Appendix 4
Sutter and Yolo Bypass HEC-RAS Two-Dimensional Hydraulic Model

MODEL REPORT

Sutter and Yolo Bypass HEC-RAS Two-Dimensional Hydraulic Model

Prepared for

State of California
Department of Water Resources

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Contents

Tables

Figures

Acronyms and Abbreviations

1D	one dimensional
2D	two dimensional
BWFS	Basin-Wide Feasibility Study
CBEC	cbec, inc.
cfs	cubic feet per second
CVFED Program	Central Valley Floodplain Evaluation and Delineation Program
CVFPP	Central Valley Flood Protection Plan
DWR	California Department of Water Resources
FDA	flood damage analysis
FESSRO	FloodSafe Environmental Stewardship and Statewide Resources Office
GIS	geographic information system
HDF	hierarchical data format
HEC-RAS	Hydrological Engineering Center's River Analysis System
HWM	high water mark
KLRC	Knights Ridge Landing Cut
LiDAR	light detection and ranging
MRLC	Multi-Resolution Land Characteristics Consortium
NA	not applicable
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
NRIL	not represented in LiDAR
RIL	represented in LiDAR
SUTYOL	Sutter and Yolo Bypass
TO 15-12	Task Order 15-12
TO 25	Task Order 25
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VRT	virtual raster translator
WSE	water surface elevation

SECTION 1

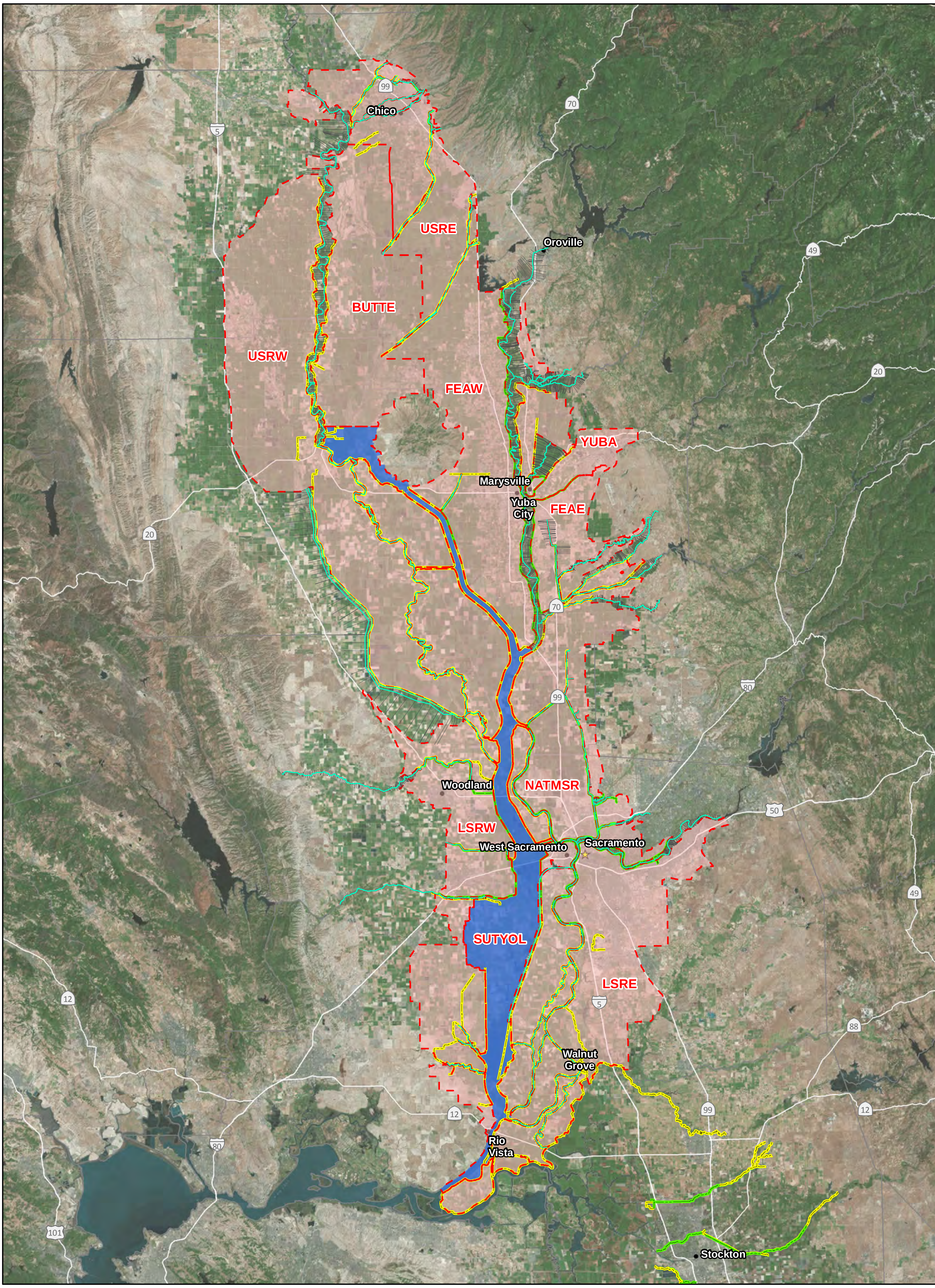
Introduction

This document summarizes development of the Sutter and Yolo Bypass (SUTYOL) Hydrologic Engineering Center's River Analysis System (HEC-RAS) Two Dimensional (2D) Hydraulic Model (SUTYOL model), developed by CH2M for the California Department of Water Resources (DWR) under Central Valley Flood Protection Plan (CVFPP) Task Order 15-12 (TO 15-12).

This model is intended to simulate hydraulics of flow in the Sutter and Yolo Bypasses caused by overtopping of the Sacramento River weirs, overflows from the Feather River, and inflows from the west side tributaries of the Yolo Bypass. The main objective of this model is to accurately simulate the complex hydraulics of flow near the Fremont Weir, and flow split between the Sacramento River and the Yolo Bypass. The model was developed as part of a suite of regional 2D models for the Sacramento River Basin.

These regional 2D models were integrated with the Central Valley Floodplain Evaluation and Delineation Program's (CVFED Program's) Task Order 25 (TO 25) Enhanced Sacramento River System One-Dimensional (1D) HEC-RAS Model.

The CVFPP's TO 15-12 final modeling product is an integrated 1D/2D model with the Sutter, Yolo and Sacramento bypasses, the Yuba River, and all overbank floodplains represented as 2D flow areas, and the channels of the Sacramento, Feather, and American rivers and major tributaries kept in 1D. The integrated 1D/2D HEC-RAS model geometry structure is shown in Figure 1 with the Sutter and Yolo Bypass project area highlighted.



LEGEND

- HEC-RAS 2D Model Boundary
- SUTYOL
- Non-Urban Levee
- Urban Levee
- CVFED TO25 River Centerlines
- CVFED TO25 Cross Sections

0 5 10 Miles

FIGURE 1
Location Map

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SECTION 2

Model Description

This model was constructed using the U.S. Army Corps of Engineers (USACE) Hydraulic Engineering Center's River Analysis System (HEC-RAS) version 5.0.1 software with 2D modeling capabilities. HEC-RAS version 5.0.1 can perform 2D (depth-averaged) hydrodynamic routing within the unsteady flow analysis module. HEC-RAS is a finite volume numerical model that computes depth and x and y components of velocities for 2D cells by solving conservation of mass and momentum equations. HEC-RAS is capable of using both structured and unstructured 2D computational mesh to represent the model domain.

The HEC-RAS version 5.0.1 2D model component uses a terrain data layer to compute geometry and hydraulic property tables for the computational 2D cells and cell faces. The model develops elevation versus volume relationships for each cell and cross sectional elevation profiles for the flow area and wetted perimeter of each cell face from detailed high-resolution subgrid terrain data. The model then uses a land cover data layer to assign spatially variable roughness coefficients to the 2D cell faces. This allows the model to more accurately simulate hydraulics with larger computational cell sizes. Additionally, the use of breaklines along the top of controlling terrain forces the placement of cell faces at critical hydraulic features and further improves the hydraulic computations (USACE, 2016a).

2.1 Model Domain

The SUTYOL model 2D domain encompasses the Sutter Bypass from the Colusa Weir to the Fremont Weir, and the Yolo Bypass from the Fremont Weir to Sacramento River at Collinsville, south of Rio Vista. Tisdale Bypass from Tisdale Weir to Sutter Bypass, and Sacramento Bypass from Sacramento Weir to Yolo Bypass are included in the 2D model domain. Colusa and Tisdale Weirs are not represented in the model as weirs; the overflows from the Sacramento River were used as inflow boundary conditions. The Fremont Weir was included in the 2D domain and was modeled as a hydraulic structure. The Sacramento Weir was included and was modeled as a 1D weir (i.e., a lateral structure). Portions of the Sacramento River, Feather River and other tributaries to Yolo Bypass near the bypass confluence area were included as 2D areas in the model to capture the complex hydraulics of these confluence zones. The Sacramento River south of Fremont Weir, the American River, and other channels in the lower Sacramento River Basin are included as 1D channels.

2.2 Model Assumptions and Limitations

The following are assumptions and limitations of HEC-RAS version 5.0.1 that impacted development of the 2D model:

- Bridges cannot be used as internal hydraulic connections within a 2D area or between 2D areas in the 5.0.1 version of HEC-RAS. All bridges within the 2D portions of the modeling domain were modeled using one of the following methods:
    1. By including the depression of the channel in the weir embankments either in the internal breaklines within a 2D area or in the storage area/2D connection between two 2D areas
    2. As a hydraulic structure specified as a weir/culvert connection with the culvert opening set roughly equivalent to the opening area of the bridge.
- Boundary conditions representing inflow or outflow points are limited to the physical boundaries of the 2D areas. Internal boundary conditions cannot be incorporated into a 2D area.

Model Development

3.1 2D Flow Areas

Figure 2 shows the SUTYOL area, which is represented by one 2D area. Table 1 lists the maximum and minimum cell sizes. The 2D area mesh was generated using a cell size of 200 feet by enforcing all the breaklines developed for the model area. The current version of HEC-RAS does not completely align the cell faces along the breaklines at their intersections. The 2D cells were manually adjusted for these locations to better align the cell faces along the embankment features.

Table 1. 2D Flow Area Parameters

2D Flow Area	Total Area (Acres)	Number of 2D Cells	Max Cell Size (square feet)	Min Cell Size (square feet)	Avg Cell Size (square feet)
2D_SUTYOL	126,256	180,957	112,677	2,075	30,392

3.2 2D Area Breaklines

Breaklines were added to represent all hydraulically significant features such as roadway embankments, railroad embankments and berms that were higher than approximately 3 feet in the bypass areas. The cell spacing for portions of the 2D areas adjacent to breaklines ranges between 100 and 200 feet.

3.3 Terrain Data

CVFED Program LiDAR survey terrain data were used as base topographical data for this model. CVFED Program LiDAR survey data are a high-resolution raster dataset with cell size of 3.125 by 3.125 feet. These data were collected between 2008 and 2009 for the Sacramento and San Joaquin basin valley floors, and were filtered to remove bridges (i.e., riverine bridges), buildings and obscure areas. These data represent ground elevations where there were no water bodies. As described above, the 2D model domain consists of river channels and tributaries for which CVFED Program LiDAR survey data do not capture channel bathymetry below the water surface. To represent ground elevations for areas in the 2D model domain where there are river channels or water bodies, additional data were acquired, processed and combined with CVFED Program LiDAR survey data. The following data sources were used to develop terrain surfaces that were combined with CVFED Program LiDAR survey data to generate a final terrain layer for the model:

- **CVFED channel bathymetry data** – Cross sectional survey data were used to develop 1D channel geometry in HEC-RAS for riverine channels in the 2D model domain. Using this channel geometry, terrain surfaces were generated in RAS Mapper and were clipped to the hydro-enforced breaklines generated from CVFED Program LiDAR survey data.
- **DWR Northern Region Office Fremont Weir bathymetric survey data** – Cross sectional survey data for the Tule Canal between Fremont Weir and Knights Landing Ridge Cut (KLRC) were used to develop 1D channel geometry in HEC-RAS. Using this channel geometry, terrain surfaces were generated in RAS Mapper and were clipped to the hydro-enforced breaklines generated from CVFED Program LiDAR survey data.

- **CBEC Tule Canal and KLRC bathymetric survey data** – Survey data collected by CBEC eco engineering for DWR, for the KLRC and Tule Canal from KLRC to the Lisbon Weir were used to develop a terrain surface using ESRI ArcGIS terrain processing tools.
- **Environmental Data Solutions Liberty Island bathymetry** –A bathymetric terrain surface for the flooded Liberty Island and Tule Canal from the Lisbon Weir south was generated from available terrain surfaces provided by Bill Fleenor of the University of California at Davis, originally generated by EDS.

Figure 3 shows the spatial extents of terrain surfaces developed using each of the above data sources, and ground elevations of the combined terrain data used in the model. The combined terrain surface was used to develop geometry and hydraulic property tables for the computational 2D cells and cell faces in this model.

The combined terrain data was clipped to the model domain with a buffer of 1,000 feet. HEC-RAS uses a GeoTIFF (*.tif) file format for terrain data, which is a compressed form of raster data storage. This allows for smaller storage space and faster computational speed when generating flood maps of model results (both in stored and dynamic maps). RAS Mapper creates hierarchical data format (HDF) and a virtual raster translator (VRT) files that contain information about how the multiple GeoTIFF files were stitched together. Table 2 lists the terrain data layers used in this model. The final GeoTIFF files used for the modeling are included in the digital deliverable.

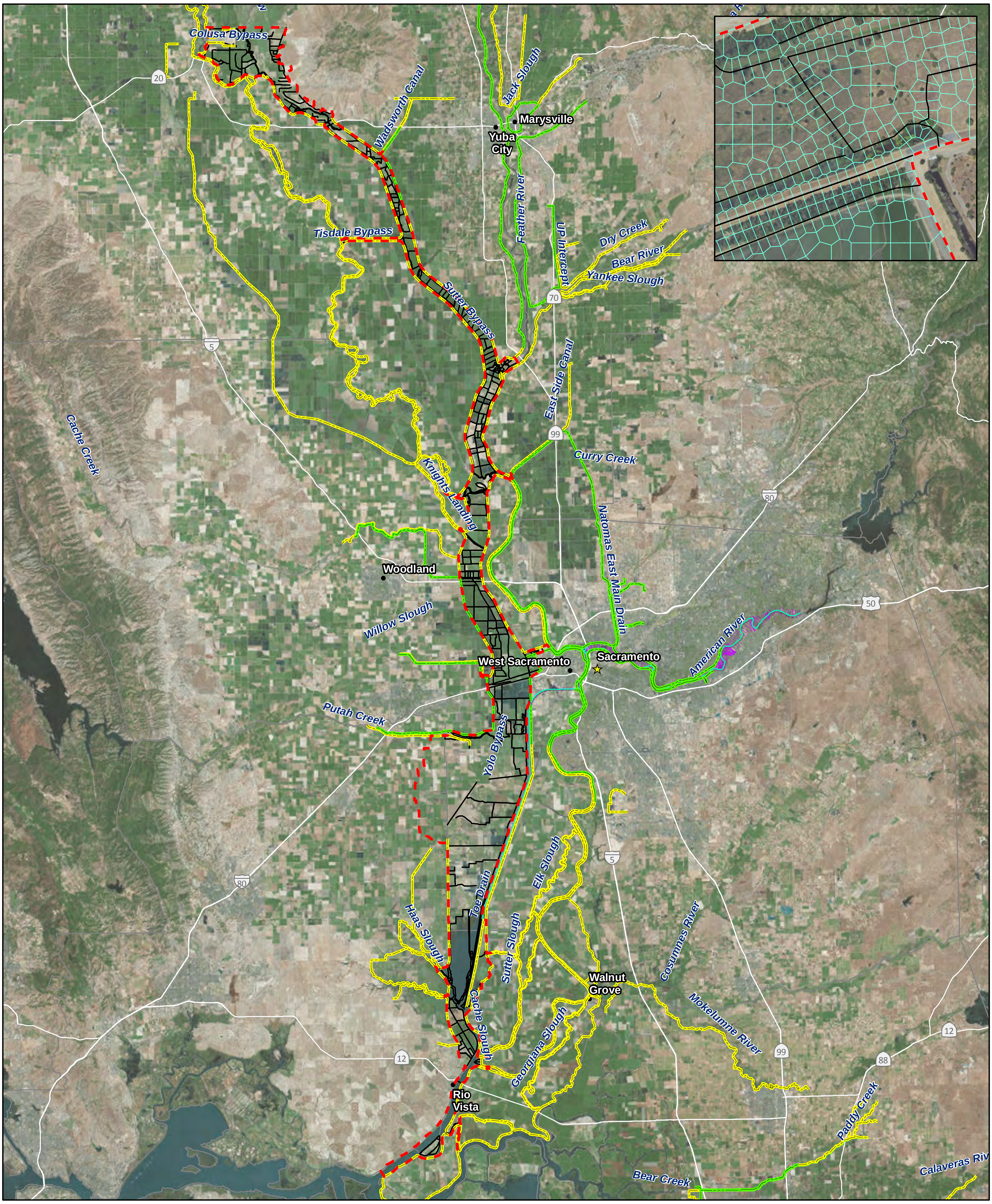
Table 2. Terrain Data Layers

Layer Name	File Type	Description
Terrain.hdf	HDF	Terrain layer used by RAS Mapper
Terrain.vrt	VRT	Terrain layer used by RAS Mapper
Terrain.yolo_final.tif	GeoTIFF	CVFED Program LiDAR survey terrain data

3.4 Roughness Parameters

Spatially variable Manning's n roughness parameters were assigned to the computational 2D cell faces in the model based on the NLCD 2011 raster dataset (USGS, 2014). This dataset is created by MRLC, an entity within USGS. It contains high-resolution land cover information (30 meter by 30 meter cells) for the entire United States in 16 classifications. Manning's n values for each NLCD 2011 classification were developed in coordination with DWR's FloodSafe Environmental Stewardship and Statewide Resources Office (FESSRO). Table 3 lists the base Manning's n values corresponding to the NLCD 2011 land cover classifications. Figure 4 shows NLCD 2011 dataset land cover variability within the model domain, acreages (as a percent) by land cover type, and base roughness parameters.

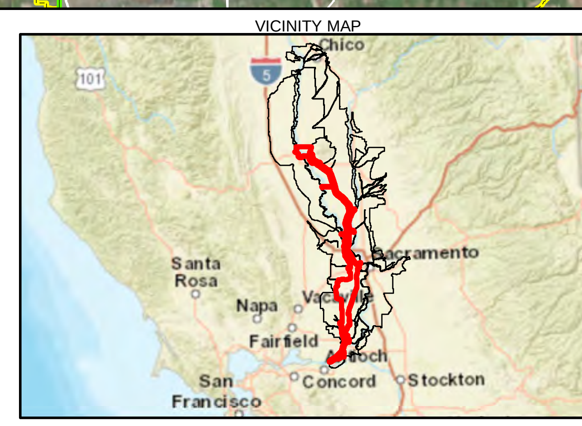
The NLCD 2011 raster dataset was clipped to the model domain and included in the model folder. LandCover.tif and LandCover.hdf layers are used by RAS Mapper to assign roughness parameters to the computational 2D cell faces.



LEGEND

- HEC-RAS 2D Model Boundary
- HEC-RAS 2D Break Lines
- Non-Urban Levee
- Urban Levee
- HEC-RAS River Centerlines
- HEC-RAS Cross Sections

VICINITY MAP



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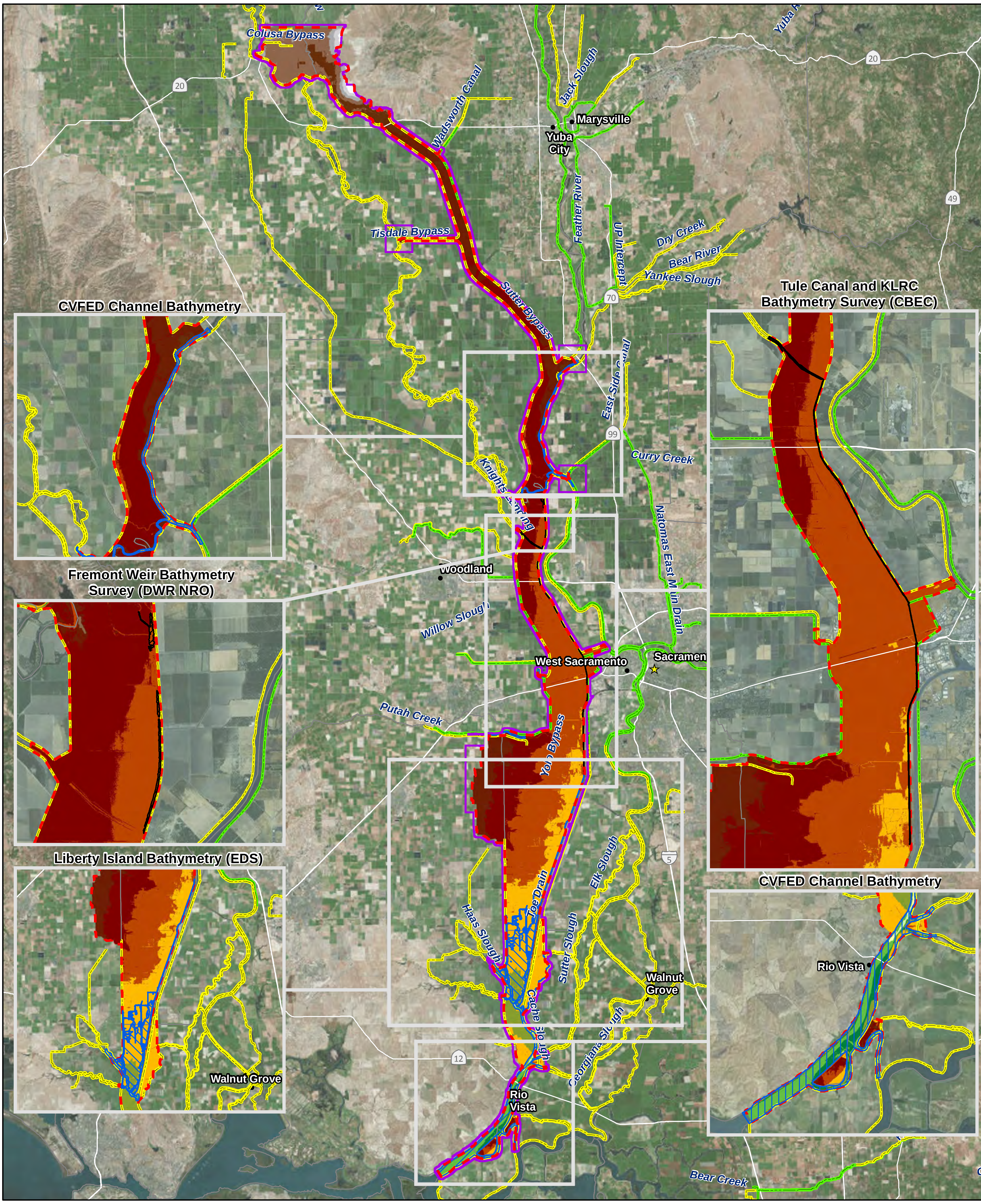
Miles

FIGURE 2
Study Area



LEGEND

- HEC-RAS 2D Model Boundary
- CVFED LiDAR Extent
- CVFED Channel Bathymetry
- Fremont Weir Bathymetry Survey (DWR NRO)
- Liberty Island Bathymetry (EDS)
- Tule Canal and KLRC Bathymetry Survey (CBEC)
- Non-Urban Levee
- Urban Levee

Terrain Elevation (ft, NAVD 88)

- -95 - -80
- -79 - -60
- -59 - -40
- -39 - -20
- -19 - -10
- -9 - -1
- 0 - 10
- 11 - 20
- 21 - 30
- 31 - 40
- 41 - 50
- 51 - 60
- 61 - 70
- 71 - 80
- > 80

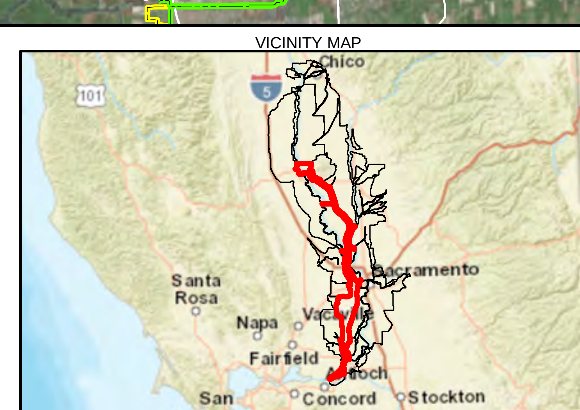


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FIGURE 3
Terrain Map

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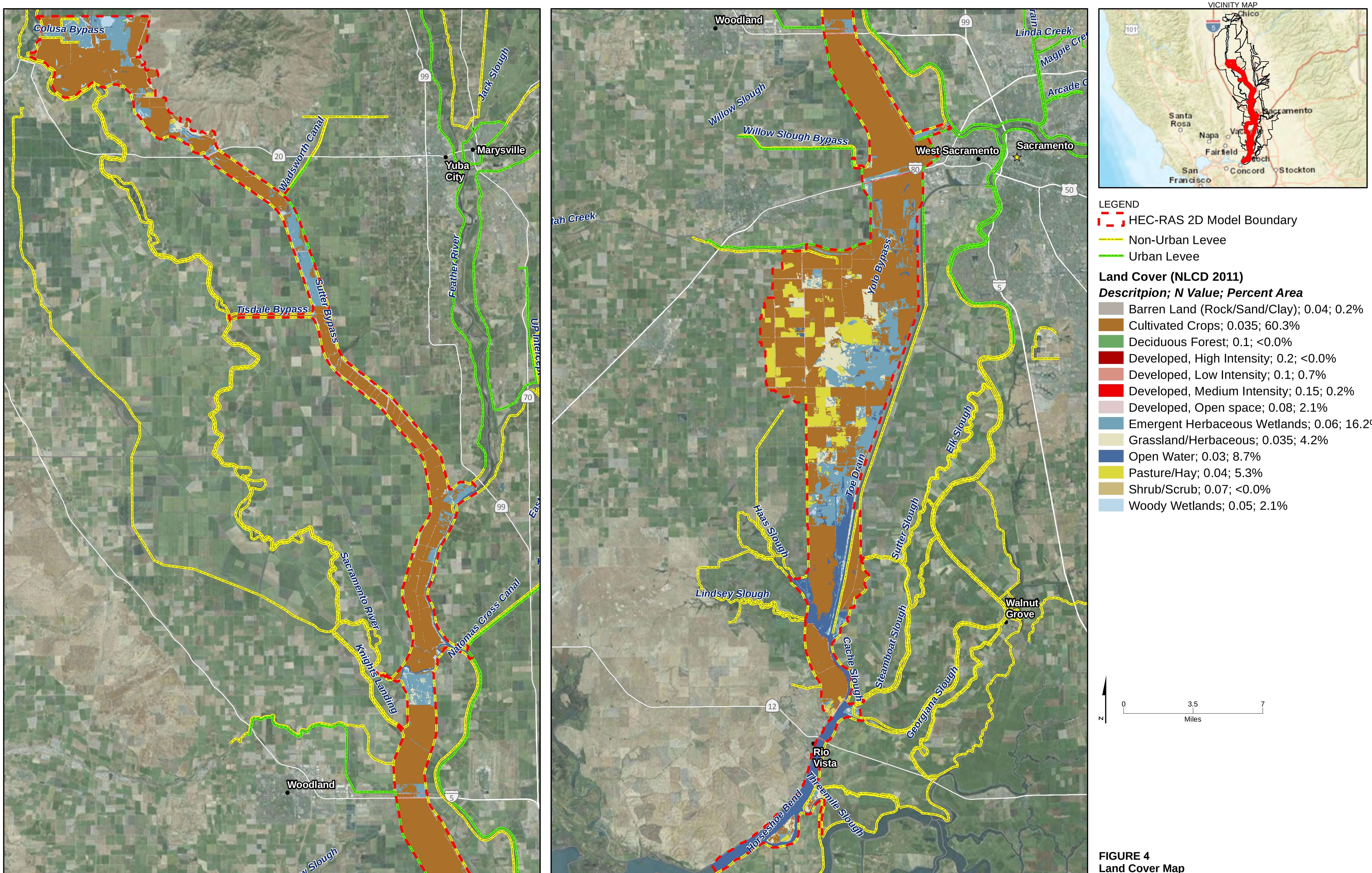

FIGURE 4
Land Cover Map

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Table 3. Base Roughness Parameters

NLCD 2011 Classification	Land Cover Description	Base Manning's n
11	Open Water	0.03
12	Perennial Ice/Snow	0.03
21	Developed, Open Space	0.08
22	Developed, Low Intensity	0.1
23	Developed, Medium Intensity	0.15
24	Developed, High Intensity	0.2
31	Barren Land (Rock/Sand/Clay)	0.04
41	Deciduous Forest	0.1
42	Evergreen Forest	0.1
43	Mixed Forest	0.1
52	Shrub/Scrub	0.07
71	Grassland/Herbaceous	0.035
81	Pasture/Hay	0.04
82	Cultivated Crops	0.035
90	Woody Wetlands	0.05
95	Emergent Herbaceous Wetlands	0.06

3.5 Hydraulic Structures

Figure 5 shows the hydraulic structures included in the SUTYOL model domain. Hydraulic structures were input into the model to represent Fremont Weir and several other bridges in the SUTYOL model domain.

The Fremont Weir was represented as a weir structure type using 2D area internal connection functionality. The weir crest elevations were set using the structure survey data and combined with the terrain profile developed by model along the centerline of the weir. The computation method for overflows along the weir was set to the "Normal 2D Equation Domain" option. When this option is selected, the model computes flow over the weir using a 2D equation set, and ignores the weir coefficient specified. The HEC-RAS *User's Manual* states that for tall weirs that are subjected to free fall over the weir with little submergence, Weir Equation is recommended (USACE, 2016b). Under flood conditions, Fremont Weir is submerged completely, and does not exhibit free fall over the weir. For this reason, the "Normal 2D Equation Domain" option was selected as the computational method for overflow calculations.

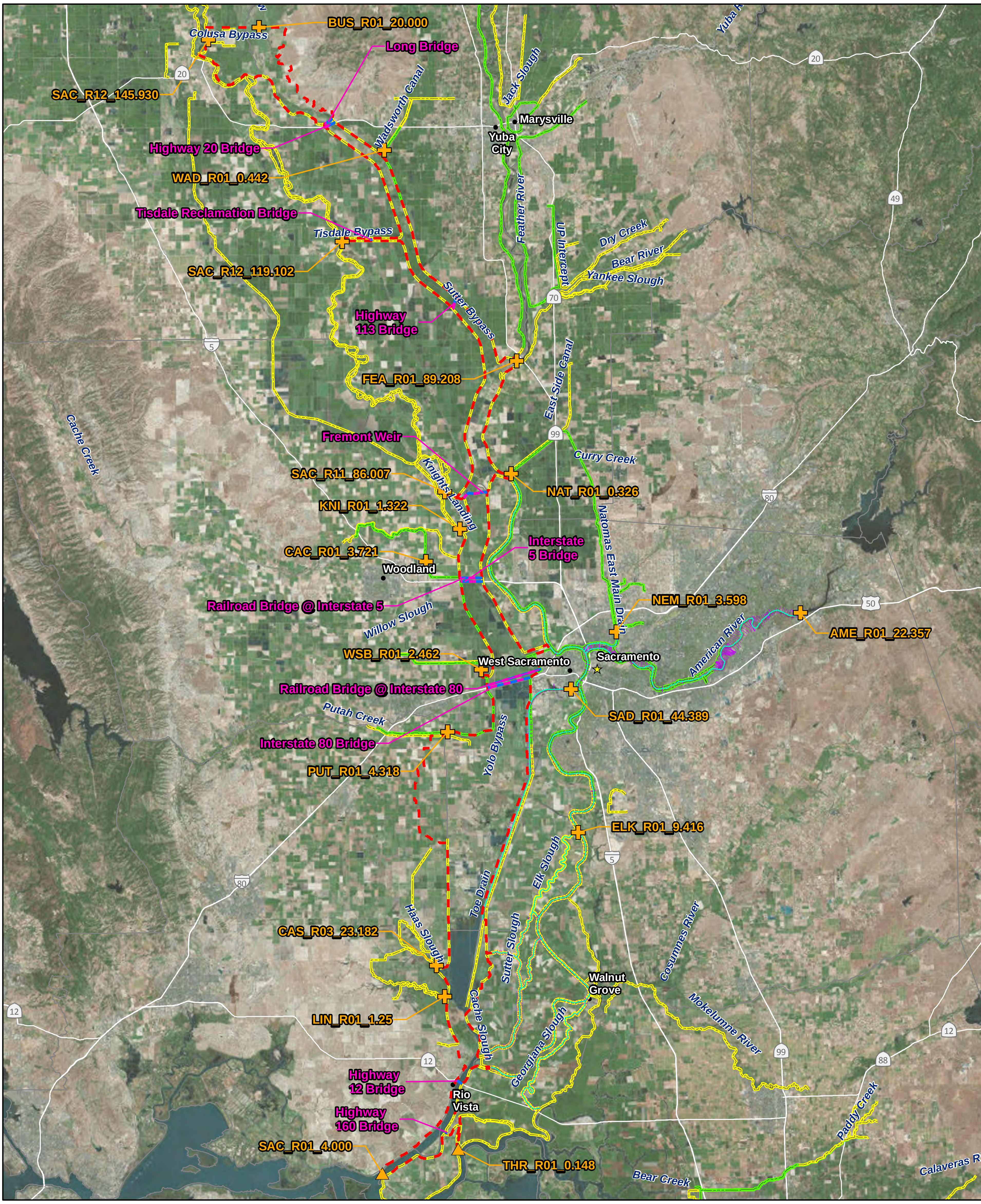
Bridges in the SUTYOL 2D model domain were input as weir structure types using 2D area internal connection functionality. The weir embankment was adjusted to represent the ground profile under the bridge and the bridge piers. Structure survey data were used to specify bridge pier widths and spacing to adjust the weir embankment and represent the opening between the bridge piers under the bridge. The bridge deck was not represented in the hydraulic structures because bridges cannot be included as internal connections in HEC-RAS version 5.0.1 2D areas. This simplification neglects any pressure flow that may occur if the bridge was overtopped.

3.6 Computational Options

Table 4 lists the computational options and parameters used when running HEC-RAS version 5.0.1.

Table 4. Computational Options

Parameter	Option
2D Flow Options	
Theta	1
Theta WarmUp	1
Water Surface Tolerance (feet)	0.01
Volume Tolerance (feet)	0.01
Maximum Iterations	20
Equation Set	Diffusion Wave
Initial Conditions Time (hours)	8
Initial Conditions Ramp-up Fraction	0.5
1D/2D Options	
Maximum Iterations between 1D and 2D	5
Water surface tolerance (feet)	0.2
Flow Tolerance (percent)	1.2
Minimum flow tolerance (cfs)	200
1D Options	
Water surface calculation tolerance (feet)	0.07
Storage Area elevation tolerance (feet)	0.1
Number of warm up time steps	200
Time step during warm up period (hours)	0.008333
Lateral Structure flow stability factor	3
Inline Structure flow stability factor	3
Weir flow submergence decay exponent	3
Gate flow submergence decay exponent	3
Unsteady Flow Options	
Computation Interval (minutes)	2
Mapping Output Interval (minutes)	60
Hydrograph Output Interval (minutes)	60
Detailed Output Interval (minutes)	60
Computed Courant Number	0.73
cfs = cubic feet per second	

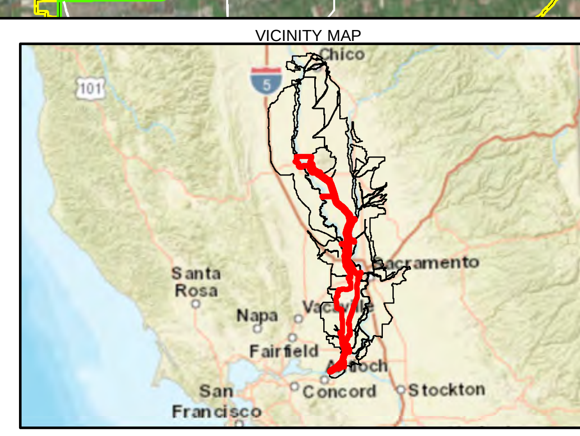


LEGEND

- HEC-RAS 2D Model Boundary
- Non-Urban Levee
- Urban Levee
- HEC-RAS River Centerlines
- HEC-RAS Cross Sections
- Hydralic Structures

Boundary Condition Locations

- Flow Hydrograph
- Stage Hydrograph



0 3.5 7
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FIGURE 5
Boundary Condition Locations and Hydralic Structures Map

Model Calibration and Validation

Model calibration and validation were performed by comparing observed gage and high water mark (HWM) data against CVFED TO 25 Enhanced Model results. 1997 storm simulated model outputs from the TO 25 model were extracted at boundary condition locations and were used as inputs to the SUTYOL model. The SUTYOL model was then calibrated to the 1997 observed flow and stage records. After the SUTYOL model was calibrated, 2006 storm simulated model outputs from the TO 25 model were used as inputs to the model; these were validated by comparing simulated results to 2006 observed flow and stage records.

