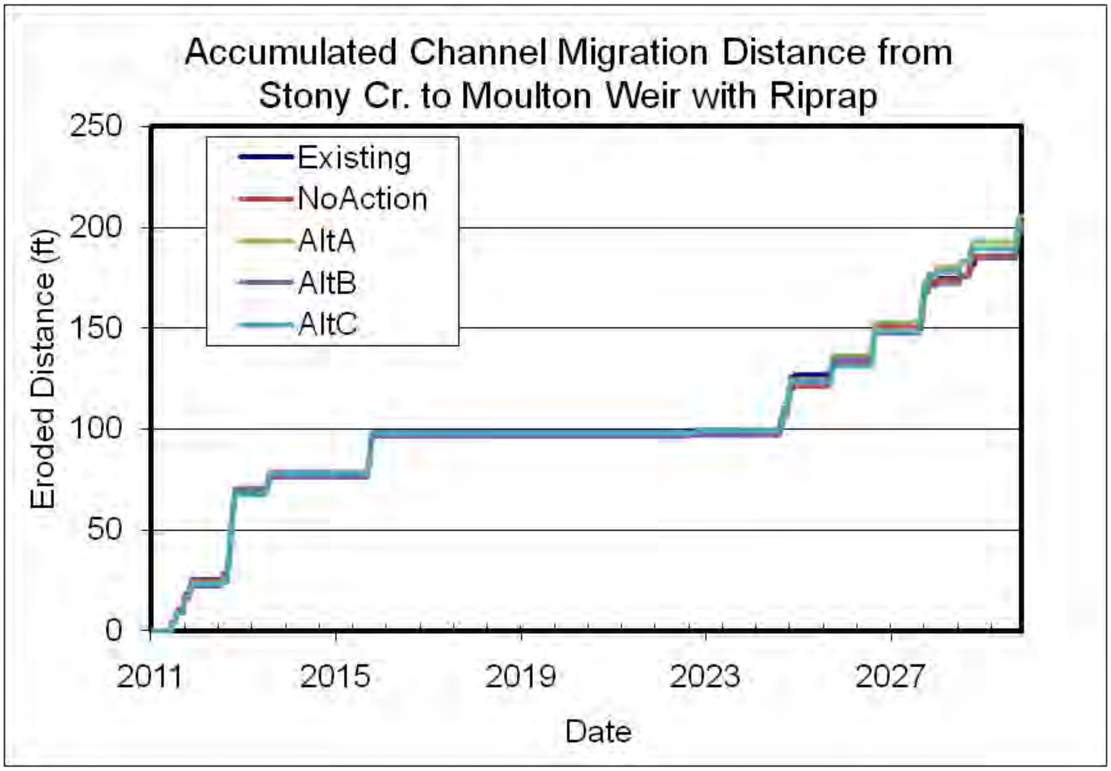


Figure 4-18. Accumulated channel migration distance in reach from Stony Creek to Moulton Weir with riprap and geologic control

