# Appendix D

Hydrodynamic Modeling Report

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# California Department of Water Resources

## *Yolo Bypass Salmonid Habitat Restoration and Fish Passage Hydrodynamic Modeling Report*

June 2017

Prepared by

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# Acronyms/Abbreviations

| | |
|---|---|
| 1D | one-dimensional |
| 2D | two-dimensional |
| 3D | three-dimensional |
| ac-ft | acre-foot |
| ADCP | Acoustic Doppler Current Profiler |
| ADF | area-duration-frequency |
| Ag crossing | agricultural crossing |
| BDCP | Bay Delta Conservation Plan |
| BKS | Barker Slough |
| BOR | Bureau of Reclamation |
| Bypass | Yolo Bypass |
| CCSB | Cache Creek Settling Basin |
| CCY | Cache Creek at Yolo |
| CDEC | California Data Exchange Center |
| CFR | Code of Federal Regulations |
| Cfs | cubic feet per second |
| CHMTT | core hydraulic modeling technical team |
| CIMIS | California Irrigation Management Information System |
| CVFED | Central Valley Floodplain Evaluation and Delineation |
| CVP | Central Valley Project |
| DEM | Digital Elevation Model |
| DES | DWR Division of Environmental Service |
| DOP | Doppler |
| DPS | Distinct Population Segment |
| DWR | California Department of Water Resources |
| EIS/EIR | Environmental Impact Statement and Environmental Impact Report |
| ESA | Endangered Species Act |

| | |
|---|---|
| ESRI | Environmental Systems Research Institute |
| FEA | Feather River |
| FEMA | Federal Emergency Management Agency |
| FIRM | flood insurance rate map |
| FLT | binary raster format |
| Fps | feet per second |
| FreSm | small channel at Fremont Weir alternative |
| FreMed | medium channel at Fremont Weir alternative |
| FreLg | large channel at Fremont Weir alternative |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| HMAT | hydraulic modeling advisory team |
| HEC-HMS | Hydrologic Engineering Center - Hydrologic Modeling System |
| HEC-RAS | Hydrologic Engineering Center – River Analysis System |
| HWM | high water mark |
| I-80 | Interstate 80 |
| in/hr | inches/hour |
| KLOG | Knights Landing Outfall Gates |
| KLRC | Knights Landing Ridge Cut |
| LDW | Last Day Wet |
| LFRCMP | Lower Feather River Corridor Management Plan |
| LiDAR | light detection and ranging |
| LSHB | Lindsey Slough Hastings Bridge |
| Management Strategy | Yolo Bypass Management Strategy |
| MWD7 | Metropolitan Water District Gauge 7 |
| NAD83 | North American Datum 1983 |
| NAVD88 | North American Vertical Datum 1988 |
| NCC | Natomas Cross Canal |

| | |
|---|---|
| NCRO | North Central Regional Office |
| NEMDC | Natomas East Main Drainage Canal |
| NFIP | National Flood Insurance Program |
| NGVD29 | National Geodetic Vertical Datum 1929 |
| NMFS | National Marine Fisheries Service |
| NMFS Operation BO | National Marine Fisheries Service Operation Biological opinion |
| NVCS | National Vegetation Classification System |
| RCS | Ridge Cut Slough |
| RD | Reclamation District |
| RM | River Mile |
| RMSE | root-mean-square-error |
| RPA | Reasonable and Prudent Alternative |
| RTK | Real Time Kinematic |
| SacW | Sacramento Weir option alternative |
| SCWA | Solano County Water Agency |
| SFHA | special flood hazard area |
| SMS | Surface-Water Modeling System |
| SUT | Sutter Bypass |
| SWP | State Water Project |
| SWRCB | State Water Resources Control Board |
| UCS | Upper Cache Slough |
| USACE | US Army Corps of Engineers |
| USGS | United States Geological Survey |
| UTM | Universal Transverse Mercator |
| WLK | Wilkins Slough |
| WSE | water surface elevation |
| WY | water year |

# 1.0 Introduction

## 1.1 Purpose

The purpose of this document is to provide an overview of the hydrodynamic modeling of the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project's Environmental Impact Statement and Environmental Impact Report (EIS/EIR) for Reasonable and Prudent Alternative (RPA) Actions I.6.1 and I.7. RPA I.6.1 and I.7 require creating floodplain habitat and fish passage in the Bypass. The Model was developed primarily for two reasons: 1) to evaluate the ability of project alternatives to create floodplain habitat and improve fish passage within the Yolo Bypass; and 2) to evaluate the relative differences between the alternatives' impacts and benefits on the environment (including flood safety, land use, and other environmental considerations), for EIS/EIR analysis purposes and to inform the selection of a preferred alternative. This report covers model development, calibration, validation, and analysis conducted and presents results based on the hydrodynamic modeling performed on potential alternatives within the Lower Sacramento River Region and Yolo Bypass (Bypass) System. The model will inform evaluations of the impacts and benefits of selected alternatives that have been identified by the Department of Water Resources (DWR) and Bureau of Reclamation (BOR), herein referred to as the Lead Agencies.

## 1.2 Scope

The scope of this hydrodynamic modeling effort was to identify and use appropriate tools to prepare inputs to other models and analyses in order to compare various impacts and benefits of a wide range of alternatives to existing conditions (no action alternative) for the EIS/EIR. Some environmental resources could be affected by changes in the inundation pattern in the Bypass, and the model will help characterize those potential impacts (including, but not limited to potential impacts to fisheries, socioeconomics, agricultural resources, methylmercury, cultural, and terrestrial resources). The intent of this modeling is to learn about how location, size, and timing of operations of gated inundation channels affect these resources. Using this modeling, the impact analyses will help identify refinements that could be made to the initial project alternatives in order to avoid and/or minimize impacts. It will also help identify refinements to alternatives and develop them for further consideration in the EIS/EIR. Key follow-on models that depend on the results of the hydrodynamic model are the Agricultural Economic Impact Analysis and Fish Benefits Simulation Model Analysis. Both of these models required unique hydrodynamic modeling data as inputs. The following requirements and outputs of the hydrodynamic model were scoped out with the help of the teams leading the Agricultural Economic Impact Analysis and the Fish Benefits Simulation Model Analysis:

Fish Benefits Simulation Model Analysis

- Daily results of existing conditions and imposed project conditions from 1997-2012 to overlap a period for which fisheries presence data is available from the Knights Landing Rotary Screw Trap.

- Daily flow, velocity, and depth of the Sacramento River from upstream of the Knight Landing Rotary Screw Trap and downstream of the confluence of Sacramento River and the Yolo Bypass.

- Daily flow, velocity, and depths within the Yolo Bypass and or proposed floodplain inundation location.

Agricultural Economic Impact Analysis

- Geographic Information System (GIS) layers of fields within the project area that will indicate the last day the field was wet under existing conditions and with imposed project conditions.

To meet the demands of the EIS/EIR analyses a 1D/2D hydrodynamic model was created using TUFLOW Classic. Comments received on suggested improvements to previous Bypass modeling efforts were incorporated into the new model as appropriate. The TUFLOW Classic model was used to perform hydrodynamic simulations of a sixteen year period from 1997-2012, with a daily time step, for five different project end dates. The simulation outputs were parsed and presented in different formats so they could easily be inserted into the Agricultural Economic Impact Analysis and the Fish Benefits Simulation Model. The standalone hydrodynamic simulation results are not intended to determine impacts to agricultural yields or benefits received to the targeted species. However, the hydrodynamic simulation results have been summarized in this report.

## 1.3 Background

Significant modifications have been made to the historic floodplain of California‘s Central Valley for water supply and flood damage reduction purposes. The resulting losses of rearing habitat, migration corridors, and food web production for fish have significantly hindered native fish species that rely on floodplain habitat during part or all of their life history. Although the primary function of the Bypass is to receive peak flood flows of Sacramento River Basin water up to 343,000 cubic feet per second (cfs) (DWR 2012b) from Fremont Weir, the Bypass has also been identified by several State and federal entities as a potential site for habitat restoration to ease pressure on and increase benefits to threatened and endangered fish species. The Bypass still retains many characteristics of the historic floodplain habitat that are favorable to various fish species. The Bypass received at least 3,000 cfs and 6,000 cfs for 7 days in approximately 80 percent and 60 percent of years, respectively, between the water years of 1940 and 2011, based on the United States Geological Survey (USGS) Woodland gauge data. Fremont Weir overtopped in approximately 70 percent of years between 1935 and 2012 (DWR 2012b), joining flows from western tributaries.

On June 4, 2009, the National Marine Fisheries Service (NMFS) issued its Biological Opinion and Conference Opinion on the Long-term Operation of the Central Valley Project (CVP) and State Water Project (SWP) (NMFS Operation BO). The NMFS Operation BO concluded that, if left unchanged, CVP and SWP operations were likely to jeopardize the continued existence of four federally-listed anadromous fish species: Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, California Central Valley steelhead, and Southern Distinct Population Segment (DPS) North American green sturgeon. The NMFS Operation BO sets forth RPA actions that would allow continuing SWP and CVP operations to remain in compliance with the federal Endangered Species Act (ESA).

- RPA Action I.6.1: Restoration of Floodplain Rearing Habitat, through the increase of seasonal inundation within the lower Sacramento River basin. The goal of RPA Action I.6.1 is to restore floodplain rearing habitat for juvenile Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, and California Central Valley steelhead in the Bypass by providing floodplain connectivity that will provide physical habitat conditions that will in turn support juvenile growth and mobility, water quality, and the forage necessary to support juvenile development. The planning and environmental compliance process will consider a reasonable range of alternatives as well as potential operations for implementing this RPA action; and

- RPA Action I.7: Reduce Migratory Delays and Loss of Salmon, Steelhead, and Sturgeon, through the modification of Fremont Weir and other structures of the Bypass. The overall goal of RPA Action I.7 is to reduce migratory delays and loss of adult and juvenile Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, California Central Valley steelhead, and Southern DPS of green sturgeon at Fremont Weir and other structures in the Bypass. RPA Action I.7 calls for the provision of a reliable means of fish passage through the Bypass. Reducing stranding by means of improved passage would provide ancillary benefits to fish utilizing the floodplain. Under current conditions, in addition to being unable to reach spawning grounds, fish stranded on the Bypass are vulnerable to illegal harvesting by poachers.

# 2.0 Project Setting

A description of the project setting is provided in the EIR/EIS.

# 3.0 Modeled Alternatives

## 3.1 Introduction to Alternatives

The Lead Agencies used the Federal Principles and Guidelines for Water and Land Related Resources Implementation Studies to evaluate and screen a large number of potential alternatives. Information regarding the alternative screening process will be contained within the final EIS/EIR. Alternative criteria and rating scales were developed with coordination and input from various technical teams. The evaluation criteria are:

- Effectiveness: How well an alternative plan would alleviate problems and achieve objectives.

    1. Increase inundation- Inundation area, duration, and timing corresponding to fish presence and percent of fish entrained onto floodplain.

    2. Fish passage- Effective adult fish passage and safe and timely juvenile fish passage.

- Completeness: Whether the alternative plan would account for all investments or other actions necessary to realize the planned effects.

    1. Improvements to all four focus fish species.

- Acceptability: The viability of a comprehensive plan with respect to acceptance by federal, State, and local entities and compliant with existing laws.

    1. Agricultural impacts- Frequency of inundation during agricultural production periods.

    2. Waterfowl impacts- Inundation of recreational areas, available foraging habitat, and food production.

    3. Education impacts- Inundation of areas used for educational outreach.

    4. Biological impacts- Impacts from construction operation.

    5. Compatibility with other related efforts.

- Efficiency: How well an alternative plan would deliver economic benefits relative to project costs.

    1. Relative benefits and costs.

The Lead Agencies decided to first focus on alternatives that could be implemented to provide seasonal floodplain habitat as required per RPA I.6.1 since these alternatives may have a larger footprint and potential impact when compared to the fish passage alternatives for RPA I.7. In addition, the seasonal floodplain habitat structure for RPA I.6.1 may also serve as the primary fish passage location for compliance with RPA I.7. Therefore, the alternatives described in this report only refer to seasonal floodplain habitat alternatives. Fish passage alternatives and elements for compliance with RPA I.7 will be added to the seasonal floodplain habitat alternatives once additional information regarding gate design and fish behavior becomes available.

After a list of preliminary alternatives was screened against the listed evaluation criteria, a smaller subset of alternatives was carried forward for hydrodynamic analysis and is described in greater detail below. Additional alternatives that may arise and that pass screening may need to be modeled at a later time.

## 3.2 Description of Alternatives

The alternatives consist of different configurations of gates and channels with lower elevations representing “notches” to either Fremont Weir or Sacramento Weir to provide a greater number of juvenile salmonids access to seasonal floodplain habitat in the Bypass. Currently Sacramento River run juvenile salmonids first have access to the Bypass once Sacramento River stage at Fremont Weir is approximately above 32.8 feet North American Vertical Datum 1988 (NAVD88). Sacramento River run juvenile salmonids can also entire the Bypass from Sacramento Weir, which brings flows into the Bypass less frequently than Fremont Weir and typically after Fremont Weir has overtopped (DWR 2012b). By lowering a section of Fremont Weir or Sacramento Weir to allow up to 6,000 cfs to enter the Bypass prior to receiving flows for flood relief purposes, juvenile salmonids will have the opportunity to enter the Bypass earlier and potentially more frequently, thus allowing them to grow at a faster rate than staying in the Sacramento River mainstem where they are subject to predation (Sommer, et al. 2001). The design flow rate was capped at 6,000 cfs through the gated alternatives because this discharge was suggested as a practical limit to balance biological benefits within the overall Sacramento River system (BDCP 2009).

Figure 3-1 illustrates nine potential alignments of alternatives near the Fremont Weir. Only four of these alternatives were selected to be modeled after a screening process. During the screening process it was learned that the alignments on the west side of Fremont Weir and east of the Yolo Bypass would not be cost effective since those alignments go through areas with higher ground elevations resulting in higher construction costs. Based on the assumption that alternatives would behave similarly in capturing water from the Sacramento River and inundation patterns further down the Bypass would be comparable as the modeled flows would not change significantly between alternatives of similar sizes, it was decided that the hydrodynamic performance of alternatives 2a, 2b, 2d, 2e, and 2g could be represented by three alternatives modeled on the east side of Fremont Weir, within the Bypass. The three alternatives to be modeled near the Fremont Weir area are:

Fremont Weir Small – 14.0 feet NAVD88, 20 feet wide bottom width, 3 to 1 horizontal to vertical side slopes

Fremont Weir Medium – 17.5 feet NAVD88, 225 feet wide bottom width, 3 to 1 horizontal to vertical side slopes

Fremont Weir Large – 14.0 feet NAVD88, 225 feet wide bottom width, 3 to 1 horizontal to vertical side slopes

### 3.2.1 No Action Alternative

For the No Action Alternative, water would behave as it has historically with natural overtopping events at Fremont Weir when the stage in Sacramento River allows. The inundation patterns within the Bypass would remain unchanged and behave as they have historically.

### 3.2.2 Alternative 2a-Fremont Weir East Small Gated Notch

For Alternatives 2a, (FreSm), water would be diverted from the Sacramento River through a gated notch in Fremont Weir located near the east end of the weir. The configuration consists of a 20-foot bottom width, with 3:1 (horizontal to vertical) side slopes, and an invert elevation of 14.0 feet NAVD88. This alternative has a significantly smaller cross-sectional area than the other alternatives described below and thus would require a higher river stage to allow 6,000 cfs to entire the Bypass than the other alternatives considered. This alternative was designed to have a narrow configuration to lessen or possible eliminate the need for gate operations to limit flows to 6,000 cfs.

### 3.2.3 Alternative 2b, -Fremont Weir East Medium Gated Notch

For Alternative 2b, 2e, and 2g (FreMed), water would be diverted from the Sacramento River through a gated notch in Fremont Weir located near the east end of the weir. The configuration consists of a 225-foot bottom width, with 3:1 side slopes, and an invert elevation of 17.5 feet NAVD88. Due to the wider configuration of this channel, limiting flows to 6,000 cfs, as the Sacramento River stage rises, would be achieved by opening and closing a series of gates.

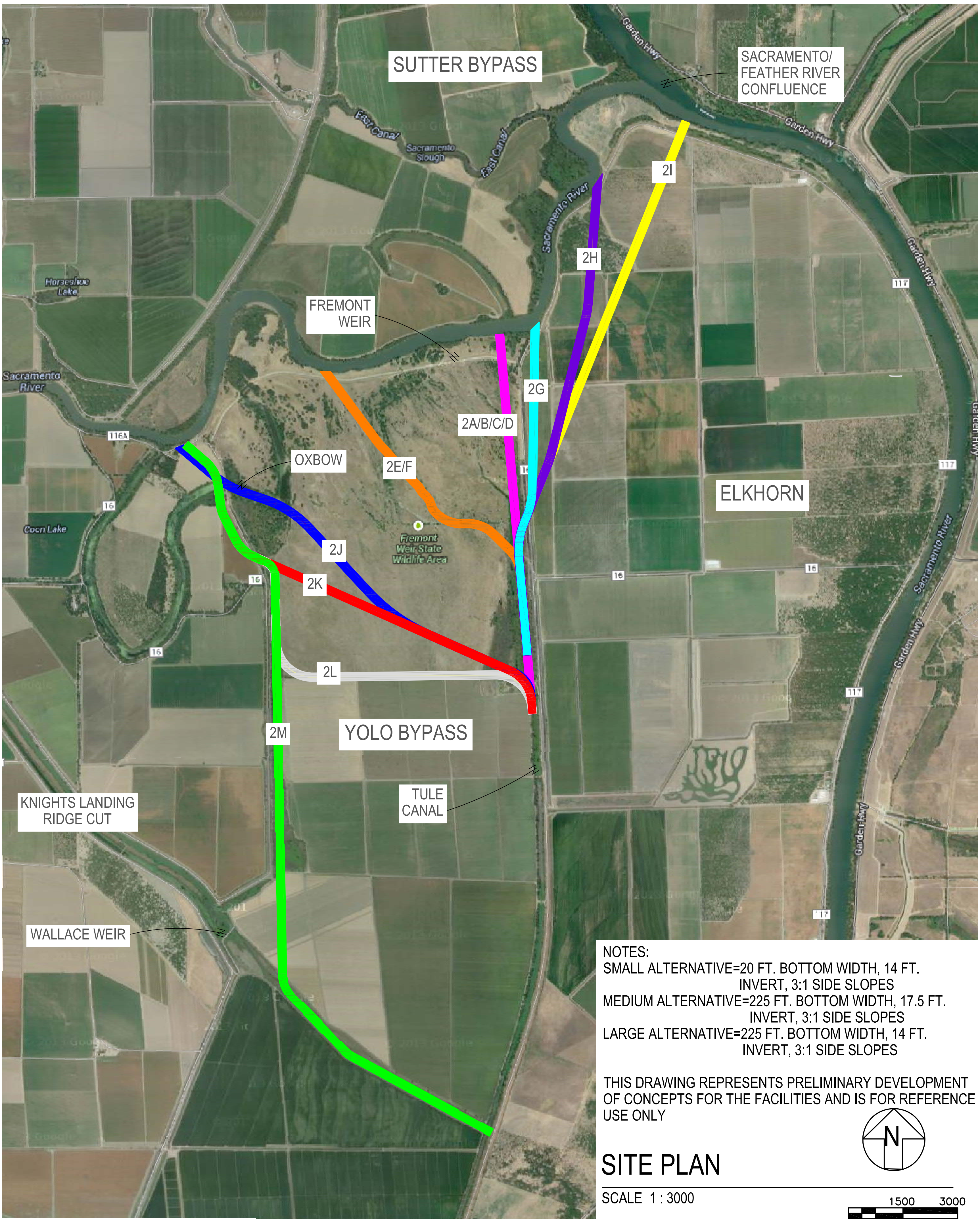
### 3.2.4 Alternative 2d-Fremont Weir East Large Gated Notch

For Alternative 2d (FreLg), water would be diverted from the Sacramento River through a gated notch in Fremont Weir located near the east end of the weir. The configuration consists of a 225-foot bottom width, with 3:1 side slopes, and an invert elevation of 14.0 feet NAVD88. Due to the wider and deeper configuration of this channel, limiting flows to 6,000 cfs, as the Sacramento River stage rises, would be achieved by opening and closing a series of gates.

### 3.2.5 Alternative 5b-Sacramento Weir Gated Notch

For Alternative 5b (SacW), water would be diverted from the Sacramento River through a gated notch in Sacramento Weir. The configuration consists of a 225-foot bottom width, with

3:1 side slopes, and an invert elevation of 7.0 feet NAVD88. Due to the wider and deeper configuration of this channel, limiting flows to 6,000 cfs, as the Sacramento River stage rises, would be achieved by opening and closing a series of gates.




NOTES:
SMALL ALTERNATIVE=20 FT. BOTTOM WIDTH, 14 FT. INVERT, 3:1 SIDE SLOPES
MEDIUM ALTERNATIVE=225 FT. BOTTOM WIDTH, 17.5 FT. INVERT, 3:1 SIDE SLOPES
LARGE ALTERNATIVE=225 FT. BOTTOM WIDTH, 14 FT. INVERT, 3:1 SIDE SLOPES

THIS DRAWING REPRESENTS PRELIMINARY DEVELOPMENT OF CONCEPTS FOR THE FACILITIES AND IS FOR REFERENCE USE ONLY

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## SITE PLAN

SCALE 1 : 3000

1500 3000

## LEGEND

- 2A - SMALL ALTERNATIVE, GATED STRUCTURE ON EAST SIDE OF FREMONT WEIR. CHANNEL AND FOOTPRINT WITHIN YOLO BYPASS.
- 2B - MEDIUM ALTERNATIVE, GATED STRUCTURE ON EAST SIDE OF FREMONT WEIR. CHANNEL AND FOOTPRINT WITHIN YOLO BYPASS.
- 2C - SAME AS 2B WITH SUPPLEMENTAL FLOWS FROM RED BLUFF DIVERISON DAM.
- 2D - LARGE ALTERNATIVE, GATED STRUCTURE ON EAST SIDE OF FREMONT WEIR. CHANNEL AND FOOTPRINT WITHIN YOLO BYPASS.
- 2E - MEDIUM ALTERNATIVE, GATED STRUCTURE NEAR CENTER OF FREMONT WEIR. CHANNEL AND FOOTPRINT LOCATED ON AN OUTSIDE BEND OF THE RIVER, MAY BE ABLE TO CAPTURE MORE FISH AND BRING THEM INTO YOLO BYPASS.
- 2F - LARGE ALTERNATIVE, GATED STRUCTURE NEAR CENTER OF FREMONT WEIR. CHANNEL AND FOOTPRINT LOCATED ON AN OUTSIDE BEND OF THE RIVER, MAY BE ABLE TO CAPTURE MORE FISH AND BRING THEM INTO YOLO BYPASS.
- 2G - MEDIUM ALTERNATIVE, GATED STRUCTURE EAST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE SEGMENT.
- 2H - MEDIUM ALTERNATIVE, GATED STRUCTURE EAST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE SEGMENT.
- 2I - MEDIUM ALTERNATIVE, GATED STRUCTURE EAST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE.
- 2J - MEDIUM ALTERNATIVE, GATED STRUCTURE WEST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE SEGMENT.
- 2K - MEDIUM ALTERNATIVE, GATED STRUCTURE WEST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE SEGMENT.
- 2L - MEDIUM ALTERNATIVE, GATED STRUCTURE WEST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE SEGMENT.
- 2M - MEDIUM ALTERNATIVE, GATED STRUCTURE WEST OF FREMONT WEIR CONNECTING TO TULE CANAL WITH NEW SEGMENT OF LEVEE PARALLEL TO CHANNEL & REMOVAL OF EXISTING LEVEE SEGMENT.

DRAWN BY: JU
CHECKED BY:

SHEET:

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0 1"

DATE: 02.17.2015

FIGURE 3-1

PRELIMINARY ALTERNATIVE ALIGNMENTS
FREMONT WEIR INUNDATION CHANNEL
CONCEPTUAL LAYOUTS

CALIFORNIA DEPARTMENT OF WATER RESOURCES

YOLO BYPASS SALMONID HABITAT
RESTORATION & FISH PASSAGE
3500 INDUSTRIAL BLVD, WEST SACRAMENTO, CA

DEPARTMENT OF WATER RESOURCES STATE OF CALIFORNIA

| REVISION NO. | DATE | DESCRIPTION |
| --- | --- | --- |

# 4.0 Hydrodynamic Model Development

## 4.1 Hydrodynamic Modeling Software Selection

A core hydrodynamic modeling technical team (CHMTT), comprised of representatives from the Lead Agencies and their hydrodynamic modeling team, worked with the fisheries and engineering technical teams to develop ranking methodology for a scoring matrix to select a two-dimensional (2D) hydrodynamic modeling software program. The scoring matrix provides a qualitative evaluation of several modeling software considered for the Bypass modeling and allows for the evaluation and comparison of model software features and considerations. Following the evaluation, the 2D model software programs were ranked by CHMTT. The scoring was subjective and is based upon CHMTT's experiences with the modeling software or based on information from the software vendor's website. The key features and considerations reflected in the ranking process were grouped into the following three categories: Key Model Software Capabilities, Other Considerations, and Optional Model Software Capabilities.

A hydraulic modeling advisory team (HMAT) assembled by the Lead Agencies, including subject matter experts from various agencies, reviewed the ranking methodology, scoring matrix, and the ranking results of the top four ranked 2D modeling software. A blank modeling software scoring matrix was provided to the HMAT members so they could fill-in scores based on their own experiences with the modeling software. The HMAT members were also requested to answer a questionnaire on what modeling software attributes they deemed most important and least important. The model attributes included: performance, cost, public domain, breadth of user base, and model longevity. Based on the information from the scoring matrix and in the supplemental questionnaires, the HMAT members viewed model performance as the most important attribute of a modeling software. The cost and breadth of user base of a modeling software were viewed to be important as well. This information was then provided to the CHMTT for consideration.

TUFLOW was ranked high along with MIKE 21, SRH, and RiverFLO. TUFLOW was chosen due to its high performance, relative low cost, a growing agency user base, GIS interface, and quick run times. TUFLOW, developed by BMT-WBM, was chosen as it scored high in the HMAT rankings and meets the stringent requirements for the project.

### 4.1.1 TUFLOW Yolo Bypass Model

The approach selected was to use a single hydrodynamic model to provide data to evaluate benefits and impacts both within the Bypass and for the larger region. The model includes simulation of existing and proposed alternatives during 16 water years, from the months of October through May, and occasionally to June for water years with May or June Fremont Weir overtopping occurrences. TUFLOW is able to meet the challenges of large computational domains and long simulation times by using a combination of 1D channels and multiple grids of varying resolution and an efficient finite-difference solver. Other aspects of TUFLOW include:

- Solves the full 2D shallow water equations
- Numerically stable even with wetting and drying
- GIS inputs and outputs
- Powerful scenario management options
- Computes flows using weir equations automatically when appropriate
- Support for hydraulic structures including operational controls
- License includes technical support

TUFLOW uses an alternating direction implicit finite difference solution scheme to solve the full 2D free surface shallow water flow equations. More information on the solution scheme is available on the TUFLOW website (www.tuflow.com).

The ability of TUFLOW to simulate a combination of 1D and 2D domains allows for coarser cells in the floodplains while maintaining high resolution in channels and was necessary to keep runtimes reasonable. Internally TUFLOW creates boundary conditions at the 1D nodes and 2D cells along the boundary of the domains. The 1D channel is assigned a flow boundary condition and the 2D cells are assigned specified WSE boundary conditions. All flows entering the boundary 2D cells are fed to the associated 1D nodes. The 1D domain incorporates these flows in its calculations. The computed WSEs at the 1D nodes are interpolated back to the 2D cells. This mass conserving approach to connect domains is robust, stable, and accurate (Syme, 1990, 1991).

As part of the computations, TUFLOW analyzes elevations and WSEs of the 2D cells to determine areas experiencing upstream controlled flow such as would exist at roadway or berm features. The broad-crested weir equation (Equation 1) is used to compute flowrates at these locations. In the equation q represents unit flowrate ($ft^3/s/ft$), g represents gravity (32.2 $ft/s^2$), and H represents the energy head upstream relative to the weir crest (Syme 2001). Weirs become submerged once the downstream H exceeds 0.75 to 0.85 of the upstream H (depending upon the characteristics of the embankment). After the weir becomes submerged the flows are calculated using the shallow water equations.

$$q = \frac{2}{3} H \sqrt{\frac{2}{3} g H} \qquad (1)$$

Additional TUFLOW model parameter values specific to this application are listed in Table 4-1.

*Table 4-1. Additional TUFLOW model parameter values*

| Parameter | | Value |
|---|---|---|
| Time Step | 100-ft grid | 6 s |
| | 200-ft grid | 12 s |
| | 400-ft grid | 12 s |
| | 1D channels | 1.5 s |
| Wet/dry depths | Cell | 0.006562 ft |
| | Cell side | 0.003281 ft |
| | Combination Smagorinsky/Constant (see TUFLOW manual) | |
| Viscosity formulation | Smagorinsky coefficient | 0.6 |
| | Constant viscosity coefficient | 0.55 |

## 4.2 Model Domain

The model domain (see Figure 4-1) extends along the Sacramento River from River Mile (RM) 118 just south of the Tisdale Bypass near Wilkins Slough to RM 12 near Rio Vista and includes the entire Yolo Bypass. River miles are based on the CVFED HEC-RAS model (described later) and are presumably USACE stationing. The domain extends 7 miles to the north along the Feather River and into the Sutter Bypass. The Feather-Sutter boundary was located far enough to the north of the flow split between the Yolo Bypass at Fremont Weir and the Sacramento River at Verona to minimize model boundary effects at the flow split (and the proposed gated channel at Fremont Weir). The domain includes the Sacramento Weir at RM 63 and extends 22 miles to the east along the American River to just below Nimbus Dam. The domain also includes various North Delta sloughs (i.e., Elk, Sutter, Miner, Steamboat, Haas, Cache, Lindsey, and Barker) and a boundary connection with the Delta Cross Channel and Georgiana Slough at RM 27.

The model domain is comprised of a combination of one-dimensional (1D) channels and 2D grids, which assist in overall computational efficiency (see Figure 4-1). The 1D channels describe the flow of water in the major sloughs, creeks, and rivers bordering or bisecting the flood control bypasses and are represented with a series of cross sections (see Section 4.3.3). The 2D grids describe the flow of water within the flood control bypasses when channel capacity is exceeded, flood control weirs are activated, and restricted height levees are overtopped. A 2D grid was also prepared for the section of the Sacramento River between Knights Landing and Verona to accurately describe the complex hydrodynamics that occur during flood conditions as Sacramento River, Sutter Bypass, and Feather River flows converge and are split between the Yolo Bypass at Fremont Weir and the Sacramento River at Verona.

The TUFLOW model includes three separate 2D grids. Multiple grids were used to vary the cell size spatially to balance required resolution and reduced runtimes. Each grid has elevations at each cell centroid, edge mid-point, and cell corner giving nine elevation values per cell. The grid elevations are assigned within the TUFLOW model based upon a Digital Elevation Model (DEM) and modifications to enforce berm and gully features (see Section 4.3.4).

The cell sizes for the grids are 400 feet-, 200 feet-, and 100 feet-square, which provide elevation values every 200 feet, 100 feet, and 50 feet, respectively. The 200 foot grid covers the majority of the 2D domain. The 100 foot grid represents the section of the Sacramento River between Knights Landing and Verona. The 400 foot grid represents Liberty Island.

## 4.3 Geometric Data

Elevation data for the 1D channels and 2D grids were prepared from multiple sources (see Table 4-2 and Figure 4-2). The cross section geometry for the 1D channels were derived from a combination of bathymetric and field surveys. The land surface elevations for the 2D grids were derived largely from light detection and ranging (LiDAR) data. The only exception is that elevations for the 100 foot grid for the Sacramento River between Knights Landing and Verona were prepared with LiDAR for the overbanks and cross section interpolation for the channel due to the absence of detailed multibeam data upstream of Verona.

### 4.3.1 LiDAR

LiDAR data for the Delta and Sacramento valley was collected by DWR (2012a) in 2007 and 2008, respectively, and subsequently processed to create hydro-enforced[1] DEMs at a 3.125 foot horizontal resolution on 5000 foot tiles. For the purposes of this project, the DEM tiles were mosaiced and resampled to a 25 foot DEM to create a manageable DEM to read into TUFLOW. The elevation of each raster cell was an average of the 64 (8 in each direction) overlapping cells in the 3.125 foot DEM. The DEM was subsequently updated with bathymetric data (see Section 4.3.2) for Liberty Island to replace the hydro-enforced water surface and for Prospect Island to fill a data void in the LiDAR.

### 4.3.2 Bathymetry

Bathymetric data was collated from multiple sources and includes a combination of field surveys, single-beam surveys, and multibeam surveys. Multibeam surveys were performed along the Sacramento River between Verona and Clarksburg (DWR 2008a) and between Clarksburg and Walnut Grove (DWR 2010) and were used to describe the below-water portion of 1D cross sections (see Section 4.3.3).

Single-beam surveys augmented with field surveys were performed along multiple channels and were used to describe the below-water portion of 1D cross sections. Liberty Island and adjoining sloughs were surveyed in 2009 by cbec (2011) as part of a modeling study in the Cache Slough Complex. Prospect Island was surveyed in 2011 by WWR (2011) in support of the Prospect Island Tidal Restoration Project. The Tule Canal/Toe Drain north of Lisbon Weir, to include Swanston Ranch check dam (in its degraded condition) was surveyed in 2010 by cbec (2012) as part of a modeling study in the Yolo Bypass. The Tule Canal north of Knights Landing Ridge Cut (KLRC), to include Tule Pond, was surveyed in 2013 by DWR (2013) in

[1] Hydrologic-enforcement (hydro-enforced) of DEMs include modified elevations of artificial impediments (such as road fills or railroad grades) to simulate how man-made drainage structures such as culverts or bridges allow continuous downslope flow.

support of this study. KLRC, Wallace Weir, the three agricultural crossings north of KLRC on the Tule Canal, Swanston Ranch check dam, and Lisbon Weir were surveyed in 2013 by cbec (2014). Putah Creek was surveyed in 2013 by WWR (2013) in support of the Lower Putah Creek Restoration Project. Sacramento Slough and Willow Slough were surveyed by cbec in 2013 as part of this study (see Appendix A). All other channels relied on data collected in 2010 by DWR (2011a).

**Table 4-2. Summary of elevation data sources**

| Coverage Area within Model Domain | Data Source | Year Collected | Method | Stated Accuracy/Resolution | Horizontal Datum | Vertical Datum | Geoid |
|---|---|---|---|---|---|---|---|
| Complete coverage for entire study | **DWR/CVFED LiDAR (DWR 2012a)** | 2008 | LiDAR | Hydro enforced HDEM (3.125ftgrid resolution) | Feet, UTM 10N, NAD83. | FeetNAVD88 | GEOID 03 South Potterfield draft 09 North |
| Sacramento River (Verona to Clarksburg) | **DWR/CVFED Multibeam Bathymetry (DWR 2008a)** | 2008 | Multibeam | 1 m horizontal and ±0.5 ft vertical at 95%; data filtered to 1 m posting on average | Feet, CA State Plane Zone 2, NAD83. | FeetNAVD88 | Not stated |
| Sacramento River (Clarksburg to Walnut Grove) | **DWR/CVFED Multibeam Bathymetry (DWR 2010)** | 2010 | Multibeam | 3 ft horizontal and ±0.5 ft vertical at 95%; data filtered to 3 ft posting on average | Feet, UTM 10N, NAD83. | Feet NAVD88 | GEOID03 |
| Feather R, Sacramento R, Natomas Cross Canal, KLRC, Elk Slough, Steamboat Sl, Miner Sl, Sutter Sl, Georgiana Sl, Lindsey Sl, Cache Sl, Hass Sl, American R, Sacramento Deep Water Ship Channel | **CVFED Single-beam Bathymetry (DWR 2010)** | 2010 | Single-beam | 6 ft horizontal and ± 0.5 ft vertical at 95% for depths < 15 ft; 12 ft horizontal and ± 1 ft vertical at 95% for depths > 15 ft; transects spaced 900 ft to 1800 ft apart | Feet. UTM 10N. NAD83. | Feet NAVD88 | NROS-2 |
| Fremont Weir, Tule Pond, Tule Canal north of KLRC | **DWR Bathymetry (DWR 2013)** | 2013 | Single-beam/RTK | Not stated | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID09 |

| Coverage Area within Model Domain | Data Source | Year Collected | Method | Stated Accuracy/Resolution | Horizontal Datum | Vertical Datum | Geoid |
|---|---|---|---|---|---|---|---|
| Lower Putah Creek within Yolo Bypass Wildlife Area | **WWR Bathymetry (WWR 2013)** | 2013 | Single-beam | ±3ft horizontal, ±0.5ft vertical | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID09 |
| Tule Canal, Toe Drain | **cbec Single-beam Bathymetry (cbec 2012)** | 2010 | Single-beam | ±3ft horizontal, ± 0.5ft vertical | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID09 |
| Knights Landing Ridge Cut | **cbec Bathymetry (cbec 2014)** | 2013 | Single-beam | ±3ft horizontal, ± 0.5ft vertical | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID12a |
| Sacramento Slough, Willow Slough | **cbec Bathymetry (see Appendix A)** | 2013 | Single-beam | ±3ft horizontal, ± 0.5ft vertical | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID12a |
| Liberty island, Little Holland Tract, Toe Drain, Stair Step, Cache Slough, Shag Slough, Prospect Slough, Liberty Cut | **cbec Single-beam Bathymetry (cbec 2011)** | 2009 | Mixed-RTK, Single-beam, Total Station | USACE Class 1 hydrographic survey[1]; transects spaced 300 ft to 1,000 ft apart | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID03 |
| Prospect Island | **WWR Bathymetry (WWR 2011)** | 2011 | Mixed-RTK, Single-beam, Total Station | Not stated | Feet, CA State Plane Zone 2, NAD83. | Feet NAVD88 | GEOID09 |

[1] USACE Class 1 Hydrographic survey:
6 ft horizontal and ± 0.2 ft (± 0.4 ft) vertical at 63% (at 95%) for depths < 15 ft
6 ft horizontal and ± 0.5 ft (± 1 ft) vertical at 63% (at 95%) for depths > 15 ft

### 4.3.3 1D Cross Sections

Cross-sections outside of the Yolo Bypass were trimmed versions of cross-sections obtained from a draft Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS model (CVFED 2013). The cross-sections within the Yolo Bypass were developed for this project based upon elevation and bathymetric data identified in Section 4.3.Both sets of cross sections were prepared from the data described in Section 4.3.1 and Section 4.3.2.

#### 4.3.3.1 CVFED HEC-RAS Derived Cross Sections

The CVFED HEC-RAS model's reaches and cross-sections were converted into TUFLOW channels and cross-sections using a combination of TUFLOW utilities, ArcGIS geo-processing scripts, and manual editing. The cross-sections were trimmed to restrict flows to the area between the levees. The geometry conversion included cross-section geometry, channel alignments, and Manning roughness coefficients. Hydraulic structures such as bridges and piers were not converted and are not represented in the model. In general, most bridges decks are out of the flow field and localized losses from these structures were not significant to capture in a large scale study. Adjustments to Manning roughness coefficients or other modeling parameters during model calibration helped to compensate for losses not captured at structures when looking at far field effects.

Some modifications were made to individual cross-sections to improve numerical stability. Significant differences in cross-section geometry between neighboring cross-sections can be a source of numerical instability unless represented by a hydraulic structure. Large changes in channel inverts can also introduce instabilities particularly during the early (warm-up) portion of the model. To reduce numerical instabilities, especially where neighboring cross-section invert elevations differed significantly, narrow pilot channels were added. The pilot channels were kept narrow to prevent excessive changes to the channel area. The change in channel area for most of the modified cross-sections was less than 3 percent at bank-full conditions.

#### 4.3.3.2 Non-CVFED HEC-RAS Cross-Sections

Non-CVFED HEC-RAS model cross-sections were generally derived from a combination of bathymetric data below the water line and LiDAR data in the overbanks. Cross-sections extracted from the elevation data extended to the crowns of bounding restricted height-features (e.g., KLRC and Putah Creek), or in the case of Tule Canal/Toe Drain, from the east levee crown to the western edge of the riparian zone along the right overbank. Due to riparian or vegetation returns not completely filtered from the LiDAR data, the cross-sections were extended through the riparian zone to the landward edge of the riparian zone to open ground or a visible berm. The purpose of keeping the riparian zone within the 1D channels was to allow flows into the 2D domain at the appropriate water surface elevation (WSE) which is controlled by the 2D cell elevations along the 1D/2D interface.

The locations of extracted cross-sections were carefully chosen along the channels to avoid aquatic vegetation returns in the single-beam bathymetry data. Aquatic vegetation was observed to be especially problematic in the Tule Canal north of KLRC where the water is slow-moving in the summer time and creates ideal growing conditions for aquatic vegetation.

#### 4.3.3.3 Additional Nodal Storage

Within a 1D/2D model, 2D cells within a 1D domain are removed from the 2D domain and 2D cells that intersect the edge of the 1D domain are treated as boundary condition cells as discussed in Section 4.1.1. Storage in the boundary conditions cells are removed from the 2D domain and partially captured in the 1D cross sections for the portion of the 2D cells overlapping the 1D domain. As such, the total storage for the system may be underrepresented in a combined 1D/2D model particularly when using coarse 2D cells and narrow 1D channels as storage for the portion of 2D boundary cells not overlapping the 1D domain is ignored.

In addition, some locations along 1D/2D boundaries within the Yolo Bypass were susceptible to numerical instabilities and created WSE oscillations at high flowrates largely due to the difference in time steps between the 1D and 2D domains. The TUFLOW manual states that adding additional storage to 1D nodes is an acceptable approach to stabilize 1D nodes but may attenuate the model results. Nodal storage was explored using two methods to enhance model stability at 1D/2D interfaces, either specifying a percent increase in nodal volume over the entire flow depth of the cross section or by modifying the cross section geometry at specific elevations. By specifying a percent increase through a storage multiplier, flow attenuation was observed, which led to a preference to apply the latter approach. For example, the cross section geometry of 1D-channels in the Yolo Bypass was modified at specific locations along the 1D/2D interface for elevations above the elevation of the 2D floodplain to limit the influence of nodal storage to higher Yolo Bypass discharges.

Widening cross-sections to provide additional storage helped to minimize instabilities at 1D/2D boundaries. Points were added to the end of the cross-sections. The first point added to the cross-section was assigned an elevation one foot higher than the highest endpoint elevation so new storage would be limited to floodplain flows. The last point added to the cross-section was assigned an elevation 15 ft higher than the first point so the maximum additional storage would only be realized in very large floods. The cross-sections that were widened are shown in Figure 4-3.

In addition to widening cross-sections, some 1D nodes were assigned storage multipliers as shown in Figure 4-4. Nodes were assigned additional storage because they encountered instabilities due to transitions between 1D/2D domains, proximity to hydraulic structures, or were connected to narrow channels perpendicular to floodplain flows (e.g., Putah Creek).

Adding additional storage has the potential to attenuate flood hydrographs. This was minimized by limiting storage multipliers to select locations and limiting the majority of added storage after reaching flood stage. A cross-section with an original width of 300 ft is widened to 600 ft gradually increasing the storage after the floodplain was activated. The calibration models verify that the storage changes do not significantly attenuate flood hydrographs.

### 4.3.4 Adjustments to Geometry

The Yolo Bypass includes many features, such as roads, field berms, ditches, drains, and culverts, that impact how water moves through the Bypass. A complete accounting for all such features is beyond the scope of this analysis but significant features were included that influence wetting and drying of the floodplain. To represent these features in TUFLOW, the crown and thalweg profiles of berms (road and field berms) and gullies (ditches and drains) were restamped into the sampled DEM to overcome data loss and surface smoothing when resampling to a coarser resolution (e.g., 200 foot grid).

The berm features were originally delineated in GIS using an automated method that was adapted for this project. The delineation approach was based upon the hydrology GIS tools for delineating streams after inverting the DEM elevations to make berm features appear like channel features. The delineation process included an automated cleanup step that removed minor berms. The automated method correctly identified significant berms, but did not always capture complete berms, often leaving gaps in the berms. Figure 4-5 shows the automated delineation results for a section of the Bypass around Interstate 80 (I-80).

During the 2010 low-flow and 2011 flood-recession calibrations, the wetting and draining of Yolo Bypass were evaluated by modifying the berm density, adding drainage features, and analyzing the elevations along the 1D/2D interface. Relative to the 200-foot grid cell size, capturing all of the interior field berms (e.g., rice checks internal to field units) proved to significantly affect field-by-field drainage by ponding shallow water for too long. As such, the field berms were limited to those berms and road features along the field perimeters.

It was further determined that primary drainage features external to the fields were needed to drain the individual fields to allow ponded water to enter/exit the Tule Canal/Toe Drain and/or westside canals. In lieu of detailed cross-section information describing the numerous drainage features and hydraulic structures (e.g., culverts, flap gates, pumps), primary irrigation supply and drainage features within the Yolo Bypass were digitized (see Figure 4-6), whereby elevations were assigned from the native 3.125 foot hydro-enforced DEM. Due to grid cell size constraints, the digitized drainage features were 200-foot-wide rectangular channels with channel inverts often derived from ponded water elevations within the LiDAR. To offset the overly wide drainage features and lack of flow impediments along their length, layered flow constrictions were implemented in TUFLOW at the drainage feature connections along the Tule Canal/Toe Drain, where hydraulic structures exist, to partially restrict conveyance into and off of the Yolo Bypass. In addition, small drainage ditches connecting the field interiors to the primary drainage features, often via small culverts, were created by adding 600-foot-long drainages that cut a 200-foot-wide swath across the field perimeter features (see Figure 4-6).

The final drainage feature that was evaluated was the 1D/2D interface (TUFLOW HX boundary) between the Tule Canal/Toe Drain and Yolo Bypass. The HX boundary was digitized along the landward edge of the riparian zone in open ground (typically north of I-80) or on top of a visible berm (typically south of I-80). Due to the potential of an agricultural berm being obscured within the riparian corridor north of I-80, the HX boundary elevations along the Tule Canal were tested by raising the HX elevations a maximum of two feet between the drainage feature connections. The tests revealed that there were insignificant changes in the water surface profiles along the Tule Canal/Toe Drain, thus there was no need to refine the HX boundary.

### 4.3.5 Horizontal and Vertical Datum

All of the model data is referenced to the horizontal North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) Zone 10. The input and output elevations are referenced to NAVD88.

Some small pockets of supplemental bathymetric and topographic data collected over the years for various projects were incorporated into the CVFED LiDAR data for the hydrodynamic modeling efforts. Based on a conference call with the CVFED LiDAR contractors, it was agreed that as long the data to be stitched into the CVFED LiDAR data set was in vertical datum NAVD88, it could be inserted directly into the LiDAR set without any GEOID conversions.

## 4.4 Hydrological Data

Long term daily average hydrologic data was prepared for water years 1997 through 2012 to serve as upstream boundary conditions for the TUFLOW model while the downstream boundary was 15-minute tidally driven stage. Data collection and estimation efforts relied on:

- Readily available flow or stage data at the stream gauges along the waterways to be modeled. The gauge information was compiled from a variety of sources such as USGS, California DWR, BOR, County of Sacramento, and Solano County Water Agency (SCWA).
- Where data was not available, flows were estimated using computer/spreadsheet models, estimation techniques, or information in previous studies.

Table 4-3 provides a list of boundary conditions and summarizes data sources used to obtain flow and stage data. Figure 4-1 shows the extents of the hydrodynamic model domain and boundary locations that informed the model.

*Table 4-3. Summary of model boundary condition data*

| Boundary Location | Data Source | Data type[2] |
|---|---|---|
| **Upstream Boundaries** | | |
| Sacramento River inflow below Wilkins Slough near Grimes | USGS 11390500 | Gauged flow |
| Knights Landing Outfall Gates inflow | DWR A02945 | Gauged flow |
| Feather River and Sutter Bypass inflows | This study[1] | Estimated flow based on data from USGS 11390500, USGS 1142500, A02930, A02945, Arcade Creek/EMC02 gauges |
| Natomas Cross Canal inflow | This study[1] | Estimated flow based on data from Arcade Creek/EMC02 gauge |
| Sacramento Weir inflow | USGS 11426000 | Gauged flow |
| **Westside Tributaries** | | |
| Knights Landing Ridge Cut inflow | DWR A02930 and this study[1] | Gauged flow and estimated flow based on data from A02976, A02945 and A02930 gauges |
| Cache Creek Settling Basin inflow | This study[1] | Estimated flow based on data from USGS 11452500 gauge |
| Willow Slough Bypass inflow | Yolo Bypass Management Strategy | Estimated flow |
| Putah Creek inflow | Yolo Bypass Management Strategy | Estimated flow based on BOR reservoir operations data |
| **American River** | | |
| American River inflow | USGS 11446500 | Gauged flow |
| Steelhead Creek (formerly called Natomas East Main Drainage Canal) inflow | This study[1] | Estimated flow from City of Sacramento's Arcade Creek/EMC02 gauge |
| **Delta Sloughs** | | |
| Delta Cross Channel and Georgiana Slough outflow | DWR's Dayflow program | Gauged flow and estimated flow |
| Haas Slough, Cache Slough, Barker Slough, and Calhoun Cut | This study[1] | Estimated flow based on data from DWR's UCS and BKS and SCWA's DOP and LSHB gauges |
| North Bay Aqueduct | DWR's Dayflow program | Gauged flow and estimated flow |

| Boundary Location | Data Source | Data type[2] |
|---|---|---|
| **Downstream Boundary** | | |
| Rio Vista downstream stage | DWR B91212 | Gauged stage[3] |
| Notes:<br>[1] Estimated as a part of the current study and largely relying on verification of local gauge records and extrapolation for the period of analysis<br>[2] Time series data for daily flows (in cfs) and stages (in feet, NAVD88) were compiled in HEC-DSS, converted to an hourly time step to maintain daily average conditions in TUFLOW, and exported to CSV.<br>[3] Rio Vista stage is in feet, USED prior to October 1, 2005; and feet, NAVD88 thereafter. | | |

### 4.4.1 Modeling Period of Record

The Fremont Weir overtopping events were initially gauged in 1968, which is also after the majority of the major reservoirs in the Sacramento River watershed were in operation, providing 44 years of comparable hydrology data through 2012 (CALFED 2001). In order to reduce model runtimes to a reasonable level (not excessively long) and to be consistent with the period when fisheries data is available for the fish benefits model, it was decided to model the 16 year period from water year 1997 through water year 2012. This period has a similar breakdown of water year types based upon a water-year classification system that provides a means to assess the amount of water originating in a hydrologic basin.

The Sacramento Valley 40-30-30 Index was developed by the State Water Resources Control Board (SWRCB) for the Sacramento hydrologic basin as part of SWRCB's Bay-Delta regulatory activities. The classification system defines:

- one "wet" year classification
- two "normal" classifications (above and below normal)
- and two "dry" classifications (dry and critical)

Using the classification standard recognized by SWRCB, a comparison of classifications for the 44years versus the 16years was performed and the results are shown in Figure 4-7.

As seen in Figure 4-7, the 16 years of data selected resemble a similar classification as the 44 years of historical data since Fremont Weir overtopping has been measured, suggesting that using the 16 years of data provides an appropriate surrogate for the longer term record. Also, using the most recent 16 years of hydrology data would reflect recently built structures and recent operations of the system as well as relatively recent climate trends.

For consistency with the fish benefits model and for efficiency, using the most recent 16 years of data across multiple analysis processes was preferred.

### 4.4.2 Boundary Locations

The following sections describe in greater detail the source data for the boundary locations summarized in Table 4-3. Source data based on direct use of published gauge data are described in brevity whereas source data based on estimation techniques applied in this analysis are described at length.

### 4.4.3 Sacramento River Near Grimes

Daily inflows along the Sacramento River below Wilkins Slough near Grimes were obtained from USGS stream gauge 11390500. This location is also just downstream of the Tisdale Bypass which diverts nearly half of the flood waters from the Sacramento River into the Sutter Bypass.

### 4.4.4 Knights Landing Outfall Gates

Daily inflows from Colusa Basin Drain to the Sacramento River via Knights Landing Outfall Gates (KLOG) were obtained from DWR's Water Data Library gauge A02945.

### 4.4.5 Feather River and Sutter Bypass

Due to the absence of flow gauges along the Feather River (FEA) and Sutter Bypass (SUT) in the vicinity of their confluence (see Figure 4-8), daily flows were estimated using the following mass balance relationship at their confluence (Method #1) based on gauge data downstream of their confluence (see Area #1 in Figure 4-8):

$$(FEA + SUT)_1 = (VON + FRE) - (WLK + KLOG + NCC)$$

where:

- $(FEA + SUT)_1$ are the summed daily flow at the Feather River and Sutter Bypass confluence for Area #1 (see Figure 4-8)
- VON are the daily flows for the Sacramento River at Verona obtained from USGS gauge 11425500
- FRE are the daily flows for Fremont Weir Spill into Yolo Bypass obtained from DWR's Water Data Library gauge A02930 until September 2003 and from DWR's California Data Exchange Center gauge FRE from October 2003 to September 2012.
- WLK are the daily inflows for the Sacramento River below Wilkins obtained from USGS gauge 11390500 and translated to Verona using a time delay of one day. The time delay was based on a typical flow velocity of 2.5 feet per second (fps) as derived from the CVFED HEC-RAS model.
- KLOG are the daily inflows from Colusa Basin Drain to the Sacramento River via Knights Landing Outfall Gates obtained from DWR's Water Data Library gauge A02945.
- NCC are the daily flows for Natomas Cross Canal as estimated from Steelhead Creek (formerly known as Natomas East Main Drainage Canal [NEMDC]) flows, which are discussed in Section 0 in more detail.

The estimated daily flows for the Feather River (FEA) and Sutter Bypass (SUT) using Method #1 were validated using the following mass balance relationship (Method #2) based on gauge data upstream of their confluence (see Area #2 in Figure 4-9):

$$(FEA + SUT)_2 = (GRL + MRY + BRW) + (BSL + TIS)$$

where:

- $(FEA + SUT)_2$ are the summed daily flow at the Feather River and Sutter Bypass confluence from Area #2 (see Figure 4-9)
- GRL are the daily flows for the Feather River at Gridley obtained from DWR's Water Data Library gauge A05165. The flows were translated using a time delay of 1 day based on a typical flow velocity of 3.0 fps derived from the Lower Feather River Corridor Management Plan (cbec 2013).
- MRY are the daily flows for the Yuba River near Marysville obtained from USGS gauge 11421000. The flows were translated using a time delay of 0.5 days based on a typical flow velocity of 3.5 fps derived from the Lower Feather River Corridor Management Plan (cbec 2013).
- BRW are the daily flows for the Bear River near Wheatland obtained from USGS gauge 11424000. The flows were translated using a time delay of 0.5 days based on a typical flow velocity of 2.5 fps derived from the Lower Feather River Corridor Management Plan (cbec 2013).
- BSL are the daily flows for Butte Slough near Meridian on the Sutter Bypass obtained from DWR's Water Data Library gauge A02972. The flows were translated using a time delay of 1 day based on a typical flow velocity of 2.0 fps derived from the Lower Feather River Corridor Management Plan (cbec 2013).
- TIS are the daily Tisdale Weir spills into the Sutter Bypass near Grimes obtained from DWR's Water Data Library gauge A02960. The flows were translated using a time delay of 0.5 days based on a typical flow velocity of 2.0 fps derived from the Lower Feather River Corridor Management Plan (cbec 2013).

Daily flows from Wadsworth Canal to Sutter Bypass were not accounted for during the flow validation as flow data was not available. Figure 4-9 presents the time series comparison of estimated daily flows at the Feather River and Sutter Bypass confluence using the mass balance methods described above. Figure 4-10 shows a scatter plot of the estimated flows shown on Figure 4-9. Given the potential uncertainty in gauged flows (i.e., rating curve error and hysteresis, lack of gauged inflows for Wadsworth Canal, and inflow estimation for Natomas Cross Canal) and simplified routing (i.e., translation) for purposes of these calculations, it is shown that Method #1 reasonably predicts the inflow at the Feather/Sutter model boundary as validated by Method #2. Method #1 inflows will be used in the TUFLOW model because it directly uses measured flows at Fremont Weir and Verona. However, the flow split between the Feather River and Sutter Bypass will be based on Method #2.

### 4.4.6 Steelhead Creek

Steelhead Creek was formerly known as the Natomas East Main Drainage Canal (NEMDC). Two stream gauges (see Figure4-11), one along Steelhead Creek and one at the confluence of Arcade and Steelhead creeks, were used to generate daily flows along Steelhead Creek to the Sacramento River. While the City of Sacramento operates these stream gauges, the long-term data is maintained by the County of Sacramento. The gauge along Steelhead Creek (NEMDC [C04]) is located just upstream of the West El Camino Avenue bridge and is the most downstream gauge with stage data and measured flows from the entire watershed. However, the stage data appears unreliable due to no observed stage variation even during known storm events. Therefore, the gauge at the confluence of Steelhead and Arcade creeks (Arcade Creek/EMD C02), located approximately 0.6 miles upstream of NEMDC (C04), was used for developing daily flows for Steelhead Creek. This gauge had two sensors that recorded stage: sensor 1691 located on the Arcade Creek side of the levee crossing and sensor1692 located on the Steelhead Creek side of the levee crossing.

DWR's Division of Environmental Service (DES) has evaluated and computed Steelhead Creek daily flows for a water quality investigation study (DWR 2008b) from July 2001 to December 2006. The study found that the real time stage data for the Arcade Creek gauge correlated very closely with the Steelhead Creek gauge at the West El Camino Avenue Bridge leading to the development of an equation that relates the two stage datasets. The study also developed a stage-discharge rating curve that can be used to convert computed stage data at Steelhead Creek gauge to flows.

The rating curve developed in the water quality investigation study was limited to a stage of 25.5 feet, which corresponds to a flow of 6,024 cfs. cbec extended the rating curve to include flows for higher stages based on the historic peak flows developed by US Army Corps of Engineers (USACE) for the American River Watershed Common Features Project for Natomas Basin (USACE 2010). The estimated peak flows and 5-day volumes for four events during the time period of interest are summarized in Table 4-4. Peak flows for the New Years 1997, February 1998 and New Years 2006 storm events were used to extend the rating curve using stage data estimated based on Arcade Creek stage as discussed before. Other events were excluded due to the lack of stage data. Figure 4-12 shows the updated rating curve for Steelhead Creek. Table 4-5 summarizes the data used to develop daily time series flows for Steelhead Creek.

The Arcade Creek stage data from both the sensors was not reported for the following periods:

- February 1997
- August- September 1997
- January - May 2001
- August - September 2008
- mid August - September 2012

The flows for the periods above were set to an observed minimum flow of 23.8 cfs. This is a valid assumption during low flow periods of August to September 1997, August to September 2008 and mid-August to September 2012. For the remaining periods, flows generated from rainfall events are likely underestimated using this simplistic assumption but they were also set to 23.8 cfs for this analysis.

The flows along Steelhead Creek will likely be influenced by backwater from high flows in the Sacramento River. The potential impact of backwater effects in estimating daily flows was not refined as part of this analysis.

*Table 4-4. Peak flows and 5-day volumes for Natomas Cross Canal to Steelhead Creek for historic floods*

| Tributary | Area (ac) | | Feb 1986 | Jan 1995 | NY 1997 | Jan 1997 | Feb 1998 | NY 2006 | Avg |
|---|---|---|---|---|---|---|---|---|---|
| Steelhead Creek (NEMDC) | 188.32 | 5-day vol (ac-ft) | 58,300 | 45,700 | 27,500 | 41,600 | 37,500 | 27,600 | --- |
| | | Peak flow (cfs) | 14,060 | 17,840 | 8,470 | 11,300 | 11,050 | 10,860 | --- |
| Natomas Cross Canal (NCC) | 288.22 | 5-day vol (ac-ft) | 89,800 | 72,900 | 42,500 | 54,300 | 49,500 | 35,000 | --- |
| | | Peak flow (cfs) | 30,700 | 43,000 | 16,100 | 23,200 | 20,800 | 21,300 | --- |
| Ratio | 1.53 | | 1.54 | 1.60 | 1.55 | 1.31 | 1.32 | 1.27 | **1.43** |

*Table 4-5. Data used for generating daily flows along Steelhead Creek*

| Time Period | Data Available | Source |
|---|---|---|
| October 1996 – December 2000 | Recorded stage (ft, NGVD 29) for the sensor 1691[1,2] | Sacramento County Department of Water Resources |
| January 2001 – December 2006 | Computed daily flows along the Steelhead Creek[2,3] | DWR's Municipal Water Quality Investigations Section |
| January 2007 – September 2012 | Recorded stage (ft, NGVD 29) for the sensor 1692 | Sacramento County Department of Water Resources |

Notes:
[1] Stage data at sensor 1691 was found to be unreliable for the time period. Therefore, stage data at sensor 1692 was used instead.
[2] The recorded stage was first converted to stage at NEMDC (C04) using published correlation and then converted to flows using the updated rating curve.
[3] Computed flow data for stages exceeding 25.5 ft was replaced using the updated rating curve (this study).

### 4.4.7 Natomas Cross Canal

As detailed in Section 4.4.6, the American River Watershed Common Features Project for Natomas Basin (USACE 2010) provides peak flows and 5-day volumes during historic floods. Ratios of 5-day volumes for Natomas Cross Canal to Steelhead Creek were computed and summarized in Table 4-4. Using an average scaling factor of 1.43, the NCC daily flows were derived as follows:

NCC = 1.43 x NEMDC

### 4.4.8 Westside Tributaries

The Yolo Bypass receives its primary inflows from four major tributaries separate from the Fremont Weir and the Sacramento Weir:

- Knights Landing Ridge Cut
- Cache Creek Settling Basin
- Willow Slough Bypass
- Putah Creek

As part of the Yolo Bypass Management Strategy (Management Strategy) prepared by Jones & Stokes (2001), measured and estimated hydrology for the flood control weirs and Westside tributaries was compiled for water years 1968 through 1998. cbec extended this data set through water year 2012 using measured data and refinements to the Management Strategy flow estimation techniques (this study). Refinements to the estimated flows for the Westside tributaries (see Figure 4-13) are discussed in the following sections.

#### 4.4.8.1 Knights Landing Ridge Cut

Gauged flow data for Ridge Cut Slough at Knights Landing (RCS) is available starting December 7, 2006 from DWR's Water Data Library for gauge A02930. This data was used to develop daily flows through water year 2012. However, due to lack of gauged data for prior years, those flows had to be estimated. One option for estimating KLRC flows was to use the current equation described in the Management Strategy. Per the Management Strategy, daily KLRC inflow to the Yolo Bypass was estimated by subtracting outflows from Colusa Basin Drain to the Sacramento River via the KLOG as measured by gauge A02945, from gauged flow for Colusa Basin Drain at Highway 20 (CDR) per gauge A02976 that was scaled up to account for the entire watershed area. This daily calculation is only performed if the rainfall rates at Colusa exceed 0.3 inches per day; otherwise the estimated KLRC inflow value falls to zero (Jones & Stokes 2001). The rainfall data used was obtained from the California Irrigation Management Information System (CIMIS) Colusa station. The calculation procedure is represented using the following logic.

If: rainfall rates at Colusa CIMIS station > 0.3 inches per day,
Then: Estimated KLRC daily inflow = (130.4/107.7)* $CDR_{obs}$ - $KLOG_{obs}$
Else: Estimated KLRC daily inflow = 0

The second option involved the development of a new regression equation based on correlation between gauged flows at Colusa Basin Drain near Highway 20 (A02976) and estimated daily flows just upstream of the Colusa Drain split to Ridge Cut Slough computed as sum of gauged flows at KLOG (A02945) and RCS (A02930), referred herein as (RCS + KLOG). The flows along Colusa Drain during non-wet season are influenced by the Davis Weir and agricultural water uses (typically April 1 to mid-October). Therefore, only the wet season flows (November 1 to March 31) were used for the analysis. A time delay of 1 day between Highway 20 and KLRC was incorporated into the CDR flows for comparison to the RCS + KLOG flows. The time delay was based on a typical flow velocity of 2.5 fps as derived from the CVFED RAS model.

Figure 4-14 shows the scatter plot of estimated daily flow at the Colusa Basin outlet (RCS + KLOG)$_{pred}$ to the flow at Highway 20 (CDR). This figure indicates a strong correlation for the lower flows with a weaker correlation for higher flows due to greater hysteresis. The RCS gauge manager revealed that the rating curve for the RCS gauge was based on measured flows within the channel of up to 1,600 cfs and extrapolated for higher flows that flow over the banks onto the floodplain. Two power curves were fitted to the data, one representing flows less than 3,400 cfs at CDR and one for flows greater than 3,400 cfs. The transition between the two curves corresponds to RCS channel capacity of 1,600 cfs. The equations are provided on Figure 4-14. Daily inflows to KLRC prior to December 2006 were computed as follows:

$$\text{KLRC} = (\text{RCS} + \text{KLOG})_{pred} - \text{KLOG}_{obs}$$

Figures 4-15,4-16, and 4-17 compare the KLRC inflows estimated for water years 2010, 2011, and 2012 using the Management Strategy (option 1) and the new regression equation (option 2). The new equation provides a better estimate of the low flows entering the Yolo Bypass from the Colusa Basin via KLRC during the wet season that would otherwise default to zero inflow per the Management Strategy in the absence of rainfall. As such, the new regression equation will be used to estimate KLRC inflows to the Yolo Bypass prior to December 2006 and RCS observed flows will be used post December 2006.

#### 4.4.8.2 Cache Creek Settling Basin

As described in the Management Strategy, inflows to the Yolo Bypass from Cache Creek are gauged by the USGS near Interstate 5 at long-term gauging station Cache Creek at Yolo (USGS ID 11452500 [CDEC ID: CCY]). While the Management Strategy notes that no significant tributaries or diversions exist downstream of this gauge, the timing and magnitude of inflows to the Yolo Bypass are likely affected by storage in the Cache Creek Settling Basin (CCSB) located adjacent to the western edge of the Yolo Bypass.

Therefore, the flows measured at CCY were transformed with basic routing to account for storage and attenuation in the CCSB. The storage routing was performed in this study using a HEC-HMS (HMS) model developed to represent CCSB and its outlet works consisting of an overflow weir and low flow outlet. The storage-volume curve and overflow weir geometry were based on the CVFED HEC-RAS model. cbec surveyed the upstream sill elevation for the low flow outlet works while the downstream invert elevation was based on Cache Creek Settling Basin Final General Design Memorandum (USACE 1987).

The tailwater of the low flow outlet will be influenced by an incised channel downstream of the outlet works. The incised channel has a scour pool followed by a shallow earthen sill at elevation 18.3 feet NAVD88 that could create a tailwater pool for the low flow outlet. In the absence of floodplain inundation in the Yolo Bypass exceeding this elevation, the tailwater pool affects outflow from the CCSB low flow outlet works. Tailwater stage for the low flow outlet was therefore assumed to be the higher of the sill elevation or the stage at Yolo Bypass Woodland as determined from measured flow and a rating curve at USGS gauge 11453000.