The SUTYOL model was calibrated by incrementally adjusting roughness parameters for selected land cover types. The initial model results, using Base Manning's n values listed in Table 3, were compared to observed flow and stage hydrographs for the Yolo Bypass at Fremont Weir and Sacramento Weir at Verona gage locations. The Manning's n values were adjusted by first specifying the spatial extents of each land cover per region and then the values of each classification per region were adjusted to match the flow split at Fremont Weir. Similar modifications to n values were made to match flows at the bridges and to align the water surface elevation (WSE) closely with HWM data. Table 5 lists the Manning's n values used for different calibration regions.

Table 5. Adjusted Roughness Parameters by Land Cover Region

NLCD 2011 Classification	Land Cover Description	Base Manning's n	Calibration Region 01 Manning's n	Calibration Region 02 Manning's n	Calibration Region 03 Manning's n	Calibration Region 04 Manning's n
11	Open Water	0.03	0.04	0.021	0.03	0.03
12	Perennial Ice/Snow	0.03	0.03	0.03	0.03	0.03
21	Developed, Open Space	0.08	0.08	0.08	0.08	0.08
22	Developed, Low Intensity	0.1	0.1	0.1	0.1	0.1
23	Developed, Medium Intensity	0.15	0.15	0.15	0.15	0.15
24	Developed, High Intensity	0.2	0.2	0.2	0.2	0.2
31	Barren Land (Rock/Sand/Clay)	0.04	0.04	0.04	0.04	0.04
41	Deciduous Forest	0.1	0.1	0.1	0.1	0.1
42	Evergreen Forest	0.1	0.1	0.1	0.1	0.1
43	Mixed Forest	0.1	0.1	0.1	0.1	0.1
52	Shrub/Scrub	0.07	0.07	0.07	0.07	0.07
71	Grassland/Herbaceous	0.035	0.035	0.035	0.035	0.035
81	Pasture/Hay	0.04	0.04	0.04	0.04	0.04
82	Cultivated Crops	0.035	0.035	0.035	0.035	0.03
90	Woody Wetlands	0.05	0.04	0.05	0.04	0.038
95	Emergent Herbaceous Wetlands	0.06	0.042	0.06	0.042	0.04

4.1 Boundary Conditions

The following calibration and validation runs were made in the SUTYOL model:

- **1997 Storm Simulation (Calibration)** – Outputs from the TO 25 Enhanced Model's 1997 calibration simulation (V0025) were extracted at 2D model boundary locations, and were used as inputs to the SUTYOL model. Stage hydrograph boundary conditions were applied at the Sacramento River at Collinsville, Georgiana Slough and Threemile Slough locations. For the rest of the boundary locations, inflow hydrographs were used. This simulation also models a levee breach at the Sutter Bypass at Meridian location that occurred during the 1997 storm. The breached levee segment was represented in the SUTYOL model as a storage area/2D area connection between the 2D area and the adjacent floodplain, which was represented as storage area.
- **2006 Storm Simulation (Validation)** – Outputs from the TO 25 Enhanced Model 2006 validation simulation (V0024) were extracted at 2D model boundary locations, and were used as inputs to the SUTYOL model. Stage hydrograph boundary conditions were applied at the Sacramento River at Collinsville, Georgiana Slough and Threemile Slough locations. For the rest of the boundary locations, inflow hydrographs were used. No levee breaches occurred during the 2006 storm; as a result, none were represented in the SUTYOL model.

Figure 5 shows the boundary condition locations and names. Boundary condition names represent the TO 25 Enhanced model's cross section river, reach, and river mile from which outputs were extracted.

4.2 Results Comparison

Stage and flow results from the calibration and validation simulations were compared to observed stage and flow hydrographs, observed HWM data, and TO 25 Enhanced Model outputs. Table 6 compares simulated peak flow and peak stage against 1997 with the observed records at gage locations. Table 7 compares results against the 2006 observed gage information. Gage locations used for both calibration and validation are shown in Figure 6.

HWM data along the Sutter and Yolo bypasses' left and right banks were compared against the simulated maximum WSE. Figure 7 shows HWM locations by storm event. WSE profiles along the centerline of the Sutter and Yolo bypasses were extracted from the SUTYOL model's maximum WSE raster data, and were compared to observed HWMs, to the maximum WSE at gages, and to the TO 25 model, as shown in Figures 8 through 11.

Figures 12 through 17 show the maximum inundation depth, WSE, and velocity maps used for calibration and validation.

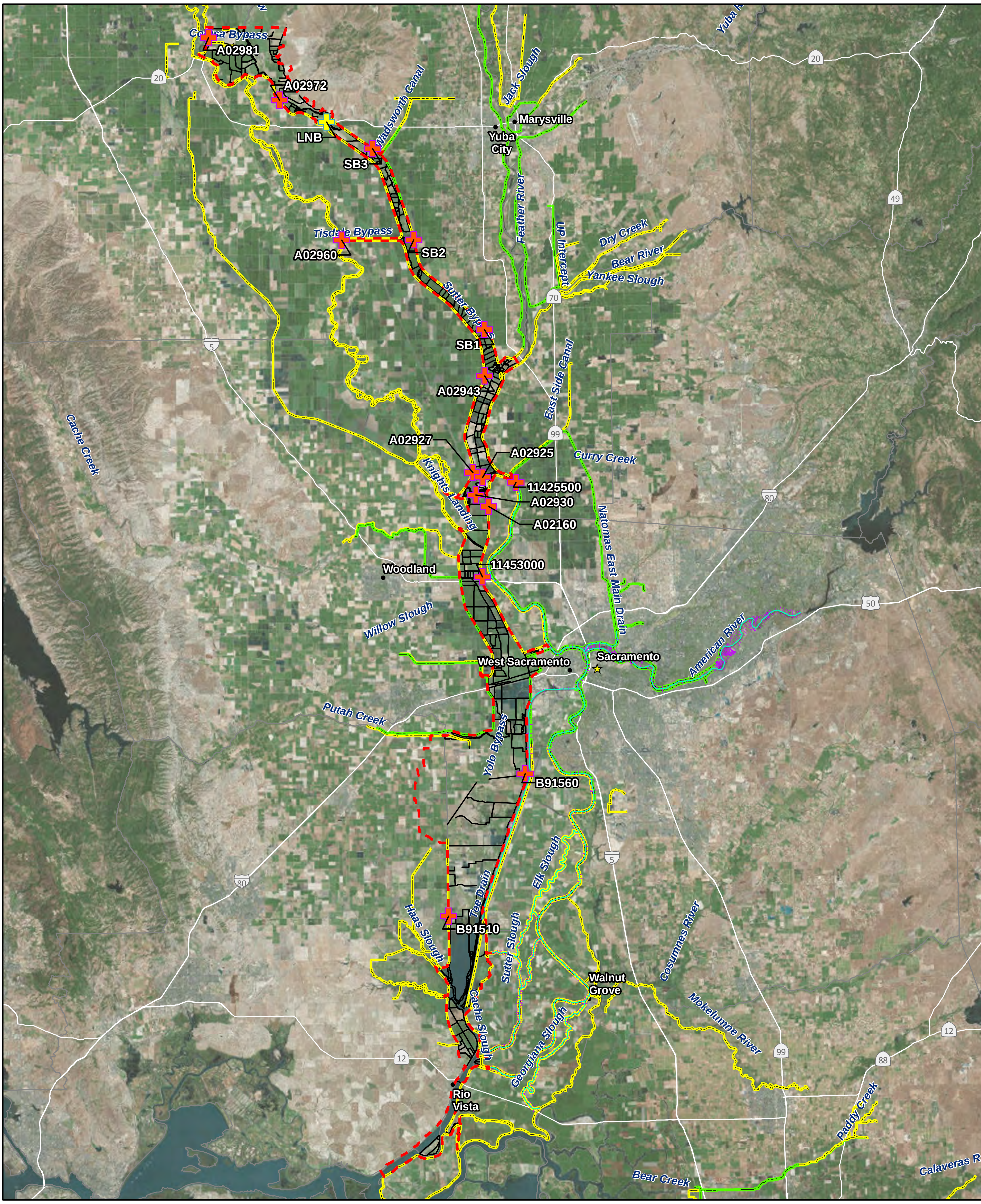
Locations in the SUTYOL 2D model domain where flow and stage hydrographs could be extracted were limited to hydraulic structure locations and boundary condition locations. As a result, gage locations at hydraulic structures and boundaries were selected for comparison against flow and stage hydrographs. Figures 18 to 33 compare flow and stage hydrographs with the observed gage hydrographs. Flow and stage hydrographs at all hydraulic structure locations (i.e., bridges) were extracted and compared to the TO 25 Enhanced Model. Figures 34 to 74 compare flow and stage hydrograph to TO 25 Enhanced Model outputs.

Table 6. Peak Flow and Stage Comparison at the Gage Locations for 1997 Calibration

		Peak Flow (cfs)			Peak WSEL (feet, NAVD88)		
Station Name	**Station ID**	**Observed**	**TO 25 Enhanced Model**	**SUTYOL 2D Model**	**Observed**	**TO 25 Enhanced Model**	**SUTYOL 2D Model**
Colusa Weir Spill to Butte Basin near Colusa	A02981	65,700	58,558	58,461	67.84	69.02	69.12
Butte Slough near Meridian	A02972	173,000	158,567	-	62.16	62.46	61.57
Sutter Bypass Channel at Pumping Plant 3	SB3	-	158,025	-	54.32	54.71	55.14
Sutter Bypass Channel at Pumping Plant 2	SB2	-	174,392	-	50.64	51.05	51.56
Tisdale Weir near Grimes	A02960	19,800	20,067	19,972	51.77	51.96	52.23
Sutter Bypass Channel at Pumping Plant 1	SB1	-	175,361	-	47.01	49.33	49.15
Willow Slough near Nicolaus	A02943	-	304,625	-	46.91	48.49	48.16
Sutter Bypass near R.D. 1500 PP near Karnak	A02927	-	361,815	-	42.50	42.30	41.80
Sacramento Slough near Sacramento River near Karnak	A02925	-	361,594	-	42.70	42.00	41.69
Fremont Weir Spill to Yolo Bypass	A02930	319,000	386,523	387,142	-	-	-
Sacramento River at Fremont Weir (East End)	A02160	-	-	-	40.90	40.51	40.97
Sacramento River at Verona, CA	11425500	102,000	101,653	99,819	41.29	41.08	40.96
Yolo Bypass near Woodland, CA	11453000	-	387,520	388,026	-	33.90	35.16
Yolo Bypass near Lisbon	B91560	-	469,385	-	26.34	26.41	27.15
Yolo Bypass at Liberty Island	B91510	-	454,138	-	19.56	20.32	18.89

Table 7. Peak Flow and Stage Comparison at the Gage Locations for 2006 Validation

		Peak Flow (cfs)			Peak WSEL (feet, NAVD88)		
Station Name	**Station ID**	**Observed**	**TO 25 Enhanced Model**	**SUTYOL 2D Model**	**Observed**	**TO 25 Enhanced Model**	**SUTYOL 2D Model**
Colusa Weir Spill to Butte Basin near Colusa	A02981	51,200	49,576	48,576	67.04	68.15	68.21
Butte Slough near Meridian	A02972	111,000	108,486	-	59.44	59.84	58.93
Sutter Bypass at Long Bridge	LNB	-	108,381	107,405	54.31	54.10	53.77
Sutter Bypass Channel at Pumping Plant 3	SB3	-	108,286	-	51.84	51.47	51.75
Sutter Bypass Channel at Pumping Plant 2	SB2	-	127,357	-	46.85	47.45	47.91
Tisdale Weir near Grimes	A02960	16,300	18,921	18,820	50.71	49.68	49.32
Sutter Bypass Channel at Pumping Plant 1	SB1	-	128,023	-	44.71	45.17	45.09
Willow Slough near Nicolaus	A02943	-	189,057	-	43.49	43.96	43.47
Sutter Bypass near R.D. 1500 PP near Karnak	A02927	-	203,758	-	39.00	38.71	38.29
Sacramento Slough near Sacramento River near Karnak	A02925	-	203,756	-	39.13	38.50	38.21
Fremont Weir Spill to Yolo Bypass	A02930	253,000	232,011	230,966	-	-	-
Sacramento River at Fremont Weir (East End)	A02160	-	-	-	38.72	37.70	37.28
Sacramento River at Verona, CA	11425500	85,600	84,759	84,508	37.94	37.65	37.51
Yolo Bypass near Woodland, CA	11453000	225,170	240,906	239,909	30.73	30.31	31.74
Yolo Bypass near Lisbon	B91560	-	272,405	-	23.33	23.19	24.07
Yolo Bypass at Liberty Island	B91510	-	272,426	-	16.98	16.26	15.01



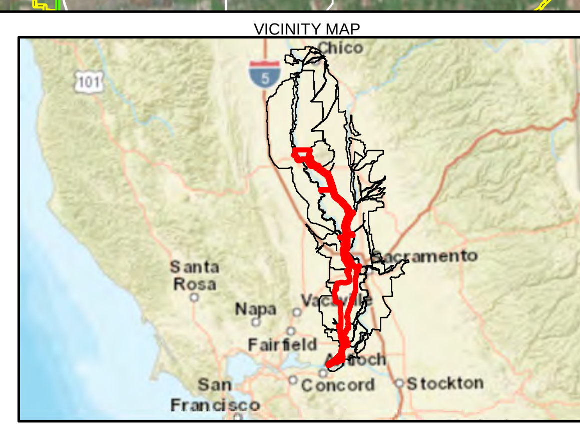
LEGEND

- HEC-RAS 2D Model Boundary
- HEC-RAS 2D Break Lines
- Non-Urban Levee
- Urban Levee
- HEC-RAS River Centerlines
- HEC-RAS Cross Sections

Gage Location

- <all other values>
- Gage Location - HEC-RAS Calibration/Validation Model
- Gage Location - HEC-RAS Validation Model

VICINITY MAP

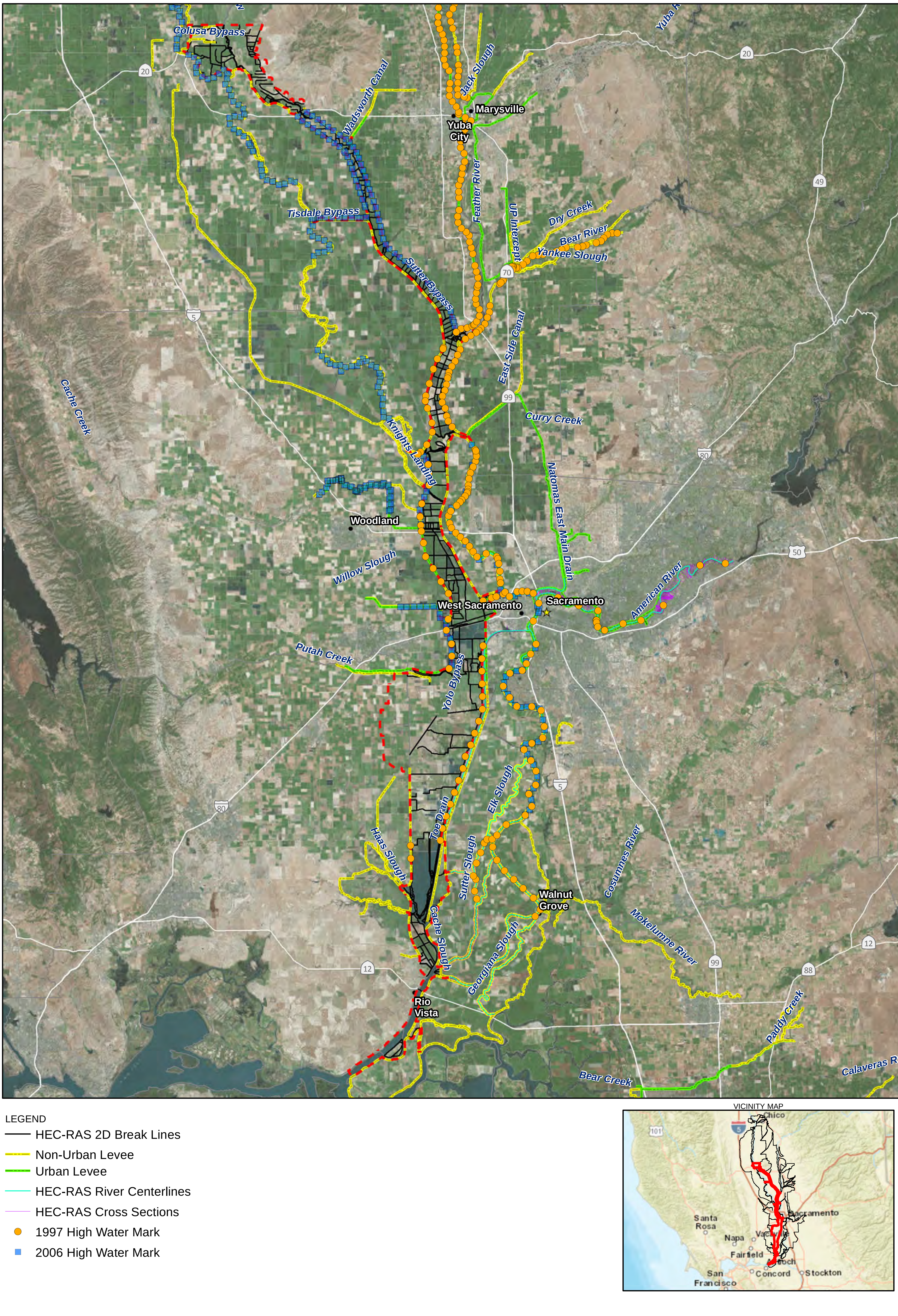


N

0 3.5 7
Miles

FIGURE 6
Gage Data for 1997 and 2006 Events

ch2m



LEGEND

- HEC-RAS 2D Break Lines
- Non-Urban Levee
- Urban Levee
- HEC-RAS River Centerlines
- HEC-RAS Cross Sections
- 1997 High Water Mark
- 2006 High Water Mark

FIGURE 7
High Water Mark Data for 1997 and 2006 Events

ch2m:

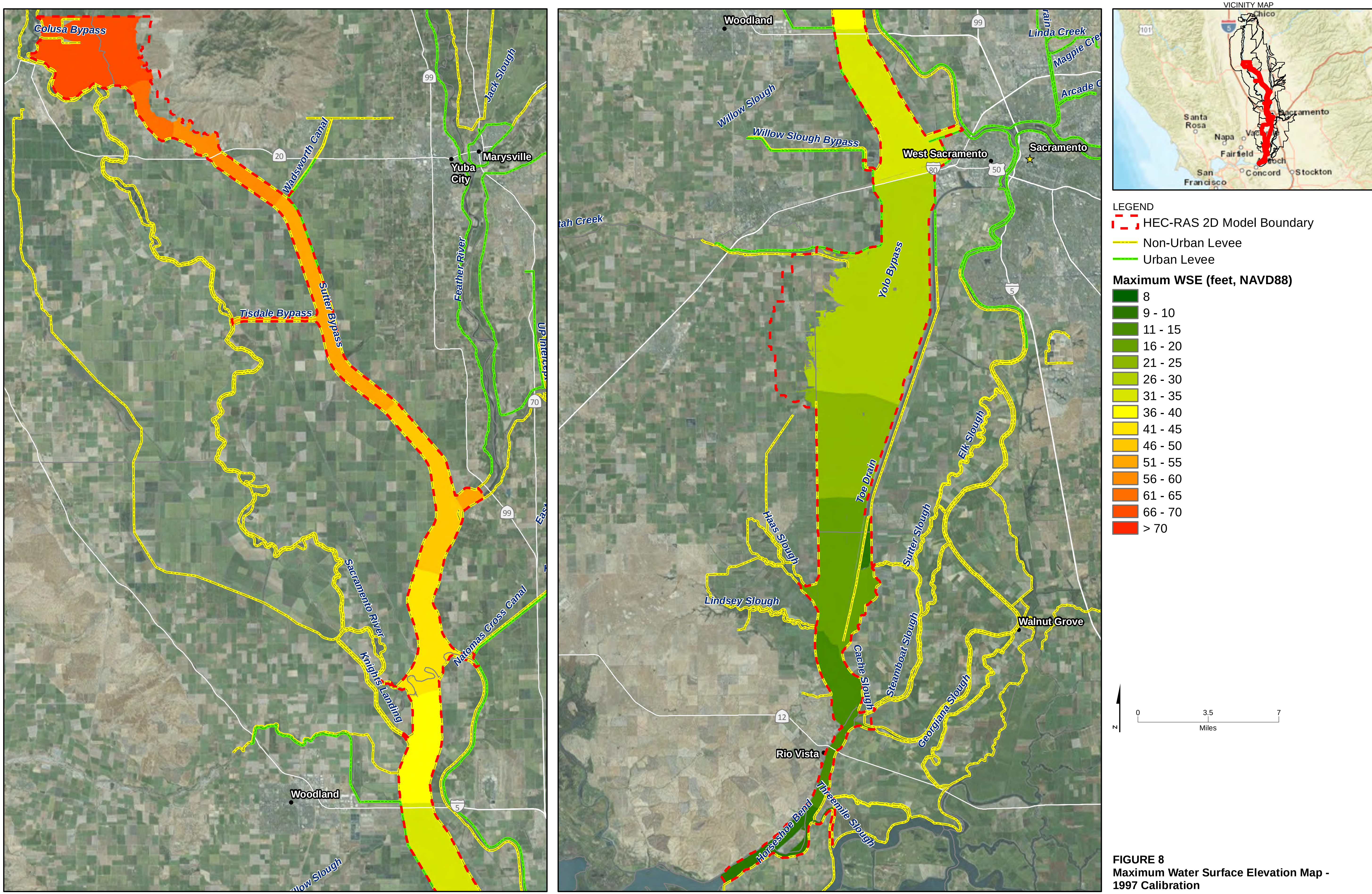
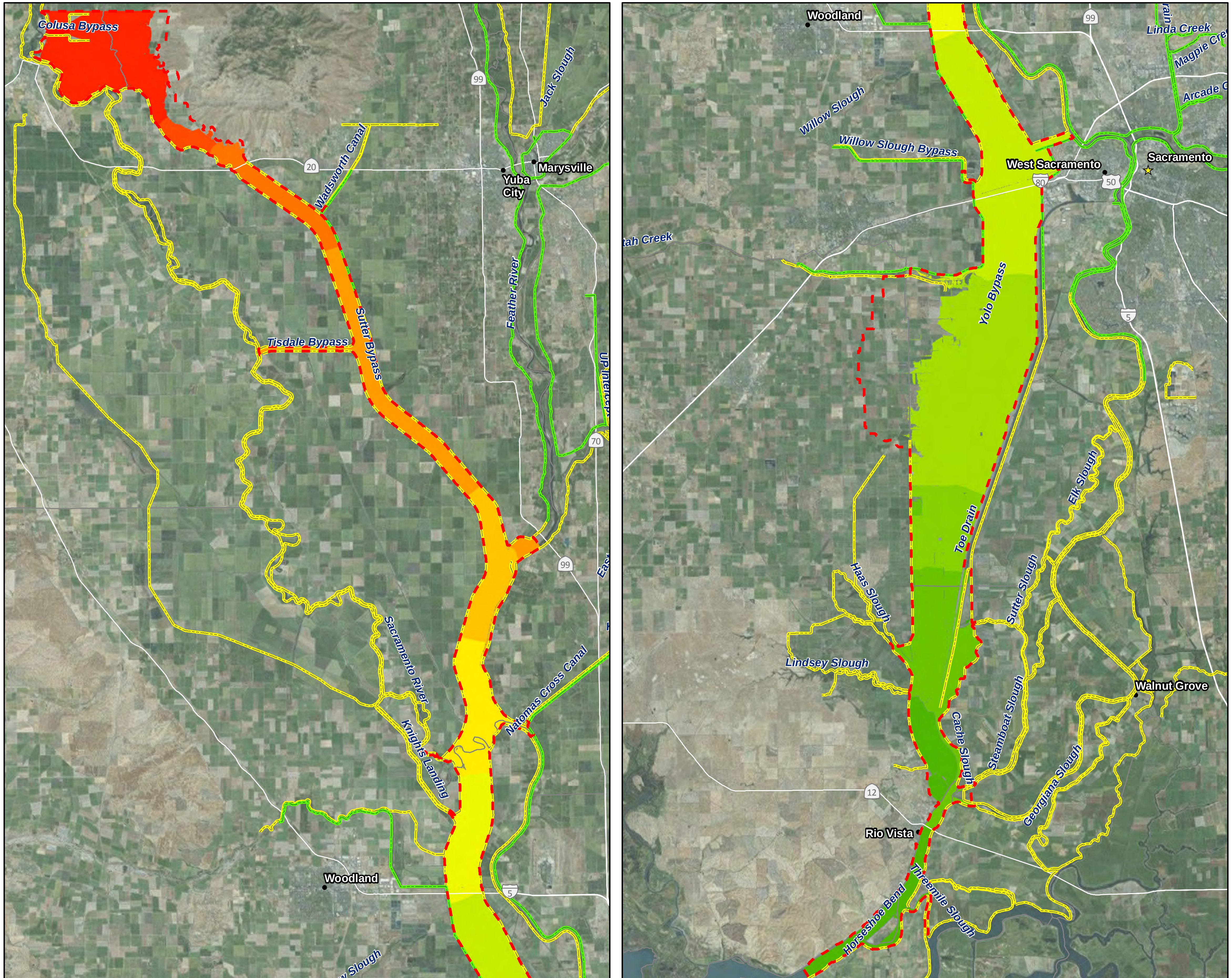


FIGURE 8
Maximum Water Surface Elevation Map - 1997 Calibration



LEGEND

- HEC-RAS 2D Model Boundary
- Non-Urban Levee
- Urban Levee

Maximum WSE (feet, NAVD88)

- 1 - 5
- 6 - 10
- 11 - 15
- 16 - 20
- 21 - 25
- 26 - 30
- 31 - 35
- 36 - 40
- 41 - 45
- 46 - 50
- 51 - 55
- 56 - 60
- 61 - 65
- 66 - 70

N

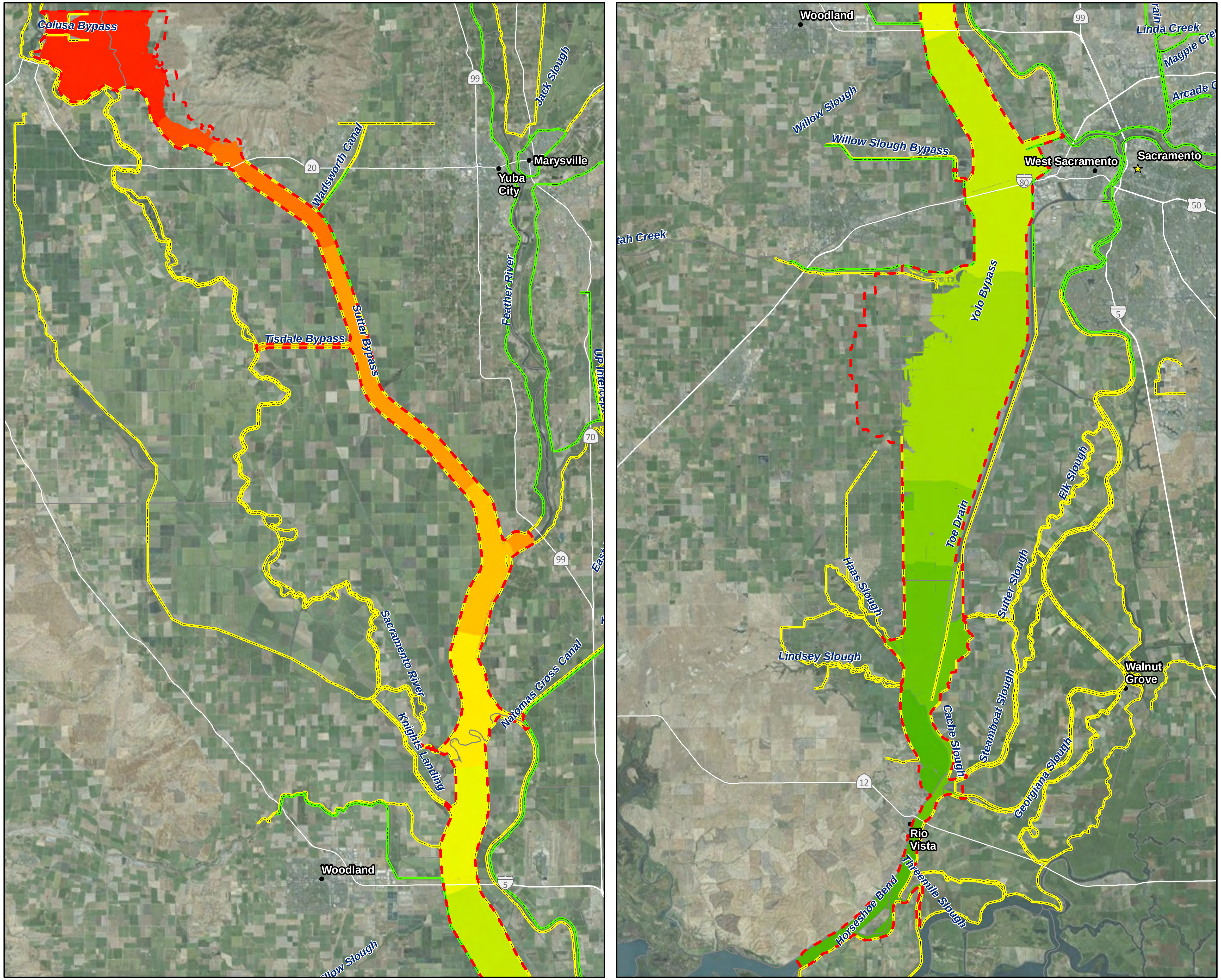
0 3.5 7

Miles

FIGURE 9
Maximum Water Surface Elevation Map - 2006 Calibration

\\SACFPP01\PROJ\CALIFORNIADEPTOFWATE\478187CVFPP\TO_15-12_FLOODPLAIN\GIS\MAPFILES\WSE\MAX_WSE_2006_CALIBRATION_SUTYOL_20170608.MXD ED035443 6/8/2017 10:26:44 AM

ch2m.



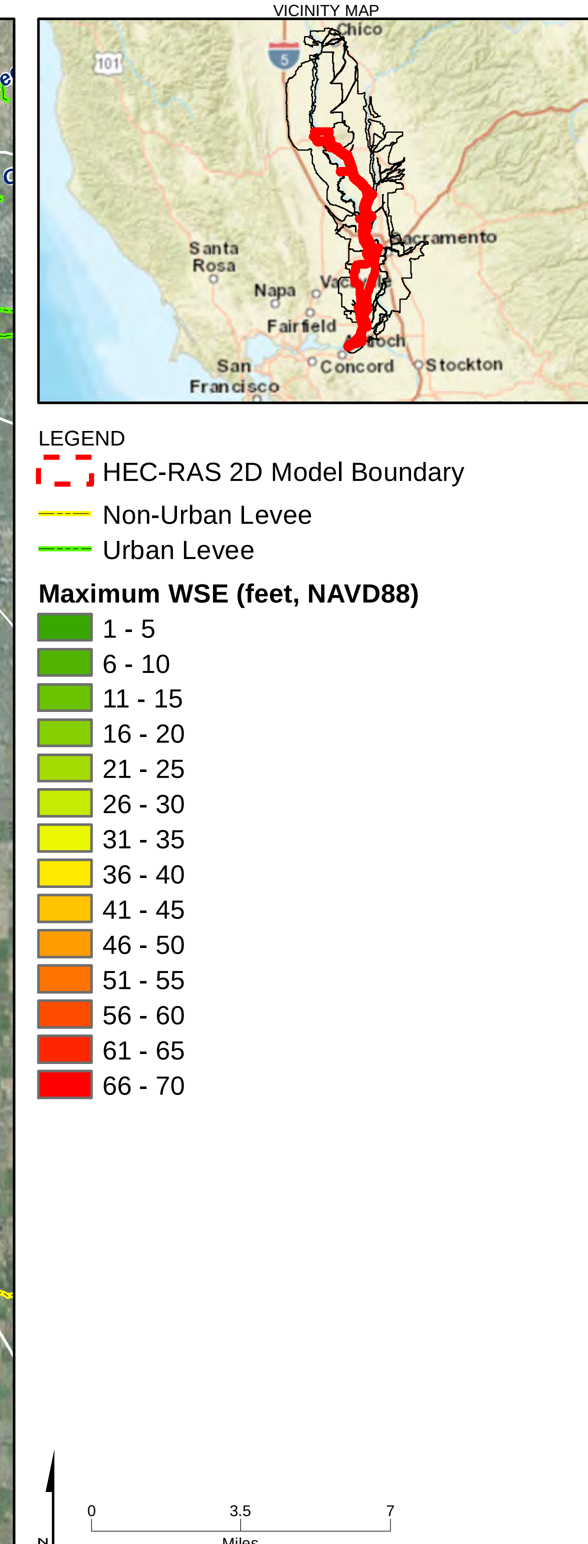
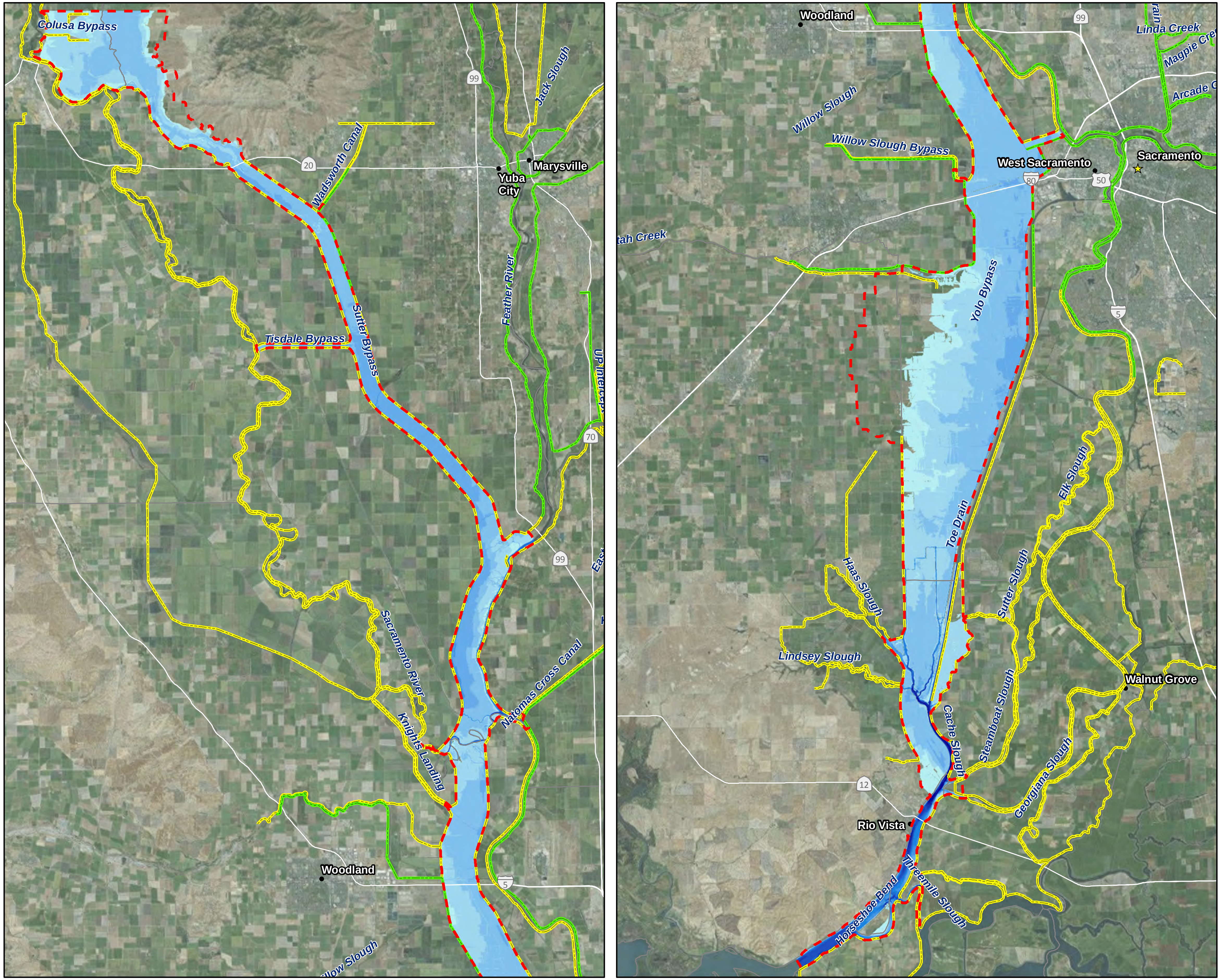