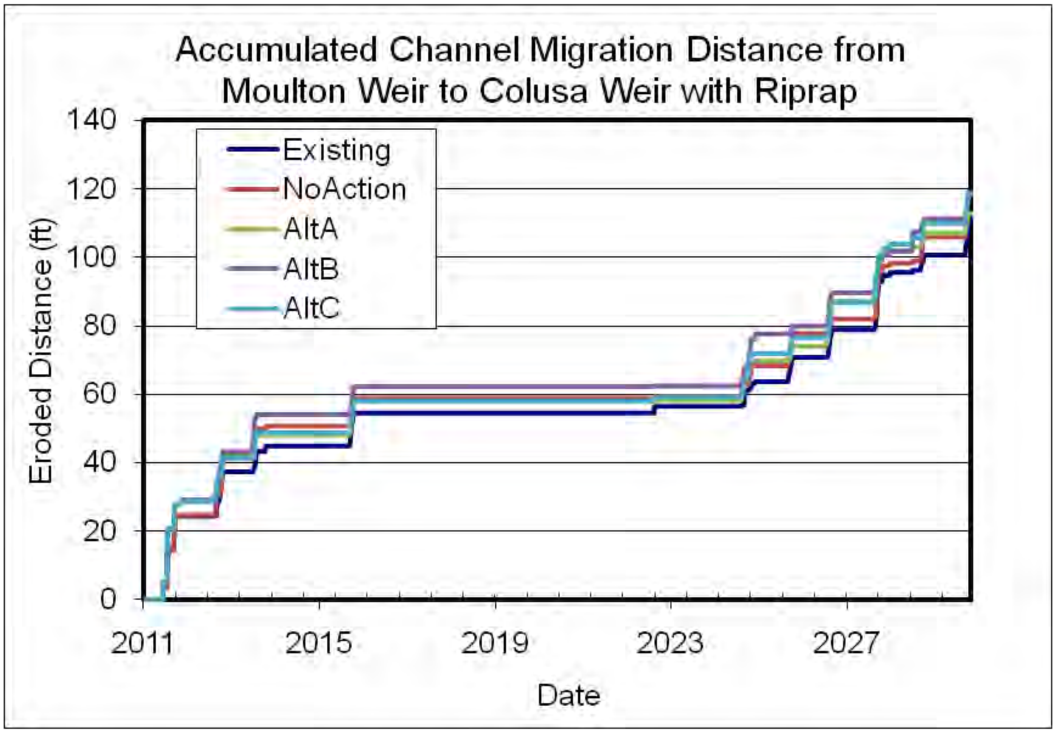


Figure 4-19. Accumulated channel migration distance in reach from Moulton Weir to Colusa Weir with riprap and geologic control.

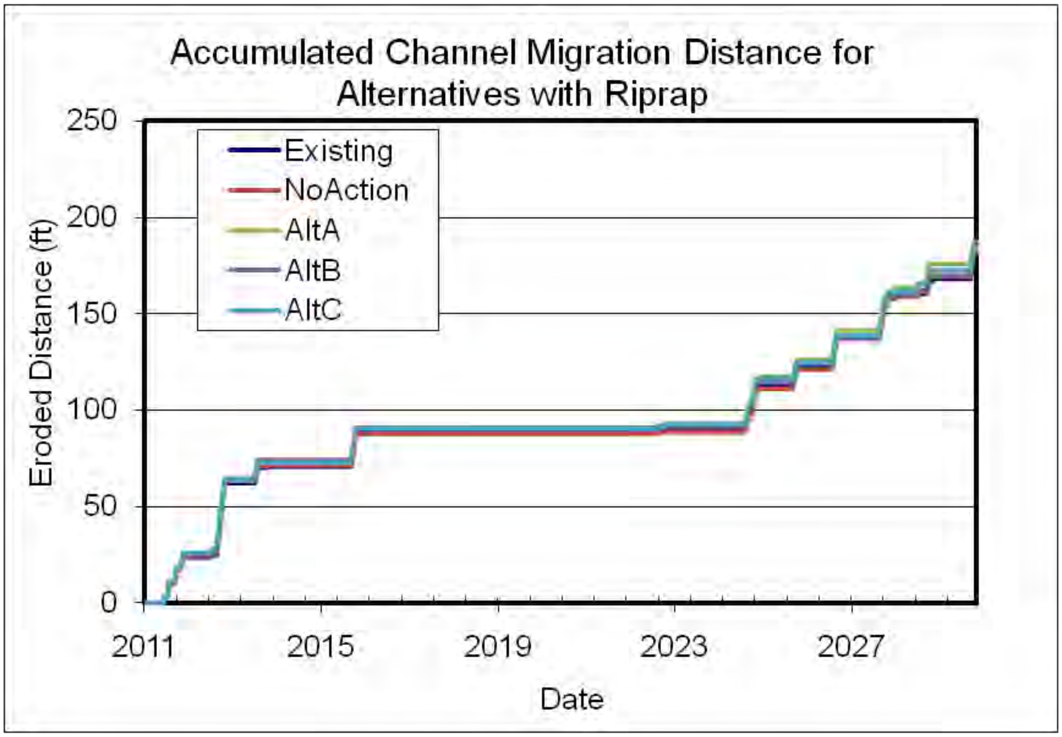


Figure 4-20. Average accumulated channel migration distance in the whole reach from Red Bluff Diversion Dam to Colusa Weir with riprap and geologic control