Limited validation of the modeled outflows was conducted by comparison to observed inflow into the CCSB using USGS gauge 11452600 and observed total outflow from the CCSB using USGS gauge 11452901 (which was installed in February 2009). Figures 4-18, 4-19 and 4-20 show a comparison of the gauged inflows, gauged outflows, and the modeled outflows for rainfall events in 2009, 2010, and 2011, respectively. These figures demonstrate that the HMS model of the CCSB does reasonably attenuate inflows through the CCSB. Peak inflows during larger rainfall-runoff events are reduced as they pass through the CCSB and smaller rainfall-runoff events are stored and slowly released into the Yolo Bypass.

#### 4.4.8.3 Willow Slough Bypass

The equations from the Management Strategy were used to estimate Willow Slough Bypass daily inflows. As described in the Management Strategy (Jones & Stokes 2001), Willow Slough has not been gauged during the historical record. Instead, historical hydrology was estimated by correlating Willow Slough flow with gauged runoff in the Interdam Reach (between Lake Berryessa and Lake Solano) of Putah Creek adjusted for drainage area. The daily flows were computed through water year 2012.

#### 4.4.8.4 Putah Creek

The equations from the Management Strategy were used to estimate Putah Creek daily inflows. The Management Strategy estimated inflows to the Yolo Bypass from Putah Creek are based on release and spill at Monticello Dam and Putah Diversion Dam. During times of no active rainfall-runoff (Condition 1), or if Monticello Dam is spilling (Condition 3), inflow to the Yolo Bypass equals Putah Diversion Dam releases minus 30 cfs for seepage and evapotranspiration losses. When there is active rainfall-runoff (Condition 2), defined as Interdam Runoff in excess of 100 cfs, then inflow to the Yolo Bypass equals two times the Putah Diversion Dam releases minus 30 cfs to account for losses. The Management Strategy provides a more detailed discussion of these assumptions.

Interdam Runoff is defined as the difference between (a) Berryessa release plus spill and (b) Putah Diversion Dam release after diversion to the Putah South Canal. The daily flows were computed through the water year 2012.

It is noted that the low flow gauges managed by SCWA were reviewed, but not used. The gauges are typically used to monitor summer irrigation flows and to check that Putah Creek Accord flow requirements are being met. Flows are not rated higher than 100 cfs and the gauges are typically removed from the creek in the winter time.

### 4.4.9 American River

Daily inflows to the American River below Nimbus Dam were obtained from USGS gauge 11446500.

### 4.4.10 Delta Cross Channel and Georgiana Slough

DWR's Dayflow program provides the most accurate daily estimates for cross-Delta flows out of the Sacramento River through Delta Cross Channel and Georgina Slough. Dayflow data was developed using measured flow at USGS gauges installed in December 2002 and January 2003, along the Delta Cross Channel and Georgiana Slough and empirical relationships for non-recorded periods and prior years.

### 4.4.11 Delta Sloughs and North Bay Aqueduct

Delta sloughs boundaries consist of inflows at Haas Slough and Upper Cache Slough on the Cache Slough system and Campbell Lake and Calhoun Cut at Highway 113 on the Lindsey and Barker Slough (BKS) system (see Figure 4-21).

The net daily flows for Haas Slough, Upper Cache Slough, Campbell Lake, and Calhoun Cut were estimated using mass balance of observed flow data on Upper Cache Slough at DWR gauge UCS, Lindsey Slough at Hastings Bridge at SCWA gauge Lindsey Slough Hastings Bridge (LSHB), Barker Slough Doppler Station at SCWA gauge Doppler (DOP), and Barker Slough Pumping Plant at DWR gauge BKS. Observed flow was tidally filtered using a Godin (1972) filter prior to mass balance computations. UCS net daily flow was split equally between Upper Cache Slough below Ulatis Channel and Hass Slough. Campbell Lake net daily flow was computed as the difference in net daily flow between DOP and BKS. Calhoun Cut net daily flow was computed as the difference in net daily flows computed for LSHB and DOP.

The gauge data for LSHB and DOP was available from February 2, 2007 and July 11, 2006, respectively, and was obtained from SCWA. The LSHB data was subject to an update in the velocity rating on April 22, 2011. Data prior to this revision exhibited a strong negative flow that indicated that Calhoun Cut was abstracting water from the system. Hence, only the data following the update was used for estimation purposes. The gauge data for UCS was available from June 21, 2008 and was obtained from DWR's North Central Regional Office (NCRO). The gauged data for BKS was available from October 1, 2007 and was obtained from CDEC.

Sinusoidal curves were used to replicate the general pattern of the tidally filtered flows as shown in Figure 4-22. The daily flow data generated using the fitted sinusoidal curves was used for time periods prior to gauge installation and to fill in missing data. The estimated daily flows are shown in Figure 4-23.

### 4.4.12 Rio Vista Tides

Sacramento River at Rio Vista serves as the downstream model boundary. Daily mean stage and 15-minute stage data for the Sacramento River at Rio Vista were obtained from DWR gauge B91212. The stage datum is in NAVD88 starting October 1, 2005. Prior to October 1, 2005, the stage data is in USED datum; however, a gauge height correction (NAVD88 = USED - 0.6 feet) was not applied. Sensitivity analysis was performed and demonstrated that the uncorrected gauge height had an insignificant affect on the model results (i.e., last day wet (LDW) and wetted area) within the Yolo Bypass (see Section 6.2).

## 4.5 Hydraulic Structures

The TUFLOW model contains several hydraulic structures within the Yolo Bypass including the Fremont and Sacramento Weirs, Swanston Ranch check dam, three agricultural crossings along the Tule Canal, and some crossings with culverts along Willow Slough Bypass as shown on Figure 4-24. For the road and railroad bridges, the bathymetry at the bridge, including the channel and embankment, was included. The piers and bridge decks were not included due the relatively small hydraulic effects anticipated from these structures. The majority of the bridges do not become submerged even in the largest events modeled. Based upon the bridge definitions in the HEC-RAS model, the bridge along Country Road 22 which passes over the Tule Canal (bridge #22C0053, just north of the I-5 Bridge) is submerged during large flood events. When the bridge is submerged, the roadway is overtopped which conveys the majority of the flow. Upstream of this bridge is a railroad bridge that becomes submerged in the 1997 water year but not in other years. This has little impact on the results because County Road 22 is the controlling hydraulic feature for the area.

The model has also been calibrated to higher Sacramento River discharges in the absence of including bridge structures in the model along the Sacramento River. Bridges were omitted from the Sacramento River portion because they were not expected to have a significant impact on the results within the Yolo Bypass. However, the presence of bridges was partially accounted for by the addition of local energy losses during calibration. Because the model is being used for comparative purposes, the omission of the details describing the bridge structures will not significantly affect the model outcomes.

### 4.5.1 Fremont Weir

The Fremont Weir was included explicitly in the model. The crest elevations assigned along the alignment of the weir were derived from the highest LiDAR elevations within a 20-foot radius of the weir alignment. In this way, if the dirt road to the immediate north of and paralleling the weir was higher than the weir, then the dirt road at discrete locations would control overtopping conditions versus the crest elevations of the weir. TUFLOW automatically checks for the presence of weir flow and computes flows based upon the weir equation as appropriate as discussed in Section 4.1.1.

### 4.5.2 Sacramento Weir

The Sacramento Weir is comprised of 48 gates that are manually opened during large flood events allowing flows from the Sacramento and American Rivers into the Bypass. The Sacramento District of the USACE defined guidelines regarding how the gates should be operated during flood events (USACE 1955). The pertinent guidelines are included in Appendix B. The gates are opened after the I Street gauge (approximately 1000 feet upstream from the I Street Bridge) reaches a stage of 30.04 feet NAVD88. The number of gates opened varies but enough should be opened to maintain a water surface elevation of less than 31.54 feet NAVD88 at the I Street gauge. The gates may be closed after the stage drops below 27.54 feet NAVD88 at the Sacramento Weir. The guidelines state that the gates should be closed within as short as period as practicable. Because the Sacramento Weir is operated manually, the DWR has to decide when to open the gates, how many to open, and when to close the gates. These decisions may be influenced by river stage forecasts, time of day, and other factors. TUFLOW cannot replicate this decision making process. Rules were defined for opening and closing the gates that are implemented consistently for all of the model runs (described below).

Within the TUFLOW model, the Sacramento Weir discharge is determined by a rating curve provided by the DWR based upon the upstream stage and number of open gates (see Appendix B). When the water surface elevation at the I Street gauge exceeds 30.04 feet NAVD88 12 gates (one-quarter of them) are opened. This continues until all of the gates are open. All of the gates are closed simultaneously when the water surface elevation at the Sacramento Weir drops below 27.54 feet NAVD88.

### 4.5.3 Lisbon Weir

Lisbon Weir is an irrigation supply feature on the Toe Drain just south of Putah Creek that creates a backwater pool to meet irrigation demands within the Yolo Bypass Wildlife Area. The structure consists of a rock weir with a crest elevation ranging from 5.0 to 6.5 feet NAVD88 and three steel flapgates to the immediate west of the rock weir. The 4- by 3-foot flap gates trap water behind the weir to an elevation of 4.5 feet, which corresponds to the top of the flap gate structure, whereby excess water drains back out overtop the flap gates on the ebb tide. After major flood events, the rock weir is rebuilt by reclaiming rock with an excavator from the pool downstream of the weir. However, every 4 to 5 years the rock weir is built back up with new rock. The weir and tide gate geometry was determined by field survey (cbec 2014).

### 4.5.4 Swanston Ranch Check Dam

The Swanston Ranch check dam is a temporary agricultural crossing that impounds water in the Toe Drain for water supply diversions (see Figure 4-24). It consists of three culverts, one (1) six foot open culvert and two (2) four foot culverts with boards at the intakes, and earth fill.

The earth fill is removed prior to the wet season. The check dam was modeled in its degraded condition based on elevations acquired during a single-beam bathymetric survey (cbec 2012).

### 4.5.5 Agricultural Crossings

Three agricultural crossings exist on the Tule Canal north of the KLRC (see Figure 4-24). The northern crossing at the downstream end of Tule Pond is an earthen berm that serves to impound water as supply to Reclamation District (RD) 1600 within the Elkhorn Basin on the east side of the levee. The middle crossing is about 0.5 miles downstream, consists of an earthen berm and a single 32-inch culvert, and is well travelled. The southern crossing is another 0.6 miles south, consists of an earthen berm and three 24-inch culverts, provides a right of way, and is primarily used by operations on the Sacramento River Ranch east of the levee. The culvert sizes and inverts were determined by field survey (cbec 2014).

### 4.5.6 Weir Culverts along Willow Slough

Within the Yolo Bypass, Willow Slough is a dual purpose drainage and irrigation supply feature. There are a series of eight 48-inch and one 30-inch culverts that provide primary access across the slough on the west side of the Yolo Bypass (see Figure 4-24). There is also a water control feature along the slough midway into the Yolo Bypass with one 48-inch and one 30-inch culverts. The culvert sizes and inverts were determined by multiple field surveys (cbec 2014; this study).

## 4.6 Surface Roughness

Manning roughness coefficients were prepared for the Sacramento River Valley based on detailed medium scale vegetation mapping digitized at a scale of 1:2000 (see Figure 4-25 and Table 4-6. Medium scale vegetation mapping roughness reclassification was prepared by California State University, Chico, as part of riparian mapping projects for the Central Valley (DWR 2011b) and Sacramento–San Joaquin River Delta (CDFG 2007) using the National Vegetation Classification System (NVCS). The Manning roughness coefficients are presented in Table 4-6. Medium scale vegetation mapping roughness reclassifications are regionally calibrated values derived from the Lower Feather River Corridor Management Plan (MBK 2011) and the Yolo Bypass (USACE 2007). Both sources use RMA-2 models calibrated to the 1997 flood event, which were originally developed by relating the NVCS categories to vegetation type characteristics, and using aerial imagery and engineering judgment.

Medium scale vegetation mapping roughness reclassifications were initially assigned to the 2D grids and non-CVFED cross-sections. For CVFED cross-sections, the Manning roughness coefficients were derived from the values assigned in the CVFED RAS model. Manning's n-values for the CVFED cross-sections were changed to improve calibration during the 1997 high flow calibration. In the Feather River, Manning's n-values were increased with a 1.2 multiplier. In the Sacramento River between Verona and Courtland, Manning's n-values were decreased with a 0.85 multiplier.

*Table 4-6. Medium scale vegetation mapping roughness reclassification for 2D grids*

| Map Unit | National Vegetation Classification System | LFRCMP (MBK, cbec)/ Yolo Bypass (USACE) | Manning Roughness Coefficients | |
|---|---|---|---|---|
| | | | Previous Studies | Calibrated Values |
| AGR | Agriculture | Agricultural fields | 0.030 | 0.031 |
| BGS | Barren | Gravel bar/sand bar | 0.035 | 0.036 |
| CAI | Mediterranean California naturalized annual and perennial grassland | Perennial grassland | 0.030 | 0.036 |
| CFG | California annual forbgrass vegetation | Perennial grassland | 0.030 | 0.031 |
| CSS | Central and south coastal California seral scrub | Upland scrub | 0.055 | 0.057 |
| CXC | Californian xeric chaparral | Upland scrub | 0.055 | 0.057 |
| DIV | Western North American Freshwater Marsh | Reeds, tules, bulrushes, cattails | 0.050 | 0.052 |
| ECW | Californian evergreen coniferous forest and woodland | Dense riparian forest | 0.080 | 0.082 |
| FAV | Western North American Freshwater Aquatic Vegetation | Open water | 0.030 | 0.031 |
| FEM | Arid West freshwater emergent marsh | Reeds, tules, bulrushes, cattails | 0.050 | 0.056 |
| FOR | Temperate Flooded and Swamp Forest | Open riparian forest | 0.050 | 0.052 |
| IMF | Introduced North American Mediterranean woodland and forest | Dense or Open riparian forest | 0.080, 0.050 | 0.082 |
| MAC | Introduced North American Mediterranean woodland and forest and Southwestern North American Riparian, Flooded and Swamp Forest/Scrubland | Open riparian forest | 0.050 | 0.052 |
| NRW | Naturalized warm-temperate riparian and wetland | High herbaceous marsh | 0.055 | 0.055 |
| RES[1] | Barren | Perennial grassland | 0.030 | 0.031 |
| RIS | Southwestern North American introduced riparian scrub | Himalayan blackberry scrub | 0.045 | 0.046 |
| RWF | Riparian Evergreen and Deciduous Woodland | Dense riparian forest | 0.080 | 0.082 |
| RWS | Southwestern North America riparian wash/scrub | Upland scrub | 0.055 | 0.056 |
| SSB | Southwestern North American salt basin and high marsh | Reeds, tules, bulrushes, cattails | 0.050 | 0.051 |

| Map Unit | National Vegetation Classification System | LFRCMP (MBK, cbec)/ Yolo Bypass (USACE) | Manning Roughness Coefficients | |
|---|---|---|---|---|
| | | | Previous Studies | Calibrated Values |
| TBM | Temperate Pacific tidal salt and brackish meadow | Reeds, tules, bulrushes, cattails | 0.050 | 0.051 |
| UNK[2] | NA | Dense riparian forest | 0.080 | 0.082 |
| URB | Urban | Rural / Developed | 0.030 | 0.031 |
| VPB | Californian mixed annual/perennial freshwater vernal pool/swale/plain bottomland | Perennial grassland | 0.030 | 0.031 |
| VRF | Vancouverian riparian deciduous forest | Dense riparian forest | 0.080 | 0.082 |
| WAT | Riverine | Open water | 0.030 | 0.034 |
| WCM | Western Cordilleran montane-boreal summer-saturated meadow | Reeds, tules, bulrushes, cattails | 0.050 | 0.051 |
| WDT | Western dogwood thicket | Dense willow scrub | 0.065 | 0.066 |
| WTM | Californian warm temperate marsh/seep | Perennial grassland | 0.030 | 0.031 |
| WVO | Californian broadleaf forest and woodland | Dense riparian forest | 0.080 | 0.082 |

Notes:
[1] Vegetation characteristics were not available. Review of aerial images indicated that the vegetation was grasslands.
[2] No NVCS description was provided for map unit UNK. Review of aerial image showed dense tree growth indicating dense riparian forest.

## 4.7 Assumptions/Limitations

This modeling effort is based upon several assumptions, including:

- The 1997-2012 timeframe provides reasonable boundary conditions for comparison purposes. Potential long term hydrology changes due to climate changes or other diversions were not considered.
- The preliminary gate/channel designs are similar enough to eventual proposed designs to provide an appropriate and effective relative comparison of the alternatives.
- The 1D modeling assumptions and limitations, especially uniform flow in the channel direction, are satisfactory for areas modeled using 1D domains.

- Areas represented by 2D domains are adequately represented using depth-averaged assumptions that do not capture 3D velocity gradients and associated losses.

For all of the alternatives, the discharges through the gates were capped at 6,000 cfs before Fremont Weir overtopping to be consistent with prior BDCP efforts (BDCP 2009). The FreSm alternative was modeled with gates that opened and closed to maintain 6,000 cfs but the preferred design would include gates that are fully open or closed. Changes to these or other gate design and operation parameters may modify the project benefits and impacts.

The long time frame simulated and the inclusion of several alternatives constrained the model to use large cell sizes. The model solution is adequate for the defined goals of the analysis which are to provide water levels and velocities and to compare inundation areas, but may not be appropriate for all purposes. The model resolution within the 2D domains is too coarse to evaluate flows around and through small features.

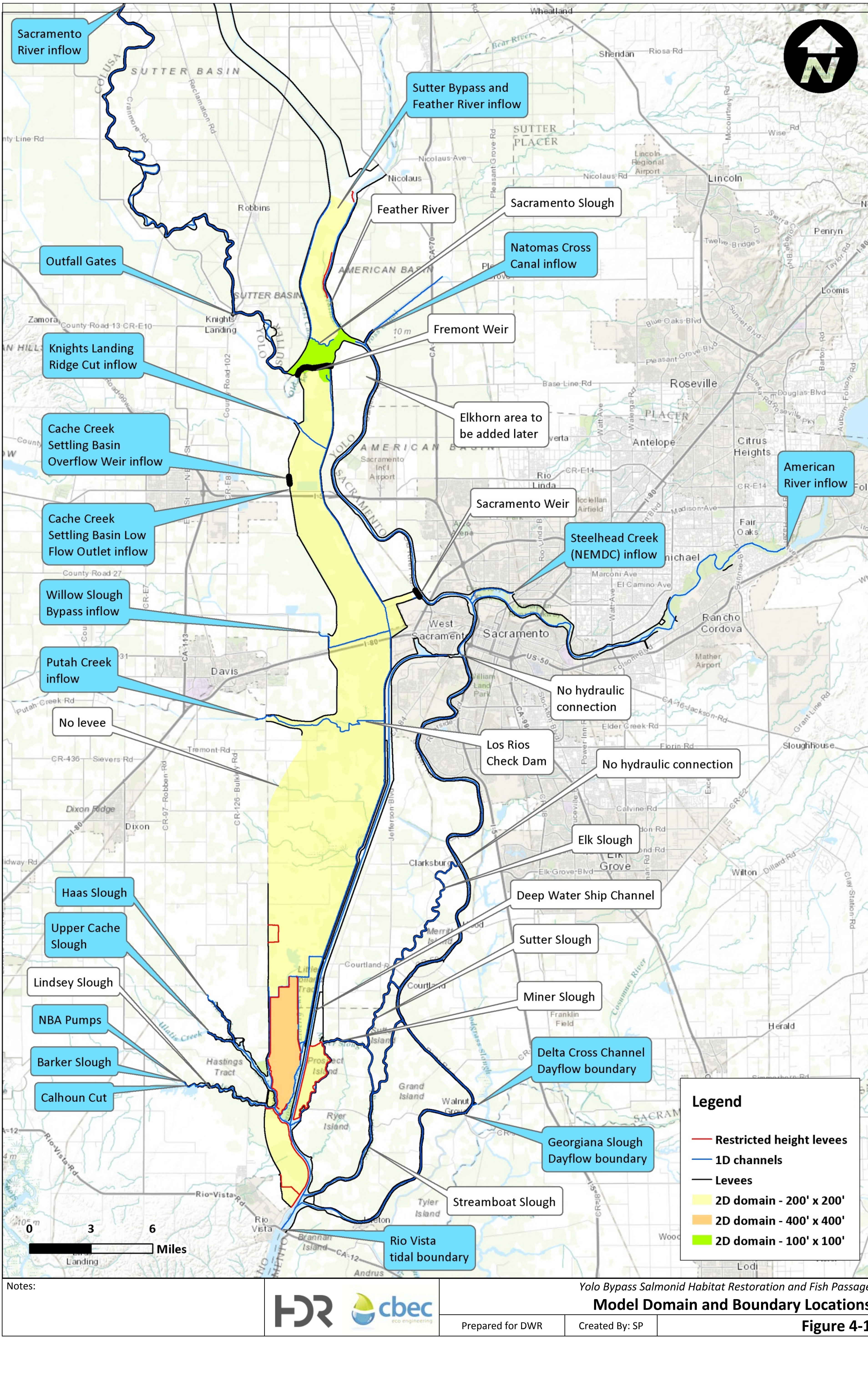
Bridge piers and decks are not included in the model so local flow patterns and energy losses may not be accurately represented in these areas. The Manning roughness coefficient changes to improve model calibration help compensate for losses not captured at structures when looking at far-field effects.

While attempts were made to capture major drainage features within the basin, modeling all drainage features was not practical. Minor drainage features such as ditches, culverts, and field drain check structures are unmapped and numerous. In addition field drain structures may change from year to year.

The model uses the most up-to-date and available topography and bathymetry but some improvements could be made. LiDAR has the ability to capture bare earth elevations in the presence of vegetation within most of the domain. However, LiDAR is unable to penetrate thick vegetation such as in the riparian zones along the Toe Drain/Tule Canal resulting in erroneous elevation data. The effects along the Toe Drain/Tule Canal were minimized by keeping these areas within the 1D domain. Had these areas been represented in 2D the vegetation returns in riparian areas may have prevented flow conveyance from the channels to the floodplain. Because flows between the 1D and 2D domains are controlled by the 2D elevations, inaccurately high elevations do not prevent floodplain inundation. Sensitivity analyses concluded that a minor berm within the riparian zone did not have a significant effect on the model results (see Section 5.4.2).

Model inflows for the Westside tributaries represent the best available information. Model inflows for KLRC and Cache Creek were developed based on regression techniques developed as part of this study. These are a significant improvement over the Management Strategy approaches as KLRC and Cache Creek, relative to Willow Slough Bypass and Putah Creek, provide the most inflow to Bypass. Model inflows for Willow Slough Bypass and Putah Creek were extended through water year (WY) 2012 based on Management Strategy approaches.

Willow Slough is ungauged and a better approach for estimating Putah Creek inflows was not discovered.




Notes:

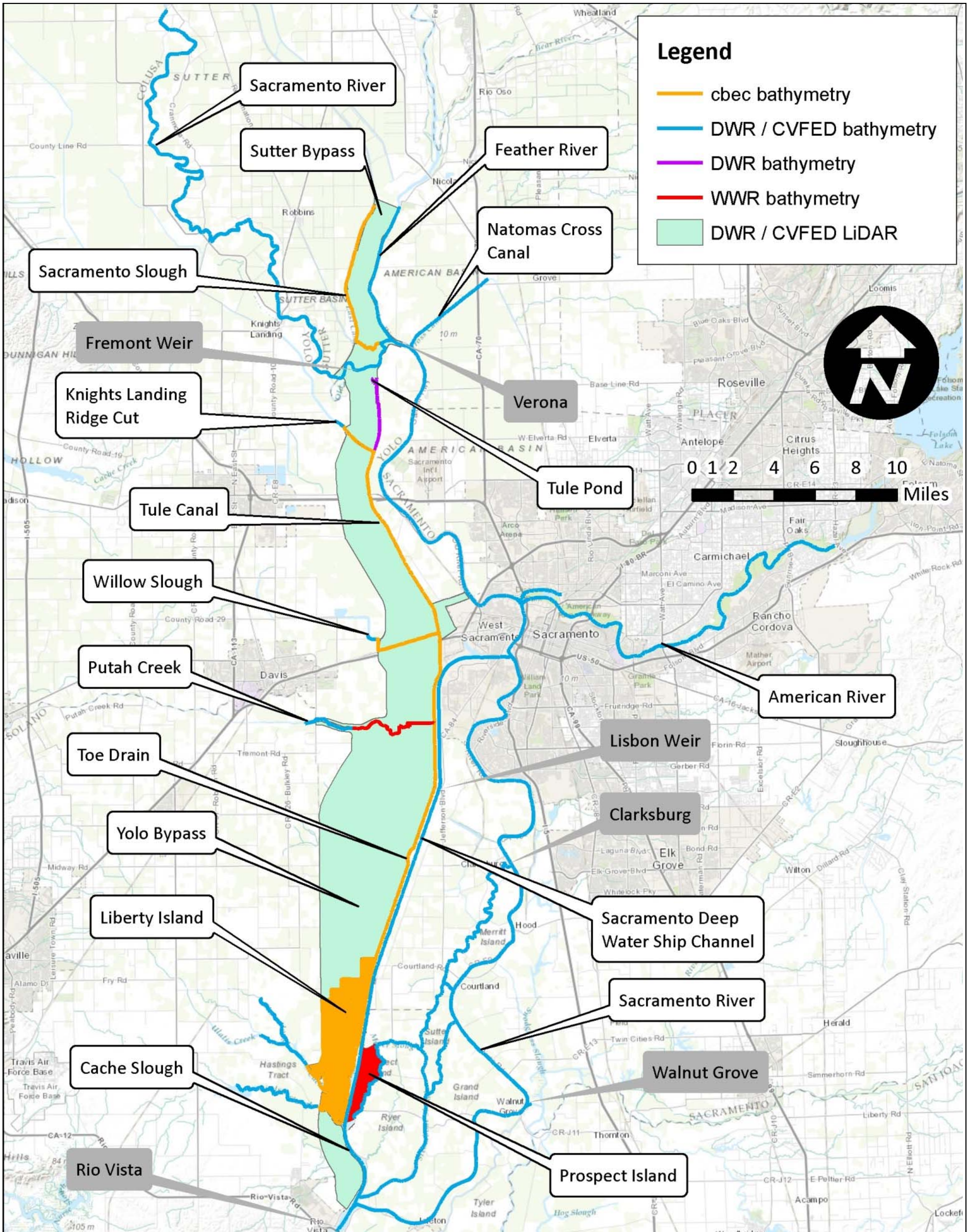
HDR cbec eco engineering

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Model Domain and Boundary Locations**

Prepared for DWR | Created By: SP

**Figure 4-1**

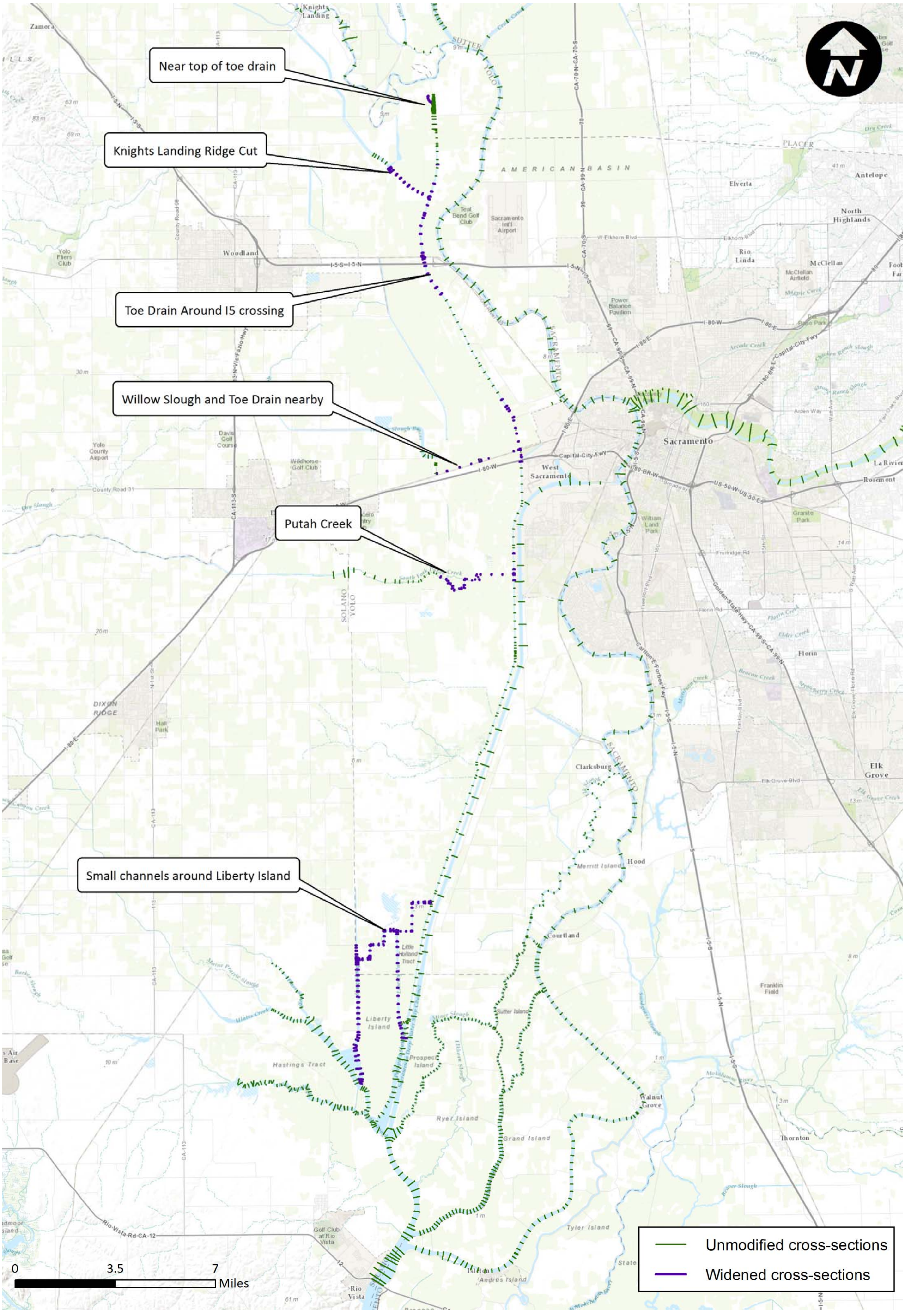



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Geometric Data Sources**

Prepared for DWR | Created By: BT | **Figure 4-2**



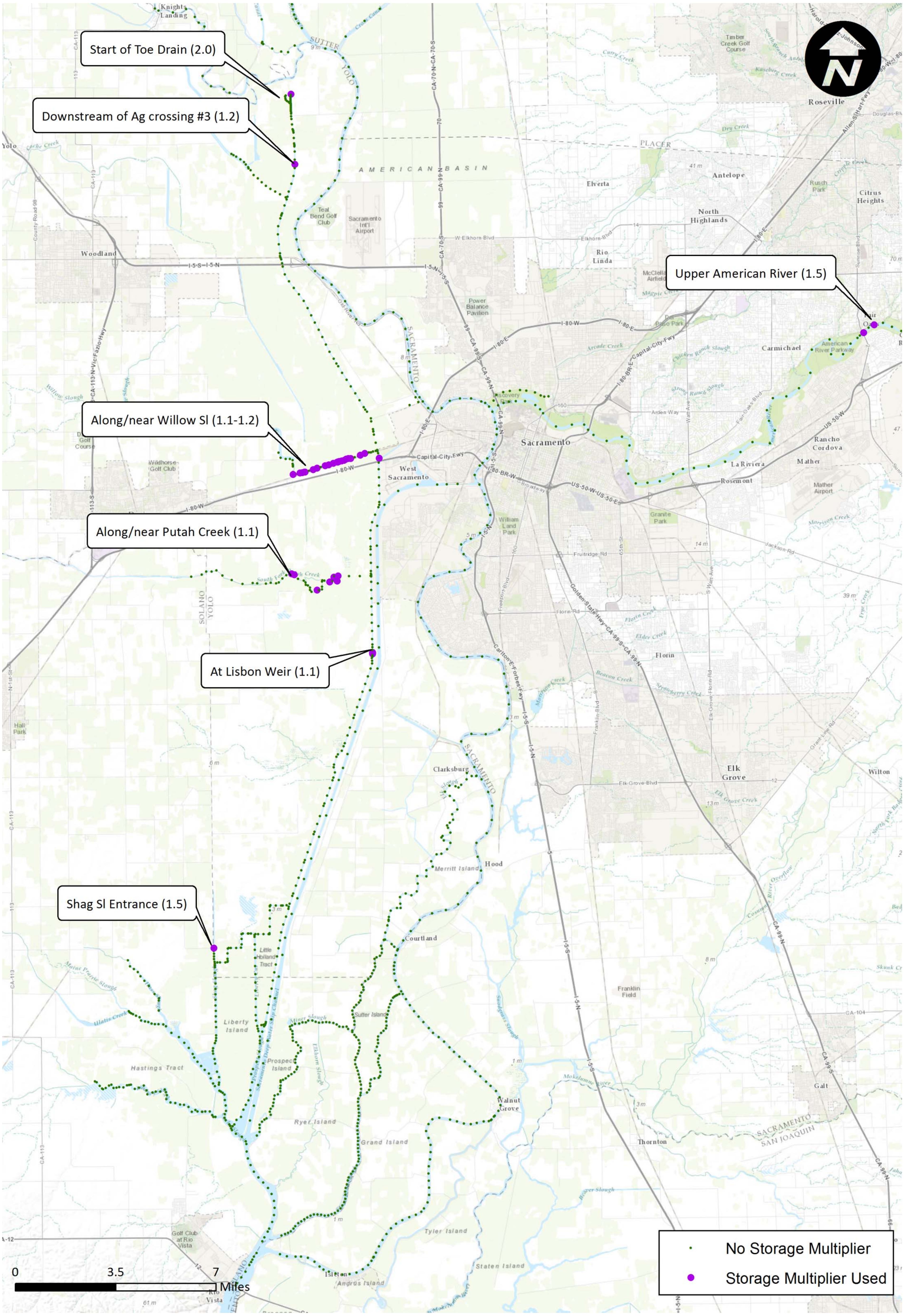

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Widened Cross-sections**

Prepared for DWR | Created By: RDJ

**Figure 4-3**




Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Storage Multipliers at 1D Nodes**

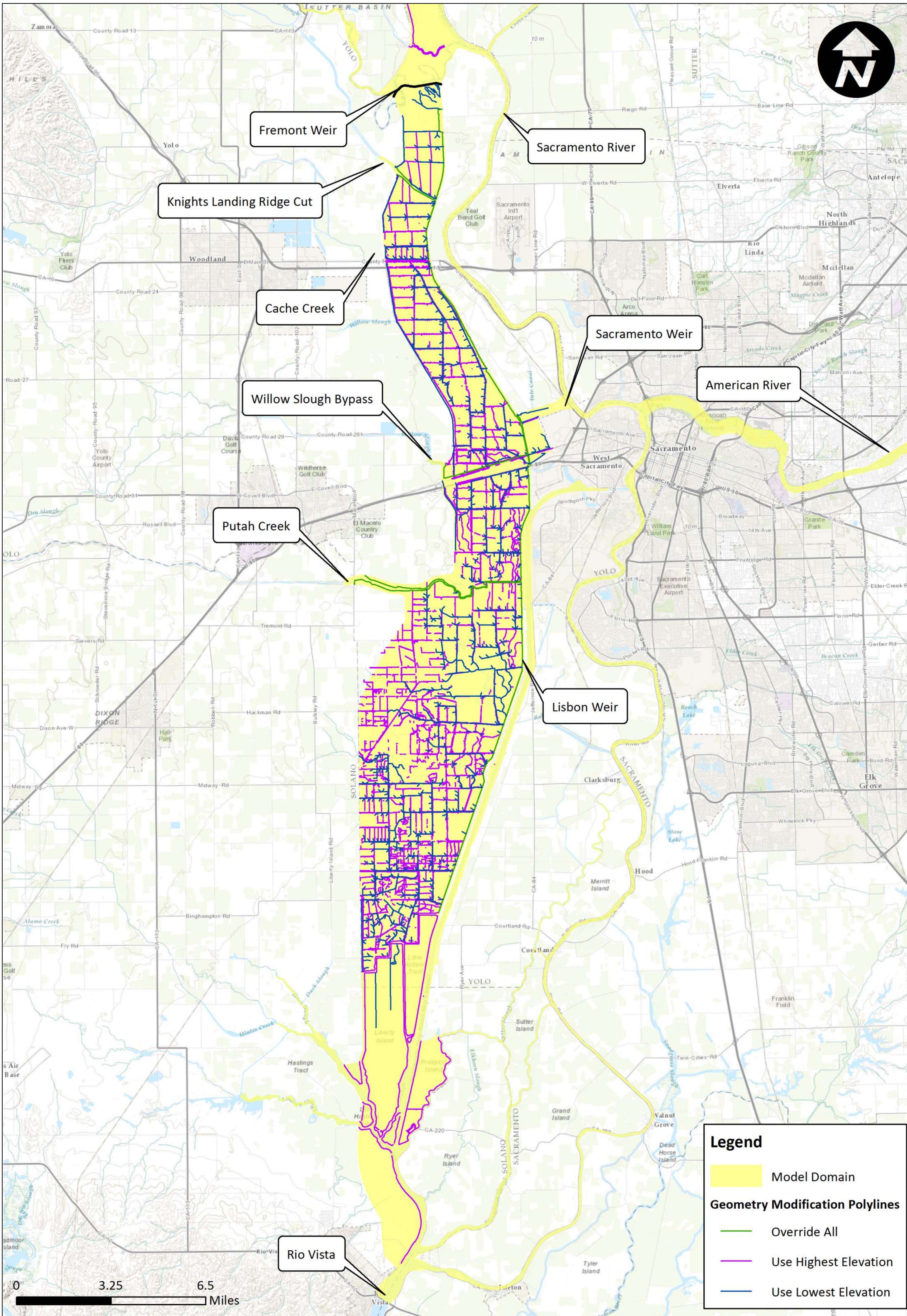
Prepared for DWR | Created By: RDJ | **Figure 4-4**


Notes: Showing one tile of several that were processed using GIS utilities

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Automatically Generated Berm Features**

Prepared for DWR | Created By: RDJ | **Figure 4-5**

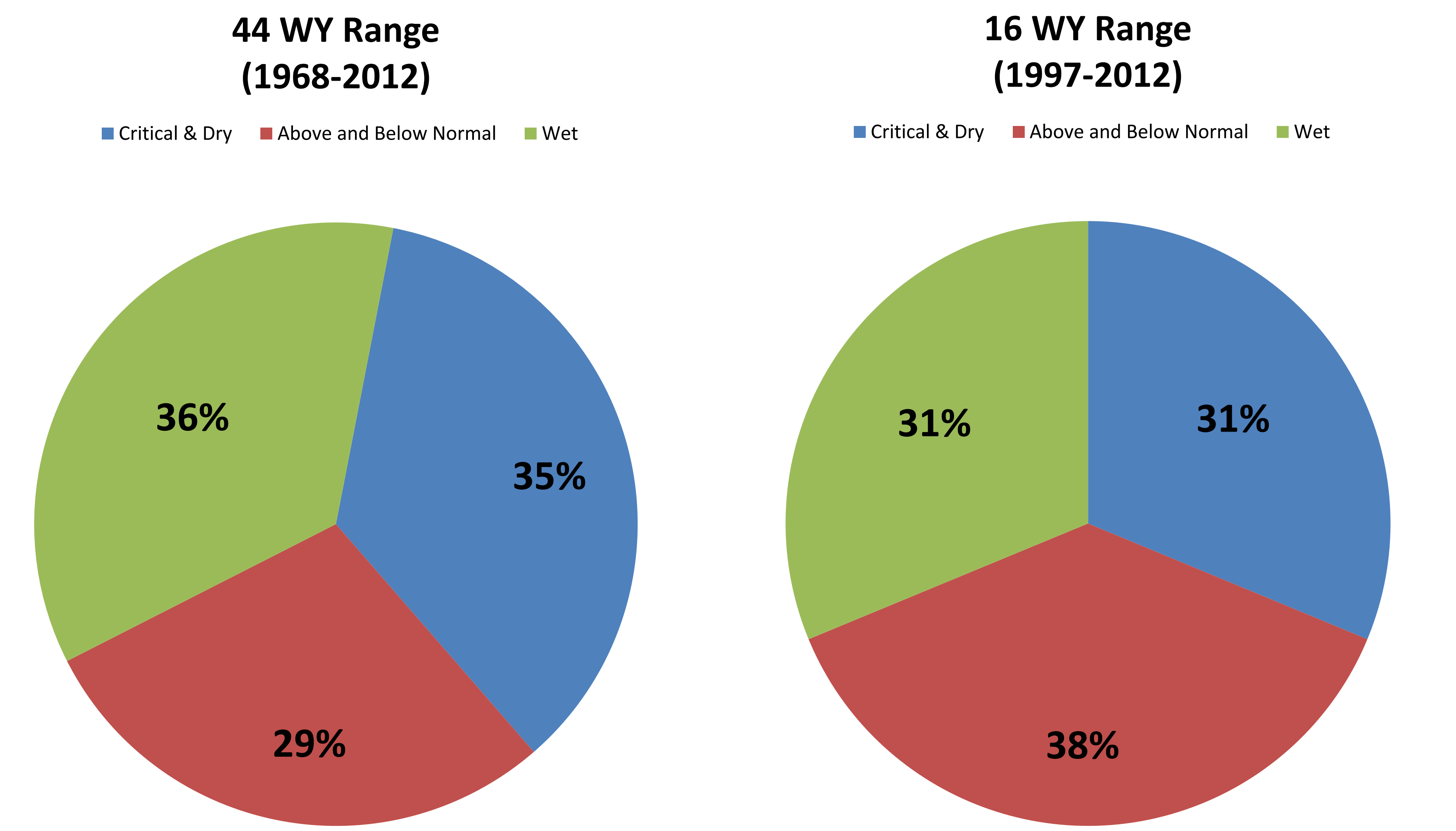



Notes:

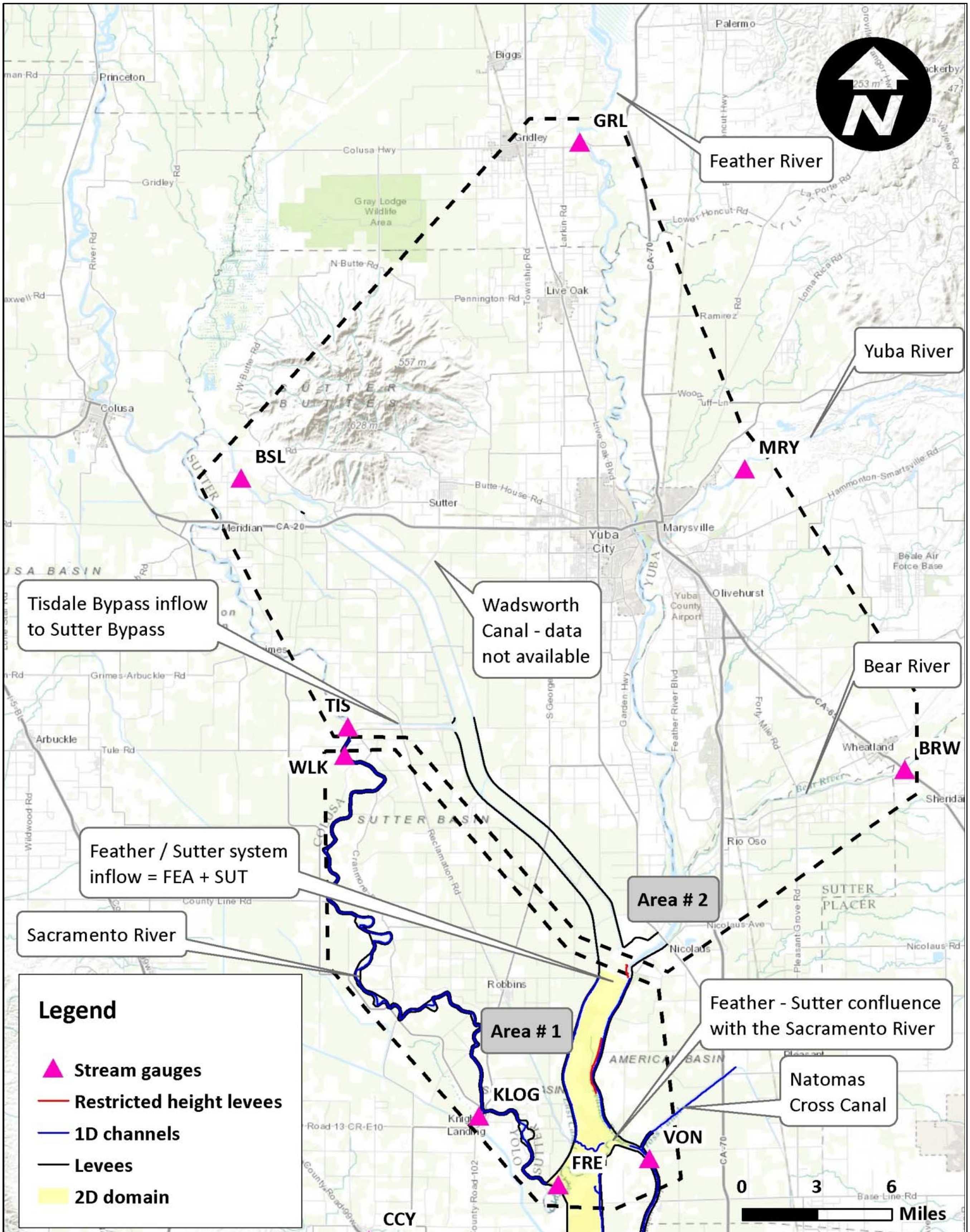
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Primary Geometry Modification Polylines**

Prepared for DWR | Created By: RDJ | **Figure 4-6**




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Water Year Selection** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SJB | **Figure 4-7** |

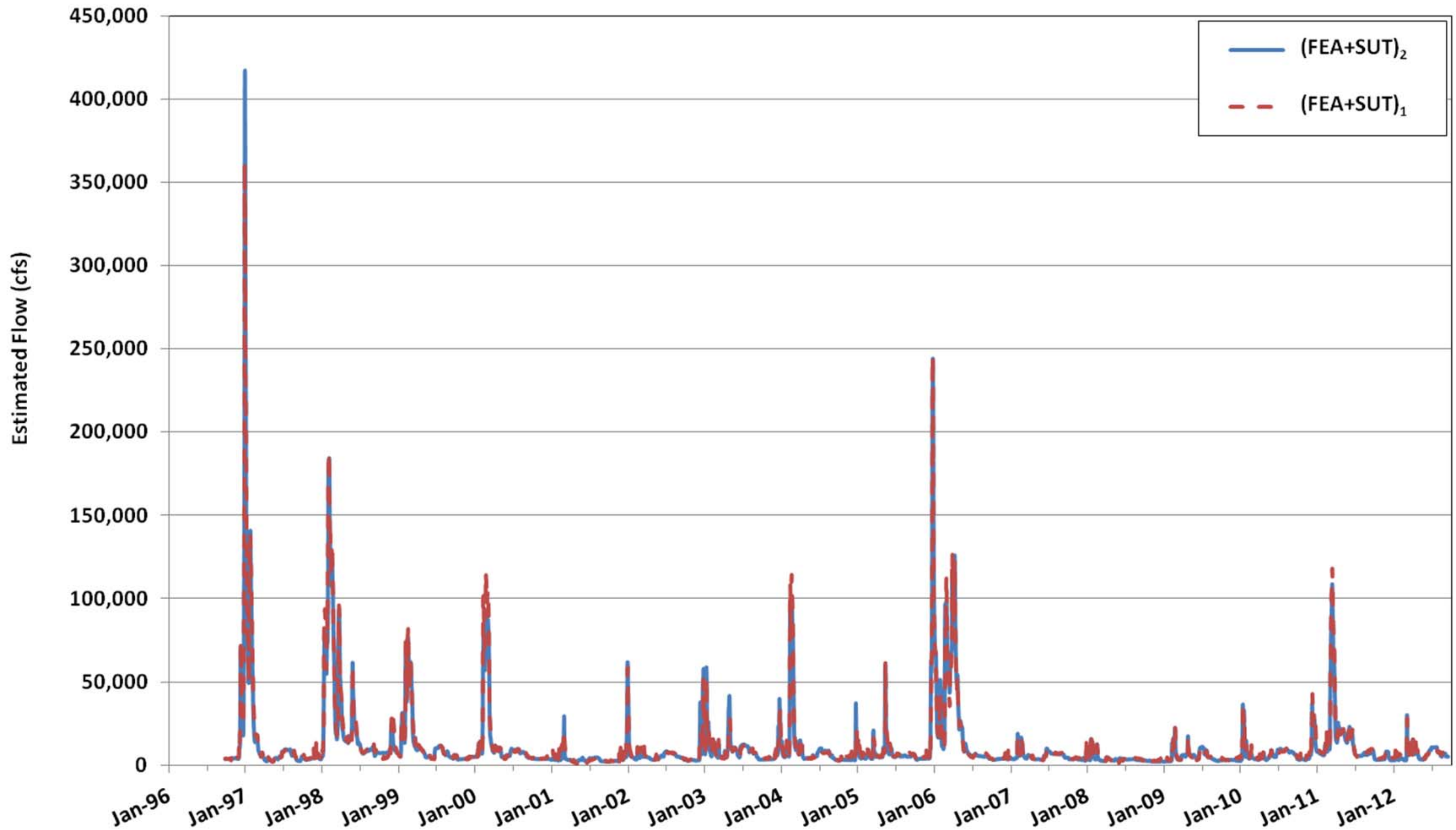



Notes:

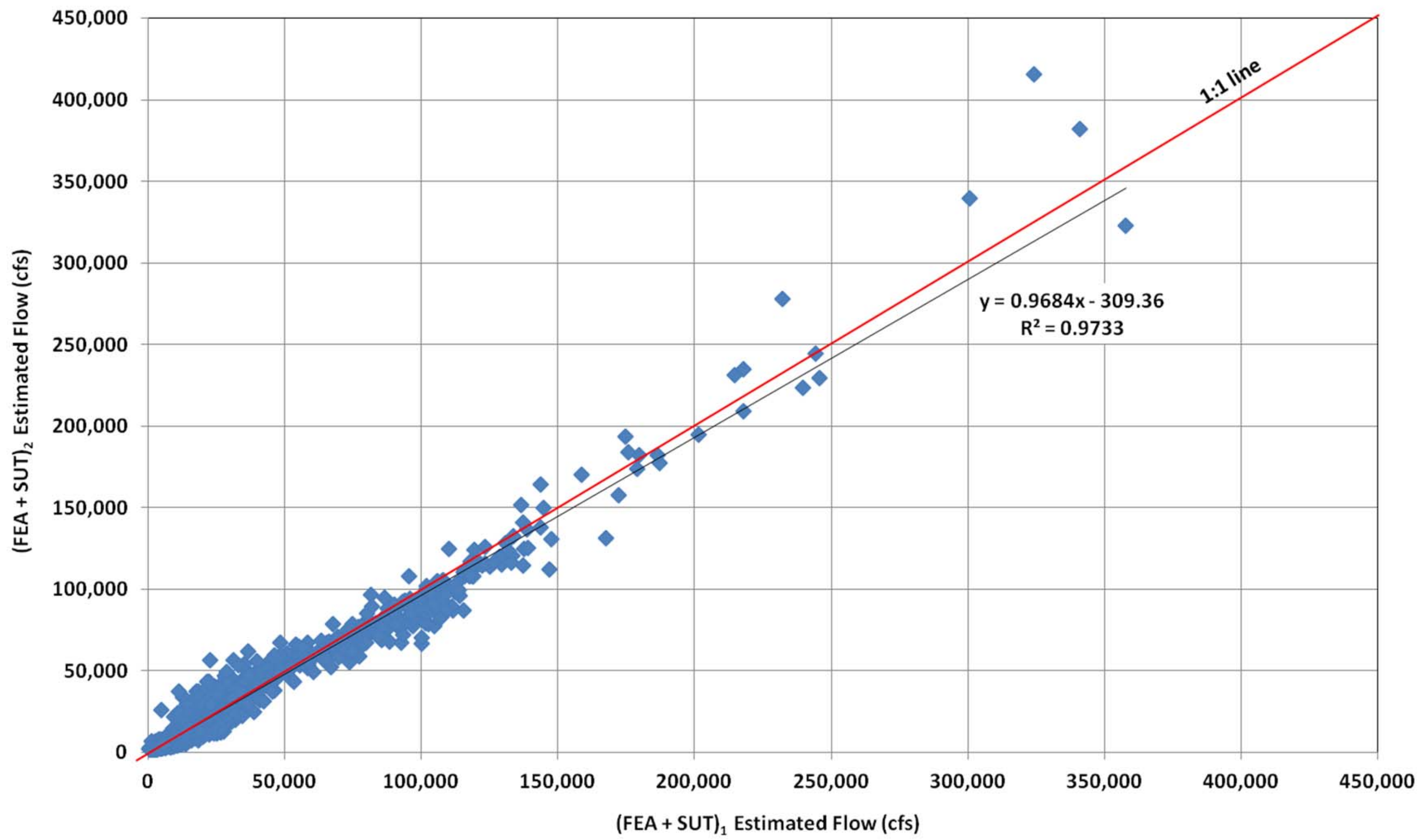
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Feather – Sutter Gauges for Flow Split**

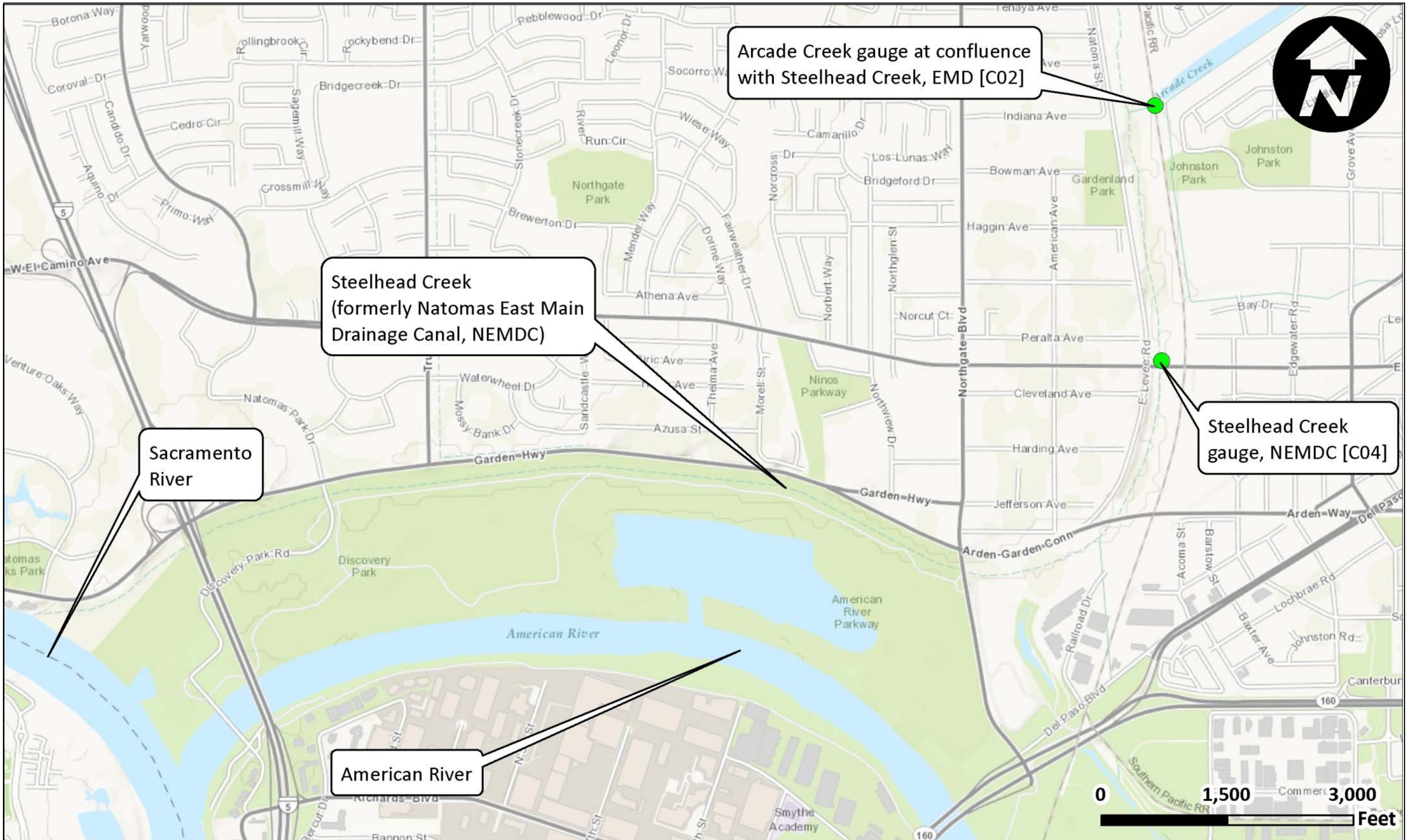
| | | |
|---|---|---|
| Prepared for DWR | Created By: SP | **Figure 4-8** |




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Feather – Sutter Flow Time Series** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-9** |




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Feather – Sutter flow Scatter Plot** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-10** |

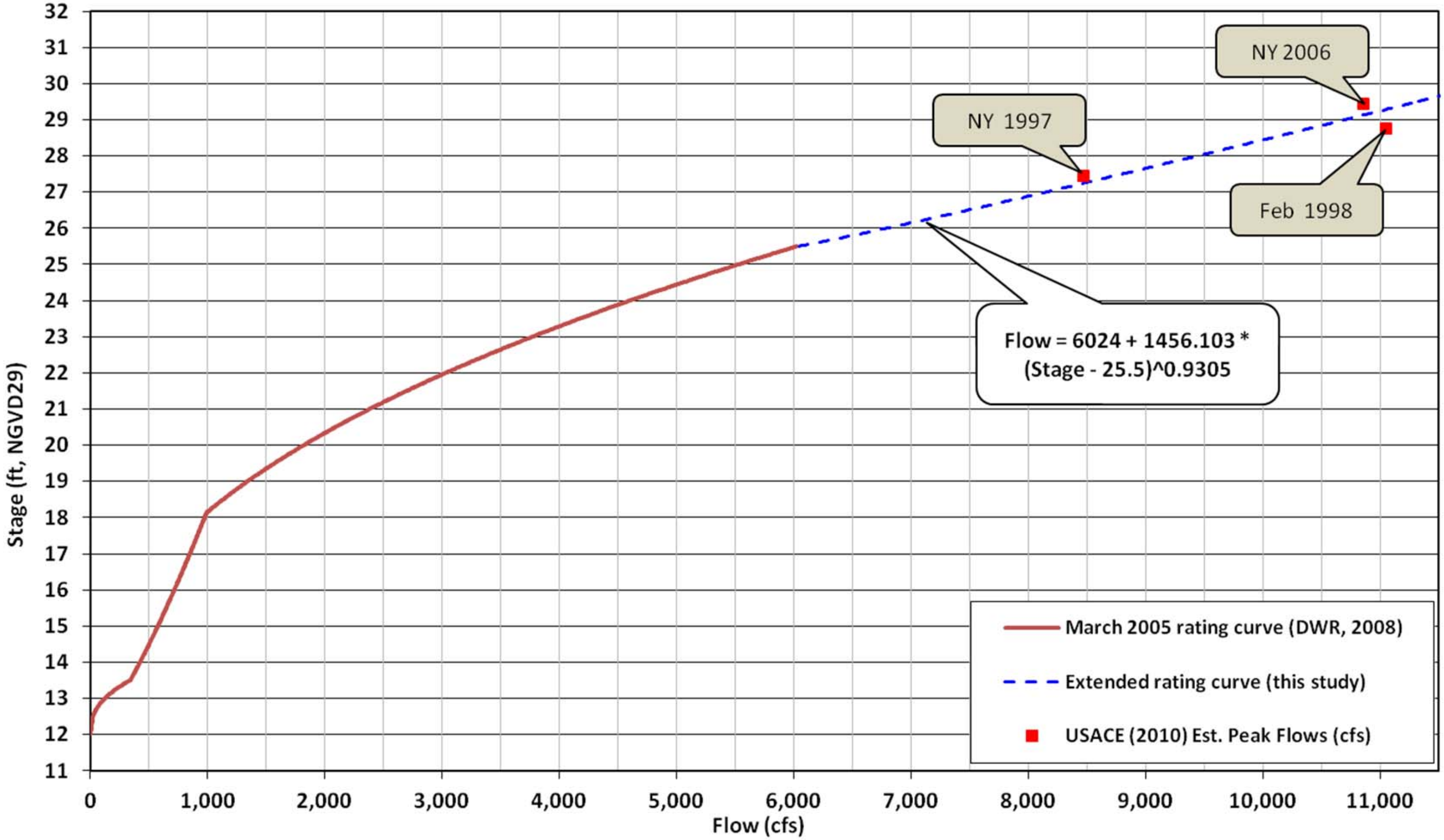



Notes:

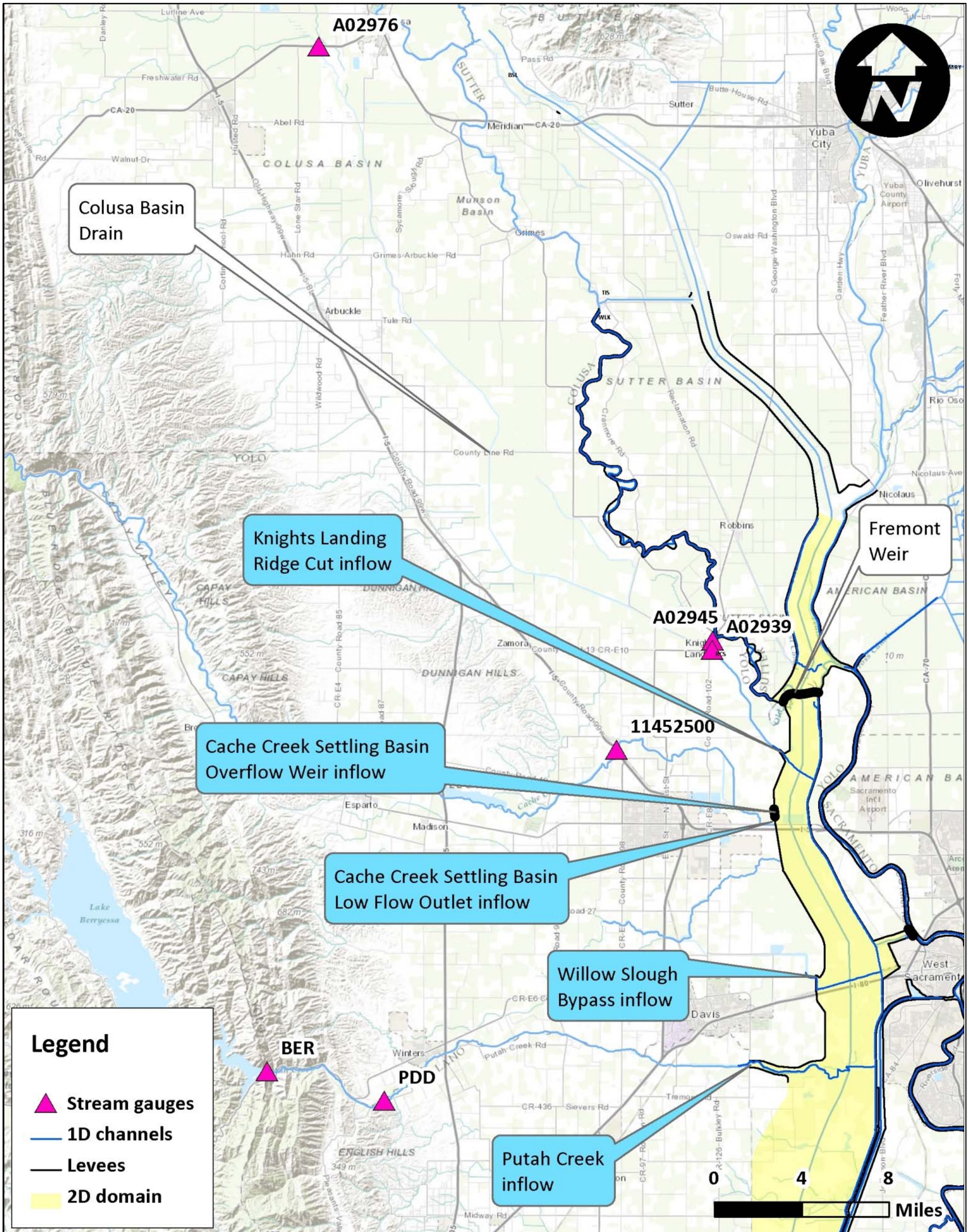
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Steelhead Creek and Arcade Creek Gauges**

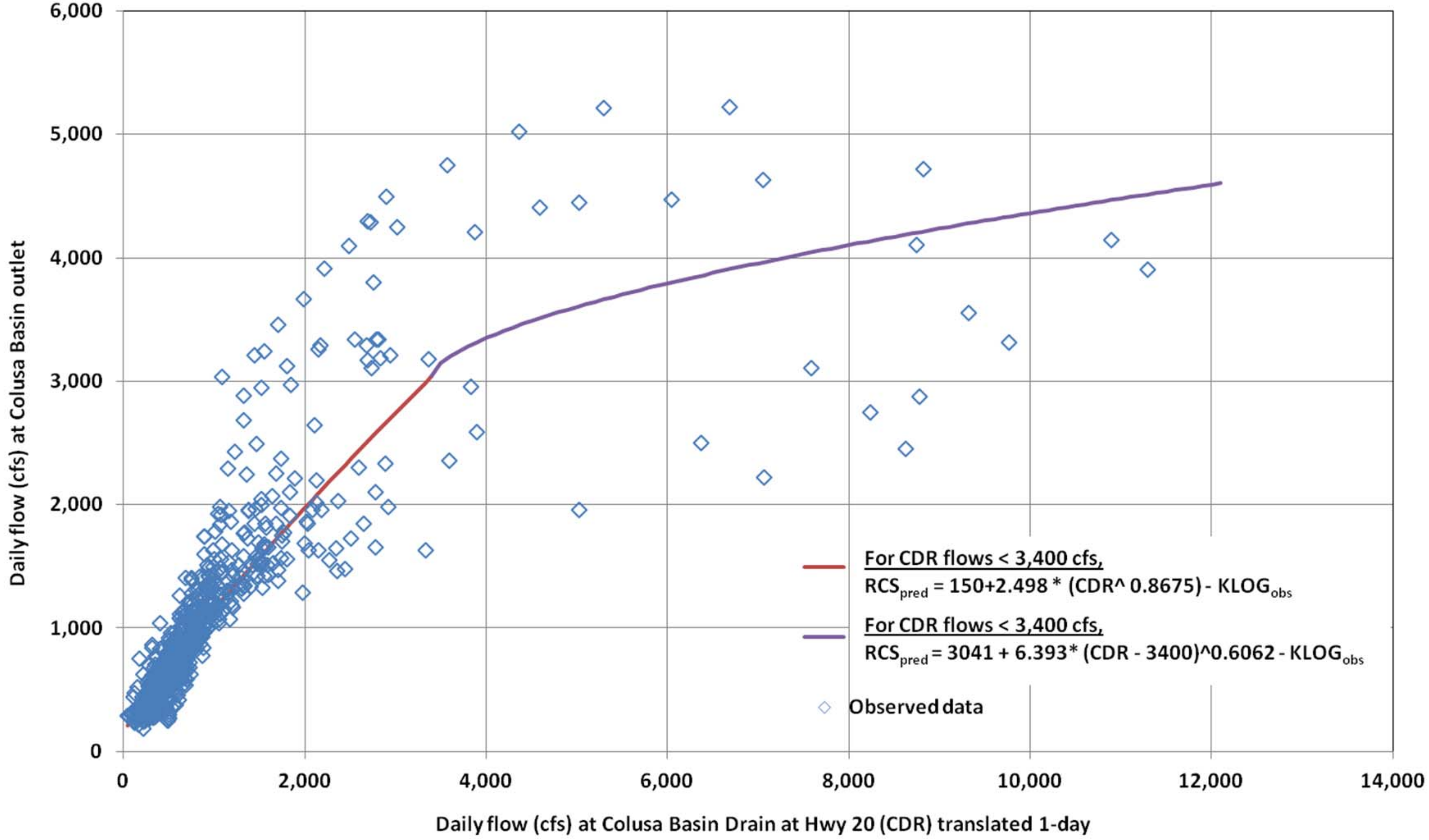
| | | |
|---|---|---|
| Prepared for DWR | Created By: SP | **Figure 4-11** |



