Public Domain HEC-RAS Model with 2-D Floodplain of the Yolo Bypass and its Connection and Effects on the Sacramento River

Yolo County Contract 2014324

William E. Fleenor
Lily Tomkovic
Alessia Siclari

Center for Watershed Sciences
University of California, Davis

UCDAVIS
CENTER FOR WATERSHED SCIENCES
Delta Solutions

University of California, Davis • One Shields Avenue • Davis, CA 94516-8527

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Abbreviations

BDCP	Bay Delta Conservation Plan
CALFED	Calfed Bay-Delta Program
cbec	cbec eco engineering, West Sacramento, CA
CWS	Center for Watershed Sciences (University of California, Davis)
DWR	Department of Water Resources
HEC	Hydrologic Engineering Center (U.S. Army Corps of Engineers)
MWD	Metropolitan Water District of Southern California
NHC	Northwest Hydraulic Consultants
UC	University of California, Davis
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
YCFCWC	Yolo County Flood Control & Water Conservation District

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1 Introduction

1.1 Goals of the project

Under partial funding from Yolo County a 1D/2D computerized hydraulic model of the Lower Sacramento River was developed at the Center for Watershed Sciences, at University of California, Davis. The work is an expansion of an earlier model focusing on the Yolo Bypass hydraulic dynamics and agricultural economic consequences (Suddeth 2014). The earlier project has been expanded, to include the Lower Sacramento River and tributaries. Updates include an improved digital elevation model (DEM) and implementation of newer features of the model software.

The purpose of this project is to provide a public domain, fully capable hydraulic model of the Lower Sacramento River for consideration of the Yolo Bypass Fisheries Enhancement Plan (reference).

The hydraulic model creation has been accomplished using the software “HEC-RAS Version 5.0.3” developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (http://www.hec.usace.army.mil/software/hec-ras/documentation.aspx).

1.2 Project Background

The Yolo Bypass is a 60,000-acre floodway, located in the counties of Yolo and Solano. The primary function of the Yolo Bypass is to provide flood control to the city and suburban areas of Sacramento, California. When the bypass is inundated during winter and early spring, it functions as a migration route and habitat for multiple species, including endangered species. Therefore, floods over the Yolo Bypass provide ecological benefit.

The Yolo Bypass is a central part of the Conservation Measure 2 (CM2) of the Bay Delta Conservation Plan (BDCP). One of the primary purposes of the CM2, Yolo Bypass Fisheries Enhancement, is to assure the accomplishment of goals related to survival, migration, distribution and reproduction of covered fish species and to enhance natural ecological processes. Improved connectivity between the Yolo Bypass and the Sacramento River can be accomplished, according to the CM2, by improving fish passage at the Fremont Weir, through structural or topographic modifications. Currently a non-habitat conservation plan (HCP) called WaterFix is the preferred alternative to BDCP, and EcoRestore accounts for some of the habitat restoration that was incorporated in the BDCP proposal and includes the Yolo Bypass Fisheries Enhancement.

The present model is suitable for future planning, current operations, and further studies. The modification suggested by the CM2 of the BDCP can be evaluated using this model.

The model will also be used for various CWS research purposes. Future studies will analyze the effects of changes to model representation (*e.g.*, inclusion of the current 1-D Toe Drain represented within the 2D area) and specific research investigations of floodplain benefits. Improvements to the model will be made available on the CWS website (https://watershed.ucdavis.edu/).

In addition, stakeholders and private companies can utilize this model for:

- Future hydraulic studies on the existing system
- Investigating possible structural or topographic modification of the Yolo Bypass
- Environmental restoration (proposed)
- Flood management emergency operations in the Sacramento Basin
- Delta water supply analysis.

The model was developed to properly represent both low flow and high flow conditions. Initially the model was run with the hydraulic conditions of the period July 2009 to Jan 2010. Because the Fremont Weir isn't overtopped every year, an especially wet year was needed for the boundary conditions for high-flow model calibration. January of 2010 was the most recent flood event that overtopped the Fremont Weir, best represents current topography, and has observed data with the best confidence. In order to calibrate the model to low flow conditions the model was run in July of 2009. By using times before the flood event in January of 2010, a restart file can be made from the run representing the previous time period.

1.3 Acknowledgements

This project has been funded in large part by Yolo County, and supplemented by the Stephen D. Bechtel, Jr. Foundation as part of the Delta Solutions Program at The Center for Watershed Sciences, at University of California, Davis.

2. Modeling Method

2.1 Model Domain

The portions of the model that are two-dimensional (red outline in Figure 1) include: the entire Yolo Bypass, the southern portion of the Sutter Bypass, the Sacramento Bypass, and a portion of the Sacramento River that runs between the Sutter and Yolo Bypasses. The one-dimensional features (blue in Figure 1) include the southern portion of the Sacramento River, the Southern extent of the Feather River, the American River, many tidally influenced tributaries at the southern end of the bypass near Liberty Island, and western tributaries including Cache Creek settling basin, Willow Creek, and Putah Creek.