FIGURE 10
Maximum Water Surface Elevation Map - 2006 Calibration

\\SACFPP01\PROJ\CALIFORNIADEPTOFWATE\478187CVFPP\TO_15-12_FLOODPLAIN\GIS\MAPFILES\WSE\MAX_WSE_2006_CALIBRATION_SUTYOL_20160802.MXD ED035443 8/5/2016 1:19:55 PM

ch2m



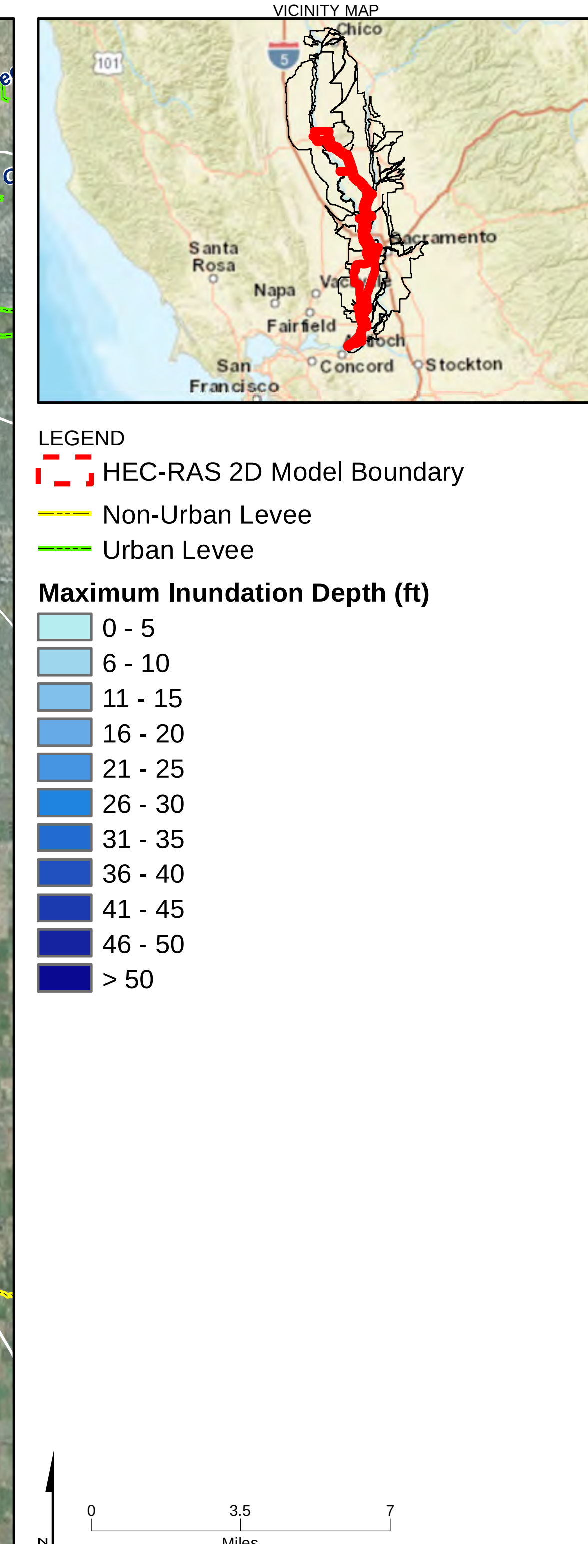


FIGURE 11
Maximum Inundation Depth Map - 2006 Calibration

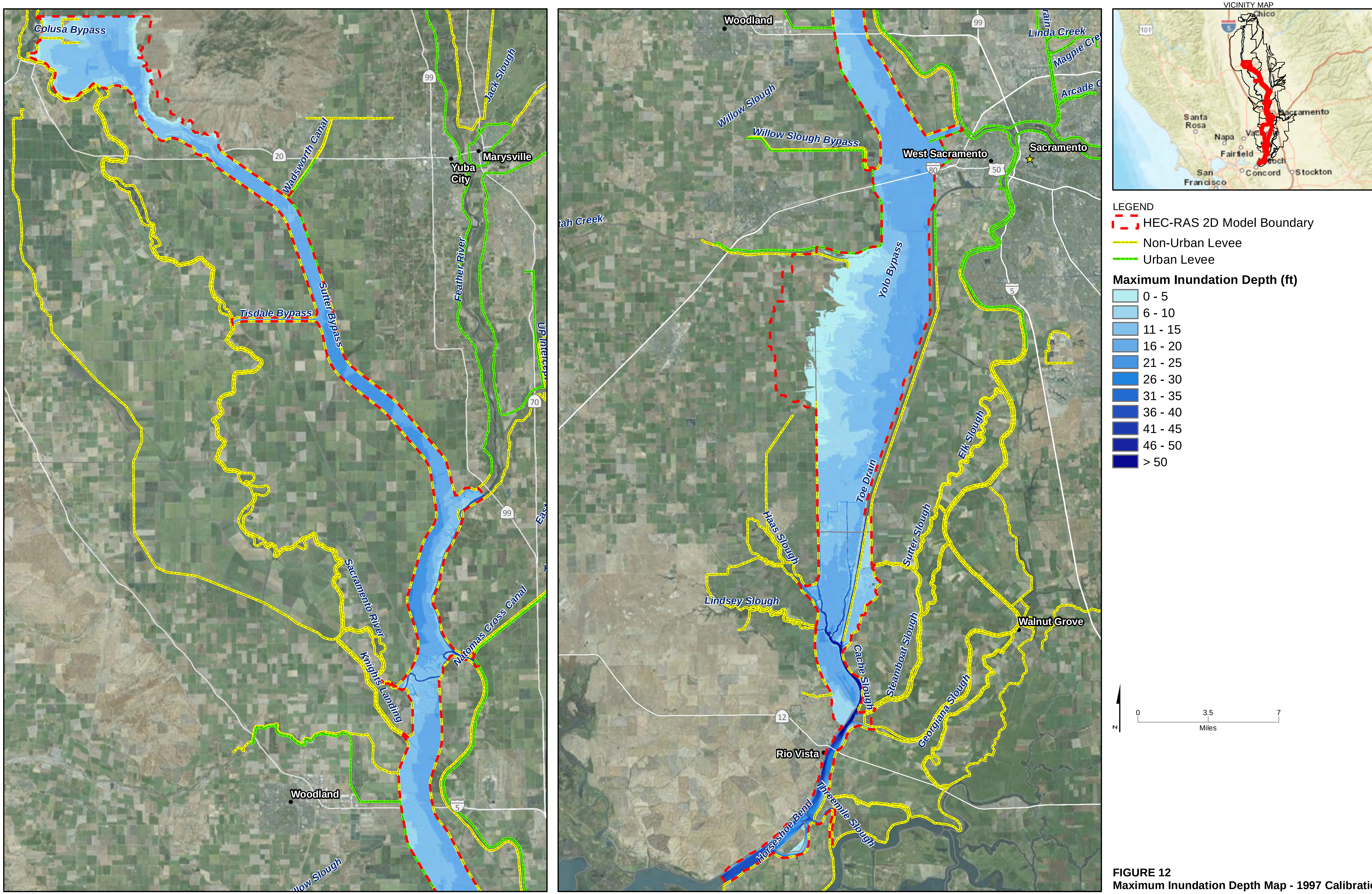


FIGURE 12
Maximum Inundation Depth Map - 1997 Calibration

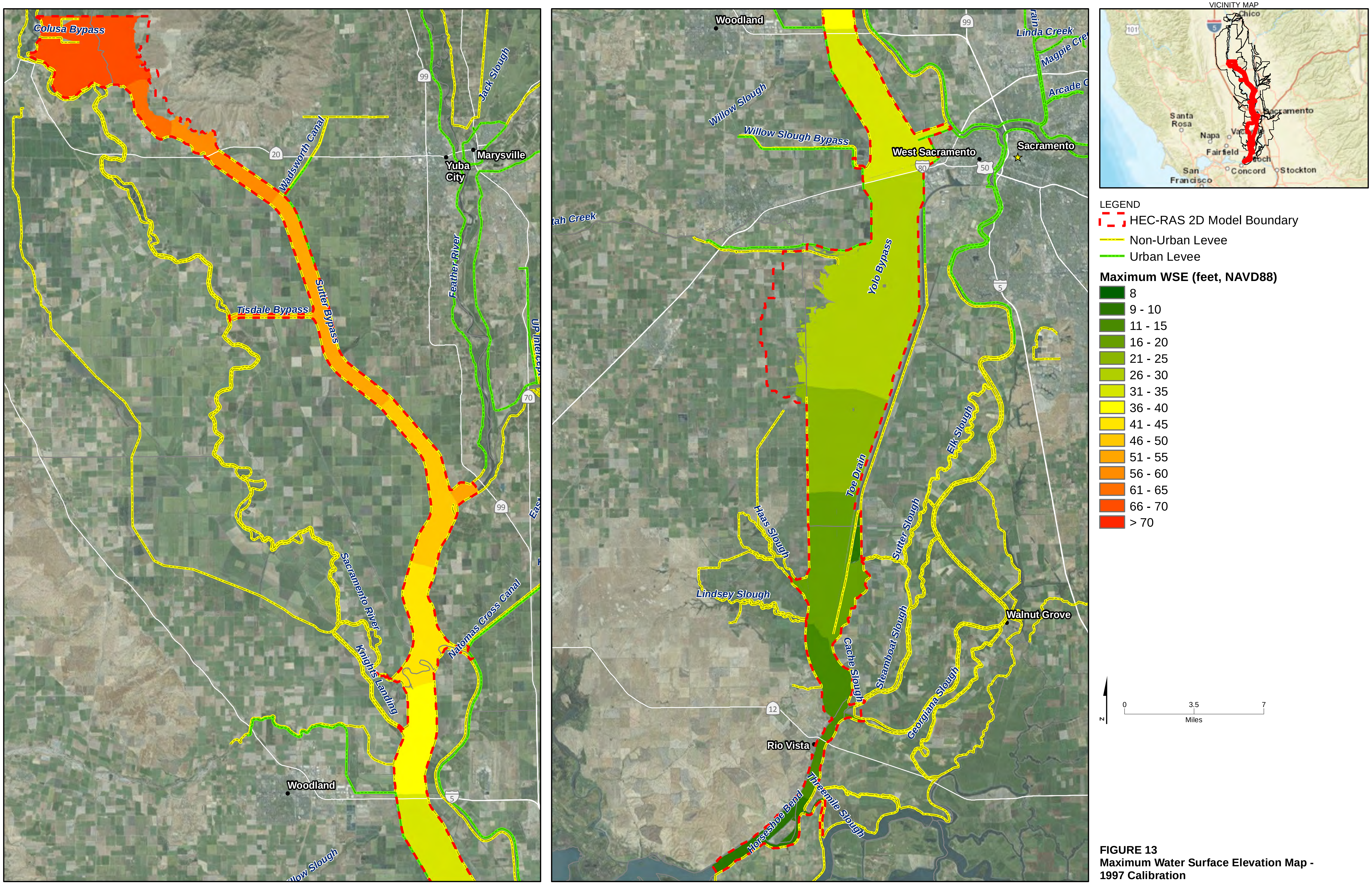


FIGURE 13
Maximum Water Surface Elevation Map - 1997 Calibration

ch2m:

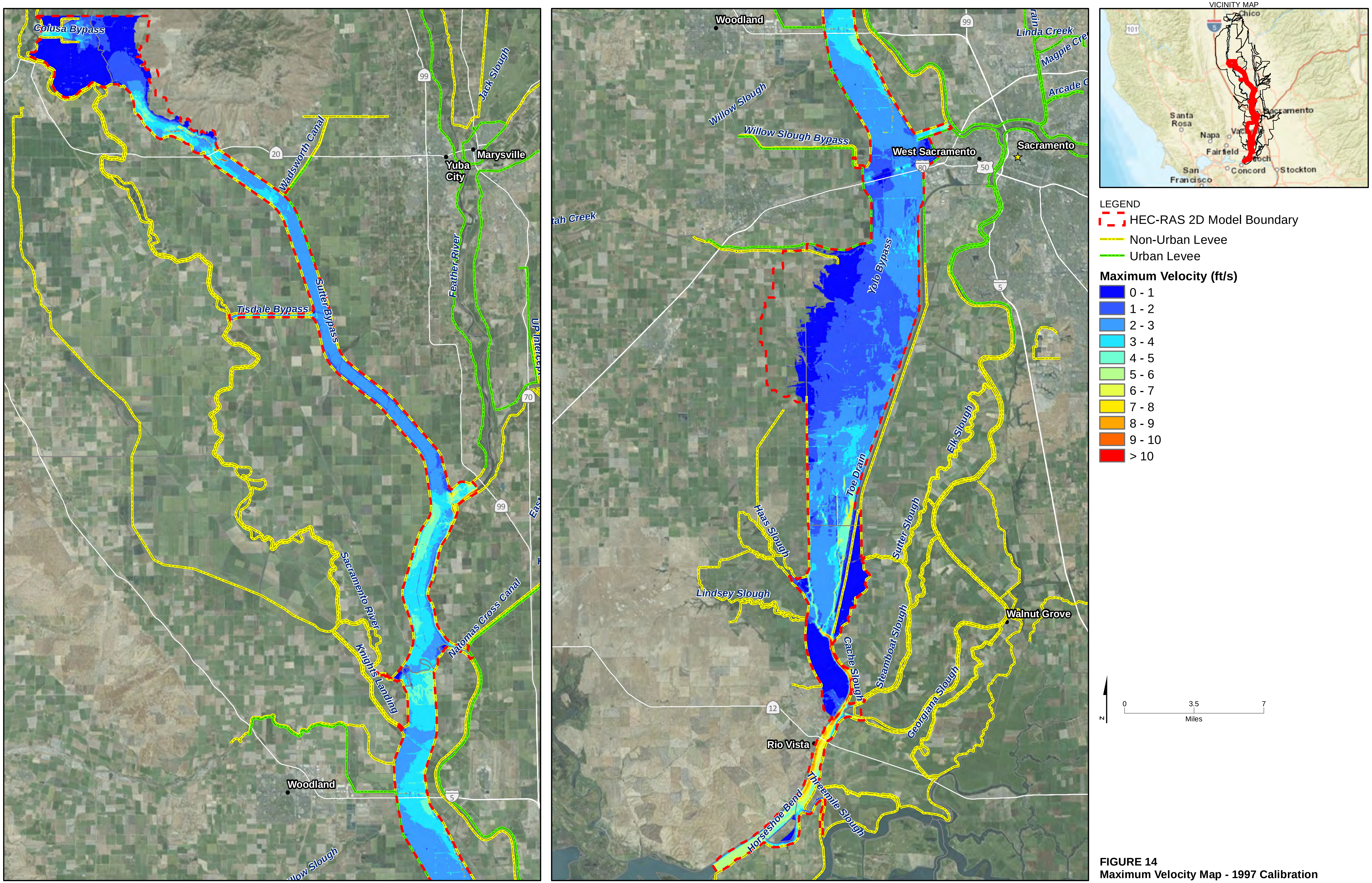


FIGURE 14
Maximum Velocity Map - 1997 Calibration

\\SACFPP01\PROJ\CALIFORNIADEPTOFWATE\478187CVFPP\TO_15-12_FLOODPLAIN\GIS\MAPFILES\VELOCITY\MAX_VELOCITY_1997_CALIBRATION_SUTYOL_20170608.MXD ED035443 6/8/2017 10:25:32 AM

ch2m

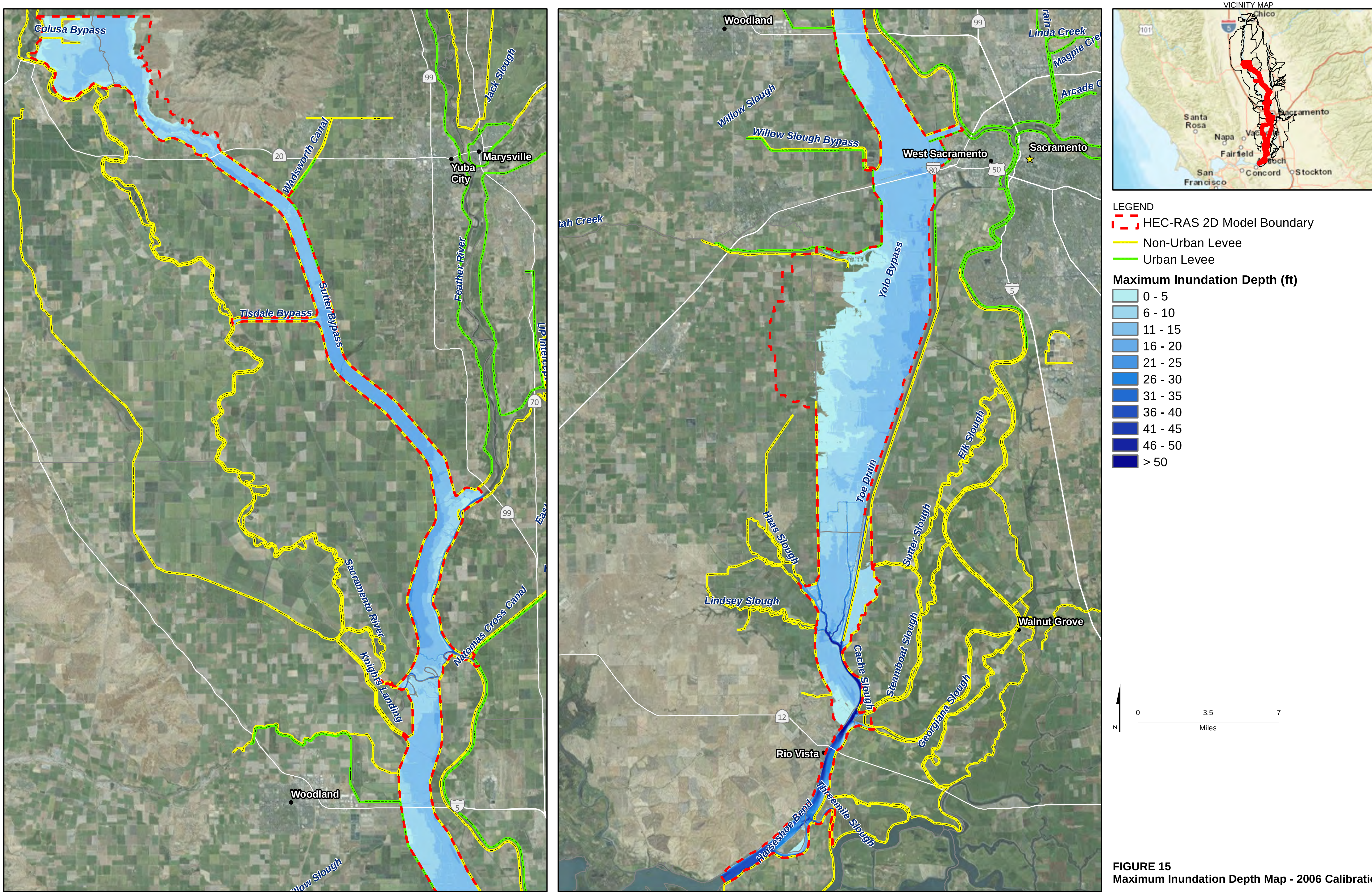


FIGURE 15
Maximum Inundation Depth Map - 2006 Calibration

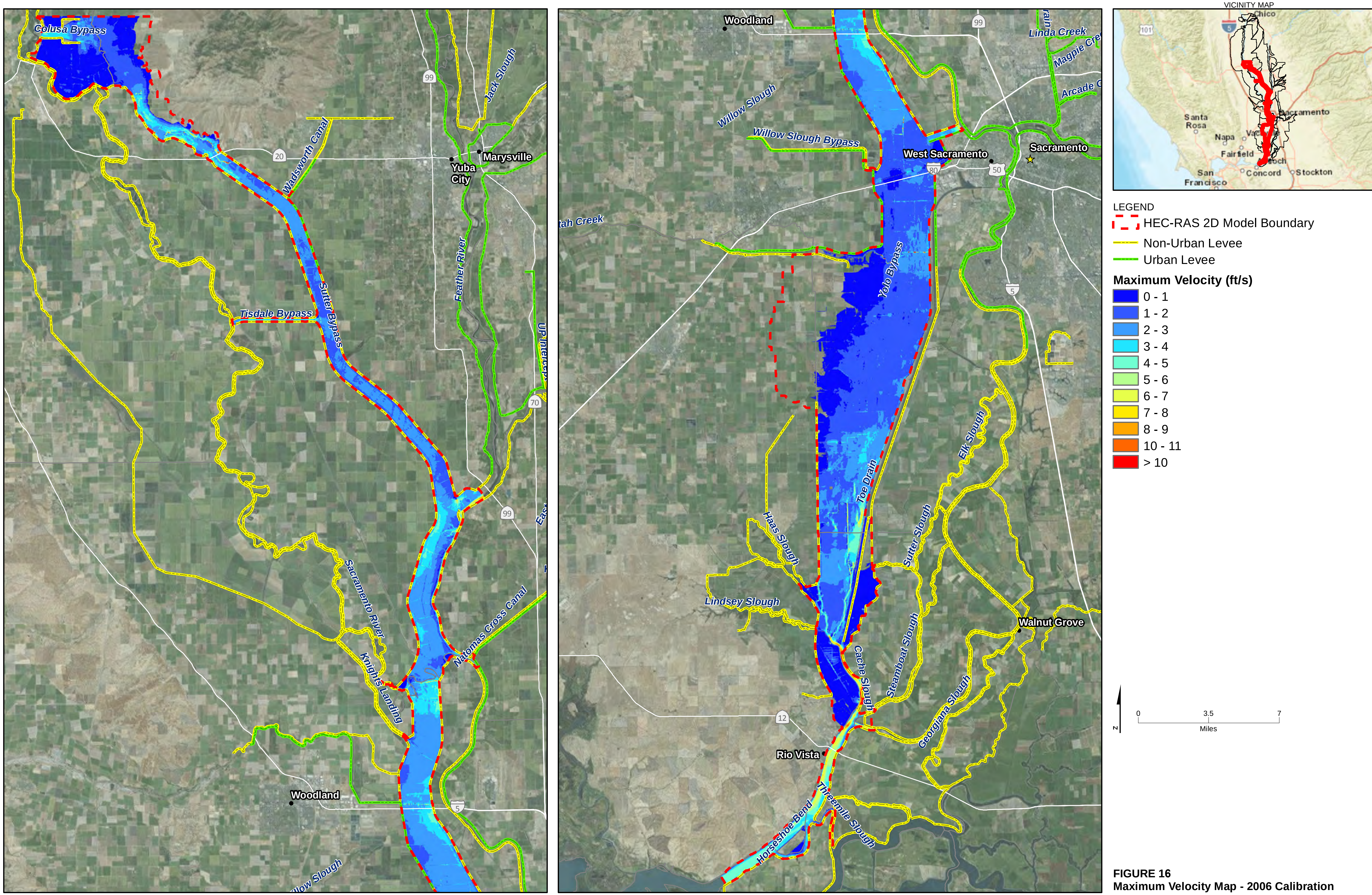


FIGURE 16
Maximum Velocity Map - 2006 Calibration

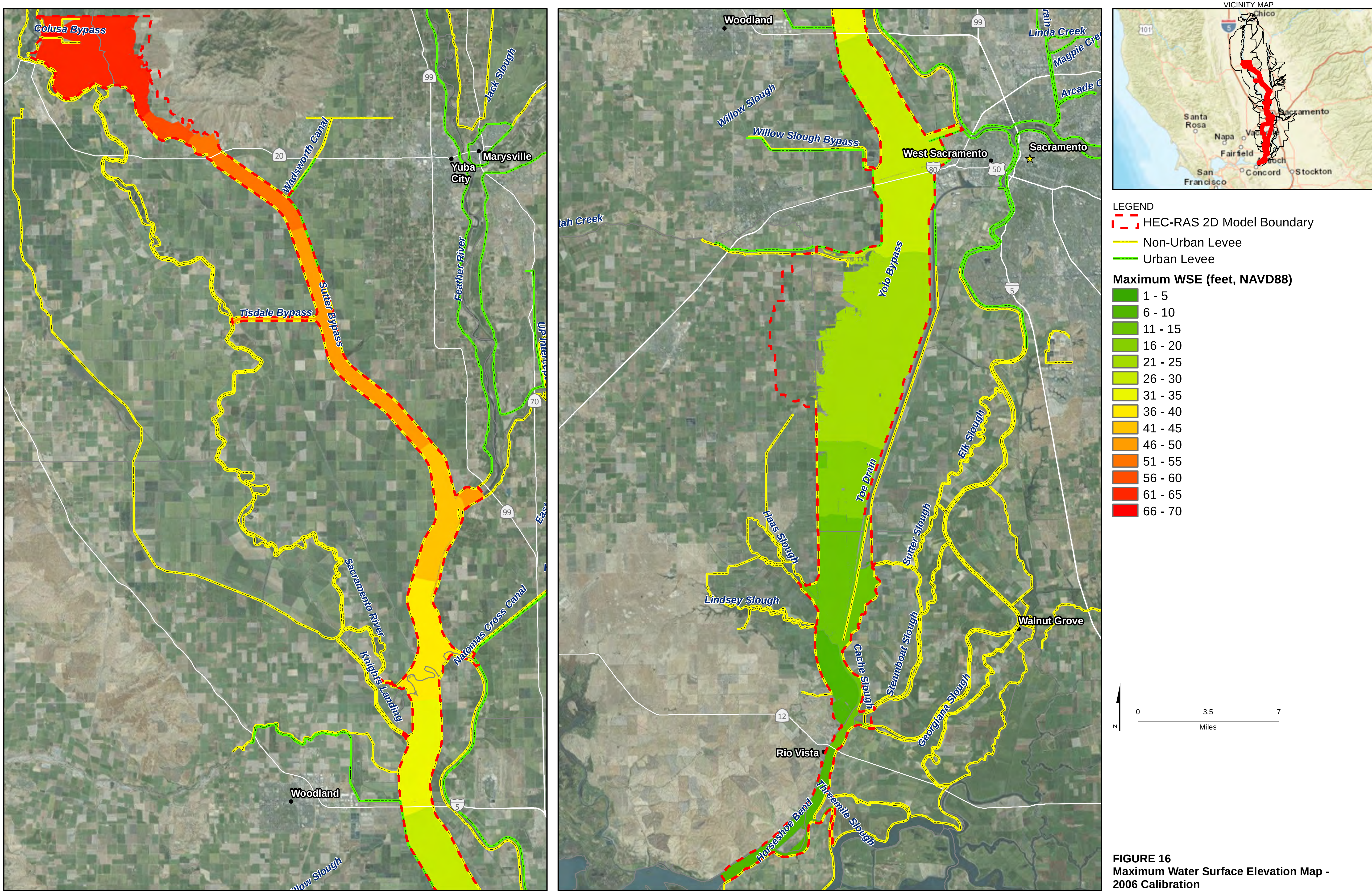


FIGURE 16
Maximum Water Surface Elevation Map - 2006 Calibration

\\SACFPP01\PROJ\CALIFORNIADEPTOFWATE\478187CVFPP\TO_15-12_FLOODPLAIN\GIS\MAPFILES\WSE\MAX_WSE_2006_CALIBRATION_SUTYOL_20170608.MXD ED035443 6/8/2017 10:26:44 AM

ch2m:

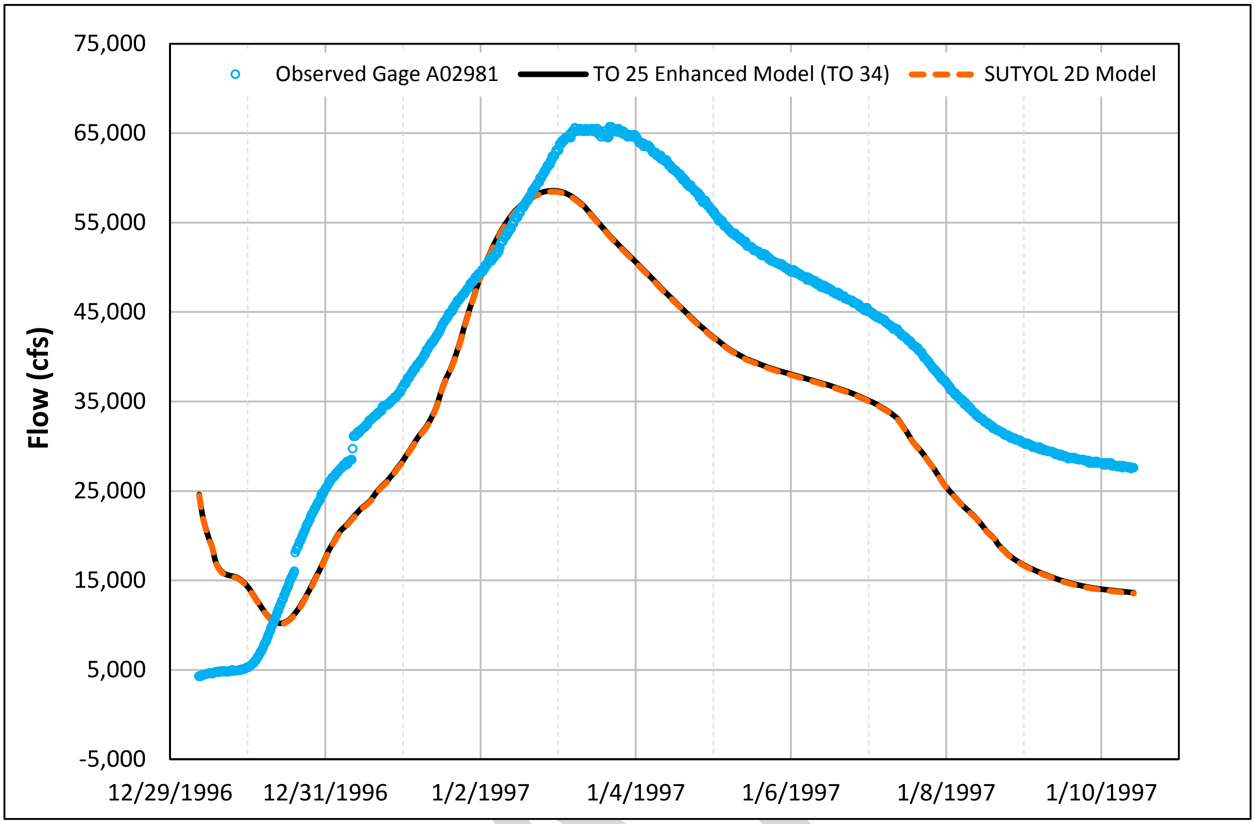


Figure 18. Sutter Bypass at Colusa Weir Flow Hydrograph for 1997 Calibration

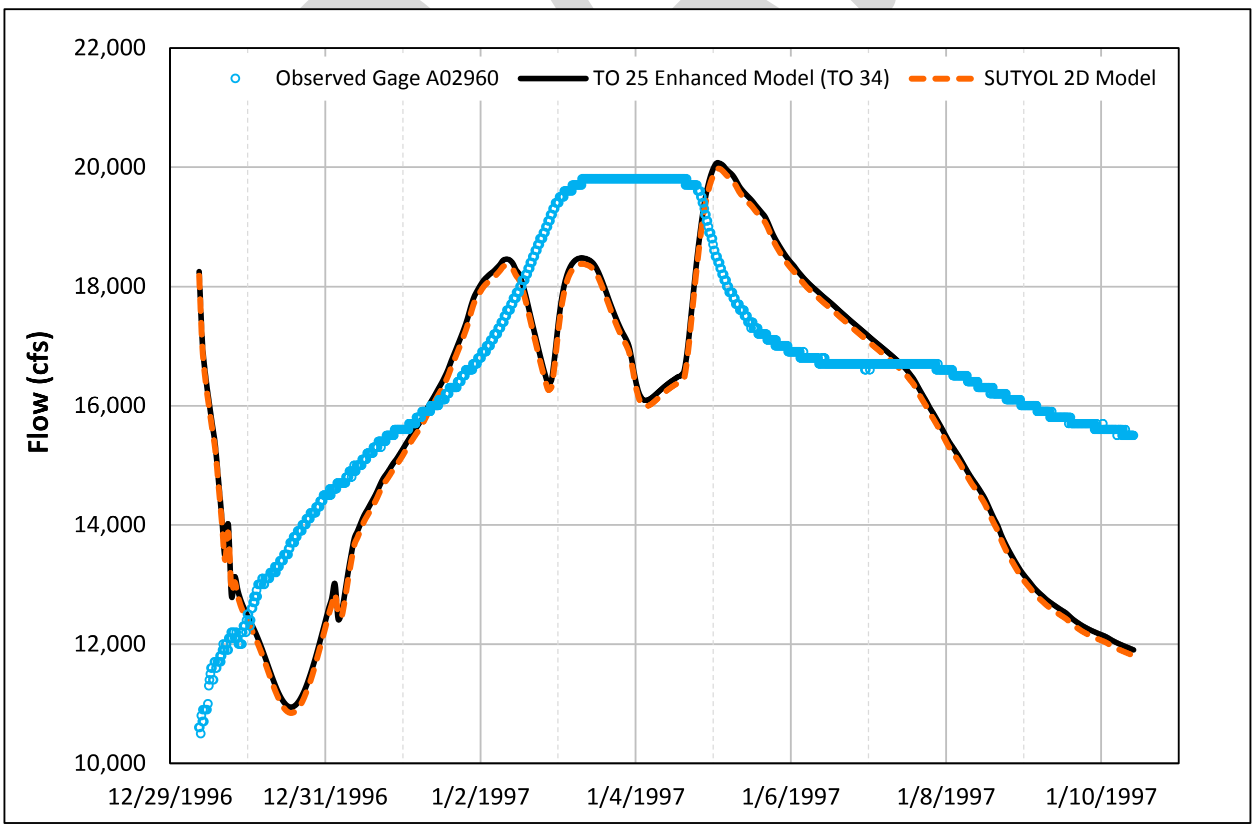


Figure 19. Tisdale Bypass at Tisdale Weir Flow Hydrograph for 1997 Calibration

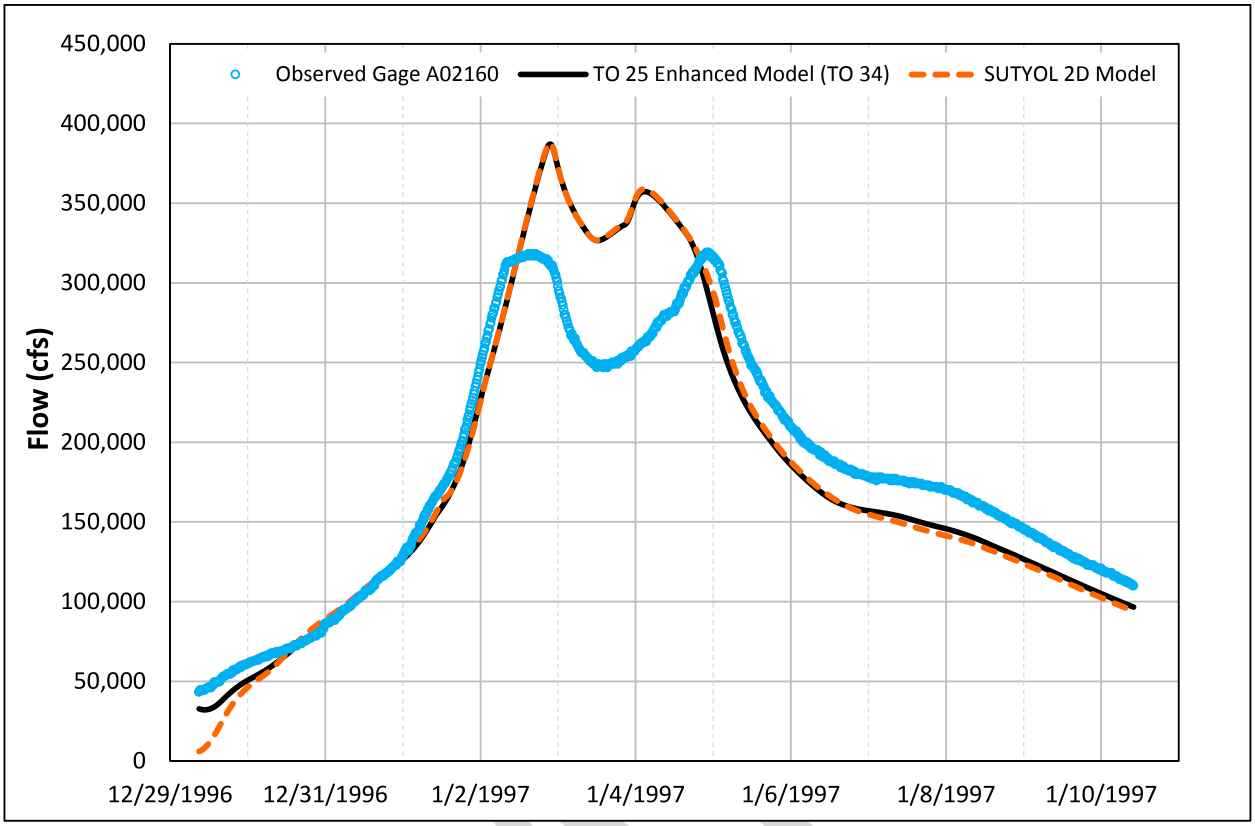


Figure 20. Yolo Bypass at Fremont Weir Flow Hydrograph for 1997 Calibration

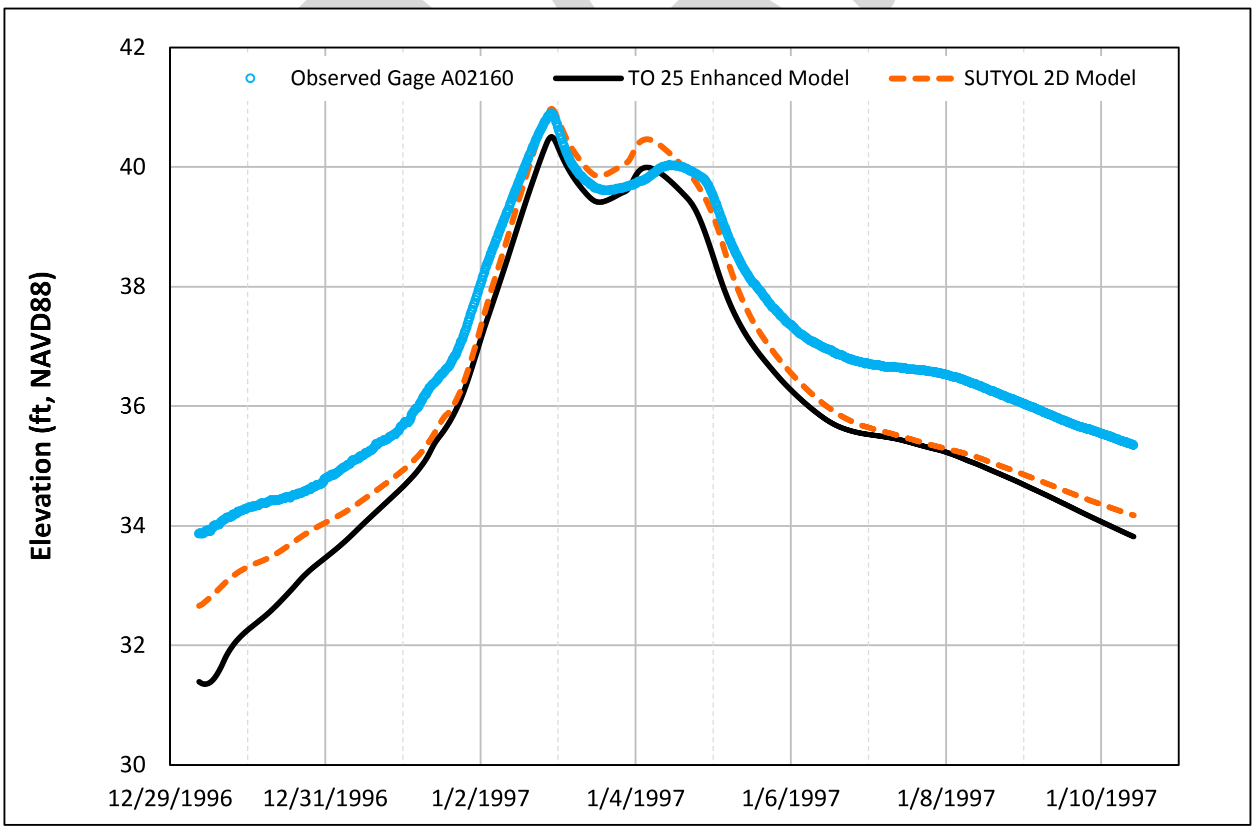


Figure 21. Yolo Bypass at Fremont Weir Stage Hydrograph for 1997 Calibration

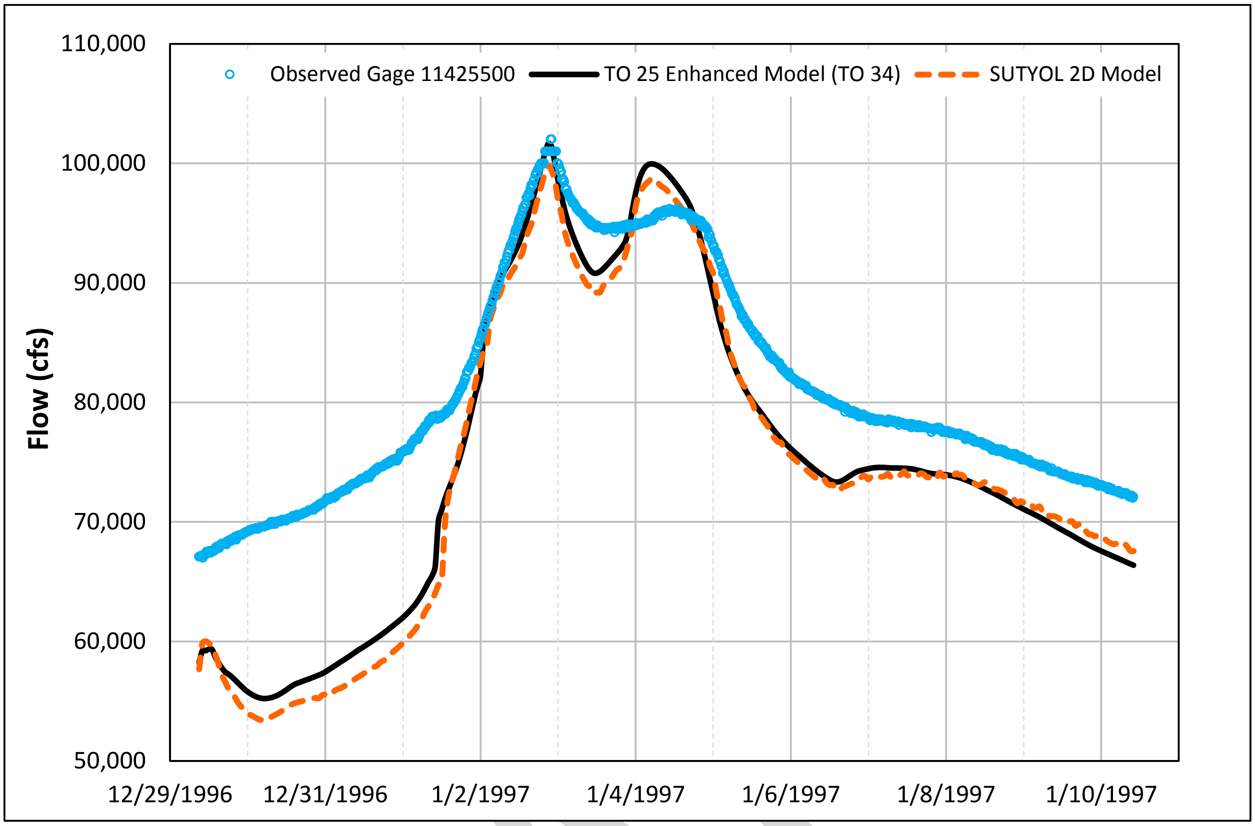


Figure 22. Sacramento River at Verona Flow Hydrograph for 1997 Calibration

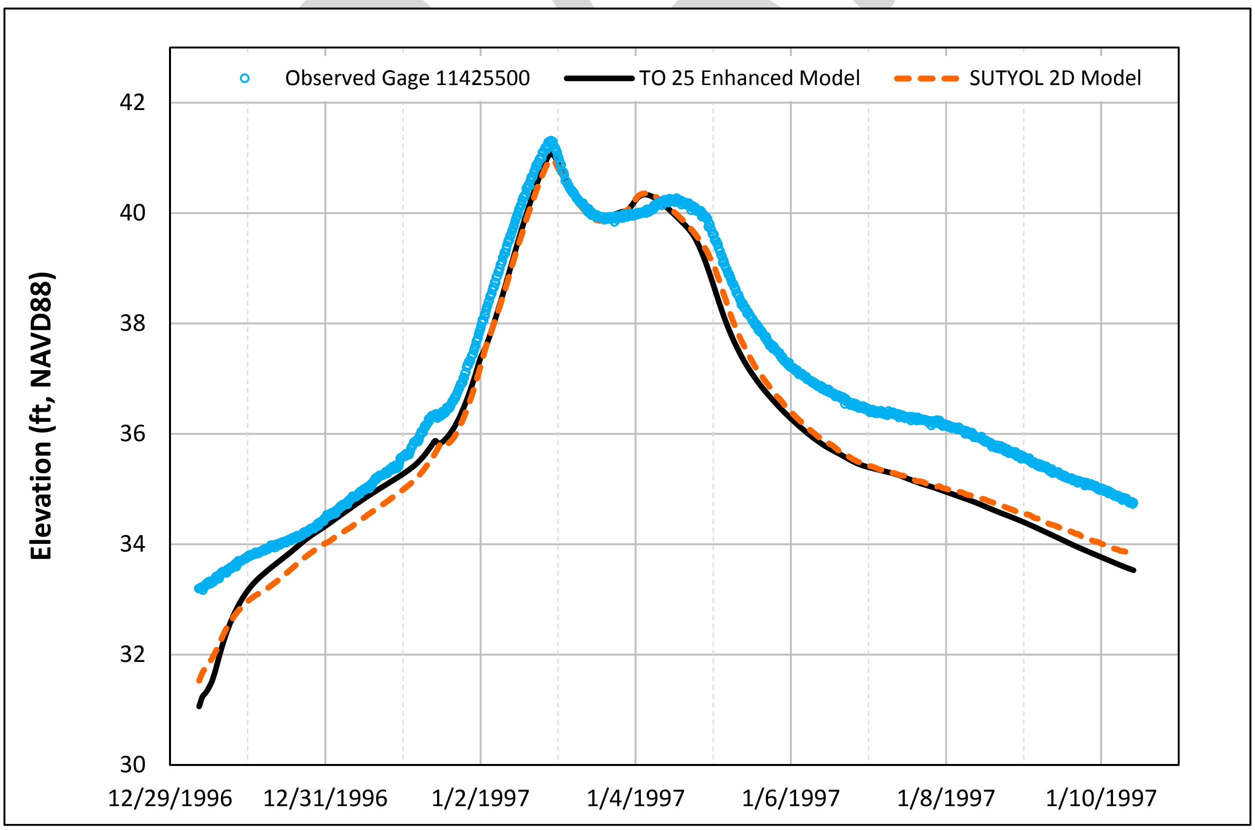


Figure 23. Sacramento River at Verona Stage Hydrograph for 1997 Calibration

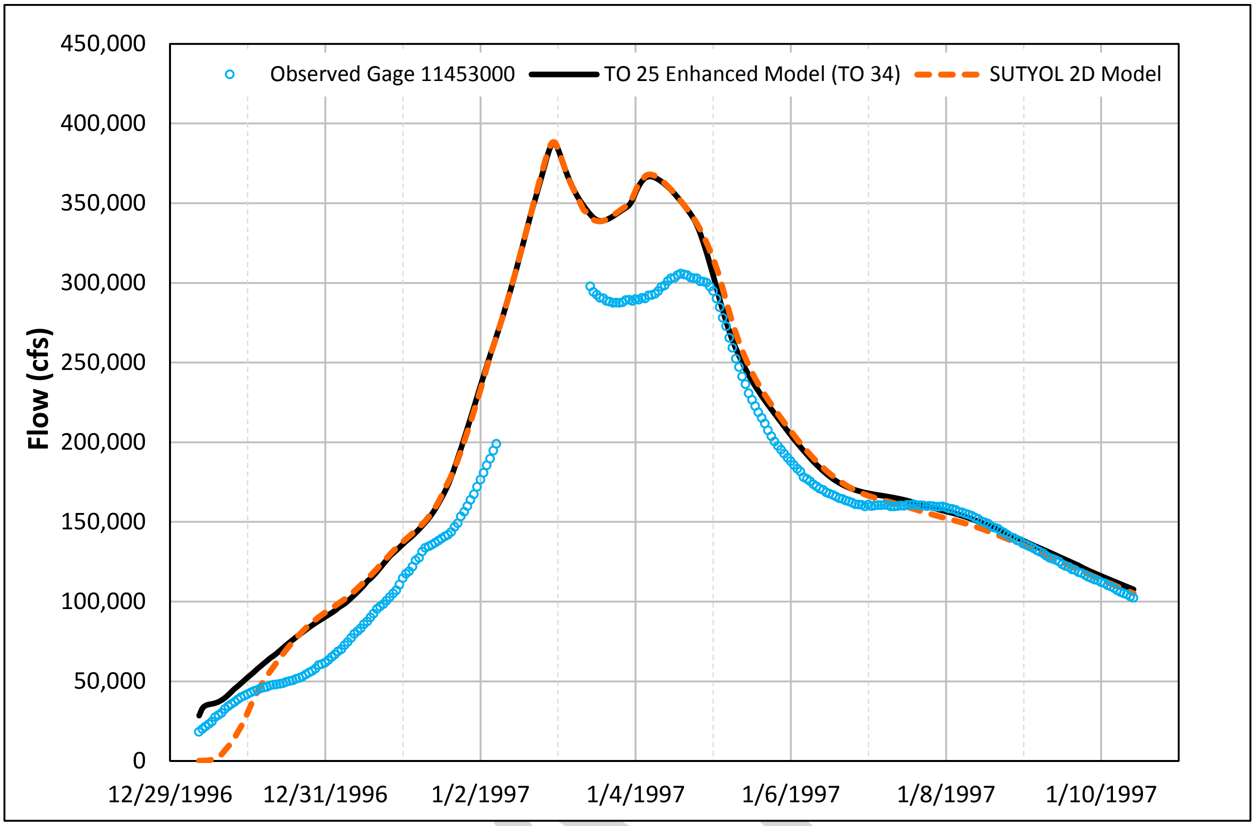


Figure 24. Yolo Bypass at Woodland Flow Hydrograph for 1997 Calibration

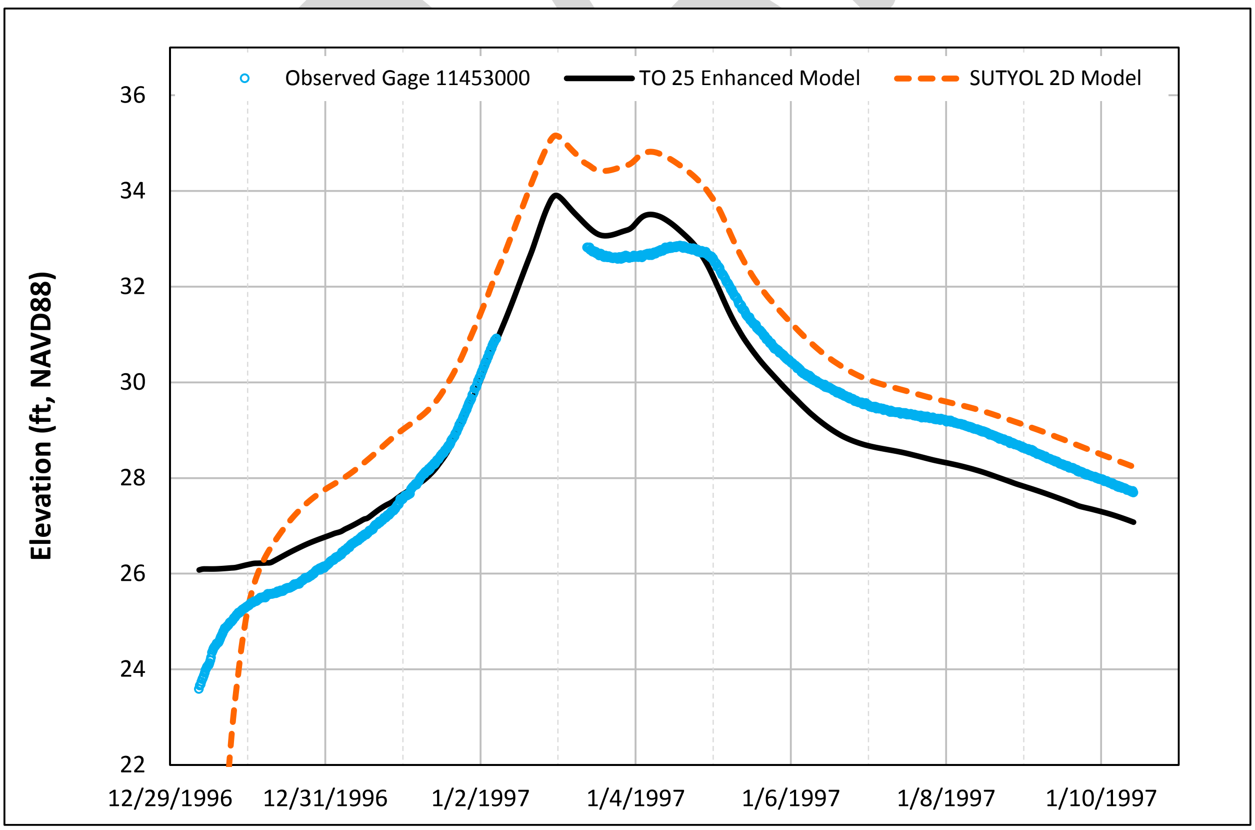


Figure 25. Yolo Bypass at Woodland Stage Hydrograph for 1997 Calibration

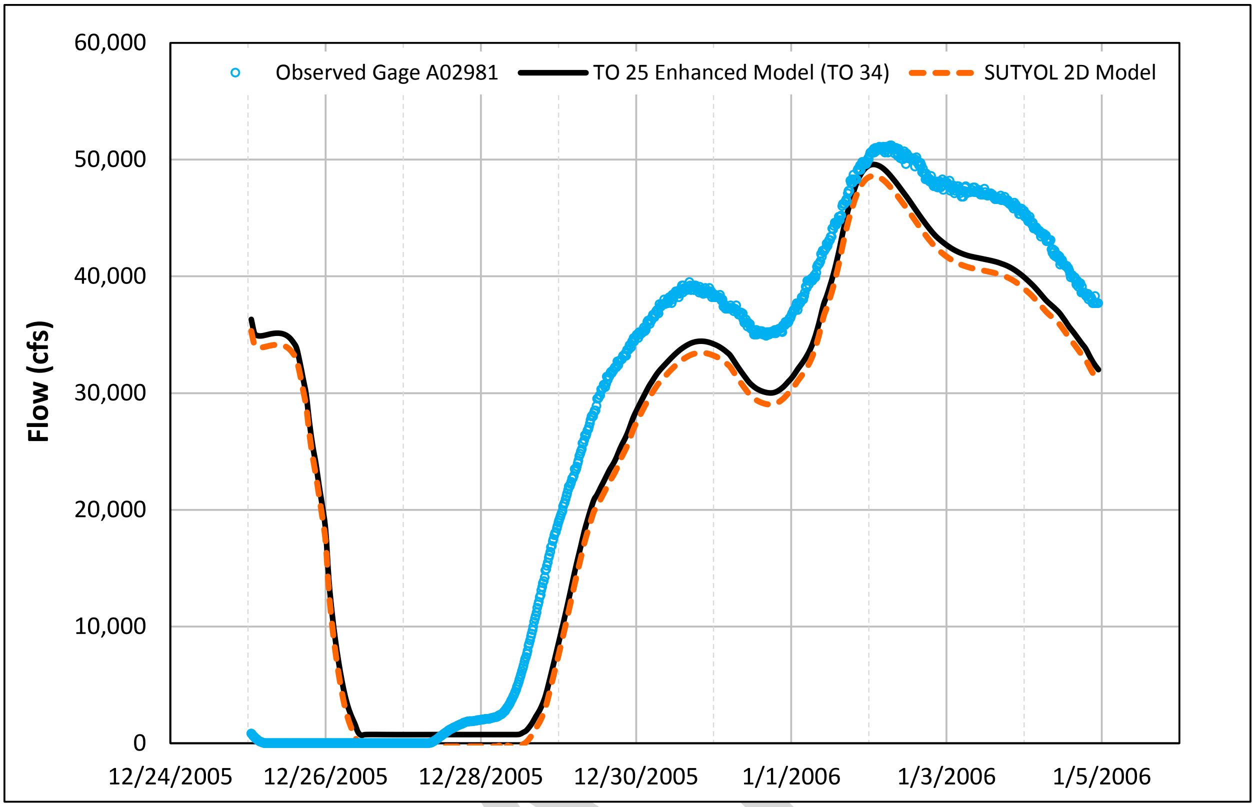


Figure 26. Sutter Bypass at Colusa Weir Flow Hydrograph for 2006 Validation

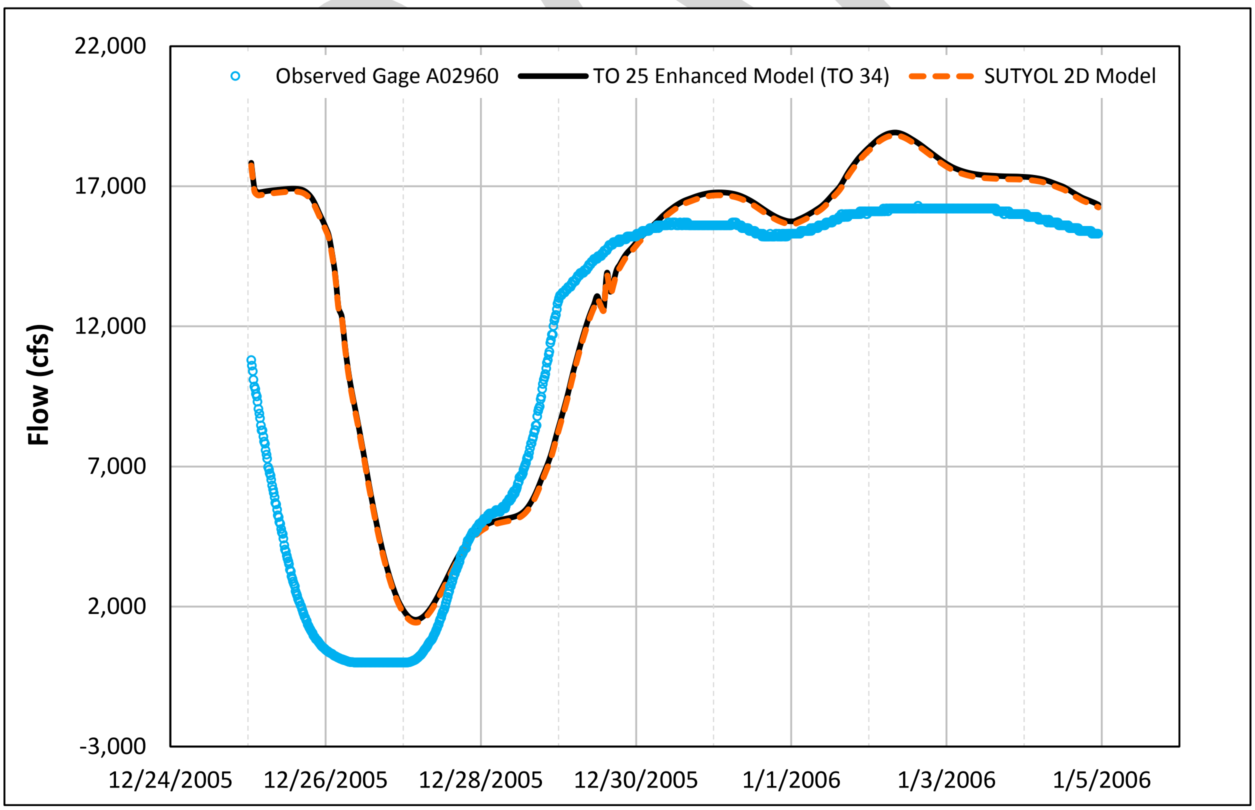


Figure 27. Tisdale Bypass at Tisdale Weir Flow Hydrograph for 2006 Validation

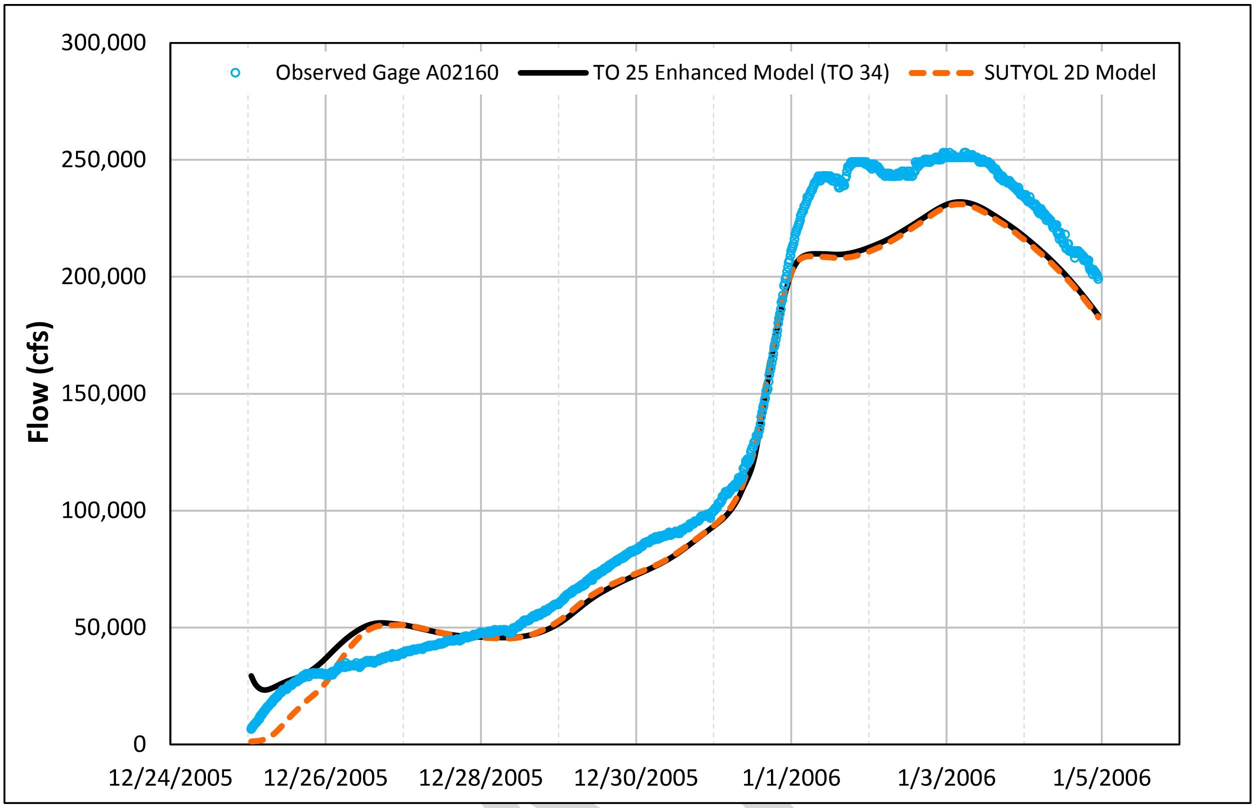


Figure 28. Yolo Bypass at Fremont Weir Flow Hydrograph for 2006 Validation

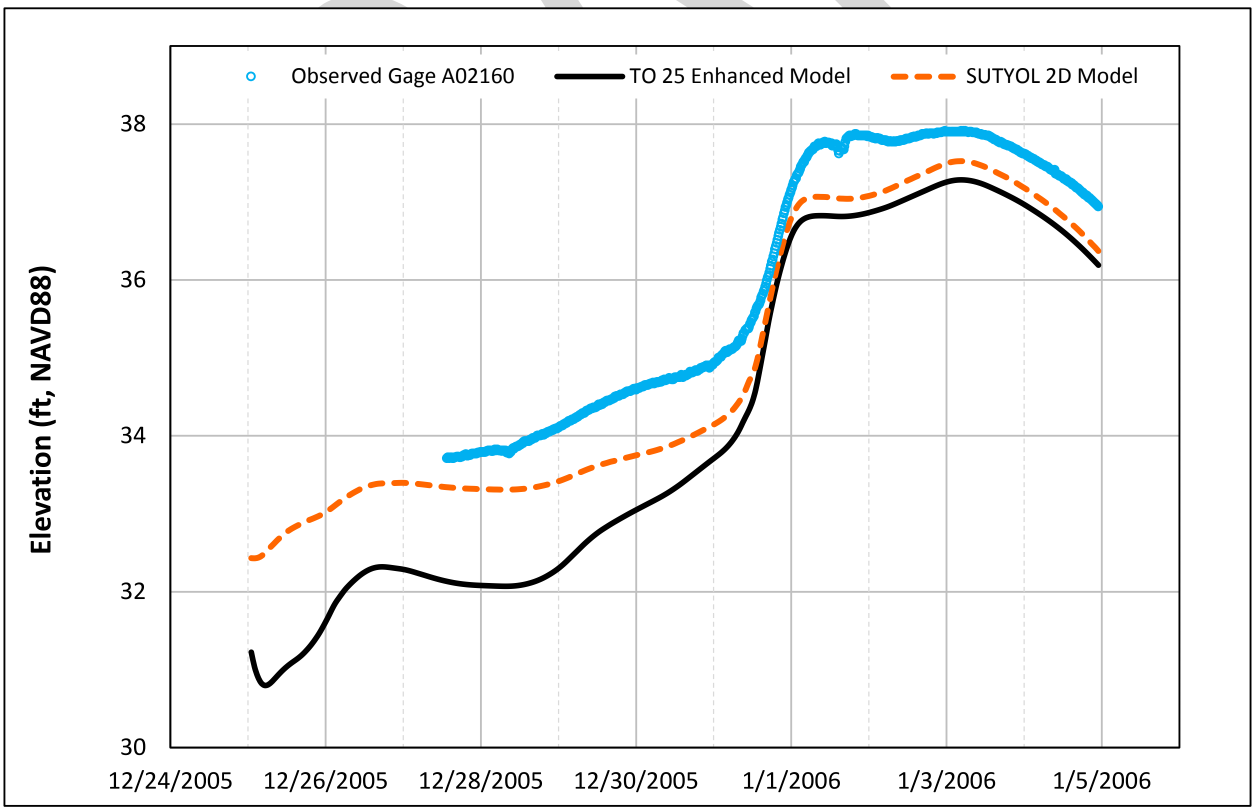


Figure 29. Yolo Bypass at Fremont Weir Stage Hydrograph for 2006 Validation

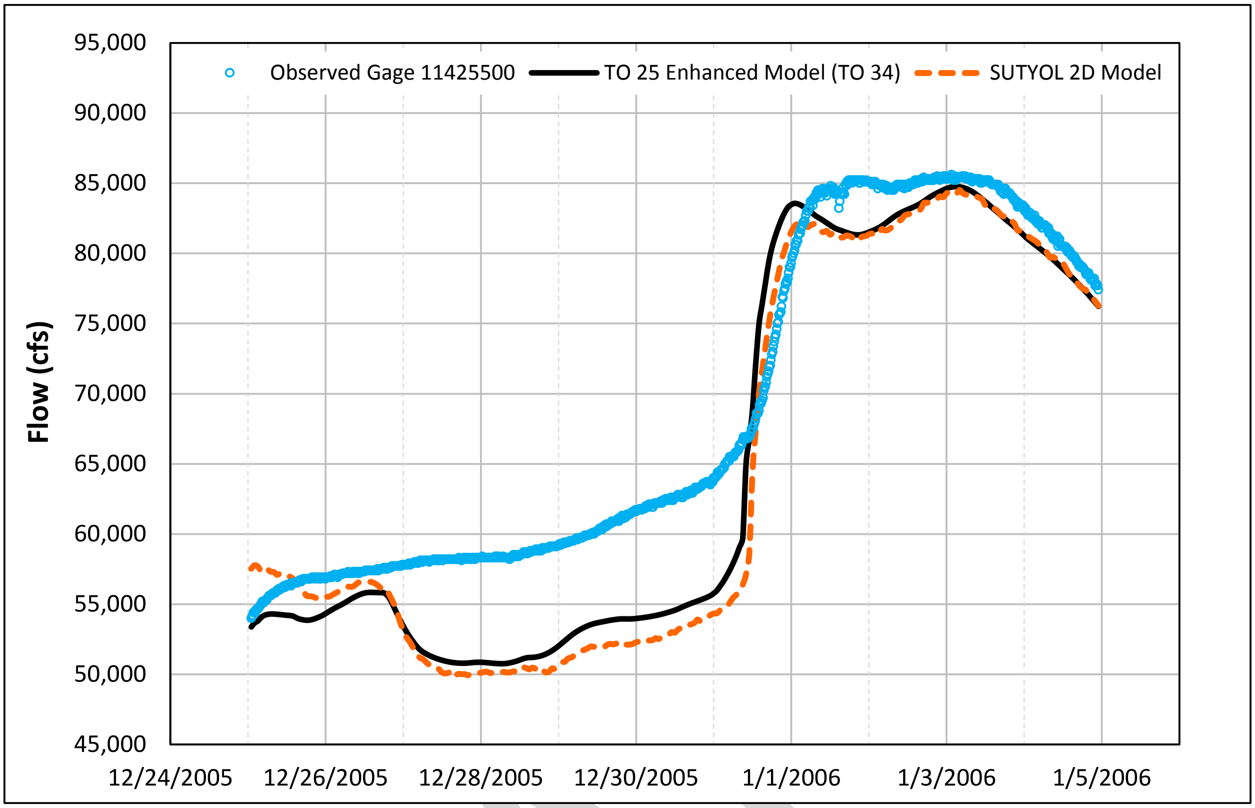