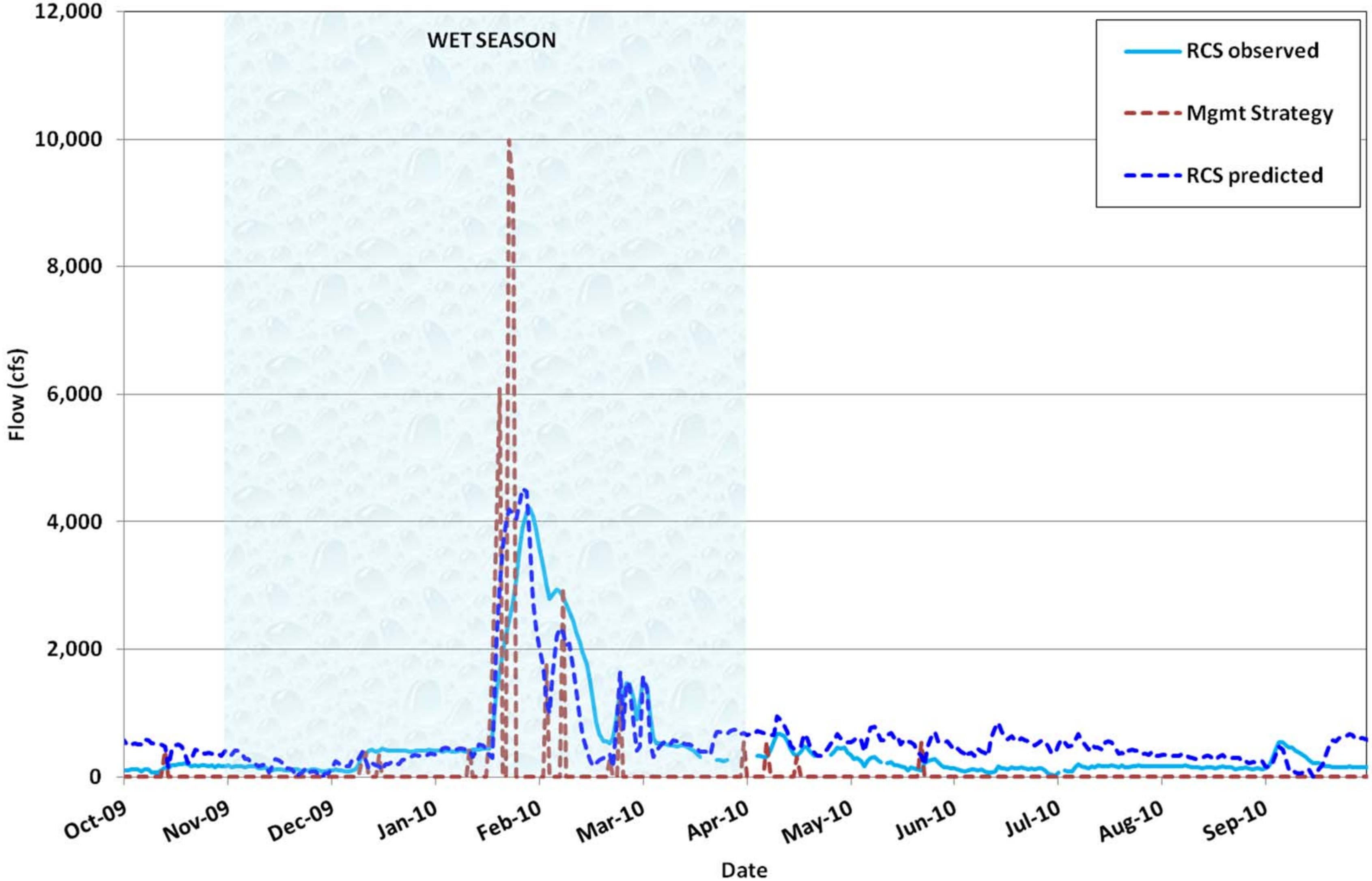

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Steelhead Creek Updated Rating Curve** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-12** |



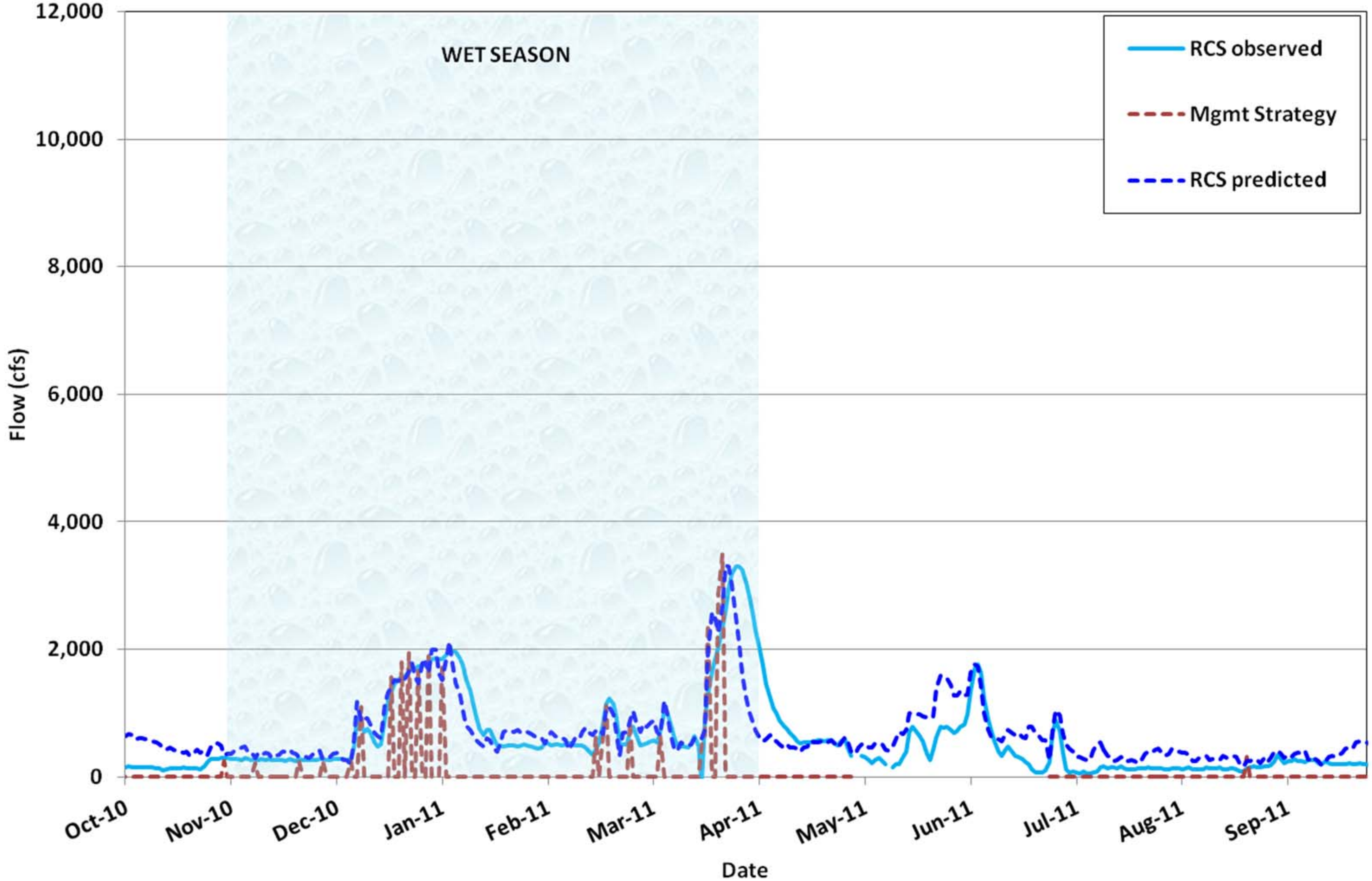

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **Westside Tributaries and Gauges** | | |
| | | Prepared for DWR | Created By: SP | **Figure 4-13** |



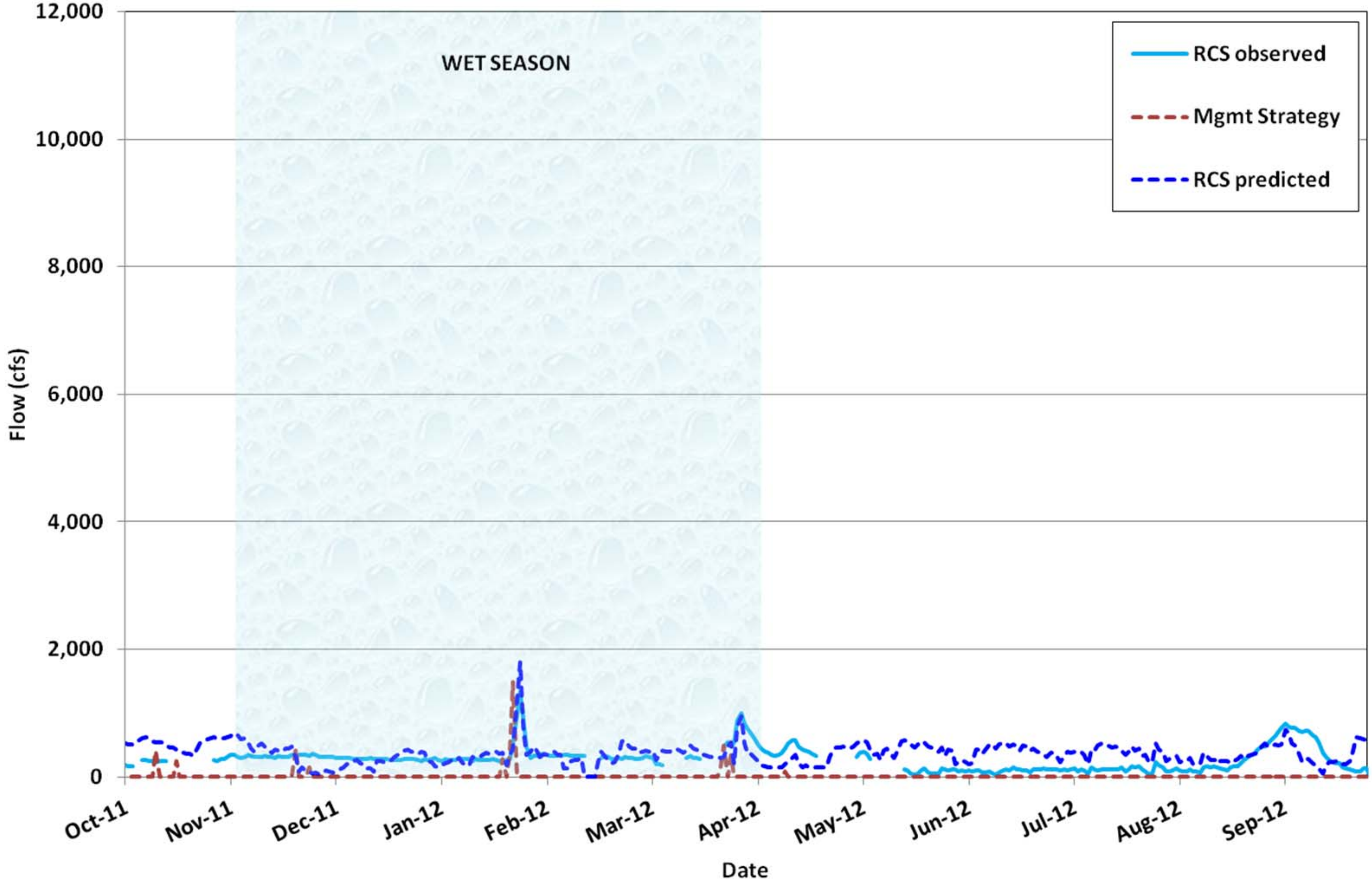

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Knights Landing Ridge Cut Inflow** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-14** |



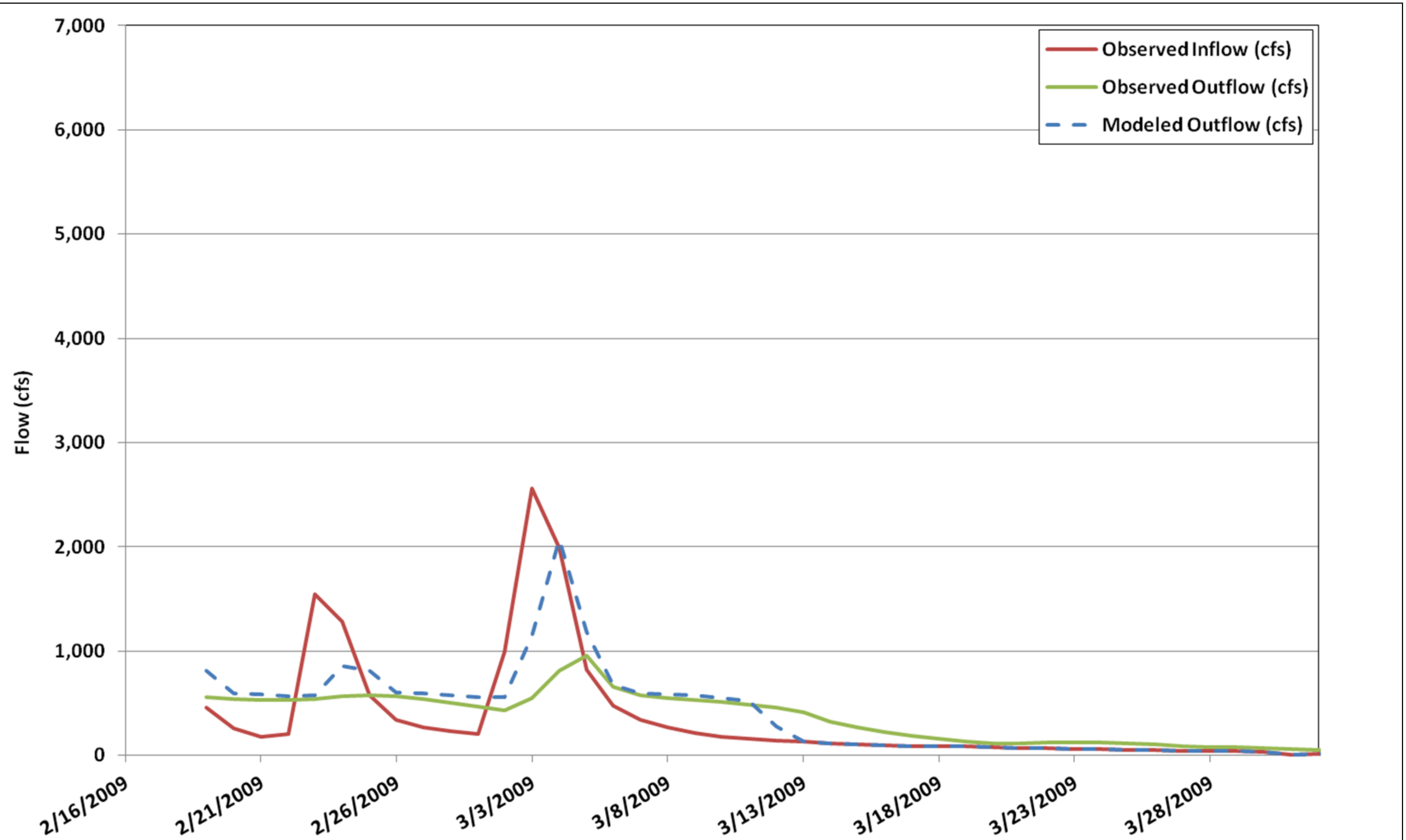

| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**KLRC Inflow Validation – WY 2010** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-15** |



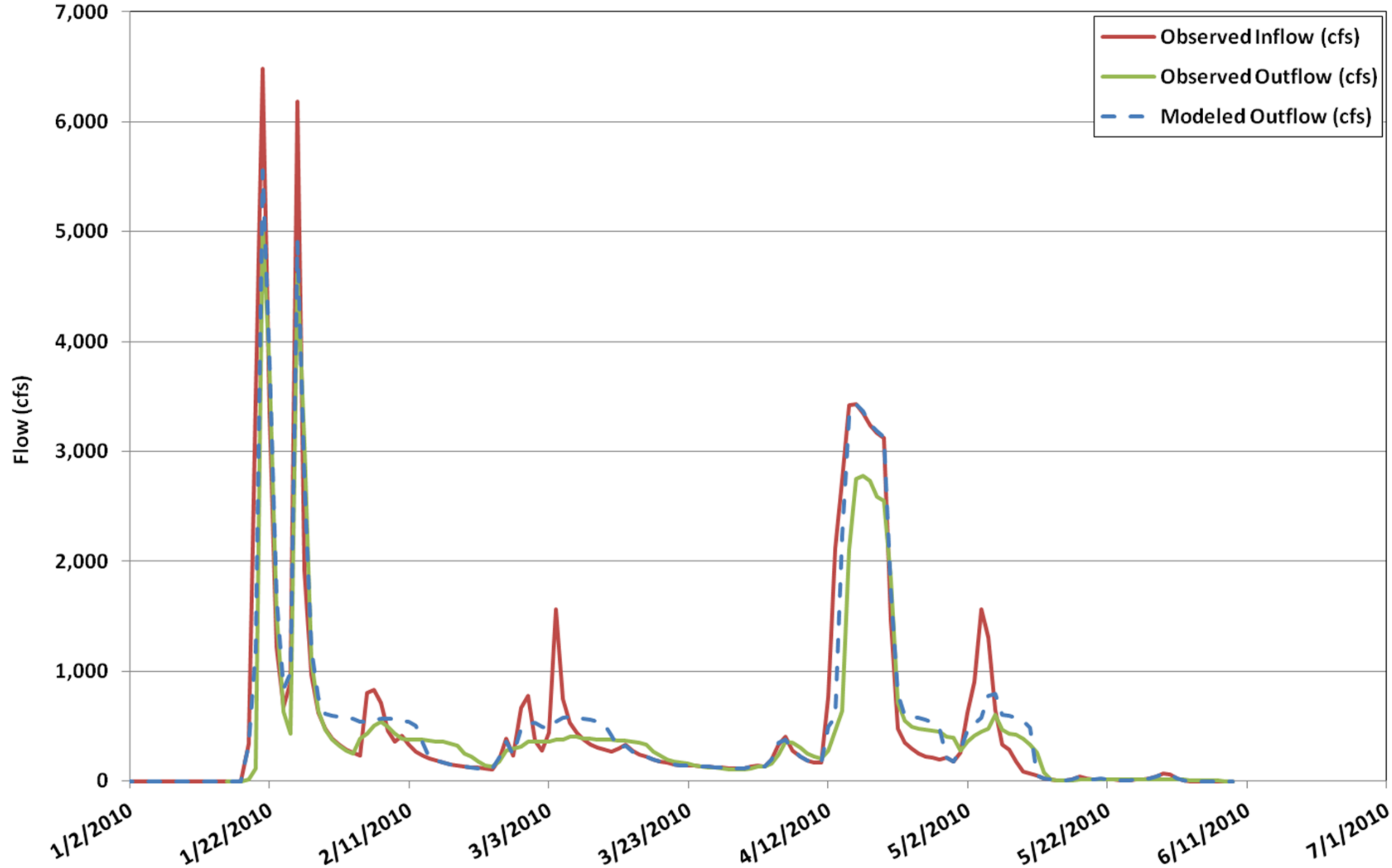

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **KLRC Inflow Validation – WY2011** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-16** |



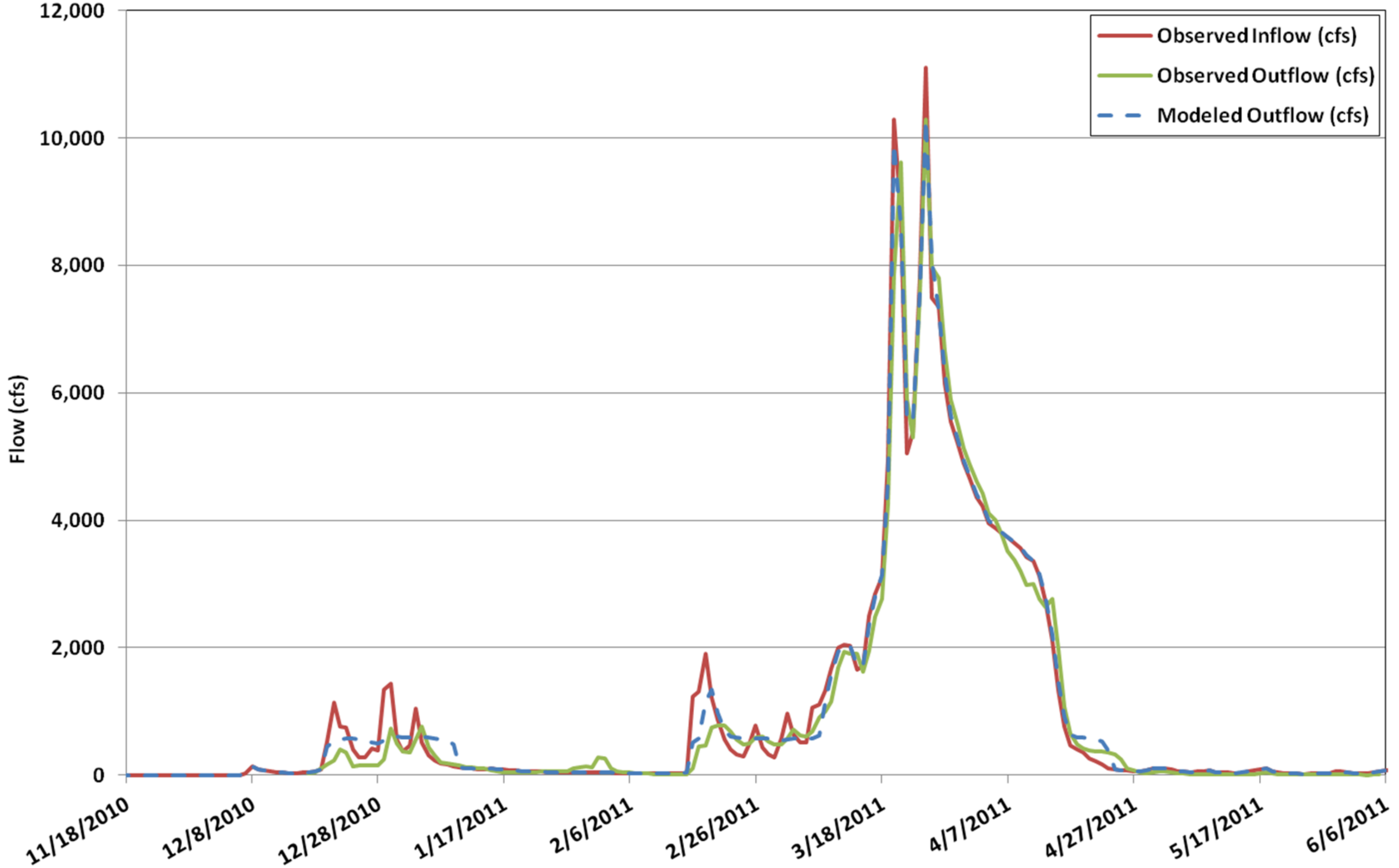

| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **KLRC Inflow Validation – WY 2012** | | |
| | | Prepared for DWR | Created By: SP | **Figure 4-17** |



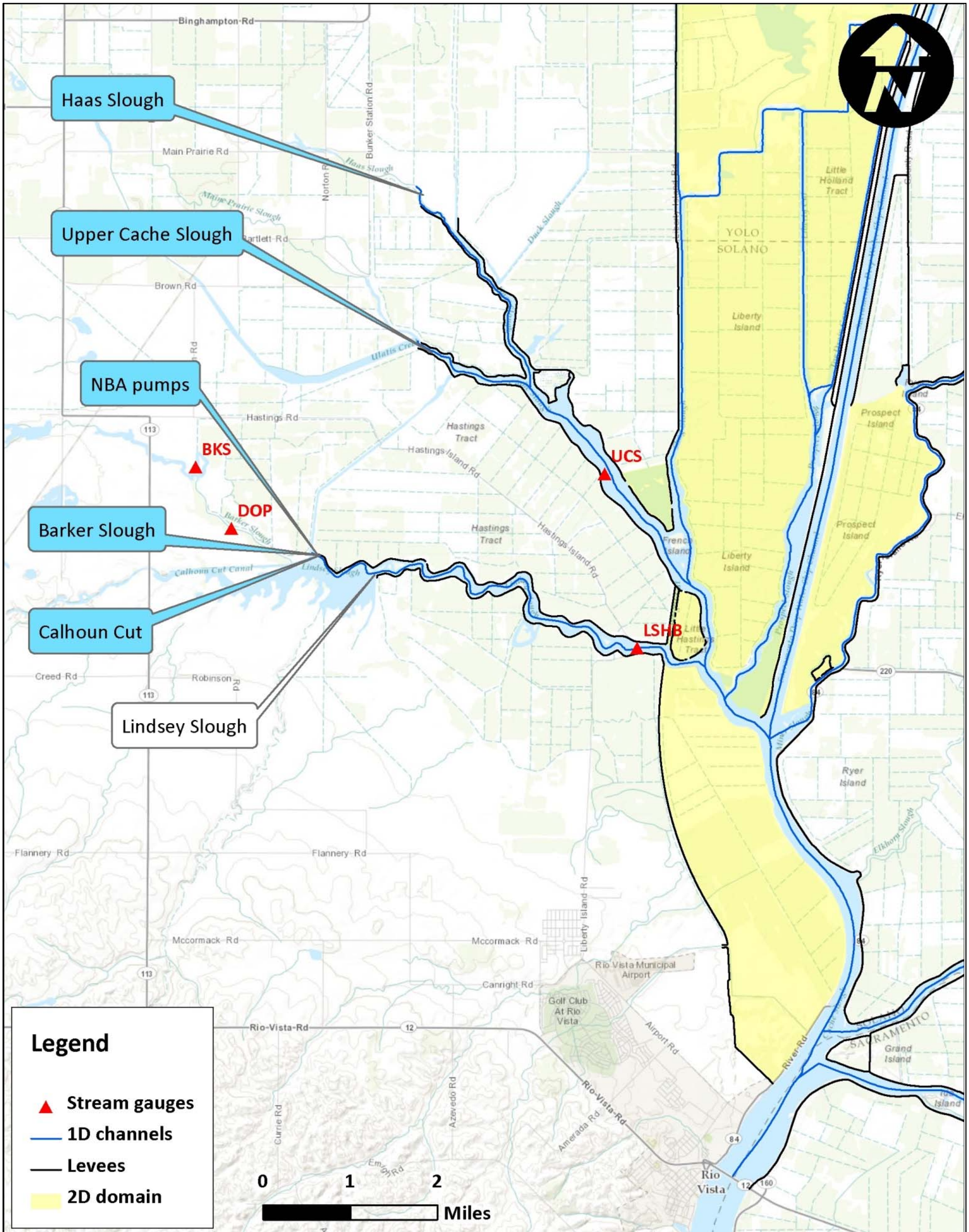

| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**Cache Creek Settling Basin Outflows – 2009 Rainfall Events** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-18** |



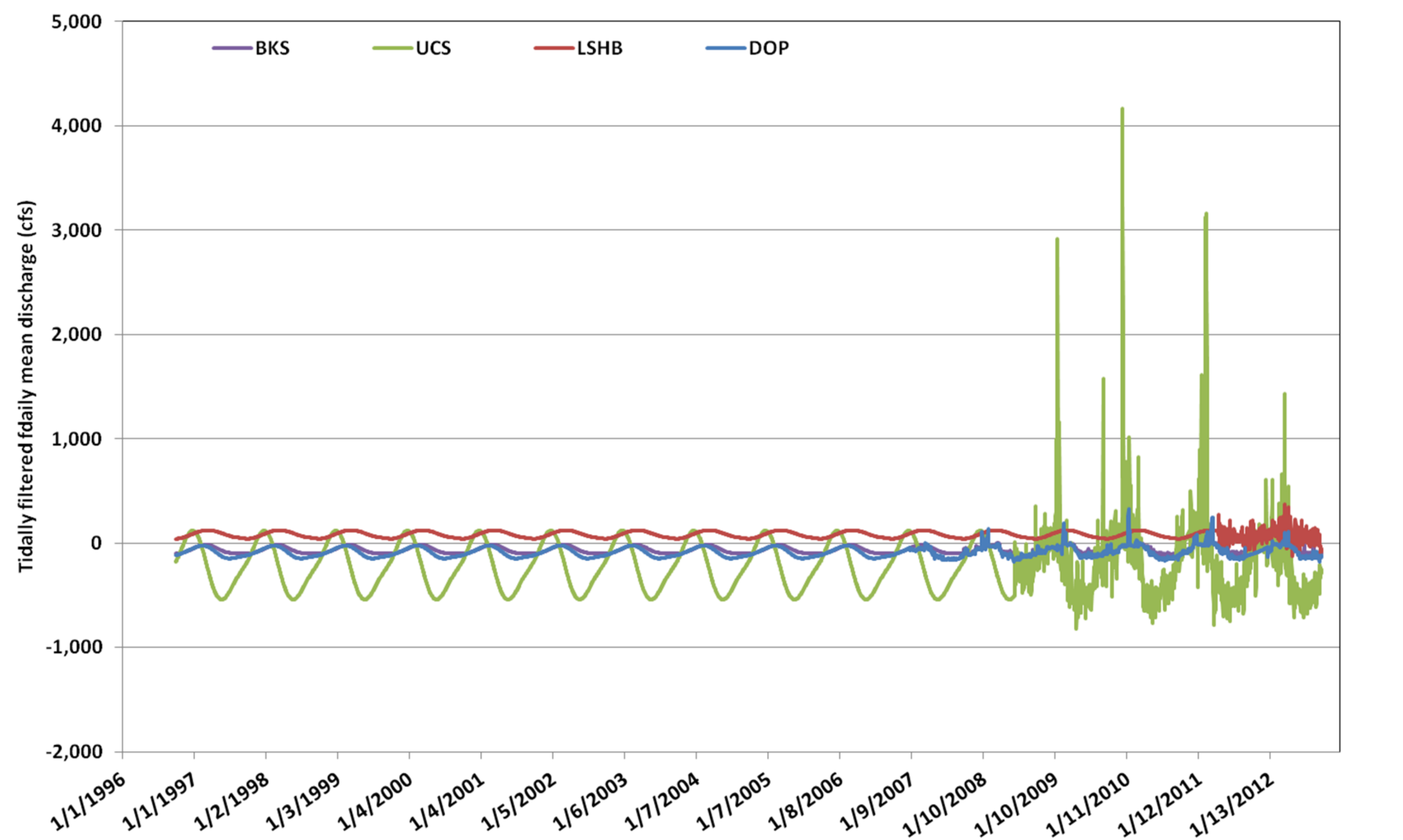

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**Cache Creek Settling Basin Outflows – 2010 Rainfall Events** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-19** |



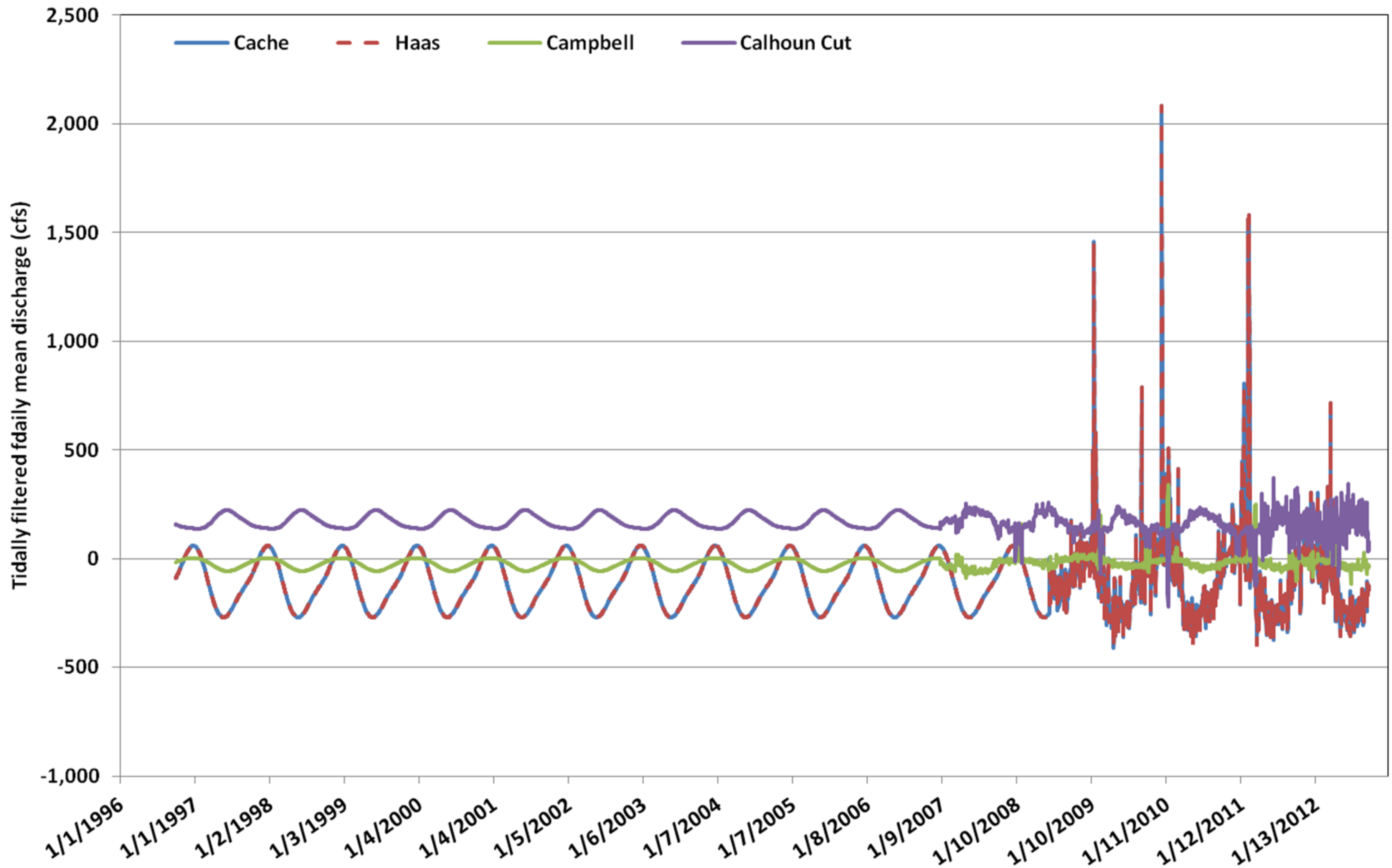

| Notes: | HDR cbec | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**Cache Creek Settling Basin Outflows – 2011 Rainfall Events** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-20** |




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **Delta Sloughs Inflows and Gauges** | | |
| | | Prepared for DWR | Created By: SP | **Figure 4-21** |




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Sinusoidal Curve Fitting for Delta Slough Gauges** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SP | **Figure 4-22** |

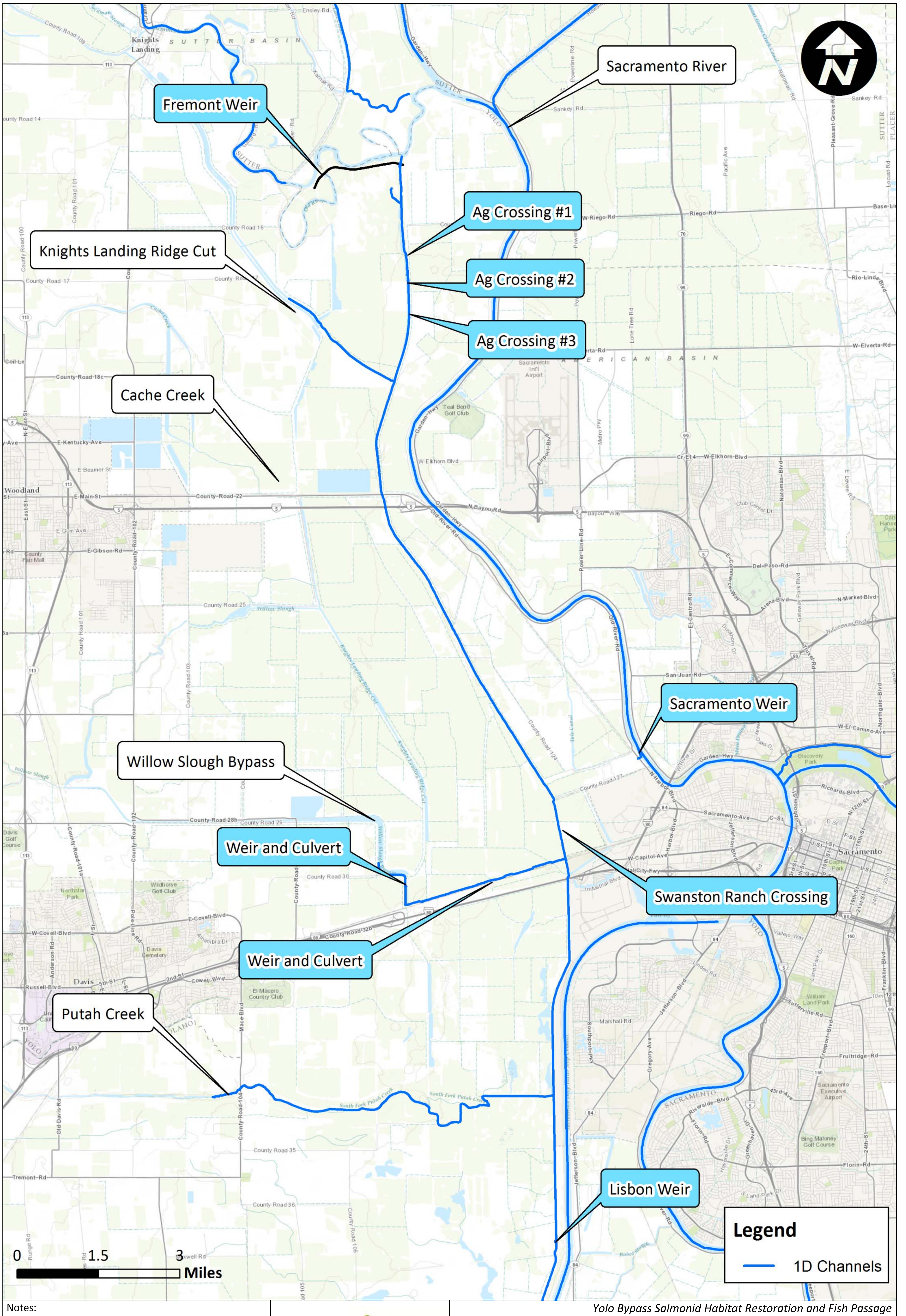



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Estimated Delta Slough Daily Flows**

| Prepared for DWR | Created By: SP | **Figure 4-23** |
|---|---|---|

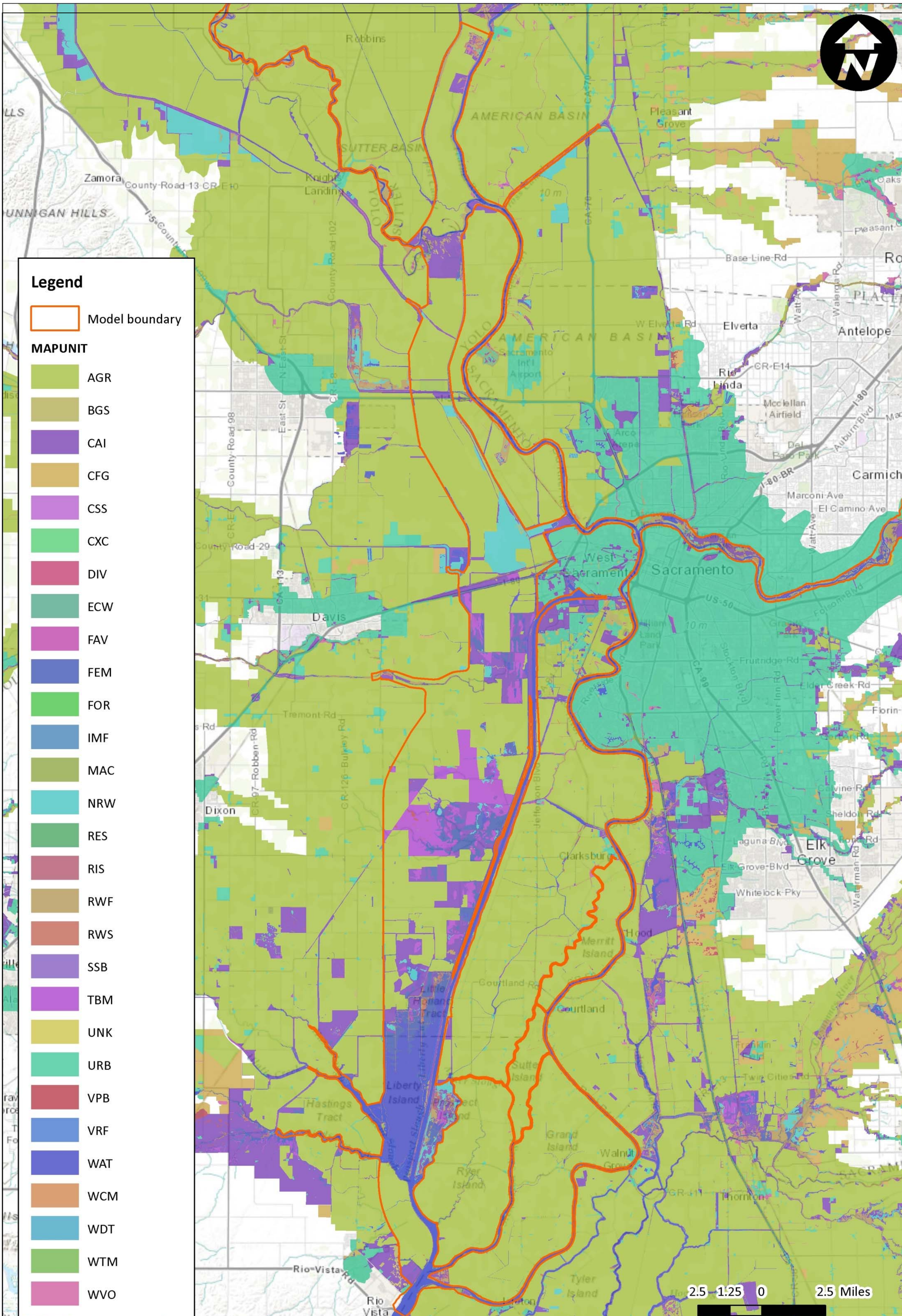



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Hydraulic Structures within the Yolo Bypass**

Prepared for DWR | Created By: RDJ | **Figure 4-24**




Notes:

HDR cbec eco engineering

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Central Valley Medium Scale Riparian Mapping**

| Prepared for DWR | Created By: SP | **Figure 4-25** |
|---|---|---|

# 5.0 Model Calibration

## 5.1 Overview of Model Calibration

TUFLOW model calibration was performed for three hydrologic conditions in the Bypass to cover the range of flow conditions modeled during the 16 water years. To support model calibration, model data was prepared to include a combination of boundary conditions, measured and gauged flows and stages, surveyed high water marks (HWMs), and gate/weir operations for the following three conditions:

- **1997 Flood** – high flow calibration of the TUFLOW model to HWMs in the Bypass, gauge data (i.e., stage and flow) in the Bypass and the Sacramento River, and the Fremont Weir flow split using gauge data and boundary conditions from the CVFED HEC-RAS model.

- **Low Flow** – calibration to flow within the Tule Canal/Toe Drain channel capacity. Flows and water surface elevations (WSEs) along the Tule Canal/Toe Drain were measured by cbec during February 2010.

- **Flood Recession** – calibration to Yolo Bypass shallow flooding during recession of the March/April 2011 Fremont Weir overtopping event. In addition to readily available gauge data, a series of aerial photographs, HWMs, and limited flow measurements were collected or acquired by cbec.

Calibration of the model was largely focused on river conditions when Fremont Weir spills during system-wide flooding (i.e., January 1997 flood) and localized inundation within the Yolo Bypass (i.e., February 2010 low flow, March/April 2011 flood recession). For conditions when Fremont Weir was not spilling, between elevations 14 to 33 feet NAVD88 when the proposed gated notch could be activated, calibration was not performed. However, the long-term time series plots in Section 6 (i.e., Figures 6-1 to 6-6) provide validation for how the existing conditions model is performing in the Sacramento River when Fremont Weir is not overtopping.

The 2D portion of the model and the 1D channels within the Yolo Bypass (i.e., four Westside tributaries and Tule Canal / Toe Drain) were given initial Manning's n assignments based on medium scale vegetation mapping provided in Table 4-5 in the Report (see tables) as derived from previous studies. The Westside tributaries initial Manning's n assignments never changed as the Westside tributaries were not individually calibrated. The Tule Canal / Toe Drain was individually calibrated and the reach roughness multipliers from the initial values specified in Table 4-5 are provided in Table 5-4 of the Report (see tables). Calibration of the 2D portion of the model by vegetation type occurred by applying global adjustments to the initial Manning's n assignments as provided in Table 4-5 to arrive at the calibrated values. For the 1D-channels outside the Yolo Bypass, in addition to adding energy losses, modifications were made to the CVFED RAS model derived cross section Manning's n values.

The 1997 flood calibration used the full model whereas the other two calibration periods used truncated model domains specific to each calibration period.. The truncated models were used to calibrate specific portions of the Yolo Bypass without having to run the full model. In this way, the team had tighter control over the boundary conditions and the benefit of reduced run times in arriving at solutions quickly. The truncated calibrations focused on refinements to the Tule Canal / Toe Drain channel capacity and relevant hydraulic structures, 1D/2D interface, reinforcement of features in the DEM affecting inundation (i.e., berms and gullies), model stability and coupling across the 1D/2D interface, and modifications to Manning's n assignments. The modifications made to the truncated models were then evaluated in the full model for the 1997 flood calibration, and if further modifications were made to the full model, they were passed back to the truncated models and re-evaluated until the model calibration was satisfactory among all three calibration models. The satisfactory calibration was then verified by the long-term time series plots provided in Section 6.

## 5.2 High Flow – 1997 Calibration Period

### 5.2.1 Model Setup

The 1997 event (December 29, 1996 through January 4, 1997) delivered the largest observed discharges into the Bypass over the 16 year period of interest. The observed WSE at the gauge for the Sacramento River on the west side of the Fremont Weir peaked on January 2, 1997 with a stage of 41.4 feet NAVD88. The peak observed flow over the Fremont Weir was 318,000 cfs. For these reasons, the 1997 event was used to calibrate the model for higher flows, with particular attention given to hydrograph timing, peak flows and WSE.

The hydrodynamic model was calibrated to HWMs in the Yolo Bypass, gauge data (i.e., stage and flow) in the Bypass and the Sacramento River, and the Fremont Weir flow split using sub-daily (i.e., 15-minute and hourly) boundary conditions that were generated following the same methods described in Section 4.4. Figure 5-1 shows the boundary conditions, gauges with recorded stage and flow, and surveyed HWMs compiled for the 1997 calibration event. The observed stage and flow data and HWMs were acquired from the CVFED HEC-RAS model. Table 5-1 summarizes the boundary conditions and recorded stage and flow locations that were used for calibration. The Delta Cross Channel gates remained closed during the flood event and diverted no flows out of the Sacramento River.

It should be noted that the gauged Fremont Weir spills for the 1997 flood event consist of a reconstructed hydrograph developed from flow measurements taken downstream of the Fremont Weir during the 1997 flood event (USACE 2007). Based on the measurements taken, DWR discovered that the rating curve was over predicting flows at higher stages and believed that to be caused by sediment buildup causing backwater conditions.

The TUFLOW model was calibrated with:

- Extensive HWMs in the Yolo Bypass and Sacramento River
- Observed stage and flow at multiple gauge locations
- The flow split between Fremont Weir and the Sacramento River

*Table 5-1. Boundary conditions and gauge data information for the 1997 calibration event*

| Boundary Location | Data Source | Stage Gauges | Data Source |
|---|---|---|---|
| **Sacramento River** | | | |
| Sacramento River inflow below Wilkins Slough near Grimes (WLK) | USGS 11390500 | Sacramento River at Knights Landing (KNL) | DWR's Water Data Library (A02200) |
| Knights Landing Outfall Gates (KLOG) | DWR's Water Data Library (A02945) | Sacramento River at Fremont Weir (FRE), West end | DWR's Water Data Library (A02170) |
| Feather River and Sutter Bypass (FEA+SUT) | Estimated using methods developed in this study[1,2] | Fremont Weir Spill | DWR's Water Data Library A02930 |
| Natomas Cross Canal (NCC) | Estimated using methods developed in this study[1,3] | Sacramento River at Fremont Weir, East end | DWR's Water Data Library (A02160) |
| | | Sacramento River at Verona (VON) | USGS 11425500 |
| American River (AFO) | USGS 11446500 | Sacramento River above Sacramento Weir (SBP) | DWR's Water Data Library (A02108) |
| Steelhead Creek | Estimated using methods developed in this study[1,4] | Sacramento Weir Spill | DWR operations data |
| Delta Cross Channel(DLC) | Closed during the flood event, no flow | Sacramento River at I Street Bridge (IST) | DWR's Water Data Library (A02100) |
| Georgiana Slough (GSS) | Estimated using methods developed in this study[1,5] | Sacramento River near Freeport Bridge (FPT) | USGS 11447650 |
| | | Sacramento River at Walnut Grove (SDC) | DWR's Water Data Library (B91650) |

| Boundary Location | Data Source | Stage Gauges | Data Source |
|---|---|---|---|
| **Yolo Bypass** | | | |
| Knights Landing Ridge Cut (KLRC) | Estimated using methods developed in this study[1] | Yolo Bypass near Woodland (YBY) | USGS 11453000 |
| Cache Creek Settling Basin | Estimated using methods developed in this study[1] | Yolo Bypass at Lisbon (LIS) | DWR's Water Data Library (B91560) |
| Putah Creek | Estimated using methods developed in this study[1] | | |
| Willow Slough Bypass | Estimated using methods developed in this study[1] | | |
| **Downstream Boundary** | | | |
| Sacramento River at Rio Vista (RVB) | DWR's Water Data Library (B91212)[6] | | |

Notes:
[1] Developed following the methods outlined in Section 4.4
[2] Estimated using a mass balance relationship: (FEA + SUT) = (VON + FRE) - (WLK + KLOG + NCC); flows split was based on ratio of (GRL+MRY+BRW) and (BSL+TIS)
[3] Estimated as 1.43 x Steelhead Creek flow
[4] Estimated using the computed stage along the Steelhead Creek near the West El Camino Avenue bridge and stage-discharge curve previously developed by DWR (2008a) and extended by cbec as a part of this study
[5] Daily flows provided by DWR's Dayflow program converted to hourly flows
[6] The stage data is in USED datum and the gauge height correction (NAVD88 = USED - 0.6 ft) has not been applied

### 5.2.1 Results Summary

Modeled maximum WSEs were compared at 43 HWMs within the Bypass and 21 in the Sutter Bypass and along the Feather River. Additionally, gauge records at 11 stream gauges (8 outside the Bypass, 3 within) were compared to model results. Reasonable changes within engineering judgment were made in the model, mainly modifications to the Manning roughness coefficients and adding energy losses to calibrate the model to these data. The model was considered calibrated when modeled peak WSE demonstrated good agreement with the majority of HWMs and gauge stage records and predicted hydrographs at flow gauge locations compared favorably with discharge records.

Additional energy losses were used to improve calibration in areas where 1D losses due to turbulence may have been underestimated such as the confluence of a river or where increasing the Manning roughness coefficients impaired the low flow calibration as shown in Figure 5-2. Energy losses are applied as a function of the velocity head so they have a very small impact at low flows.

A comparison of the peak computed WSEs to collected HWMs is shown in Figure 5-33. The computed WSE within the Yolo Bypass are typically high (average error 0.2 feet) and those in the Sutter Bypass are typically low (average error -0.2 feet). The root-mean-square error (RMSE) for the Sutter Bypass is 1.1 feet. The RMSE for the higher priority HWMs within the Yolo Bypass is 0.8 feet. The RMSE for all of the HWMs is 0.9 feet.

The flow split between the Fremont Weir and Verona are of particular concern for modeling of the Yolo Bypass. Figure 5-4 shows a comparison of the computed and observed relationship between flows into the Bypass and flows down the Sacramento River, indicating that the model is reasonably predicting the flow split.

Outside of the Bypass, calibrated model results were compared at 8 gauges (3 gauges included discharge). Comparison plots are shown in Figure 5-5 through Figure 5-18. Generally, the shape of the predicted stage hydrographs match reasonably well to observed stages. In several instances, although the general shape and magnitude of the predicted WSEs compare well to the gauge records, the full magnitude of peaks and dips observed at gauges are not reproduced in the model. Potential inaccuracies in the assumed Sacramento Weir gate operations and/or boundary conditions may hamper the ability of the model to capture peak stages. At discharge gauges, flow hydrographs from the model reproduce the shape and magnitude of hydrographs well. The WSEs in the Sacramento River at Walnut Grove Stage shown in Figure 5-15 are consistently high but the tidal signal timing matches well.

## 5.3 Low Flow– February 2010 Calibration Period

### 5.3.1 Model Setup

The TUFLOW model was calibrated to the capacity of Tule Canal/Toe Drain during low flows in February 2010. Flows and WSEs along the Tule Canal/Toe Drain were measured by cbec (2010) on February 19, 2010 at 19 locations from the northerly extent of the Tule Canal (south of Tule Pond) to just downstream of Lisbon Weir near the DWR Lisbon Weir gauge. Flow in the channel was measured with an Acoustic Doppler Current Profiler (ADCP). WSEs were collected using Real Time Kinematic (RTK) Global Positioning System (GPS) survey equipment and referenced to NAVD88. Figure 5-19 shows the locations of flow and stage measurements. Table 5-2 provides a summary of the flow and stage measurements. The benefit of obtaining these measurements in February 2010 was that the flows in the Tule Canal/Toe Drain were at a point where in most places they were just passing onto the floodplain, or just below the top of bank, thus providing a relatively reasonable estimate of the flow capacity of the Tule Canal/Toe Drain.

For the low flow calibration of the Tule Canal/Toe Drain, the TUFLOW model was truncated to the 1D channel between Tule Pond and Little Holland Tract. The 2D domain was also truncated to these general extents. The flows in Tule Canal/Toe Drain were based on measured flows, as shown in Table 5-2, with incremental flows added or subtracted from the channel. There were minimal spills over the Fremont Weir (less than 3,000 cfs) and no spills over

Sacramento Weir during this low flow event. Flows from the Westside tributaries are included within the measured flows, so inflows from these tributaries are accounted for in the incremental flows. The tidal boundary at Little Holland Tract was based on recorded elevations collected by cbec (unpublished) in support of the Lower Yolo Restoration Project at Metropolitan Water District Gauge 7 (MWD7).

*Table 5-2. Summary of flow and stage measurements taken in the Toe Drain/Tule Canal*

| Location | Elevation (ft NAVD88) | Measured Flow (cfs)[1] |
|---|---|---|
| ADCP1 | 17.08 | --- |
| ADCP2 | 17.26 | 151 |
| ADCP3 | 16.86 | 920 |
| ADCP4 | 16.37 | 1072 |
| ADCP5 | 16.10 | 1344 |
| ADCP6 | 15.71 | 1281 |
| ADCP7 | 15.60 | 1443 |
| ADCP8 | 15.15 | 1408 |
| ADCP9 | 14.90 | 1539 |
| ADCP10 | 14.46 | 1541 |
| ADCP11 | 13.56 | 1644 |
| ADCP12 | 11.52 | 2154 |
| ADCP13 | 11.12 | 2307 |
| ADCP14 | 11.00 | 2278 |
| ADCP15 | 10.59 | 2526 |
| ADCP16 | 10.28 | 2622 |
| ADCP17 | 10.30 | 2692 |
| ADCP18 | 9.79 | 2609 |
| ADCP19 | 8.58 | 2805 |

Notes:
[1] Flow measurements recorded in the Toe Drain/Tule Canal were validated with flow measurements observed at Lisbon Weir. Flow measurements taken by cbec near Lisbon Weir were within 3.0% of those at Lisbon Weir.

### 5.3.2 Results Summary

Low flow calibration of the Tule Canal/Toe Drain north of Lisbon Weir was achieved by adjusting the hydraulic roughness coefficients (see Table 5-4 for 1D channel multipliers on the 1D channel base values provided by Table 4-6) and implementing energy losses to account for woody debris, hydraulic structures (e.g., piers), and flow transitions (e.g., scour holes downstream of hydraulic structures). These adjustments were made to minimize the RMSE between the measured and modeled values in the water surface profile. At this flow condition, there was minimal flow interaction between the 1D channel and 2D grid, as flows were largely contained to the channel. As shown by Figure 5-20, the RMSE for the WSEs was within 0.3 feet, with the largest errors occurring in the vicinity of hydraulic constrictions (i.e., upstream of KLRC confluence, at Swanston Ranch check dam, and upstream of Lisbon Weir).

## 5.4 Flood Recession- March/April 2011 Calibration Period

### 5.4.1 Model Setup

The TUFLOW model was calibrated for shallow flooding on the Bypass during the receding limb of the March/April 2011 Fremont Weir overtopping event. The flows as measured at Yolo Bypass near Woodland per USGS gauge 11423000 show that the overtopping event peaked around March 27 and receded thereafter. The TUFLOW model 1D channel and 2D floodplain was truncated between Fremont Weir in the north and Little Holland Tract in the south. Figure 5-21 shows the model extents, boundary conditions, gauges with recorded stage and flow, and surveyed WSEs compiled for the 2011 calibration event. Table 5-3 summarizes the boundary conditions and recorded stage and flow locations that were used for calibration. Sub daily boundary condition data was largely based on gauged data and estimated where gauged data was not available following the methods outlined in Section 4.4. The Sacramento Weir gates remained closed during the flood event and diverted no flows out of the Sacramento River into Yolo Bypass.

In addition to readily available gauge data, a series of aerial photographs, WSEs, and limited flow measurements were collected or acquired by cbec (unpublished). The aerial photographs were collected on April 9, 2011 around 4 pm (see Figure 5-22) and on April 12, 2011 around 1:45 pm (see Figure 5-23), and were subsequently georeferenced using flight crosses. WSEs along the Tule Canal/Toe Drain were collected on the same days as the aerial photographs using RTK GPS survey equipment. The WSE data collected on April 9, 2011 extended from Fremont Weir to Lisbon Weir. The WSE data collected on April 12, 2011 extended from Tule Pond to Yolo Flyway Farms.

In addition to the WSEs, an ADCP was used to measure flow in the Tule Canal just downstream of the USGS Yolo Bypass at Woodland gauge from the County Road 22 bridge over the Tule Canal. This location includes flows from Fremont Weir, KLRC, Cache Creek Settling Basin, and floodplain drainage north of County Road 22. The measured discharges on April 9, 2011 at 12:30 pm and on April 12, 2011 at 2:25 pm were 7,290 cfs and 4,250 cfs respectively, while the flows reported at the Yolo Bypass at Woodland gauge were 5,750 cfs and 3,460 cfs. Potential discrepancies between USGS published and measured values could be due to an older USGS rating curve or local conditions at the time of the measurements (e.g., presence of aquatic vegetation or debris loading on the railroad track trestle bents).

The TUFLOW model was generally calibrated with:

- Measured WSEs in the Tule Canal/Toe Drain
- Limited measured flows at County Road 22
- Georeferenced aerial photographs showing floodplain inundation

*Table 5-3. Boundary conditions and gauge data information for the 2011 calibration event*

| Boundary Location | Data Source | Gauge Data | Data Source |
|---|---|---|---|
| **Yolo Bypass** | | | |
| Fremont Weir spill into Yolo Bypass | CDEC (FRE) | | |
| Knights Landing Ridge Cut | DWR's Water Data Library (A02939) | | |
| Cache Creek Settling Basin | USGS 11452800 and USGS 11452900 | Yolo Bypass near Woodland (YBY) | USGS 11453000 |
| Putah Creek | Estimated using methods developed in this study[1] | | |
| Willow Slough Bypass | Estimated using methods developed in this study[1] | Yolo Bypass at Lisbon (LIS) | DWR's Water Data Library (B91560) |
| **Downstream Boundary** | | | |
| Little Holland Tract | Westland Water District gauge (WWD6)[2] | | |
| Notes:<br>[1] *Long-term Boundary Conditions Development* technical memorandum (cbec 2014)<br>[2] See cbec (2011) | | | |

### 5.4.2 Results Summary

During the 2011 flood recession calibration, the wetting and draining of Yolo Bypass was evaluated by modifying the berm density, adding drainage features, and analyzing the elevations along the 1D/2D interface for the Tule Canal/Toe Drain, as previously described in Section 4.3.4. It was determined that adding berms and drainage features to the 2D grid was necessary, but modifying the elevations along the 1D/2D interface was not necessary. Energy losses were also implemented at specific locations to account for woody debris, hydraulic structures, and flow transitions, same as the 2010 low flow calibration.

Infiltration losses were also added to the 2D grid to accommodate 1) sub grid scale field drainage not captured by the drainage features described in Section 4.3.4 and 2) to remove isolated ponding so as not to affect the LDW calculations. The infiltration or loss rate was set to 0.05 inches/hour (in/hr), which corresponds to a typical value for the saturated hydraulic conductivity of the limiting layer for the silty clay to clay soils underlying the Bypass. At this loss rate, 1 foot of ponded water would take approximately 10 days to be infiltrated. It should be noted that infiltrated water is lost from the model and does not reenter the Tule Canal/Toe Drain.

In addition to these changes, the Fremont Weir inflows to the Yolo Bypass were modified specific to this model calibration. Because the Fremont Weir inflows are derived from a rating curve established for a 1.8-mile-long weir, the estimated inflows are sensitive to small changes in stage. After reviewing the April 9, 2011 aerial photograph (see Figure 5-22), it was determined that there was a relatively small amount of flow through the fish ladder as well as very shallow overtopping over a 100-ft segment of the weir immediately to the east of the fish ladder. However, the published inflow would suggest that there was approximately 5000 to 10000 cfs over the weir, which is incorrect based on the aerial photograph. As such, the Fremont Weir inflows were manually modified given uncertainty in the Fremont Weir gauge data so the modeled flows at County Road 22 would reasonably match the measured flows on April 9 and 12, 2011 (see Section 5.4.1). This was also done to provide the best fit with the measured water surface profiles and inundation extents while keeping Manning roughness coefficients within reasonable limits. In doing so, the Westside tributary flows were left unchanged. The final inflows are a slight modification to the Fremont Weir inflows (see Figure 5-24). However, it should be noted that the long-term simulation for water year 2011 used the full model whereby inflow over Fremont Weir was computed by the model per the long-term hydrologic boundary conditions.

The adjustments described above were made to minimize the RMSE between the measured and modeled values in the water surface profiles as well as minimize the difference in flooded extents between observed and modeled. Figure 5-25 and Figure 5-26 show the modeled water surface profile and wetted extents, respectively, compared to observations made on April 9, 2011. The RMSE for the WSEs was within 0.3 feet, with the largest increases in the profile occurring north of County Road 22. The modeled wetted extents north of I-80 were 3.6 percent (or a net 400 acres) higher than observed, with the largest deviations occurring north of County Road 22. The increases in stage and wetted extents north of County Road 22 are closely linked to the modeled flows being 1,110 cfs higher than measured on April 9, 2011.

Figure 5-27 shows the water surface profile on April 12th. Figure 5-28 and Figure 5-29 show the wetted extents north and south of I-80, respectively, on April 12, 2011. The RMSE for the WSEs was within 0.5 feet, but generally under predicting the measured profile. The modeled wetted extents for the entire model domain were 10 percent (or a net 2800 acres) lower than observed, with the largest deviations occurring along Conaway Ranch and south of Lisbon Weir. The decreases in stage and wetted extents could be linked to the modeled flows being 775 cfs lower than measured on April 12, 2011 and a simplified drainage network that is perhaps too efficient at draining the Yolo Bypass.

Given the uncertainties in the modeled inflows over Fremont Weir and contributions from major drainage features not represented by the Westside tributaries (such as the City of Davis and RD 2068), along with simplified representation of field berms and drainage features, the 2010 low flow and 2011 flood recession calibration results are presumed to be satisfactory and to provide a relatively reasonable description of the inundation patterns within the Yolo Bypass during frequent events.

Table 5-4 shows the resultant Tule Canal/Toe Drain subreach multipliers that were applied to the composite Manning roughness coefficients assigned from the medium scale vegetation mapping.