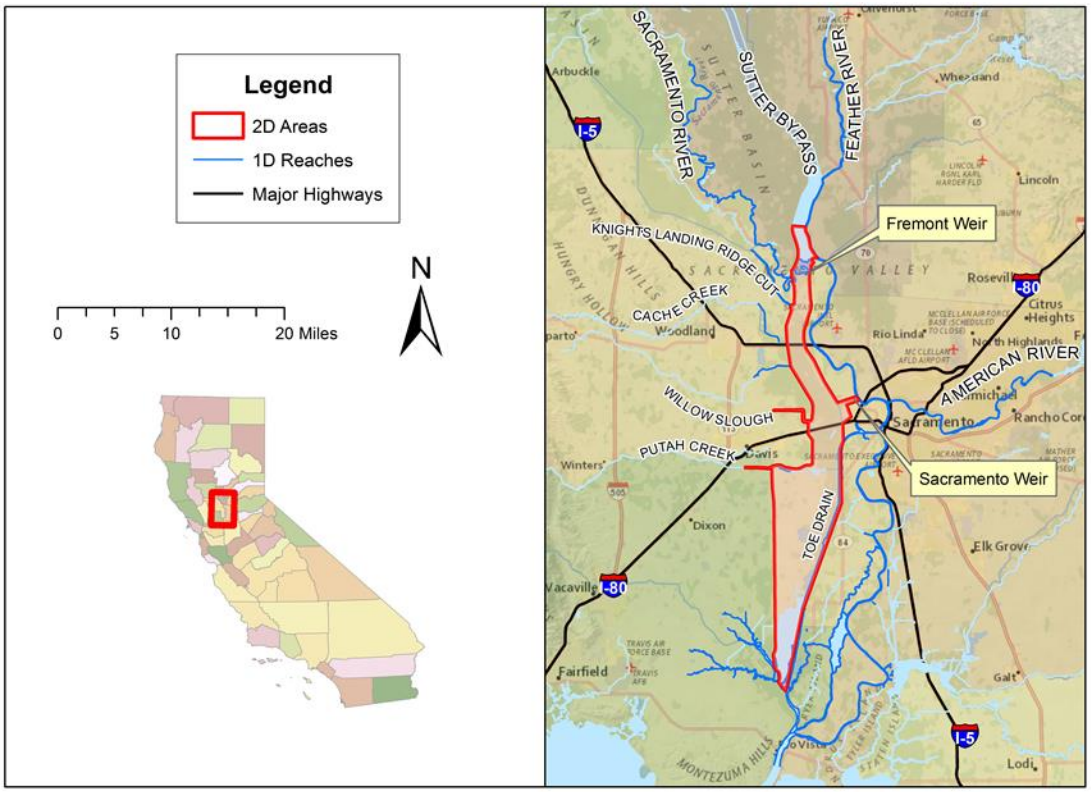

Figure 1 Lower Sacramento River area

2.2 Previous Hydraulic studies

The Yolo Bypass is a critical component of the Flood Control Project, and provides important existing habitats and the possibility for future habitat enhancement. It has been, and continues to be, the subject of numerous modeling studies, programs, and reports (*CALFED, 2001*) (see Table 1).

Table 1 - Previous Hydraulic Studies on the Yolo Bypass

Dimension	Software	Description	Sponsor	Year
1-D	HEC-1 and HEC-2	Willow Slough, Dry Slough, Covell Drain	Yolo County Flood Control & Water Conservation District	1992
1-D	UNET	Steady state, 1-D model for the Upper and Lower Sacramento Valley	USACE	1995
1-D	HEC-2	Putah Creek	USACE	1995
1-D	HEC-2	Cache Creek	USACE	1995
1-D	HEC-RAS	Updated model for the Sacramento River.	USACE	2006
2-D	MIKE 21	2-D unsteady flow model for the Yolo Bypass. Boundary conditions for western tributaries based on estimates.	MWD, DWR, cbec eco-engineering	2007
2-D	RMA2	2-D hydrodynamic model for the Yolo Bypass. Steady state. Designed for high flow scenarios.	USACE	1995 2007 (Updated)
1-D/2-D	HEC-RAS	Coarse-level HEC-RAS model of the Yolo Bypass from Fremont Weir to Liberty Island	CWS	2007
1-D/2-D	HEC-RAS 4.2	As part of the CVFED effort, an unsteady model was developed for the entire Sacramento Valley using the UNET model as the basis.	DWR	2010
2-D	RMA2	2-D unsteady flow model developed to examine low flow field-scale drainage	UC Davis	2012
1-D/2-D	TUFLOW	TUFLOW is a 1-D/2-D flood modeling software – it was used to develop flooding extents in Cache Creek, Willow Slough and Putah Creek. Breach hydrographs from the HEC-RAS model were used as inputs.	Yolo County	2012
1-D/2-D	HEC-RAS 4.2	Coupled 1-D/2D for the Yolo Bypass.	US Davis	2012/2013
1-D/2-D	HEC-RAS 5.0	Coupled 1-D/2D for the Yolo Bypass and part of the Sutter Bypass south of Tisdale Weir.	CWS	2013-2015

Since the primary purpose of the Yolo Bypass was to provide flood control to the city of Sacramento, the Yolo Bypass has been subject of several flood capacity modeling studies in the past. Such studies provide little information of flood duration and extent. The most recent models will be discussed.

In 1992, the Yolo County Flood Control & Water Conservation District (YCFCWCD) developed HEC-1 and HEC-2 models of Willow Slough, Dry Slough, and Covell Drain, to evaluate 2-to 100-year peak flood flows, elevations, and floodplains. The models have the capability to simulate the effects of land use changes or channel modifications on local flooding (Source: Yolo County Water Resources Association, and DWR, 2002).

In 1995, the U.S. Army Corps of Engineers developed a UNET 1-D hydraulic model of the entire Sacramento River Flood Control Project. The model, which included the Yolo and Sutter Bypass, was part of the Corps Comprehensive Study for the Sacramento-San Joaquin River Basin (*HEC, 1997*).

In 1995, the U.S. Army Corps of Engineers developed a HEC-2 model of Putah Creek. The purpose of the model was to analyze flood impacts of habitat restoration at City of Davis. The model can be used to evaluate opportunities/constraints for diverting floodwaters to Putah Creek and for riparian habitat restoration (Source: Yolo County Water Resources Association, and DWR, 2002).

In 1995, the U.S. Army Corps of Engineers developed also a HEC-2 model of Cache Creek to evaluate 100-year flood water surface profile and floodplain. The model has been used to evaluate opportunities for diverting floodwaters to Putah Creek and for riparian habitat restoration (Source: Yolo County Water Resources Association, and DWR, 2002).

In 2006, the 1995 UNET model was updated for use in a newer 1-D version of HEC-RAS, calibrated against the 2006 floods and the boundary conditions were updated for use in unsteady modeling (*USACE, 2007*). While this model is suitable for analyzing flood-related issues at a system scale, it may not be appropriate for restoration projects that require analyzing shallow flooding in smaller distributary channels.

The U.S. Army Corps of Engineers also developed an RMA2 2-D hydraulic model, which has been applied in a number of restoration projects, for example the Yolo Wildlife Area Expansion (*YCFCWC, 2002*; *USACE,2006*). Besides minor instability issues, the main drawback of this model was its topography and values for roughness coefficients, both of which were based on the 1997 USACE Comp Study. In 2007, although the model was updated with improved representation of bathymetry, the model has only been calibrated to the 1997 floods (*USACE, 2007*). As a result, consultants have reviewed this model to be unsuitable for unsteady, low-flow conditions. Since this application of RMA2 model is steady-state, it cannot deal with tidal conditions, variable hydrographs, or draining in the lower Bypass nor can it model hydrographs. (*NHC, 2012*).