5 Conclusions

SRH-Meander was used to predict the channel alignments in 2030 based on 2009 channel alignment and modeling twenty years of hydrology from 10/1/2010 to 9/30/2030 using USRDOM flows under the Existing, NoAction, AltA, AltB, and AltC conditions. The channel migration study results are summarized below:

Near the New Delevan Pipeline,

- No major difference exists between channel alignments along Existing, NoAction, AltA, AltB, and AltC conditions .
- The bend upstream of the diversion will continue to migrate downstream unless the bank is protected. Given 20 years, the channel will migrate 650 ft downstream and to the left.
- The channel near the intake will migrate to the right (looking downstream) where levee is close to the main channel. In 20 years, the channel will migrate about 300 ft to the right.
- A cutoff may occur in the bend downstream of the New Delevan Pipeline.
- Bank protection in the vicinity of the intake will prevent the channel from migrating at that location and will not affect the channel migration upstream and downstream of the two ripraped bends.

For the whole reach from Red Bluff to Colusa,

- No major differences exist between the channel alignments for Existing, NoAction, AltA, AltB, and AltC conditions . AltA and AltC conditions yield slightly more meander tendency than other conditions.
- The reach between Stony Creek to Moulton Weir will experience most active channel migration. In twenty years, the channel will migrate more than 400 ft on average. The reach between Moulton Weir to Colusa Weir will experience less channel migration. In twenty years, the channel will migrate 110 ft on average.

6 References

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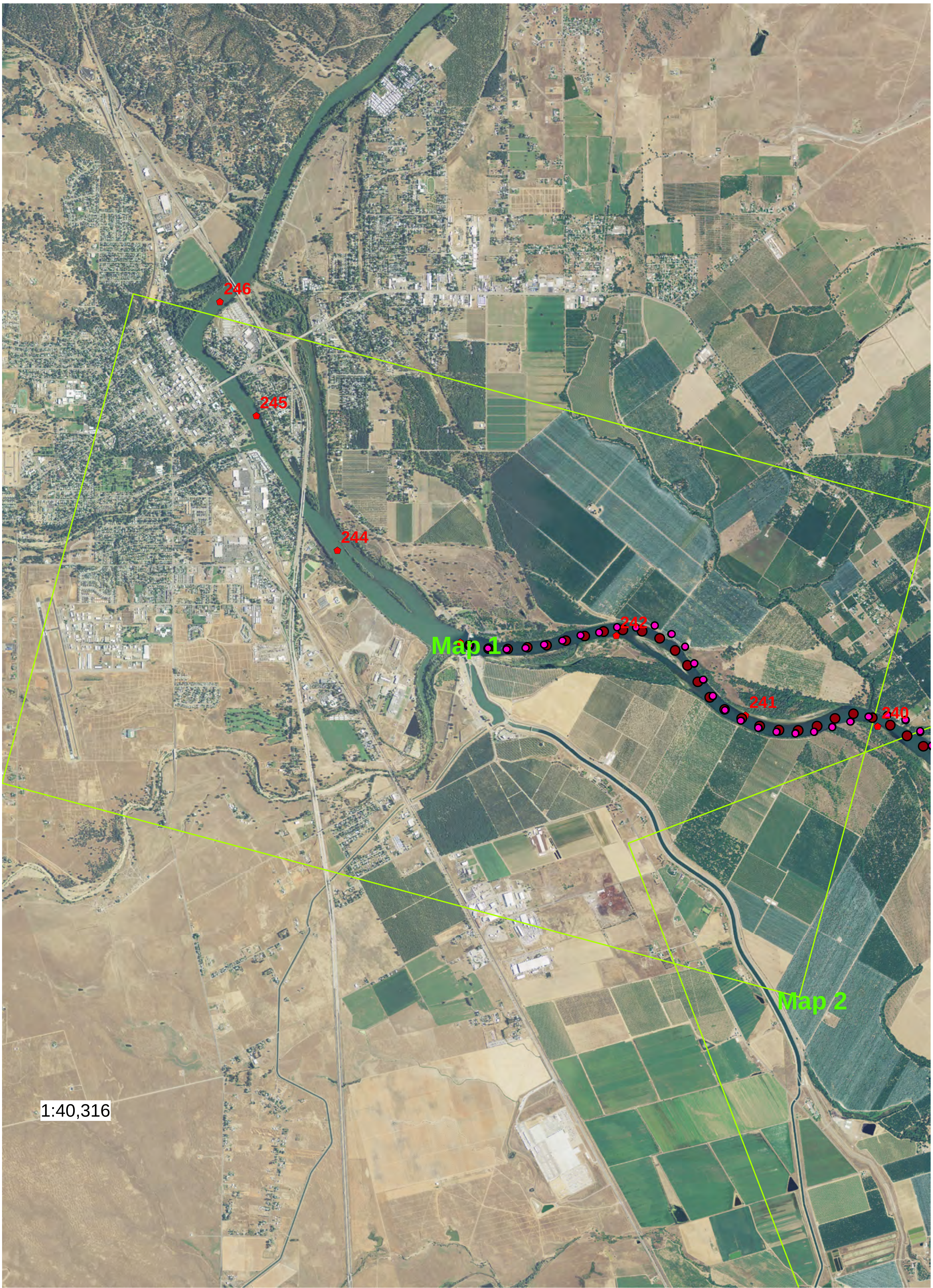
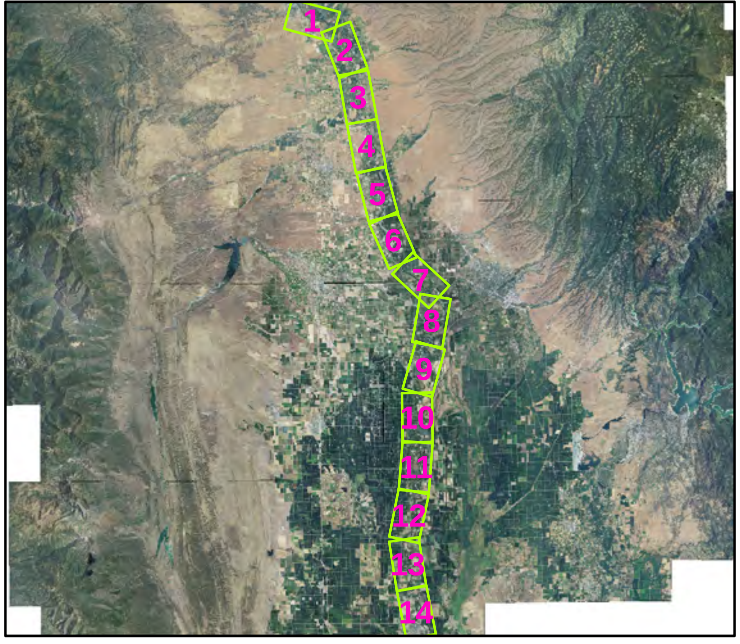
Appendix A