Figure 30. Sacramento River at Verona Flow Hydrograph for 2006 Validation

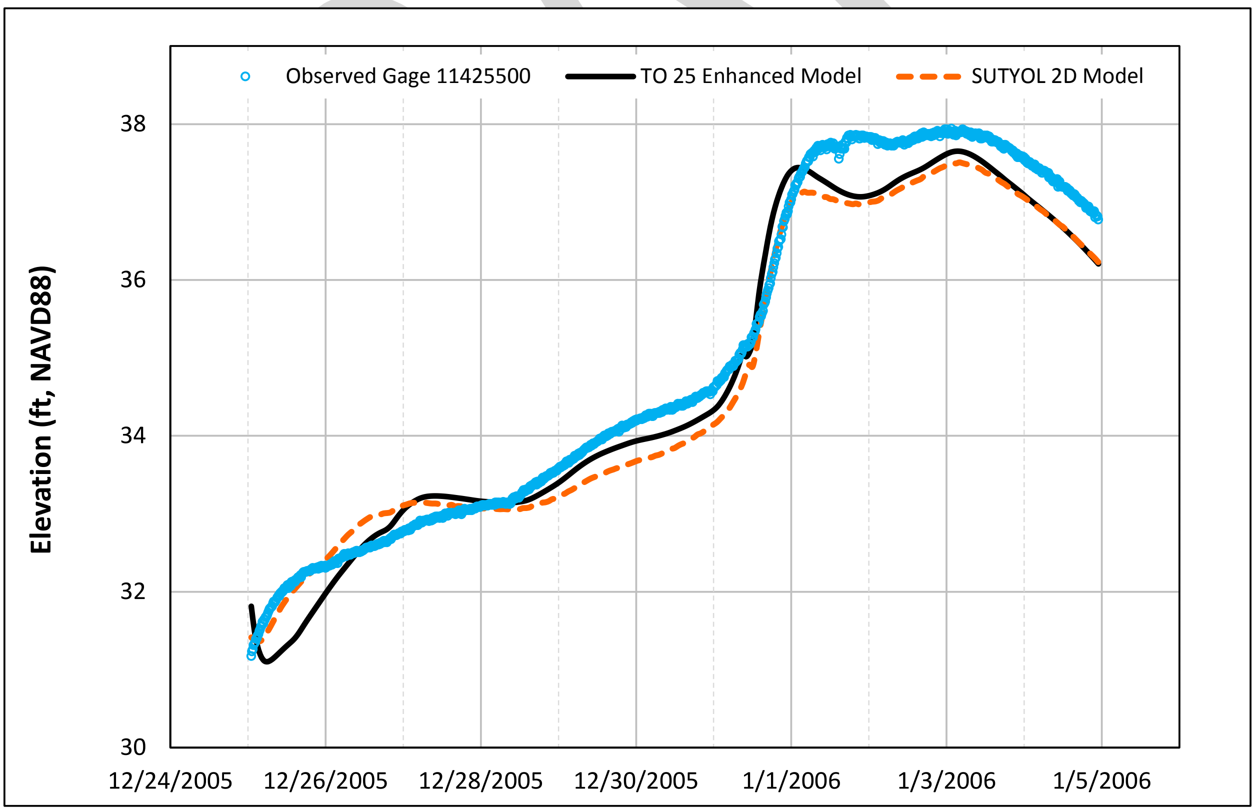


Figure 31. Sacramento River at Verona Stage Hydrograph for 2006 Validation

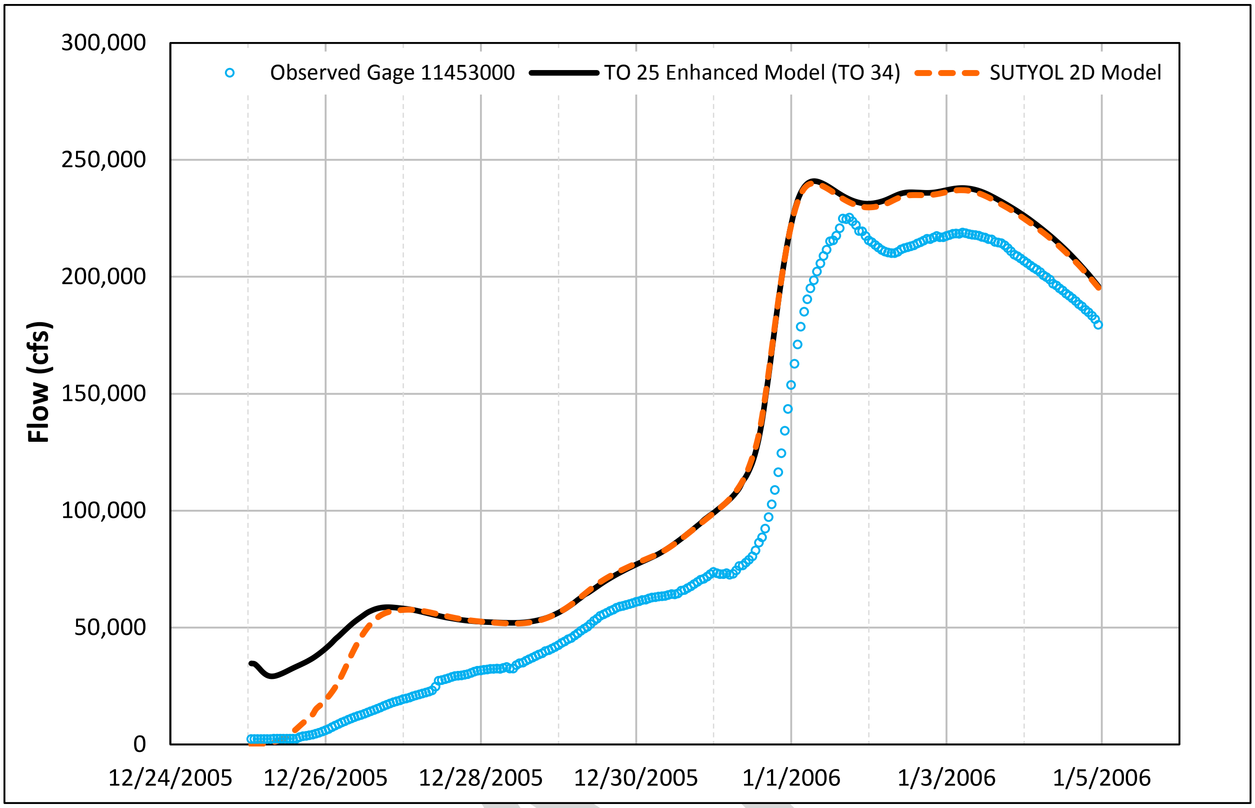


Figure 32. Yolo Bypass at Woodland Flow Hydrograph for 2006 Validation

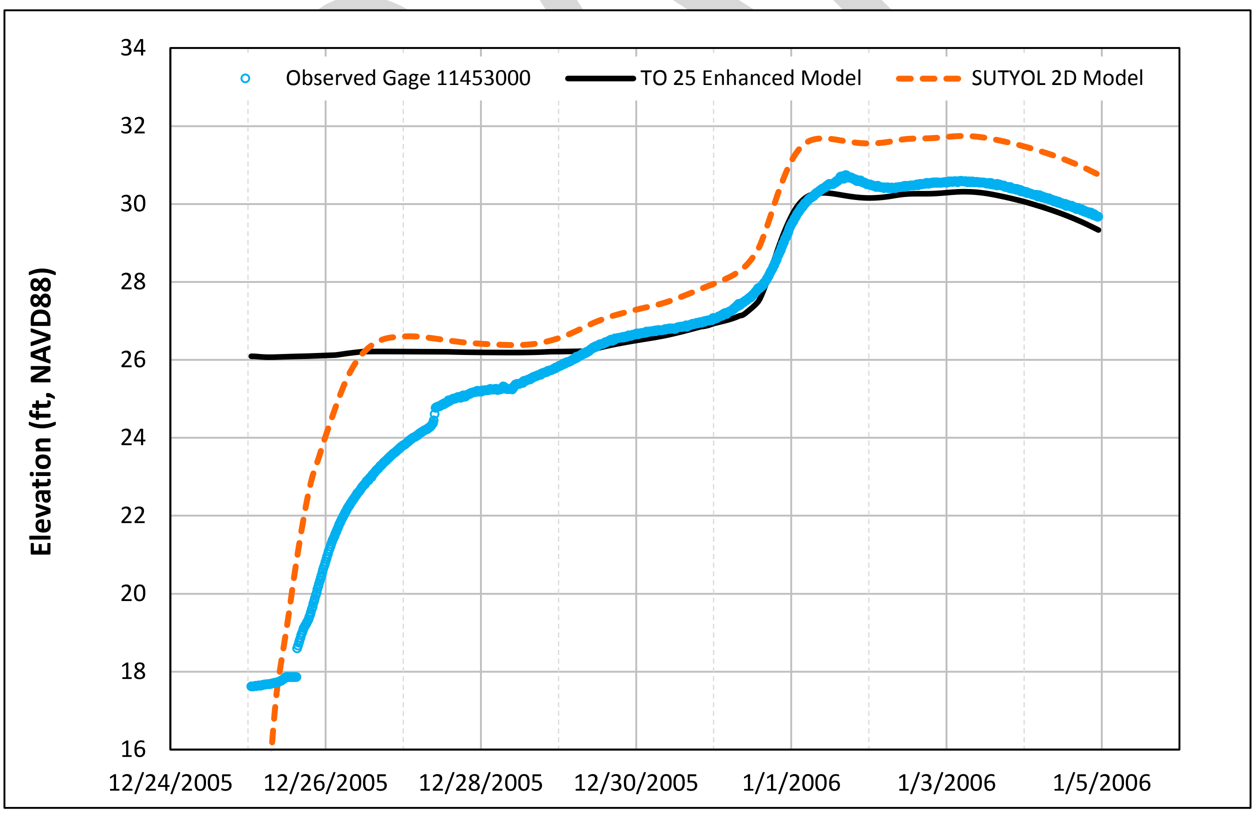


Figure 33. Yolo Bypass at Woodland Stage Hydrograph for 2006 Validation

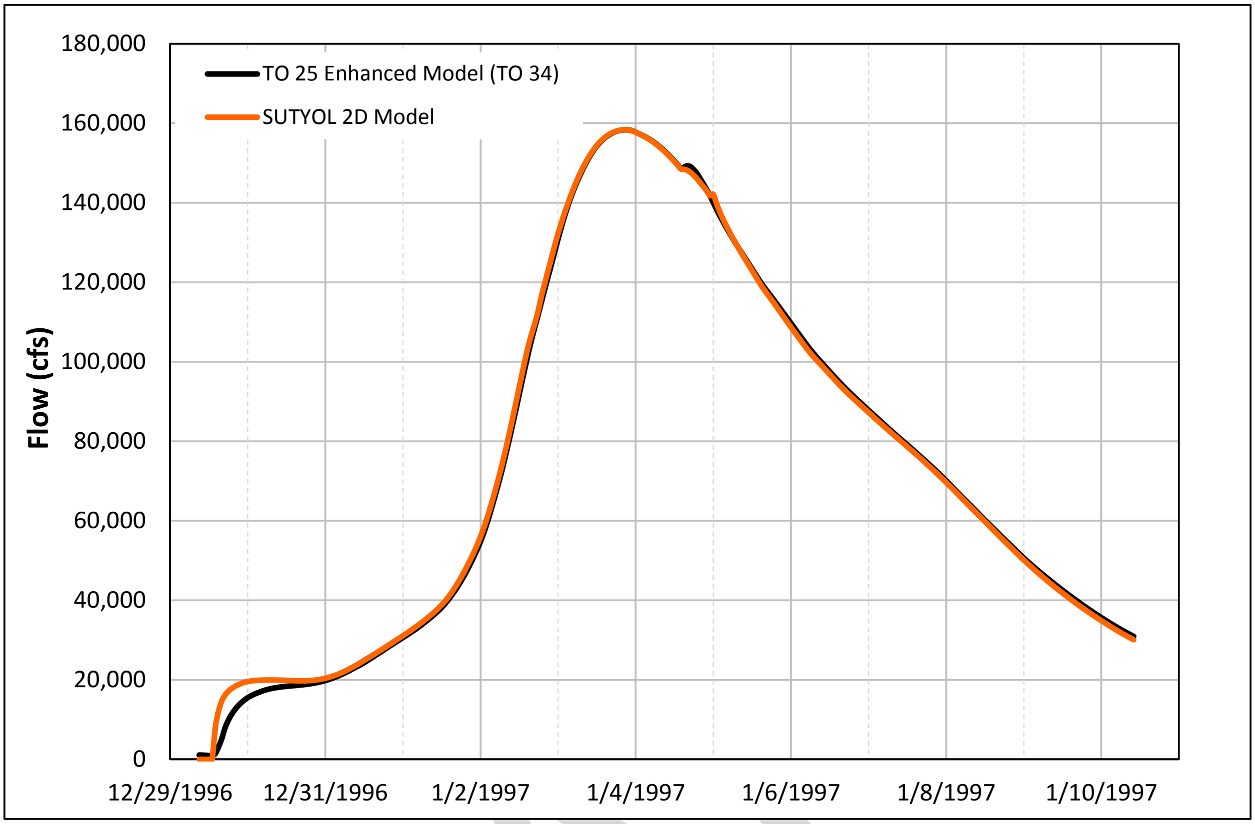


Figure 34. Sutter Bypass at Long Bridge Flow Hydrograph for 1997 Calibration

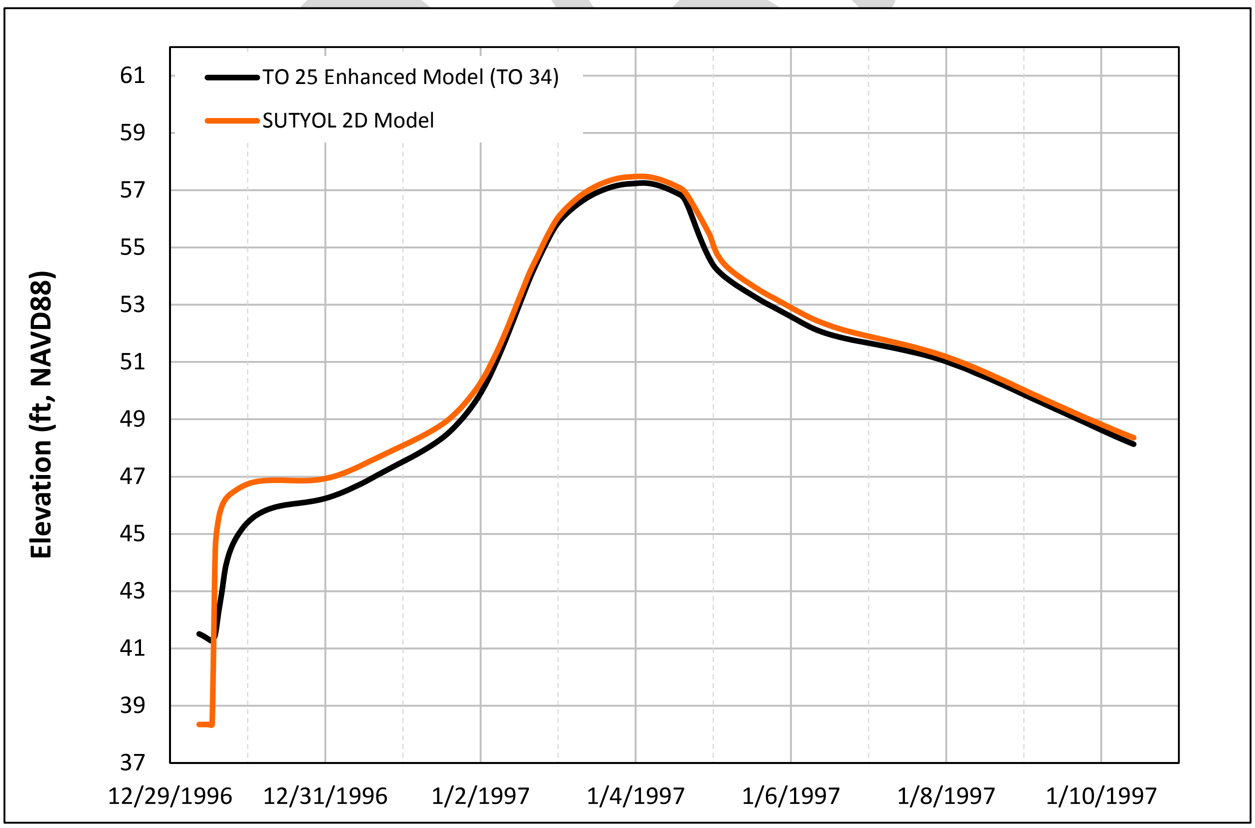


Figure 35. Sutter Bypass at Long Bridge Stage Hydrograph for 1997 Calibration

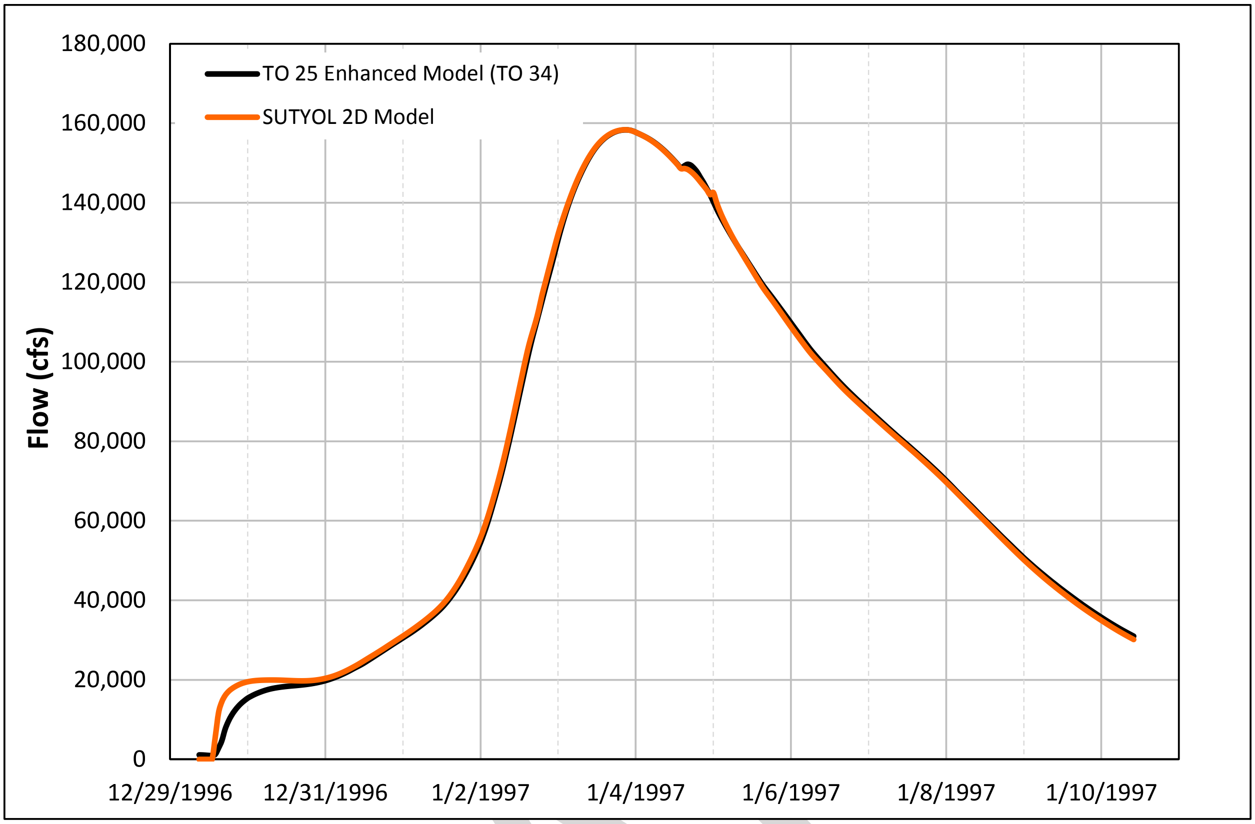


Figure 36. Sutter Bypass at Highway 20 Bridge Flow Hydrograph for 1997 Calibration

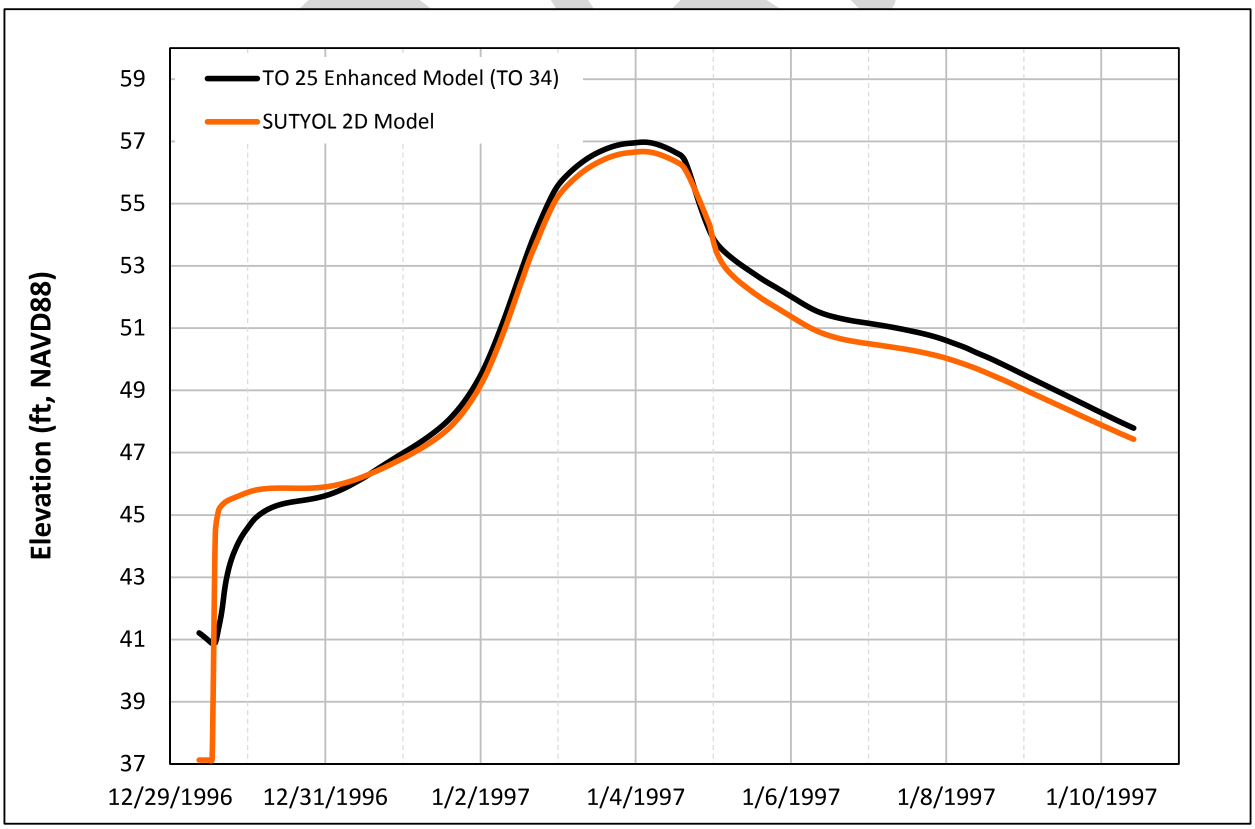


Figure 37. Sutter Bypass at Highway 20 Bridge Stage Hydrograph for 1997 Calibration

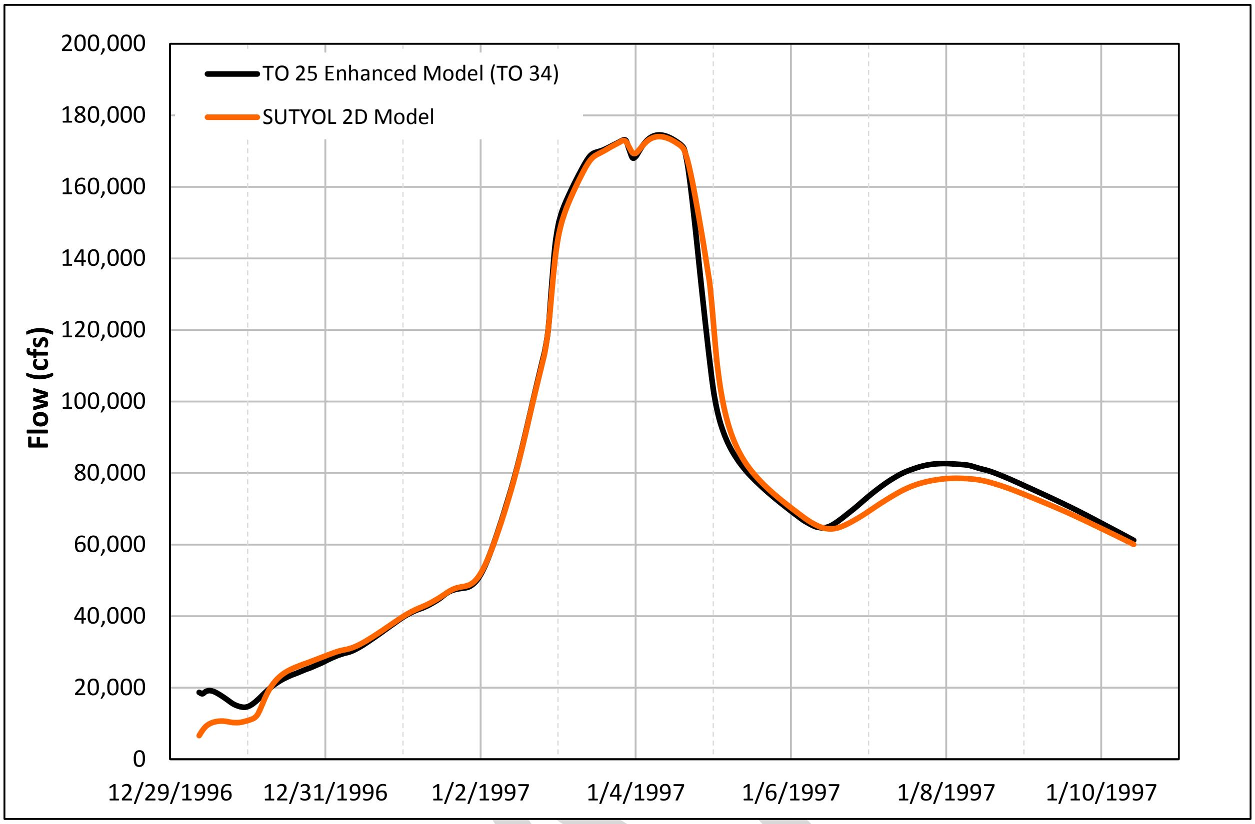


Figure 38. Sutter Bypass at Highway 113 Bridge Flow Hydrograph for 1997 Calibration

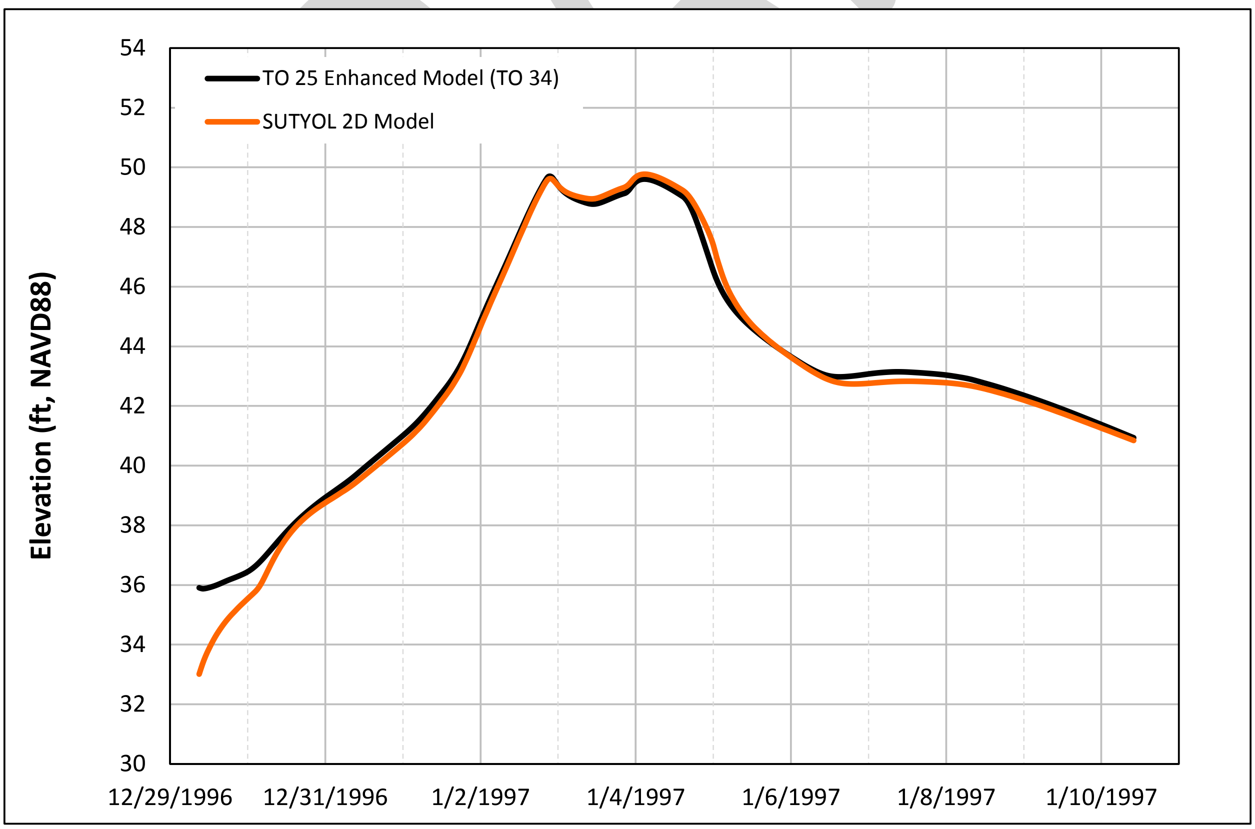


Figure 39. Sutter Bypass at Highway 113 Bridge Stage Hydrograph for 1997 Calibration

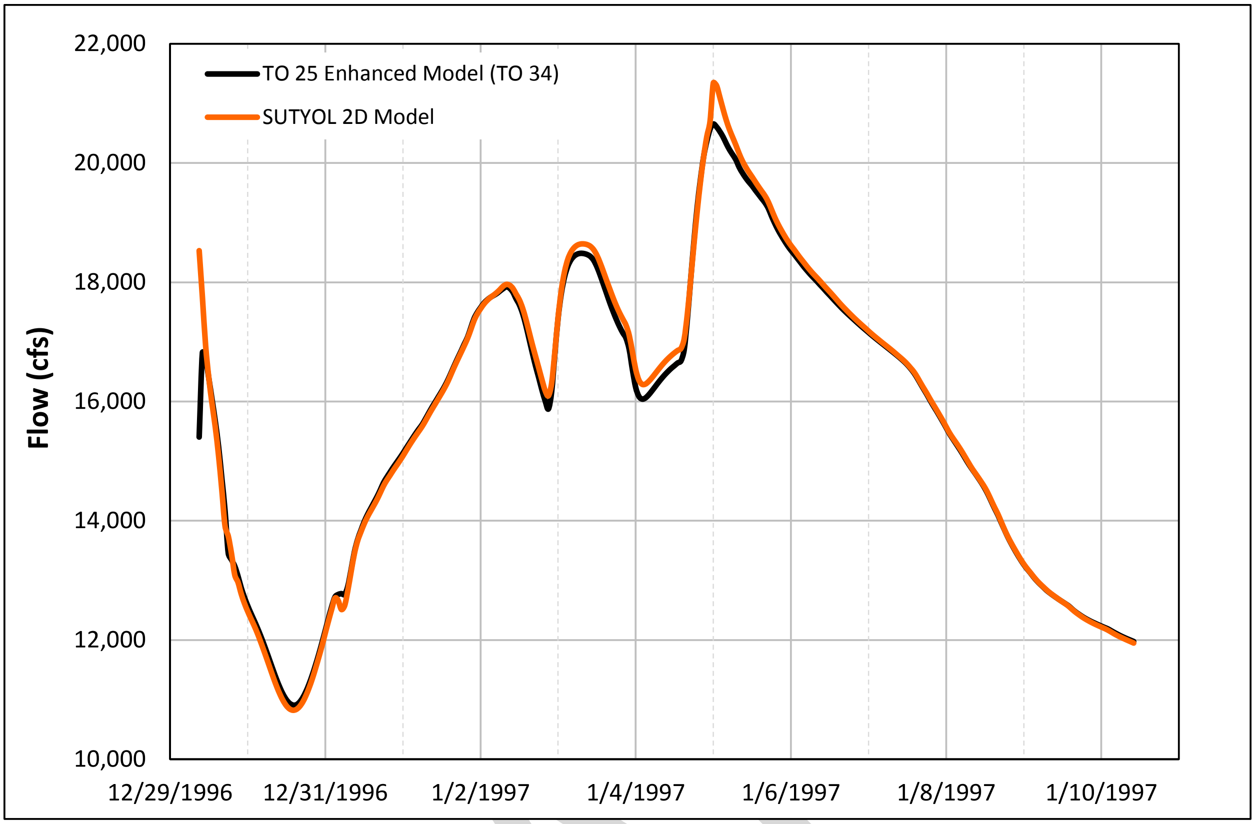


Figure 40. Tisdale Bypass at Reclamation Road Bridge Flow Hydrograph for 1997 Calibration

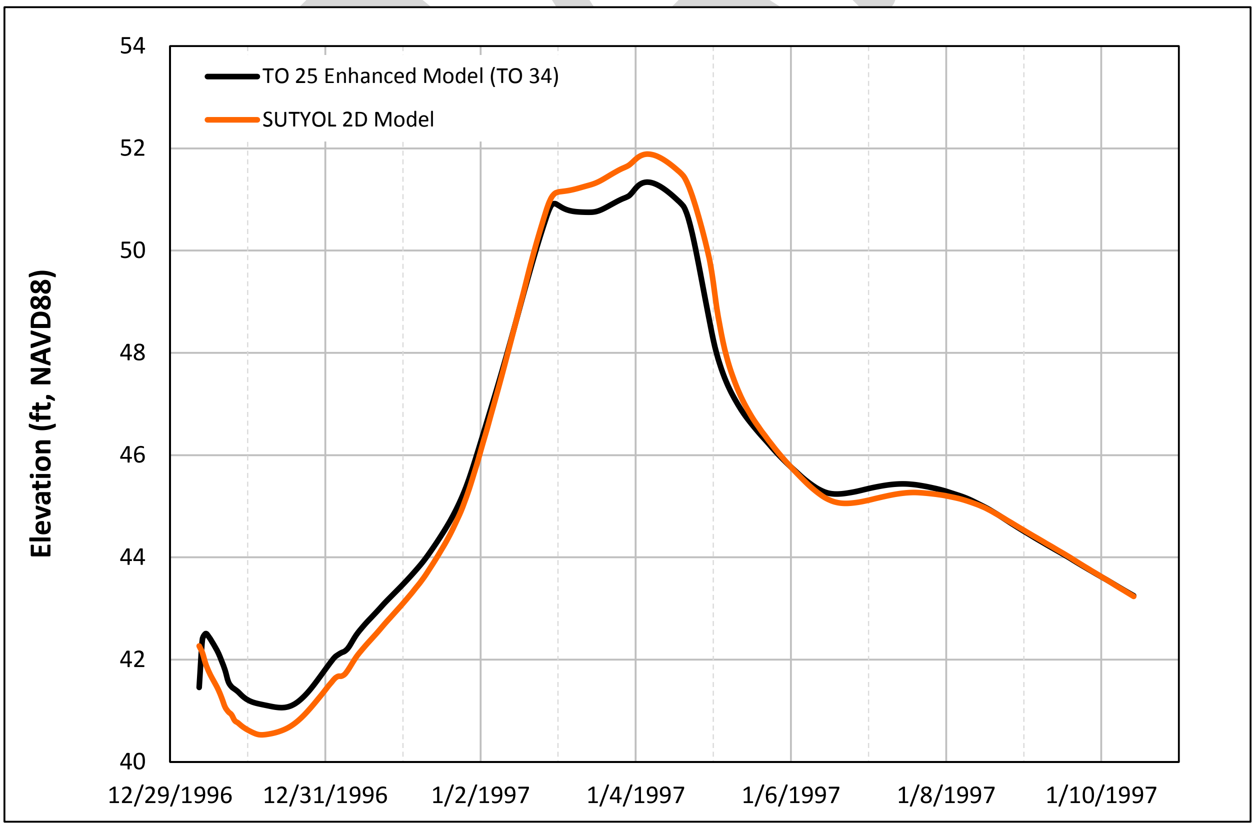


Figure 41. Tisdale Bypass at Reclamation Road Bridge Stage Hydrograph for 1997 Calibration