A newer 2-D model, using MIKE-21 was developed by cbec eco-engineering, for Department of Water Resources (DWR) to simulate several flow alternatives past the Fremont Weir and obtain approximate flooding extents and depths. The model was reviewed by Northwest Hydraulic Consultants (NHC) who felt that besides not being a public domain model, it was not fully tested and the boundary conditions were based on poor estimations (*NHC, 2012*).

More recently, a TUFLOW model also has been developed by cbec eco-engineering but model reviews have not been released. The TUFLOW model analyzes multiple alternatives aimed at increasing seasonal floodplain inundation in the lower Sacramento River Basin and improving fish passage throughout the Yolo Bypass (Campbell *et al*. 2014).

2.2 Combined 1D/2D modeling software

The model produced under the scope of this report uses HEC River Analysis System (HEC-RAS), developed by U.S. Army Corps of Engineers. It was developed using several beta versions of the software and confirmed with the newest release of the software, HEC-RAS 5.0.0. The 5.0 release allows for combined one- and two-dimensional modeling. In addition to combined 1D/2D modeling, the 5.0 release of HEC-RAS has many other new features that allow the modeler to more precisely control the modeling environment.

As mentioned previously, the current model was built from a model built with an earlier version of HEC-RAS by William Fleenor for PhD student, Robyn Suddeth. One of the goals of the most current version of the model is to include two-dimensional modeling of tidal areas, which were previously represented as 1D reaches. The 2D representation provides a more accurate representation of flooding and drying of floodplains. In addition, the model includes momentum of flow coming southward from the Sutter Bypass over the Sacramento River and into the Yolo Bypass. The capture of momentum is accomplished by modifying the portion of river that separates the two bypasses to a two-dimensional domain.

HEC-RAS uses a semi-implicit, Eulerian-Lagrangian Finite Volume scheme, and solves the full 2D shallow water equations. HEC-RAS has some two-dimensional capabilities which other 2D hydraulic modeling software do not. One capability is the implementation a sub-grid bathymetry, which allows larger computational cells to represent the underlying topography of a smaller grid size while still better representing the cell area/volume relationship and the actual area of the cell faces. Another feature is that the modeler is capable of defining and developing a computational mesh that reflects the features of the river and floodplain by use of breaklines within the mesh, as well as by manually determining cell location. The roughness of various landforms are captured through use of a GIS layer of land use.

2.3 Boundary and Initial Conditions

2.3.1 Horizontal and Vertical Datum

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

2.3.2 Hydrologic Data

The hydrologic data for the upstream boundary conditions were developed by cbec eco-engineering, which were used in their study "Yolo Bypass Salmonid Habitat Restoration and Fish Passage Hydrodynamic Modeling Draft Report".

Most of the data for the western tributaries were developed by Jones & Stokes (2001) for the Yolo Bypass Management Strategy (YBPMS). Jones & Stokes acknowledges that these data were for rough planning purposes and not ideal for habitat restoration work (pers. comm.).

Some of the boundary condition inputs were flow or stage data at the stream gauges, and where data were not available, flows were estimated. The data sources are as follows: USGS, California DWR, BOR, County of Sacramento, and Solano County Water Agency (SCWA). Table 2 summarizes the location, source, and data type for each boundary condition of the model domain (Figure 2).

Table 2 - Model Boundary Conditions adapted from cbec

Boundary Condition	Source	Data Type
Sacramento River flow below Wilkins Slough	USGS 11390500	Gaged flow
Knight's Landing Outfall Gates inflow	DWR A02945	Gaged flow
Feather River and Sutter Bypass flows	Based on USGS 11390500, 1142500; DWR A02930, A02945; Arcade Creek EMC02 gages	Calculated
Natomas Cross Canal flow	Based on Arcade Creek EMC02 gage	Calculated
Sacramento Weir flow	USGS 11426000	Gaged flow
Knight's Landing Ridge Cut flow	DWR A02930	Gaged and calculated from A02976, A02945, A02930 gages
Cache Creek Settling Basin	USGS 11452500	Gaged flow
Willow Slough Bypass flow	Yolo Bypass Management Study	Calculated
Putah Creek flow	Yolo Bypass Management Study	Calculated
American River flow	USGS 11446500	Gaged flow
Steelhead Creek flow (Natomas East Main Drainage Canal)	Based on Arcade Creek EMC02 gage	Calculated
Delta Cross Channel & Georgiana Slough flows	DWR's Dayflow program	From gages and estimates
North Bay Aqueduct	DWR's Dayflow program	From gages and estimates
Rio Vista tidal stage	DWR B91212	Gaged stage