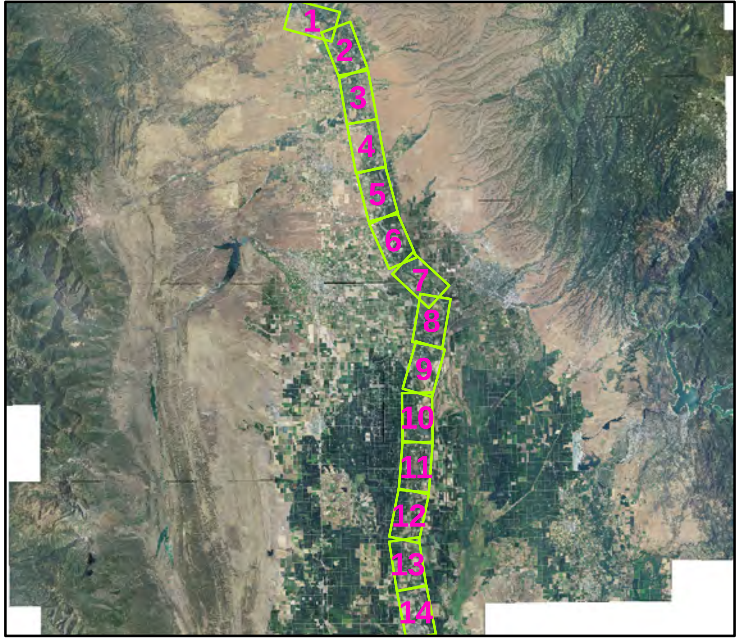
Legend

- ● SRH_M-2030_AltA
- ● SRH_M-2030_AltB
- ● SRH_M-2030_AltC
- ● SRH_M-2030_Existing
- ● SRH_M-2030_NoAction
- ● SRall_2009_Central_Points MZ
- ⬟ River Miles