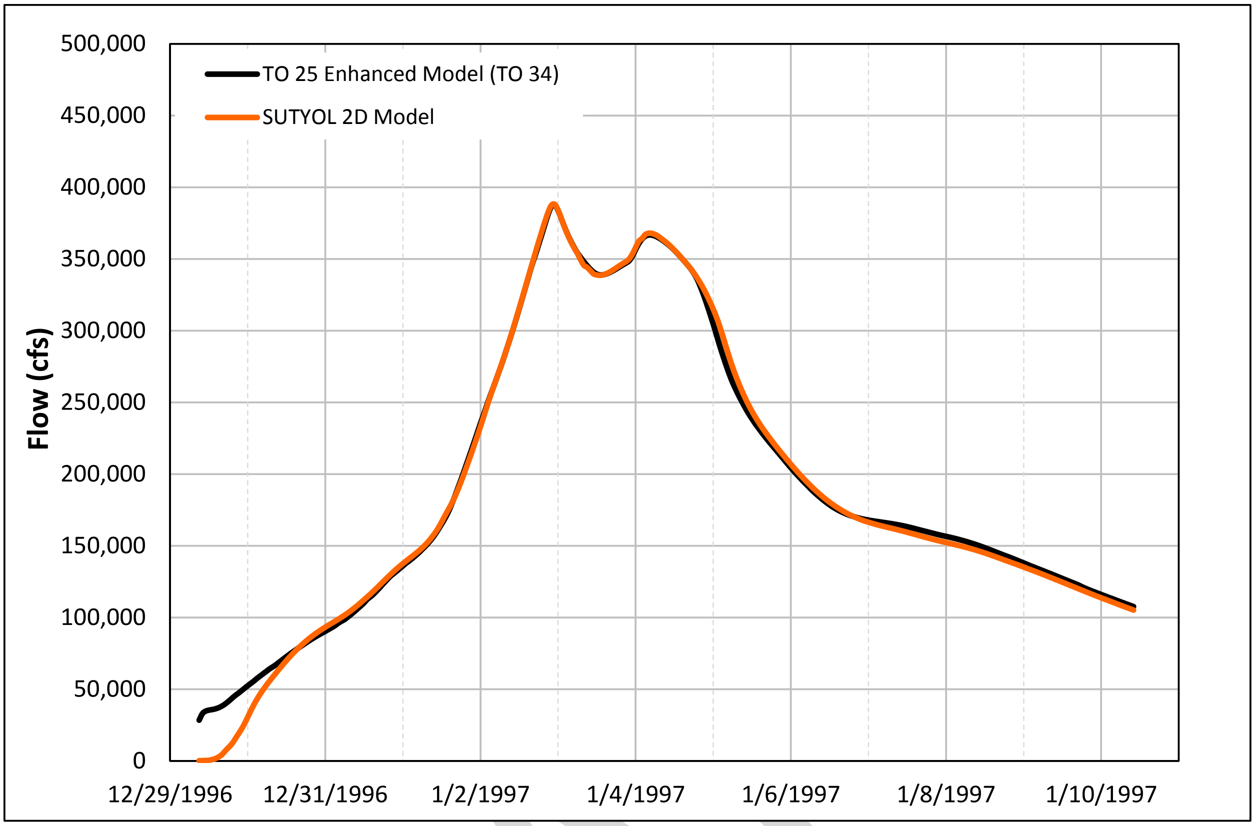


Figure 42. Yolo Bypass at I5 Road Bridge Flow Hydrograph for 1997 Calibration

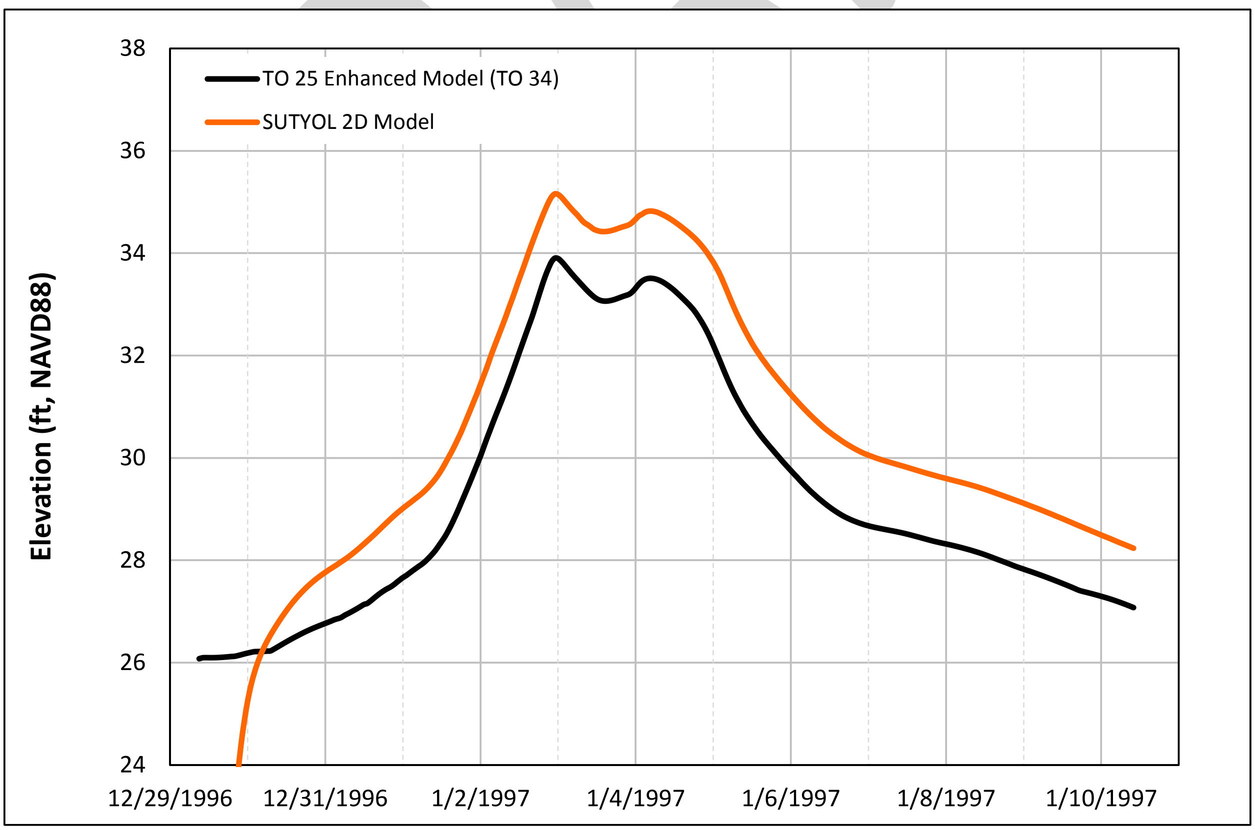


Figure 43. Yolo Bypass at I5 Road Bridge Stage Hydrograph for 1997 Calibration

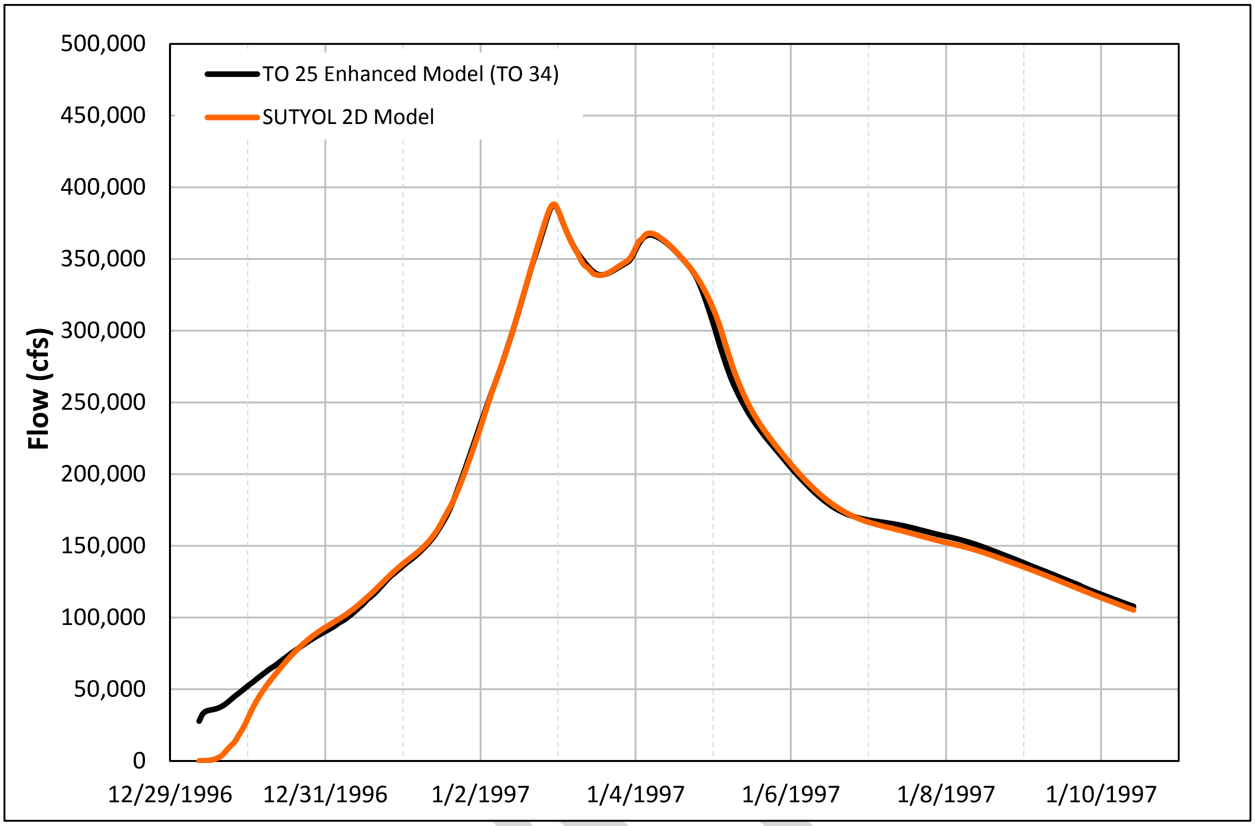


Figure 44. Yolo Bypass at I5 Bridge Flow Hydrograph for 1997 Calibration

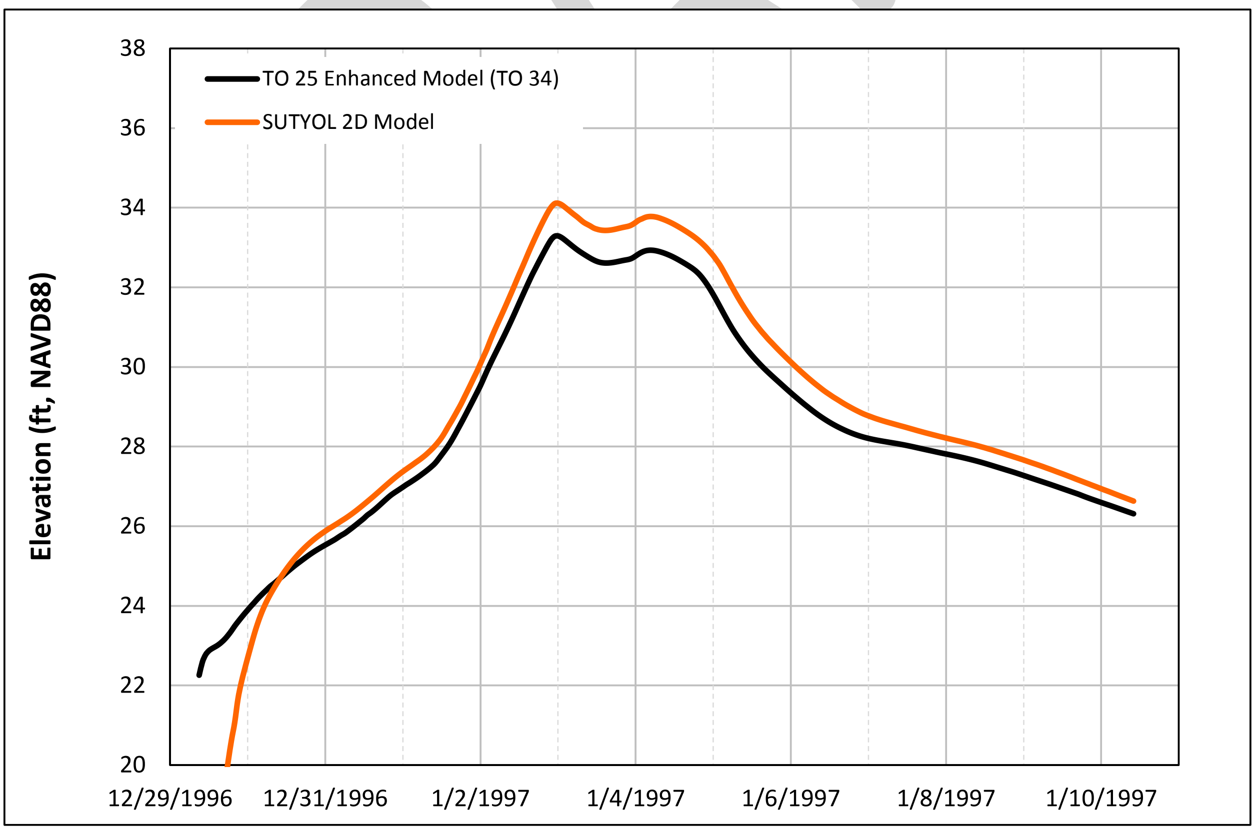


Figure 45. Yolo Bypass at I5 Bridge Stage Hydrograph for 1997 Calibration

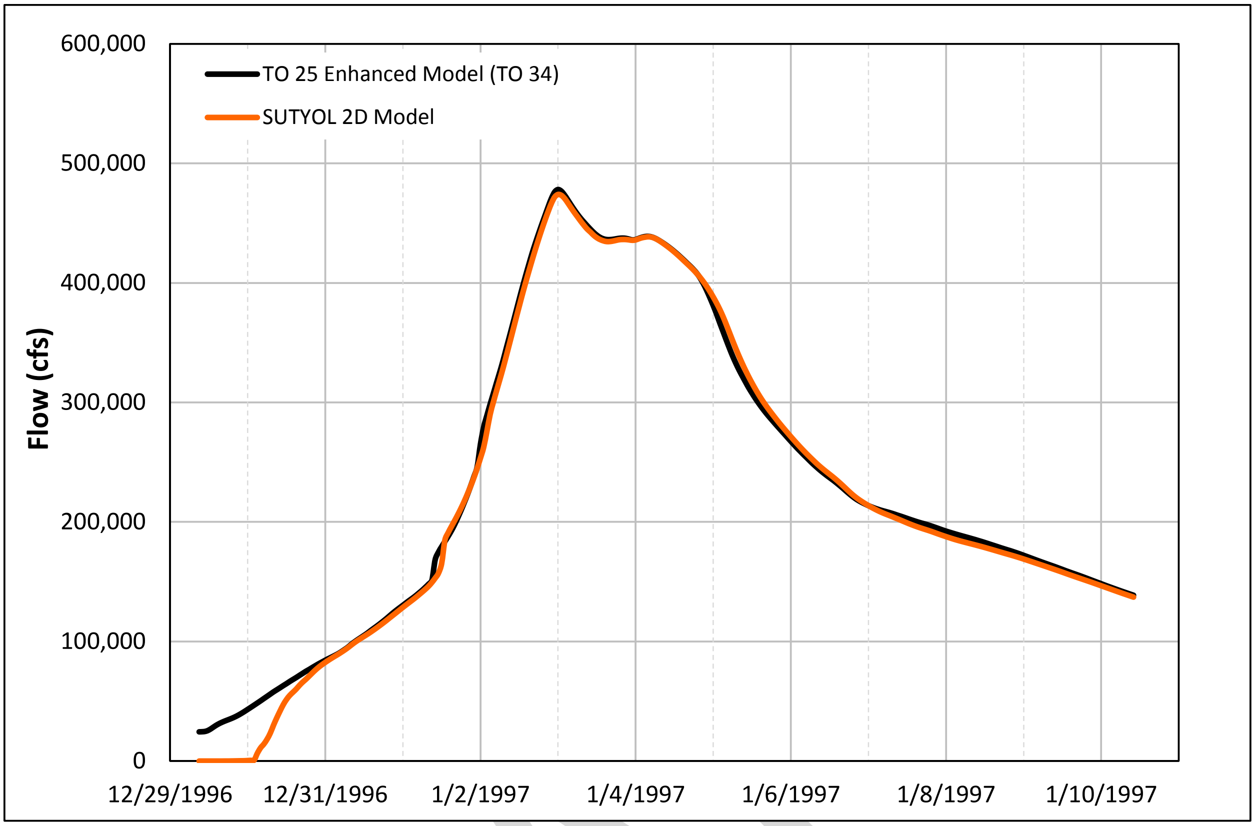


Figure 46. Yolo Bypass at I80 Railroad Bridge Flow Hydrograph for 1997 Calibration

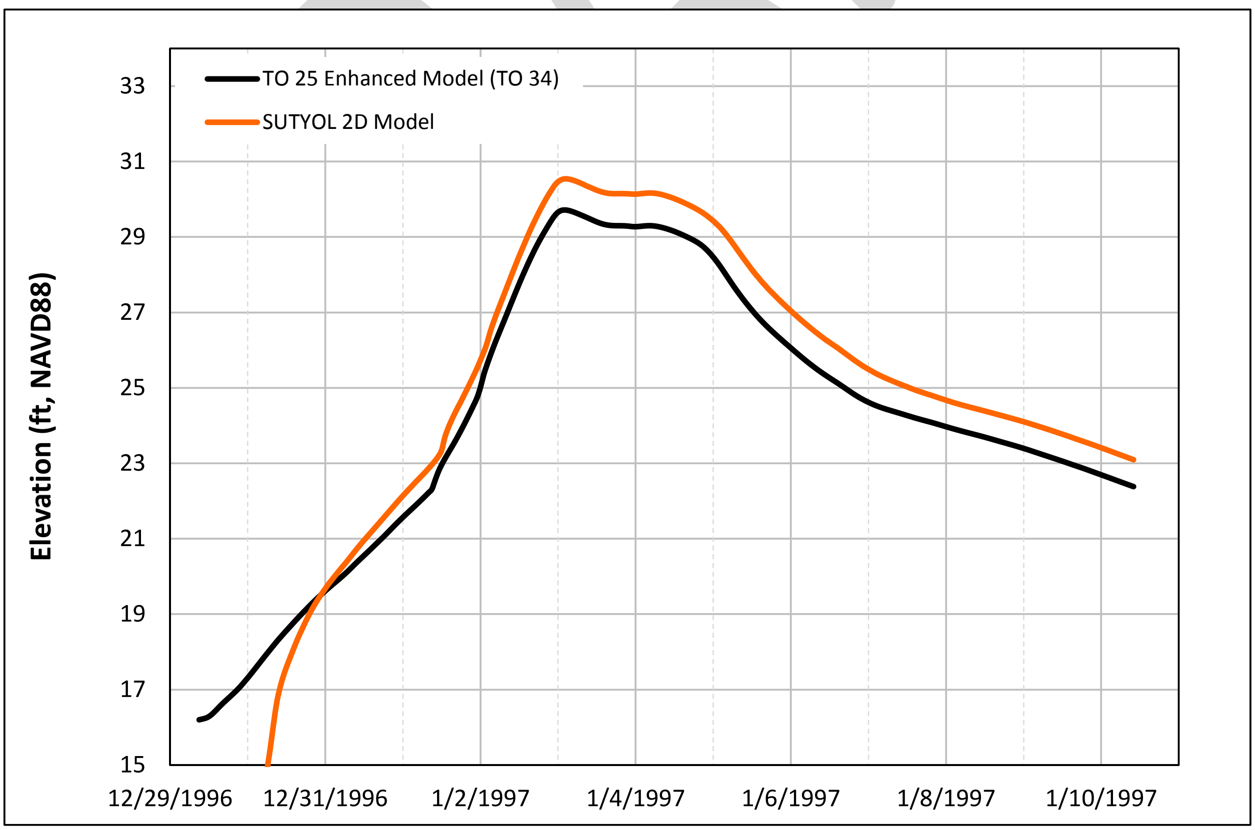


Figure 47. Yolo Bypass at I80 Railroad Bridge Stage Hydrograph for 1997 Calibration

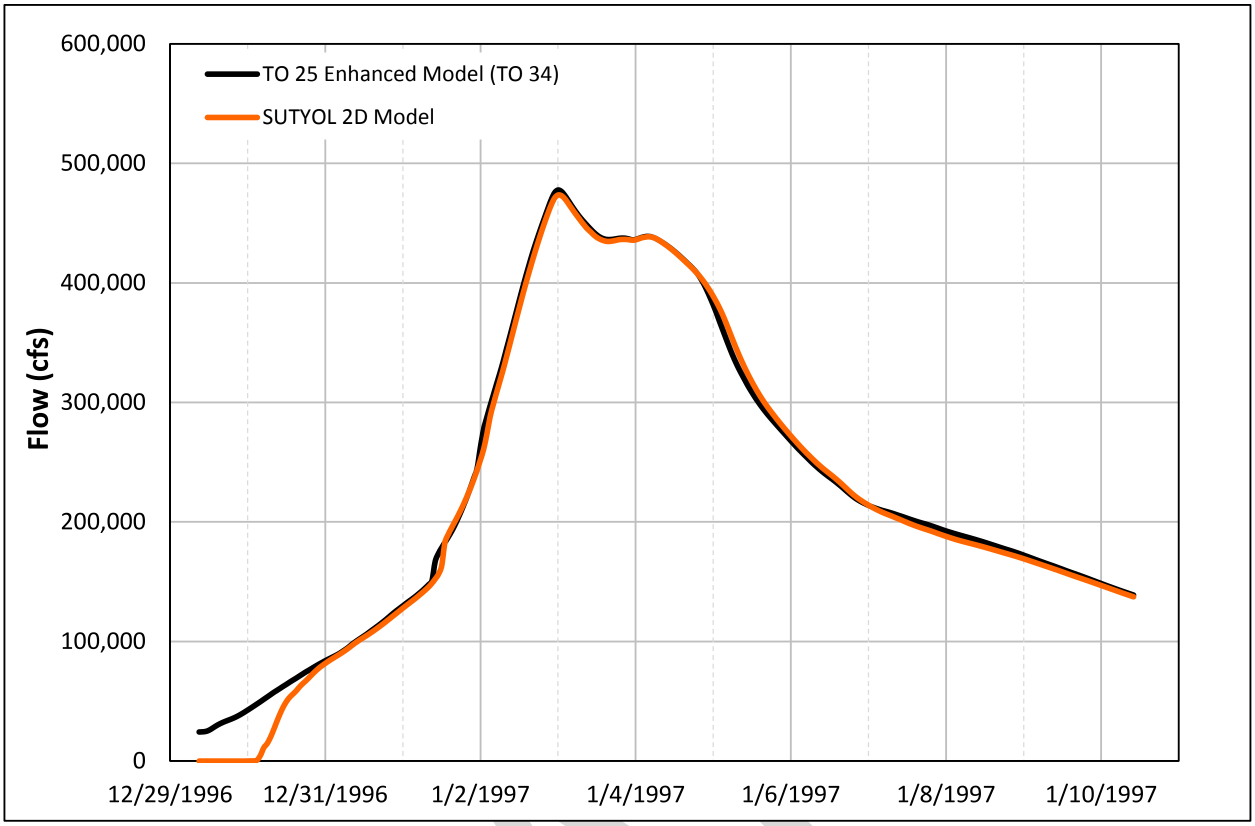


Figure 48. Yolo Bypass at I80 Bridge Flow Hydrograph for 1997 Calibration

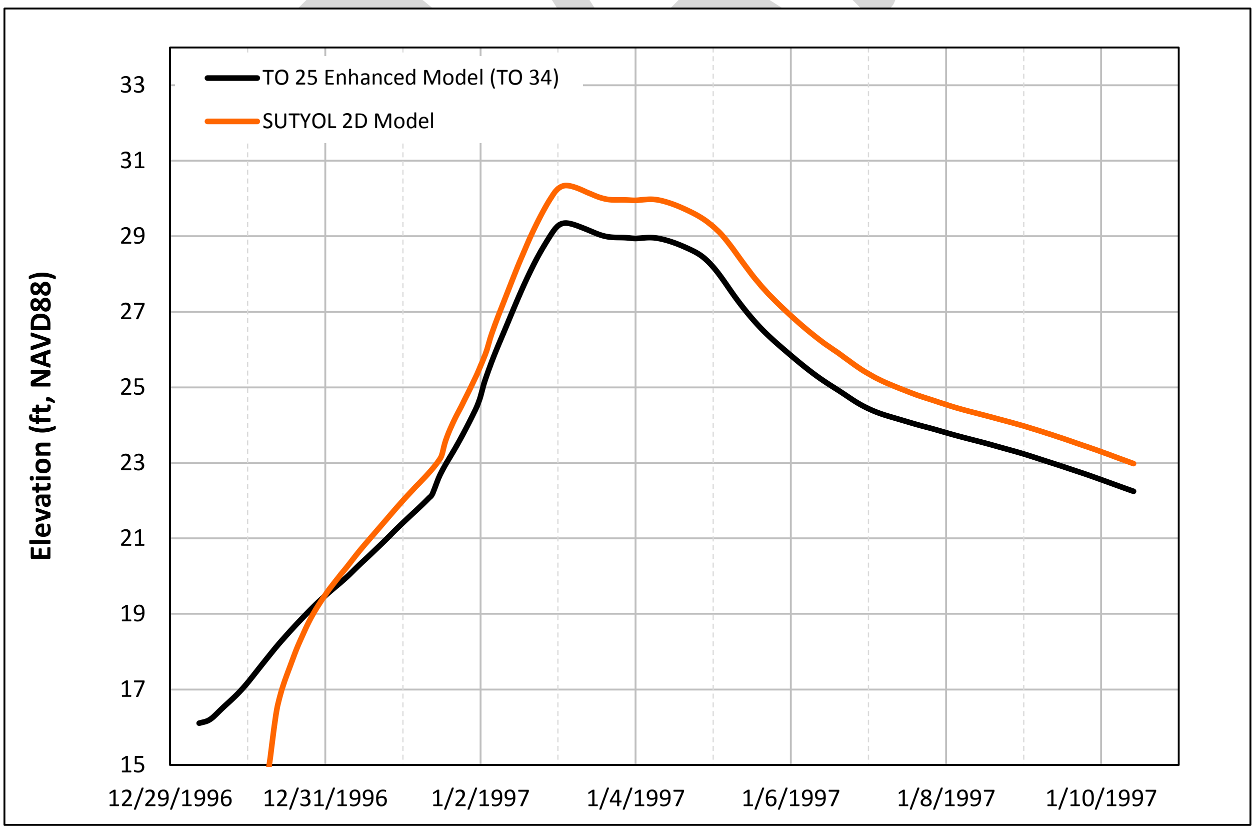


Figure 49. Yolo Bypass at I80 Bridge Stage Hydrograph for 1997 Calibration

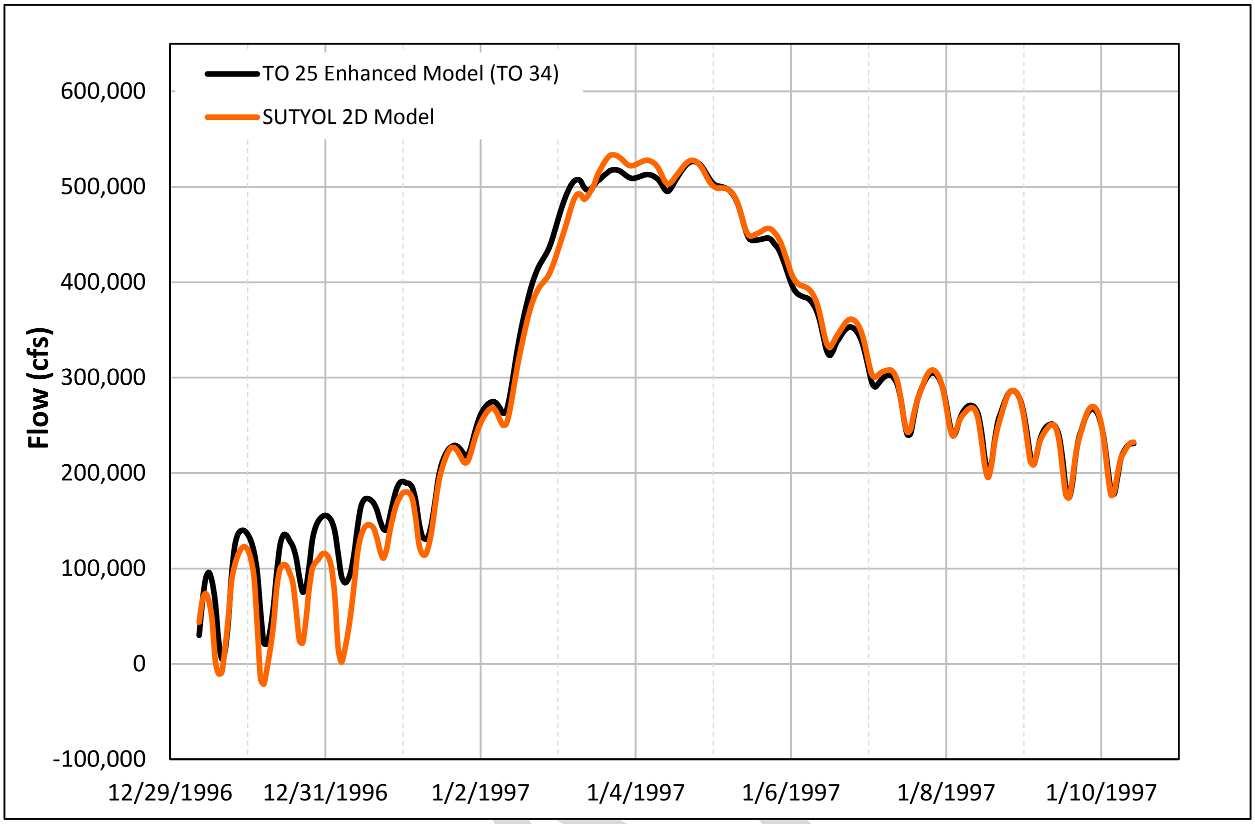


Figure 50. Sacramento River at Highway 12 Bridge Flow Hydrograph for 1997 Calibration

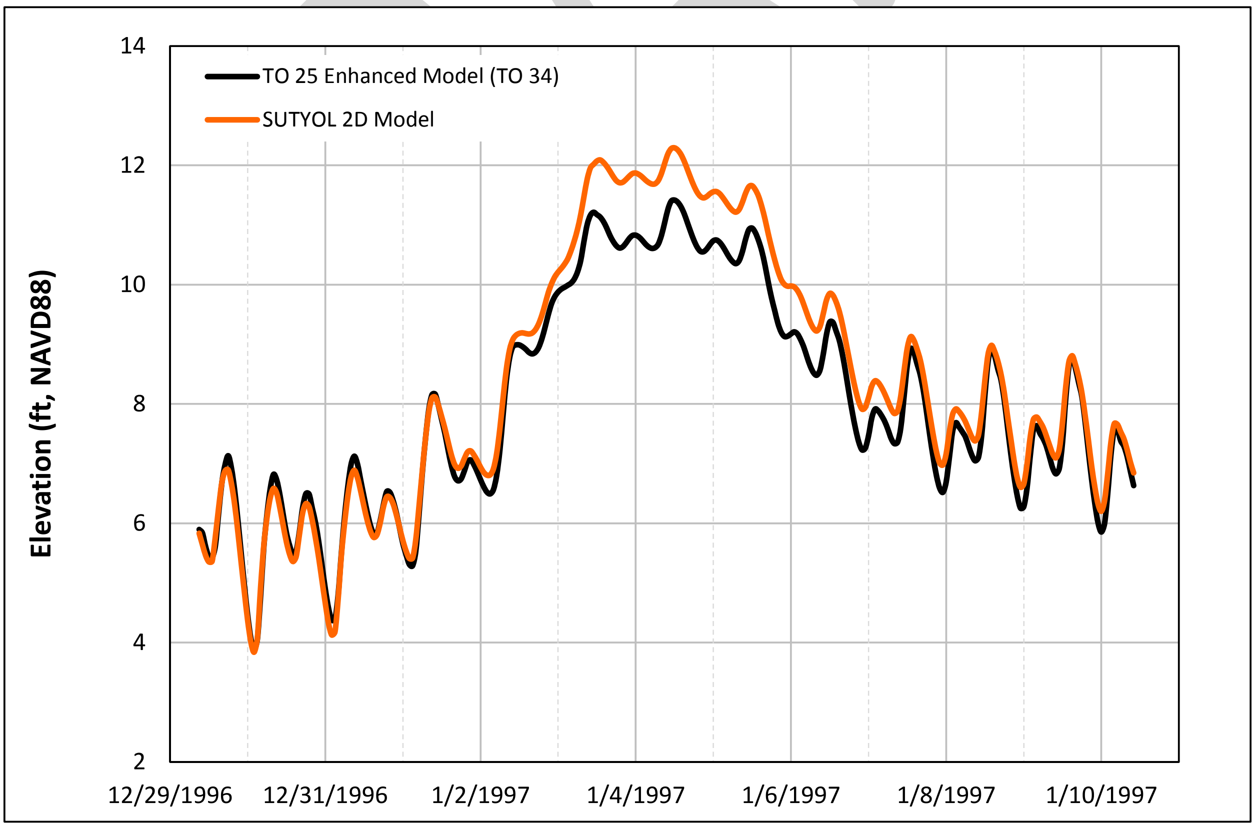


Figure 51. Sacramento River at Highway 12 Bridge Stage Hydrograph for 1997 Calibration

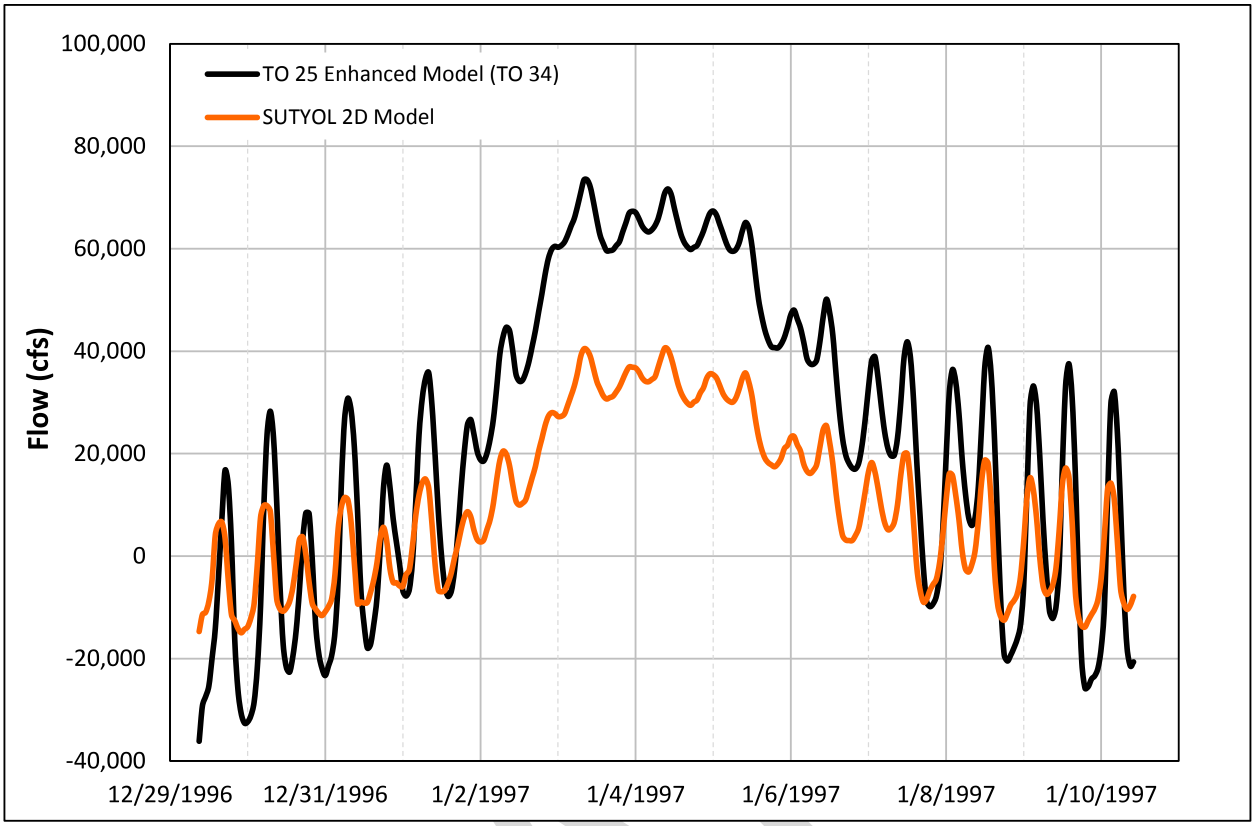


Figure 52. Threemile Slough at Highway 160 Bridge Flow Hydrograph for 1997 Calibration