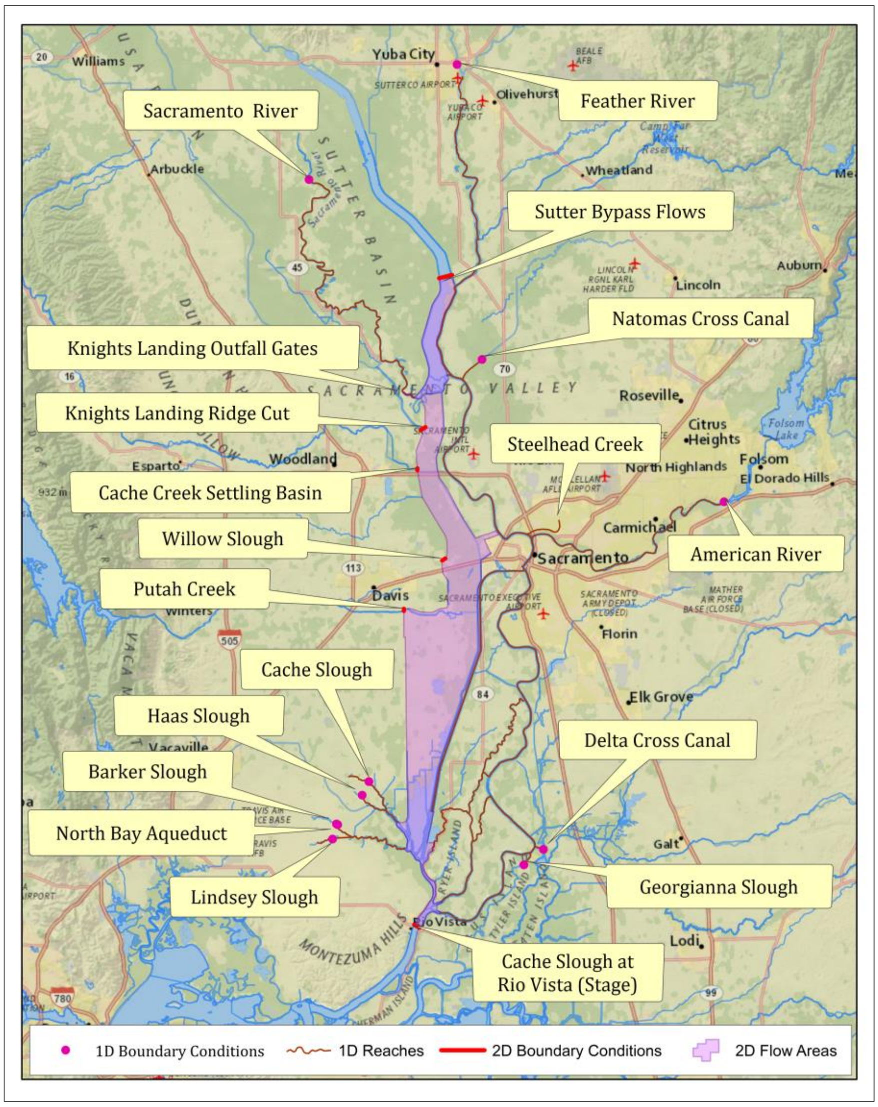

Figure 2 Boundary conditions and gauge locations

2.3.3 Boundary Locations (Source: cbec eco-engineering)

Sacramento River Near Grimes

Daily inflows along the Sacramento River below Wilkins Slough near Grimes were obtained from USGS stream gauge 11390500.

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.

Feather River and Sutter Bypass

Flow gauges along the Feather River (FEA) and Sutter Bypass (SUT) in proximity of their confluence are not present. For this reason, daily flows were estimated using a mass balance relationship at their confluence: (cbec 2014)

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

The terms in the above relationship are daily flows from the hydraulic elements described in Table 3 Feather River and Sutter Bypass boundary condition evaluation.

Table 3 Feather River and Sutter Bypass boundary condition evaluation

Hydraulic Element	Description	Data source
VON	Sacramento River at Verona	USGS gauge 11425500
FRE	Fremont Weir Spill into Yolo Bypass	DWR's Water Data Library gauge A02930 until September 2003 and DWR's California Data Exchange Center gauge FRE from October 2003 to September 2012
WLK	Sacramento River below Wilkins	USGS gauge 11390500
KLOG	Colusa Basin Drain to the Sacramento River via Knights Landing Outfall Gates	DWR's Water Data Library gauge A02945
NCC	Natomas Cross Canal	Estimated from Steelhead Creek (formerly known as Natomas East Main Drainage Canal [NEMDC]) flows

Natomas Cross Canal

Peak flows and 5-day volumes during historic floods provided by the American River Watershed Common Features Project for Natomas Basin (USACE 2010) have been used. Using an average scaling factor of 1.43, the Natomas Cross Canal daily flows were estimated as:

NCC = 1.43 x NEMDC

Steelhead Creek

The stage data from the gauge along Steelhead Creek (NEMDC [C04]) was unreliable, because no stage variations were recorded, even during known storm events. For this reason, the gauge at the confluence of Steelhead and Arcade creeks (Arcade Creek/EMD C02) was used to generate daily flows for Steelhead Creek.

The DWR Division of Environmental Services (DES) has evaluated Steelhead Creek daily flows for a water quality investigation study (DWR 2008b) from July 2001 to December 2006. Real time stage data for the Arcade Creek gauge proved to be correlated with the Steelhead Creek gauge at the West El Camino Avenue Bridge. An equation that relates the two stage datasets has been developed.

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. It was extended including 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).

Westside Tributaries

The Yolo Bypass major western tributaries are Knights Landing Ridge Cut, Cache Creek Settling Basin, Willow Slough Bypass, Putah Creek.

The Westside Tributaries hydrology conditions have been evaluated by Jones & Stokes (2001) for the Yolo Bypass Management Strategy (YBPMS). In the YBPMS report, data were compiled for water years 1968-1998. The methods defined in the YBPMS were extended for the periods modeled in this report.

2.4 DEM development

Process to Create Bare-Earth DEM

In order to construct a digital elevation model (DEM) as input into the hydrodynamic model, several sources of data were used. The most expansive source of data was LiDAR data provided by the Central Valley Floodplain Evaluation and Delineation Program (CVFED) in the form of a large point cloud dataset. The data were stored in ASCII and LAS files, which were imported to ArcGIS. Because of the enormous quantity of data points within the LAS files, a thinning method called the "Window Size" method was used to reduce the number of points. Within ArcGIS, breaklines were added which allow for resolution of flow networks and boundaries once the points were converted to a raster. The entire dataset was then converted to a non-continuous 1-meter raster using the LAS to Raster tool in ArcToolbox. The raster was then made continuous by the Natural Neighbor interpolation method.

The data acquired from CVFED didn't cover the whole extent of the model domain, so other sources were compiled and added to the raster. The California Department of Water Resources (DWR) and the United States Geographic Survey (USGS) provided a 10-meter DEM resampled from 2-meter data for the San Francisco Bay and Sacramento – San Joaquin Delta from LiDAR which was composed of several single- and multi-beam sonar soundings along with integrated maps collated from multiple sources.

For the portion of the model that lies north of Interstate 80, a public DEM produced by National Oceanic and Atmospheric Administration (NOAA), DWR, and others was used. It is a 10 meter DEM using a North American Vertical Datum (NAVD) 1988 datum. Any other missing data were supplemented with the USGS National Elevation Dataset (NED) 10 meter DEM.

All these DEMs were projected to Universal Transverse Mercator (UTM) Zone 10 with a horizontal datum of North American Datum of 1983 (NAD83) with units of meters and NAVD88 as the vertical datum. The DEMs were resampled to 1 meter and combined according to the following priority (lowest to highest): NED 10-meter, NOAA/DWR 10-meter, USGS/DWR 10-meter, CVFED 2-meter LiDAR dataset.

In order to create a digital surface which would honor the flows that are to be passed through the model, additional steps needed to be taken. Features such as bridges, highways, and vegetation are visible to the airplane collecting LiDAR data, but are not physically present at the surface level where water flows. These features were removed manually.