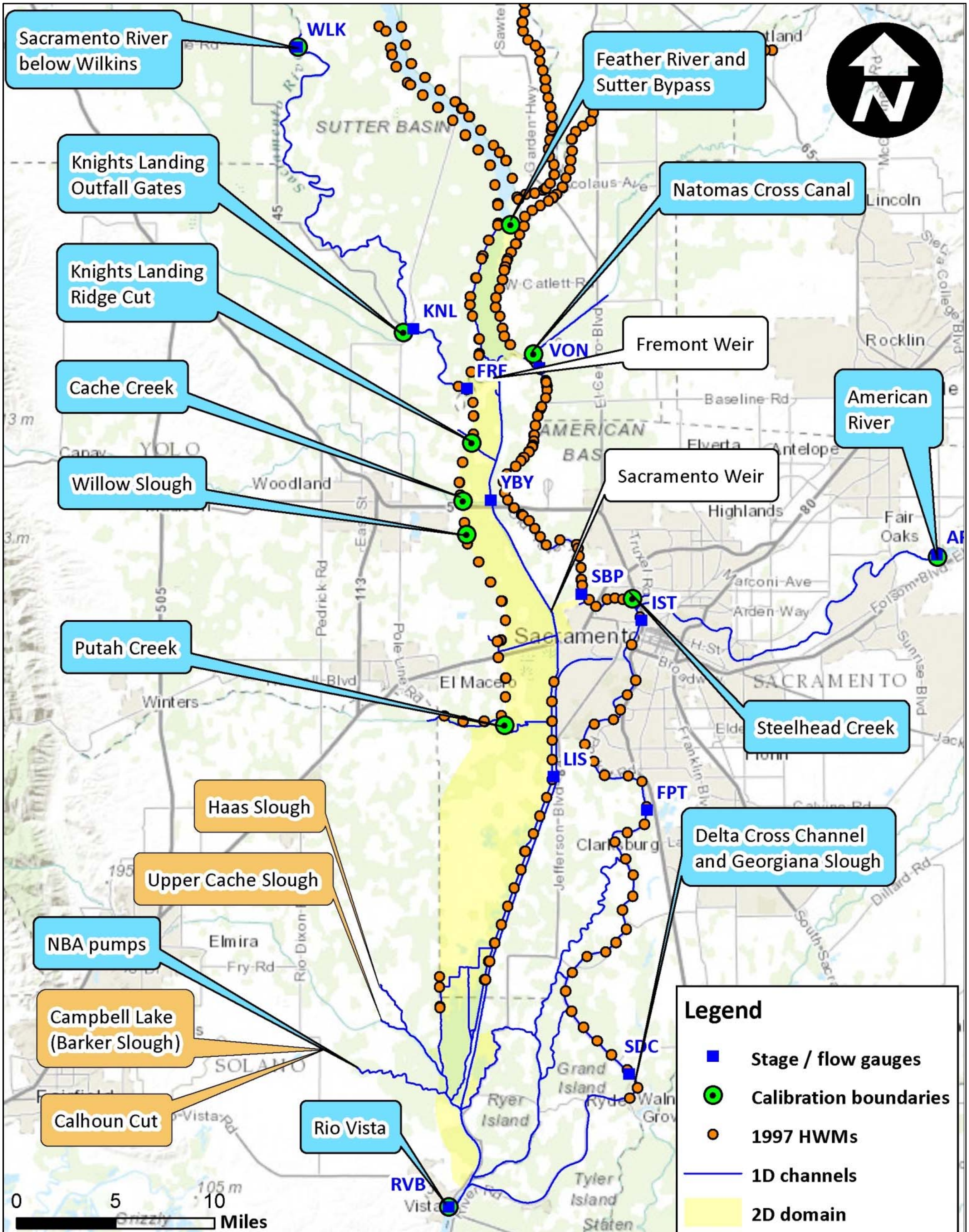
*Table 5-4. Tule Canal/Toe Drain 1D low flow roughness multipliers*

| Subreach Stationing (feet) | Manning Roughness Coefficients Multiplier | Subreach Stationing (feet) | Manning Roughness Coefficients Multiplier |
|---|---|---|---|
| 2500 - 69227 | 1.5 | 84226 - 91726 | 0.95 |
| 70606 - 75726 | 1.25 | 93226 - 98226 | 1.1875 |
| 77226 - 80726 | 1.1 | 99726 - 108470 | 1.25 |
| 81226 - 82726 | 1.045 | 108727 - 157227 | 0.95 |

## 5.5 Results Summary

Three calibration events were used to optimize model parameters and demonstrate that the model performs as expected. Both low flow and high flow scenarios were conducted to ensure the model handles the range of expected flow rates. The RMSE for the WSEs for the low and high flow calibration events were 0.3 ft and 0.9 ft, respectively, providing good fit between observed and modeled results. The 2011 flood recession calibration included aerial photos which provided the ability to compare modeled and observed inundations extents. The RMSE for the WSEs for April 12, 2011 were within 0.5 ft and the area of inundation was within 10% as shown in the aerial photographs. The results of the three calibration events provide assurance that the model represents well the flooding and draining processes in the bypass. The 2010 and 2011 calibrations also provide verification that the flow estimation techniques for the Westside tributaries (see Section 4.4.8) are reasonably accurate given the low RMSE for the WSEs despite the uncertainty in the inflows from major drainage features.

We recognize that the USGS has a comprehensive network of gauges recording stage and flow in the slough system south of the Stair Step and Courtland that can be used to calibrate the flow splits within the Cache Slough Complex. Model calibration was not performed in great detail within the Cache Slough Complex during the 2010 and 2011 calibrations as those calibrations were focused on the Yolo Bypass north of Liberty Island. However, the long-term stage verification at Liberty Island (see Figure 6-6) and downstream boundary sensitivity (see Figure 6-7 and Figure 6-8) demonstrate that the model reasonably predicts WSEs south of the Stair Step and that small deviations in stage do not affect the model results within the area of interest (i.e., Yolo Bypass bounded by Fremont Weir and the Stair Step).



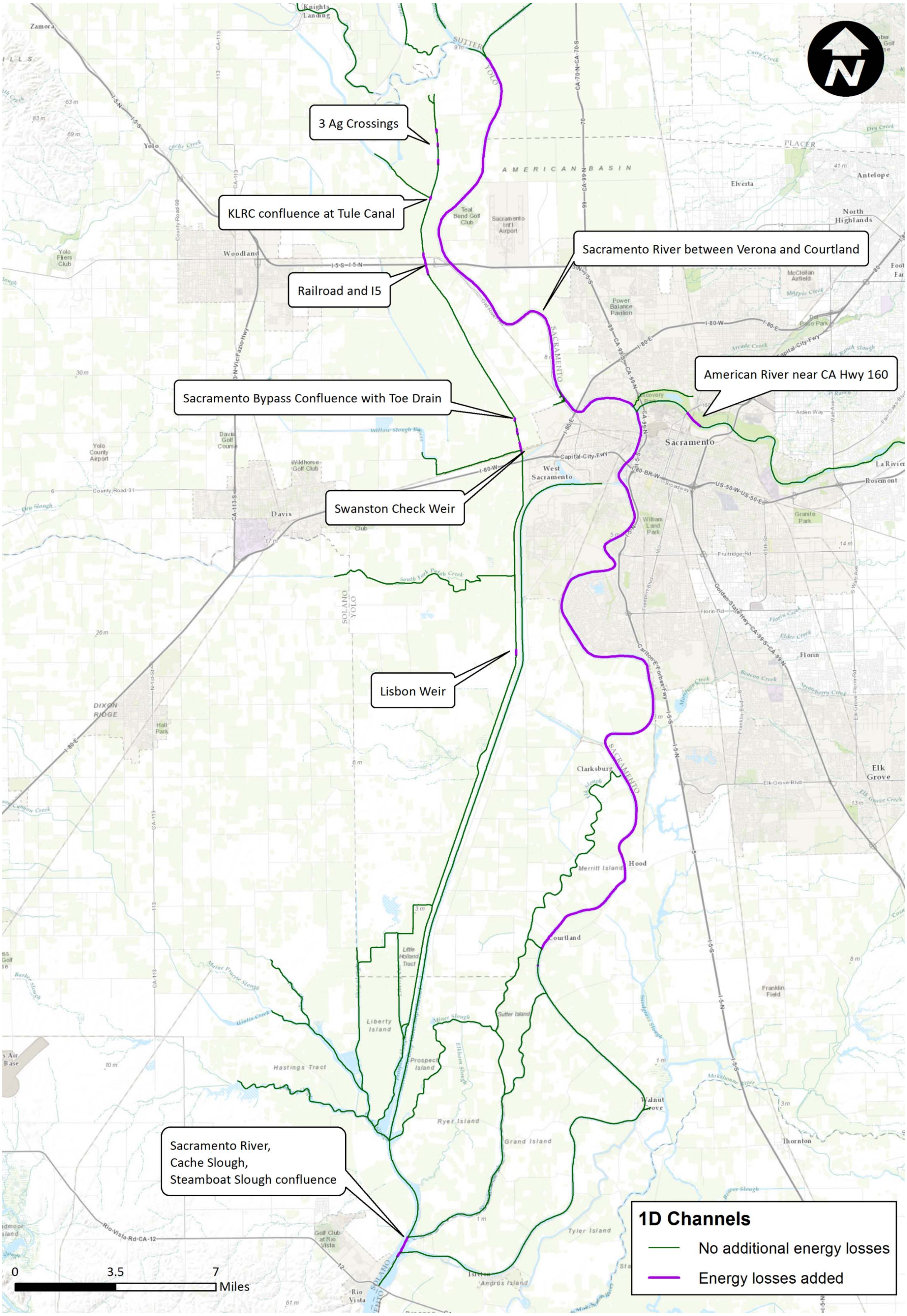

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**1997 Flood Calibration Data**

Prepared for DWR | Created By: SP

**Figure 5-1**



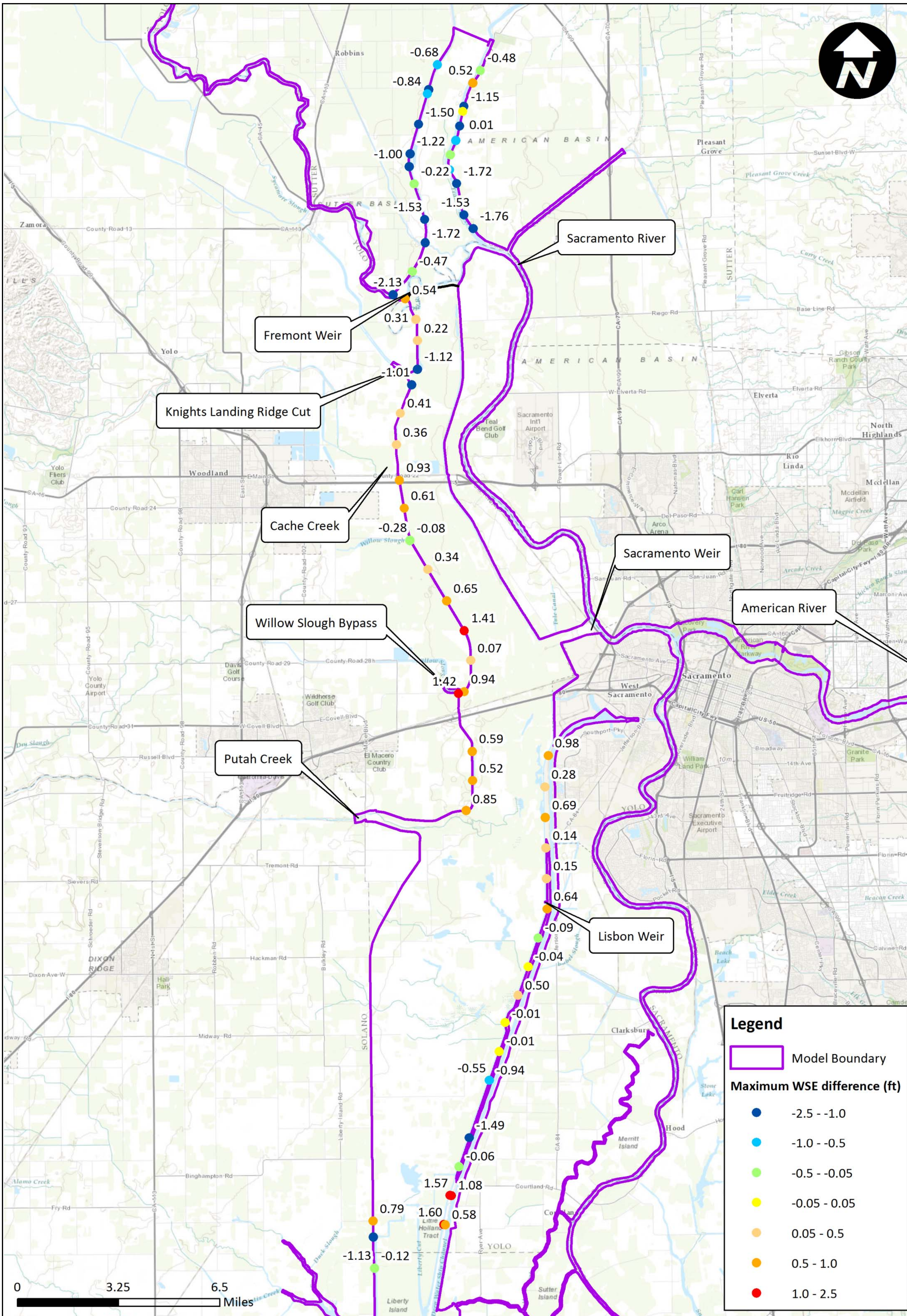

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**1D Channels with Additional Energy Losses**

Prepared for DWR | Created By: RDJ

**Figure 5-2**



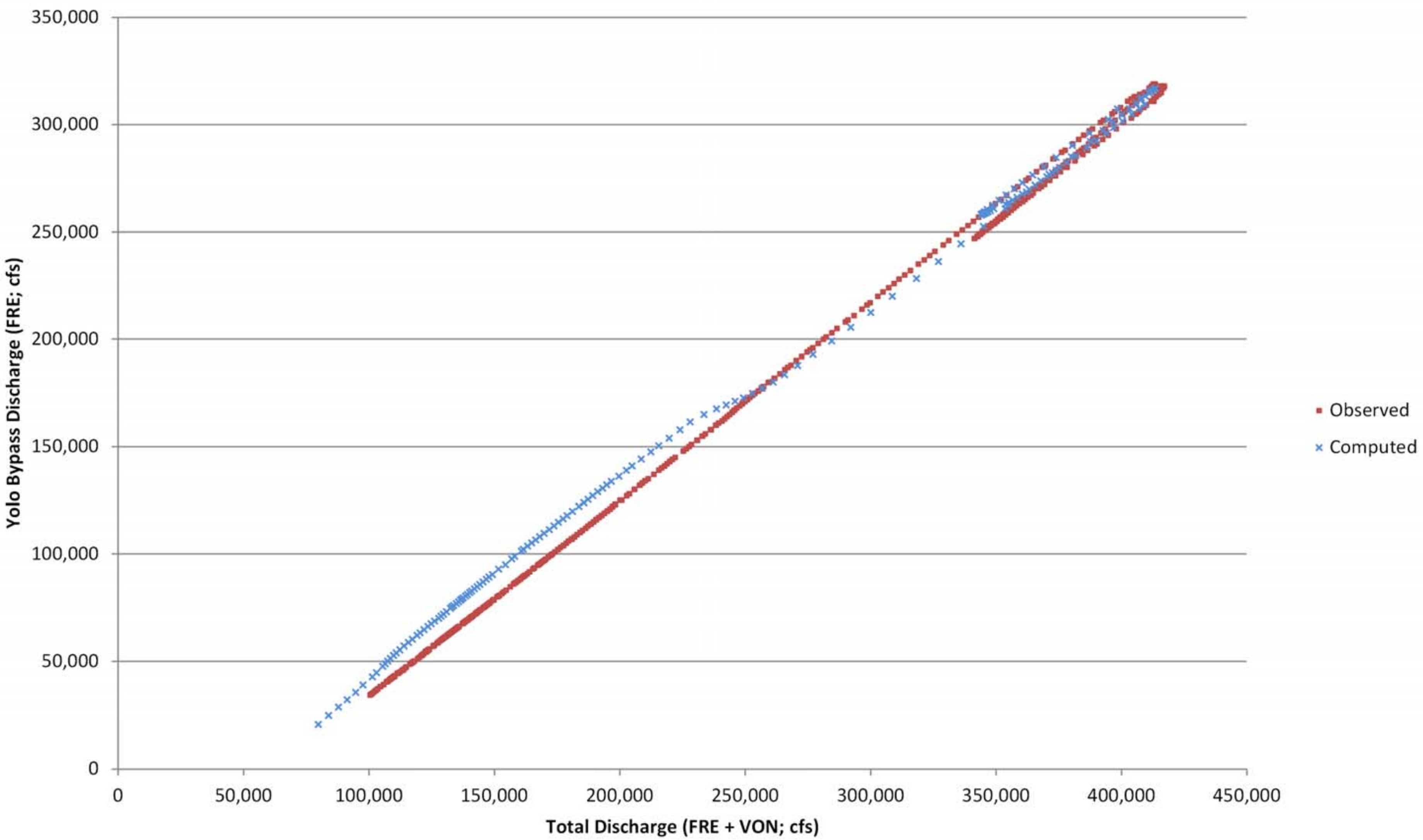

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**1997 Calibration Comparison to High Water Marks**

Prepared for DWR | Created By: RDJ

**Figure 5-3**

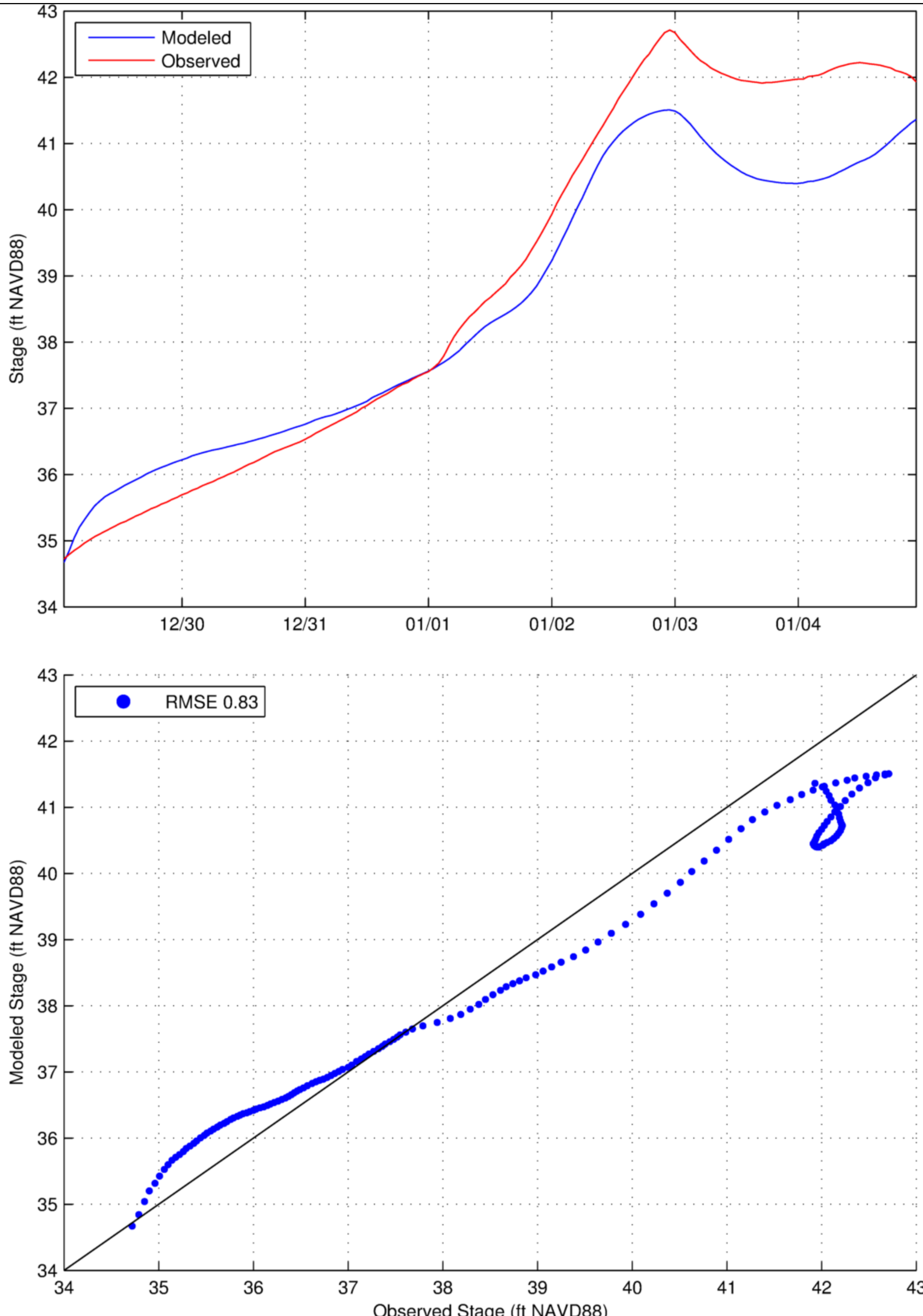



Notes: Comparison of Yolo Bypass discharge vs total discharge for computed and observed data.

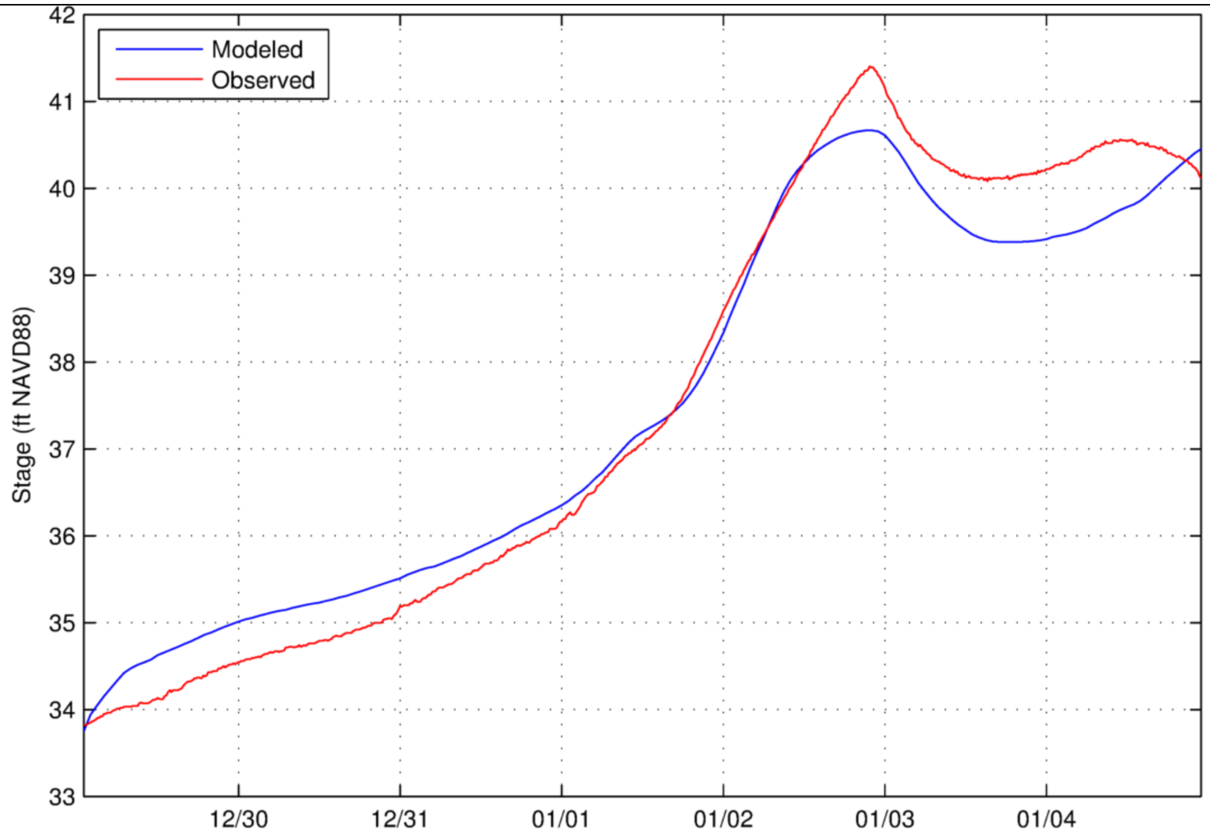
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

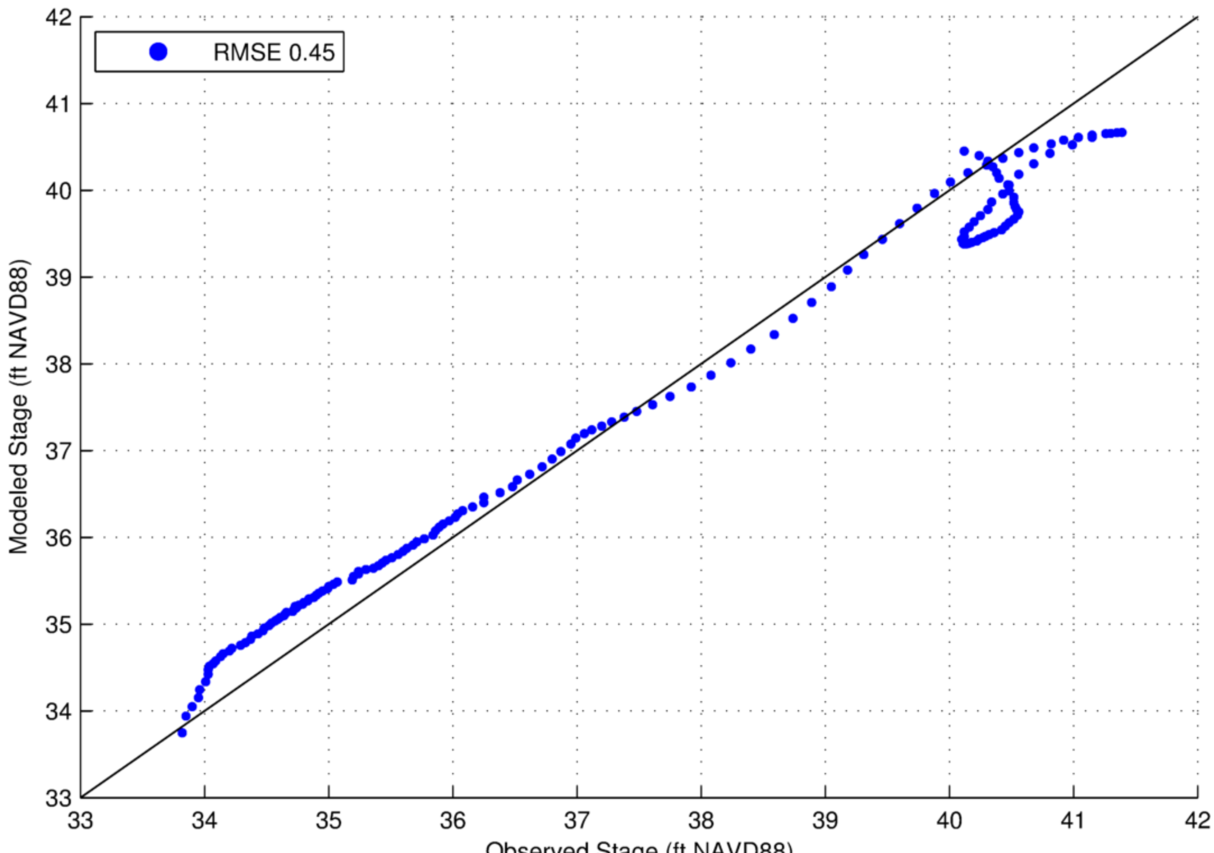
**1997 Calibration Sacramento River Flow Split**

| Prepared for DWR | Created By: RDJ | **Figure 5-4** |
|---|---|---|

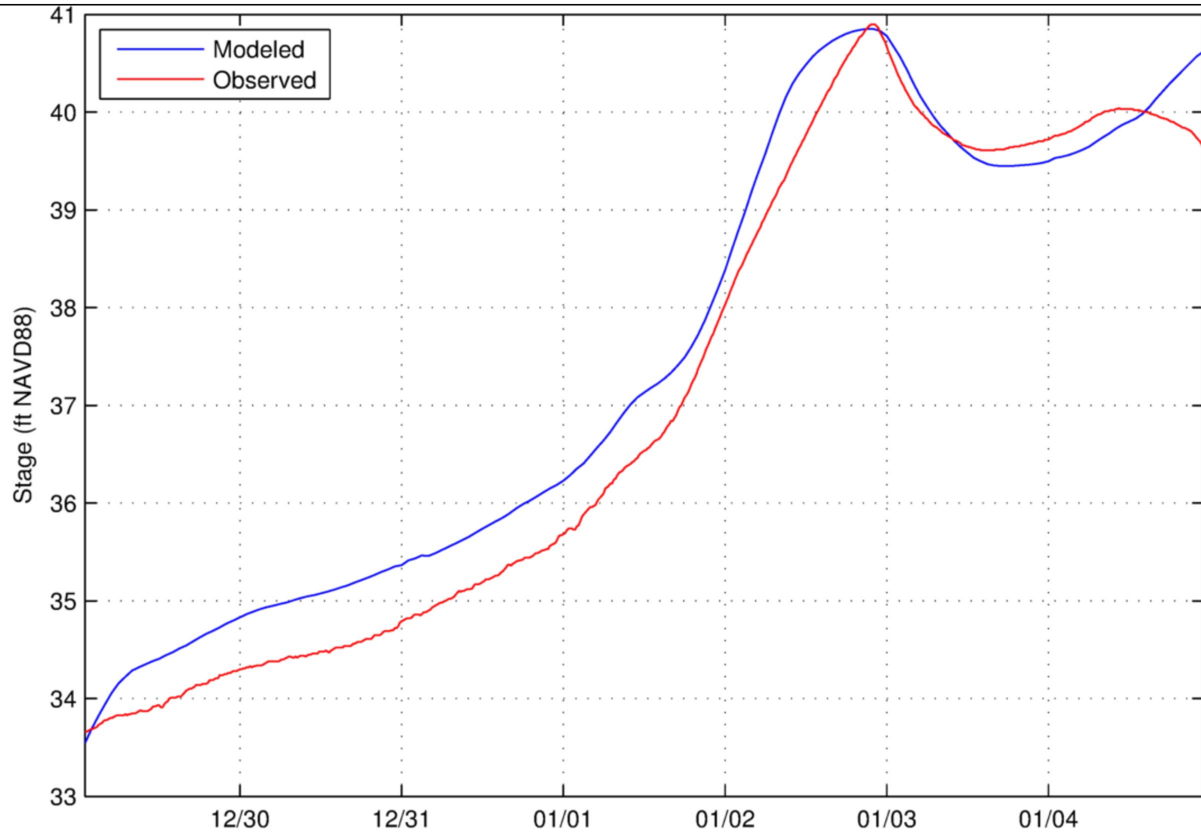


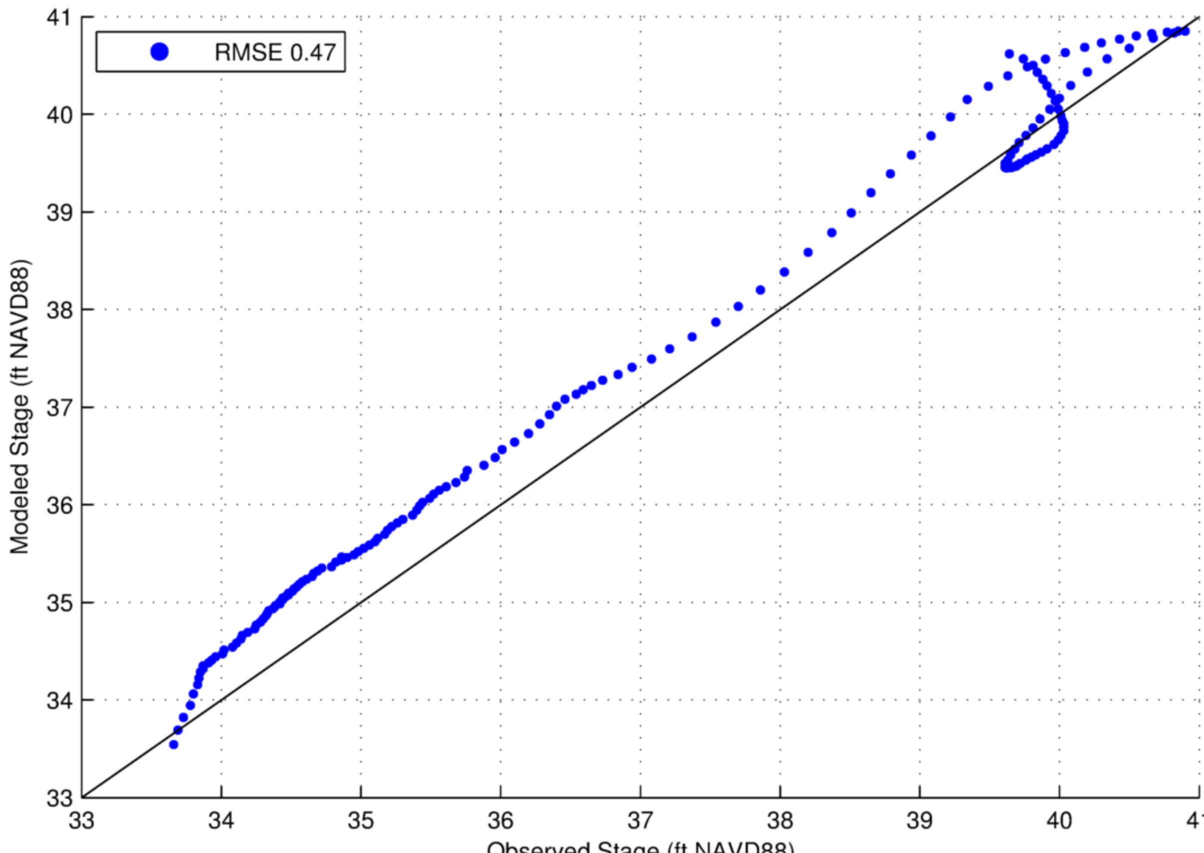

| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **1997 Calibration Sac at Knights L Stage** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: RDJ | **Figure 5-5** |



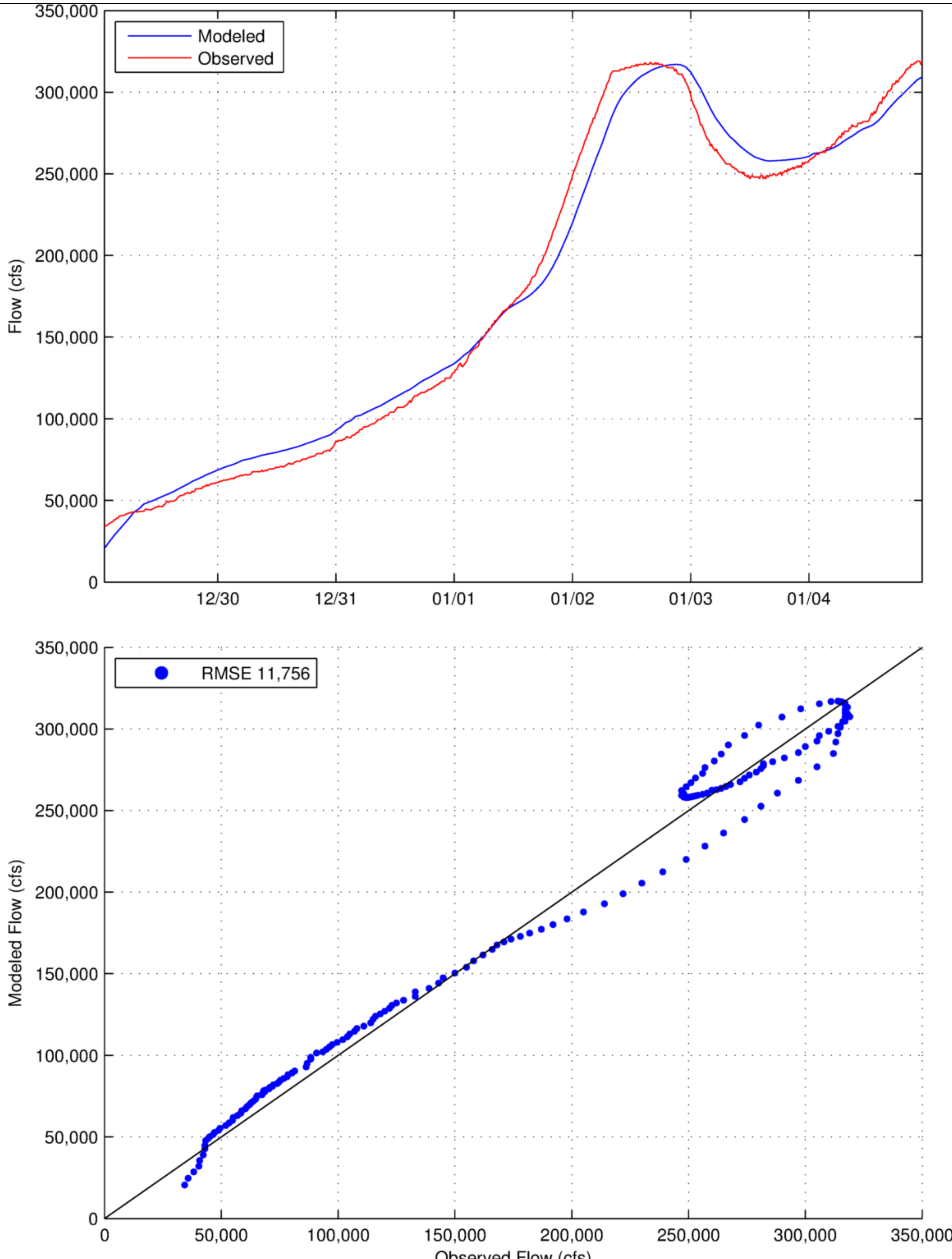




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**1997 Calibration Fremont Weir West Stage** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: RDJ | **Figure 5-6** |

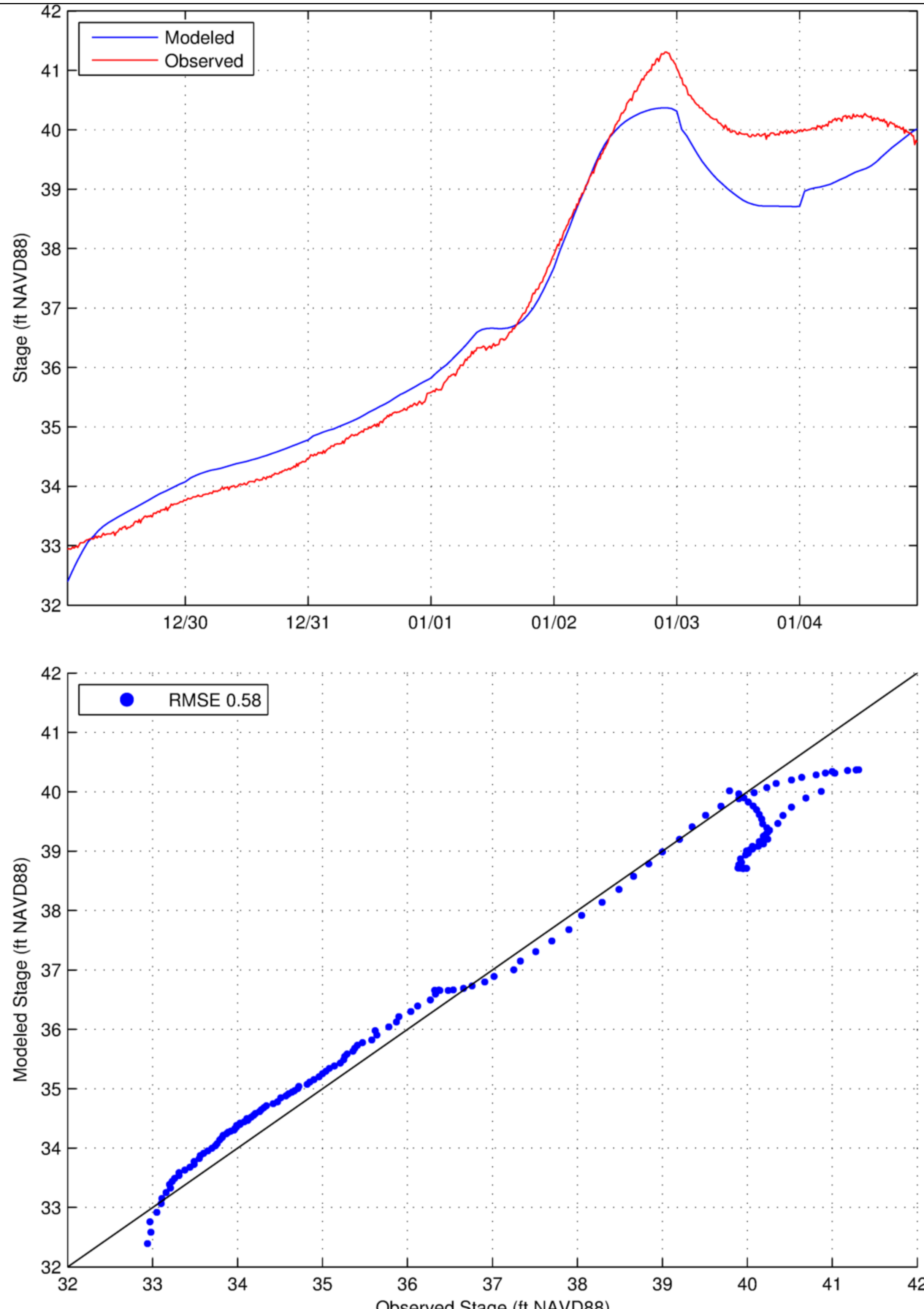


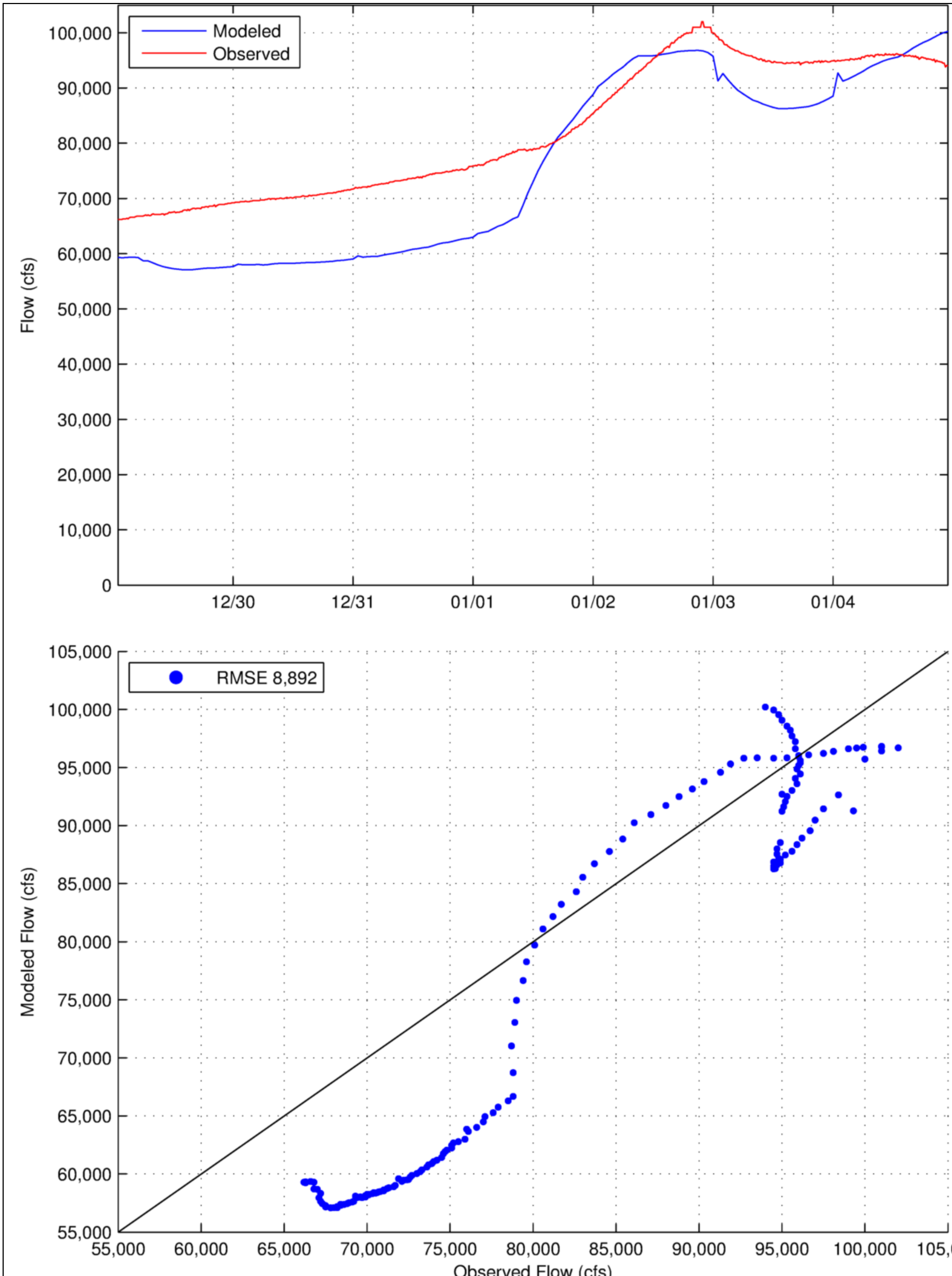

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **1997 Calibration Fremont Weir East Stage** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-7** |



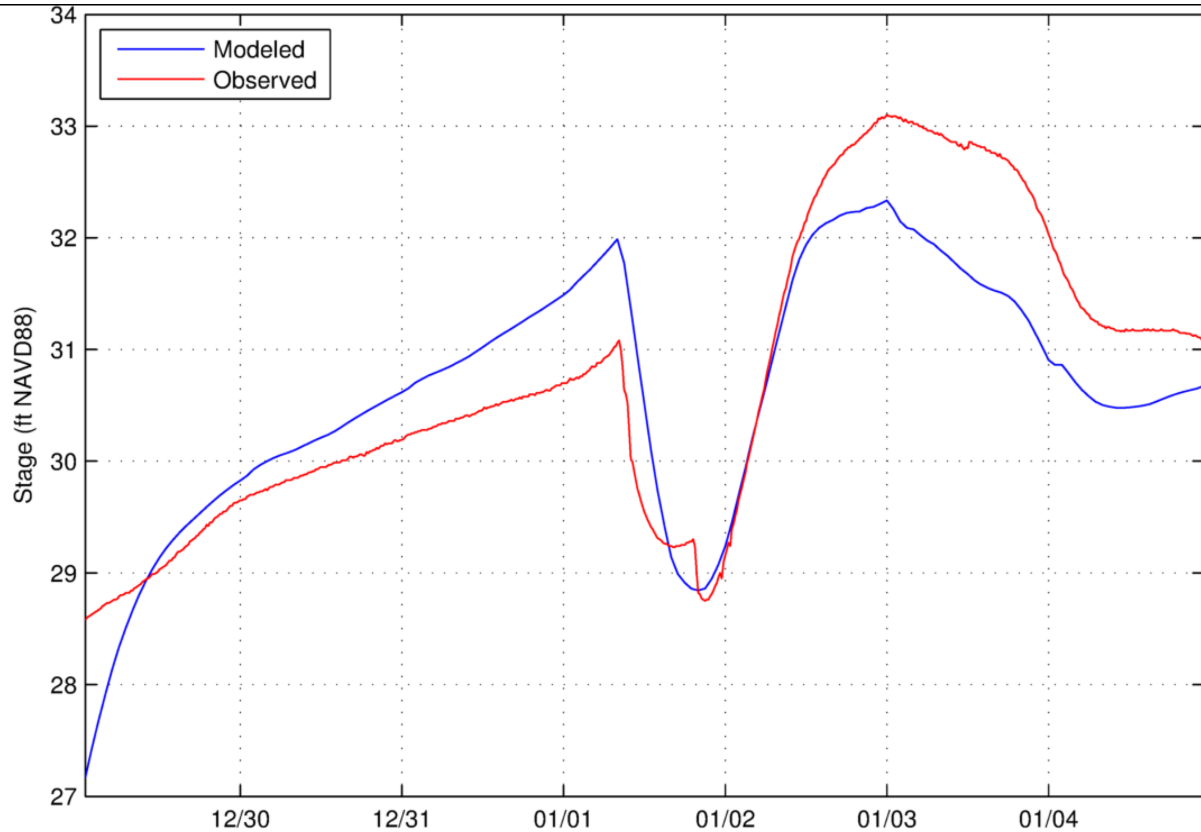

| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **1997 Calibration Fremont Weir Flow** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-8** |

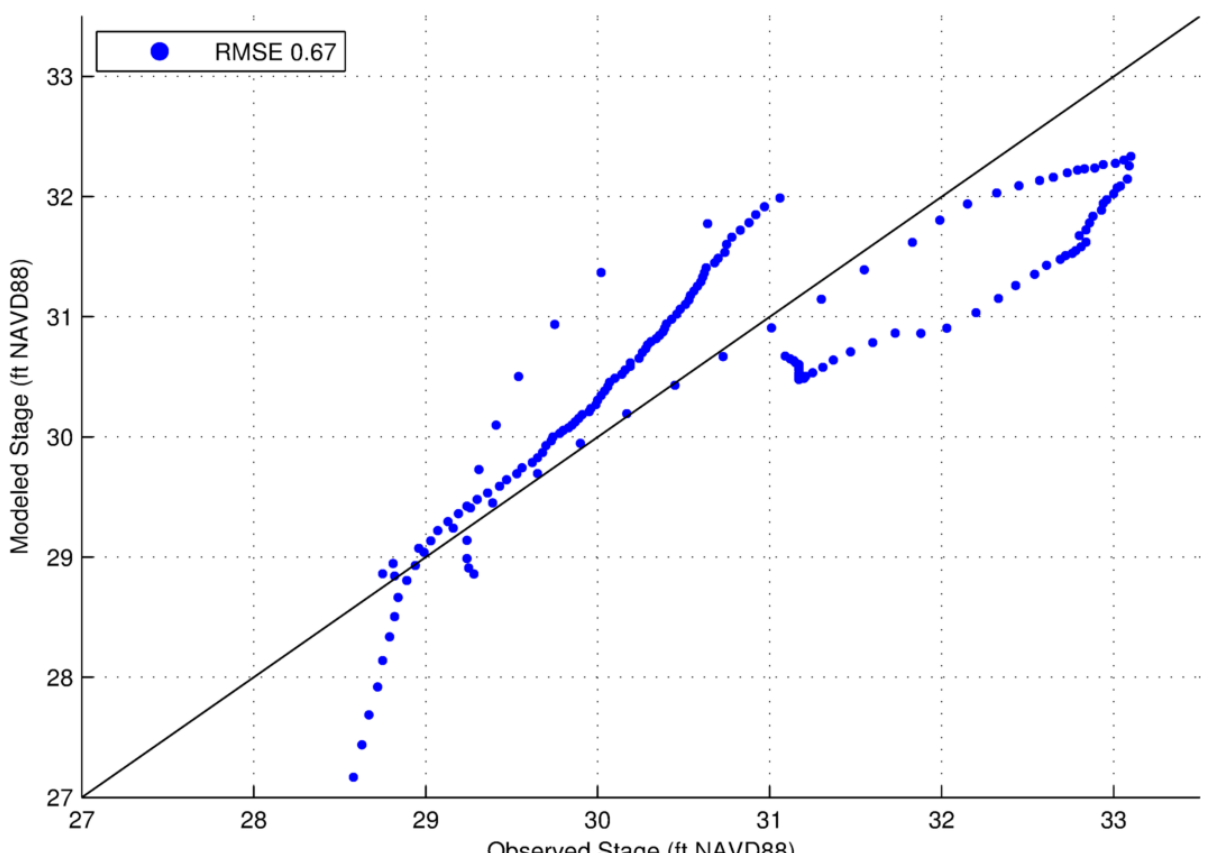



| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **1997 Calibration Verona Stage** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-9** |

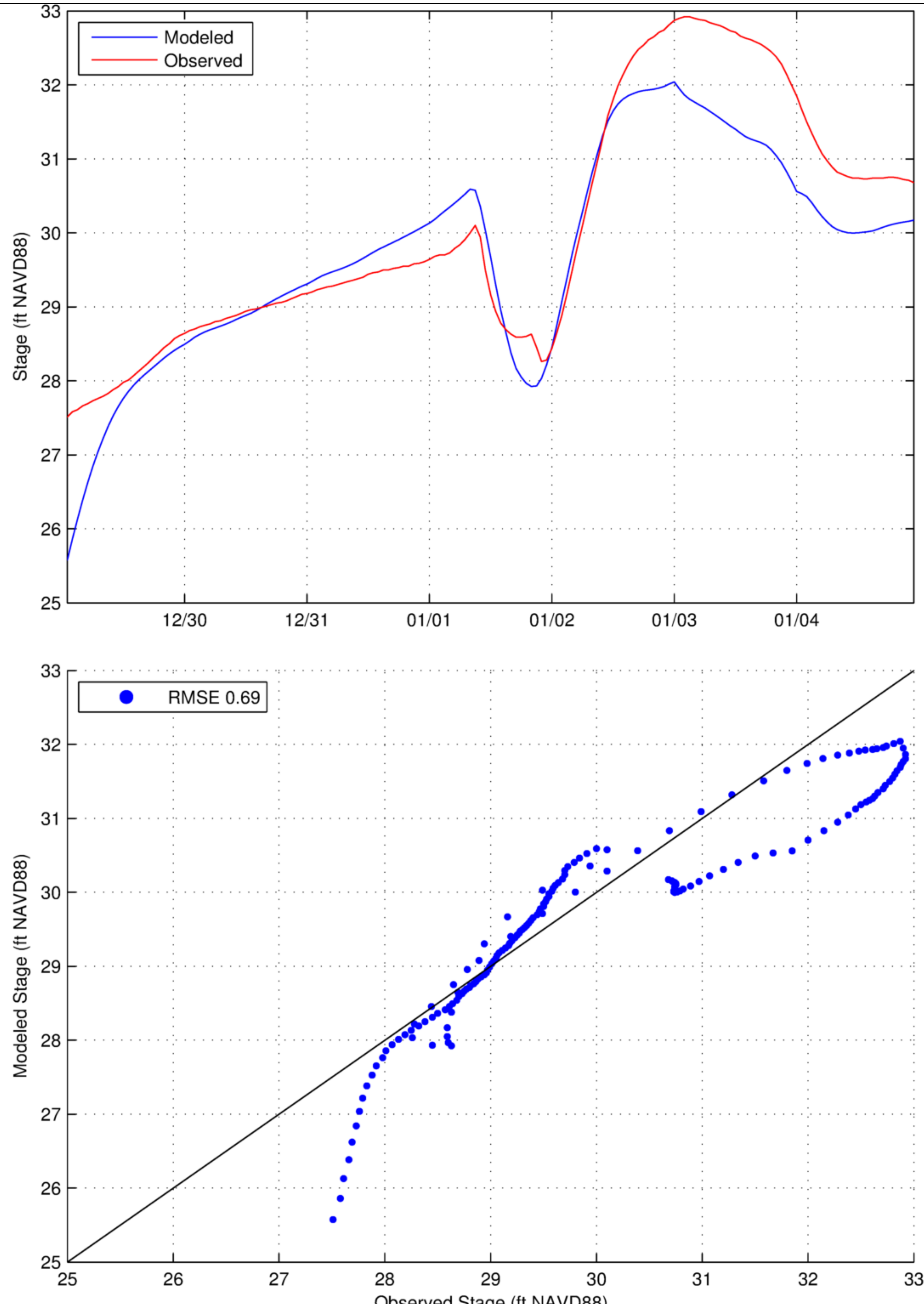



| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**1997 Calibration Verona Flow** |
|---|---|---|
| | | Prepared for DWR \| Created By: RDJ \| **Figure 5-10** |

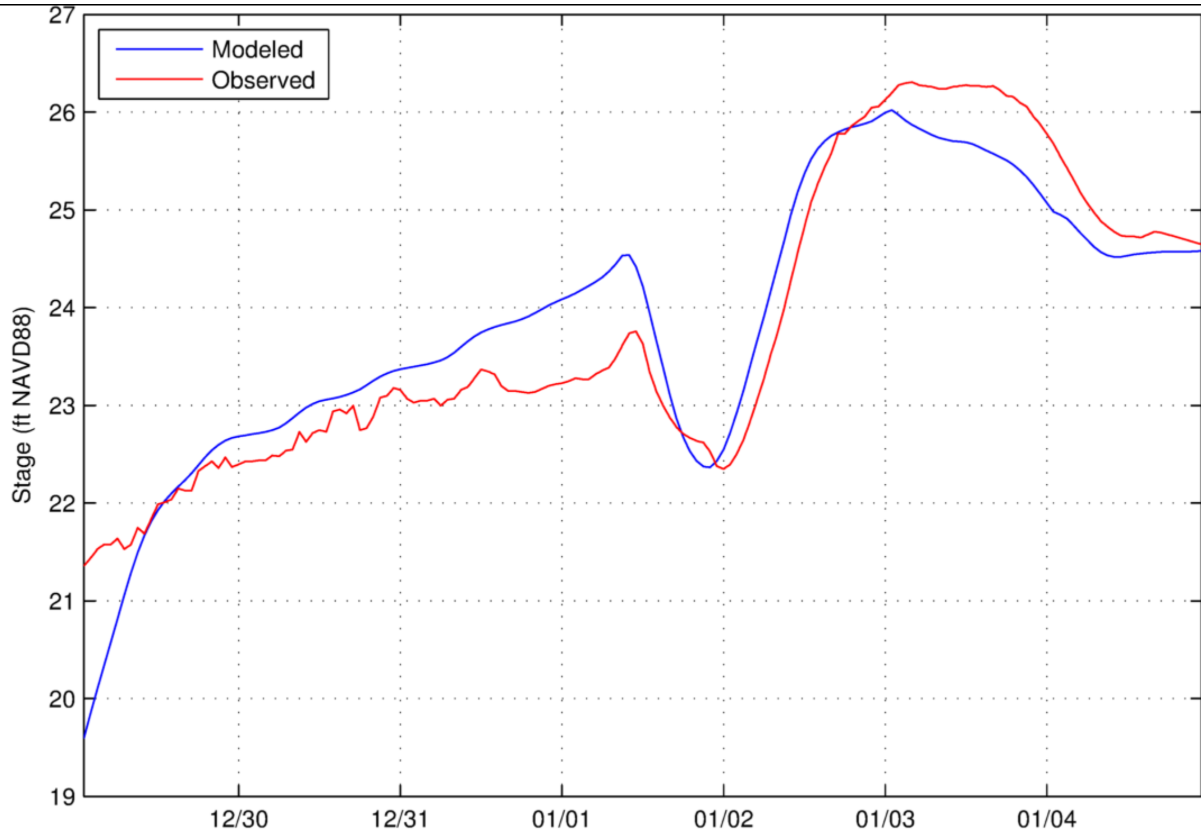


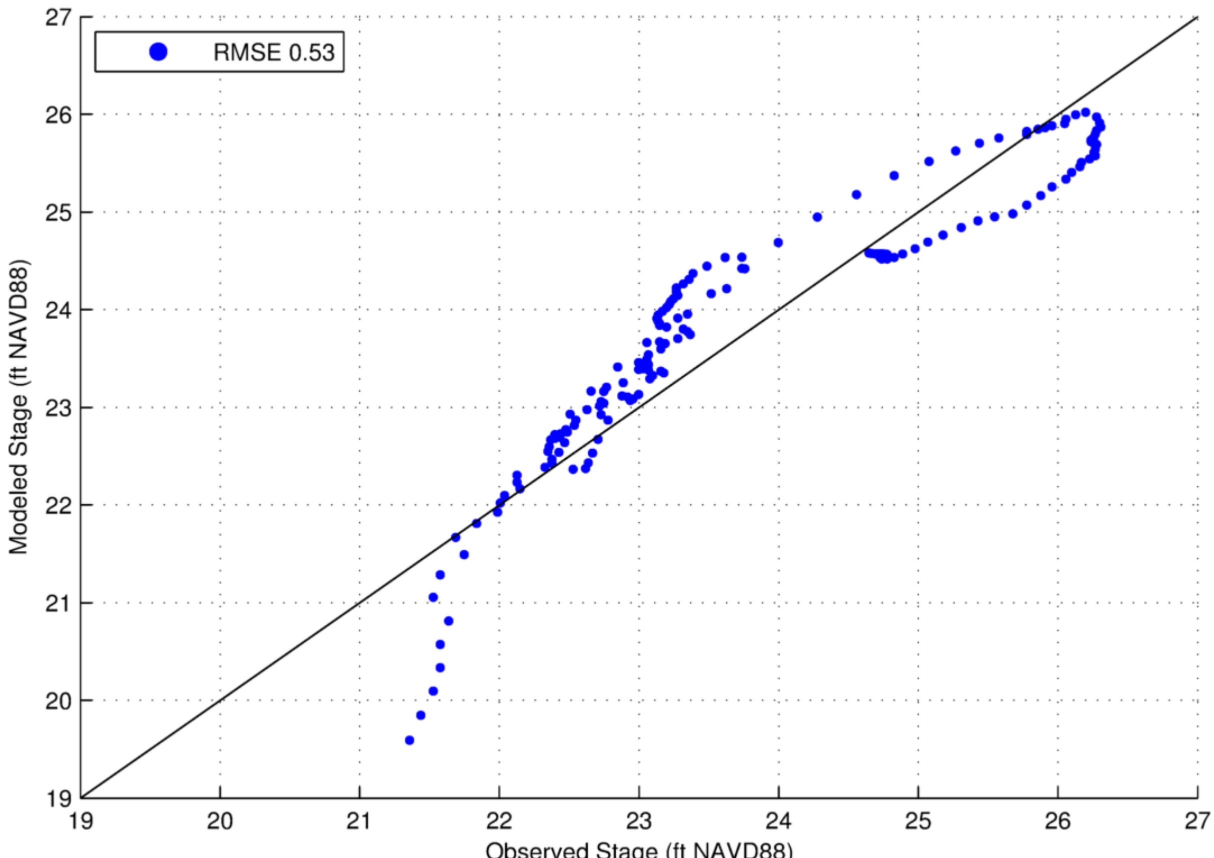




| Notes: Upstream of Weir | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **1997 Calibration Sacramento Weir Stage** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: RDJ | **Figure 5-11** |

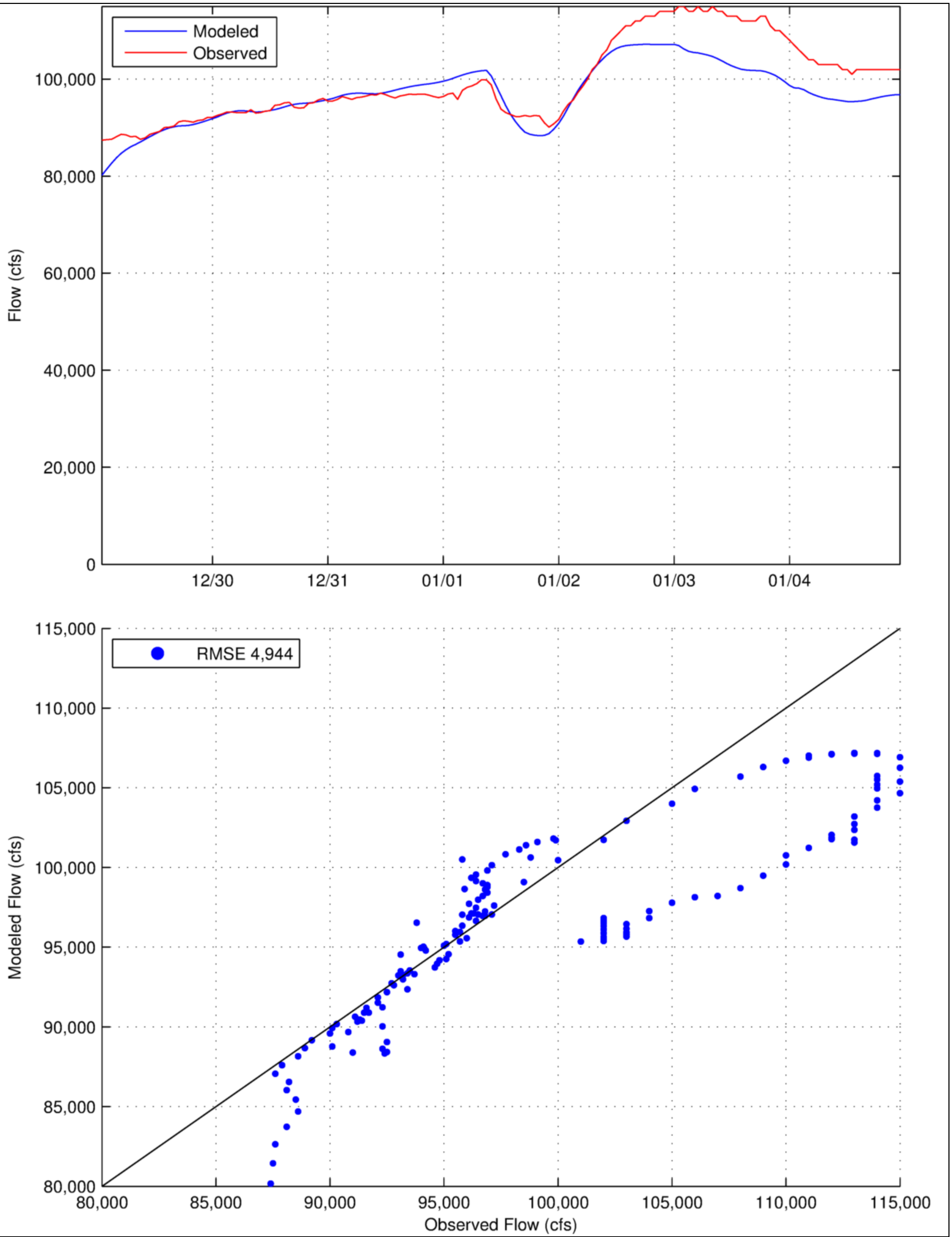



| | | | |
|---|---|---|---|
| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **1997 Calibration Sac U/S Ist Stage** | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-12** |