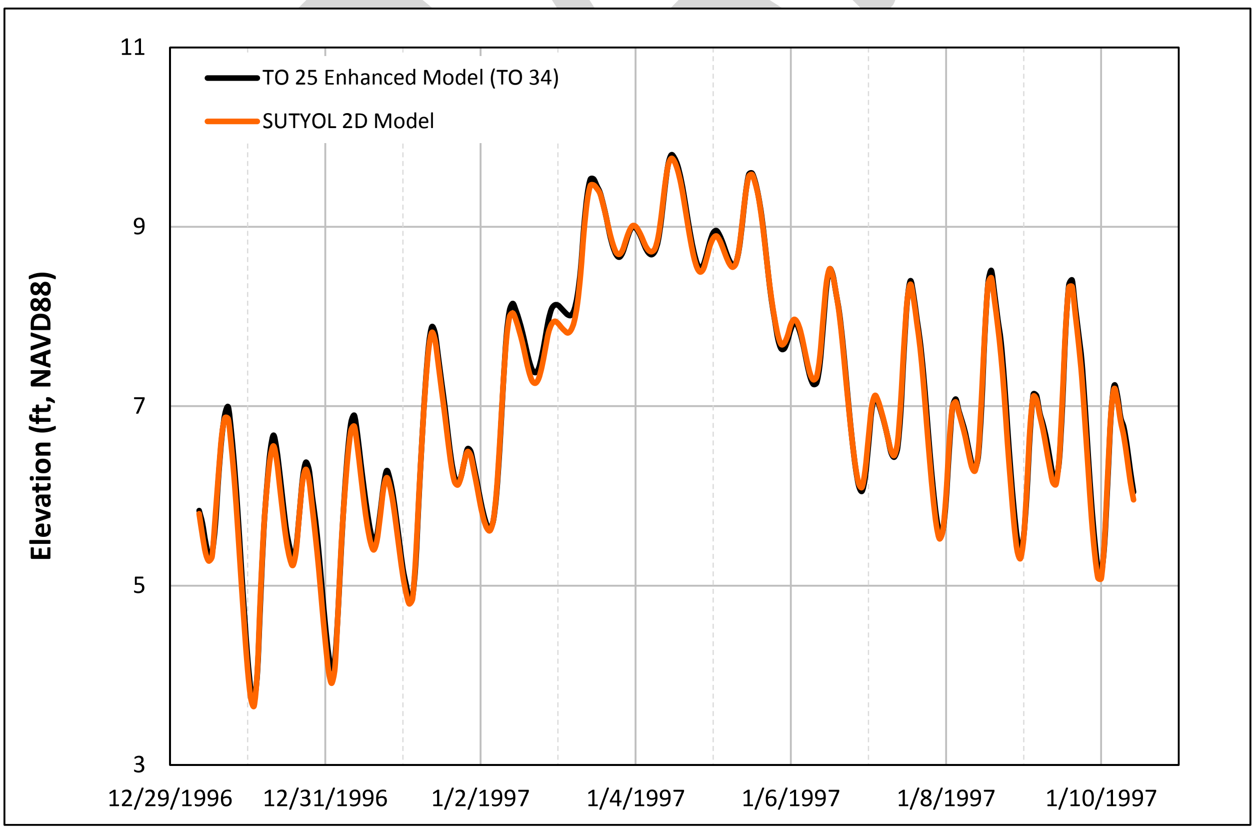


Figure 53. Threemile Slough at Highway 160 Bridge Stage Hydrograph for 1997 Calibration

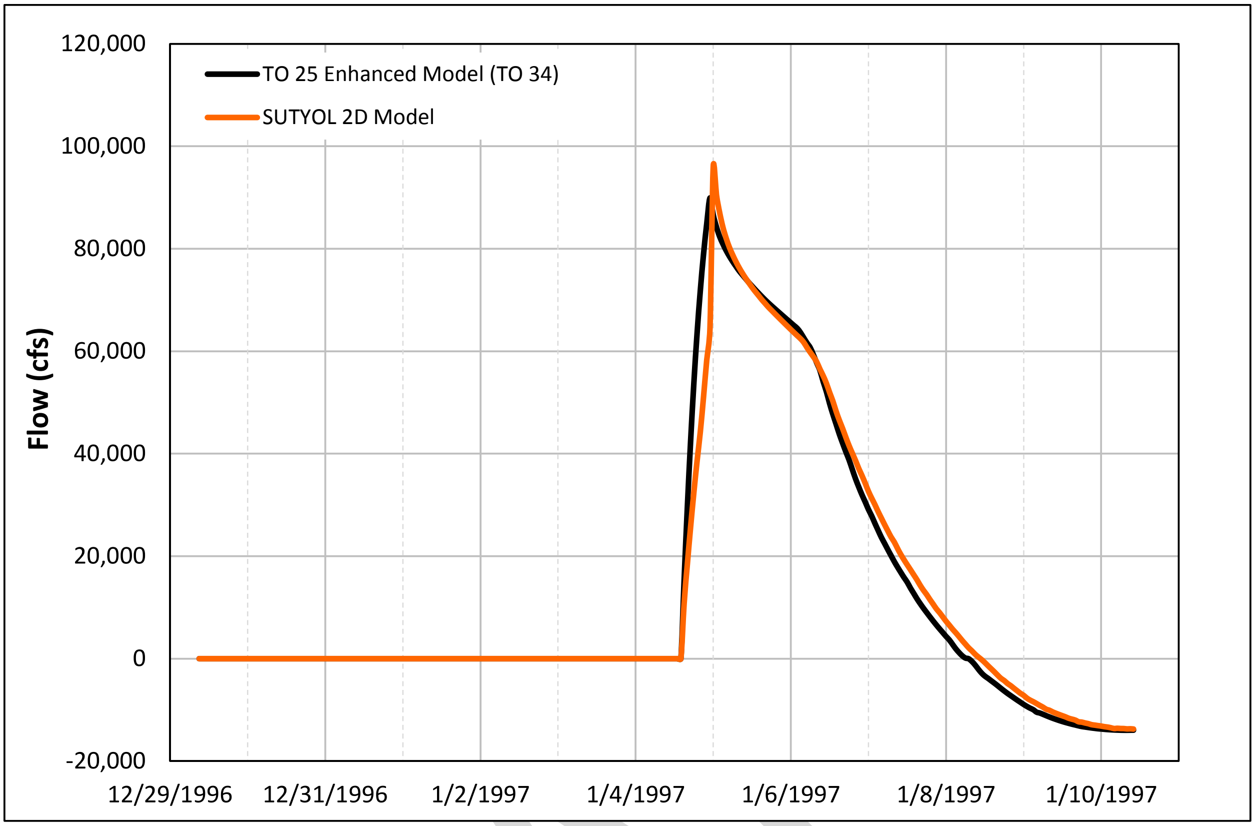


Figure 54. Sutter Bypass Breach at Meridian Flow Hydrograph for 1997 Calibration

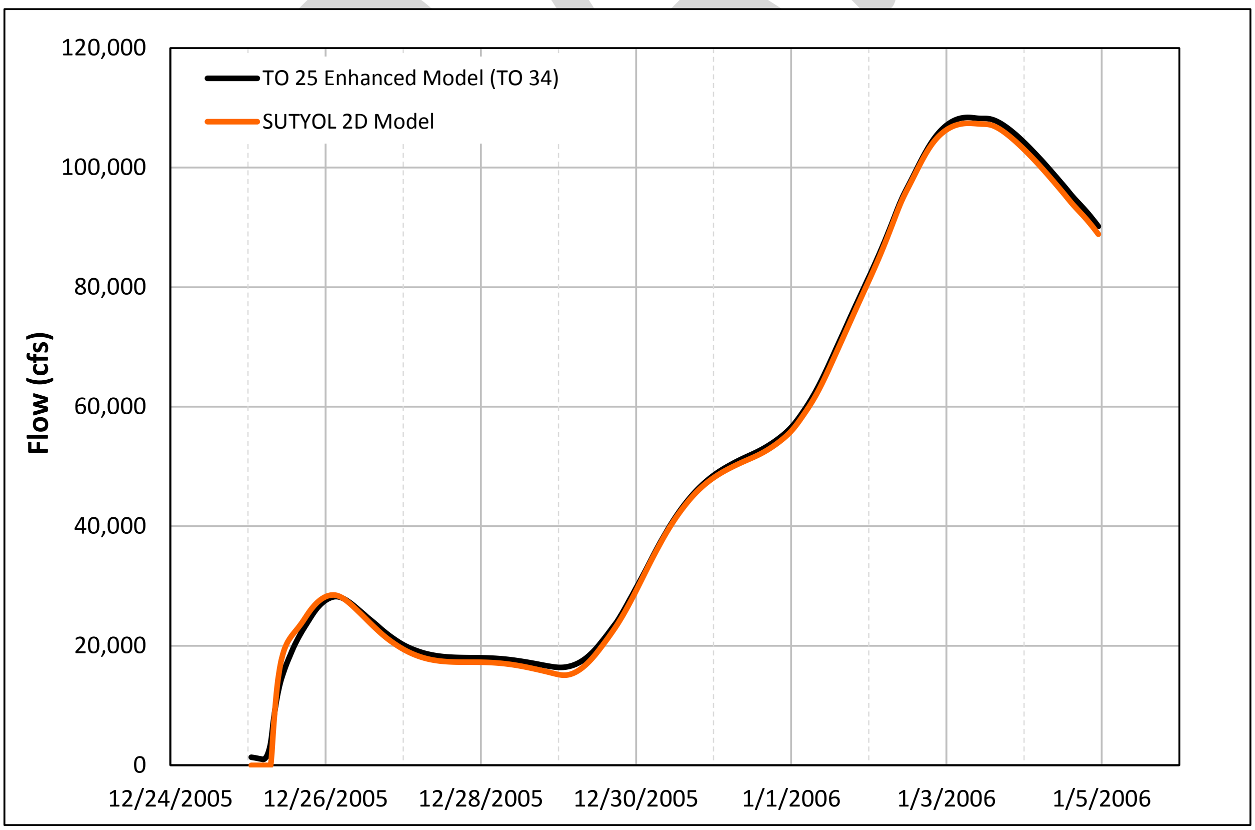


Figure 55. Sutter Bypass at Long Bridge Flow Hydrograph for 2006 Validation

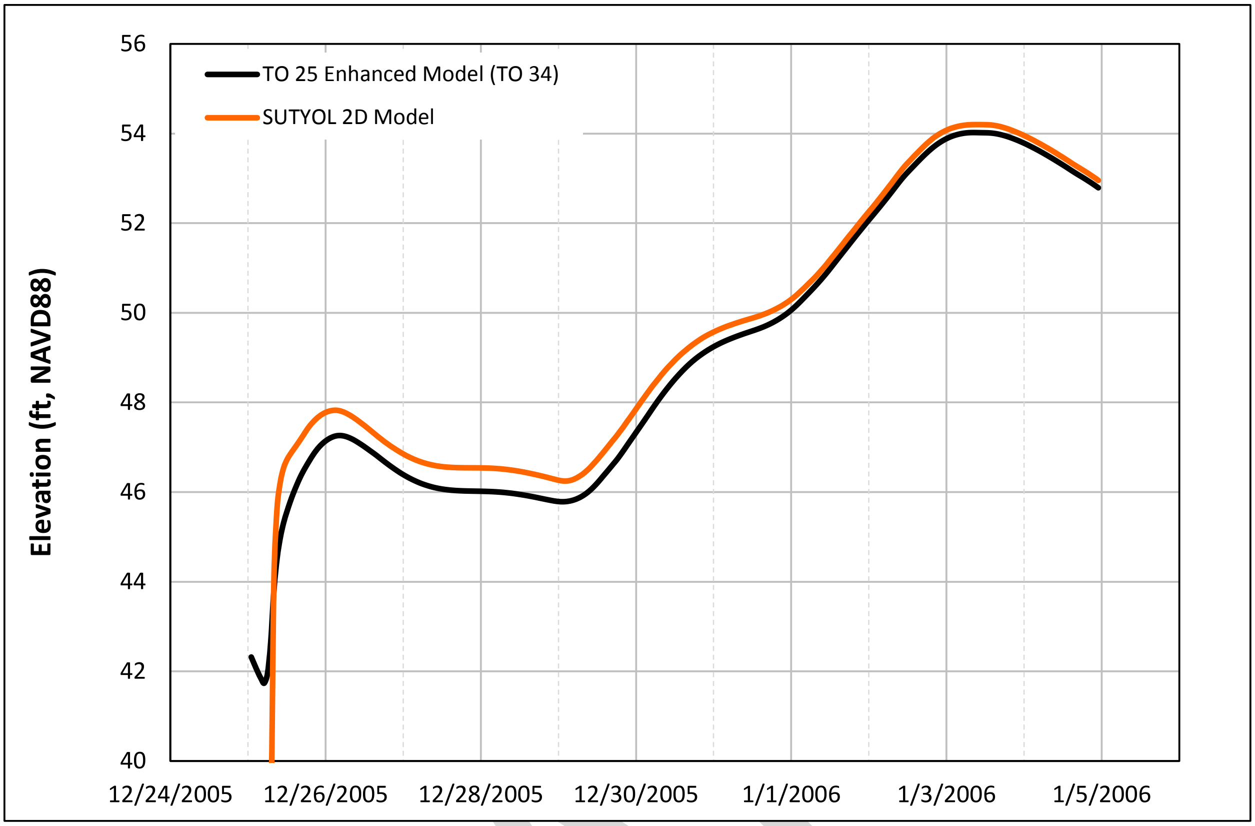


Figure 56. Sutter Bypass at Long Bridge Stage Hydrograph for 2006 Validation

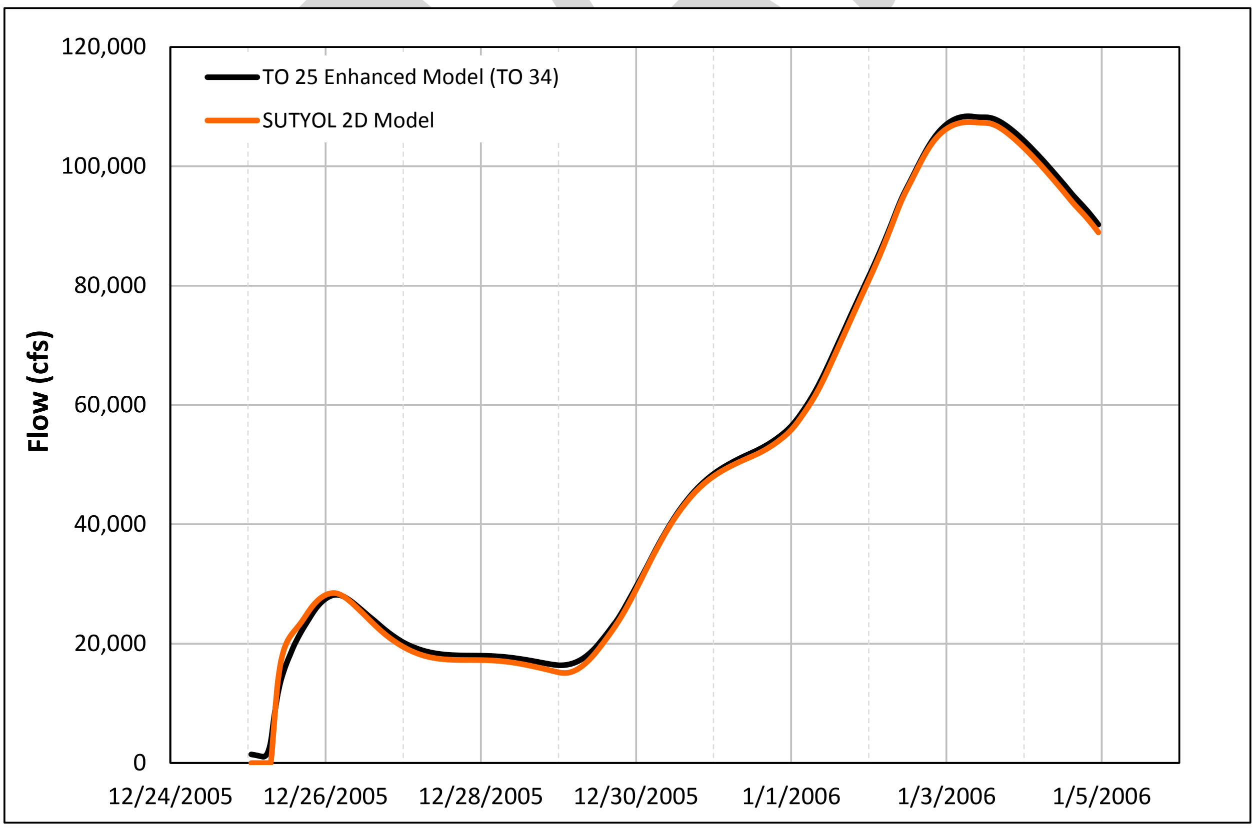


Figure 57. Sutter Bypass at Highway 20 Bridge Flow Hydrograph for 2006 Validation

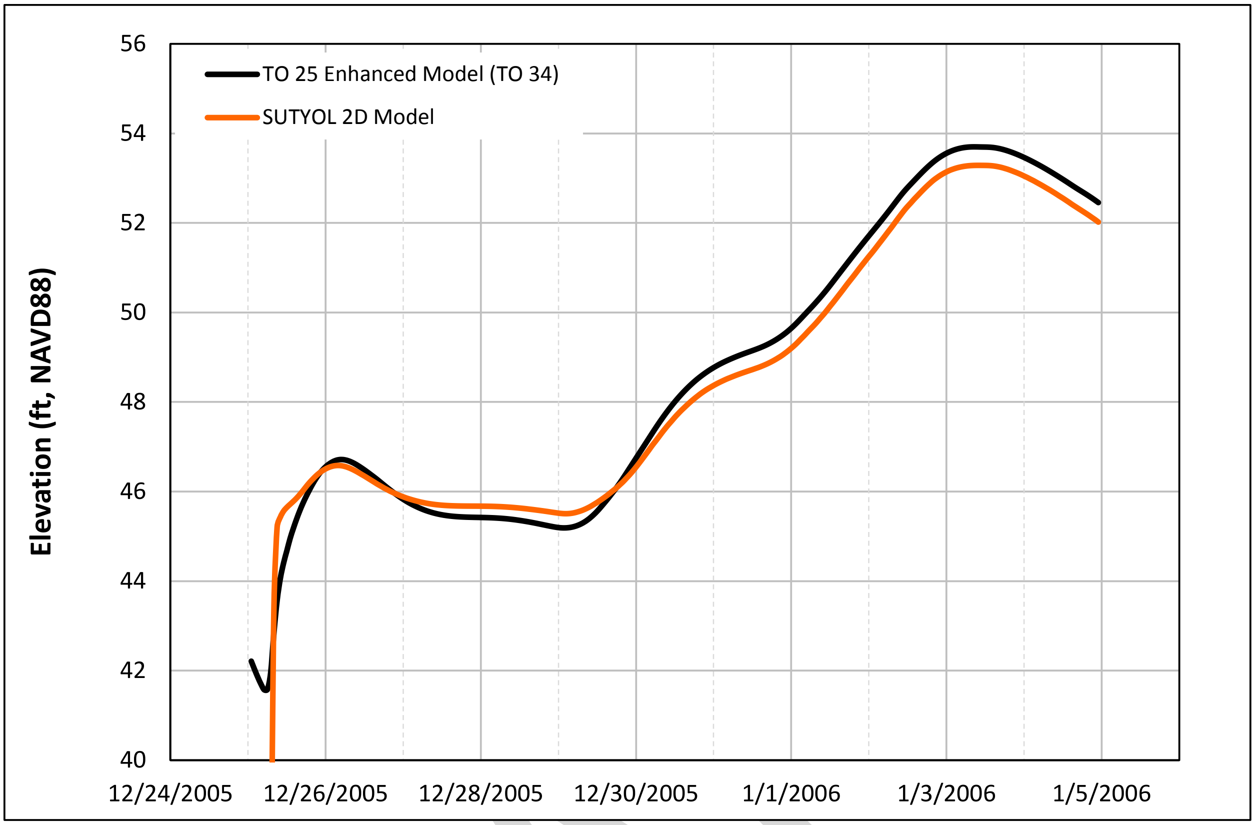


Figure 58. Sutter Bypass at Highway 20 Bridge Stage Hydrograph for 2006 Validation

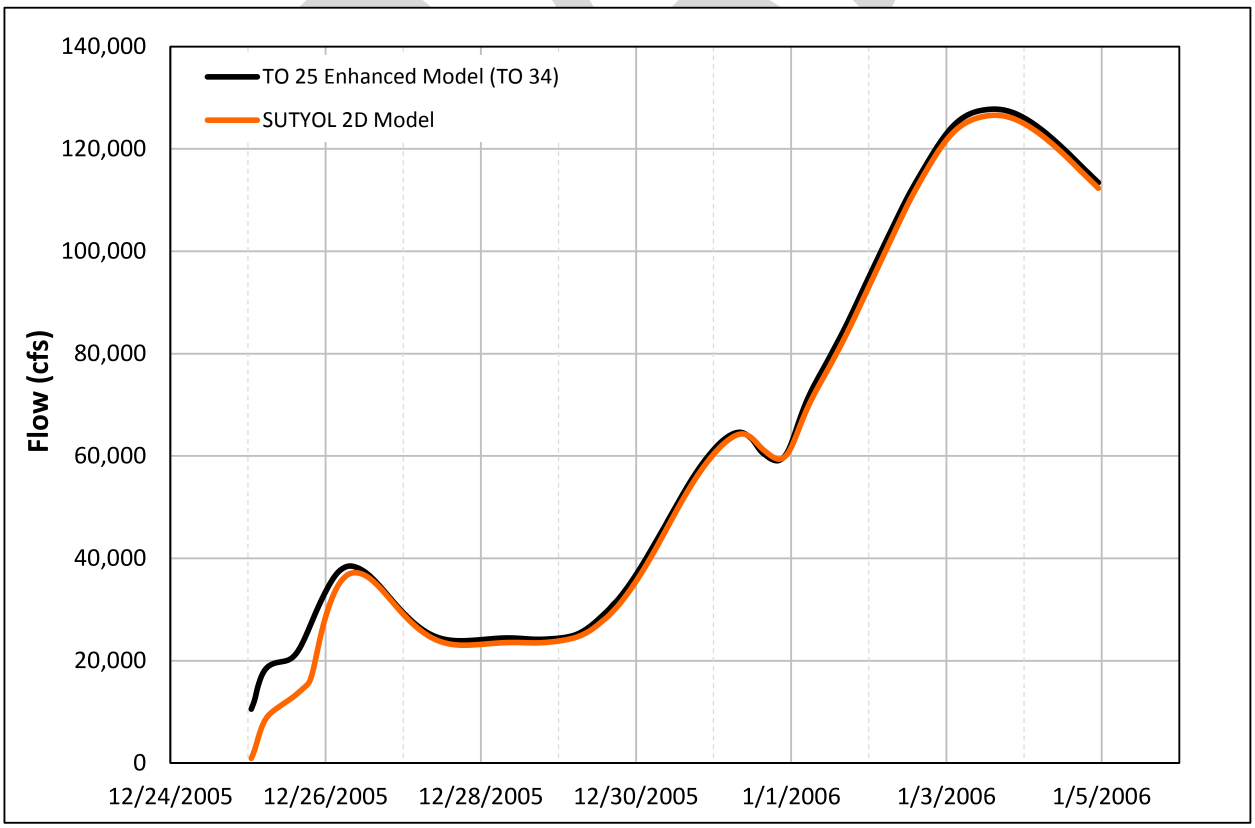


Figure 59. Sutter Bypass at Highway 113 Bridge Flow Hydrograph for 2006 Validation

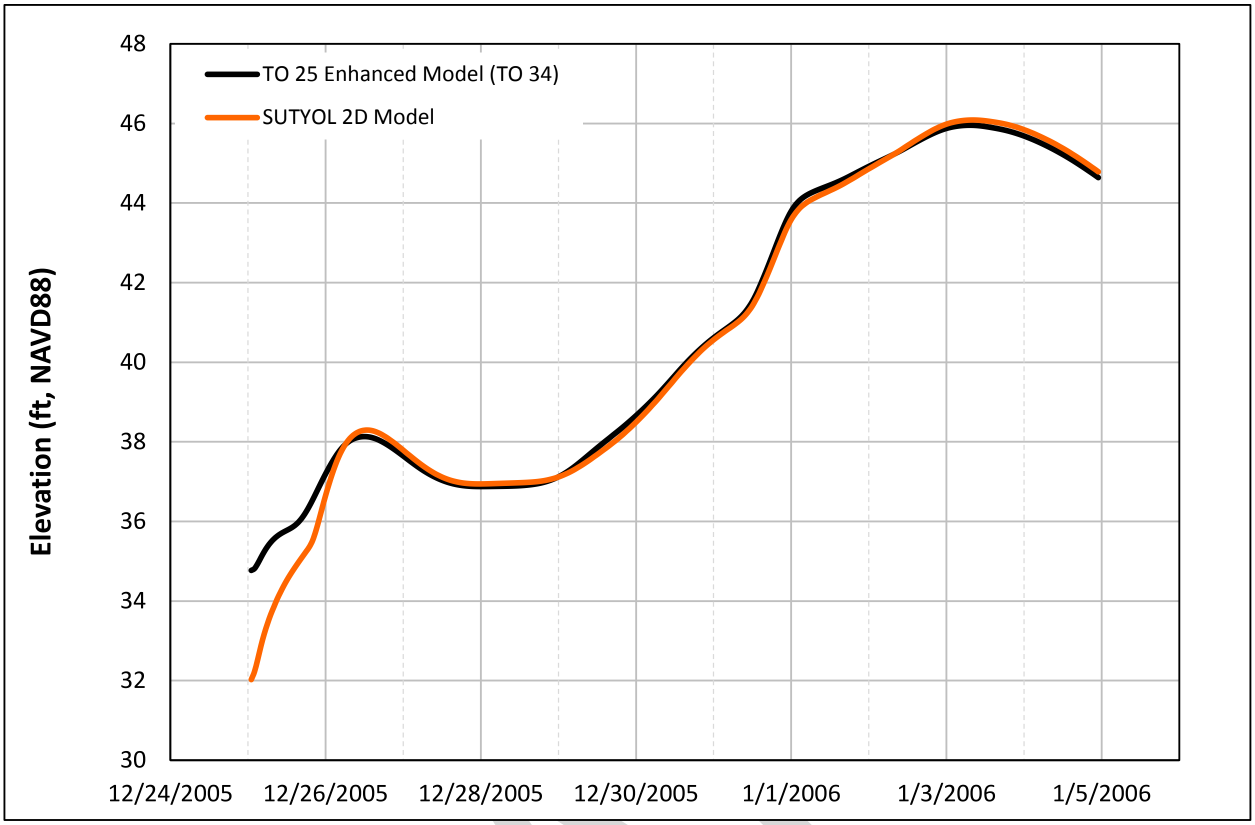


Figure 60. Sutter Bypass at Highway 113 Bridge Stage Hydrograph for 2006 Validation

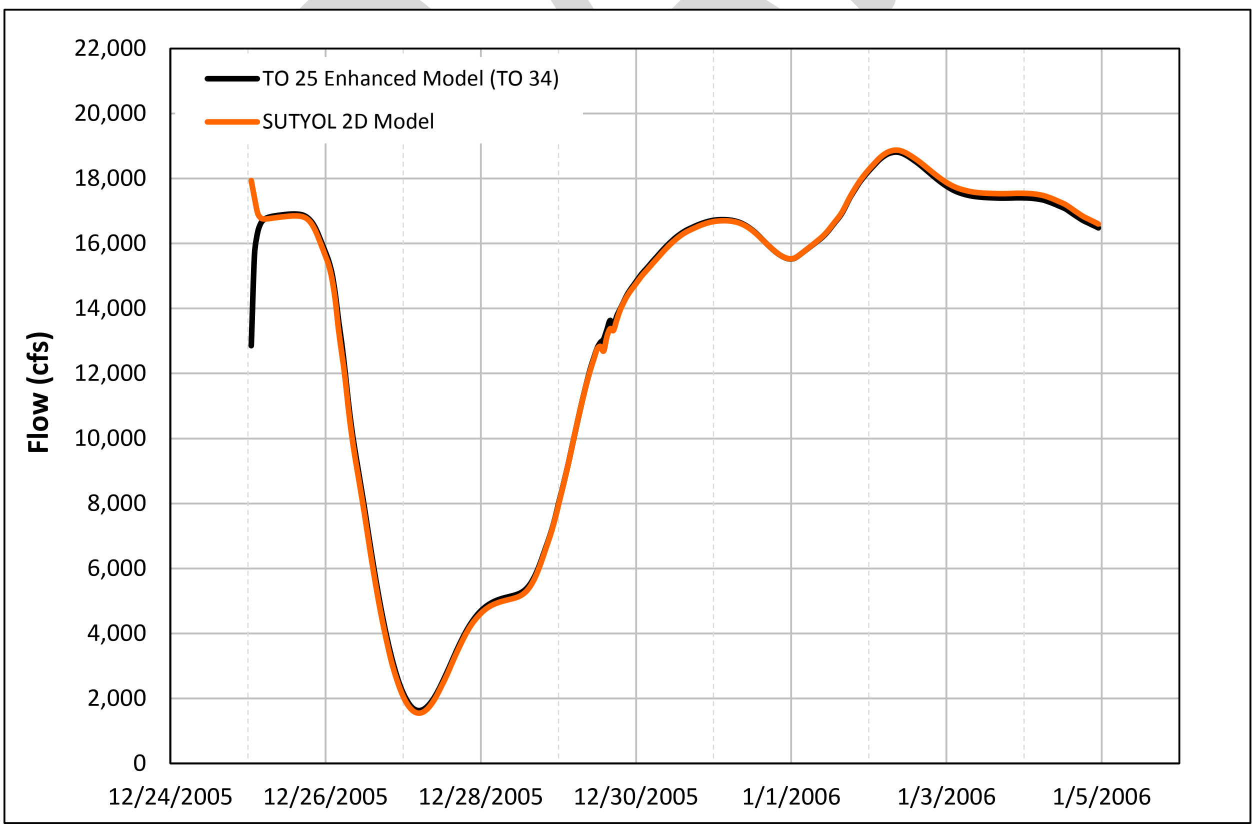


Figure 61. Tisdale Bypass at Reclamation Road Bridge Flow Hydrograph for 2006 Validation

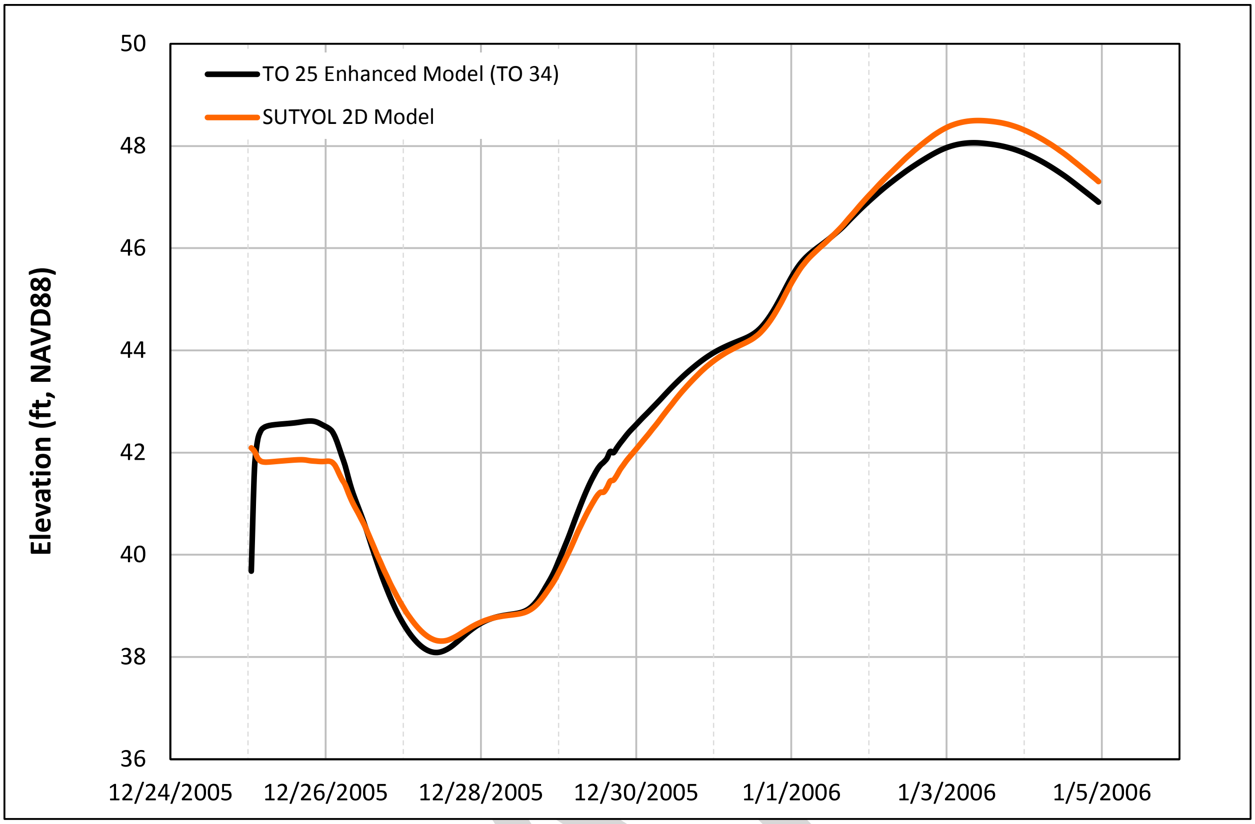


Figure 62. Tisdale Bypass at Reclamation Road Bridge Stage Hydrograph for 2006 Validation

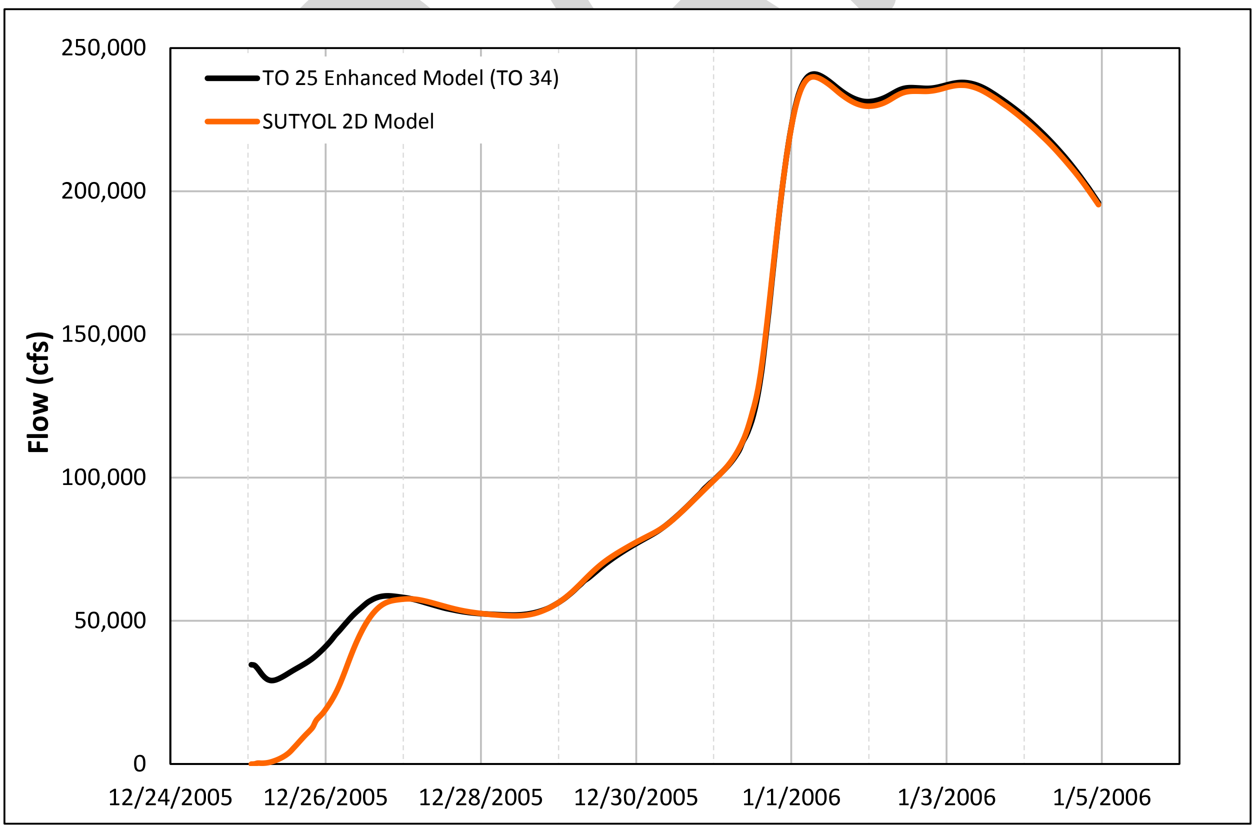


Figure 63. Yolo Bypass at I5 Railroad Road Bridge Flow Hydrograph for 2006 Validation