Another consideration when looking at LiDAR-generated DEMs is that water surfaces reflect the beams sent by the plane sonar. The surface reflection obstructs the underwater terrain, or bathymetry, present in stream channels. To resolve this, different methods were used for varying stream types. For small channels and agricultural drainage ditches, polygons were drawn and the water surface elevation was lowered using ArcGIS. Our own information pertaining to the locations and conveyance of the channels was supplemented by the use of the Yolo Bypass Drainage and Water Infrastructure

Improvement Study (cbec 2014b). For larger streams, river channels from the 10-meter Sacramento-San Joaquin Delta DEM were extracted and then mosaicked into the working DEM using a ‘con’ statement in the Raster Calculator tool within ArcGIS which allowed for the replacement of terrain data only if it was lower than the working DEM. Once this work was done, the raster was re-interpolated using the Natural Neighbors interpolation method. The final DEM was imported into HEC-RAS Mapper.

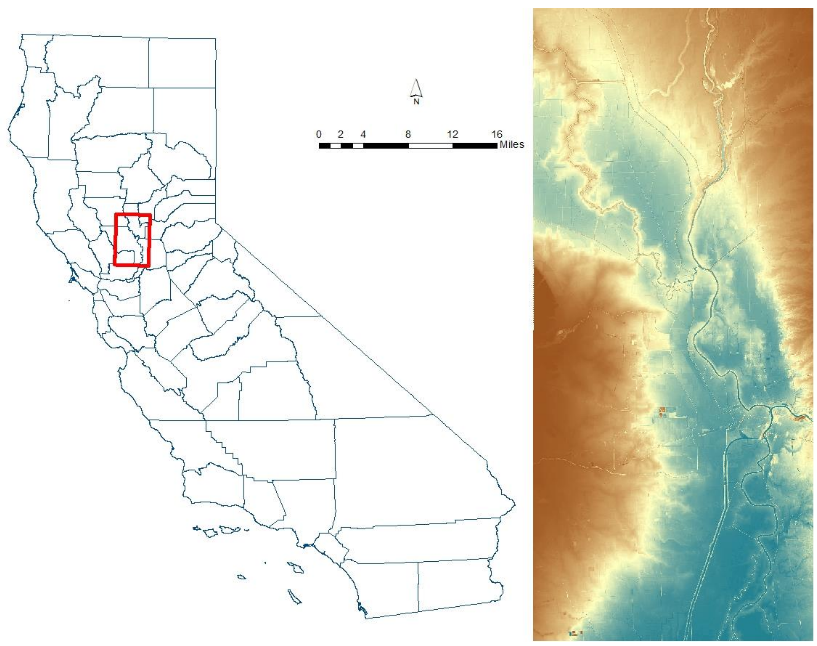

Figure 3 - Final Terrain

In October of 2014 conditions were such that the Upper Tule Canal Pond near the Fremont Weir was dry. This allowed for Eric Holmes, a Research Ecologist at the Center for Watershed Sciences, to conduct a Real Time Kinematic survey that produced terrain data in this area, much more accurate than the existing bathymetric data that was in the original DEM. The new surveyed data were set to a spatial reference of NAD83 UTM10N with a vertical datum of NAVD88, angular units of meters, and referenced to a National Geodetic Survey benchmark (NGS ID# AI5063) on the east concrete abutment of the Fremont Weir. Using ArcGIS, extraneous points were deleted, and the resulting points interpolated into a Triangulated Irregular Network (TIN). A raster was created using the Raster from TIN tool in ArcToolbox, fitting the cell size to 1 meter and setting the snap raster to the working DEM raster. Then the raster was clipped using a bounding polygon and laid into the working DEM raster using a ‘con’ statement in the Raster Calculator tool.

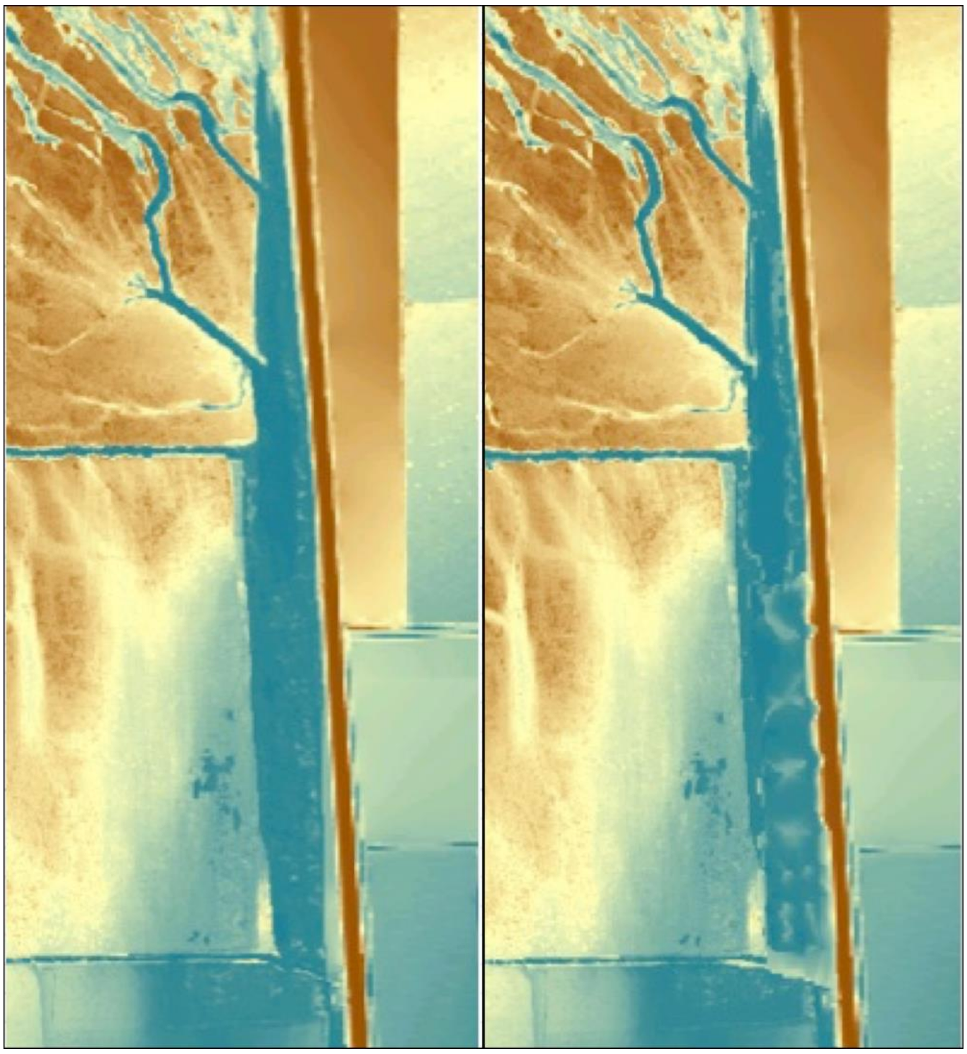

Figure 4 - Canal Pond Editing (Before on the left, and After on the right)