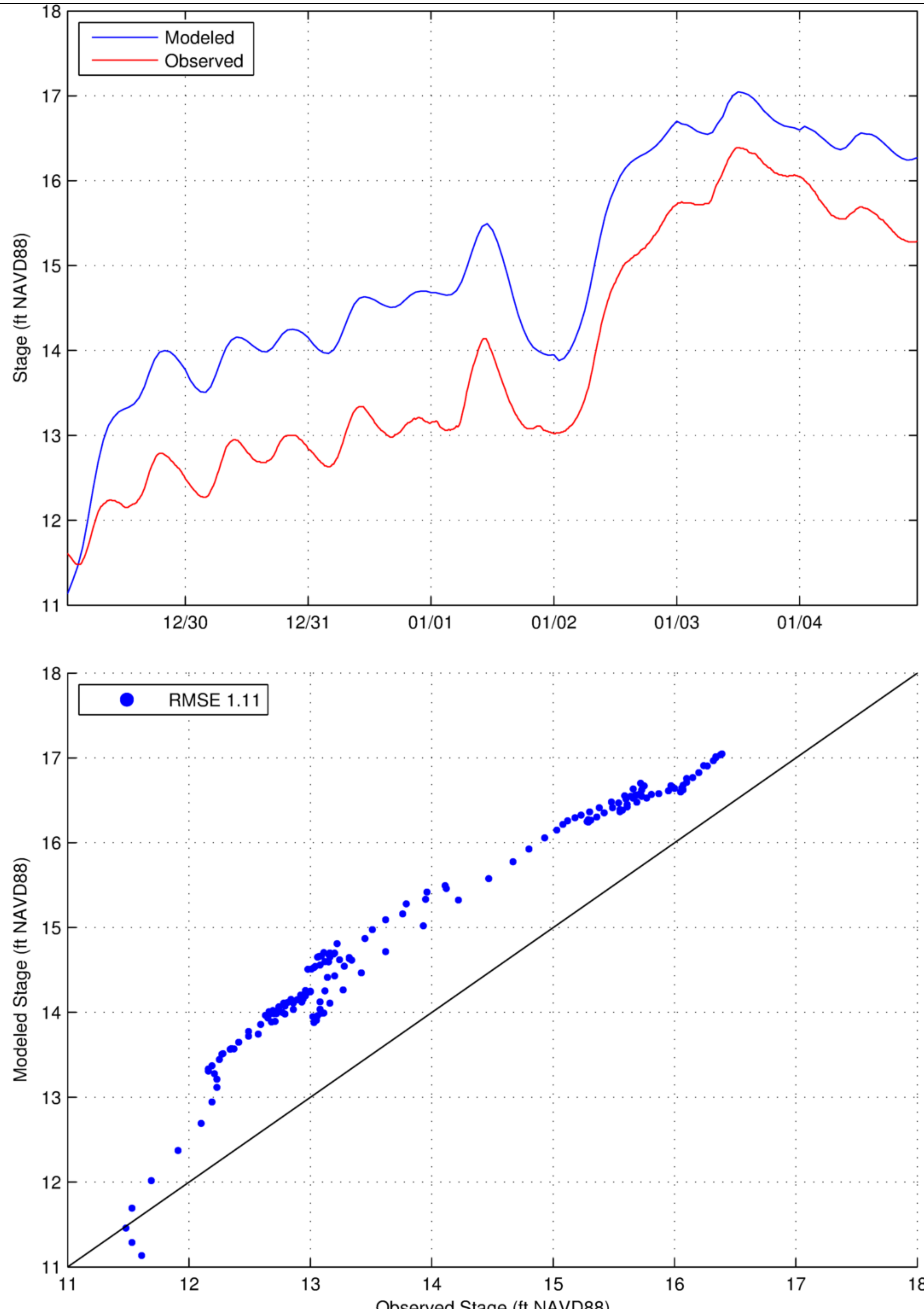


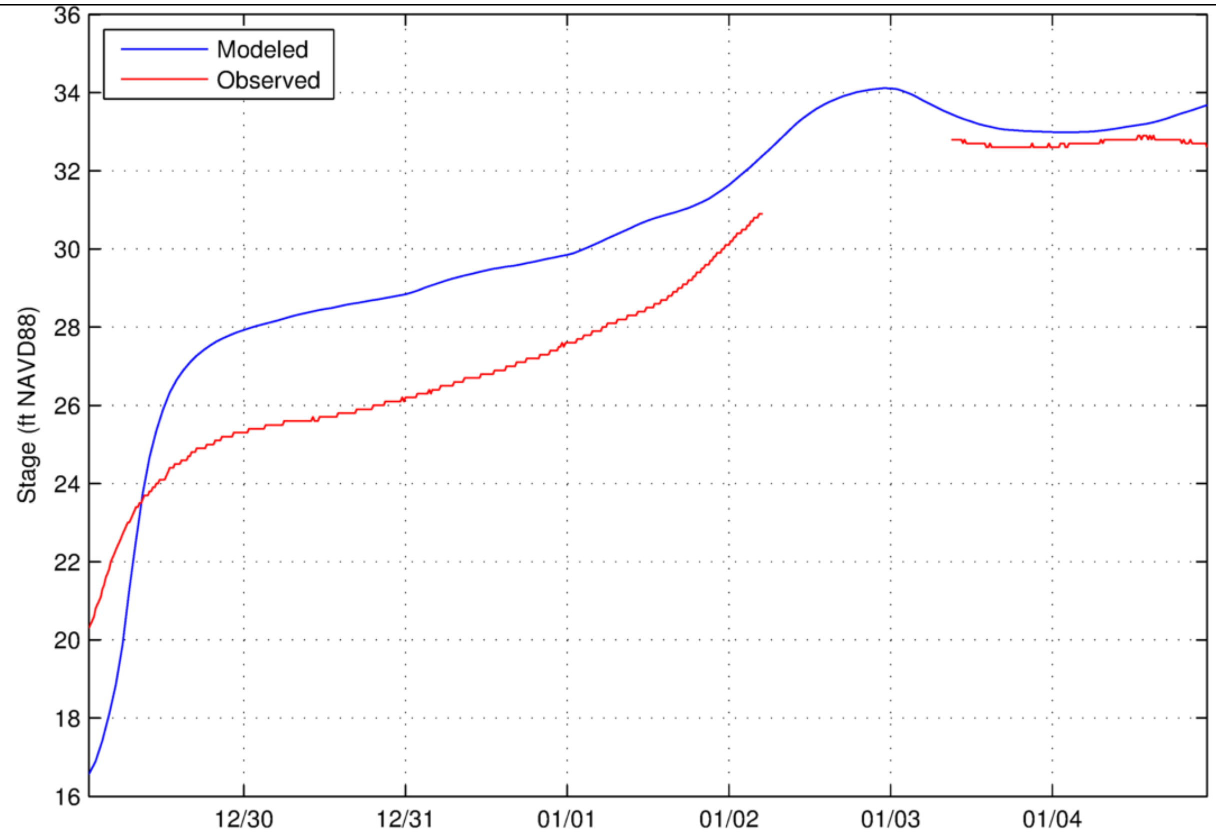

| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **1997 Calibration Sac at Freeport Stage** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-13** |

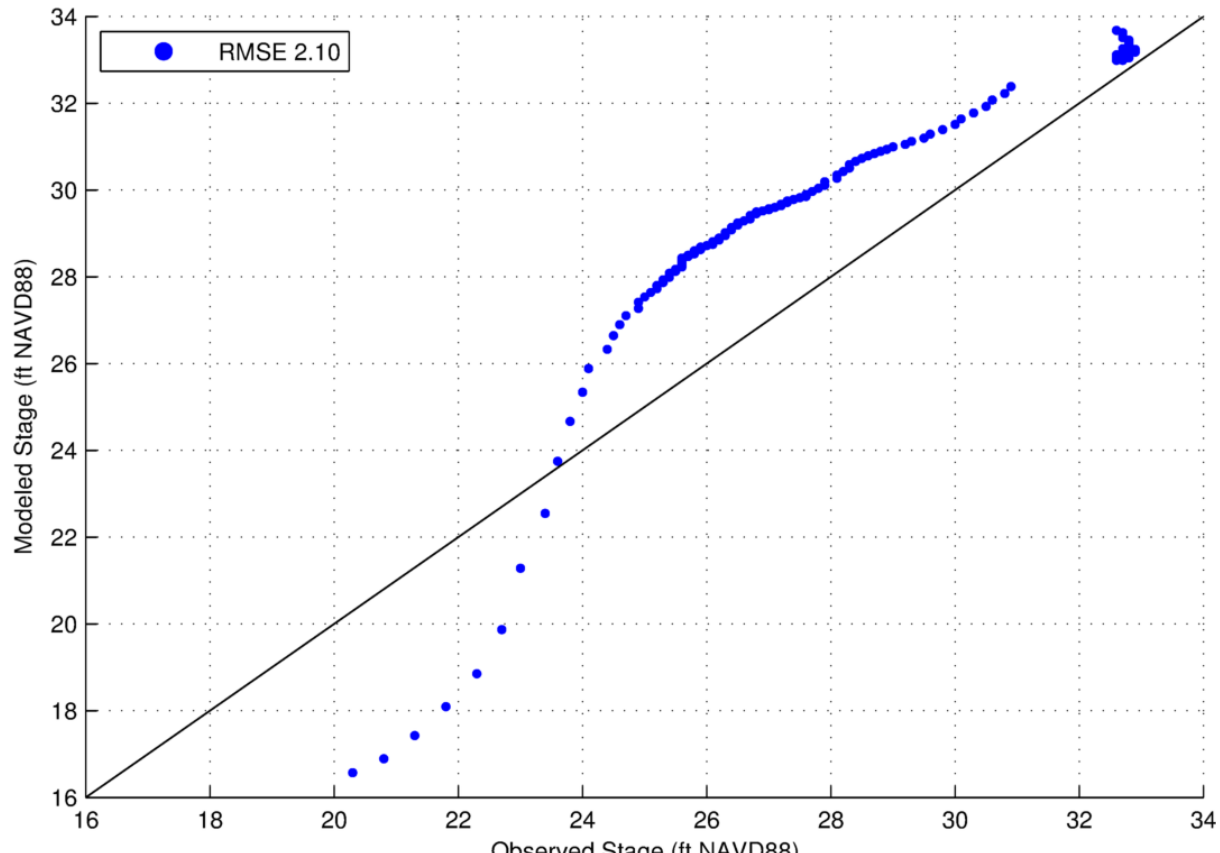



| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **1997 Calibration Sac at Freeport Flow** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-14** |

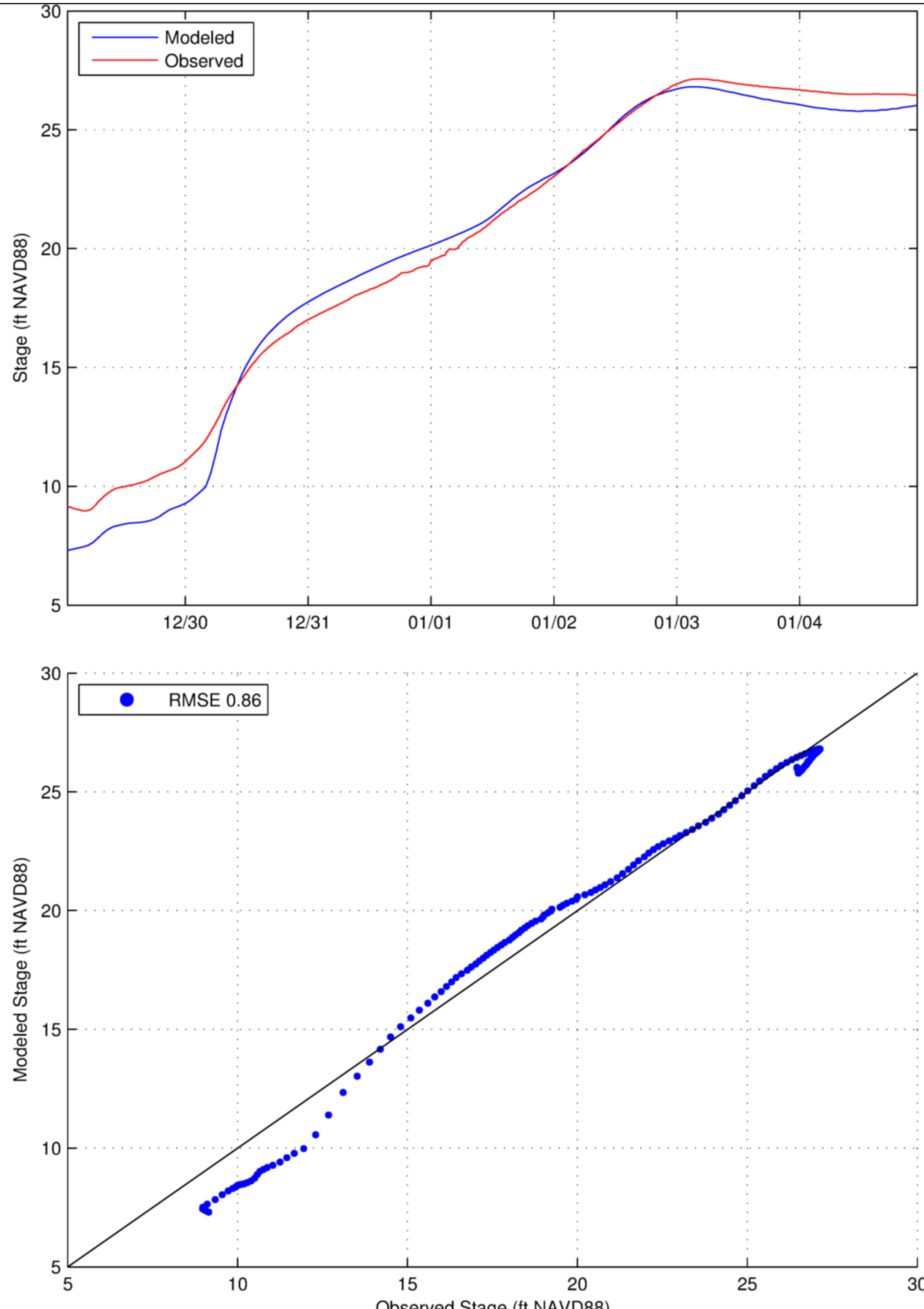



| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**1997 Calibration Sac at Walnut Grove Stage** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: RDJ | **Figure 5-15** |

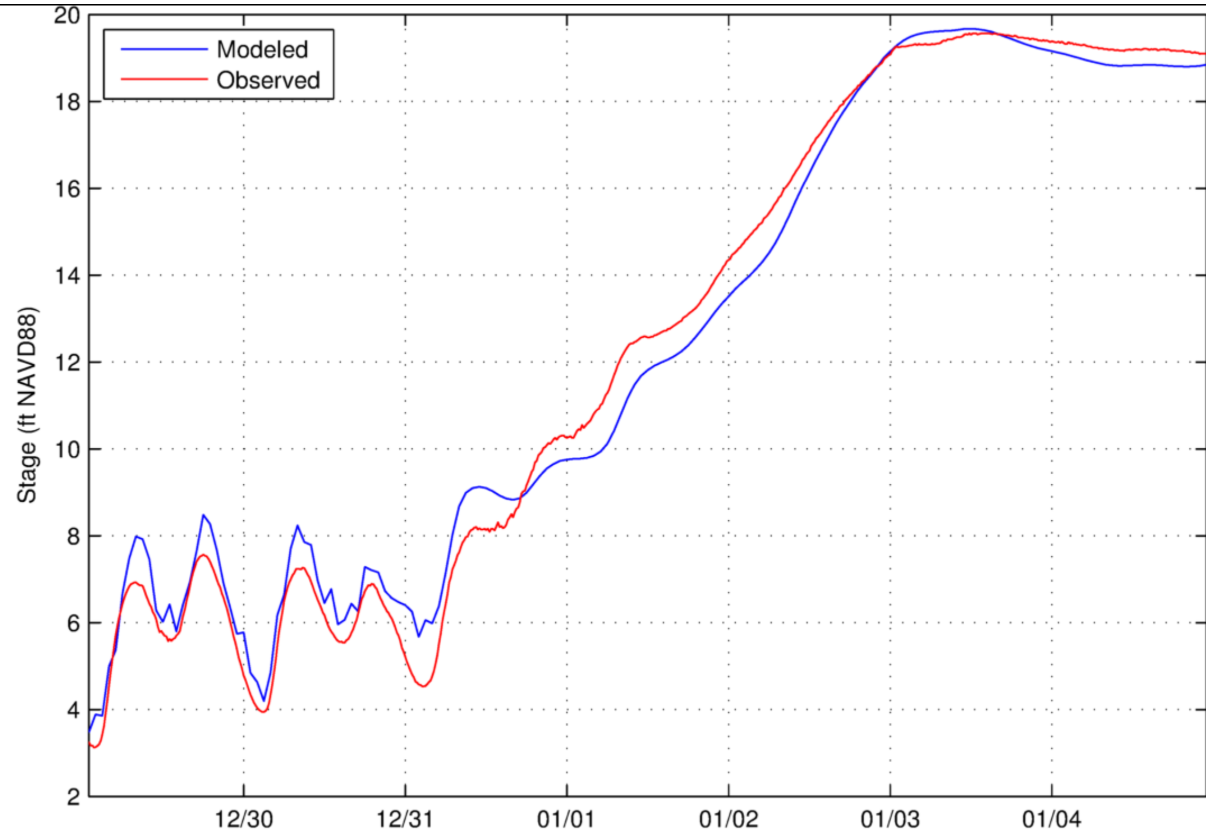


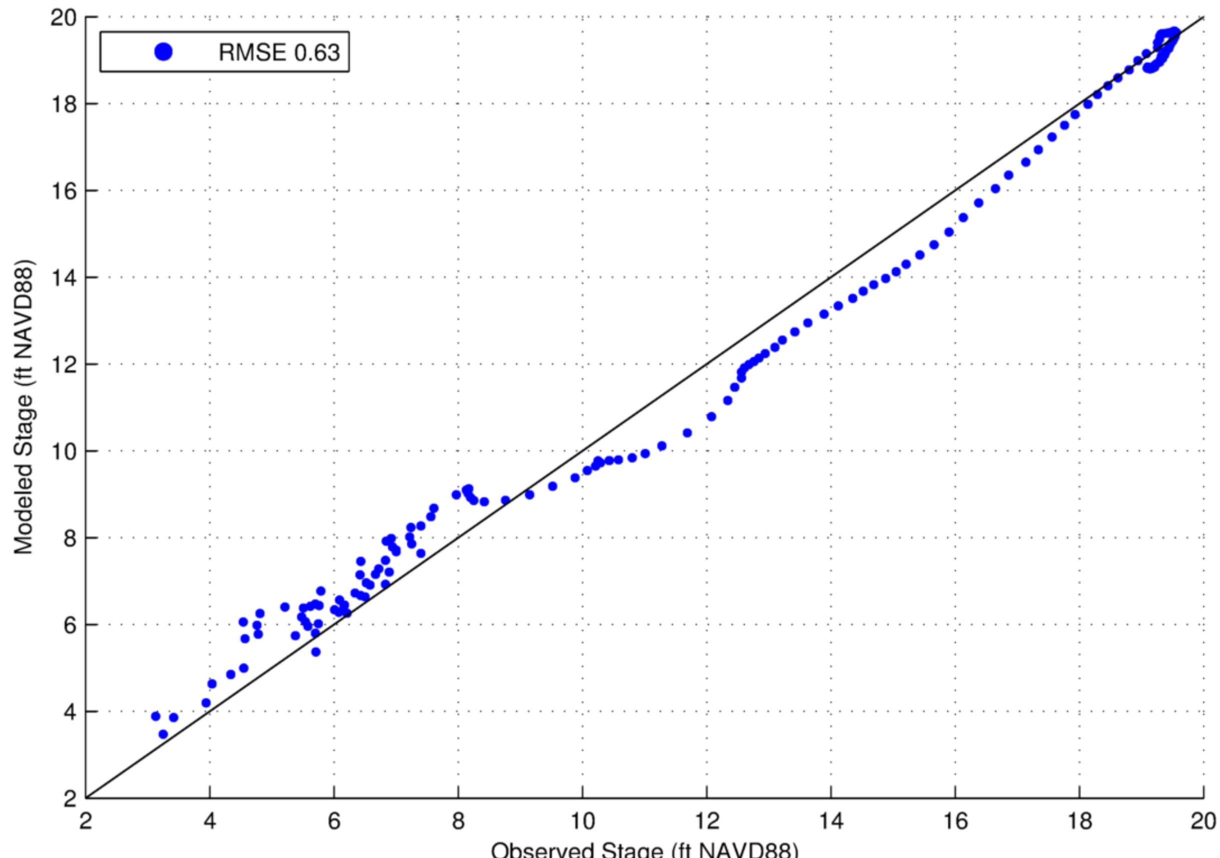




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **1997 Calibration Near Woodland Stage** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: RDJ | **Figure 5-16** |

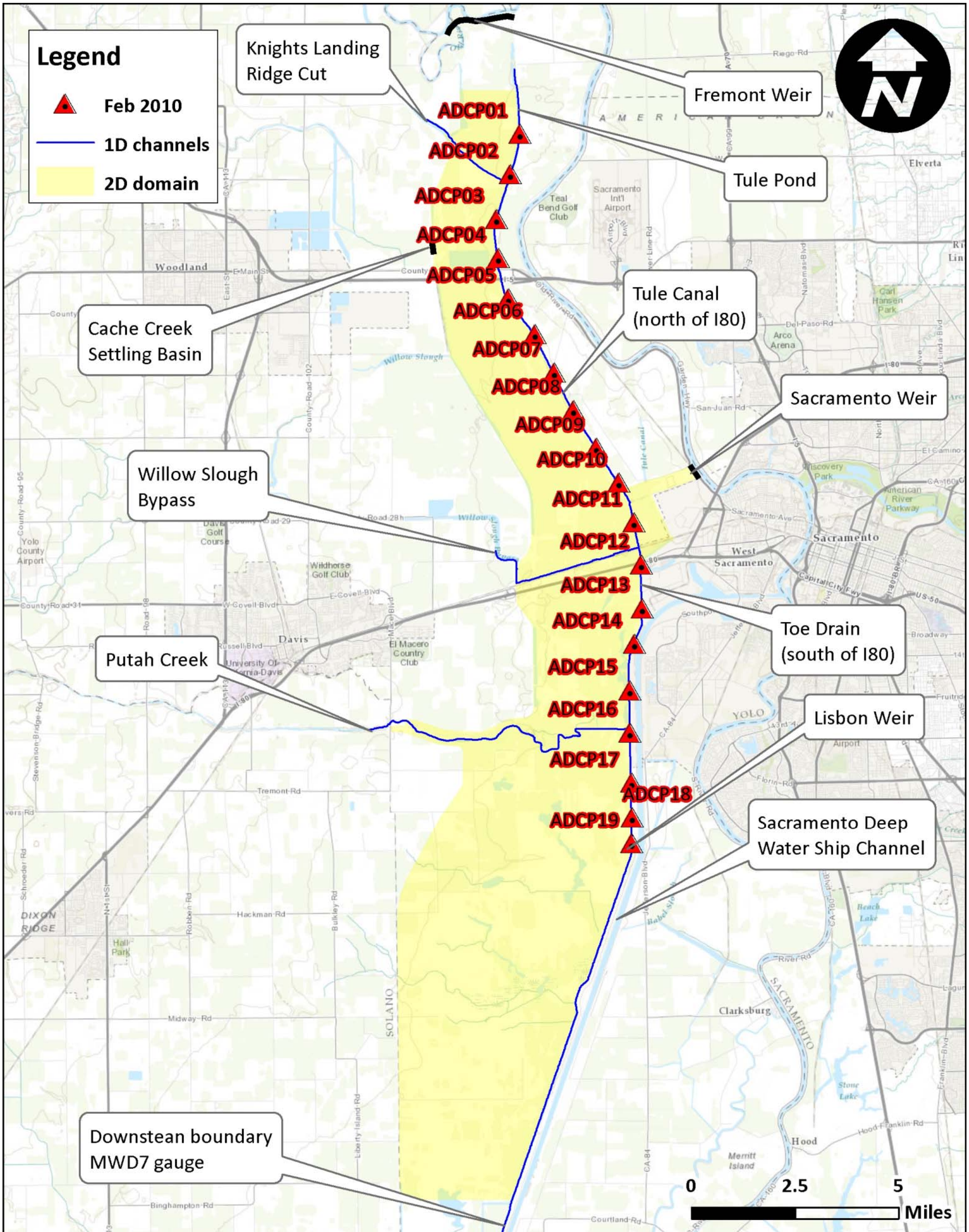



| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **1997 Calibration Lisbon Weir Stage** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 5-17** |




| | | | |
|---|---|---|---|
| Notes: Upstream of Weir | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | |
| | | **1997 Calibration Liberty Island Stage** | |
| | Prepared for DWR | Created By: RDJ | **Figure 5-18** |



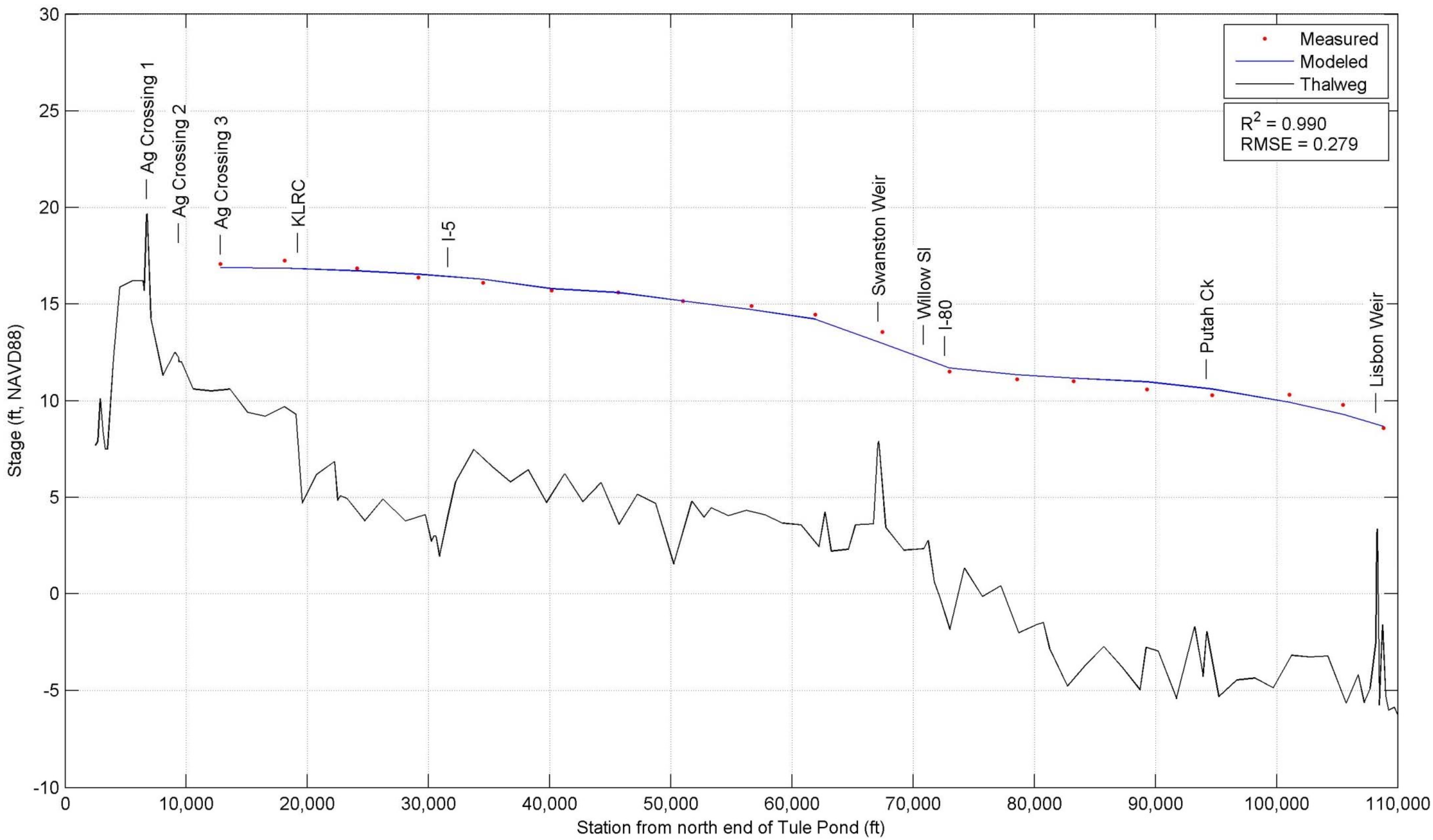

Notes:

HDR cbec eco engineering

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**2010 Low Flow Calibration Data**

| Prepared for DWR | Created By: SP | **Figure 5-19** |
|---|---|---|

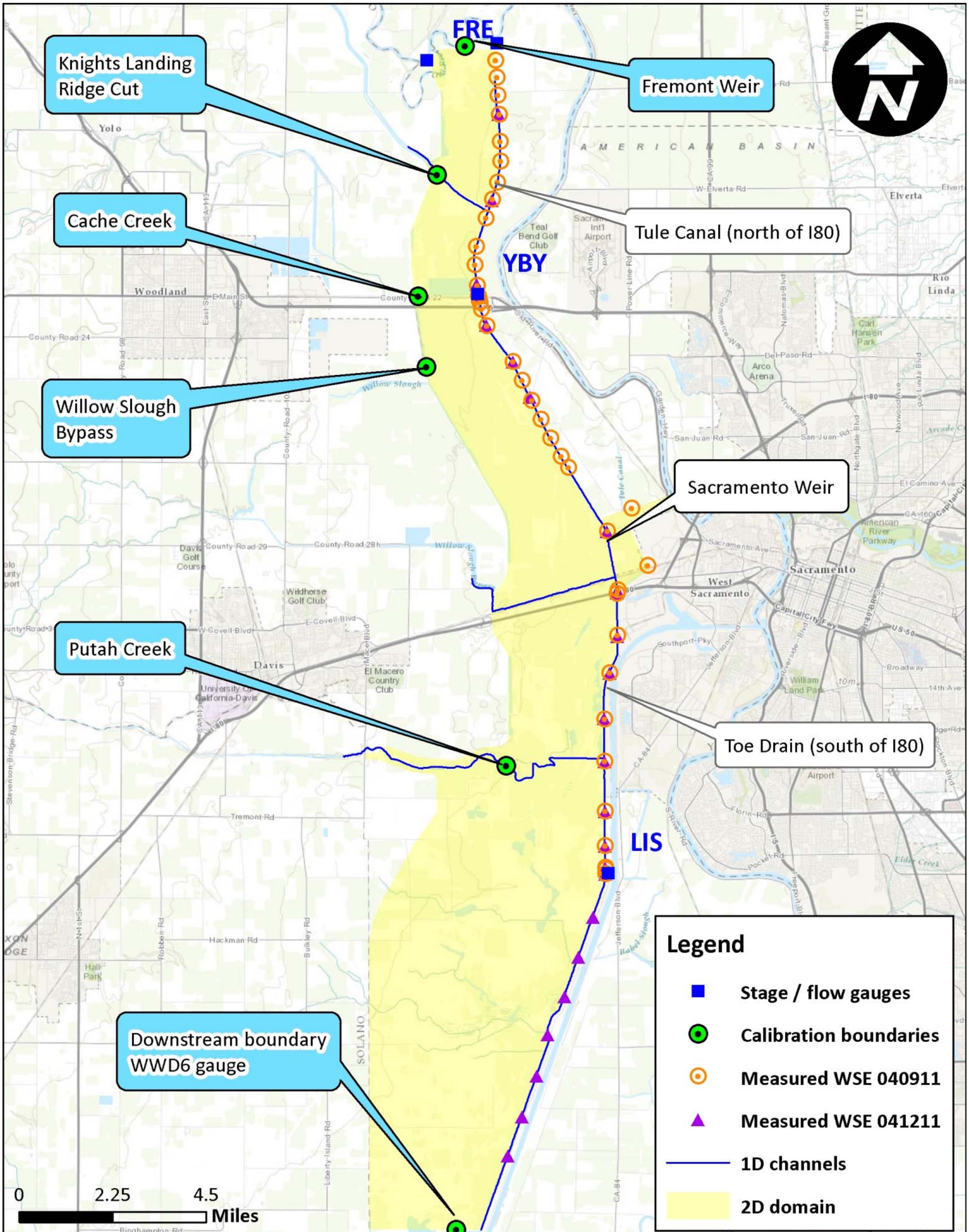



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**2010 Low Flow Calibration-Comparison of WSEs**

| Prepared for DWR | Created By: SJB | **Figure 5-20** |
|---|---|---|

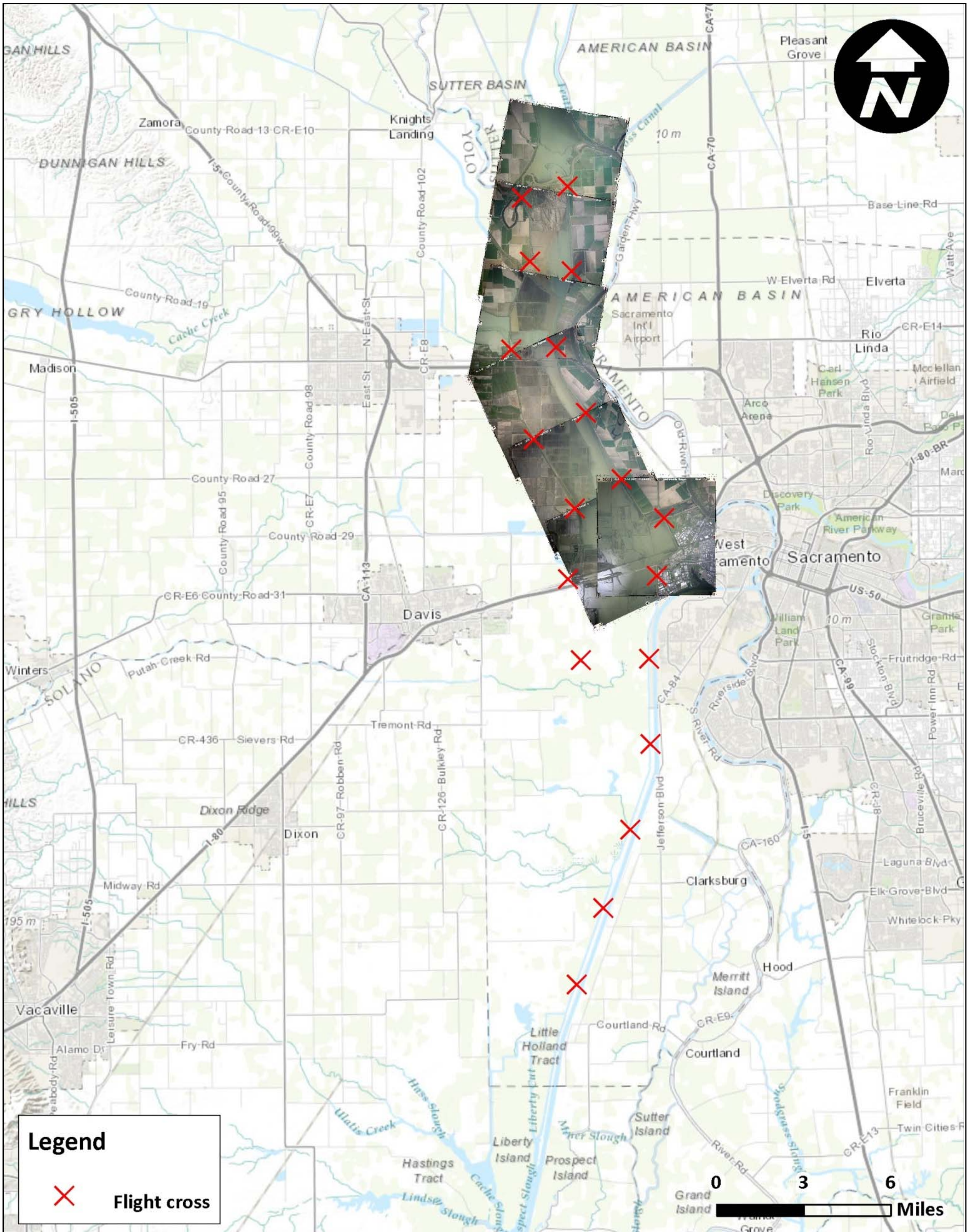



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**2011 Flood Calibration Data**

Prepared for DWR | Created By: SP | **Figure 5-21**




Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Aerial Photos of Yolo Bypass-April 9, 2011**

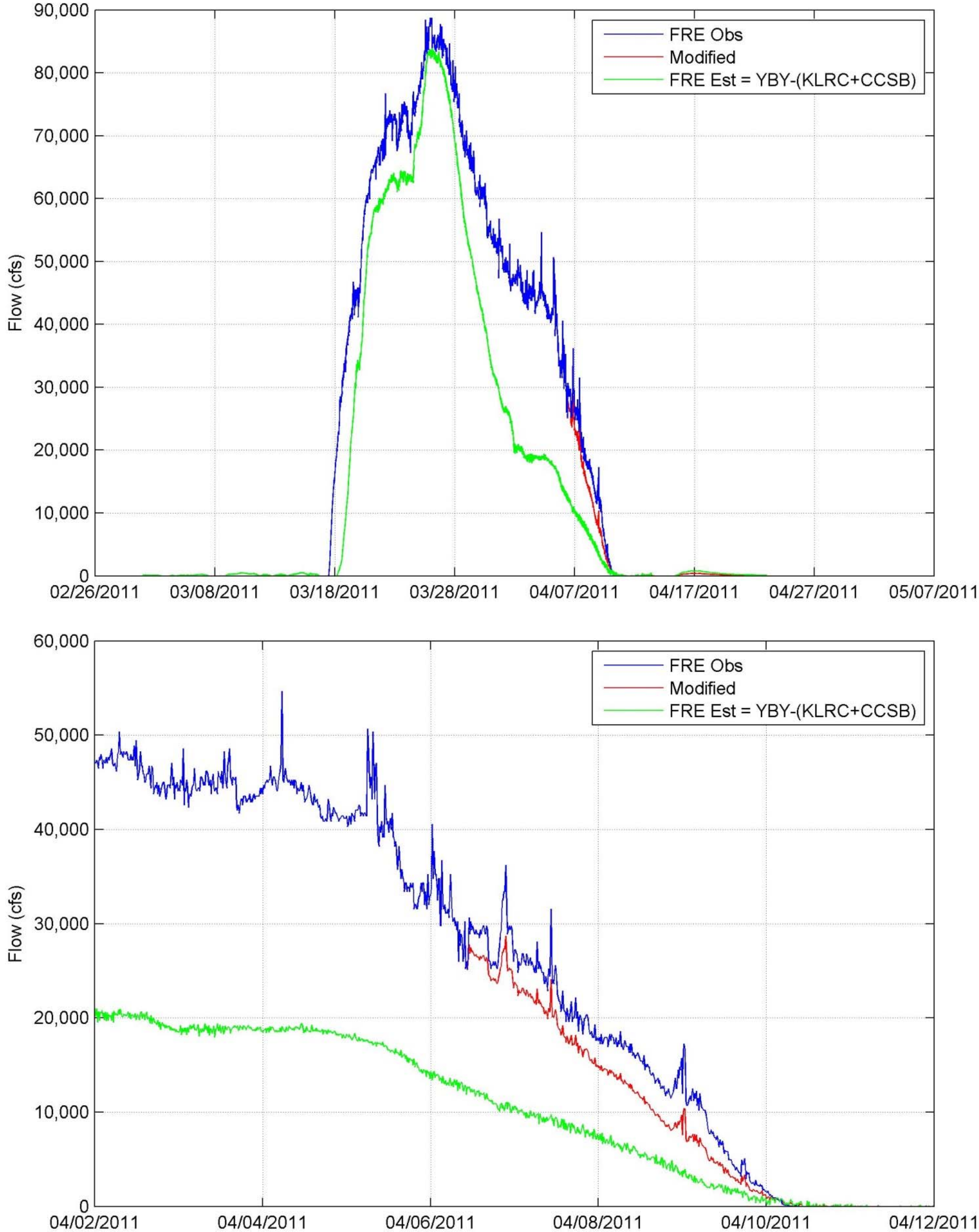
| | | |
|---|---|---|
| Prepared for DWR | Created By: SP | **Figure 5-22** |


Notes:

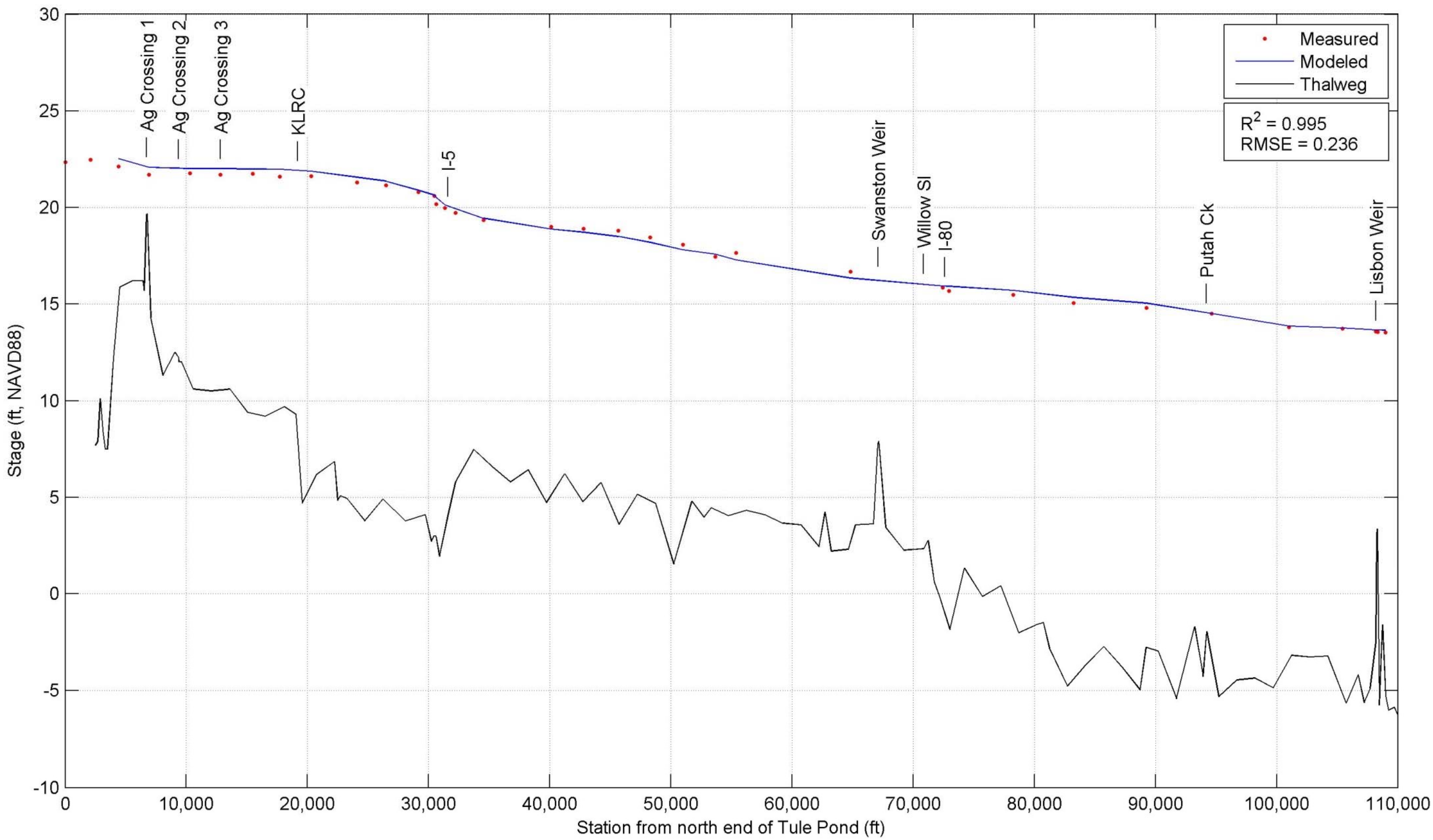
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Aerial Photos of Yolo Bypass-April 12, 2011**

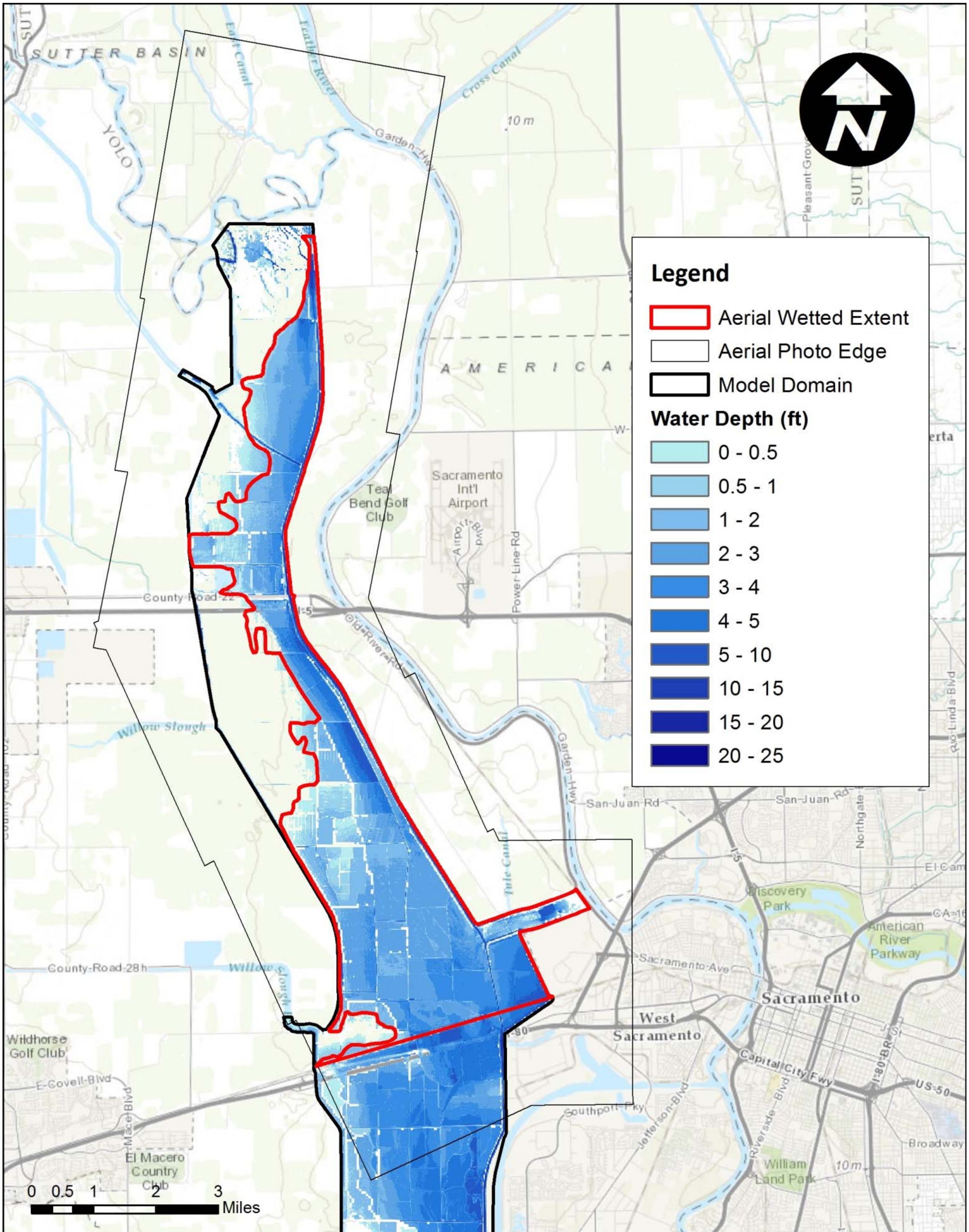
| Prepared for DWR | Created By: SP | **Figure 5-23** |
|---|---|---|



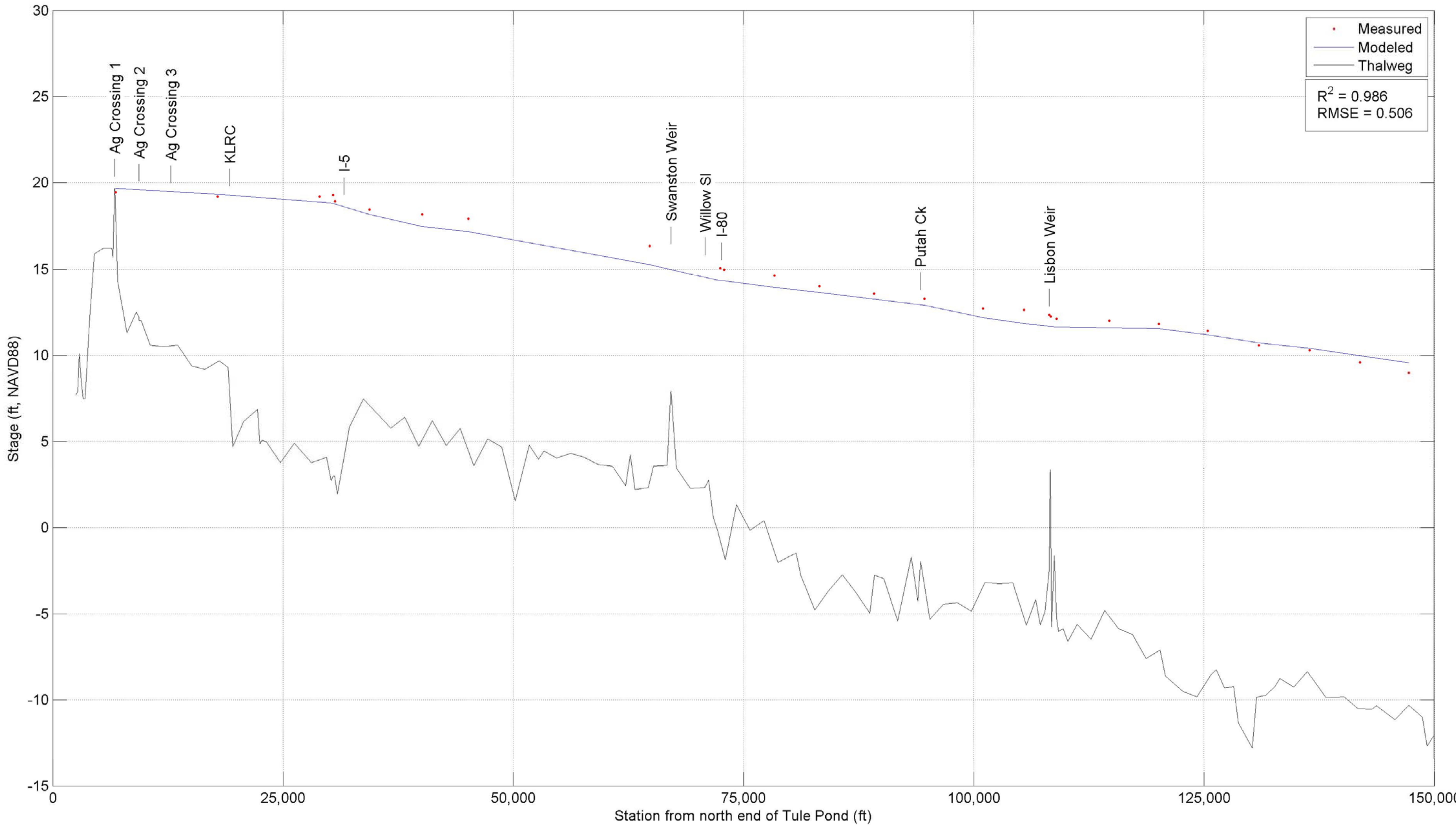

| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **2011 Flood Calib-Mods to Fremont Inflows** | | |
| | | Prepared for DWR | Created By: CMB | **Figure 5-24** |




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **2011 Flood Calib-Comparison of April 9 - WSEs** | | |
| | | Prepared for DWR | Created By: SJB | **Figure 5-25** |




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **2011 Flood Calibration – April 9, 2011** | | |
| | | Prepared for DWR | Created By: CMB | **Figure 5-26** |

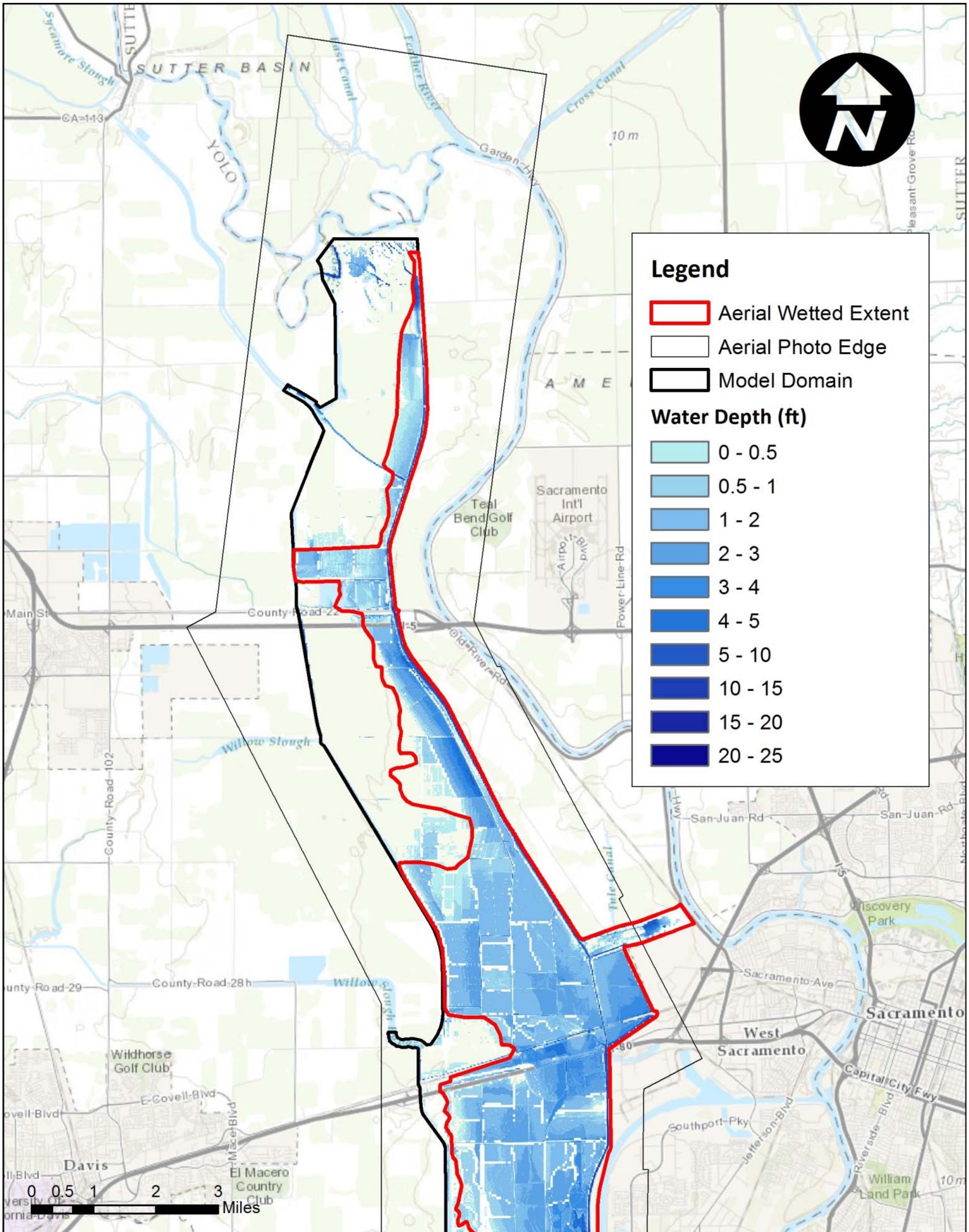



Notes:

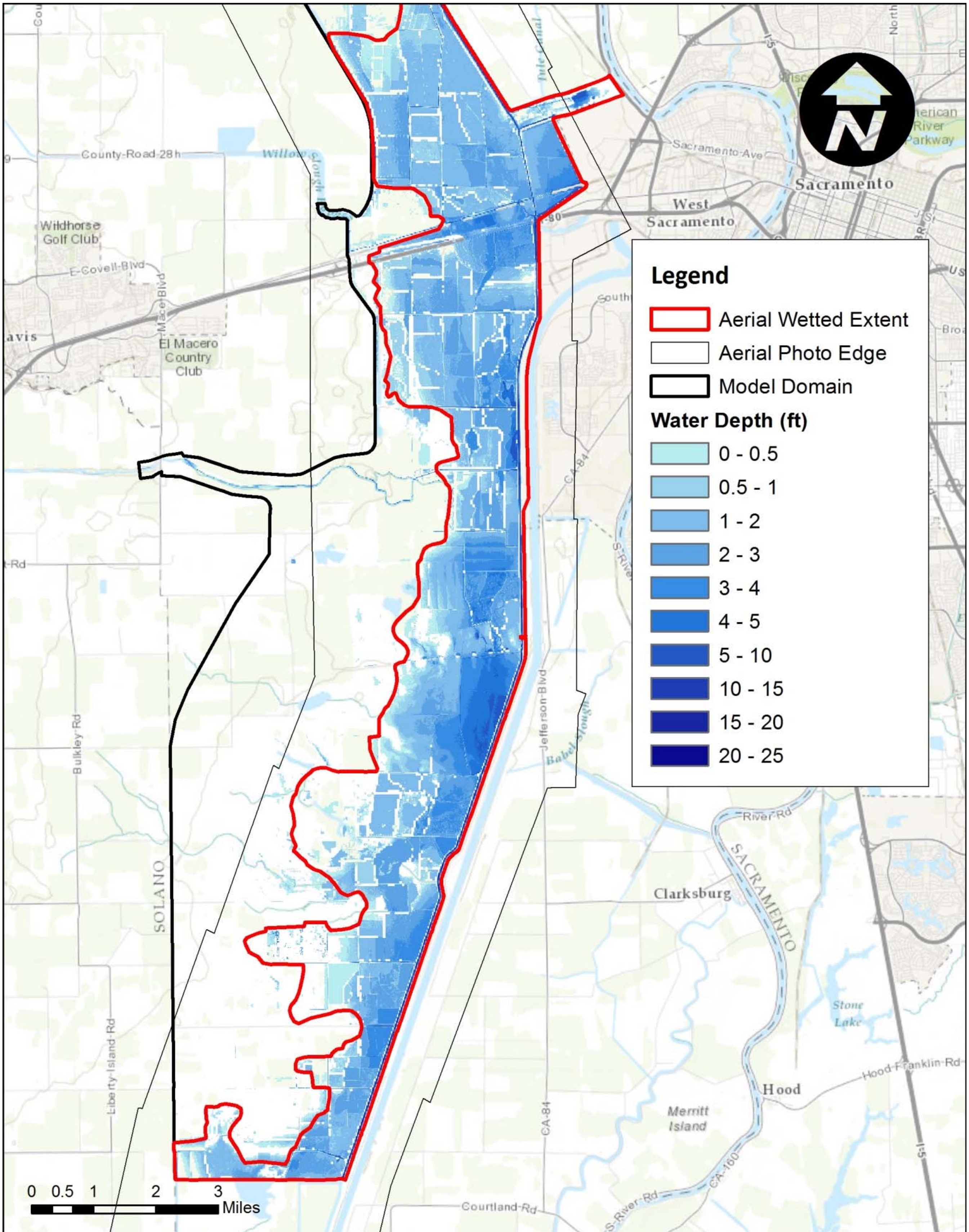
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**2011 Flood Calibration- Comparison of April 12- WSEs**

| Prepared for DWR | Created By: SJB | **Figure 5-27** |
|---|---|---|




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **2011 Flood Calibration – April 12, 2011** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: CMB | **Figure 5-28** |




Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**2011 Flood Calibration – April 12, 2011**

Prepared for DWR | Created By: CMB | **Figure 5-29**

# 6.0 Existing Conditions Analysis

## 6.1 Overview of Results

The existing conditions model was run for the 16-year period from water year 1997 through water year 2012. All model runs start on October 2. Most runs end on May 31, but the wetter years were extended at least through June 31 to capture late season inundations and/or provide results for extended fish habitat periods (1997, 1998, 1999, 2000, 2003, 2005, 2006, and 2011).

The results for the existing conditions model include daily WSEs, depths, and velocities for the entire model domain extracted from the Model at the 24th hour of each day. Discharge values through time were output at 1D channels and across predefined polylines within the 2D domain. Spatial time-varying results are in the mesh/dataset format used by the Surface-Water Modeling System (SMS) and in Environmental Systems Research Institute (ESRI) binary raster format (FLT).

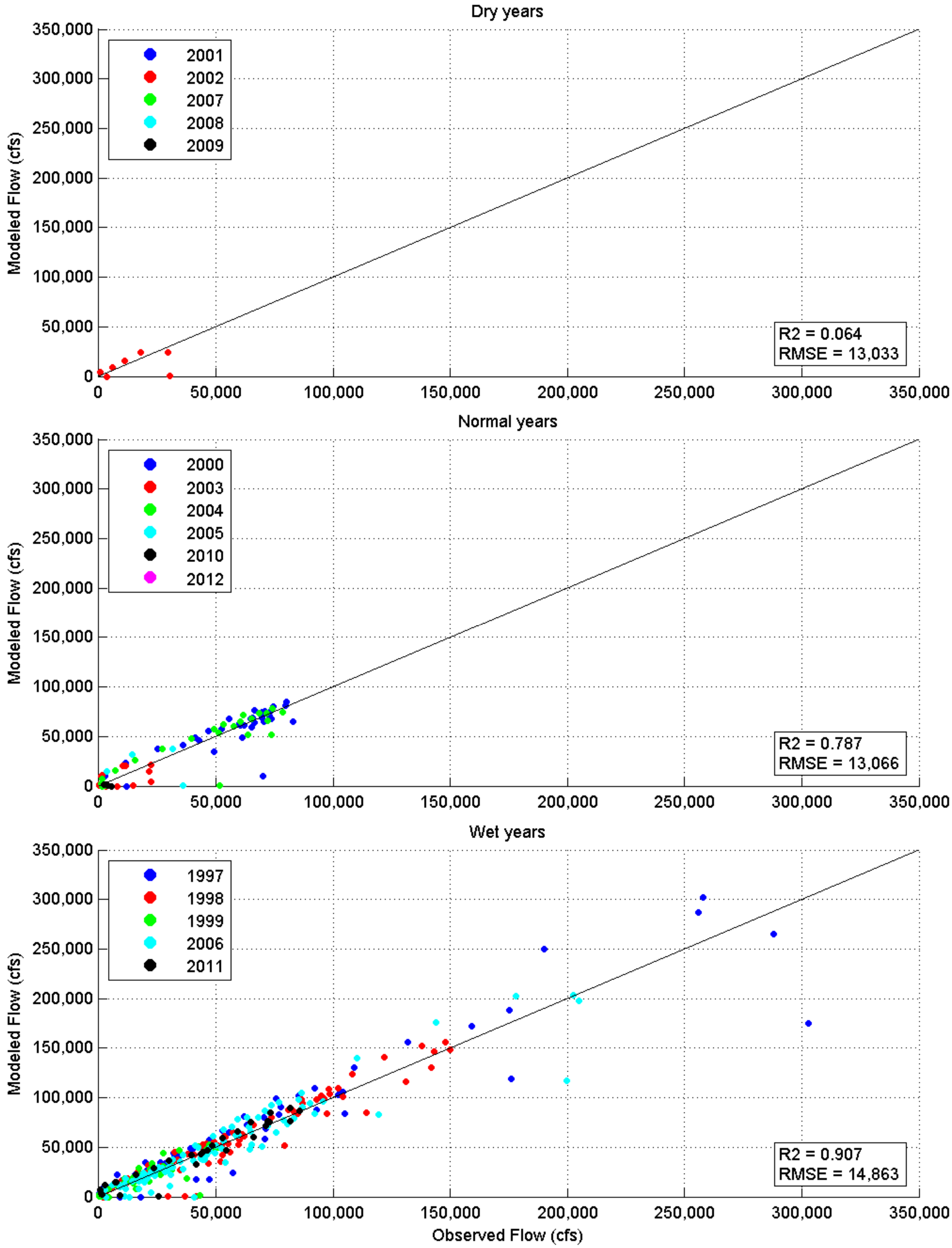
## 6.2 Comparisons to Observed Data

To verify that the model and underlying assumptions could reasonably simulate existing conditions over the long term, a suite of modeled versus observed scatter plots were prepared. Figure 6-1 shows that the flow over Fremont Weir has a RMSE of 13,000 to 15,000 cfs over the full range of conditions, which compares favorably with the RMSE from the 1997 calibration. Figure 6-2 shows that the Sacramento River stage in front of Fremont Weir has a RMSE of 0.9 to 1.3 feet, which is more than twice as large as the RMSE for the 1997 calibration. Figure 6-3 shows that the Sacramento River flow at Verona has a RMSE of 1,300 to 3,200 cfs over the full range of conditions, which is better than the RMSE 8900 cfs for the week-long 1997 calibration. Figure 6-4 shows that the stage at Yolo Bypass at Woodland has a RMSE of 2.4 to 3.0 feet, which is similar to that observed during the 1997 calibration. The most significant errors occur below an elevation of 17 feet, which is lower than the February 2010 calibration conditions. Flows are largely confined to the Tule Canal below elevation 17 feet and are below the adjacent floodplain, but modeled stages are sometimes more than 5 feet higher than recorded by the USGS. This discrepancy is not considered to impact the results of this study in the larger scale because the larger errors occur when the flows are largely confined to the Tule Canal and such times are not of interest for the current analysis.

In preparing these figures, it was discovered that the datum conversion from USED to NAVD88 was inadvertently not applied for water years 2005 and prior. This resulted in the tidal boundary at Rio Vista being 0.6 feet too high. This error presents itself in Figure 6-5 and Figure 6-6, hence the reason for computing RMSE twice. Figure 6-5 shows that for water years 2005 and prior, the stage at Lisbon Weir has a RMSE of 0.9 to 1.0 feet, whereas later years have a RMSE of 0.7 to 0.8 feet. Figure 6-6 shows that for water years 2005 and prior, the stage at Liberty Island has a RMSE of 0.7 to 1.0 feet, whereas later years have a RMSE of 0.3 to 0.5 feet.

To understand if this datum correction error has an influence on the inundation results in the Yolo Bypass, Figure 6-7 and Figure 6-8 were prepared to test the sensitivity of wetted acres and LDW, respectively, during water year 2002 with a datum correction applied at Rio Vista. Water year 2002 was classified as a dry year and experienced a small spill event over Fremont Weir. Figure 6-7 shows that there is an insignificant difference in wetted area through time. This is corroborated by Figure 6-8 which shows that a dozen fields between Lisbon Weir and the Stair Step are drier one day sooner with the corrected (or lowered) stage boundary at Rio Vista. As such, inundation and drainage within the Bypass are not significantly affected by the datum error.

Given that model impact outcomes in the Bypass are insensitive to the relatively small datum error, the Lead Agencies with the guidance from the modelers determined not to re-run the model, and to use the original results. Based on the original model results, Figure 6-9 shows the wetted acres time series for existing conditions by water year and water year type. These time series will serve as the basis for making relative comparisons amongst the alternatives.