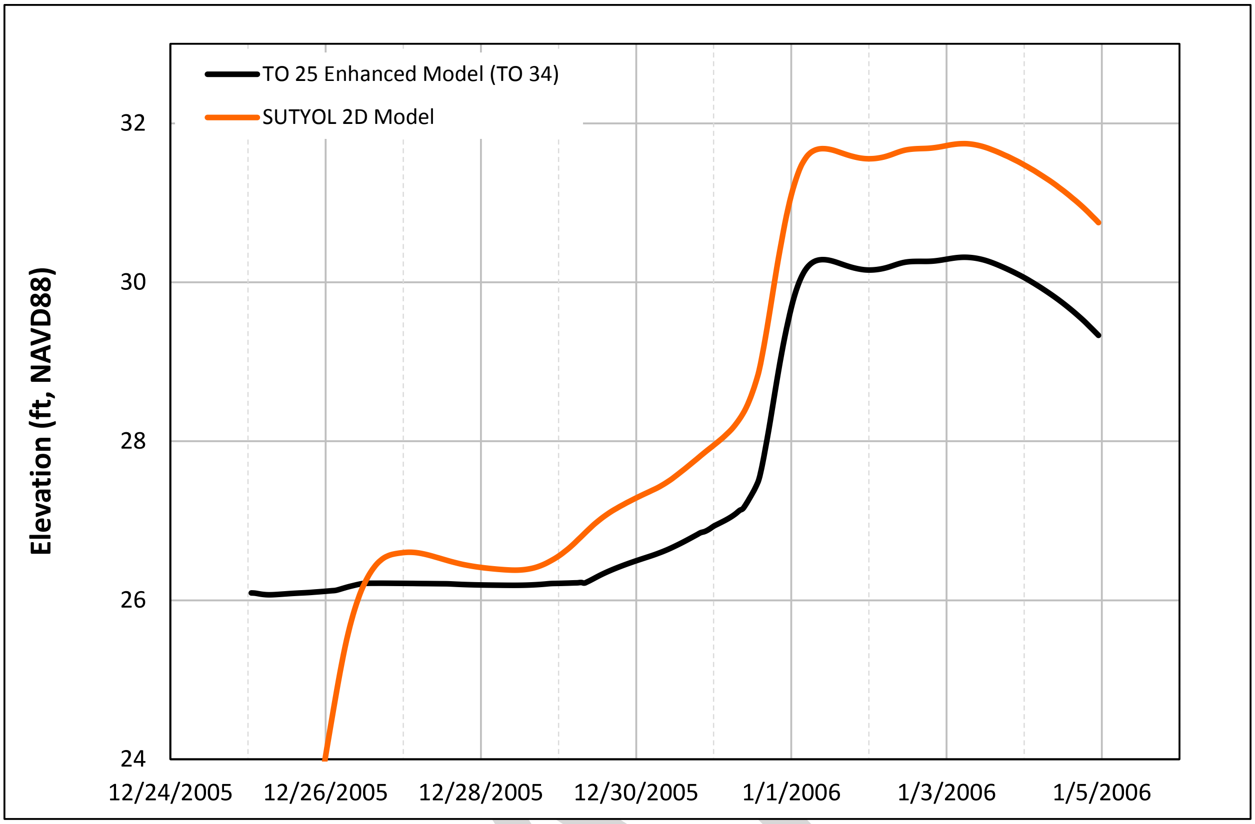


Figure 64. Yolo Bypass at I5 Railroad Road Bridge Stage Hydrograph for 2006 Validation

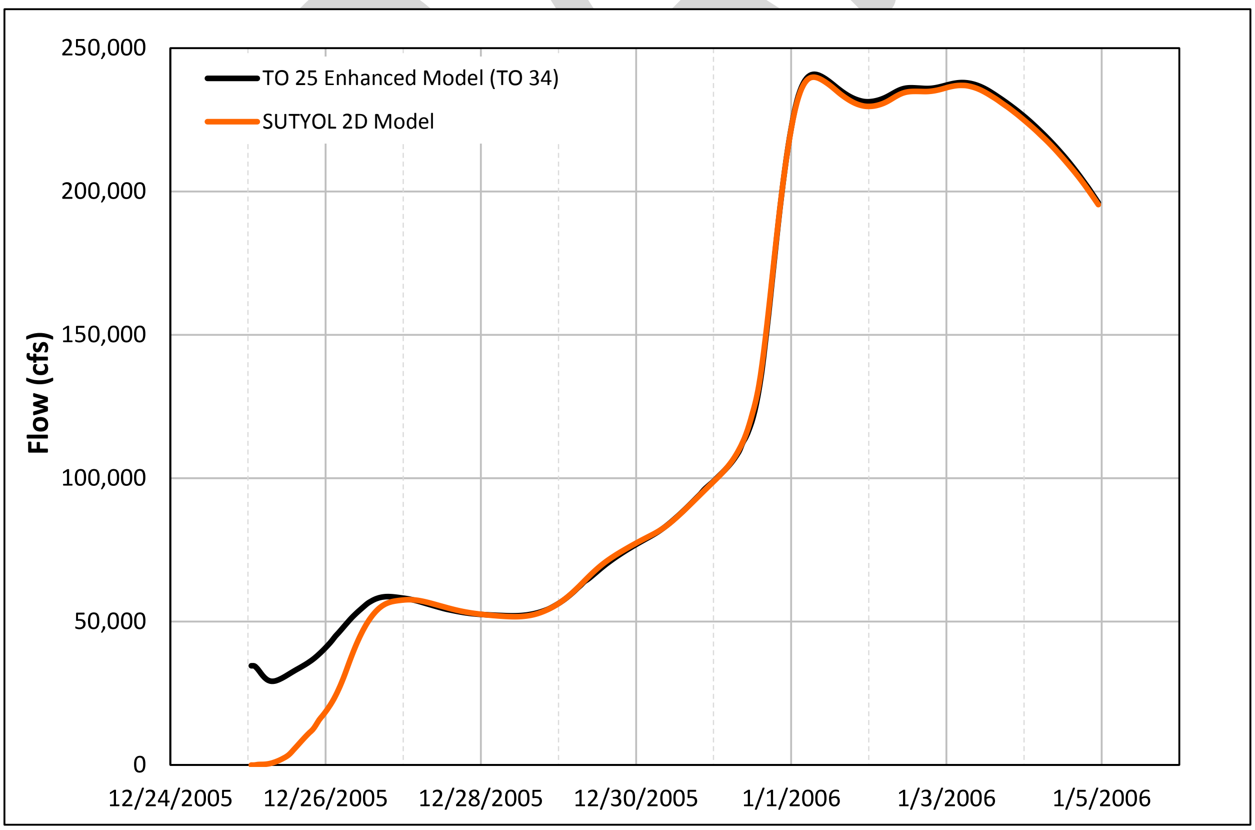


Figure 65. Yolo Bypass at I5 Bridge Flow Hydrograph for 2006 Validation

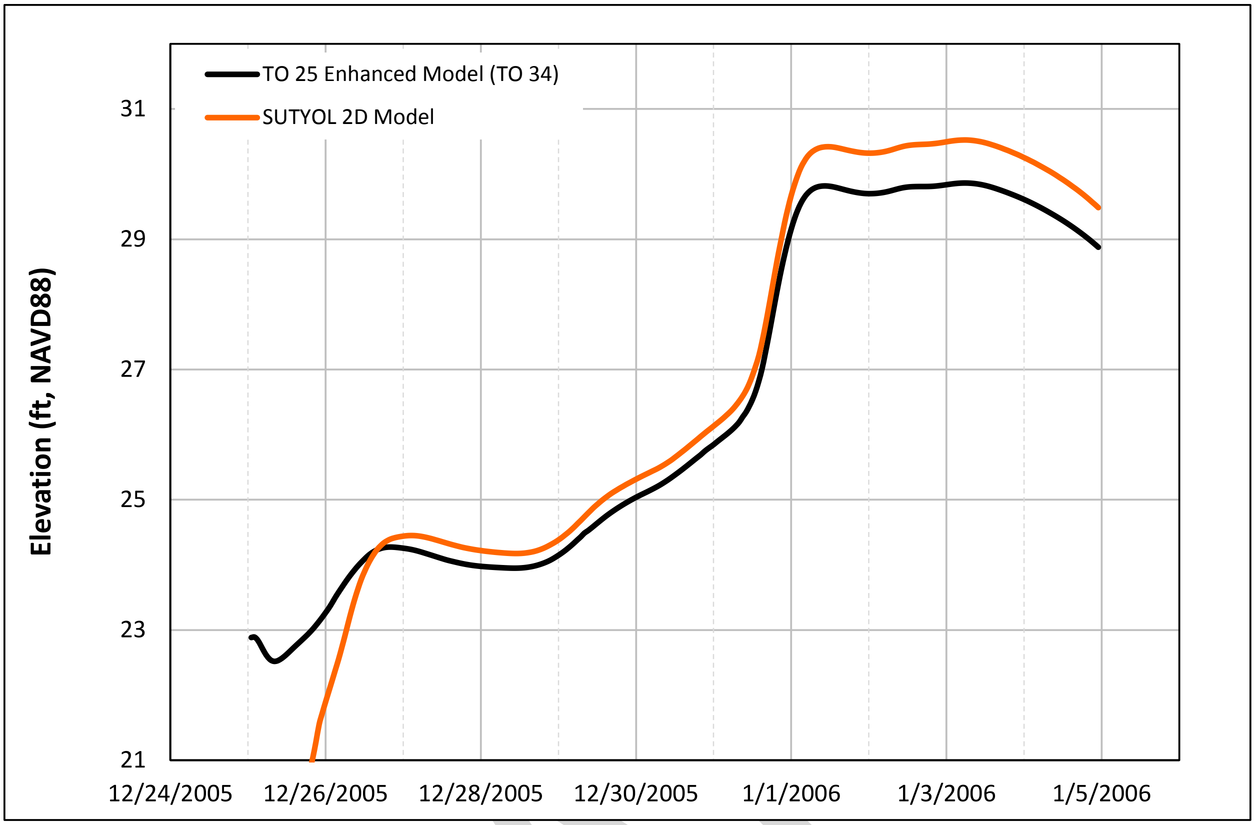


Figure 66. Yolo Bypass at I5 Bridge Stage Hydrograph for 2006 Validation

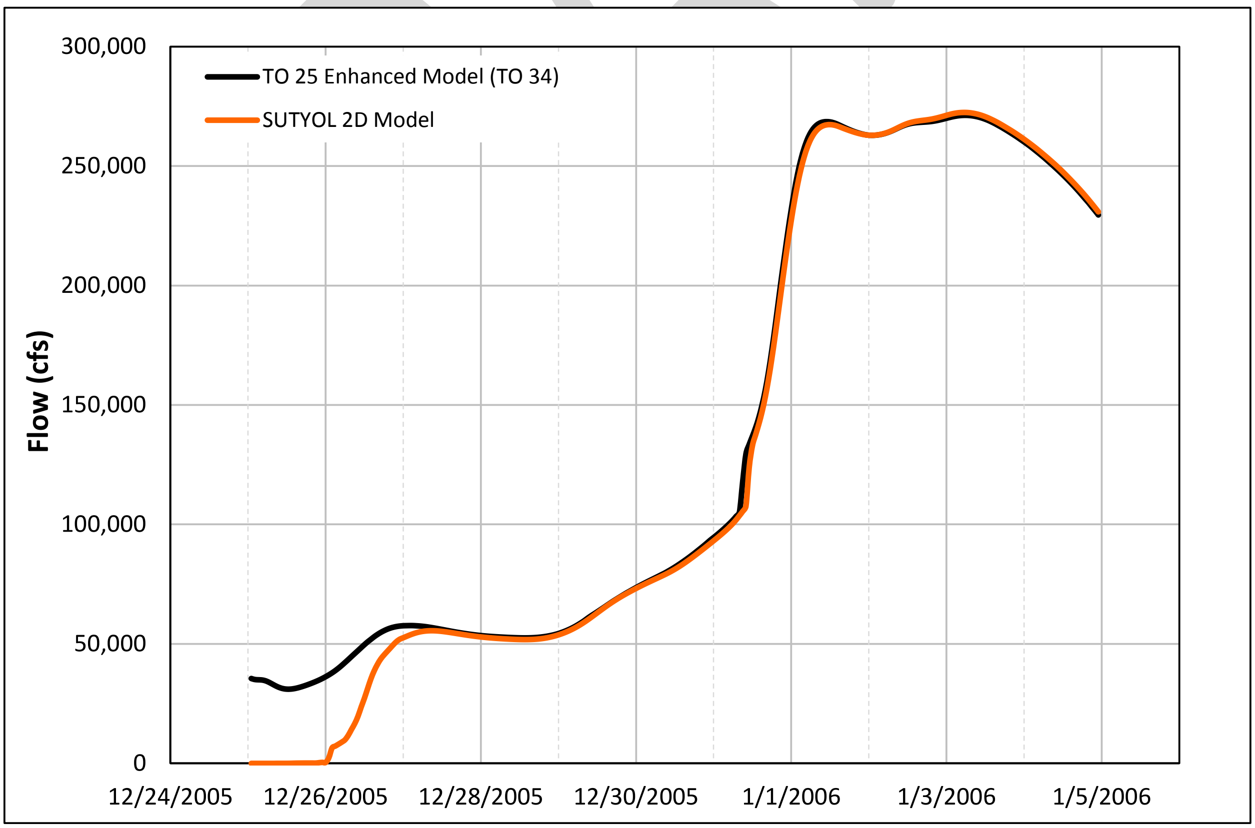


Figure 67. Yolo Bypass at I80 Railroad Bridge Flow Hydrograph for 2006 Validation

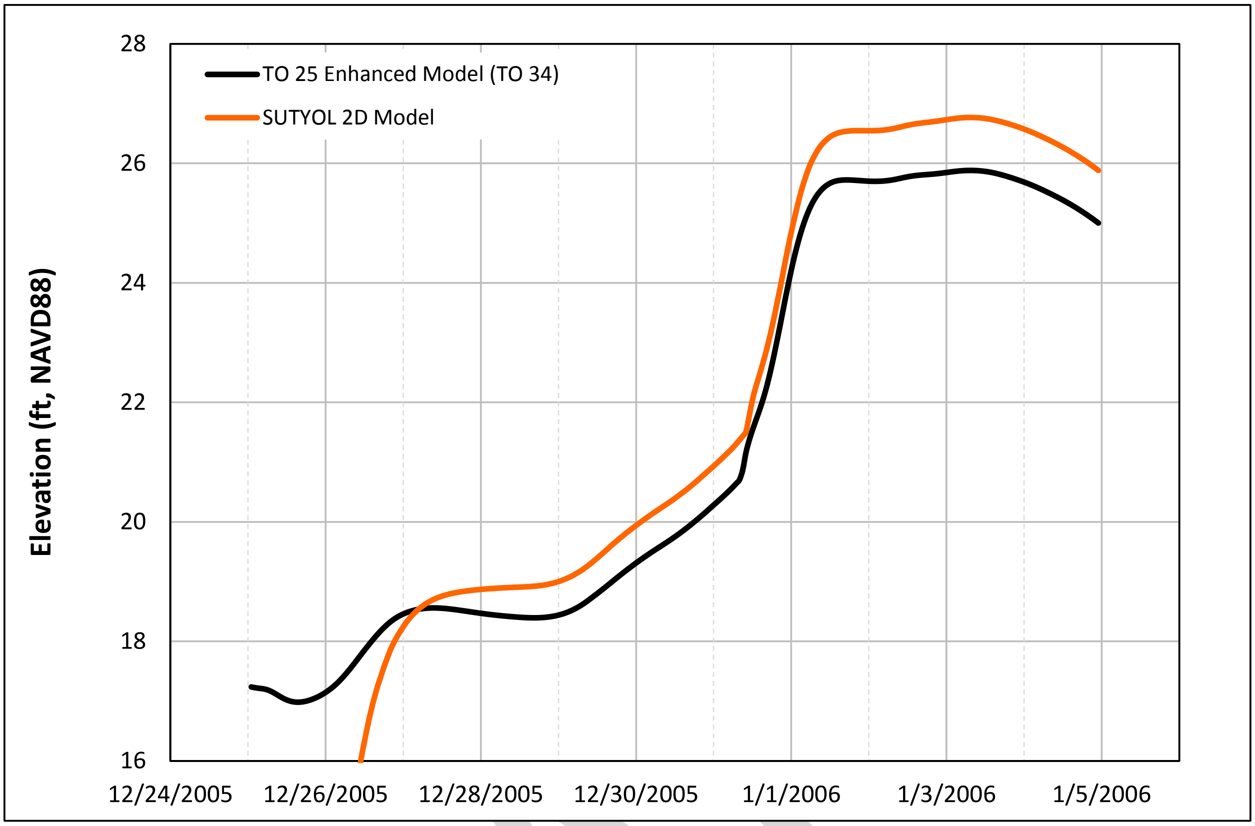


Figure 68. Yolo Bypass at I80 Railroad Bridge Stage Hydrograph for 2006 Validation

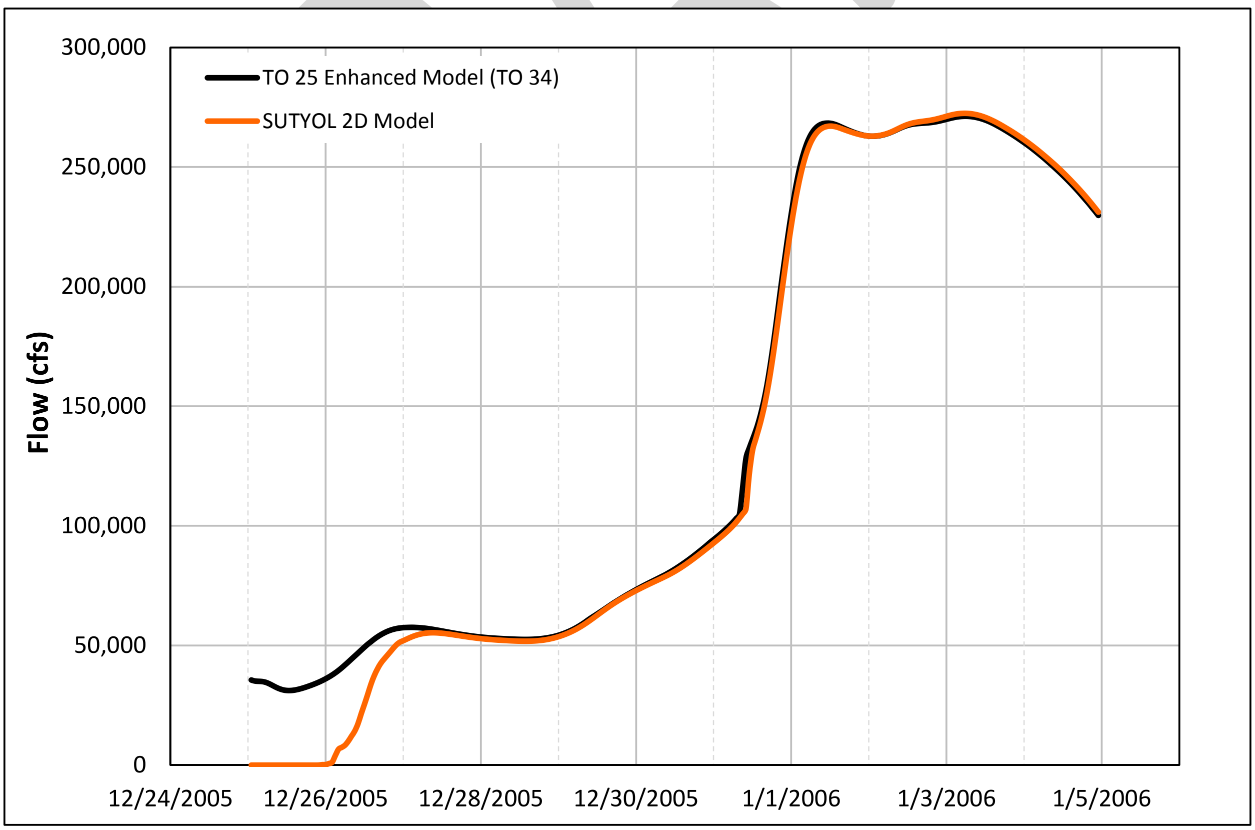


Figure 69. Yolo Bypass at I80 Bridge Flow Hydrograph for 2006 Validation

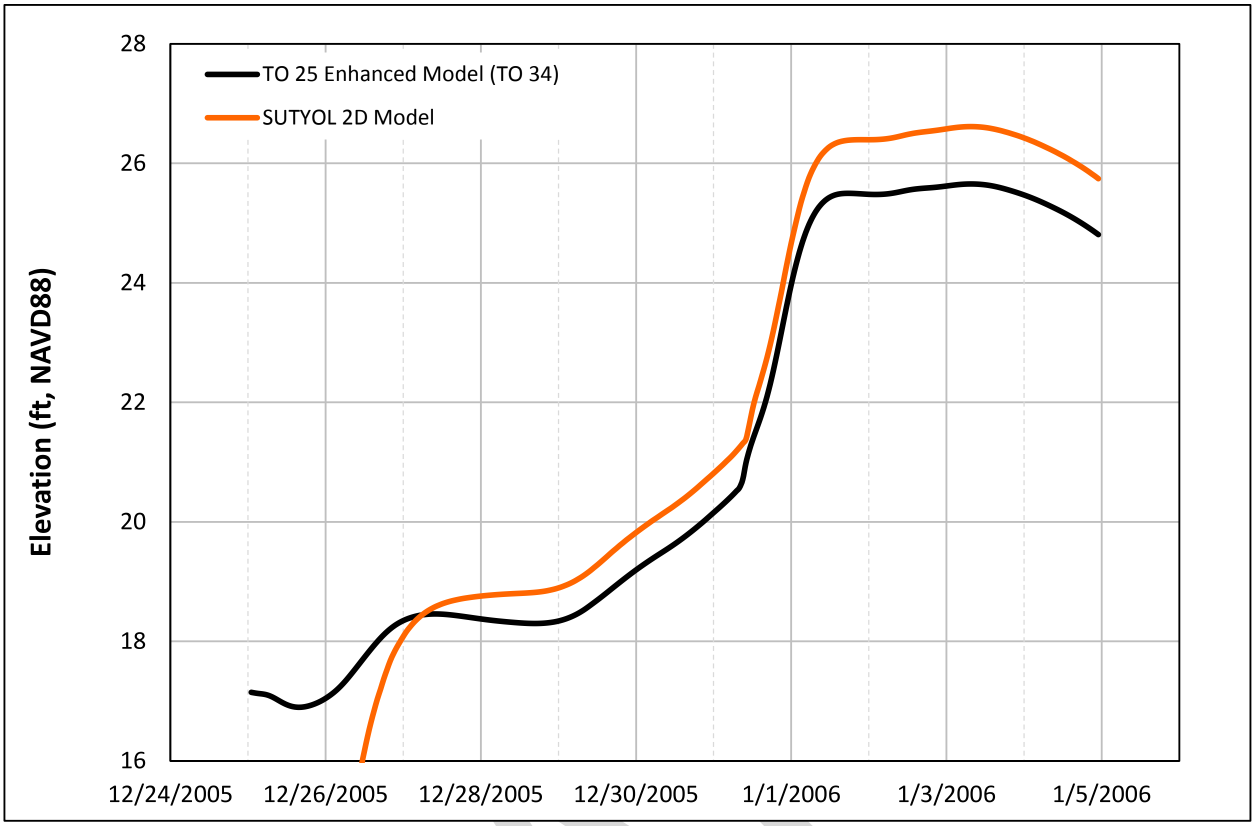


Figure 70. Yolo Bypass at I80 Bridge Stage Hydrograph for 2006 Validation

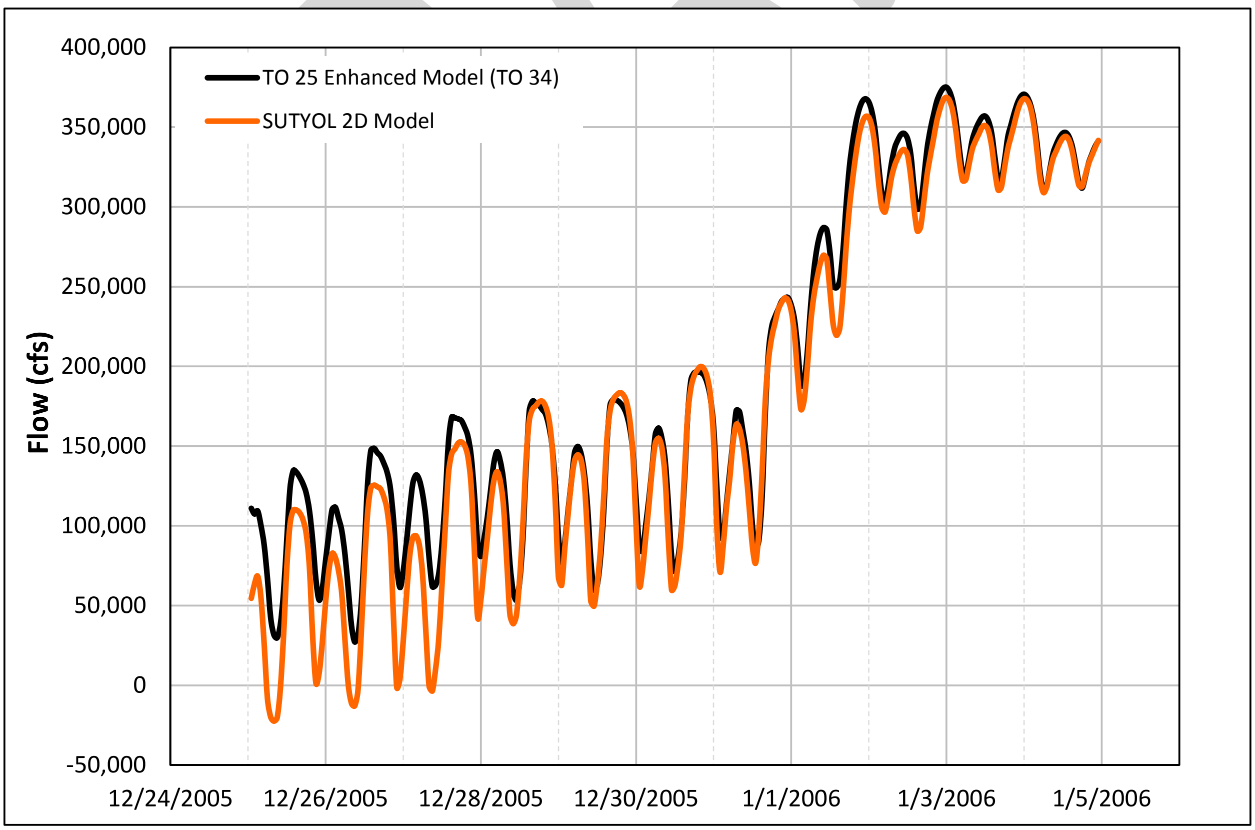


Figure 71. Sacramento River at Highway 12 Bridge Flow Hydrograph for 2006 Validation

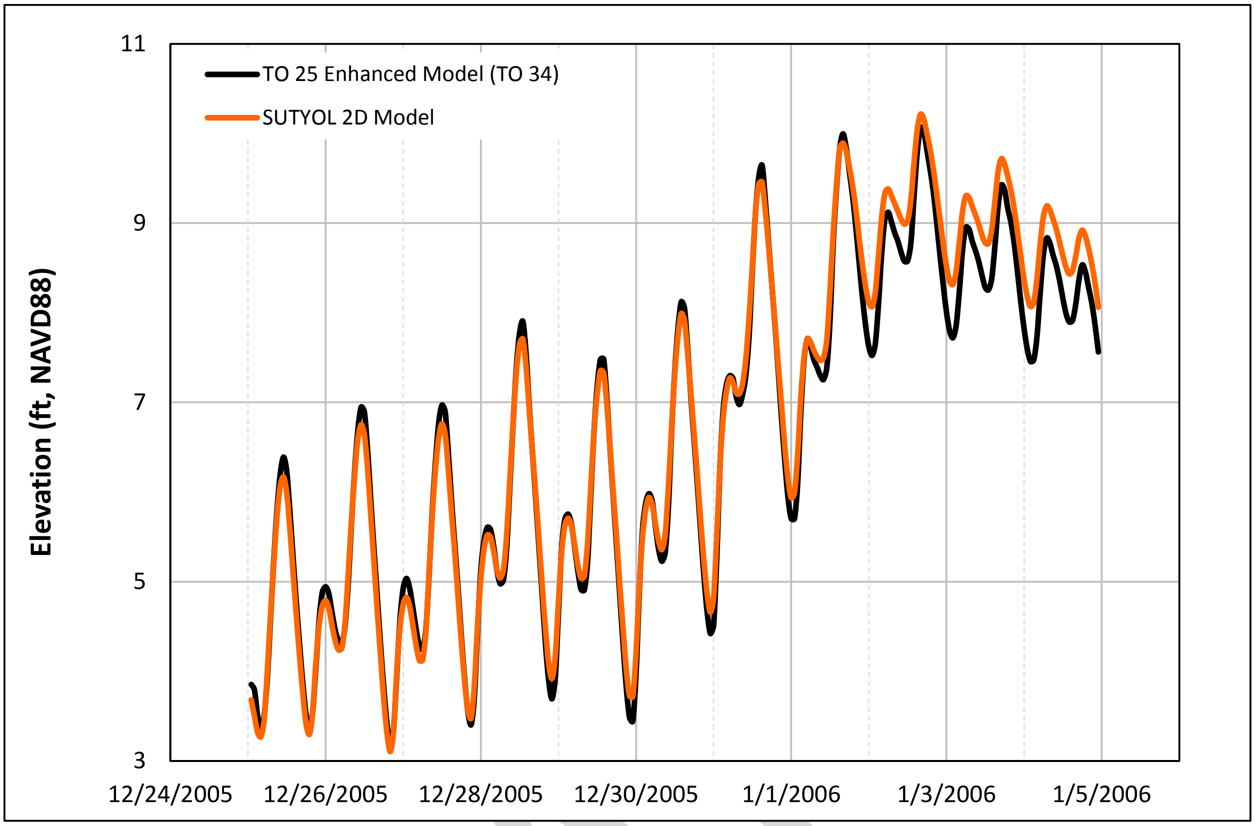


Figure 72. Sacramento River at Highway 12 Bridge Stage Hydrograph for 2006 Validation

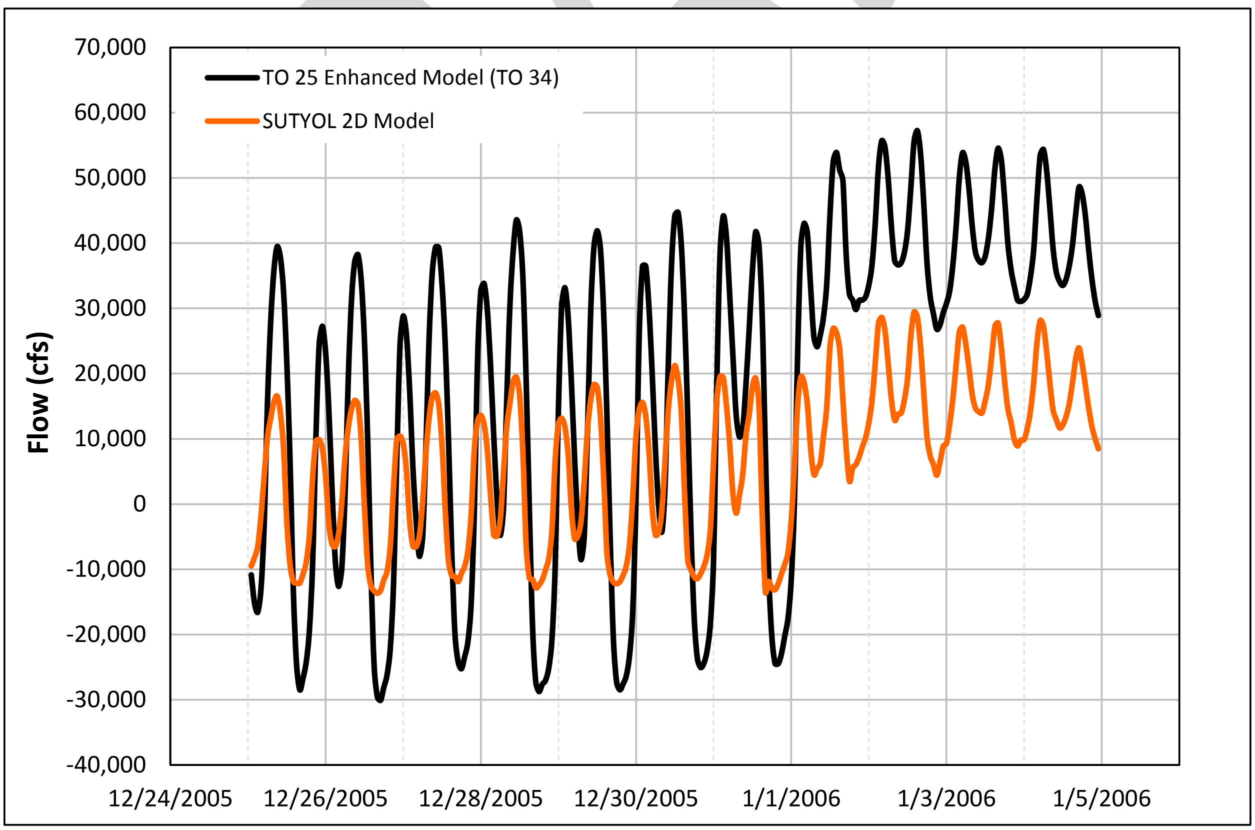


Figure 73. Threemile Slough at Highway 160 Bridge Flow Hydrograph for 2006 Validation

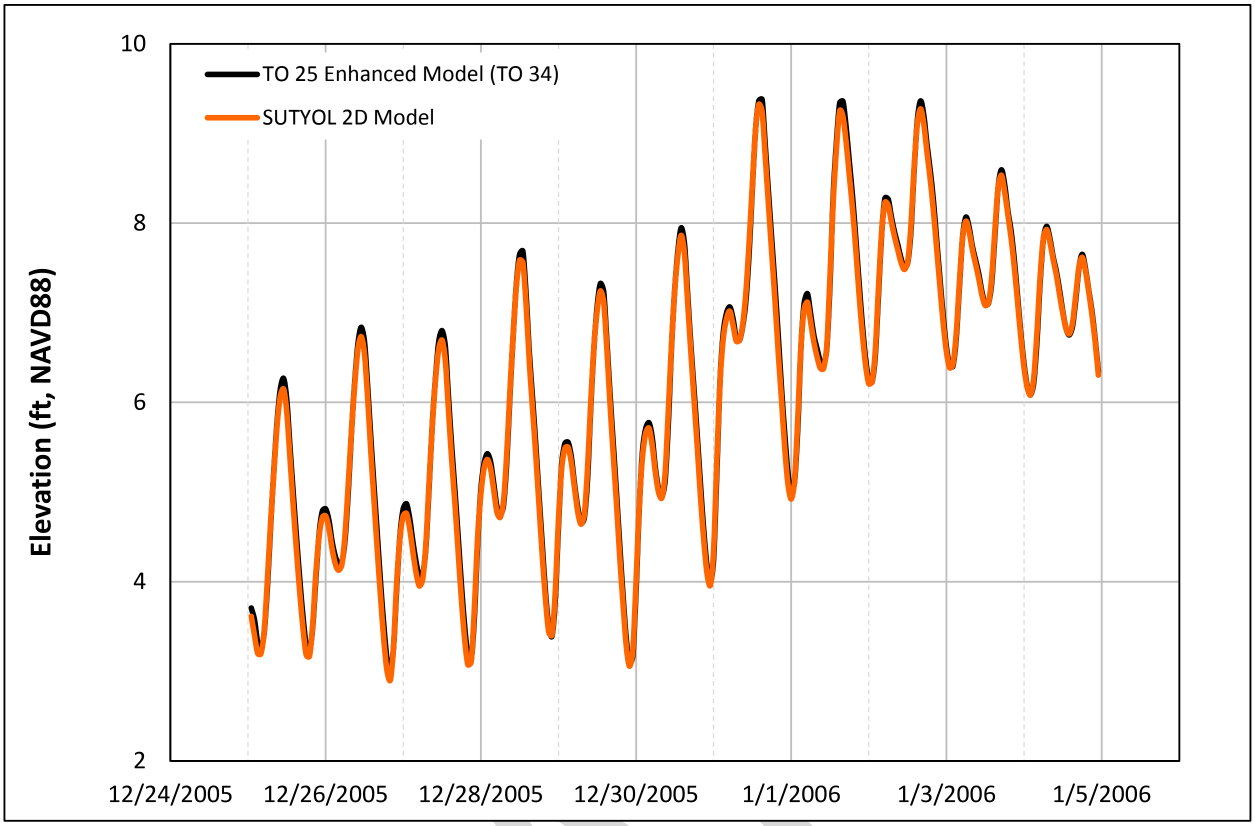


Figure 74. Threemile Slough at Highway 160 Bridge Stage Hydrograph for 2006 Validation

SECTION 5

Recommendations

This primary purpose of generating the SUTYOL 2D model is to accurately model the complex hydraulic function of the Feather River/Sacramento River and Sutter Bypass confluence, as well as the hydraulic function of the Sacramento Bypass. The SUTYOL model is meant to serve as the backbone of the overall Sacramento Basin 1D/2D model. For expediency during the modeling task, assumptions and approximations were made, particularly when representing hydraulic structures in the bypasses. For additional precision in the future, the following refinements are recommended:

1. Collect as-built or survey data for the hydraulic structures based solely on LiDAR survey data, and incorporate these more accurate data into the model.
2. Incorporate updated land use information from other sources to increase the accuracy of roughness coefficients.
3. Collect detailed bathymetry data for the Sacramento River and Threemile Slough confluence, and incorporate into the model to increase the accuracy of model.

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