Bathymetry data were not available for the portion of the Sacramento River that runs along the Fremont Weir, but sparse cross-sectional data were known from the 1-Dimensional CVFED model. In addition to this reach, there was a portion of the Sacramento Slough in the Sutter Bypass that had no bathymetry. Data were collected to account for that portion of the Sacramento River and Sacramento Slough using the methods developed by Thomas Handley of the Center for Watershed Sciences (Handley 2015). A fish sonar was attached to a boat that was then navigated across the channels. The sonar data were recorded and then analyzed geospatially to create bathymetric data for the Sacramento River and Sacramento Slough (Figure 5 – The DEM created for the Sacramento River and Sacramento Slough). New techniques for interpretation of these data were implemented.

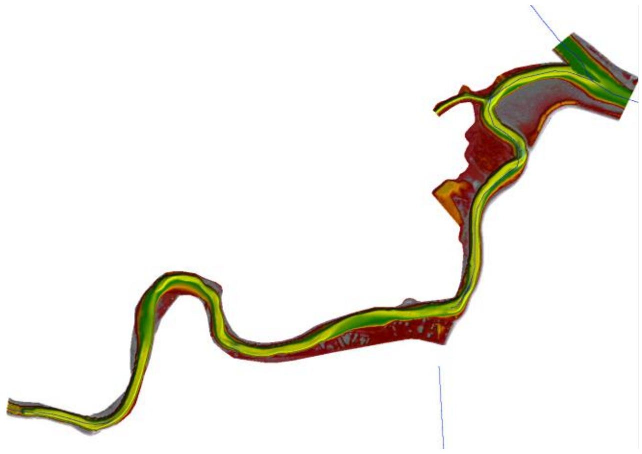

Figure 5 – The DEM created for the Sacramento River and Sacramento Slough

Additionally, there were portions of bathymetry that were collected as the project evolved. These portions were then added on top of the existing DEM using the RAS Mapper "Create New Terrain" feature. Portions updated include: Cache and Lindsey Sloughs, Little Holland Tract, and the Liberty Island Stairstep.

In order to produce an inundation map that renders appropriately, a tool in RAS Mapper was used which interpolates cross sections and creates a raster (tiff format) from the cross section channels. The resulting raster was then stitched together with the existing DEM (the most current version with up-to-date bathymetry) and resulted in a DEM that wouldn't "hide" water surface elevations lower than the LiDAR values of the existing DEM.

2.5 Land Use Classification File

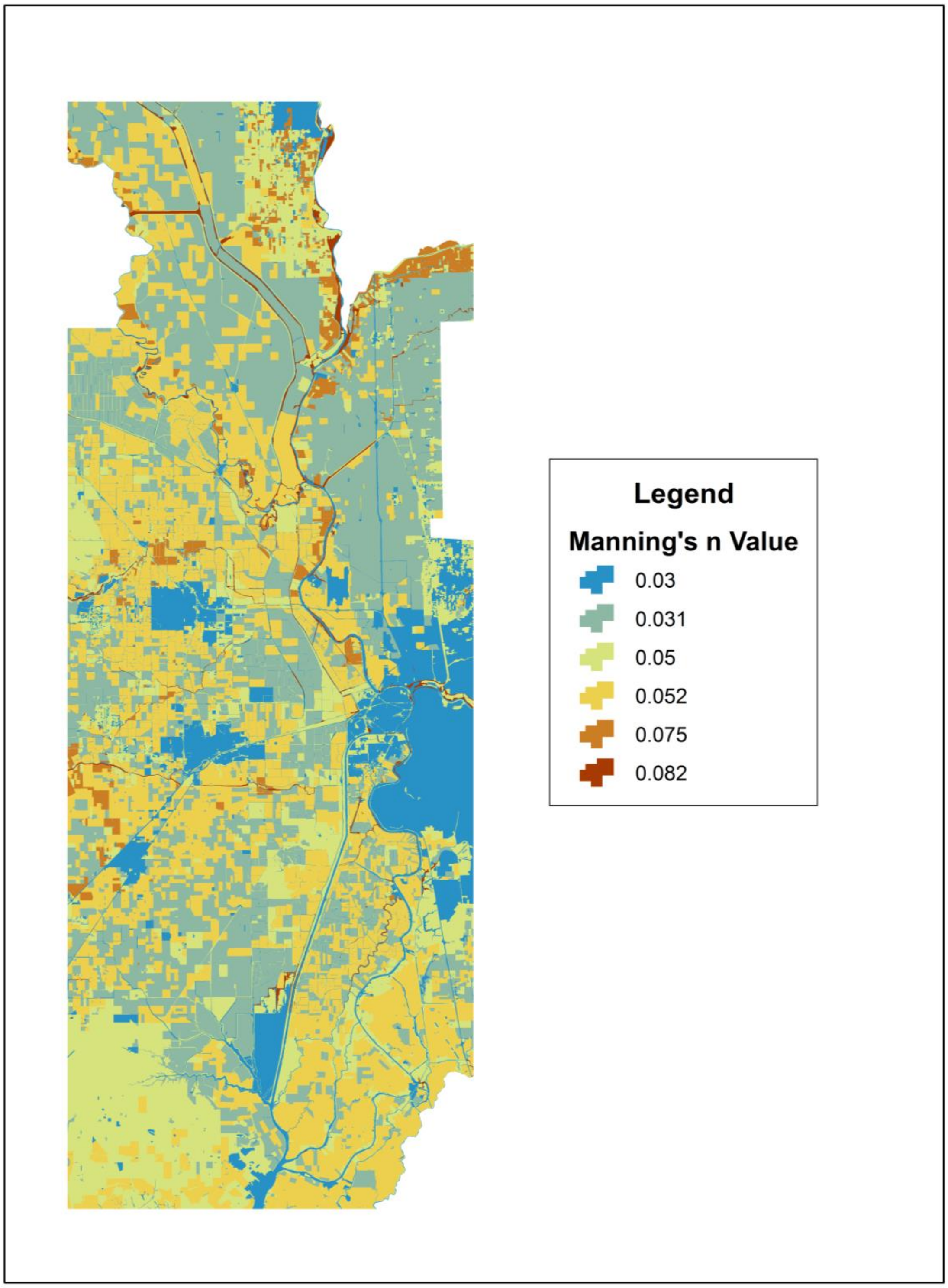

Figure 6 The final Land Use Classification raster used in the Yolo Bypass model, shown in RAS mapper with part of the legend shown on the right

A new feature of HEC-RAS in which multiple Manning's n values can be used in a geometry based on an input shapefile. Several steps were necessary in ArcGIS and in RAS in order to implement the new feature.