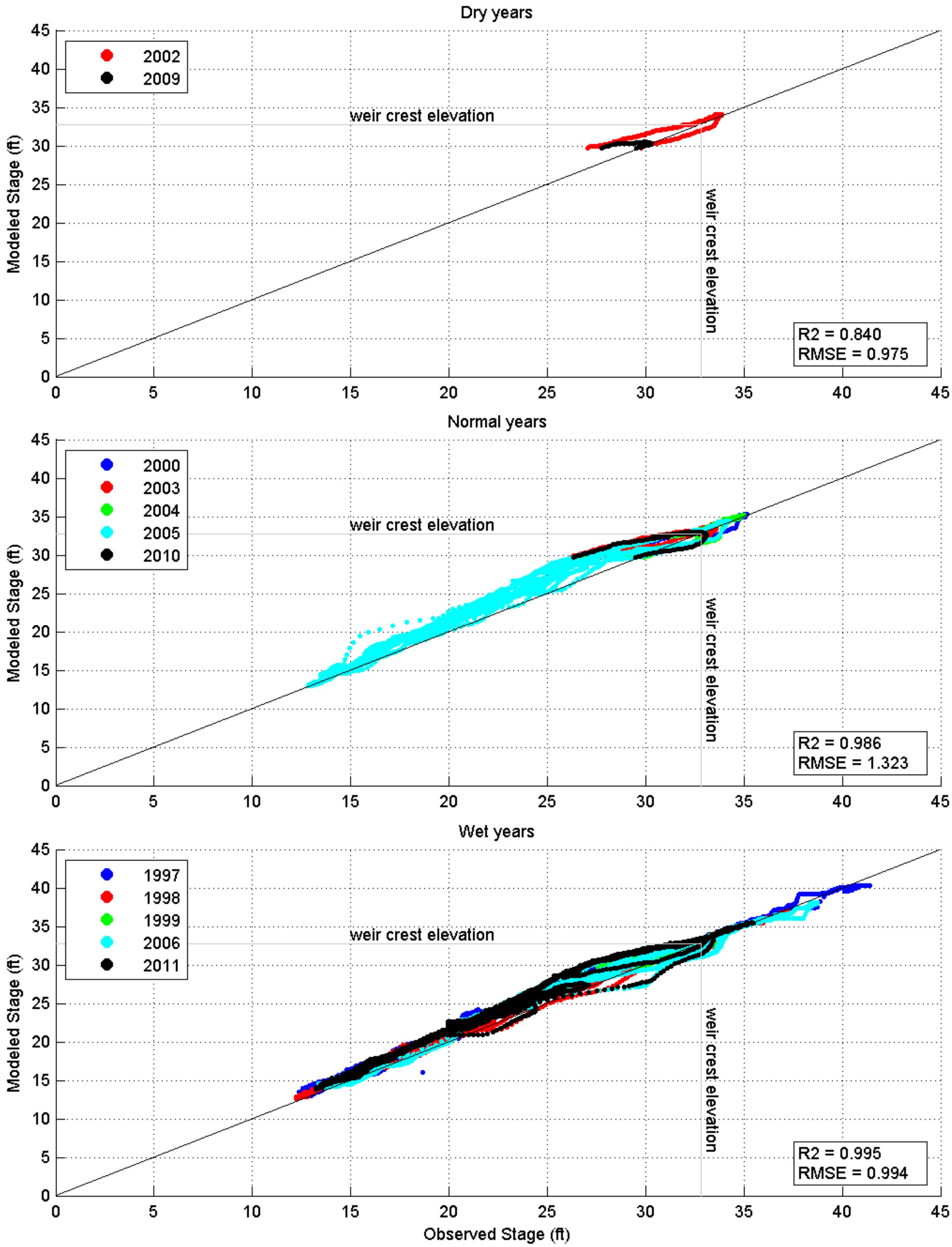



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing Fremont Weir Flow Comparison**

Prepared for DWR | Created By: SJB | **Figure 6-1**

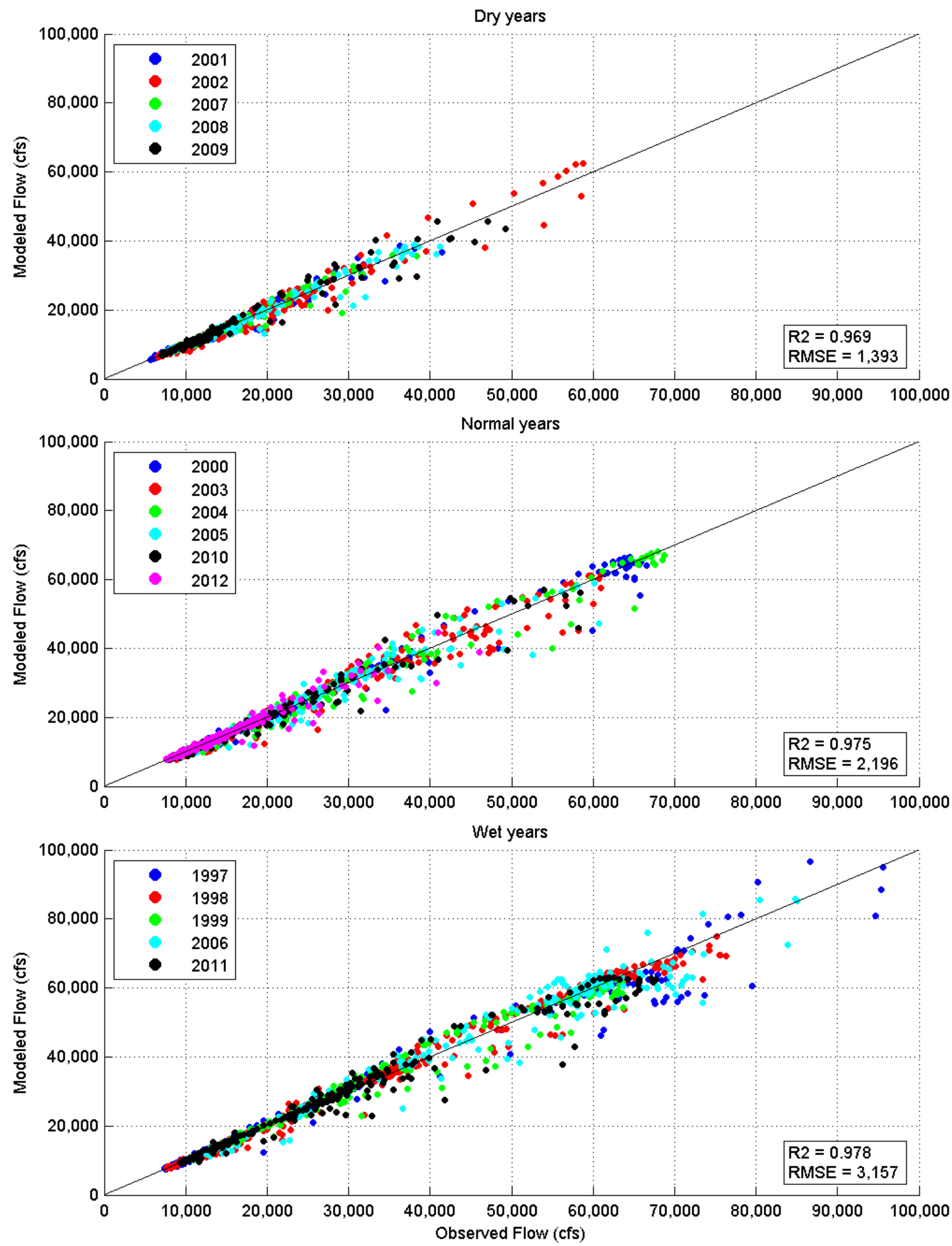



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing Fremont Weir Stage Comparison**

| Prepared for DWR | Created By: SJB | **Figure 6-2** |
|---|---|---|

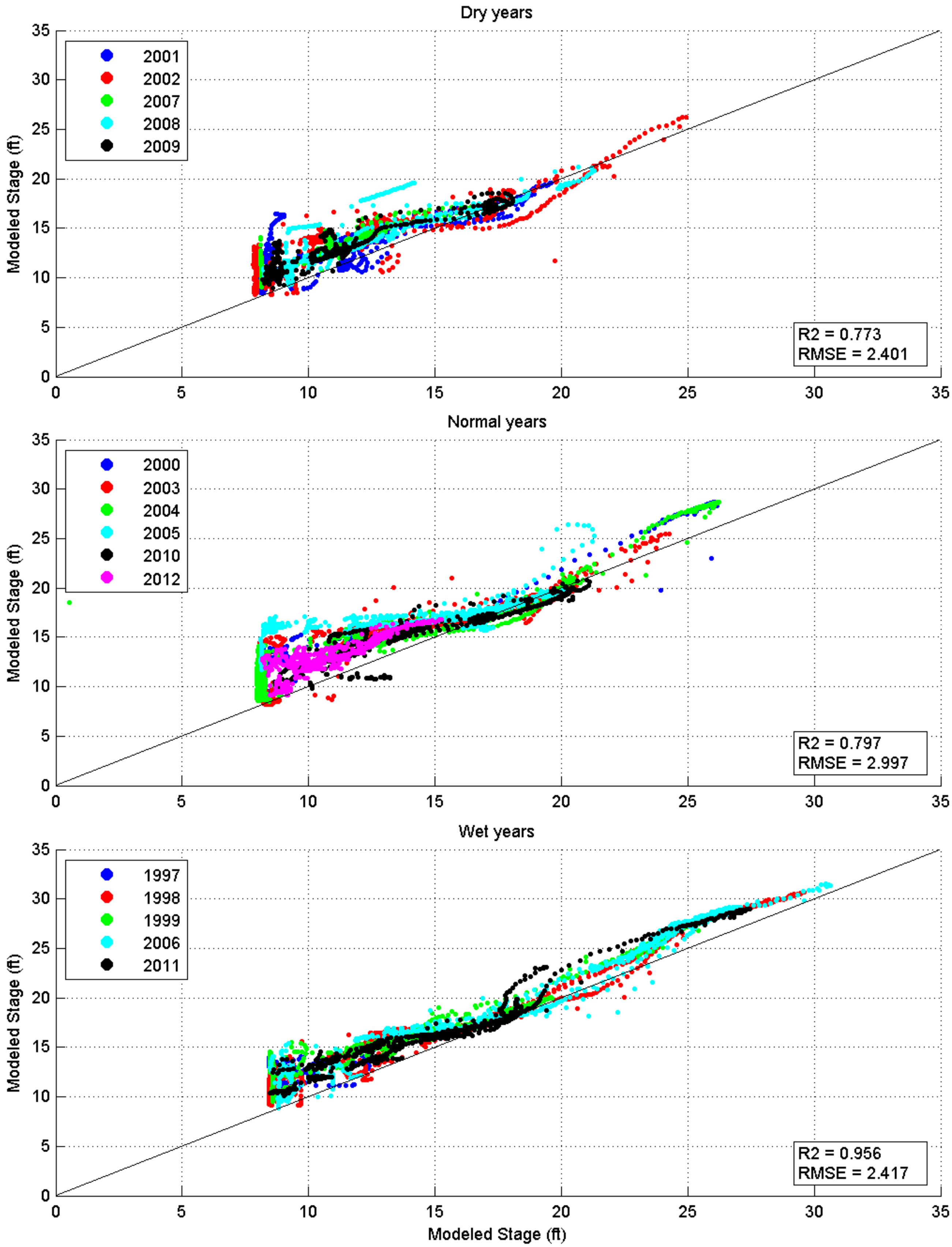



Notes:

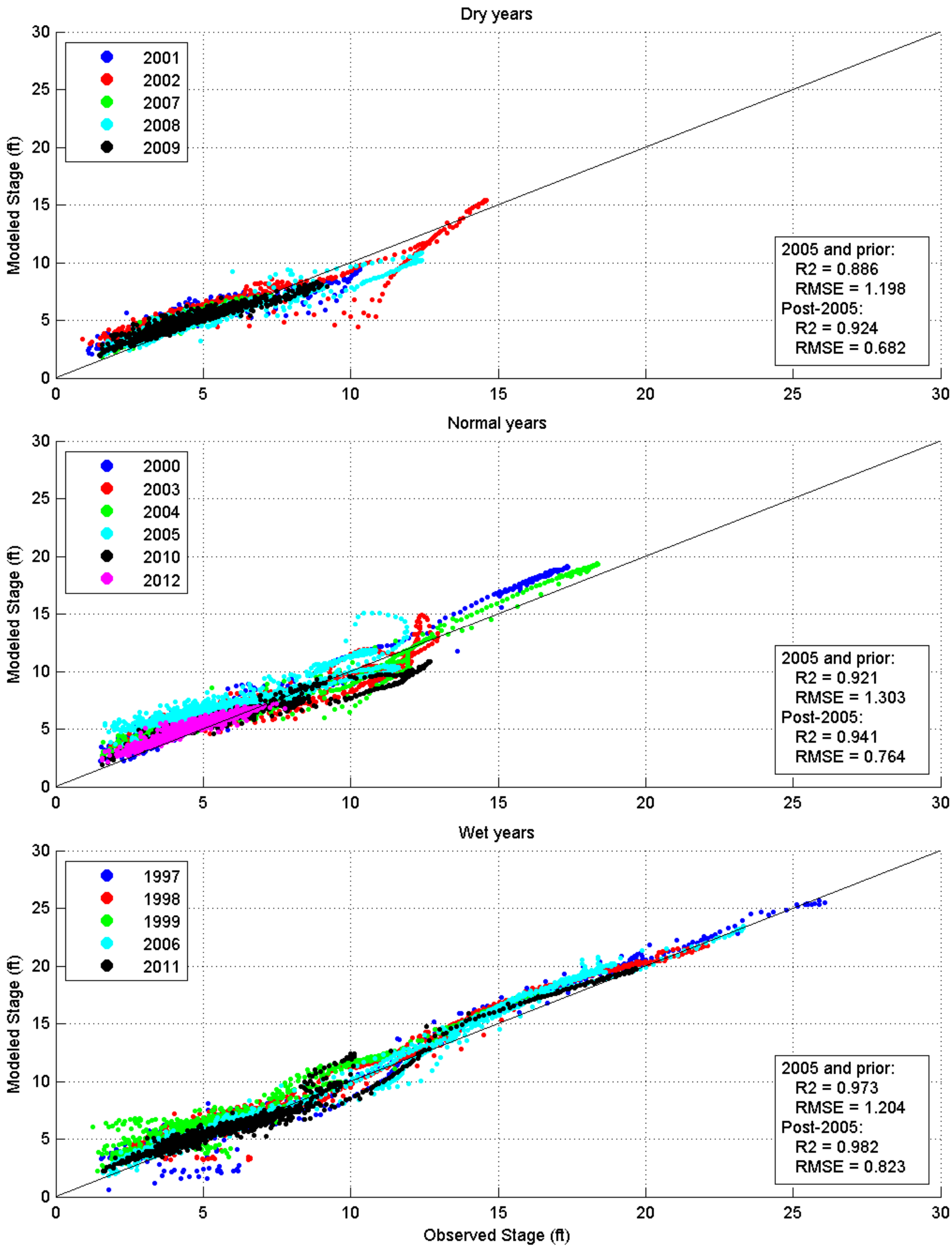
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing Sac R at Verona Flow Comparison**

| Prepared for DWR | Created By: SJB | **Figure 6-3** |
|---|---|---|




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **Existing YB at Woodland Stage Comparison** | | |
| | | Prepared for DWR | Created By: SJB | **Figure 6-4** |

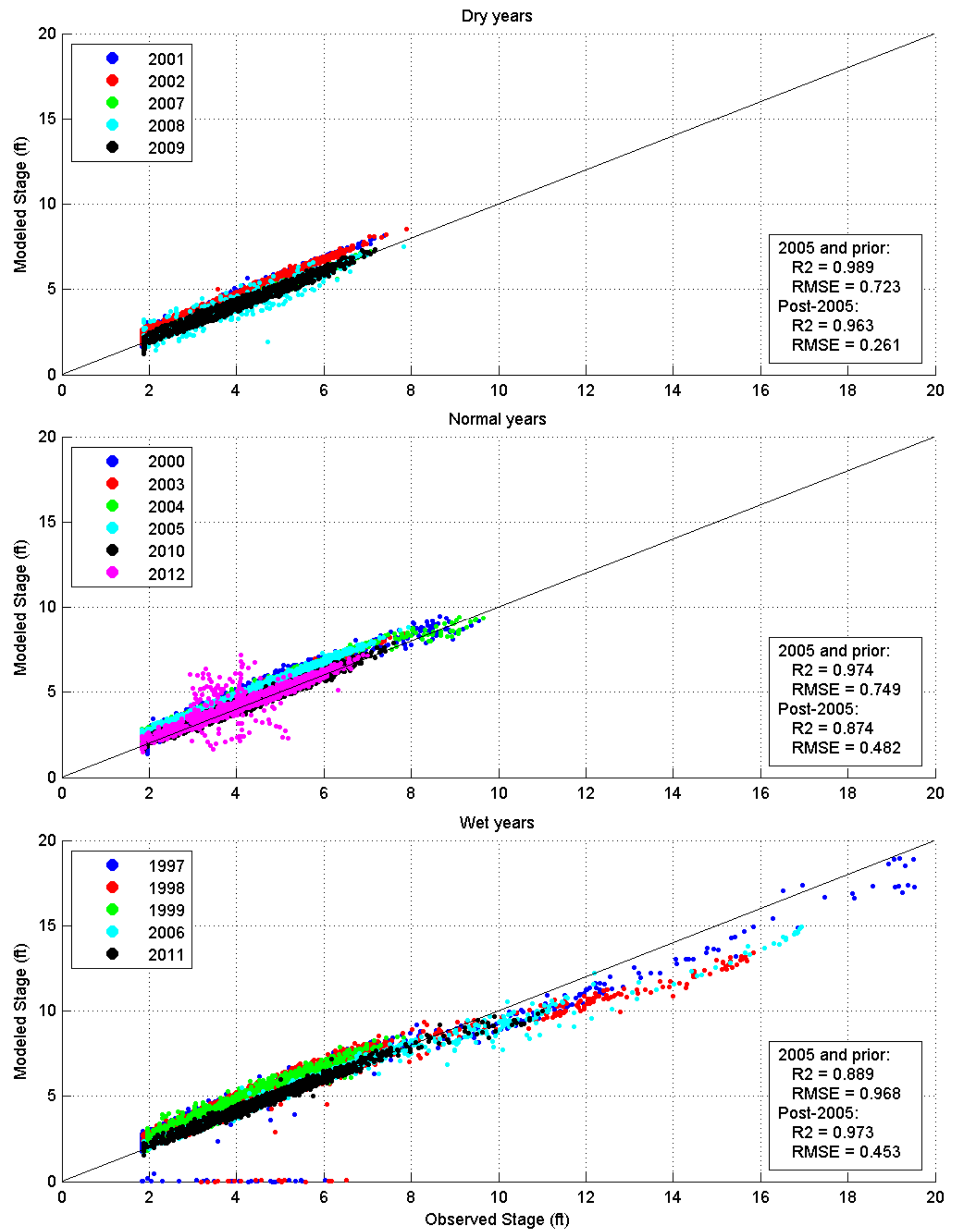



Notes:

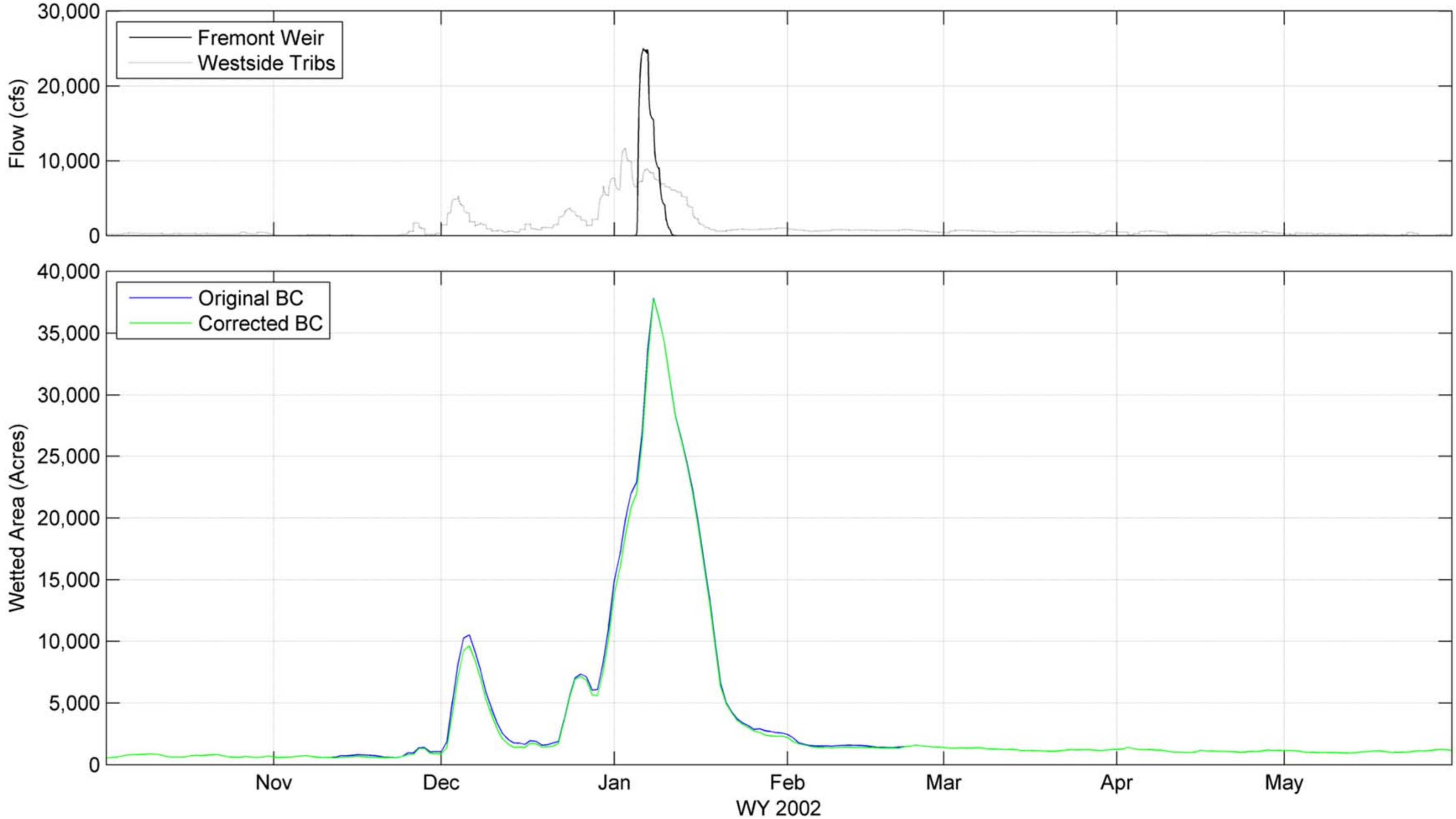
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing Lisbon Weir Stage Comparison**

| Prepared for DWR | Created By: SJB | **Figure 6-5** |
|---|---|---|



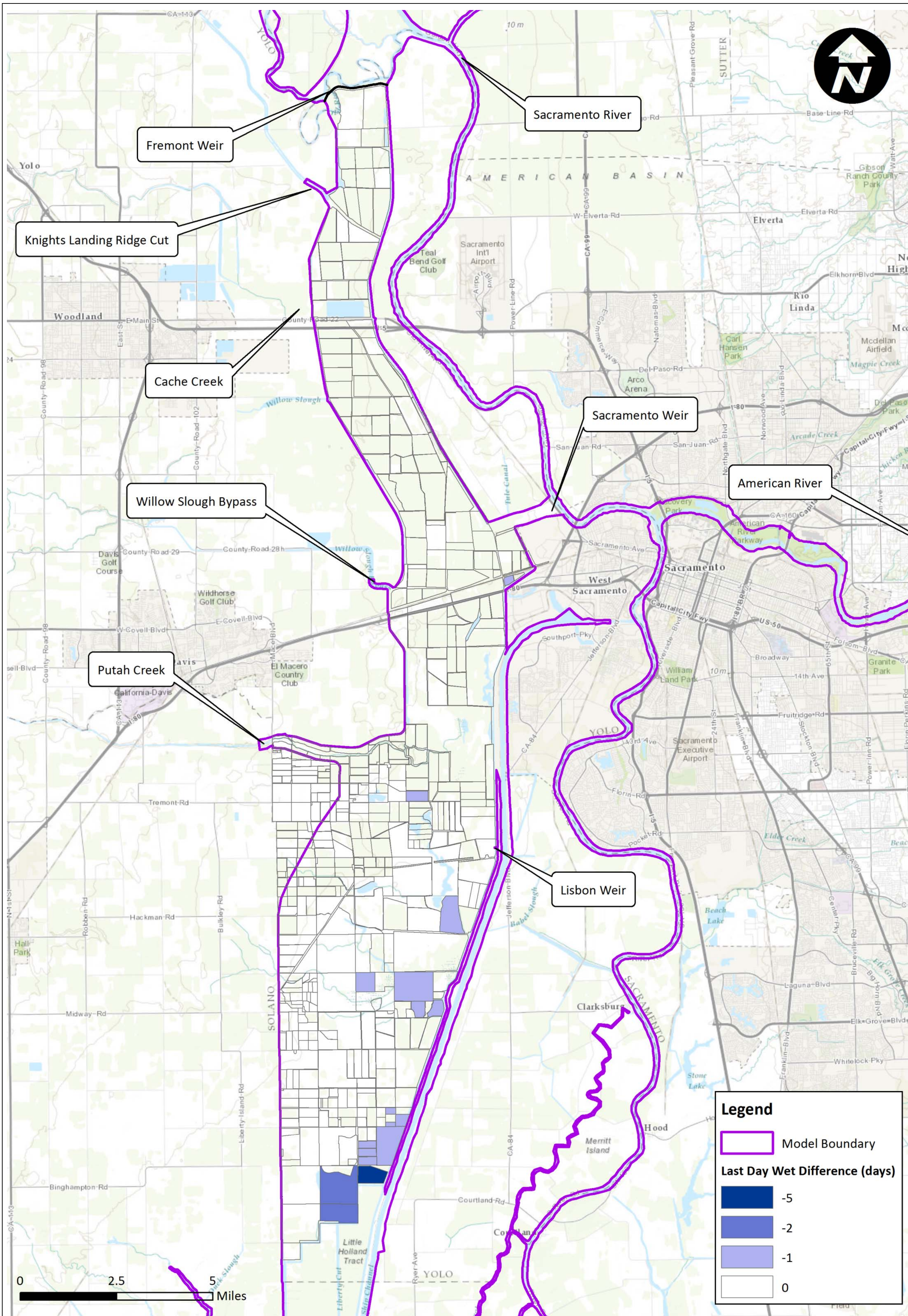

| Notes: | HDR cbec | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**Existing YB at Liberty Is Stage Comparison** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SJB | **Figure 6-6** |




*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Downstream BC Sensitivity – Wet Area 2002**

| Prepared for DWR | Created By: RDJ | **Figure 6-7** |
|---|---|---|



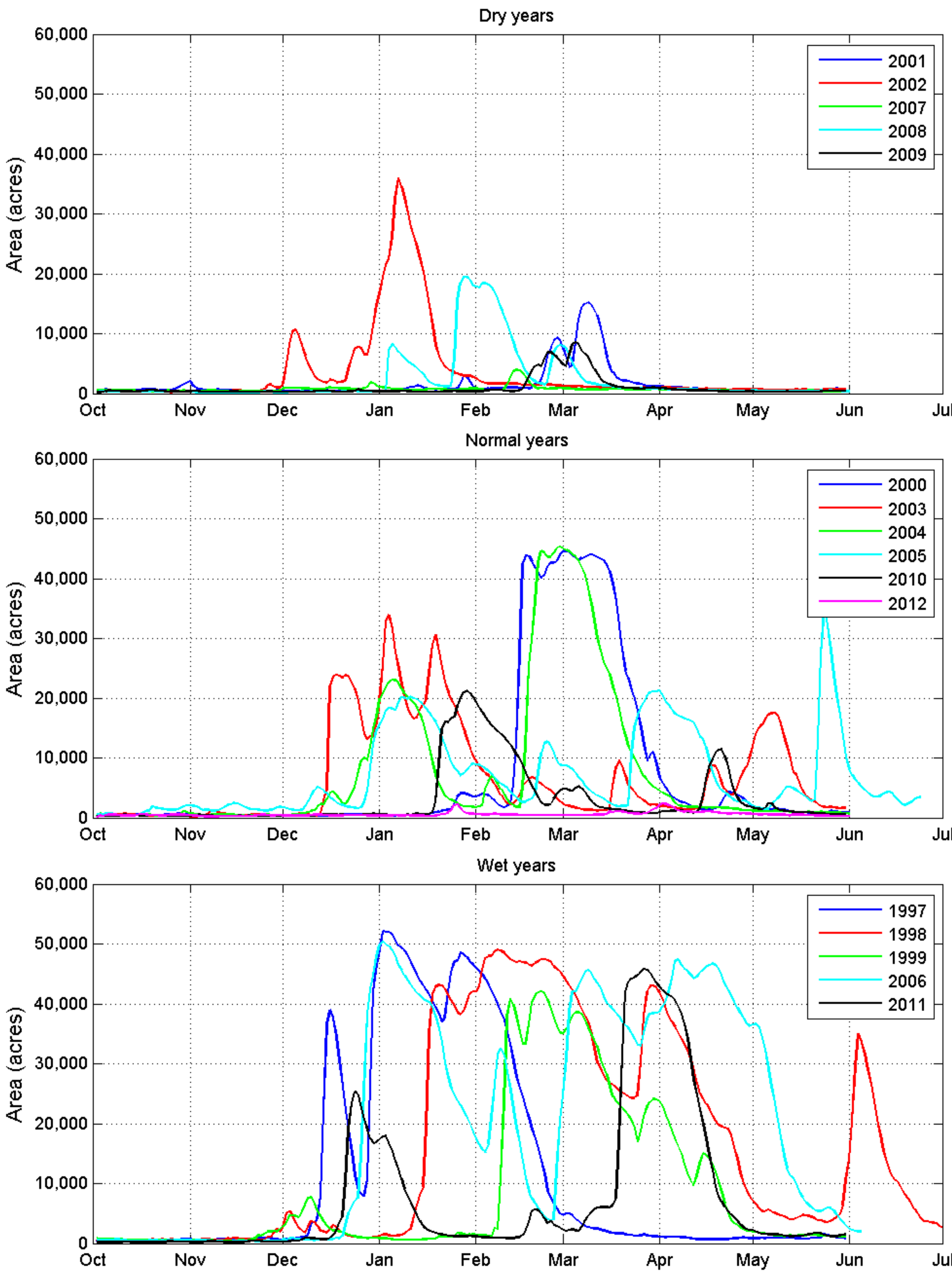

Notes:

HDR cbec eco engineering

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Exg Downstream BC Sensitivity – LDW 2002**

| Prepared for DWR | Created By: RDJ | **Figure 6-8** |
|---|---|---|




| Notes: | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* |
|---|---|---|
| | | **Existing Wetted Acres by WY Type** |
| | | Prepared for DWR · Created By: SJB · **Figure 6-9** |

# 7.0 Alternatives Analysis

Each of the project alternatives was modeled for the 16 year period including simulations to model different project end dates when all of the gates are closed. The different gate closure dates that were modeled were February 15, March 1, March 15, April 1, and April 30. Each of the simulations for the April 30 gate closure date covered the period from October 2 to May 31. Simulations for the other gate closure dates used the April 30 solution as a “hotstart,” that is, starting just before the gate closure date and ending 30 days afterwards. Once the gates have been closed for at least 30 days the alternative results and existing conditions results are nearly equivalent. Output data in the same formats as generated for the existing condition runs were generated for the alternatives.

## 7.1 Model Implementation

The channel profiles and preliminary gate configurations for the Fremont Weir and Sacramento Weir Gated Channel Alternatives were initially screened in HEC-RAS (see Appendix C) to 1) understand the backwater effects on the gates from Yolo Bypass inundation given that proposed upstream inverts at the river are below the baseline water levels in the Tule Canal; and 2) optimize the notched gate openings ability to divert 6,000 cfs from the Sacramento River to the Bypass during non weir overtopping periods with the objective to maximize fish entrainment while minimizing head losses across the gate. Gate optimization was performed in HEC-RAS because such a function was not yet available in TUFLOW and gate logic was a relatively new feature in TUFLOW.

For the HEC-RAS analysis, the Tule Canal was assumed to have baseline flow contributions of 500 cfs, 350 cfs, 50 cfs, and 300 cfs from KLRC, Cache Creek Settling Basin, Willow Slough, and Putah Creek, respectively, for existing conditions and all four alternatives. Rule operations in the HEC-RAS unsteady flow editor were used to optimize gate operations for the gated channel alternatives to maximize gate flows up to 6,000 cfs based on the Sacramento River WSEs and gate characteristics.

Following gate optimization in HEC-RAS, the Fremont Weir and Sacramento Weir Gated Channel Alternatives were implemented in TUFLOW. The Fremont Weir alternatives were modeled by adding a 1D channel connecting the Sacramento River through Tule Pond to the northern end of Tule Canal. The 1D channel included the proposed gate configurations at Fremont Weir (see Section 7.1.1), which vary in size, number, and gate closure operations by alternative. The Sacramento Weir alternative includes modifications to the 2D grid to represent the proposed channel within the Sacramento Bypass. A 1D channel at the Sacramento River connects the river to the Sacramento Bypass, which includes the proposed gate configuration at Sacramento Weir (see Section 7.1.2). For each alternative, the Sacramento River stage-dependent rule curves were implemented in the TUFLOW for all but one of the multiple bays representing each gate configuration. The remaining bays for each alternative used gate logic in

TUFLOW to regulate flows in the proposed channels downstream of the gates so channel flows would not exceed 6,000 cfs.

### 7.1.1 Fremont Weir Gated Channel Alternatives Setup (1D channels, gates, Ag crossings)

For the Fremont Weir Gated Channel Alternatives, each alternative included a proposed channel excavated at the east end of Fremont Weir and parallel to the flood levee, connecting the Sacramento River with the Tule Canal (see Figure 7-1). The channel dimensions of the three Fremont Weir alternatives are provided in Table 7-1. For the reach of the proposed channels between the Sacramento River and Fremont Weir, a length of approximately 800 feet, the channel was graded from Fremont Weir to the Sacramento River at a slope of 0.0025 with a bottom width of 225 feet and 3:1 side slopes. This was done to reduce head losses within the channel upstream of the gate and minimize the change in the WSE between the river and the weir.

*Table 7-1. Fremont Weir alternatives channel dimensions*

| Channel Size | Invert at Fremont Weir(ft, NAVD88) | Bottom Width (ft) | Slope | Side Slopes |
|---|---|---|---|---|
| Small | 14.0 | 20 | 0.00016 | 3:1 |
| Medium | 17.5 | 225 | 0.00035 | 3:1 |
| Large | 14.0 | 225 | 0.00016 | 3:1 |

Downstream of the gated channel, there are three agricultural crossings (Ag crossings) on the Tule Canal between Tule Pond and the confluence with KLRC (see Section 4.5). Ag Crossing #1 is an earthen berm 1.7 miles south of Fremont Weir at the bottom of Tule Pond that impounds irrigation water for RD 1600 so it can be conveyed through the levee to the Elkhorn Basin. This berm can become degraded during Fremont Weir overtopping events. Ag Crossing#2 is 0.5 miles further south and is an earthen berm with one 32-inch culvert. Ag Crossing #3 is 0.6 miles further south and is an earthen berm with three 24-inch culverts.

The Small and Large channels tie into the Tule Canal just downstream of Ag Crossing #2. The Medium channel ties into the Tule Canal just upstream of Ag Crossing #2. As a result, all three channel alternatives require the partial removal and modification of the earthen berm forming Ag Crossing #1, but only the Small and Large channels require the additional modification to Ag Crossing #2. For the purposes of this analysis, and as demonstrated by the backwater effects on the future gate location at the river during low flows due to the limited capacity of the Tule Canal downstream of KLRC and the agricultural crossings upstream of KLRC (see Appendix C), it was assumed that all three agricultural crossings were replaced with railcar bridges as part of the alternatives to maximize the frequency of inundation from the Sacramento River. The railcar bridges were assumed to be 90 feet long, 3 feet in vertical depth, and situated on 2-foot-wide abutments with wing walls. Under gate operations, all future agricultural crossings were assumed to be fully open.

A series of radial gates (final gate types and design will be determined later) at the channel connection with the Sacramento River was used to maximize the flow into the Yolo Bypass for non-overtopping flow events up to 6,000 cfs. In general, gate widths were limited to 30 feet in width with 3 feet pillars between them. Some of the gates were limited in height to prevent them from extending above the existing weir crest (32.8 feet NAVD88) during an overtopping event. Combinations of gate heights were used to optimize gate openings to achieve the 6.000 cfs discharge cap. After Fremont Weir overtops, the gates remain in their last configuration within the model (either fully open, partially open, or closed). If additional analysis indicates that this modeling assumption increases flood impacts, it is assumed that gate operations will be changed or design modifications will be made to mitigate impacts. For the Small channel, the bottom width of the channel was widened to accommodate three gates to minimize the head loss across the gate structure. The resulting gate configurations are shown in Table 7-2 and Figure 7-2, Figure 7-3, and Figure 7-4 for the Small, Medium, and Large channels, respectively.

*Table 7-2. Fremont Weir gate configurations*

| Channel Size | Invert at River (ft, 88) | Bottom Width at Gate (ft) | Gate Invert (ft) | Gate Height (ft) | Gate Width (ft) | Number of Gates |
|---|---|---|---|---|---|---|
| Small | 14 | 115 | 14 | 8, 14 | 30 | 3 |
| Medium | 17.5 | 225 | 17.5 | 6, 12 | 30 | 6 |
| Large | 14 | 225 | 14 | 7.5, 10 | 30 | 6 |

### 7.1.2 Sacramento Weir Gated Channel Alternative Setup (1D channels, gates)

The Sacramento Weir Gated Channel Alternative was assumed to be constructed just north of the southern Sacramento Bypass levee, connecting the Sacramento River with the Tule Canal (see Figure 7-5). The proposed channel has an invert elevation of 7 feet NAVD88 with a 225-foot bottom width and 3:1 side slopes.

WSEs in the Sacramento Bypass are controlled by the low flow conveyance capacity within Tule Canal and an agricultural crossing 2,300 feet downstream of the Sacramento Bypass as operated by Swanston Ranch. The minimum WSE in Tule Canal at the confluence with the Sacramento Bypass during baseline flows (i.e., 850 cfs as contributed by KLRC and Cache Creek) was 10.65 feet NAVD88. At stages below 11 feet NAVD88, flow through the Sacramento Bypass gated channel is limited due to backwater from Tule Canal.

A series of six new radial or sluice gates (final gate types and design will be determined later) at the Sacramento Weir were used to regulate flows into the Sacramento Bypass up to 6,000 cfs. It was assumed that the new gates were installed directly below the existing bays of the Sacramento Weir on the southern end of the weir (see Figure 7-6). The new gate dimensions are provided in Table 7-3, and generally consist of 30-foot-wide gates with inverts at 7 feet NAVD88 and 12 foot pillars between them. The pillars are wider than the Fremont Weir alternatives because the 30 foot new gates are situated directly beneath individual bays of the

Sacramento Weir which are generally 40 feet wide. Gate operations were optimized to maximize discharges into the Sacramento Bypass up to 6,000 cfs for river stages in front of the Sacramento Weir up to elevations corresponding to the I Street WSE trigger of 30.04 feet NAVD88. After the I Street elevation trigger is met, the Sacramento Weir is opened and the new gates will remain open to their last configuration within the model. If additional analysis indicates that this modeling assumption increases flood impacts, it is assumed that gate operations will change or design modification will be made to mitigate flood impacts. Gates 1 and 2 were limited in height to prevent the top of the gate from extending above the existing weir sill (24 feet NAVD88) during a flood event when the Sacramento Weir is open and the two gates are partially open to convey up to 6,000 cfs. The resulting gate configuration is shown in Table 7-3 and depicted in Figure 7-6.

*Table 7-3. Sacramento Weir gate configuration*

| Gate # | Gate Invert (NAVD88 ft) | Gate Height (ft) | Gate Width (ft) |
|---|---|---|---|
| Gate 1 | 7 | 7 | 30 |
| Gate 2 | 7 | 11 | 30 |
| Gate 3 to Gate 6 | 7 | 14 | 30 |

## 7.2 Alternatives Results and Analysis of Results

### 7.2.1 Yolo Bypass Inundation

Modeled inundation area of the Yolo Bypass, relative to existing conditions, has been determined to include the Tule Canal/Toe Drain, as defined north to south between Fremont Weir and the north bank of the Stair Step, and east to west between the project levees. Figures 7-7 through Figure 7-11 show wetted acres and gate flows for all alternatives for WY 2003 for the five gate closure dates. A complete set of graphics for all water years and all gate closure dates can be found in Appendix D. These figures clearly show the increased frequency and duration of inundation and generally demonstrate that the increases in inundation acreage are greatest with the large channel at Fremont (FreLg), followed by medium channel at Fremont (FreMed), small channel at Fremont (FreSm), and Sacramento Weir option (SacW).

To augment these figures, a series of animation snapshots (see Figures 7-12 through Figure 7-15 and Appendix E) were prepared that spatially depict the potential differences in wetted area for each alternative for the April 30 gate closure relative to existing conditions. These figures also show wetted-area times-series comparisons for all gate closure dates within a specific water year for each gate closure date.

To understand and quantify the increased inundation provided by each alternative, expected annual inundation was computed directly from the wetted-area time-series following the recently published methods by Matella & Jagt (2013). To streamline the analysis, the wetted-area time-series outputs for the 16 water years were used directly in the analysis. The wetted-area time-series were imported into HEC-EFM and statistical queries were generated for the period of November 1 to May 30 to populate area-duration-frequency (ADF) curves for durations of 2, 3, 7, 14, 21, 28, and 60 days. The wetted-area time-series considers all wet areas within the previously defined Yolo Bypass extents, and were not further screened for suitable depths or velocities for a specific fish species nor refined for shorter periods of time corresponding to specific fish life history needs; otherwise this may have been stated as expected annual habitat, but this determination is outside the scope of this modeling effort.

The ADF curves were then used in two ways. First, the curves were used to identify inundation acreages at flow frequencies of 1 in 3 years (33 percent exceedance), 1 in 2 years (50 percent exceedance), and 2 in 3 years (67 percent exceedance). Table 7-4, Table 7-5, and Table 7-6 presents the inundation acreages for 33 percent, 50 percent, and 67 percent exceedances, respectively. These tables generally demonstrate that: 1) longer duration events (i.e., > 4 weeks) are inundated longer in 1 out of 3 years; 2) medium duration events (i.e., 2 to 4 weeks) are inundated longer in 1 out of 2 years; and 3) shorter duration events (i.e., < 3 weeks) are inundated longer in 2 out of 3 years. The FreLg alternative provides the greatest inundation increase ranging from 7,700 acres in 2 out of 3 years to 8,800 acres in 1 out of 2 years. The other Fremont Weir alternatives are not too far behind in terms of acres inundated, but the Sacramento Weir alternative typically provides half of the inundation increase as the Fremont Weir alternatives.

Second, the area under the ADF curves were integrated to compute expected annual inundation based on the 16 years of model outputs. Table 7-7 and Figure 7-16 show similar trends amongst the alternatives. Expected annual inundation relative to existing conditions predicted to be 3,650±550 acres for FreLg, 3,350±500 acres for FreMed, 2,800±350 acres for FreSm, and 1,400±350 acres for SacW.

It is noted that the ADF curves and expected annual inundation results are based on an annual maxima approach per Matella & Jagt (2013) for a relatively short 16-year period. Given that there can be multiple discrete inundation events in the Bypass, a partial duration series approach could be considered.

*Table 7-4. Inundated area in 33% of years between November 1 and May 30*

| Duration (days) | Inundated Area (acres) | | | | | Inundation Increase (acres) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Existing | FreLg | FreMed | FreSm | SacW | FreLg | FreMed | FreSm | SacW |
| 2 | 47,806 | 47,832 | 47,852 | 47,824 | 48,112 | 26 | 46 | 18 | 307 |
| 3 | 47,690 | 47,718 | 47,735 | 47,705 | 48,001 | 28 | 46 | 16 | 312 |
| 7 | 46,461 | 46,501 | 46,513 | 46,484 | 46,817 | 41 | 52 | 23 | 356 |
| 14 | 45,085 | 45,154 | 45,165 | 45,148 | 45,458 | 68 | 80 | 63 | 373 |
| 21 | 36,267 | 36,378 | 36,375 | 36,432 | 37,068 | 111 | 108 | 165 | 801 |
| 28 | 30,330 | 32,630 | 32,505 | 32,481 | 32,024 | 2,300 | 2,176 | 2,152 | 1,695 |
| 60 | 2,152 | 14,650 | 13,137 | 10,526 | 5,432 | 12,498 | 10,985 | 8,374 | 3,281 |

*Table 7-5. Inundated area in 50% of years between November 1 and May 30*

| Duration (days) | Inundated Area (acres) | | | | | Inundation Increase (acres) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Existing | FreLg | FreMed | FreSm | SacW | FreLg | FreMed | FreSm | SacW |
| 2 | 36,180 | 36,588 | 36,571 | 36,622 | 37,256 | 408 | 391 | 442 | 1,076 |
| 3 | 34,140 | 36,214 | 36,271 | 36,169 | 36,769 | 2,074 | 2,131 | 2,029 | 2,629 |
| 7 | 27,068 | 31,430 | 31,433 | 31,472 | 30,246 | 4,362 | 4,365 | 4,404 | 3,178 |
| 14 | 19,704 | 26,771 | 26,507 | 26,082 | 22,102 | 7,067 | 6,803 | 6,378 | 2,398 |
| 21 | 15,823 | 24,695 | 24,551 | 23,135 | 18,949 | 8,872 | 8,728 | 7,312 | 3,126 |
| 28 | 15,823 | 24,695 | 24,032 | 22,775 | 18,733 | 8,872 | 8,209 | 6,952 | 2,910 |
| 60 | 1,667 | 5,683 | 4,953 | 4,081 | 2,293 | 4,016 | 3,286 | 2,414 | 626 |

*Table 7-6. Inundated area in 67% of years between November 1 and May 30*

| Duration (days) | Inundated Area (acres) | | | | | Inundation Increase (acres) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Existing | FreLg | FreMed | FreSm | SacW | FreLg | FreMed | FreSm | SacW |
| 2 | 24,850 | 30,818 | 30,842 | 30,919 | 29,675 | 5,968 | 5,992 | 6,069 | 4,824 |
| 3 | 24,320 | 30,026 | 30,040 | 30,131 | 28,797 | 5,706 | 5,720 | 5,811 | 4,477 |
| 7 | 19,982 | 26,854 | 26,572 | 25,812 | 23,797 | 6,872 | 6,590 | 5,830 | 3,815 |
| 14 | 16,391 | 23,456 | 22,820 | 21,592 | 19,129 | 7,065 | 6,429 | 5,201 | 2,738 |
| 21 | 9,976 | 17,670 | 16,919 | 15,530 | 10,545 | 7,694 | 6,943 | 5,554 | 569 |
| 28 | 6,231 | 9,709 | 9,556 | 9,222 | 6,690 | 3,478 | 3,324 | 2,991 | 459 |
| 60 | 1,402 | 2,189 | 1,717 | 1,684 | 1,469 | 787 | 315 | 282 | 67 |

*Table 7-7. Expected annual inundation*

| Duration (days) | Expected Annual Inundation (acres) | | | | | Expected Annual Increase (acres) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Existing | FreLg | FreMed | FreSm | SacW | FreLg | FreMed | FreSm | SacW |
| 2 | 34,534 | 38,413 | 38,204 | 37,614 | 36,318 | 3,879 | 3,670 | 3,080 | 1,784 |
| 3 | 34,063 | 37,903 | 37,699 | 37,079 | 35,745 | 3,840 | 3,636 | 3,016 | 1,682 |
| 7 | 30,787 | 34,965 | 34,695 | 34,019 | 32,363 | 4,178 | 3,908 | 3,232 | 1,576 |
| 14 | 27,803 | 31,495 | 31,172 | 30,605 | 28,912 | 3,692 | 3,369 | 2,802 | 1,109 |
| 21 | 23,499 | 26,605 | 26,313 | 25,758 | 24,319 | 3,106 | 2,814 | 2,259 | 820 |
| 28 | 19,255 | 21,990 | 21,729 | 21,440 | 20,385 | 2,735 | 2,475 | 2,186 | 1,131 |
| 60 | 7,029 | 11,152 | 10,531 | 9,955 | 8,693 | 4,122 | 3,502 | 2,926 | 1,663 |

## 7.3 Post-processed Data

The TUFLOW model results will inform other analyses including agriculture economic impacts, fisheries benefits model, and CALSIM modeling. The model results required post-processing to prepare the output data into the appropriate format for each type of analysis.

### 7.3.1 Last Day Wet Determination

The most extensive post-processing involved the determination of the last day wet (LDW) for individual field units within the Bypass. Yolo County performed landowner outreach to gather additional information to use in the Yolo Bypass Agricultural Impact Analysis for this project. During those discussions with landowners it was learned that that farmers are likely to begin planting their fields when at least 70 percent of their fields were dry (or conversely, the last day when more than 30% of the area is wet). Based on this information and discussions with the lead modeler of the Yolo Bypass Agricultural Impact Analysis, it was agreed upon to use this assumption as the ratio for last day wet (LDW) calculations. The field units were provided by the Agriculture Economics team which will be utilizing the LDW to inform their analysis regarding the potential impacts the proposed channels may have on agriculture within the Bypass.

It should be noted that the LDW data is produced by post-processing the Model results and the ratio used for determining LDW can be changed without altering the Model. The LDW is determined by analyzing the raster solutions for each day of the simulation (specific water year, alternative, and gate closure date) by subtracting the 25-foot base DEM from the TUFLOW water surface elevation outputs to create 25-foot depth rasters. LDW results for water year 2001 for each configuration are shown in Figures 7-17 through Figure 7-21. Additional LDW results are included in Appendix F. The number of output raster cells that are dry for each field unit are counted and compared with the number of raster cells within the field unit. The last day in the simulation where less than 70 percent of the raster cells are dry is assigned to the LDW attribute.

### 7.3.2 Post-processing for Fisheries Team

Minor post-processing was required to fulfill the fisheries benefits models hydrodynamic data input needs. The fisheries team requested depth and velocity magnitude raster datasets covering the Bypass in ESRI ASCII format and daily average discharge values for the Fremont Weir (including channel flows), the Sacramento at Verona, and the Sacramento River at Freeport. The raster results from TUFLOW were converted from ESRI binary float format to ESRI ASCII format. The discharge values from the 1D and 2D time-series output were averaged on a daily basis and provided in csv format as requested.

### 7.3.3 Rating Curve Derivation for CALSIM Modeling

The CALSIM modeling group requested flow versus flow rating curves at the Fremont Weir. Because flows from the Sutter Bypass, the Feather River, and the Sacramento River intermix, the rating curves are based upon comparing flows at Verona with the sum of the flows over the Fremont Weir and through the proposed gate channels. A rating curve was developed for existing conditions based upon the TUFLOW model results and matches well to rating curves previously used in the CALSIM model confirming the approach used.

The rating curves were developed as scatterplots containing a point for each output value where the Fremont Weir overtopped or the gate channels were open and active. The resulting rating curves are shown in Figure 7-22. The lower discharge portion of the rating curves are shown in Figure 7-23.

## 7.4 Preliminary Flood Impact Analysis

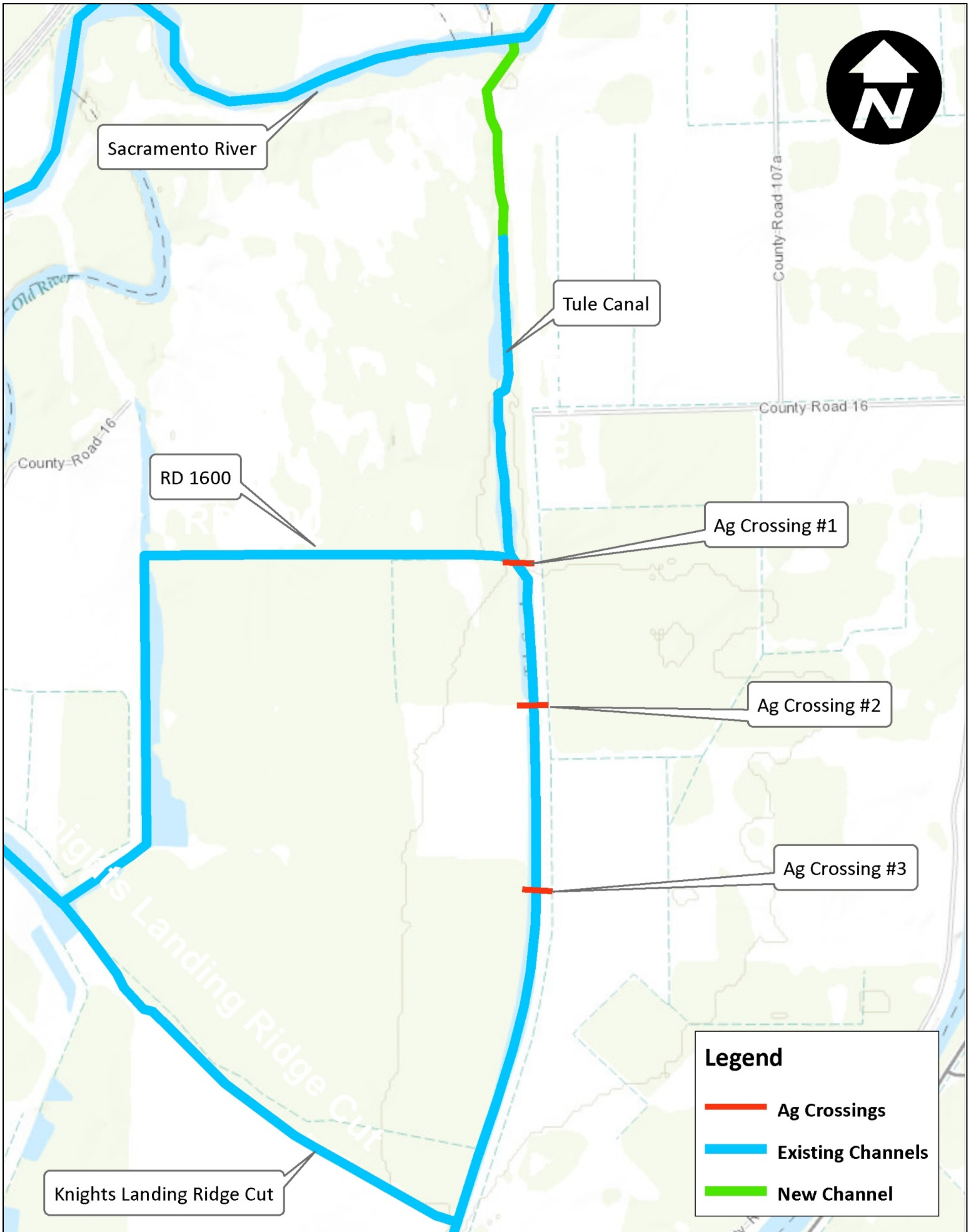
While a complete analysis of flood impacts for permitting purposes is beyond the scope of this report, the results for the water years with the largest floods were compared to predict potential flood impacts. The peak WSE for the existing conditions and the large channel alternative configurations for the 1997, 1998, and 2006 water years were compared to evaluate the potential project impacts on flooding. The analysis is based upon the previously analyzed configuration and operations. The gates were regulated to prevent more than 6,000 cfs through the channel until the Fremont Weir overtops. Once Fremont Weir overtops, the gate openings are held steady (not changed from opened or closed position) until the overtopping has ceased or the project end date (gates closed) has been reached.

Differences in maximum WSEs for the existing conditions and large channel configuration are shown in Figures 7-24 through Figure 7-26.Because the large channel configuration allows higher discharges into the Yolo Bypass than under existing conditions, the maximum WSEs are higher within the Bypass for this alternative. However, this decreases the discharge down the Sacramento River past Verona and lowers the maximum WSEs compared to existing conditions.

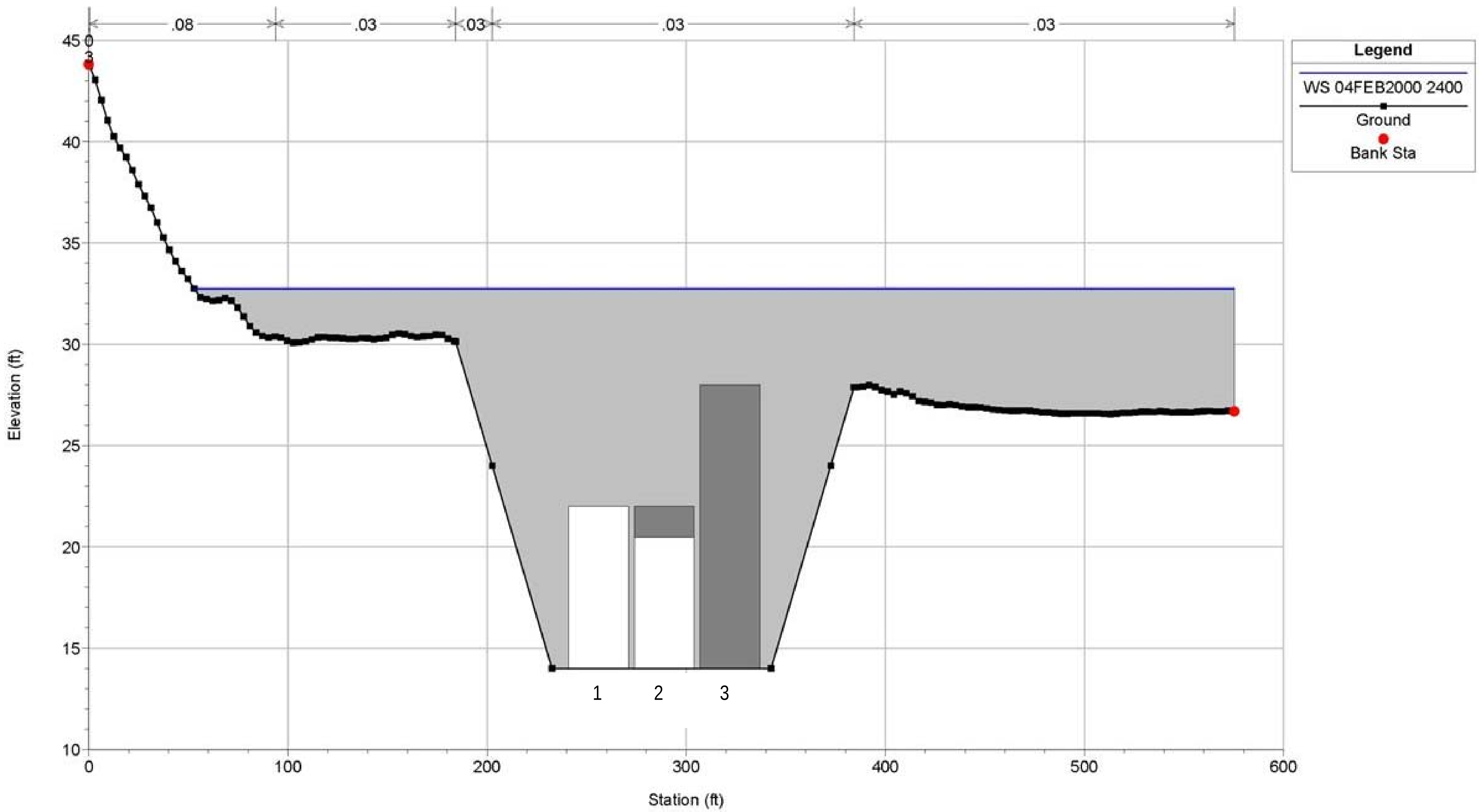
The increases in maximum WSEs within the Yolo Bypass are small for the large channel alternative. Near the proposed channels there are local increases and decreases in WSE because of the geometry changes in these areas. The increase in maximum WSE for most of the Bypass is less than 0.02 feet for all three water years analyzed. The largest flood occurred in 1997 and some portions of the Bypass experienced increases in maximum WSE between 0.02 and 0.05 feet.

Because the Sacramento River downstream of Verona is more constricted than the Bypass, the diversion of additional flows has a larger effect upon the maximum WSEs than was experienced within the Bypass. The decreases in maximum WSE extend upstream of the Yolo Bypass but the effect diminishes moving upstream.

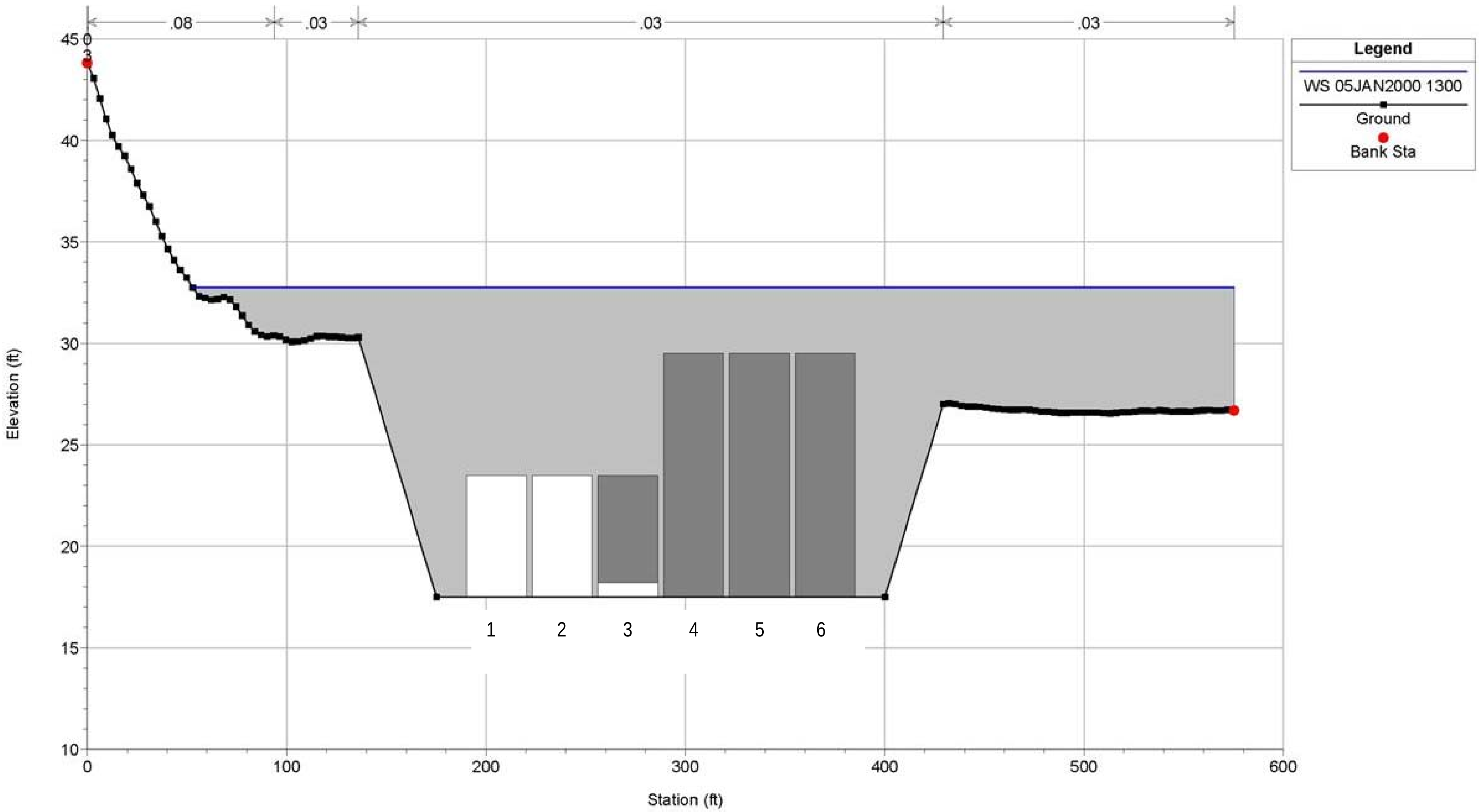
This analysis suggests that the project impacts to flooding will be minor based upon preliminary channel/gate designs and operations. Design changes to the project configuration or operations may alter flood impacts. Further analysis will be required after designs and operations have been finalized and to meet Federal Emergency Management Agency (FEMA) and other agency requirements. The required analysis to meet FEMA floodplain regulations is summarized in Appendix G.




