

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

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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 1.6.1 and 1.7. RPA 1.6.1 and 1.7 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 1.6.1 since these alternatives may have a larger footprint and potential impact when compared to the fish passage alternatives for RPA 1.7. In addition, the seasonal floodplain habitat structure for RPA 1.6.1 may also serve as the primary fish passage location for compliance with RPA 1.7. Therefore, the alternatives described in this report only refer to seasonal floodplain habitat alternatives. Fish passage alternatives and elements for compliance with RPA 1.7 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.

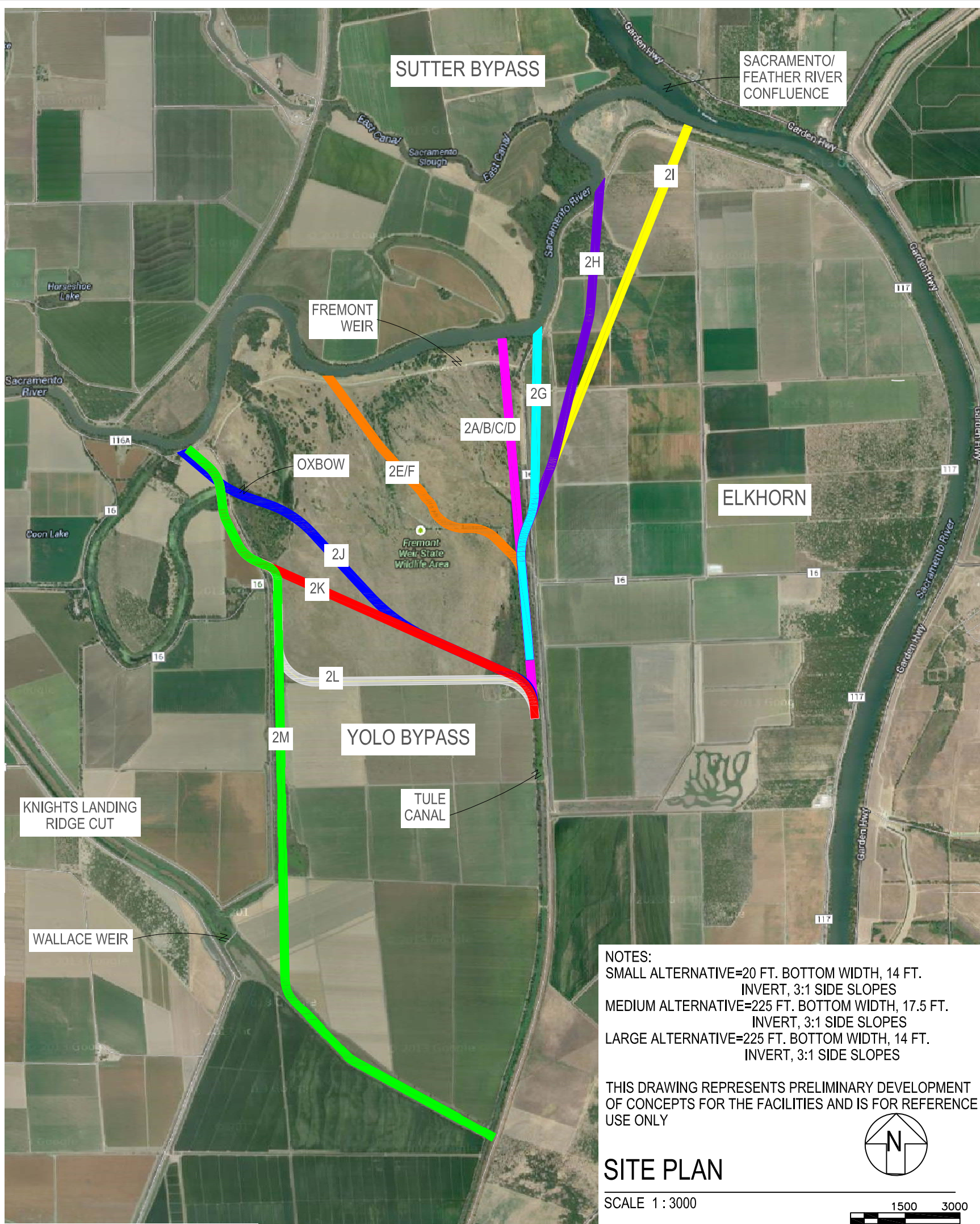
3.2.4 Alternative 2d-Fremont Weir East Large Gated Notch

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.

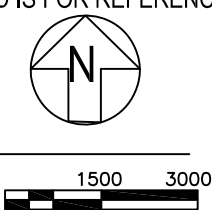


NOTES:
 SMALL ALTERNATIVE=20 FT. BOTTOM WIDTH, 14 FT. INVERT, 3:1 SIDE SLOPES
 MEDIUM ALTERNATIVE=225 FT. BOTTOM WIDTH, 17.5 FT. INVERT, 3:1 SIDE SLOPES
 LARGE ALTERNATIVE=225 FT. BOTTOM WIDTH, 14 FT. INVERT, 3:1 SIDE SLOPES

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

SITE PLAN

SCALE 1 : 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:
BAR IS ONE INCH ON ORIGINAL DRAWINGS; ADJUST SCALE FOR REDUCED PLOTS 		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		
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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 ($\text{ft}^3/\text{s}/\text{ft}$), g represents gravity ($32.2 \text{ ft}/\text{s}^2$), 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.

$$q = \frac{2}{3}H \sqrt{\frac{2}{3}gH} \quad (1)$$

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-enforced¹ 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.	FeetNAV D88	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.	FeetNAV D88	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
<p>[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</p>							

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
<p>Notes:</p> <p>[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</p> <p>[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.</p> <p>[3] Rio Vista stage is in feet, USED prior to October 1, 2005; and feet, NAVD88 thereafter.</p>		

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 Figure 4-11), 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 sensor 1692 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:

$$\text{NCC} = 1.43 \times \text{NEMDC}$$

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 = $(130.4/107.7) * \text{CDR}_{\text{obs}} - \text{KLOG}_{\text{obs}}$
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:

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

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 Georgiana 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 Haas 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 a 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.