The basis of the roughness shapefile comes from the California Department of Water Resources (DWR), which collects land use surveys in order to map agricultural lands, irrigation methods, and water sources. The surveys used aerial photos and satellite imagery to define boundaries and then department staff identified the agricultural areas in the survey. The fieldwork was done with GPS to cross reference boundaries from satellite imagery with their current location. Using GIS software, summaries of land use were created and stored as shapefiles.

Four counties are included in the study area for the Yolo Bypass: Yolo, Sutter, Sacramento, and Solano Counties. The year the survey data were collected and geographic projections for each county are shown in Table 4.

Table 4 DWR County Surveys listed with year collected and geographic projection

County	Year Collected	Projection
Yolo	2008	NAD 1983 UTM Zone 10
Sutter	2004	GCS North American 1927
Sacramento	2000	GCS North American 1927
Solano	2003	NAD 1983 UTM Zone 10

For the GIS shapefiles to be used as an accurate representation of land use in the HEC-RAS software, all of the counties needed to be converted to NAD 1983 UTM Zone 10 – the projection used in the HEC-RAS project geometry and other geospatially referenced files. The four counties were merged together into a single file and assigned a Manning's n value based on the land use classification assigned to them. Two studies were used to determine the roughness coefficient used for each land use classification, the first was Yolo Bypass Drainage & Water Infrastructure Improvement Study 2 by cbec (cbec 2014b) and the second was Lower Feather River Corridor Management Plan Geomorphic & Ecological Modeling (cbec 2013). The land use classifications and roughness coefficients used, along with which resource used to determine the coefficient are shown in Table 5. Both studies referenced a report by CSU Chico, which was performed in the Central Valley and the Sacramento – San Joaquin Delta using the National Vegetation Classification System reference).

Table 5 Land use classification assignments

	Class	Subclass	Description of Class	Description of Subclass	Manning's n	Source: Feather River Study	Source: Yolo Salmonid EIR/EIS
Agricultural Classes	G		Grain and Hay Crops		0.052	*	
	R		Rice		0.03	*	*
	F		Field Crops		0.052	*	
	P		Pasture		0.031	*	*
	T		Truck, Nursery and Berry Crops		0.052	*	
	D	1-12,14,15	Deciduous Fruits and Nuts	Fruits, Nuts, Smaller trees	0.05	*	
		13		Walnuts	0.075	*	
	C		Citrus and Subtropical		0.05	*	
	V		Vineyards		0.052	*	
Semi-Ag	I		Idle		0.031		*
Urban Classes	S		Semiagricultural & Incidental to Agriculture		0.031		*
	U		Urban		0.03	*	
	UR		Residential		0.03	*	
	UC		Commercial		0.03	*	
	UI		Industrial		0.03	*	
	UL		Urban Landscape		0.03	*	
Native Classes	UV		Vacant		0.03	*	
	NC		Native Classes Unsegregated		0.03	*	
	NV	1	Native Vegetation	Grass land	0.031		*
		2		Light brush	0.031		*
		3		Medium brush	0.036		*
		4		Heavy brush	0.036		*
		5		Brush and timber	0.036		*
		6		Forest	0.082	*	*
		7		Oak grass land	0.082		*
	NR	1	Riparian Vegetation	Marsh lands	0.052		*
		2		Natural high water table meadow	0.052		*
		3		Trees, shrubs or other larger stream side or watercourse vegetation	0.082		*
		4		Seasonal duck marsh, dry or only partially wet during summer	0.052		*
		5		Permanent duck marsh, flooded during summer	0.052		*
	NW		Water Surface		0.03	*	
	NB		Barren and Wasteland		0.031		*

2.6 Quality of the data and uncertainties

Even measured data contain errors which cannot always be eliminated. Much of the boundary condition data used to model the Yolo Bypass and the Lower Sacramento River region suffer from not being measured at all, rather they are back calculated from other measured data. The land use data that supply estimates of floodplain roughness are fraught with errors and are not available for multiple years. The west-side tributaries are the least monitored and the estimates made by Jones & Stokes were not intended for habitat restoration work. A sensitivity study on estimated ranges of the west-side tributaries is being performed by CWS and should provide an understanding of the overall error these boundary flows can produce.

3 Calibration

Calibration began with simulating a low flow event and then evaluating a higher flow event and so on so as to incrementally model the system. Following these guidelines eliminates any chance that changing parameters to match observed values will affect earlier improvements.

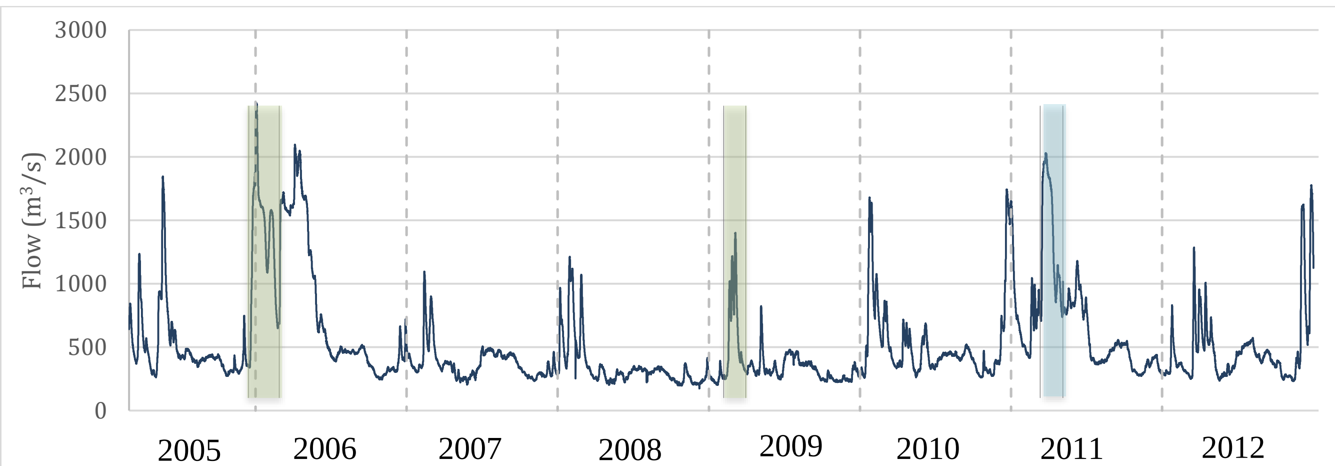

Figure 7 Plot of Sacramento River discharge at Verona (USGS gage 11425500). Green areas indicate model calibration periods and the blue area represents the validation simulation period.