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | | |
|---|---|---|---|---|
| | | **Fremont Weir Alternatives Location Map** | | |
| | | Prepared for DWR | Created By: CRC | **Figure 7-1** |




| Notes: Gate closure shown represents 6000 cfs at maximum Sacramento River Stage before Fremont Weir begins to overtop for gates operated individually. (white = gate opening, grey = partial gate closure) | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Fremont Weir Small Gate Configuration** |
|---|---|---|
| | Prepared for DWR | Created By: CRC | **Figure 7-2** |

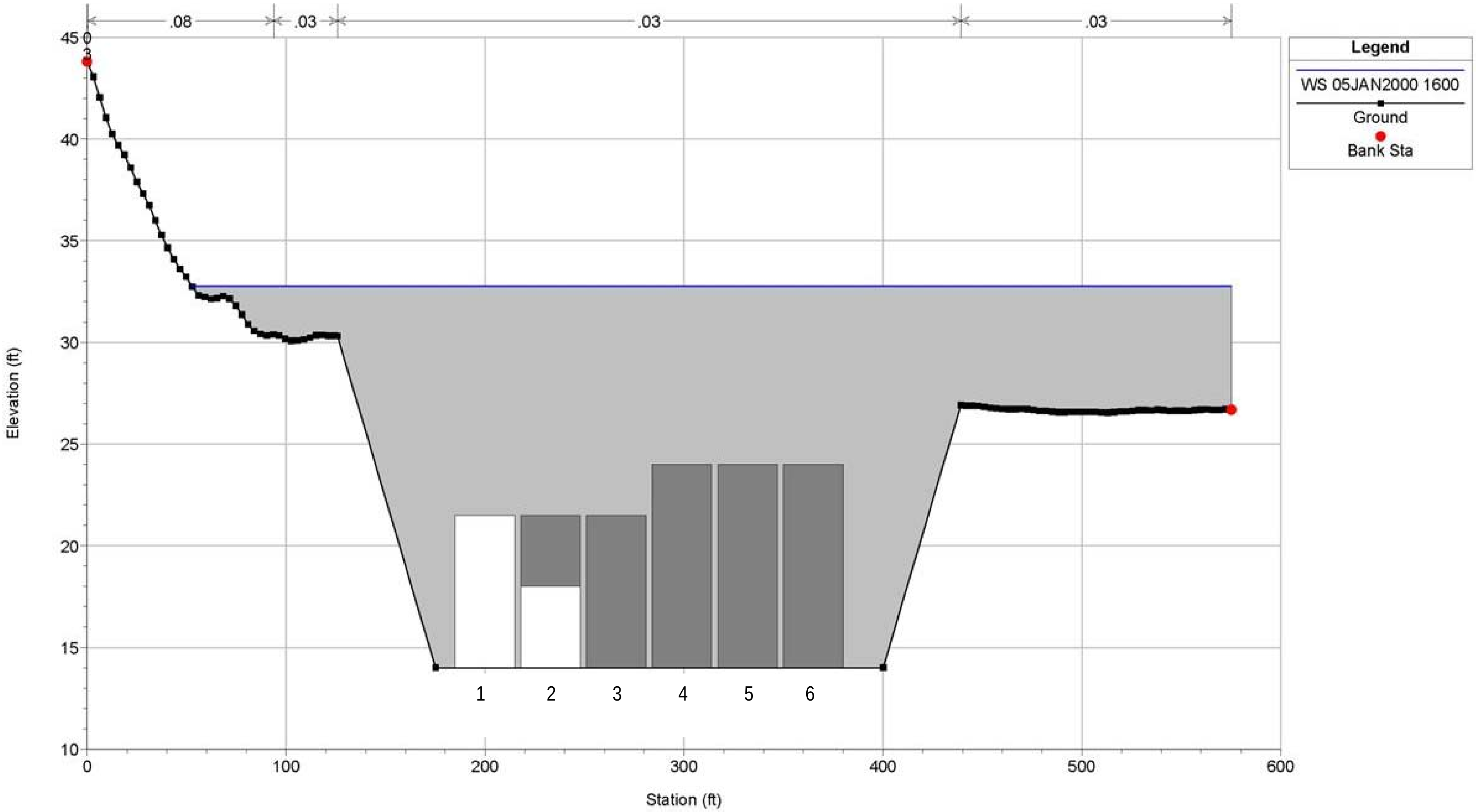



Notes: Gate closure shown represents 6000 cfs at maximum Sacramento River Stage before Fremont Weir begins to overtop for gates operated individually. (white = gate opening, grey = partial gate closure)

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Fremont Weir Medium Gate Configuration**

| Prepared for DWR | Created By: CRC | **Figure 7-3** |
|---|---|---|




Notes: Gate closure shown represents 6000 cfs at maximum Sacramento River Stage before Fremont Weir begins to overtop for gates operated individually. (white = gate opening, grey = partial gate closure)

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Fremont Weir Large Gate Configuration**

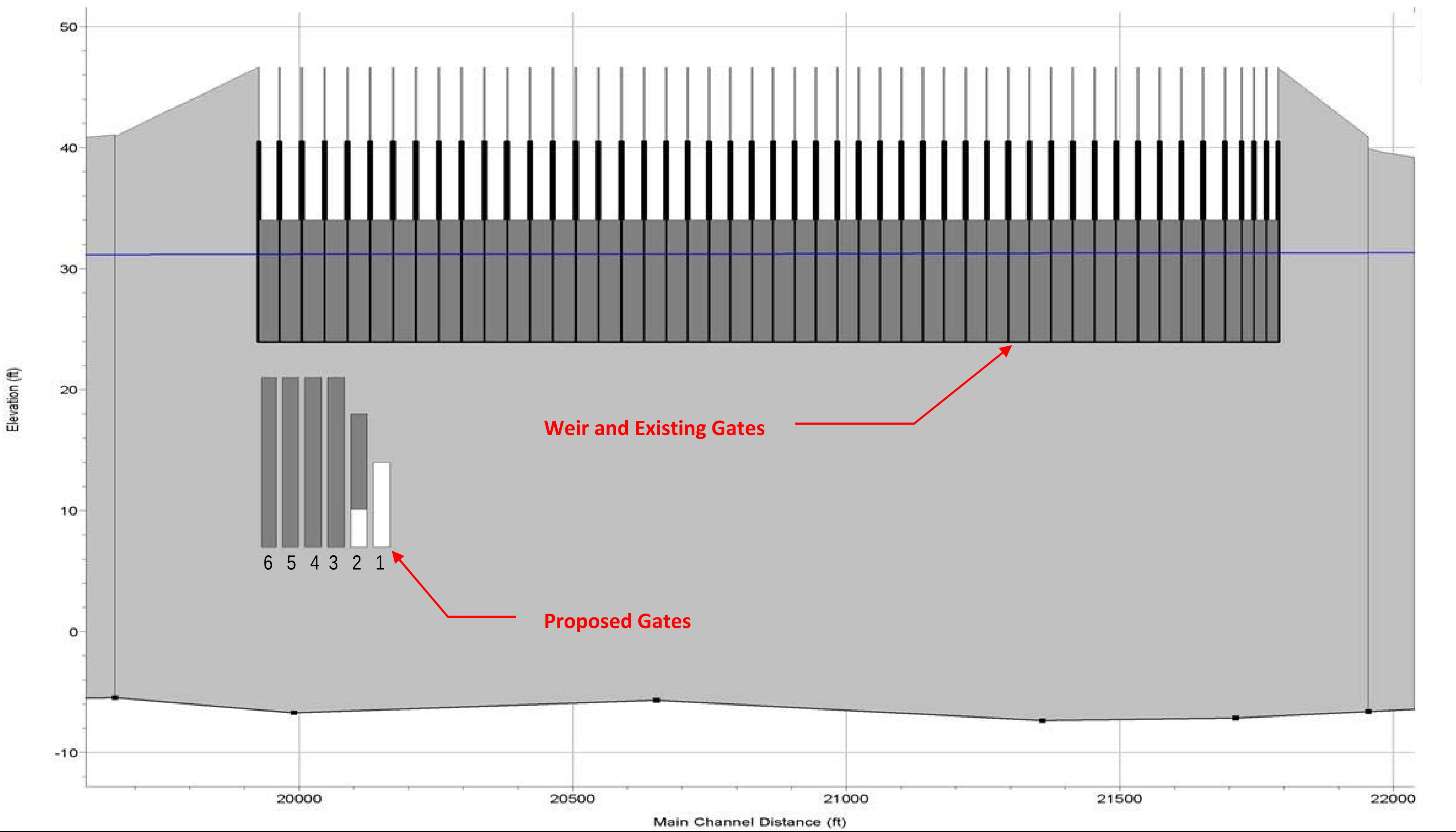
| | | |
|---|---|---|
| Prepared for DWR | Created By: CRC | **Figure 7-4** |


Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Sacramento Weir Alternative Location Map**

| Prepared for DWR | Created By: CRC | **Figure 7-5** |
|---|---|---|

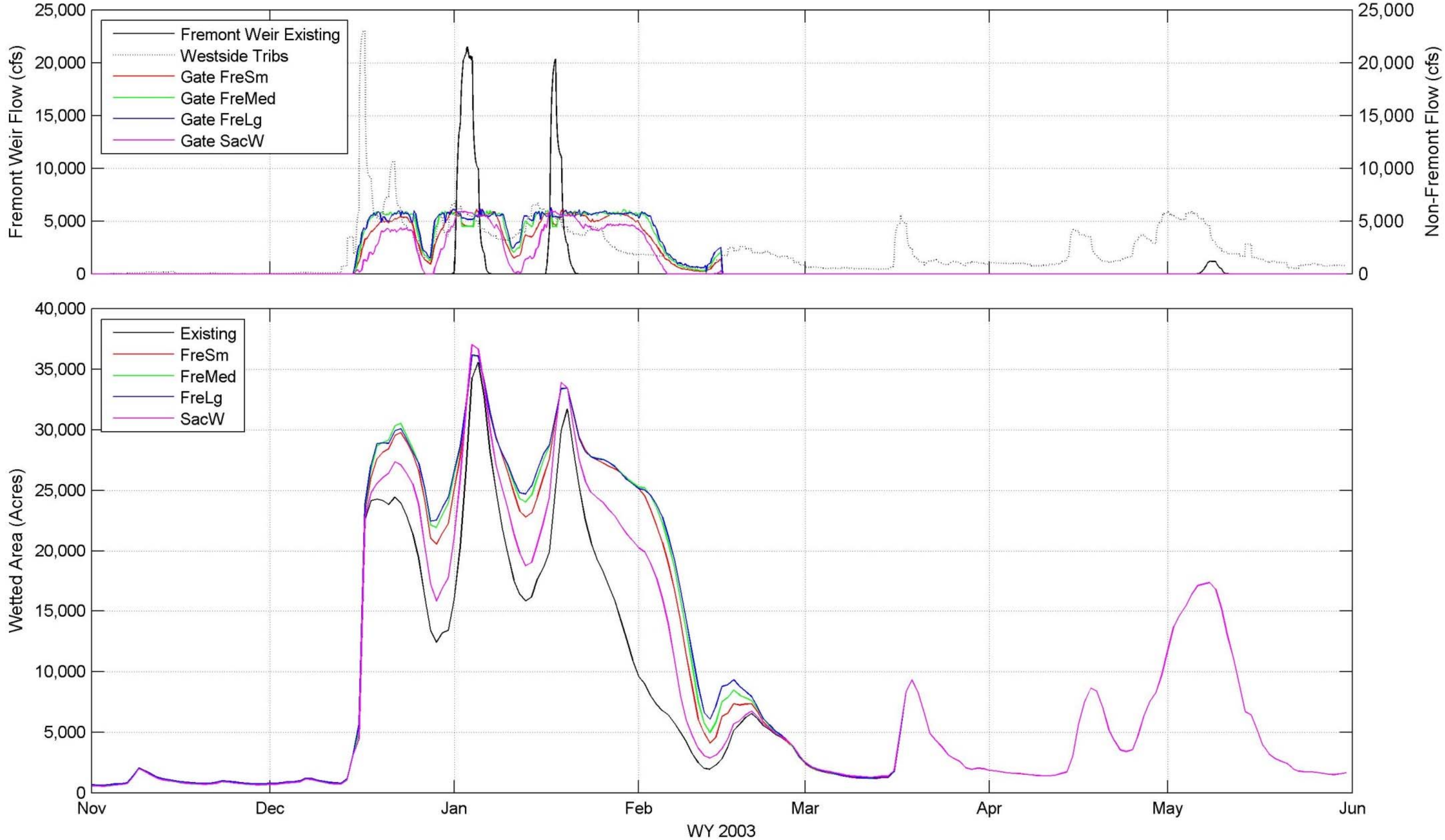



Notes: Gates 1 and 2 were limited in height to prevent the top of the gate from extending above the existing weir sill during a flood event when the Sacramento Weir is open and the two gates are partially open to convey up to 6,000 cfs. (white = gate opening, grey = partial gate closure)

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Sacramento Weir Alternative Proposed Gates**

Prepared for DWR | Created By: CRC | **Figure 7-6**

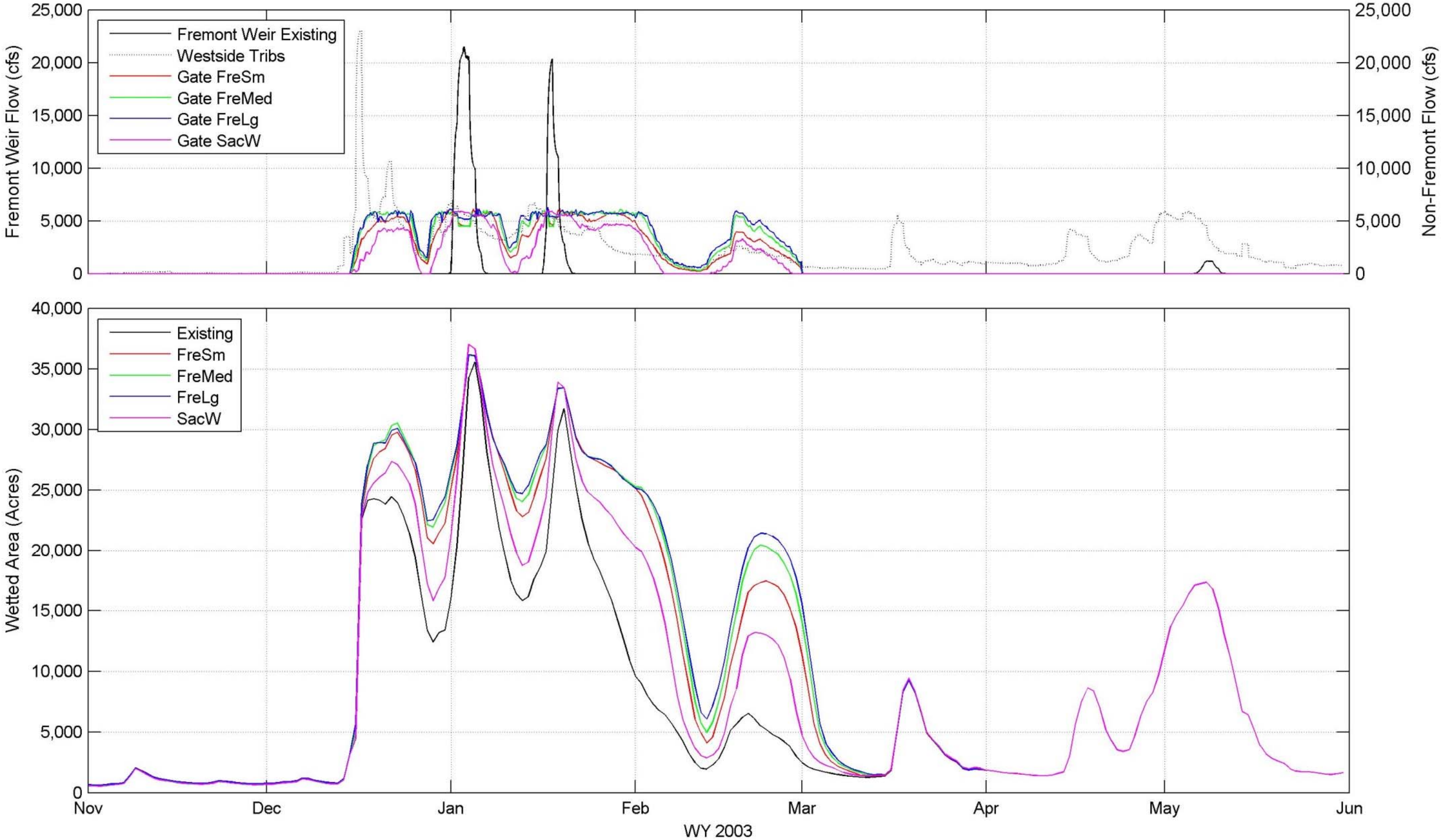



Notes:

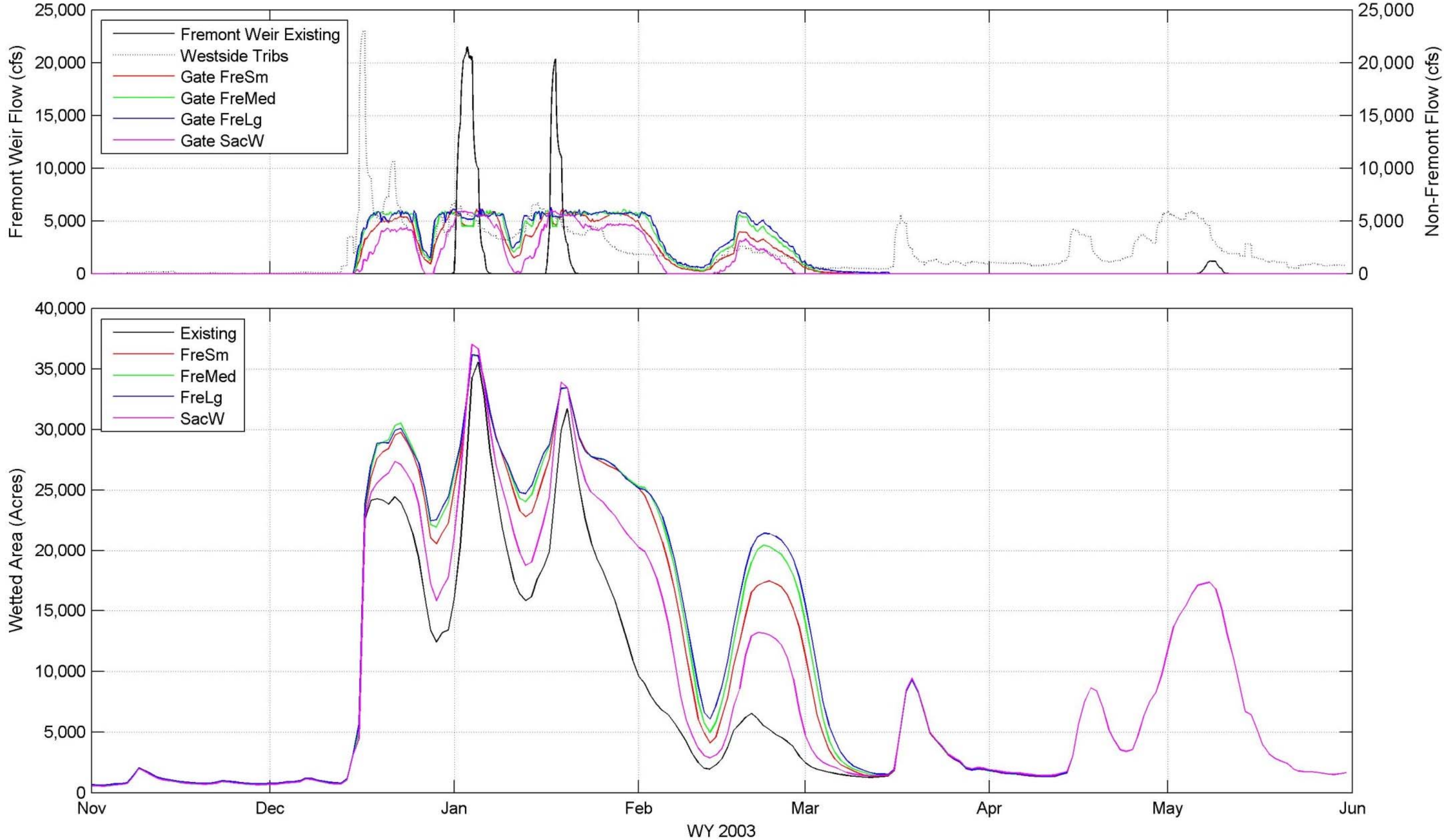
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for Alternatives-WY 2003 Feb. 15 Gate Closure**

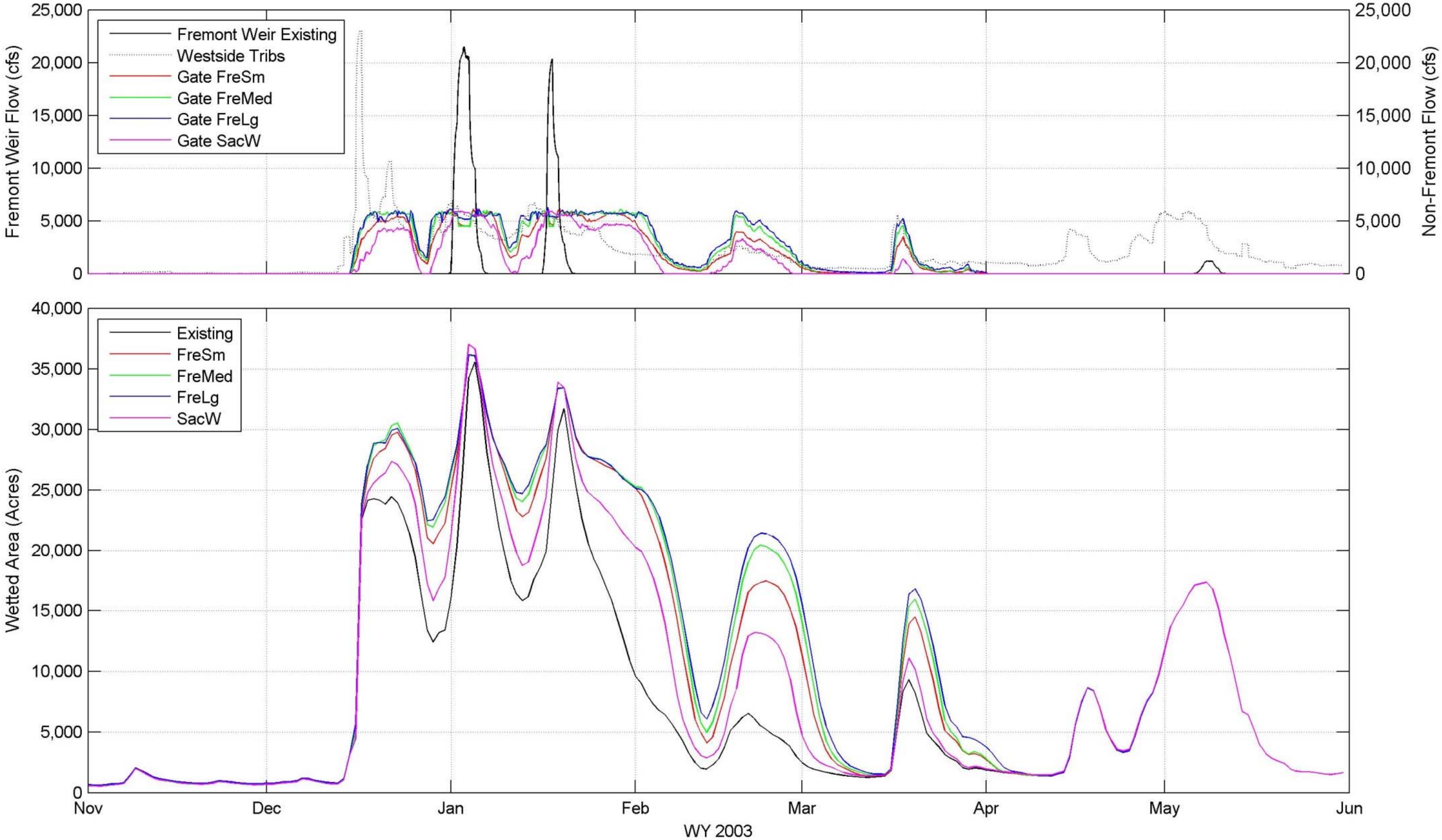
| | | |
|---|---|---|
| Prepared for DWR | Created By: SJB | **Figure 7-7** |




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**Wetted Acres for Alternatives-WY 2003 Mar. 1 Gate Closure** | | |
|---|---|---|---|---|
| | HDR cbec eco engineering | Prepared for DWR | Created By: SJB | **Figure 7-8** |




| Notes: | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage*<br>**Wetted Acres for Alternatives-WY 2003 Mar. 15 Gate Closure** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: SJB | **Figure 7-9** |

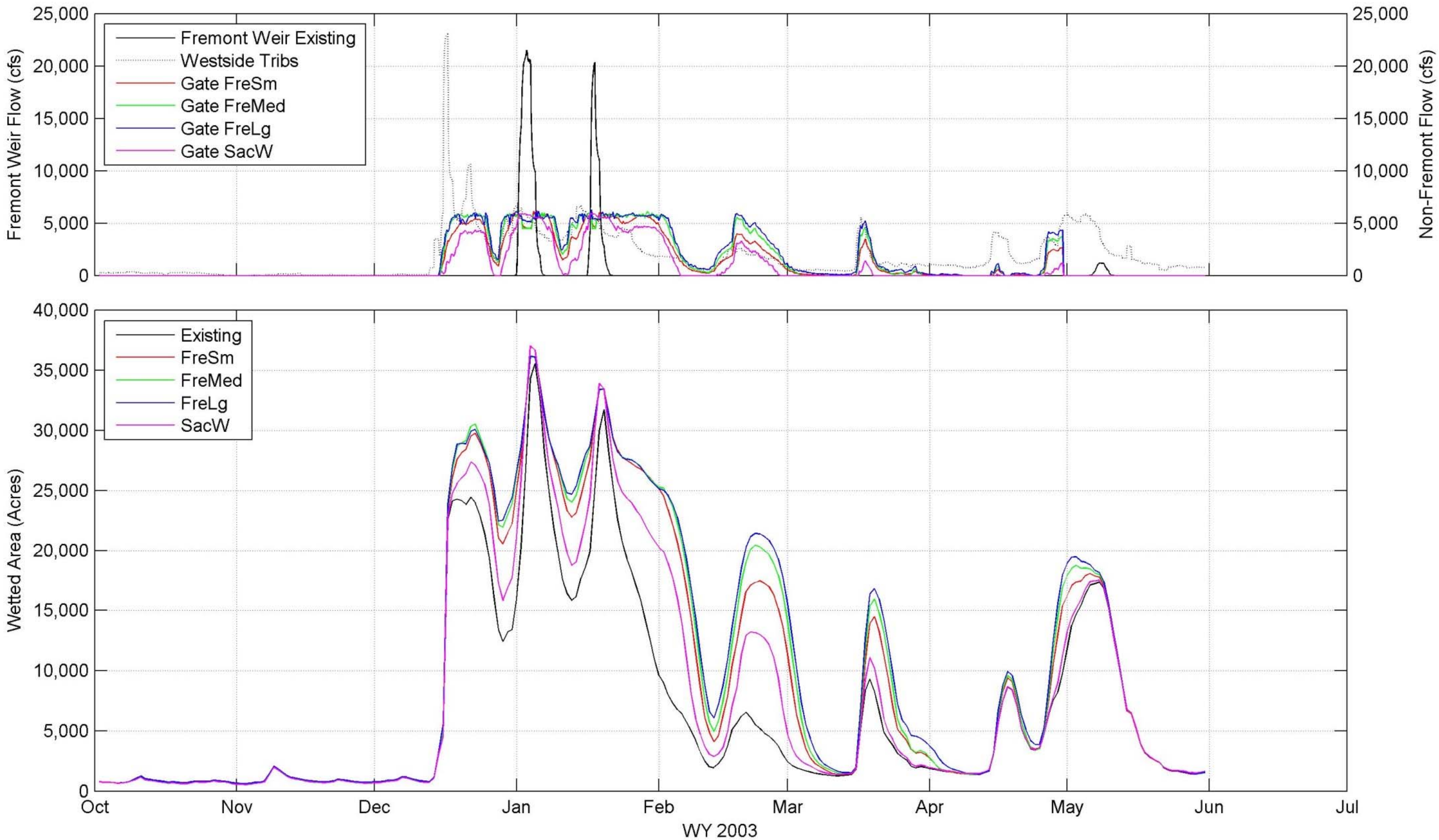



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for Alternatives-WY 2003 Apr. 1 Gate Closure**

| Prepared for DWR | Created By: SJB | **Figure 7-10** |
|---|---|---|

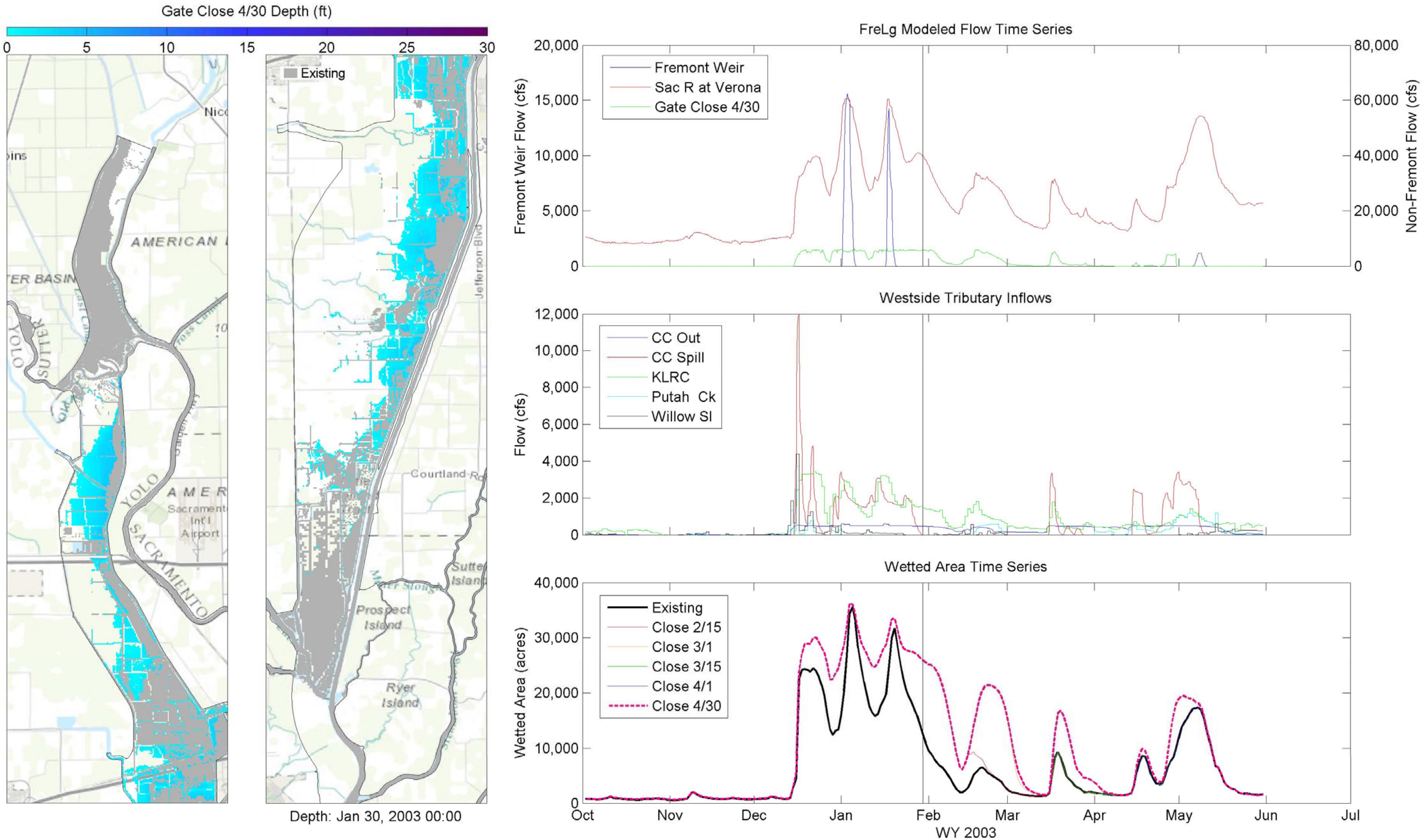



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for Alternatives-WY 2003 Apr. 30 Gate Closure**

| Prepared for DWR | Created By: SJB | **Figure 7-11** |
|---|---|---|

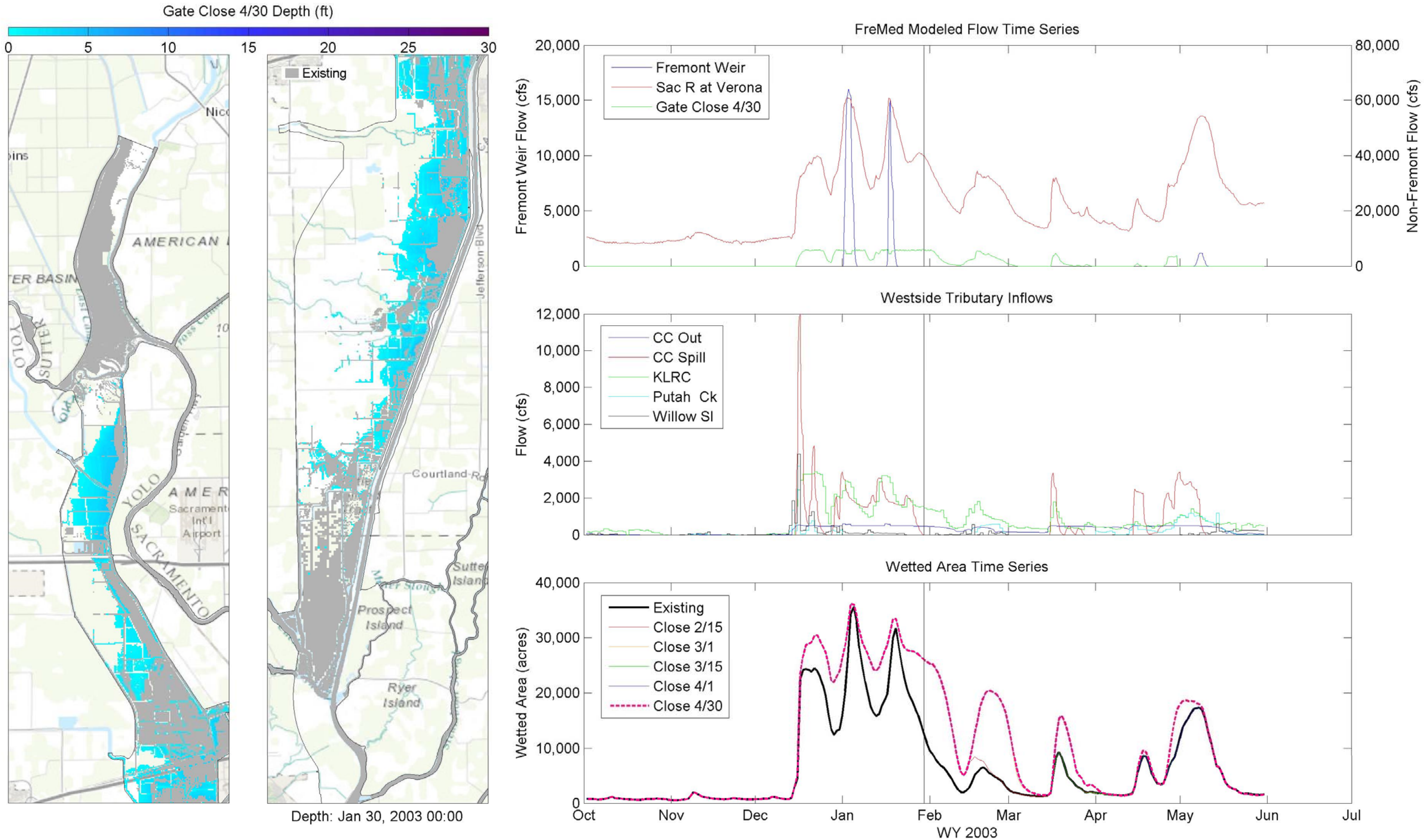



Notes: TUFLOW model results showing 2D inundation patterns (at specified time stamp) for existing and 4/30 gate closure (left panes), Yolo Bypass inflows (upper right panes), and wetted area for all five gate closures (lower right pane). The vertical bar in the right panes corresponds to the time stamp below the left panes, whereby the blue hatching represents 4/30 gate closure conditions as overlain by the grey hatching representing existing conditions.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for All Gate Closures for FreLg – WY2003**

| Prepared for DWR | Created By: SJB | **Figure 7-12** |
|---|---|---|




Notes: TUFLOW model results showing 2D inundation patterns (at specified time stamp) for existing and 4/30 gate closure (left panes), Yolo Bypass inflows (upper right panes), and wetted area for all five gate closures (lower right pane). The vertical bar in the right panes corresponds to the time stamp below the left panes, whereby the blue hatching represents 4/30 gate closure conditions as overlain by the grey hatching representing existing conditions.

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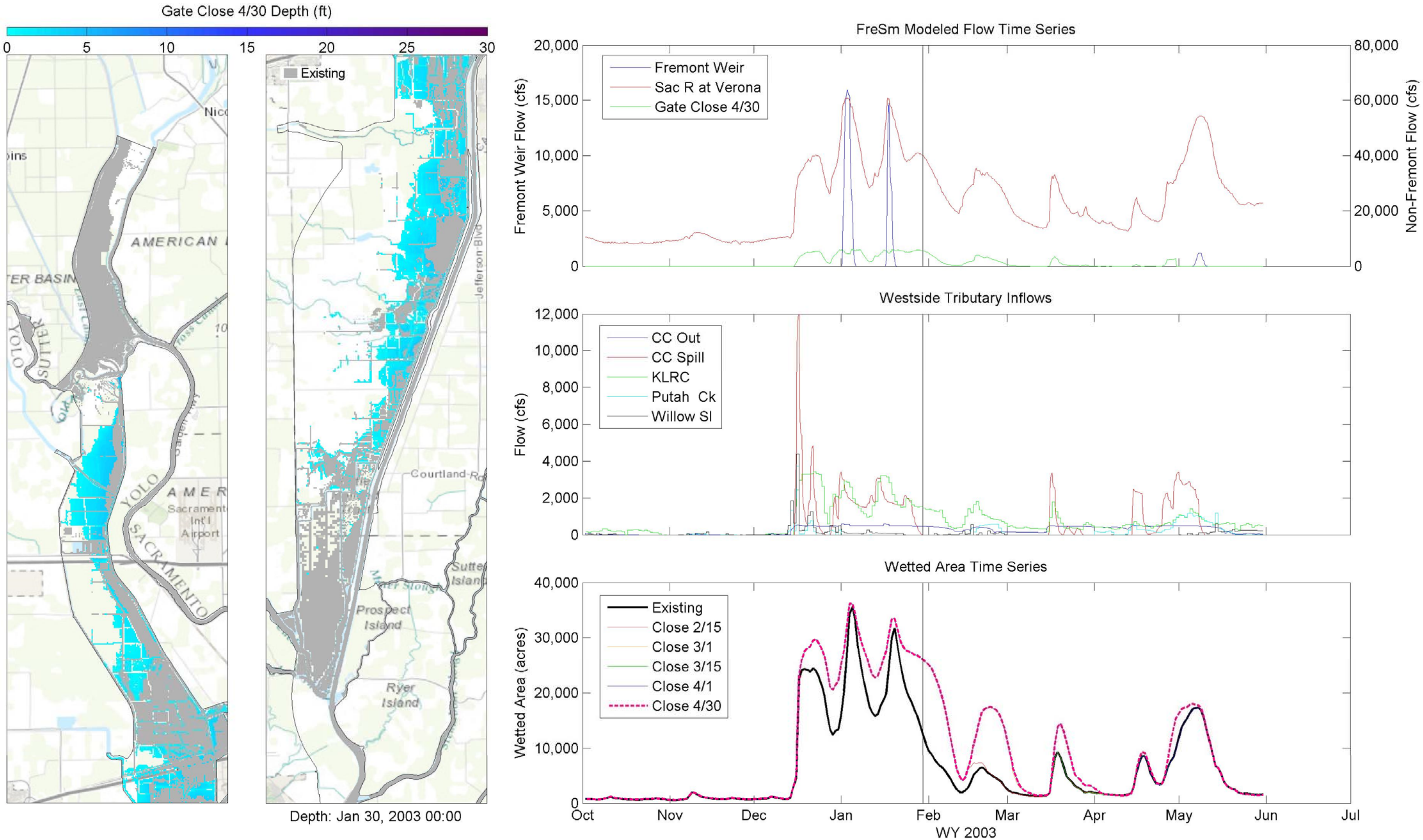
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for All Gate Closures for FreMed – WY2003**

| Prepared for DWR | Created By: SJB | **Figure 7-13** |
|---|---|---|

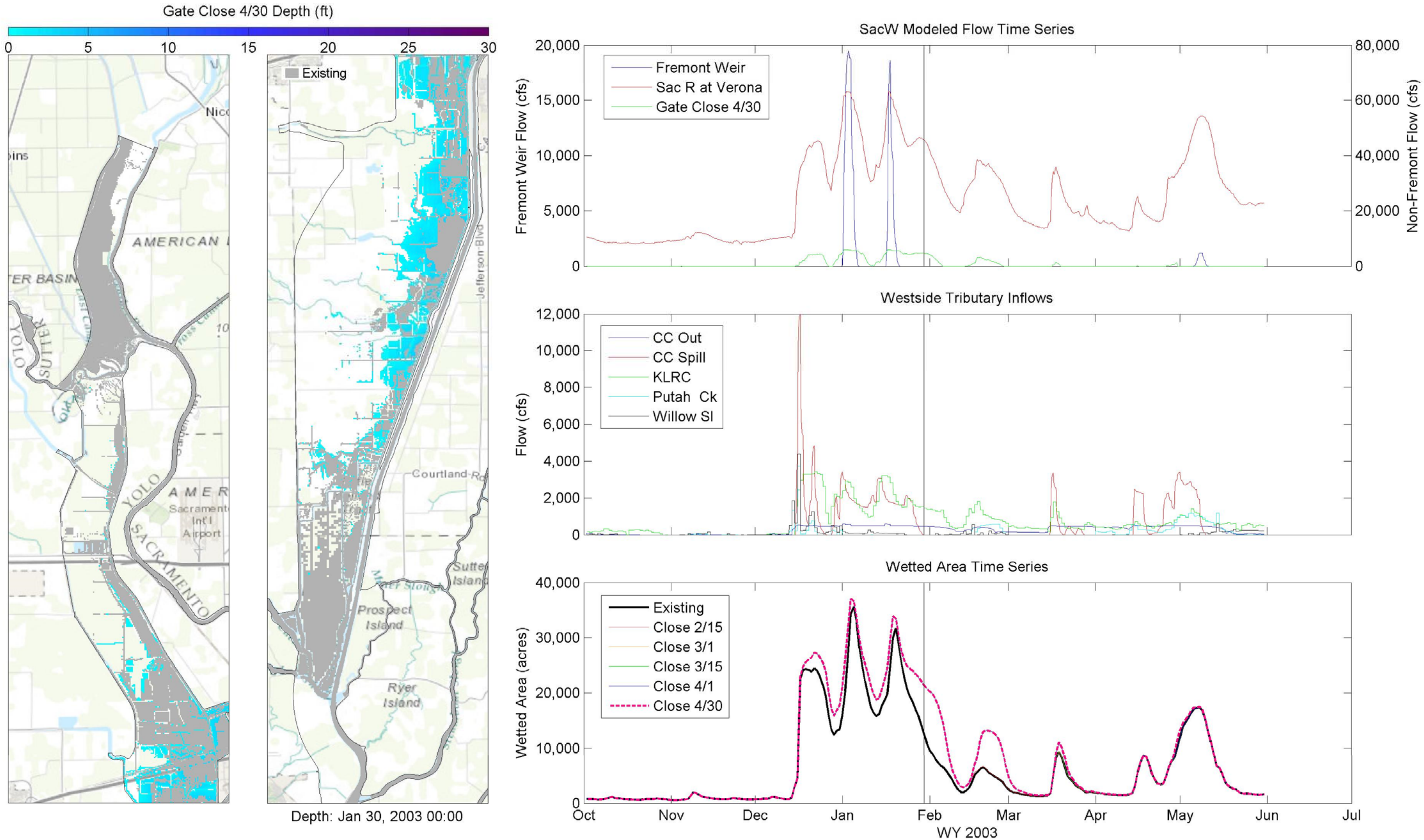



Notes: TUFLOW model results showing 2D inundation patterns (at specified time stamp) for existing and 4/30 gate closure (left panes), Yolo Bypass inflows (upper right panes), and wetted area for all five gate closures (lower right pane). The vertical bar in the right panes corresponds to the time stamp below the left panes, whereby the blue hatching represents 4/30 gate closure conditions as overlain by the grey hatching representing existing conditions.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for All Gate Closures for FreSm – WY2003**

| Prepared for DWR | Created By: SJB | **Figure 7-14** |
|---|---|---|




Notes: TUFLOW model results showing 2D inundation patterns (at specified time stamp) for existing and 4/30 gate closure (left panes), Yolo Bypass inflows (upper right panes), and wetted area for all five gate closures (lower right pane). The vertical bar in the right panes corresponds to the time stamp below the left panes, whereby the blue hatching represents 4/30 gate closure conditions as overlain by the grey hatching representing existing conditions.

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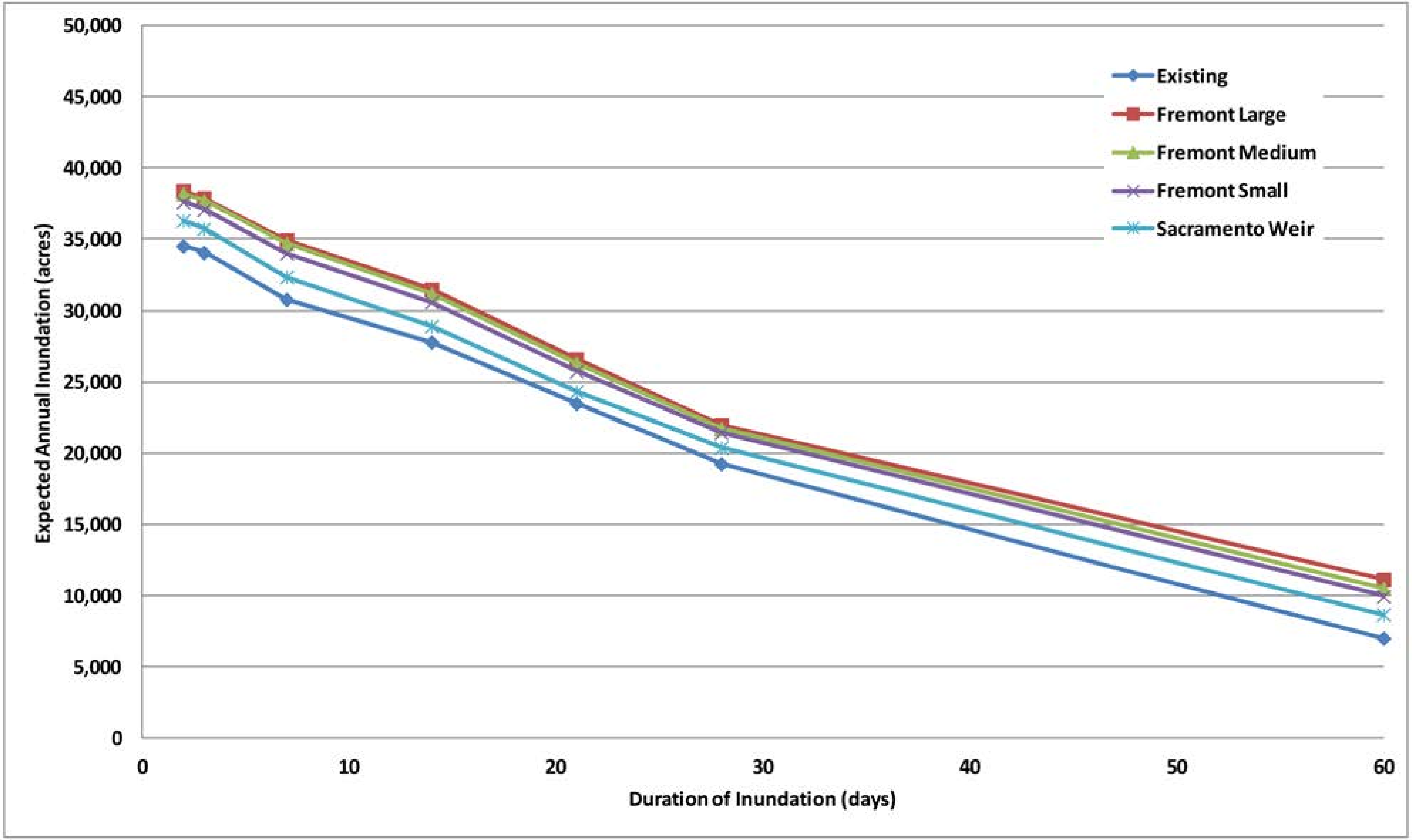
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Wetted Acres for All Gate Closures for SacW – WY2003**

Prepared for DWR | Created By: SJB | **Figure 7-15**

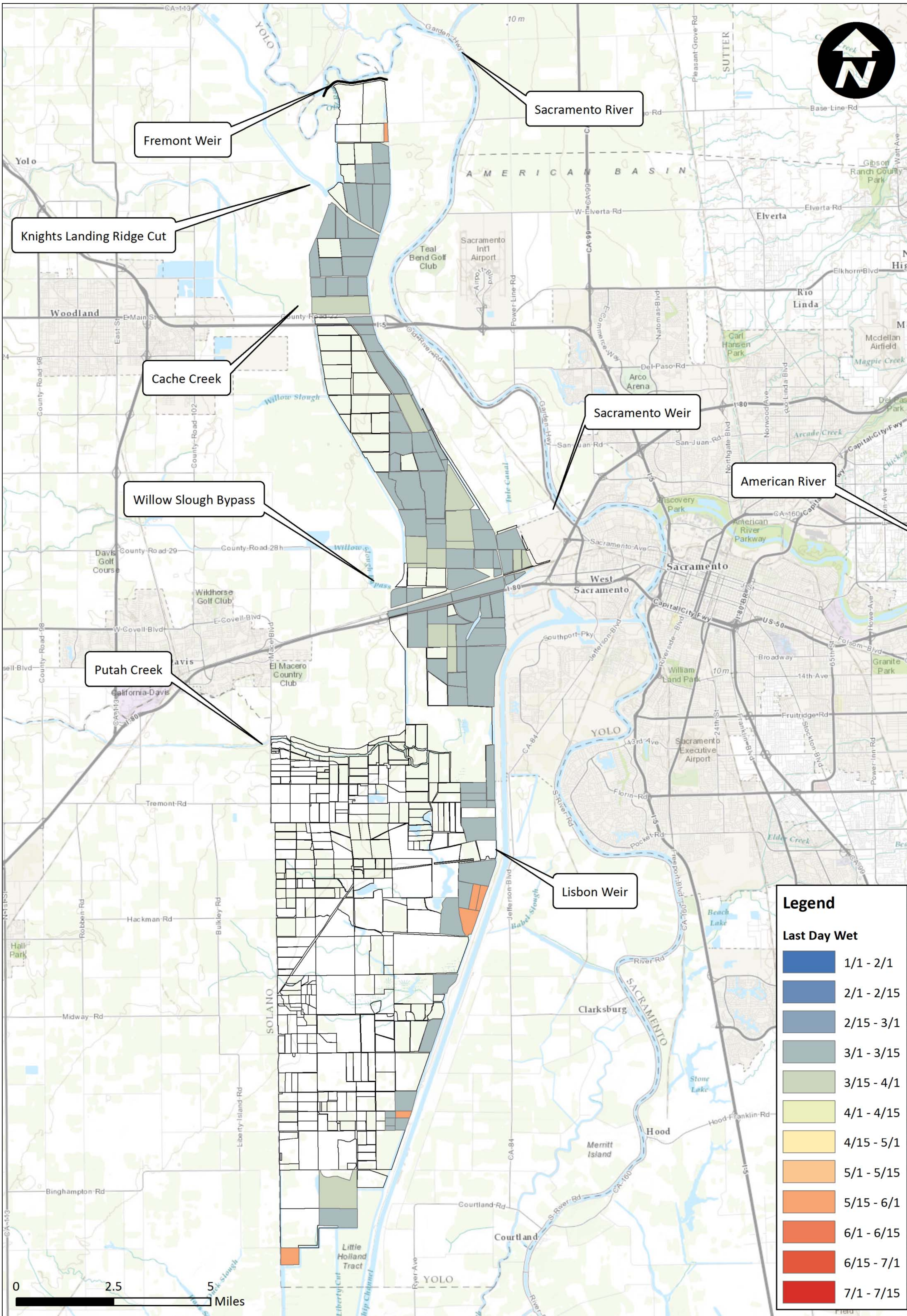



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Expected Annual Inundation for FreLg 4/30 Closure**

| Prepared for DWR | Created By: CRC | **Figure 7-16** |
|---|---|---|

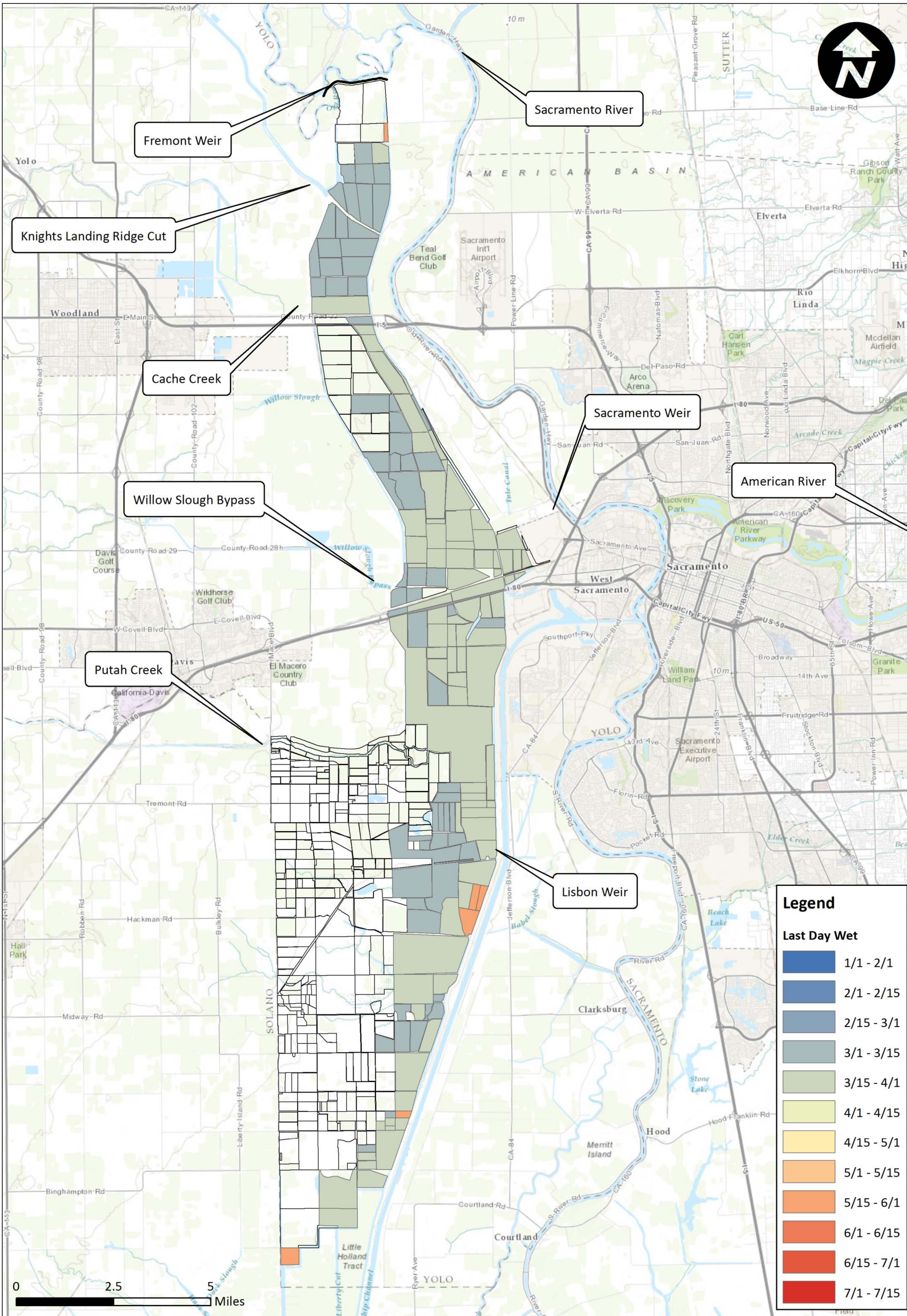



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Last Day Wet Existing Conditions WY 2001**

Prepared for DWR | Created By: RDJ | **Figure 7-17**

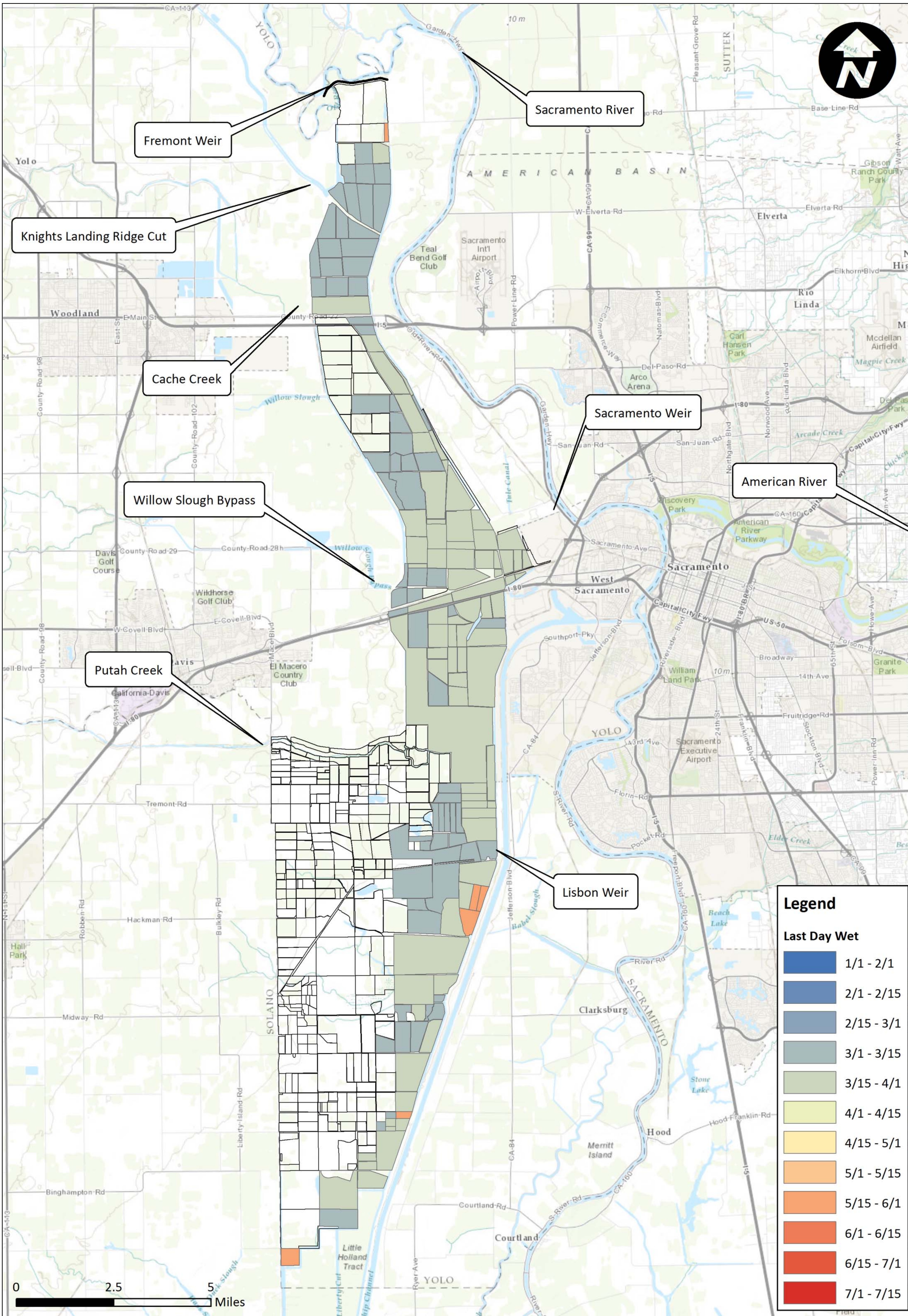



Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Last Day Wet FreLg Channel 4/30 Closure WY 2001**

Prepared for DWR | Created By: RDJ | **Figure 7-18**



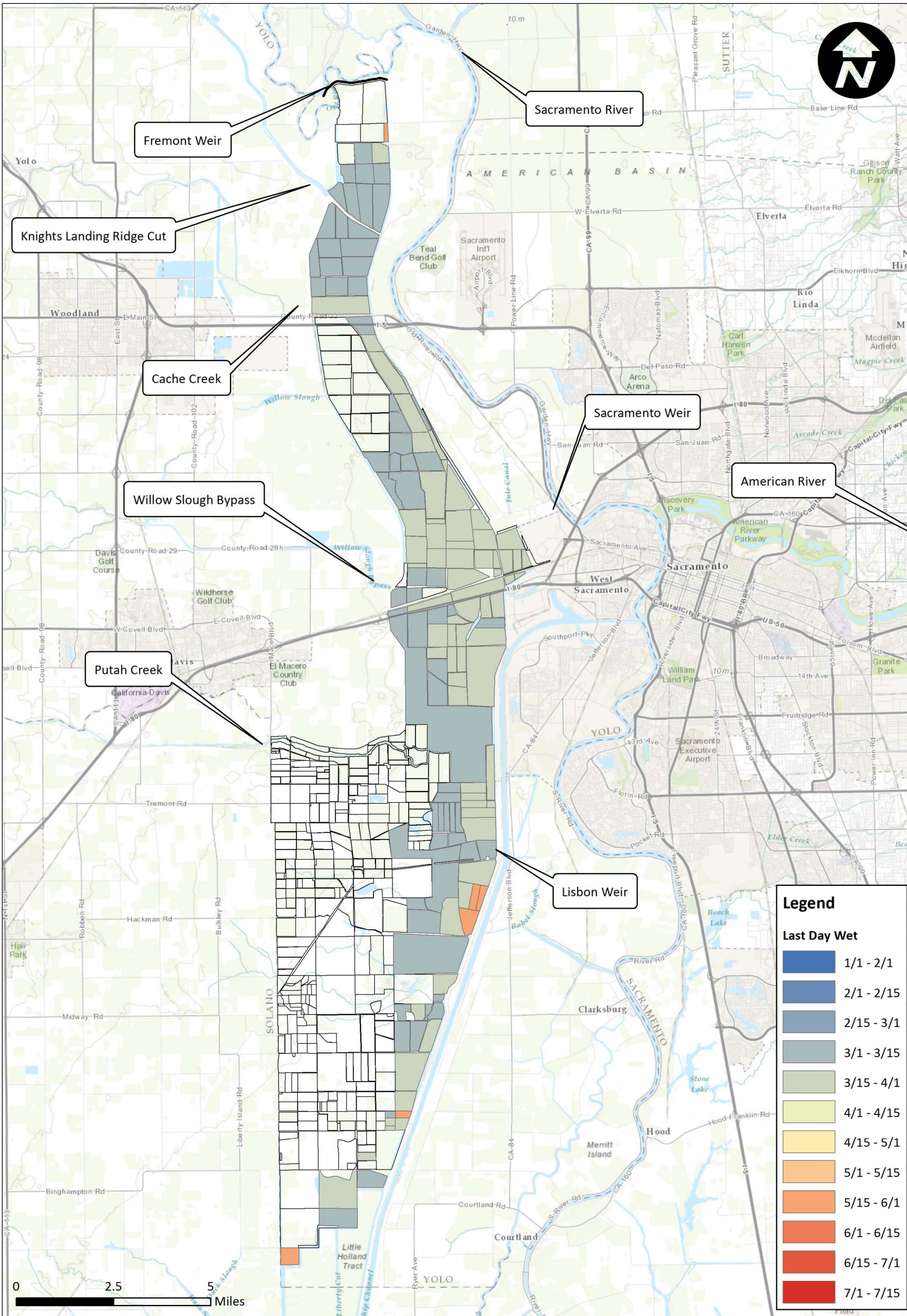

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Last Day Wet FreMed Closure 4/30 WY 2001**

Prepared for DWR | Created By: RDJ

**Figure 7-19**



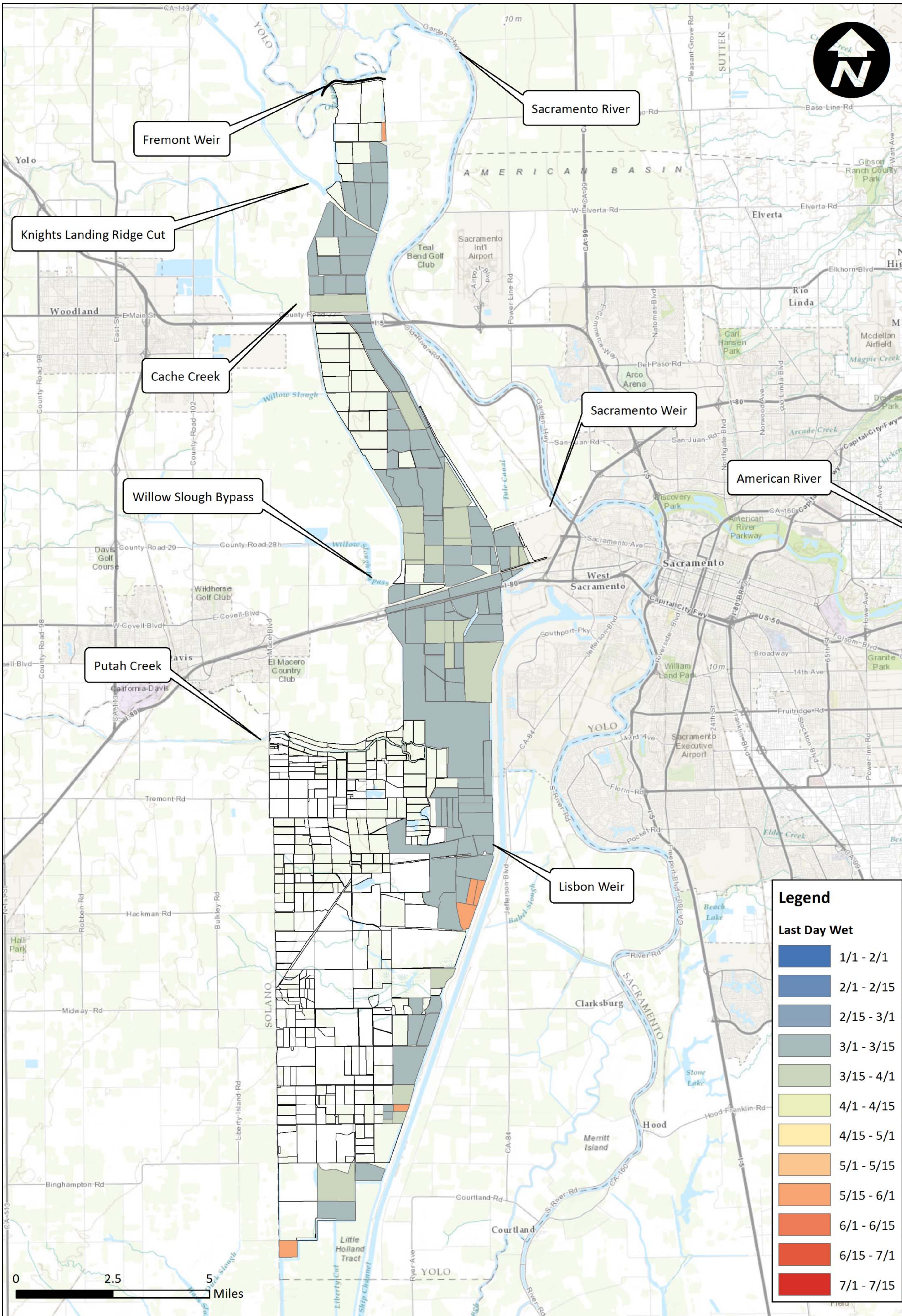

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Last Day Wet FreSm Channel 4/30 Closure 2001**