N

0 2,200 4,400 8,800
Feet

Sacramento River, California
Channel Migration Predictions
Sedimentation and River Hydraulics
Bureau of Reclamation
Denver, CO



Legend

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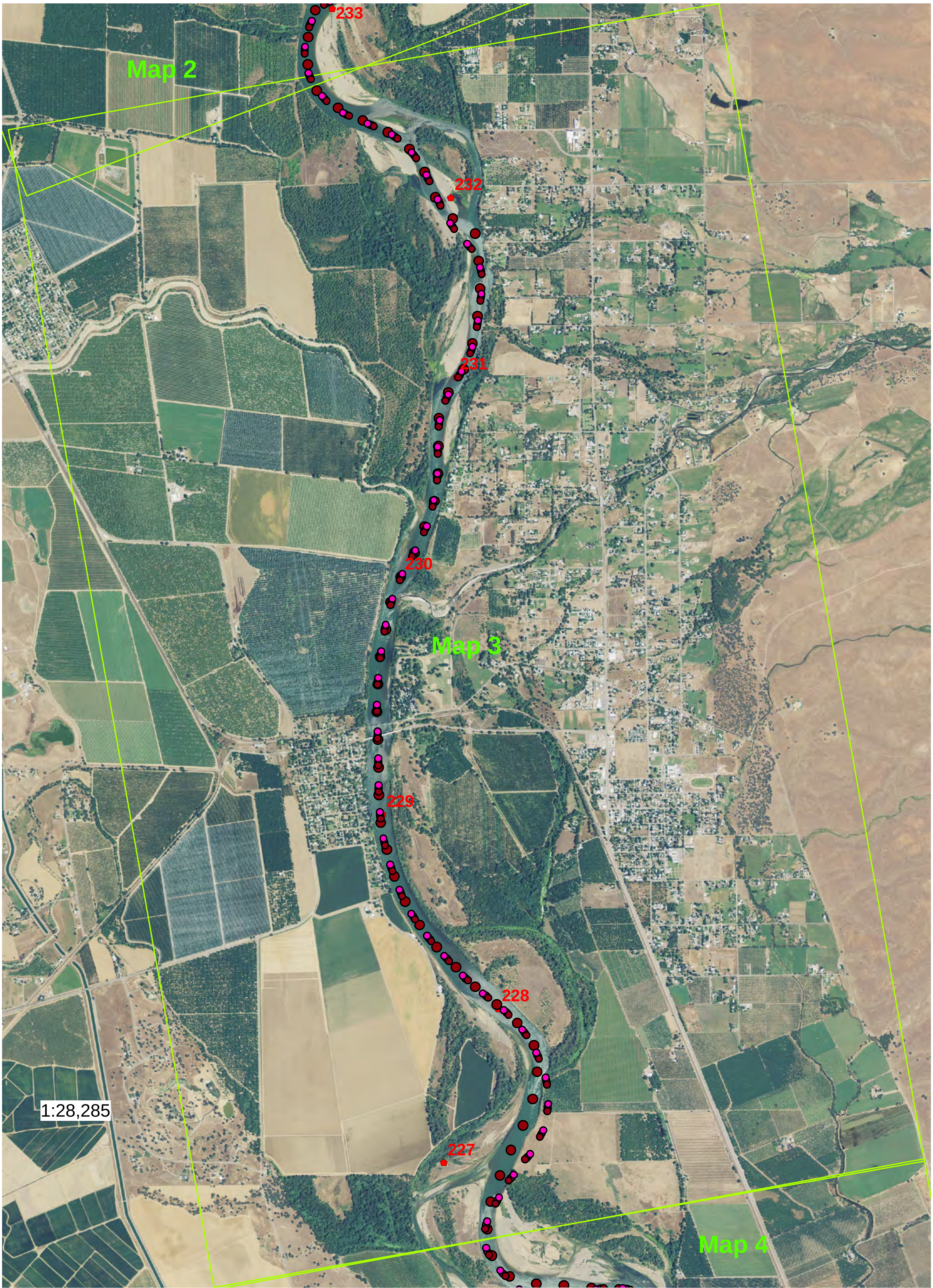
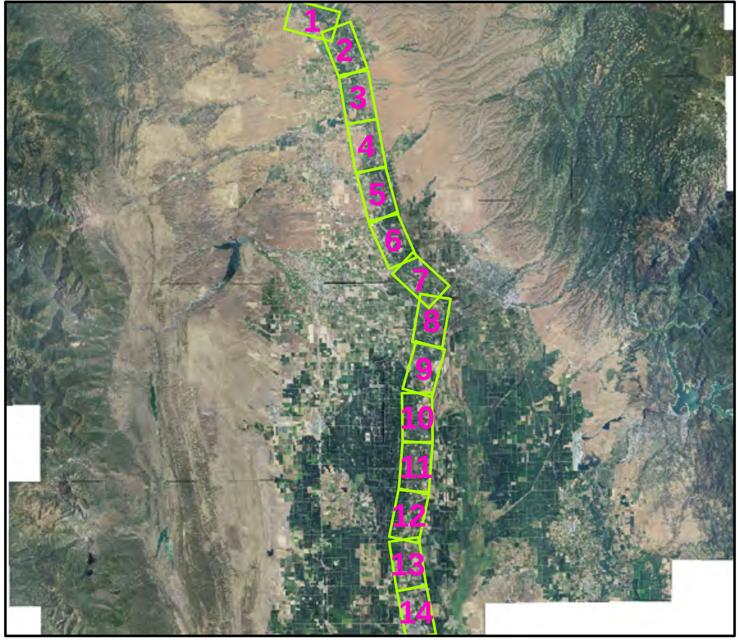
- ● SRH_M-2030_AltB
- ● SRH_M-2030_AltC
- ● SRH_M-2030_Existing
- ● SRH_M-2030_NoAction
- ● SRall_2009_Central_Points MZ
- ⬟ River Miles