Prepared for DWR | Created By: RDJ

**Figure 7-20**



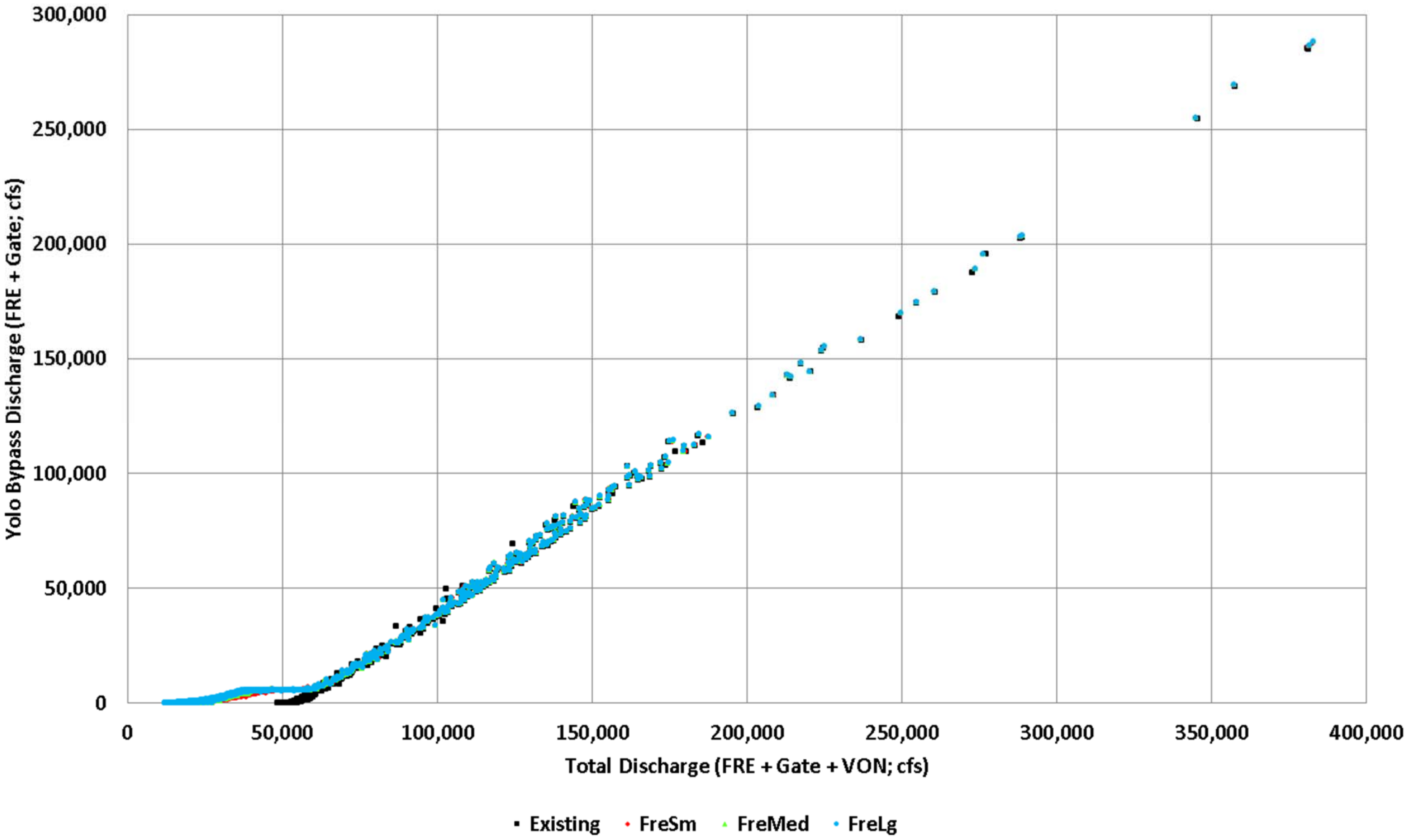

Notes:

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

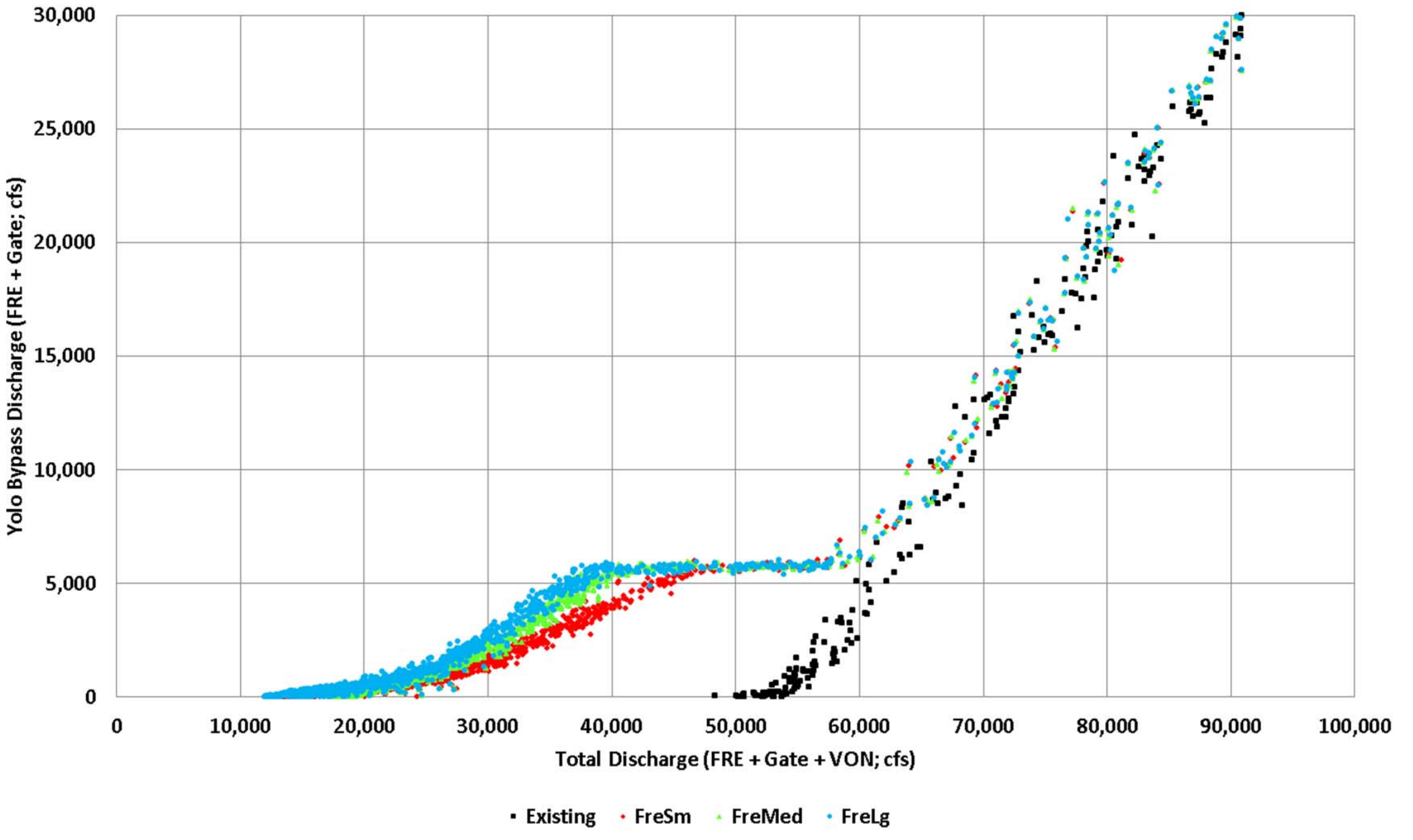
**Last Day Wet SacW 4/30 Closure 2001**

Prepared for DWR | Created By: RDJ

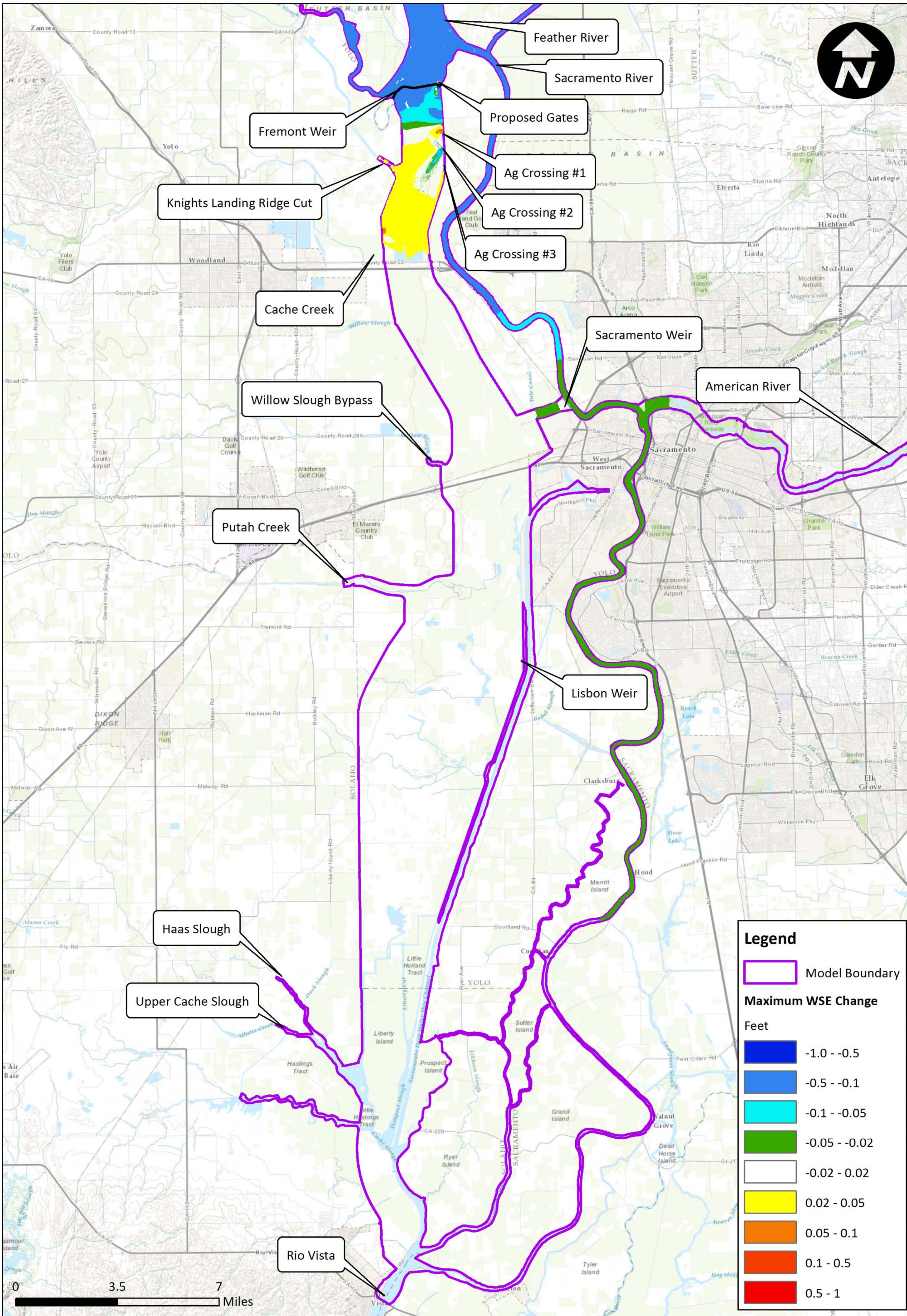
**Figure 7-21**




| Notes: Flow entering the Yolo Bypass vs total discharge going into the bypass or down the Sacramento River. | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Flow Rating Curves for Fremont Weir** | | |
|---|---|---|---|---|
| | | Prepared for DWR | Created By: RDJ | **Figure 7-22** |




| | | | | |
|---|---|---|---|---|
| Notes: Flow entering the Yolo Bypass vs total discharge going into the bypass or down the Sacramento River. | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Flow Rating Curves for Fremont Weir Zoomed** | | |
| | | Prepared for DWR | Created By: RDJ | **Figure 7-23** |

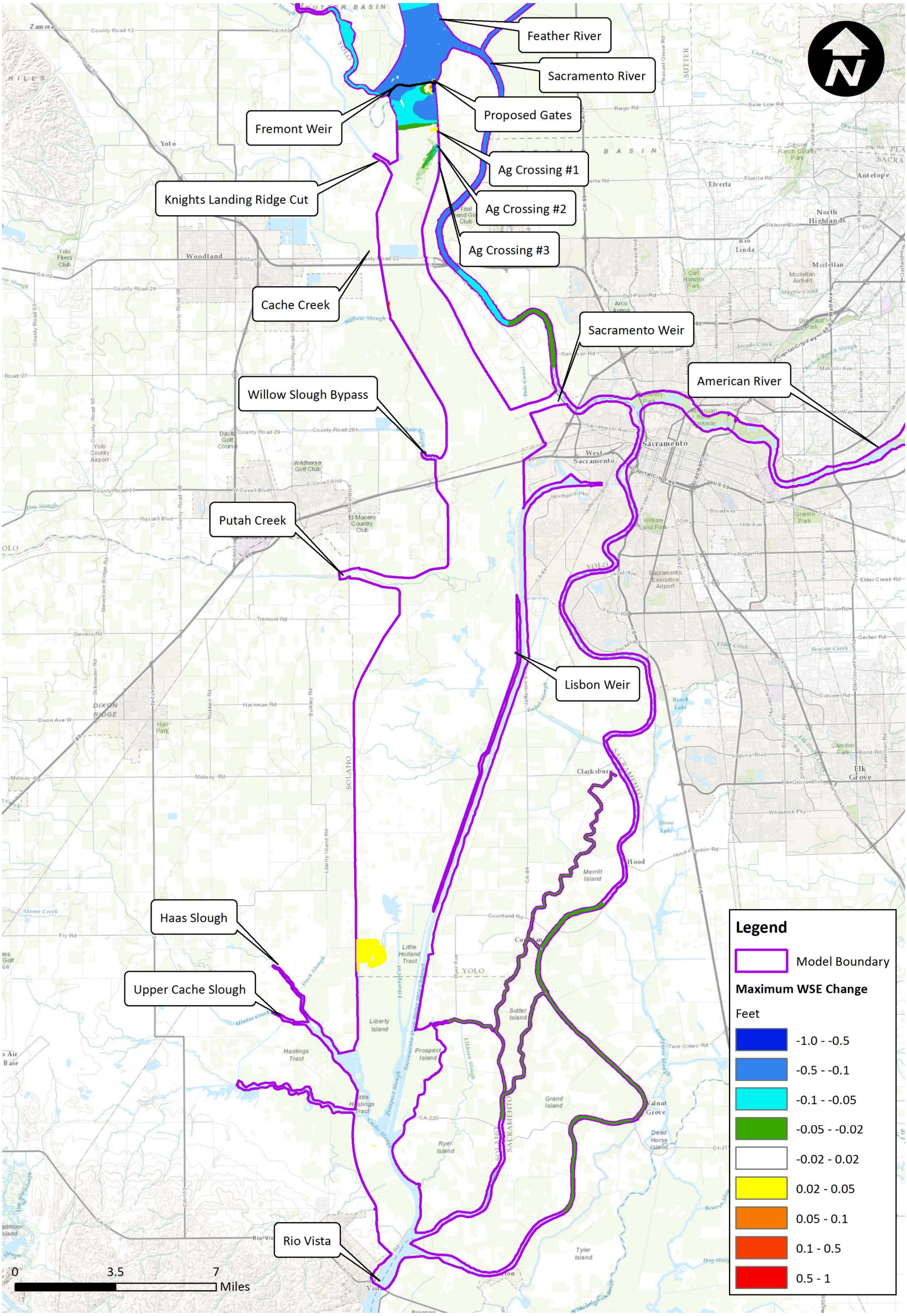



Notes: Comparing Large Channel configuration with existing conditions. Positive values indicate increases in maximum water surface elevations.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Change in Maximum WSE for Large Channel 1997**

Prepared for DWR | Created By: RDJ | **Figure 7-24**



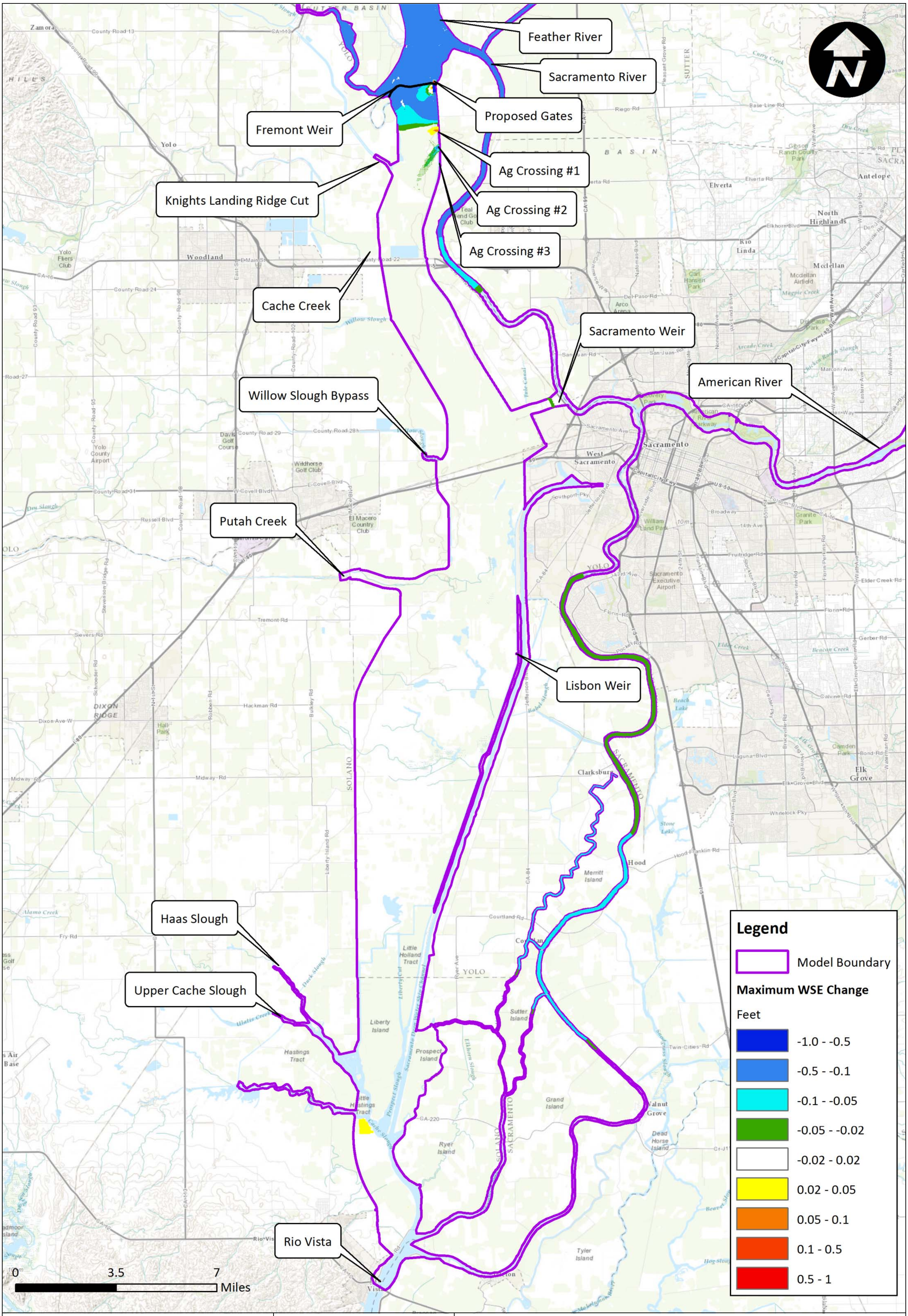

Notes: Comparing Large Channel configuration with existing conditions. Positive values indicate increases in maximum water surface elevations.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Change in Maximum WSE for Large Channel 1998**

Prepared for DWR | Created By: RDJ

**Figure 7-25**




Notes: Comparing Large Channel configuration with existing conditions. Positive values indicate increases in maximum water surface elevations.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Change in Maximum WSE for Large Channel 2006**

Prepared for DWR | Created By: RDJ

**Figure 7-26**

# 8.0 Sensitivity Analyses

Two sensitivity analyses were performed to determine the impact of changes upon model results. The concern has been raised that the proposed project will inundate the Bypass later in the year thus delaying the planting of crops and negatively impacting yields. The first sensitivity analysis evaluates whether removal or changes to structures within the Bypass could reduce drainage time for the Bypass. The second sensitivity analysis evaluates the effect that increases and decreases in inflow discharges have upon model results.

## 8.1 Drain Time Sensitivity (Sensitivity to Lisbon Weir and Ag Crossing Removal)

There are five structures included in the model along the Tule Canal/Toe Drain: three agricultural crossings on the northern end, Swanston Ranch check dam, and Lisbon Weir. A sensitivity analysis was performed to evaluate the reduction in drainage times if all of the structures were removed. The upstream and downstream cross-section geometries were interpolated to provide the geometry for the channel sections replacing the structures. While complete removal of the structures is not practical, this analysis without structures provides an estimate of the maximum decrease in drain time that could be achieved and gives some insight of potential decrease in drain time that could be achieved by modifying the structures.

The five Toe Drain/Tule Canal structures were removed for existing and all alternate configurations simulations for the 2001 and 2011 water years. The wet area through time and LDW post-processing results were compared to the original results for each simulation.

The comparison of wet area through time for the simulations with and without structures for the 2001 and 2011 water years is shown in Figure 8-1 and Figure 8-2. The results are nearly identical and it is often impossible to differentiate between them.

The impacts on LDW for the FreLg configuration for the 2001 and 2011 water years are shown in Figure 8-3and Figure 8-4. Light to dark blue colors indicate decreases to the LDW compared to the original structure configuration. Yellow to red represent increases to LDW values with dark red representing fields that became wet but were dry during the original simulation.

For the 2001 simulation 5 field units had an earlier LDW, 7 field units had a later LDW, and 438 field units showed no change. For the 2011 simulation 11 field units had an earlier LDW, 12 had a later LDW, and 427 field units showed no change. The unexpected later LDW values occurred because the model setup created small changes to drainage changing the timing of when the wet/dry threshold was crossed.

The results suggest that the structures included in the sensitivity analysis do not significantly affect drainage time in the Bypass. Comparing the WSEs upstream and downstream of the Lisbon Weir for the existing conditions 2011 simulations, as shown in Figure 8-5, suggests that the Lisbon Weir effectively increases WSEs at lower discharges but has no significant difference if the water levels rise above 8 feet (NAVD88), which is approximately 3 feet below the adjacent floodplain.

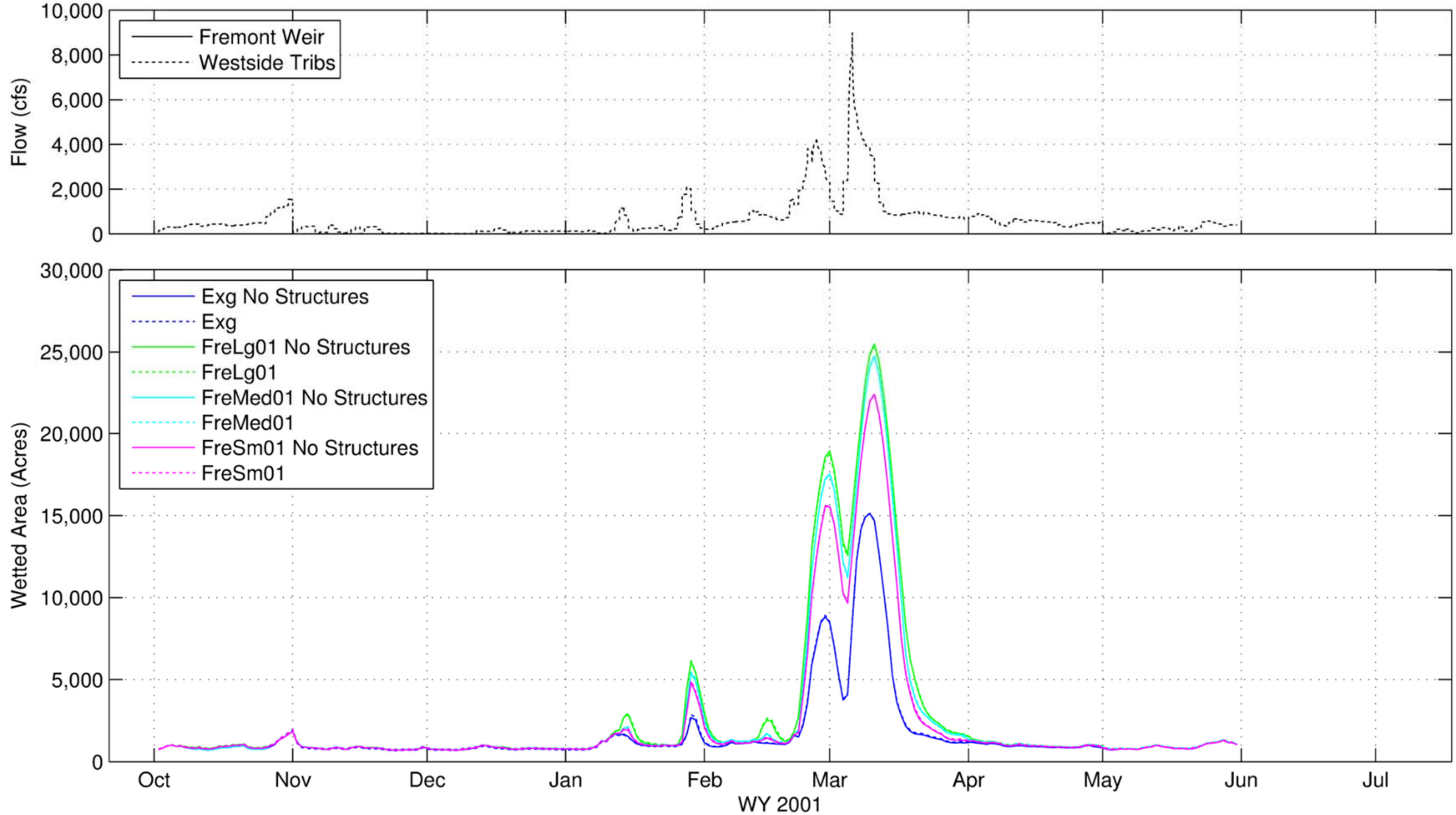
The project alternatives modeled included changing the agricultural crossings to railcar bridges increasing conveyance at these locations. A separate simulation was run using the large channel configuration for the 2011 water year that has Swanston Ranch check dam and Lisbon Weir removed but keeps the proposed railcar bridges. The wetted area through time results shown in Figure 8-6 illustrate that the railcar crossings have a negligible effect upon wetted area within the Bypass.

## 8.2 Sensitivity to Changes in Inflow Hydrographs

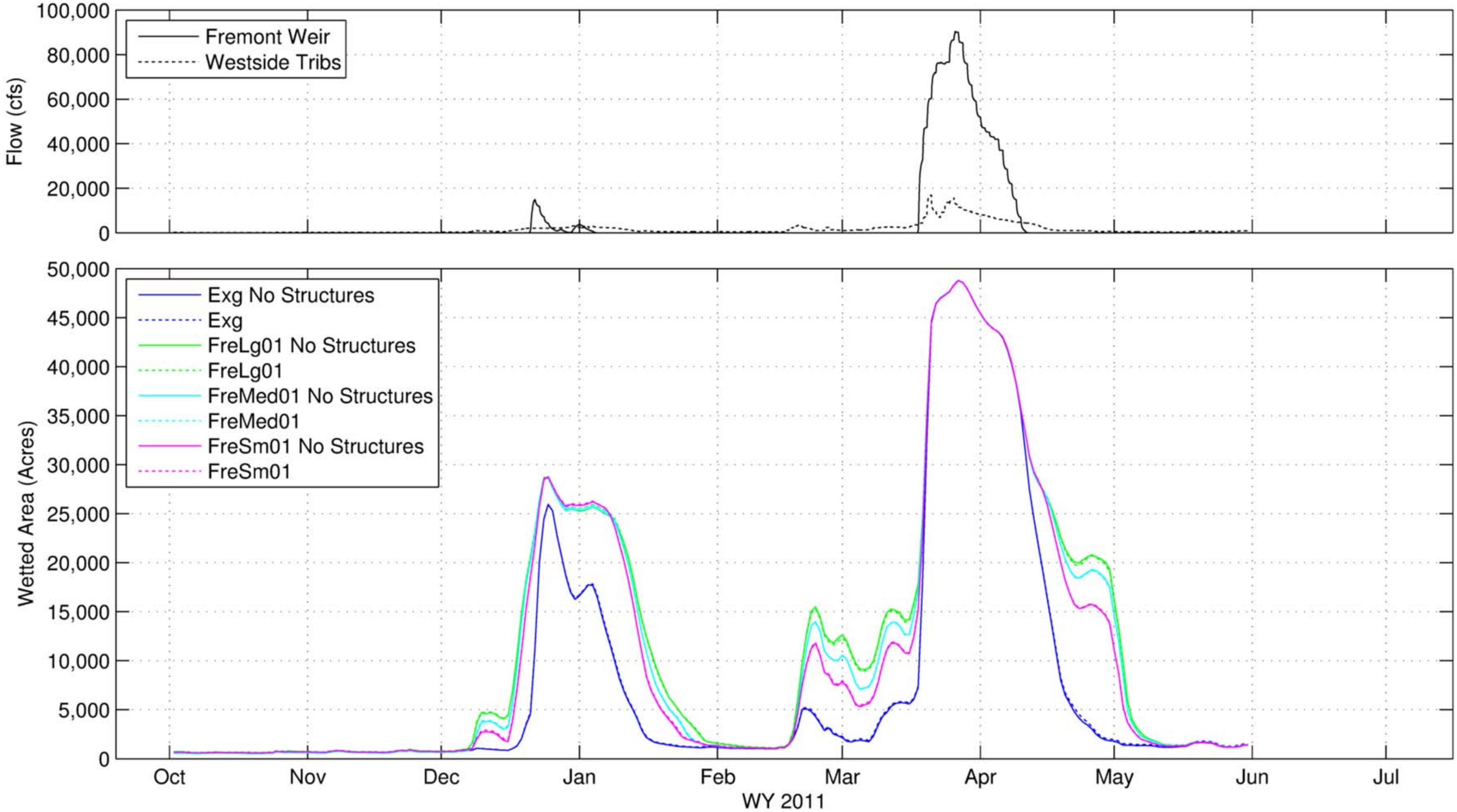
To assess the sensitivity of the results to inflow changes, simulations with increases and decreases of 10 percent for all boundary inflows were evaluated for the 2001 and 2011 water years under existing conditions. Water year 2001 represents a dry period when Fremont Weir did not overtop and inflows to the Yolo Bypass are limited to the Westside tributaries. As such, changes in Yolo Bypass inundation are directly linked to changes in the Westside tributary inflows. Water year 2011 is a wet year when there were significant contributions from Fremont Weir.

A comparison of the change in wetted area through time due to increases or decreases in inflow discharges is shown in Figure 8-7 and Figure 8-8. During low flow periods (e.g., when contributions are limited to the westside tributaries), there is a small change in inundation (i.e., ± 500 acres below 5,000 acres and ± 1,000 acres above 5,000 acres) because the flows are contained in the channels. The change in inundation area during very high flow periods is small because so much of the floodplain is already inundated. The most notable changes occur when the flows are too large to be contained in the channel but not large enough to fill a majority of the Bypass. The event between December and January in the 2011 water year illustrates the large effect that a 10 percent change can make on inundation, with increases and decreases of up to 10,000 acres.

The effect of a 10 percent increase or decrease on LDW for the 2001 and 2011 water years is shown in Figures 8-9 to 8-12. In these figures, light to dark blue symbolizes earlier LDW and yellow to red symbolizes later LDW values. Dark blue indicates fields that had been inundated during the original run but remained dry for the sensitivity run. Bright red indicates fields that were dry during the original run but became wet during the sensitivity run. The LDW for a significant number of fields is impacted but nearly all of the LDW values change by less than one week.




| Notes: Simulations without structures do not include Lisbon Weir, Swanston Ranch Weir, and the three Agriculture crossings in the northern end of the bypass. | HDR cbec eco engineering | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* **Sensitivity Analysis Structures and Drainage 2001** |
|---|---|---|
| | Prepared for DWR | Created By: RDJ | **Figure 8-1** |

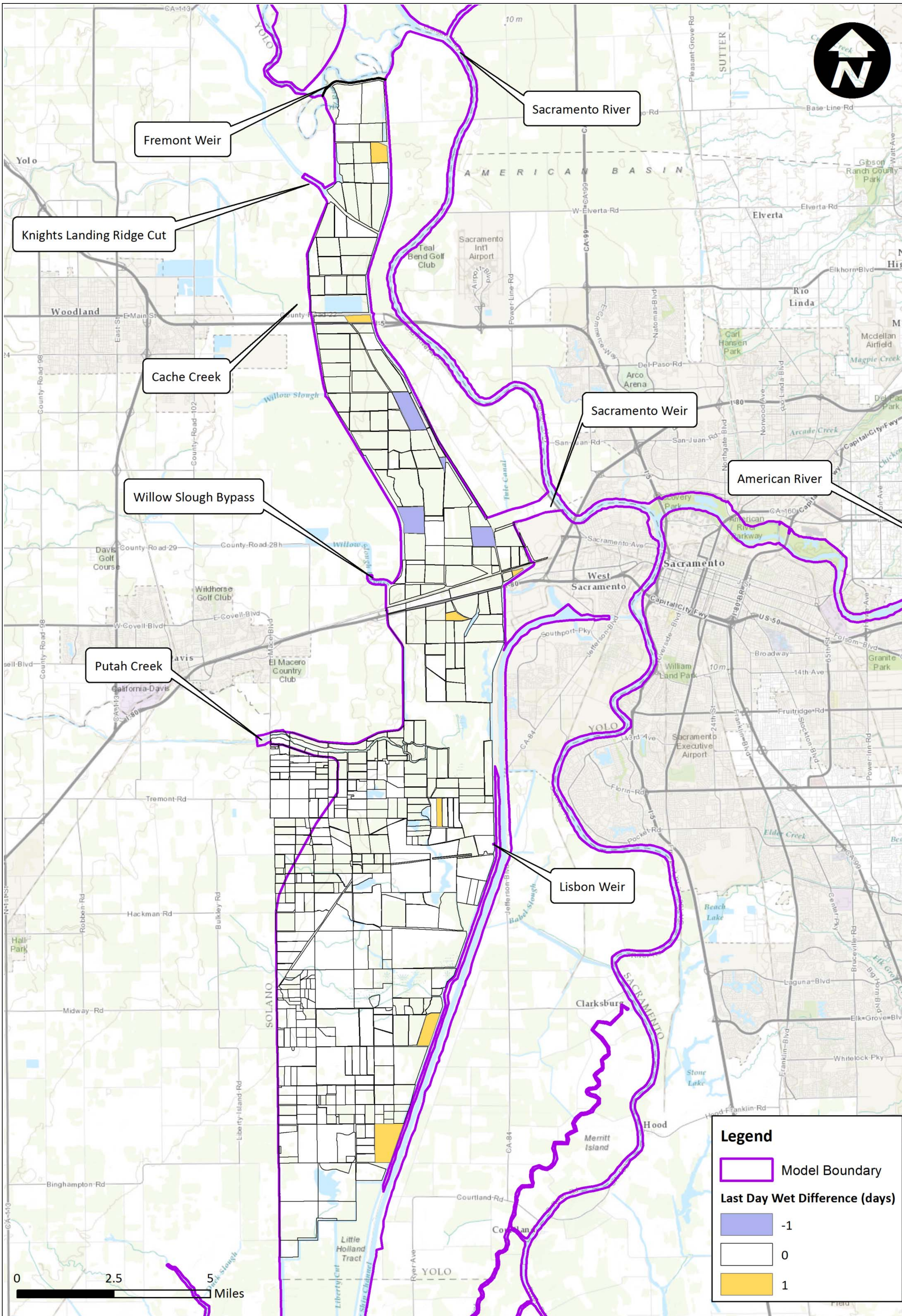



Notes: Simulations without structures do not include Lisbon Weir, Swanston Ranch Weir, and the three Agriculture crossings in the northern end of the bypass.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Sensitivity Analysis Structures and Drainage 2011**

| Prepared for DWR | Created By: RDJ | **Figure 8-2** |
|---|---|---|




Notes: Differences to Last Day Wet after removing structures from the Yolo Bypass. Negative values indicate earlier Last Day Wet.

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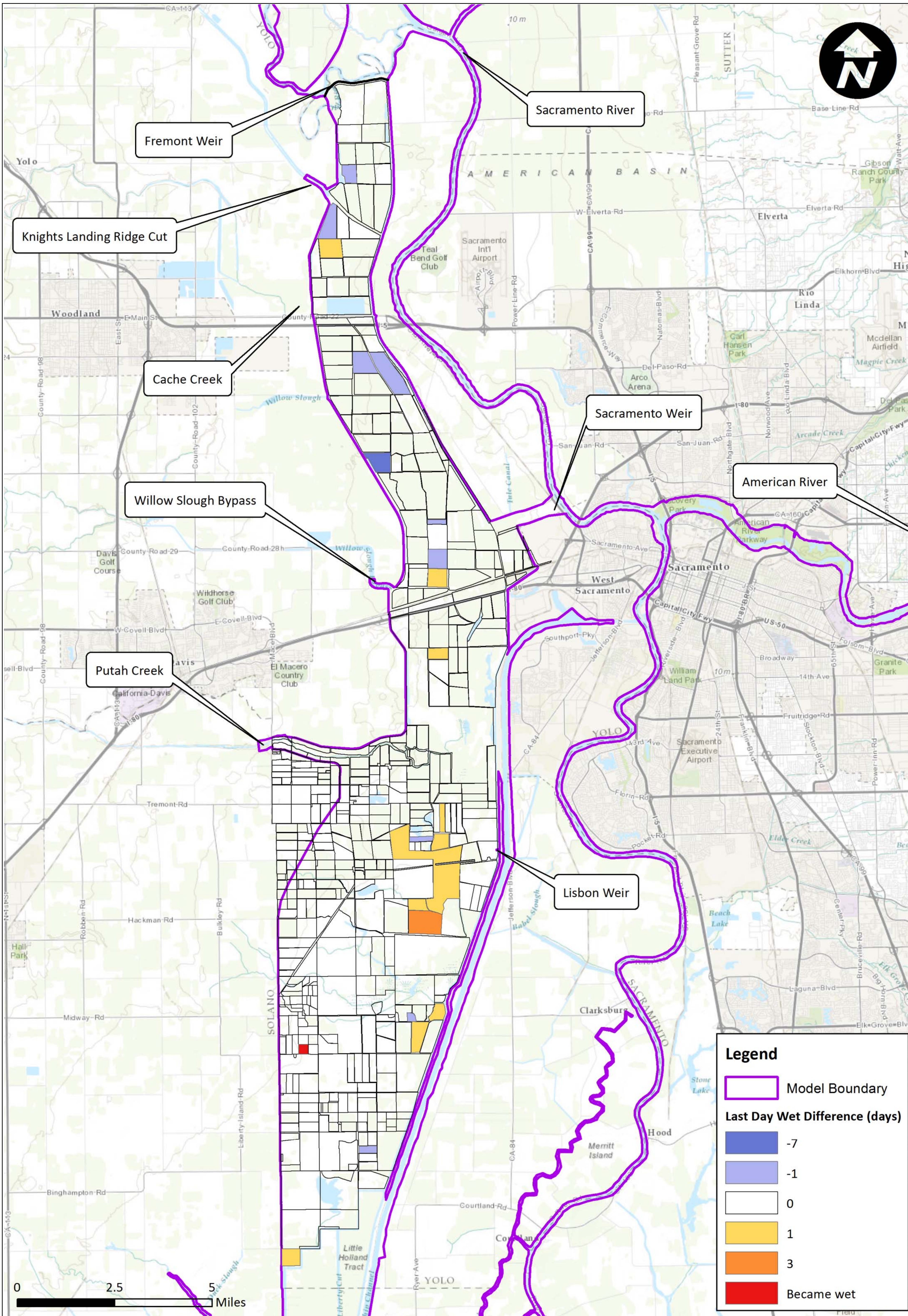
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**FreLg LDW Diff Sensitivity Drain Structures WY 2001**

Prepared for DWR | Created By: RDJ | **Figure 8-3**

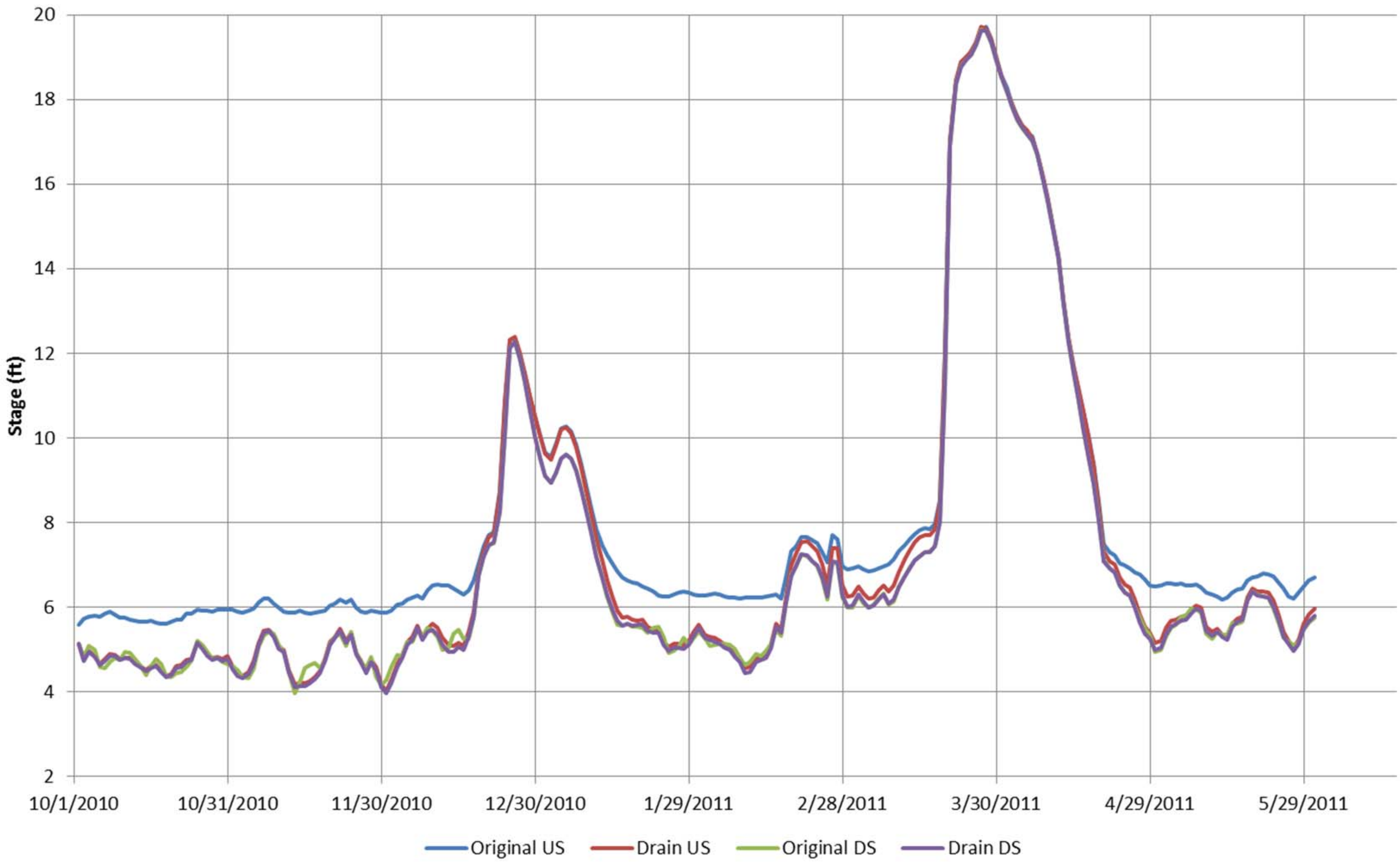



Notes: Differences to Last Day Wet after removing structures from the Yolo Bypass. Negative values indicate earlier Last Day Wet.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**FreLg LDW Diff Sensitivity Drain Structures WY 2011**

Prepared for DWR | Created By: RDJ | **Figure 8-4**

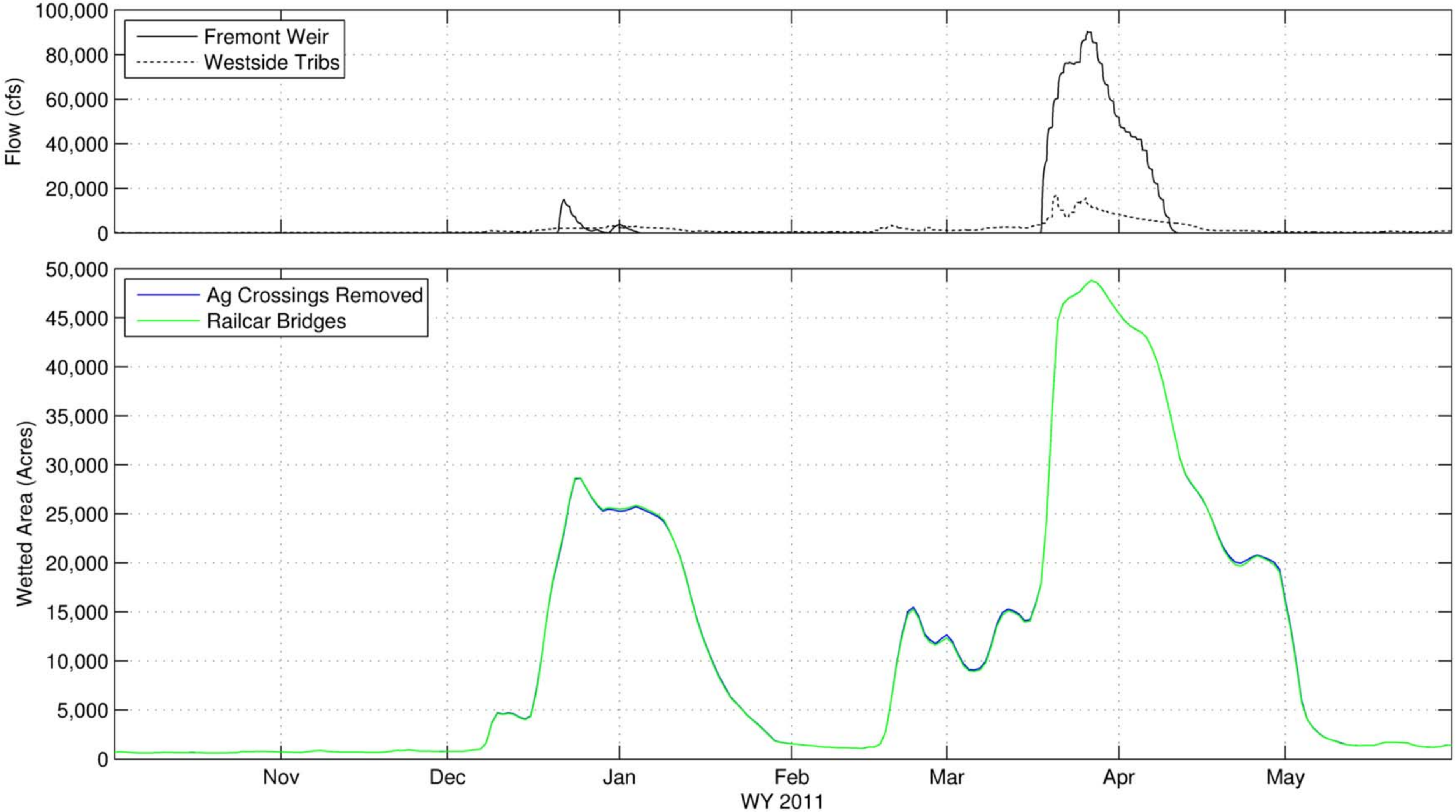



Notes: Water surface elevations measured upstream and downstream of Lisbon Weir existing conditions and with Yolo Bypass structures removed.

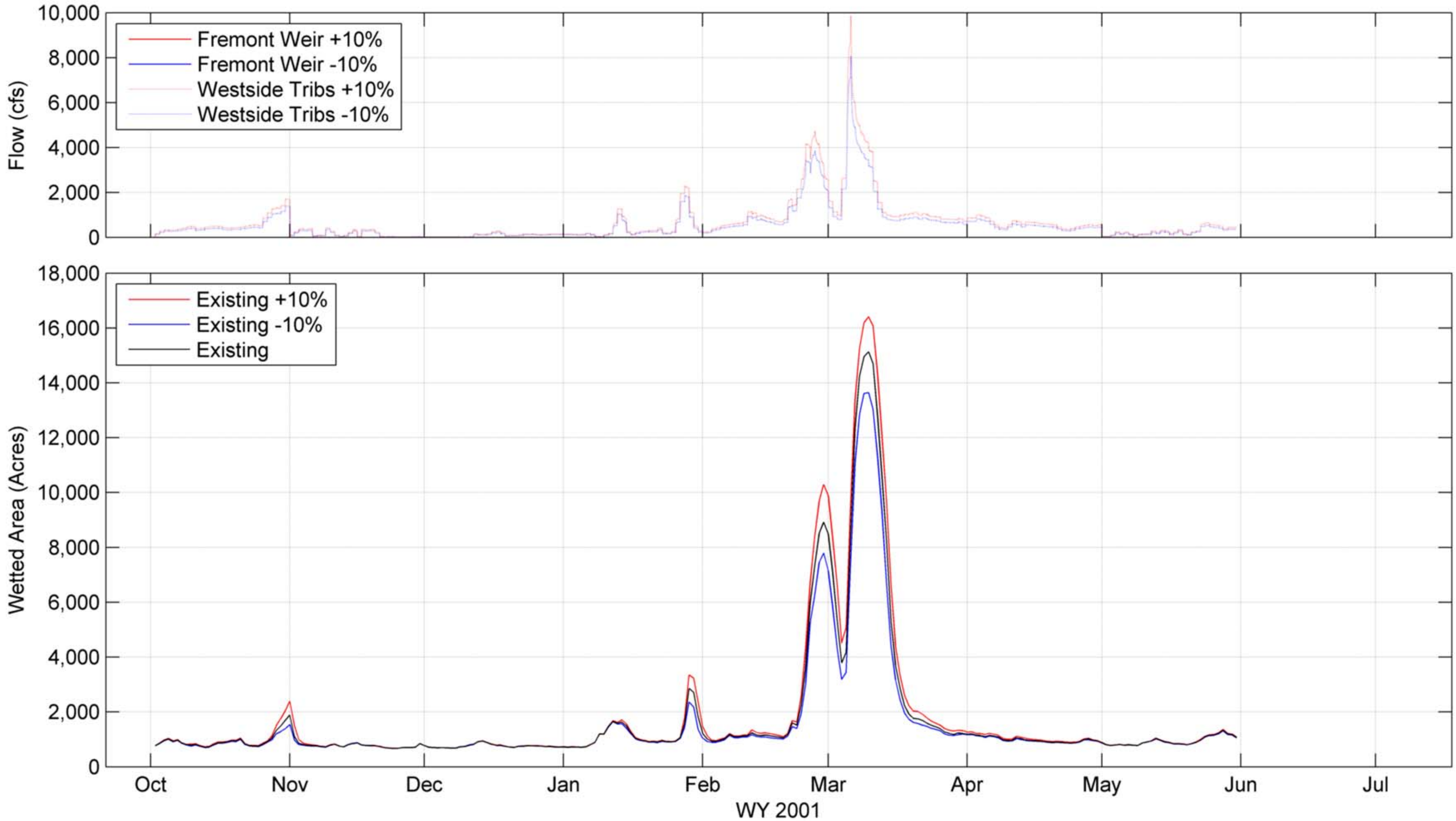
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Exg Stage US/DS of Lisbon Weir Sensitivity Drain**

| | | |
|---|---|---|
| Prepared for DWR | Created By: RDJ | **Figure 8-5** |




| | | | |
|---|---|---|---|
| Notes: The large channel configuration was used for these sensitivity runs. | | *Yolo Bypass Salmonid Habitat Restoration and Fish Passage* | |
| | | **FreLg Wet Area Sensitivity to Railcar Bridges 2011** | |
| | Prepared for DWR | Created By: RDJ | **Figure 8-6** |

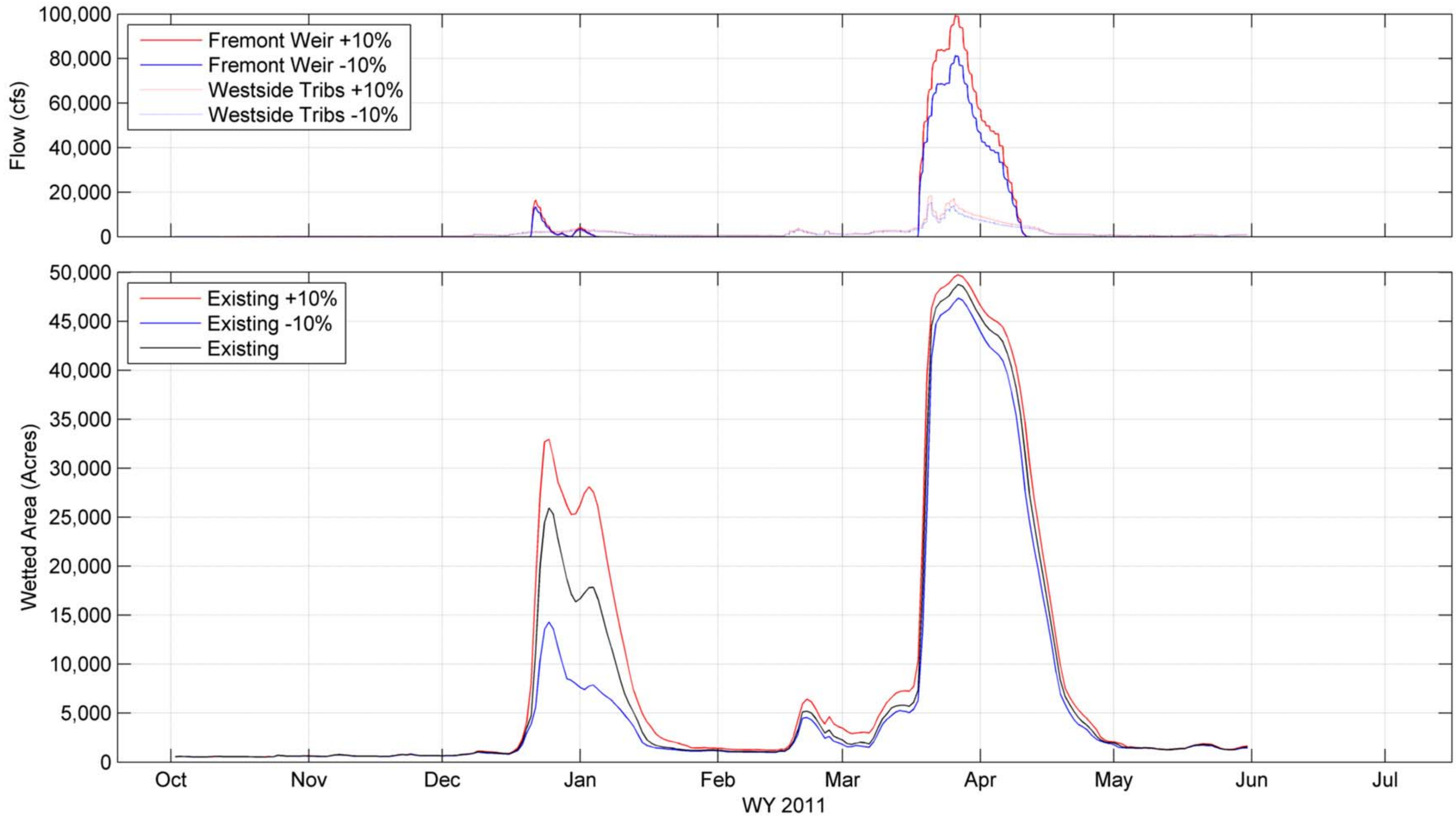



Notes: Simulations were run increasing and decreasing all of the inflow boundary conditions 10%. The Fremont Weir did not overtop in 2001.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Exg Sensitivity Analysis Wetted Area Flows 2001**

| Prepared for DWR | Created By: RDJ | **Figure 8-7** |
|---|---|---|

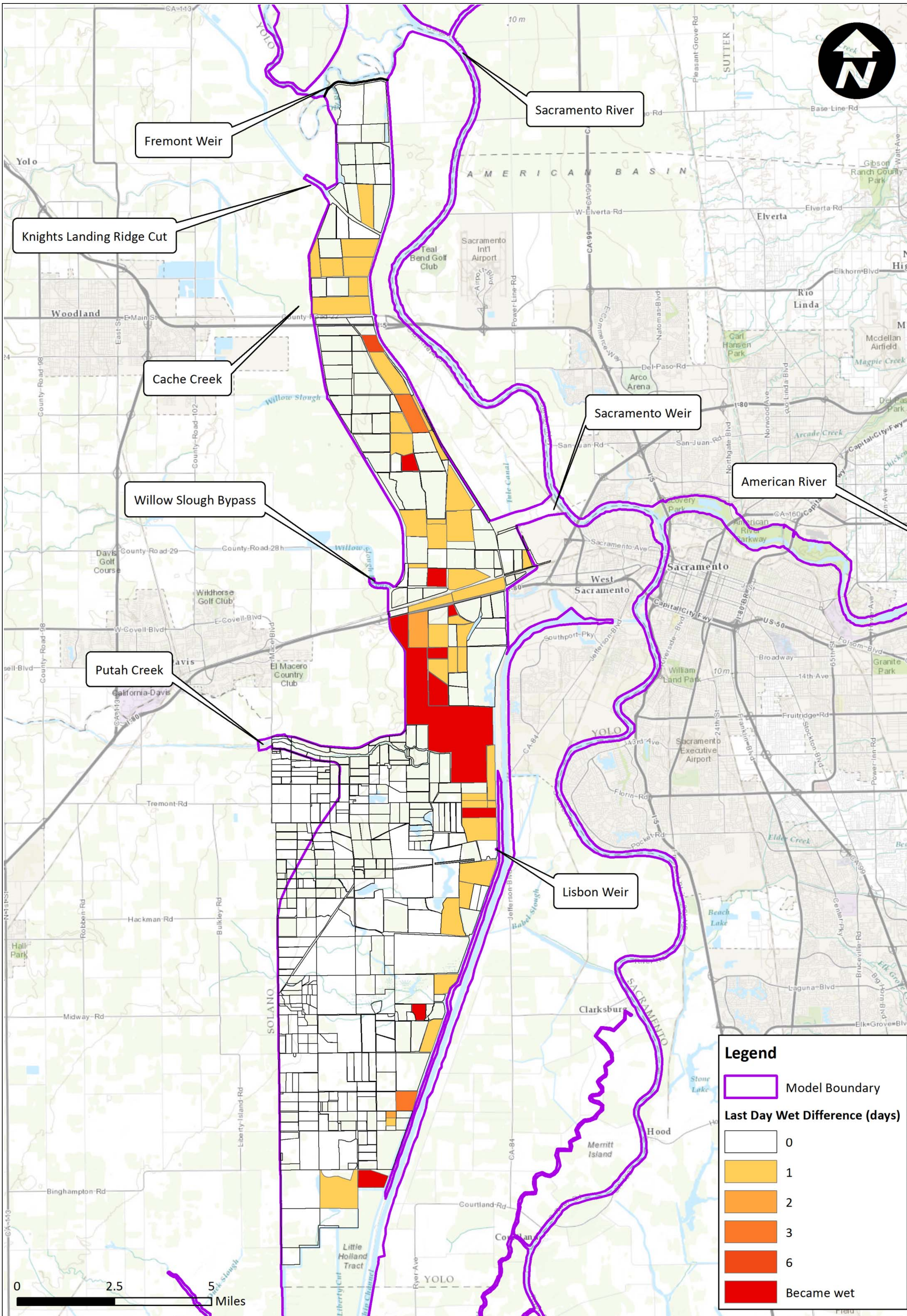



Notes: Simulations were run increasing and decreasing all of the inflow boundary conditions 10%.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Exg Sensitivity Analysis Wetted Area Flows 2011**

Prepared for DWR | Created By: RDJ | **Figure 8–8**



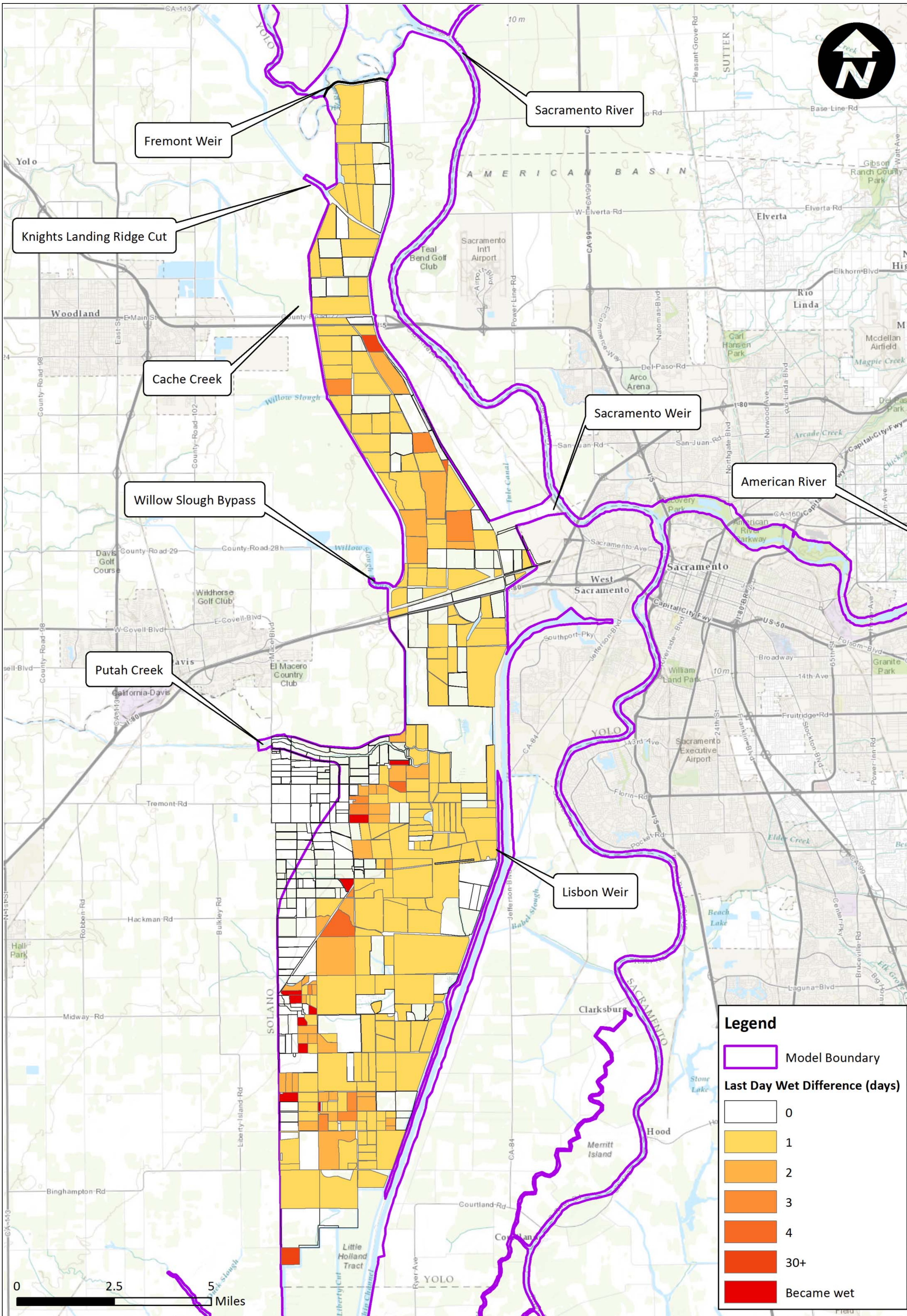

Notes: Differences to Last Day Wet for existing conditions when increasing inflows 10%. Positive values indicate later Last Day Wet.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing LDW Sensitivity to 10% Increase in Flow WY 2001**

Prepared for DWR | Created By: RDJ

**Figure 8-9**




Notes: Differences to Last Day Wet for existing conditions when increasing inflows 10%. Positive values indicate later Last Day Wet.

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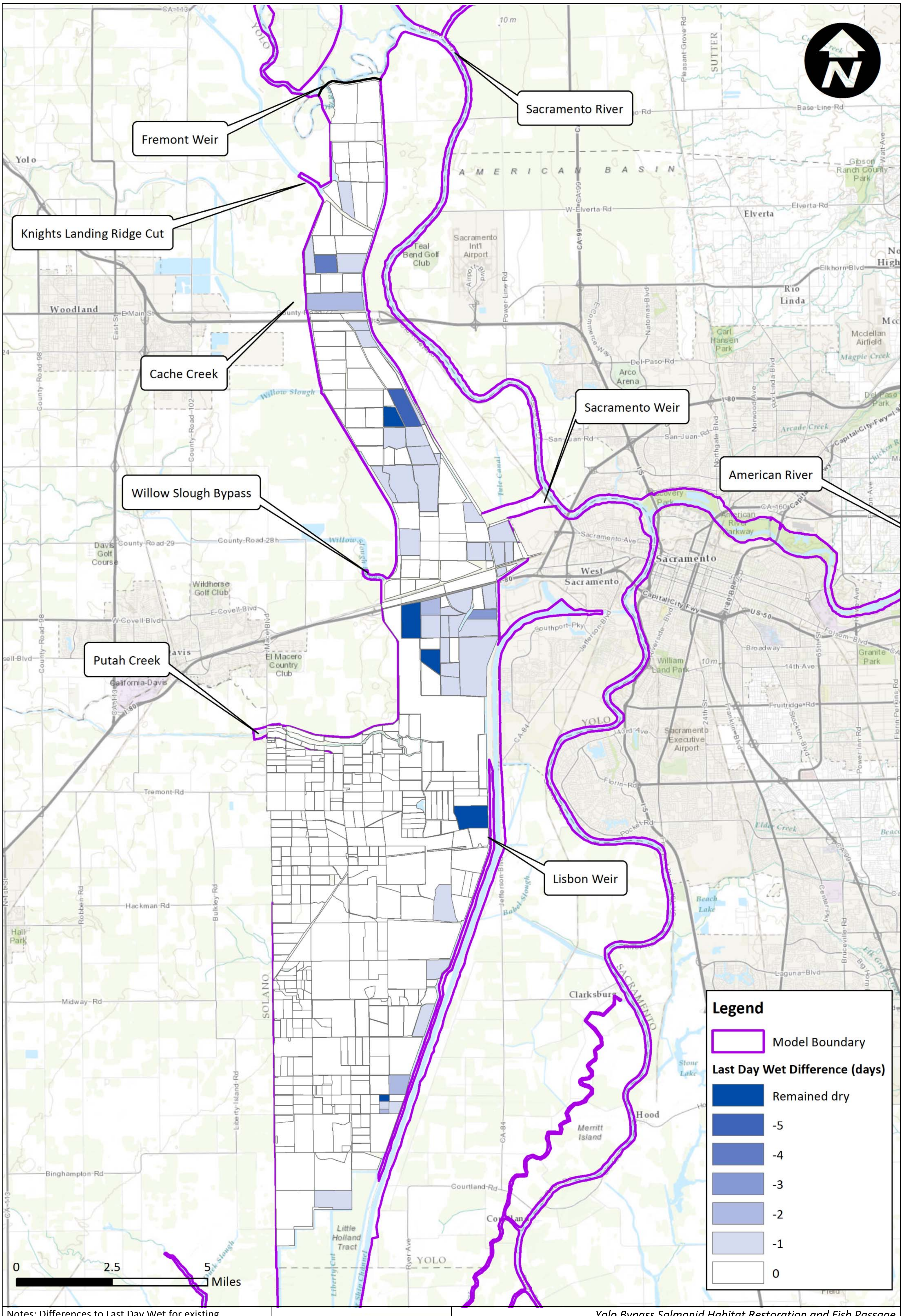
*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing LDW Sensitivity to 10% Increase in Flow WY 2011**

Prepared for DWR | Created By: RDJ

**Figure 8-10**




Notes: Differences to Last Day Wet for existing conditions when decreasing inflows 10%. Negative values indicate earlier Last Day Wet.

*Yolo Bypass Salmonid Habitat Restoration and Fish Passage*

**Existing LDW Sensitivity to 10% Decrease in Flow 2001**

Prepared for DWR | Created By: RDJ | **Figure 8-11**