Sacramento River, California
Channel Migration Predictions
Sedimentation and River Hydraulics
Bureau of Reclamation
Denver, CO





Legend

● SRH_M-2030_AltA

● SRH_M-2030_AltB

● SRH_M-2030_AltC

● SRH_M-2030_Existing

● SRH_M-2030_NoAction

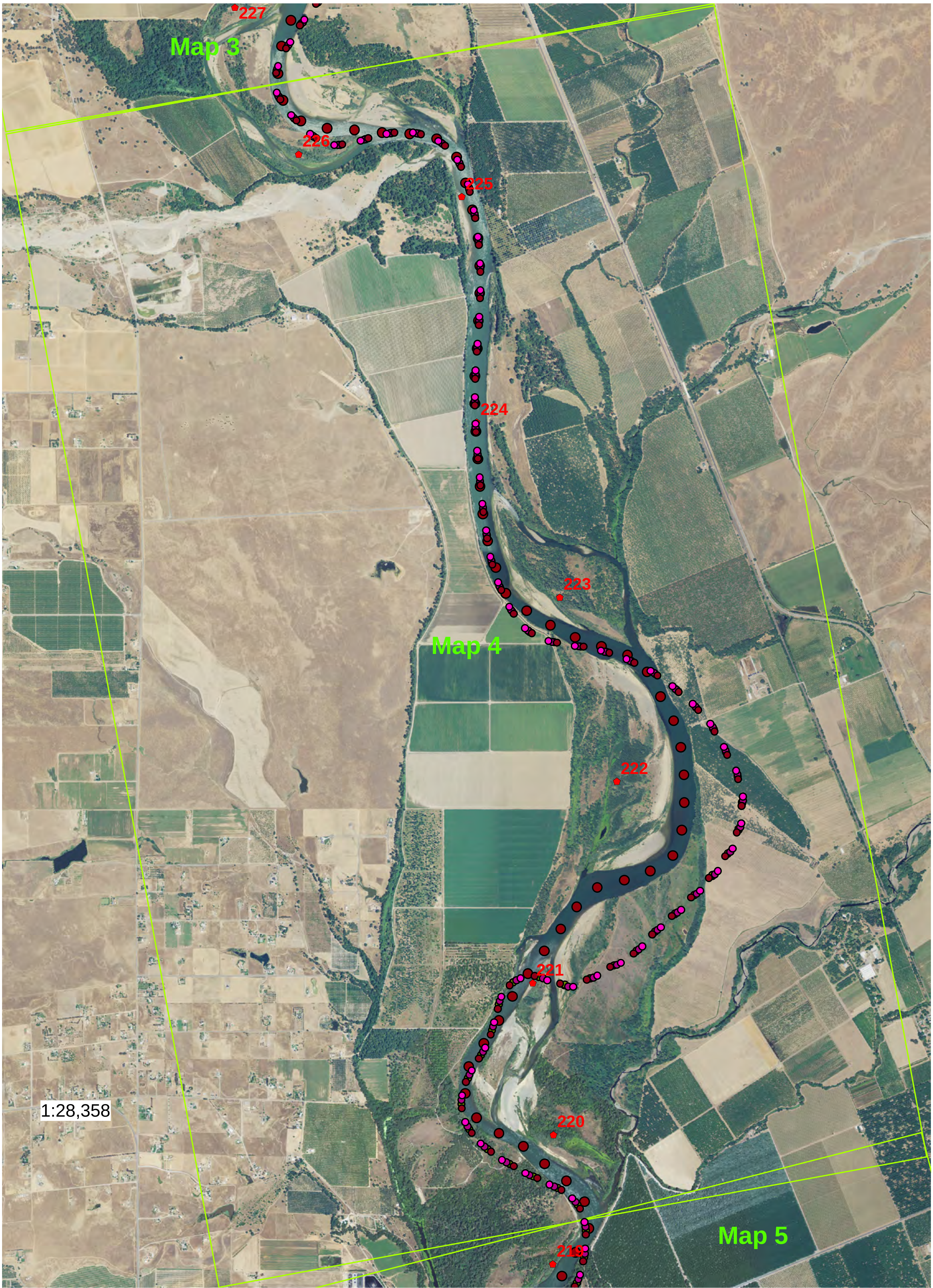
● SRall_2009_Central_Points MZ

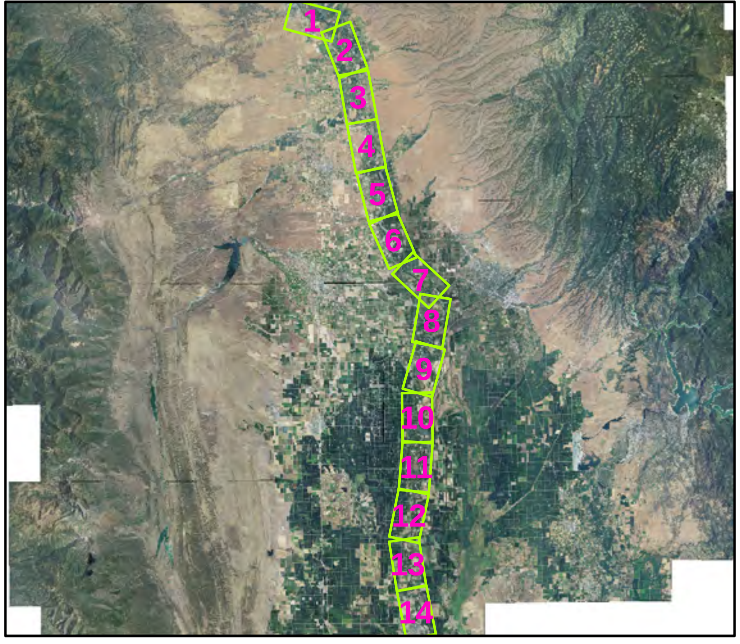
⬟ River Miles

N

0 1,650 3,300 6,600
Feet

Sacramento River, California
Channel Migration Predictions
Sedimentation and River Hydraulics
Bureau of Reclamation
Denver, CO





Legend

- ● SRH_M-2030_AltA
- ● SRH_M-2030_AltB
- ● SRH_M-2030_AltC
- ● SRH_M-2030_Existing
- ● SRH_M-2030_NoAction
- ● SRall_2009_Central_Points MZ
- ⬟ River Miles

N

0 1,700 3,400 6,800 Feet

Sacramento River, California
Channel Migration Predictions
Sedimentation and River Hydraulics
Bureau of Reclamation
Denver, CO