To evaluate model agreement, both stage and flow values were compared with observed data. The February 2009 flood event was the first event that was simulated. In this event there was no spilling over the Fremont Weir and floodplain coverage was low, limiting most of the flows to the channels of the lower Sacramento River Basin and spillage from the Western tributaries onto the Bypass.

In order to calibrate the flood events to closely match observed time series, the roughness values assigned to the domain were modified by region. For example, to modify the flows and stages on the Nicolaus gage on the Feather River, the roughness values within the downstream area outlined inside of the 2D flow area were modified. This was done using the *2D Manning's n Region* feature in the HEC-RAS geometry editor (see Figure 8). Using this method, the roughness values which were set based on land use classification as described in the **2.5 Land Use Classification** File section are scaled proportionally within the region delineated.

Figure 8 Demonstration of *2D Manning's n Region* feature downstream of the Nicolaus gage on the Feather River

To adjust roughness for gages on 1D sections of the model domain, roughness values were modified according to flow using the *Flow roughness factors* tool in the geometry editor. Setting flow roughness factors allows an entire reach of 1D cross sections' Manning's n values to be modified using a multiplier which corresponds to a flow magnitude at the gage. Table 6 demonstrates the multipliers used for the stretch of Sacramento River downstream of the I Street Gage. In all of the tables for the flow roughness values, the multipliers increase with flow and never exceed a reasonable roughness value considering the riparian canopy. The increase in roughness with flow is justified when thinking of the increased riparian vegetation encountered with rising stage. This doesn't necessarily take into consideration spatially specific regions of roughness along the river reach, but allows for an approximation that expresses an appropriate behavior given the known information.

Table 6 Flow roughness factors downstream of the I Street gage on the Sacramento River

Flow at Gage (m^3/s)	Multiplier
0.	1.
400.	1.
600.	1.
800.	1.
900.	1.
1000.	1.1
1200.	1.3
2000.	1.4

In order to contextualize the observed gage locations, Appendix A displays the internal gage locations in the model domain. Flows and stages in the rivers outside of the Bypass' 2D area are in very good agreement with observed data for the 2009 simulation. See Appendix B for plots of stage and flow comparisons.

Once the model results at the gaged locations were more or less in agreement with observed data, the same approach was taken for a flood in 2006, plots and results in Appendix C. Modifications were made to the flow roughness factors and to the regional modifications of 2D roughness values, and then the 2009 event was run again in order to ensure that these 2006 modifications did not alter the agreement of the 2009 simulation.

There appears to be a limitation of model agreement across simulation periods due to the many unknown and unquantifiable components of a flood event. Hydrologic components of the flood including evaporation, infiltration, surface runoff from adjacent areas, low volume diversions and pumping, and smaller stream influences were not considered in this hydrodynamic model and these components are temporally variable. The hydrologic variability in these excluded features could explain some of the model disagreements across simulation periods.

4 Validation

Subsequent to calibration, a high flow flood event in March of 2011 was simulated and compared to observed data in order to further support the efficacy of the calibration, results in Appendix D. During this event, aerial photographs (Figure 31, Figure 32), observed time series data for flow and stage, and high water points (Figure 29, Figure 30) were used to validate the model results.

Given the range of flows simulated and the agreement in the stage and discharge, the following flow ranges are valid to use the model in simulations: at Sacramento River below Wilkins Slough 150 m^3/s (5,300 cfs) – 895 m^3/s (31,600 cfs), at Sacramento River at Verona 250 m^3/s (8,700 cfs) – 2,400 m^3/s (85,500 cfs), and at Sacramento River at Freeport 0/negative (Tidal) – 2,700 m^3/s (94,000 cfs).

5 Future work

There is currently a sensitivity study on estimated ranges of the west-side tributaries is being performed by CWS and the study should provide an understanding of the overall error these boundary flows produce.

The model is stable and able to be modified by any qualified hydraulic modeler to examine any proposed changes to the system and determine the effects.

Reference:

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Campbell, Chris (cbec), Rusty Jones (HDR), Manny Bahia (DWR) (2014). Hydrodynamic Modeling in the Yolo Bypass to Support Salmonid Habitat Restoration, Bay-Delta Conference, Poster Abstract

cbec (2013). Appendix H, Lower Feather River Corridor Management Plan Geomorphoc and Ecological Modeling, prepared for California Department of Water Resources and AECOM

cbec (2014a). Yolo Bypass Salmonid Habitat Restoration and Fish Passage Hydrodynamic Modeling Draft Report, prepared for California Department of Water Resources

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Handley, T. B. (2015) Cost-Effective Methods for Accurately Measuring Shallow Water Bathymetry with Single-Beam Sonar, thesis, University of California, Davis

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Yolo Bypass Working Group, Yolo Basin Foundation, and Jones & Stokes (2001)." A Framework for the Future: Yolo Bypass Management Strategy Final Report.

US Army Corps of Engineers Sacramento District 2007. (2007). Yolo Bypass 2-D Hydraulic Model Development and Calibration.

Resources

1 http://www.water.ca.gov/landwateruse/lusrvymain.cfm Department of Water Resources Land Use Survey

2 http://www.yolocounty.org/home/showdocument?id=23985 Yolo Bypass Drainage and Water Infrastructure Improvement Study. cbec. April 2014

3 http://www.water.ca.gov/floodmgmt/fmo/docs/LFRCMP-AppH-cbec2013a-GeomorphicEcologicalModeling-June2014.pdf Lower Feather River Corridor Management Plan Geomorphic and Ecological Modeling. cbec. October 2013

Appendix A Internal gage locations

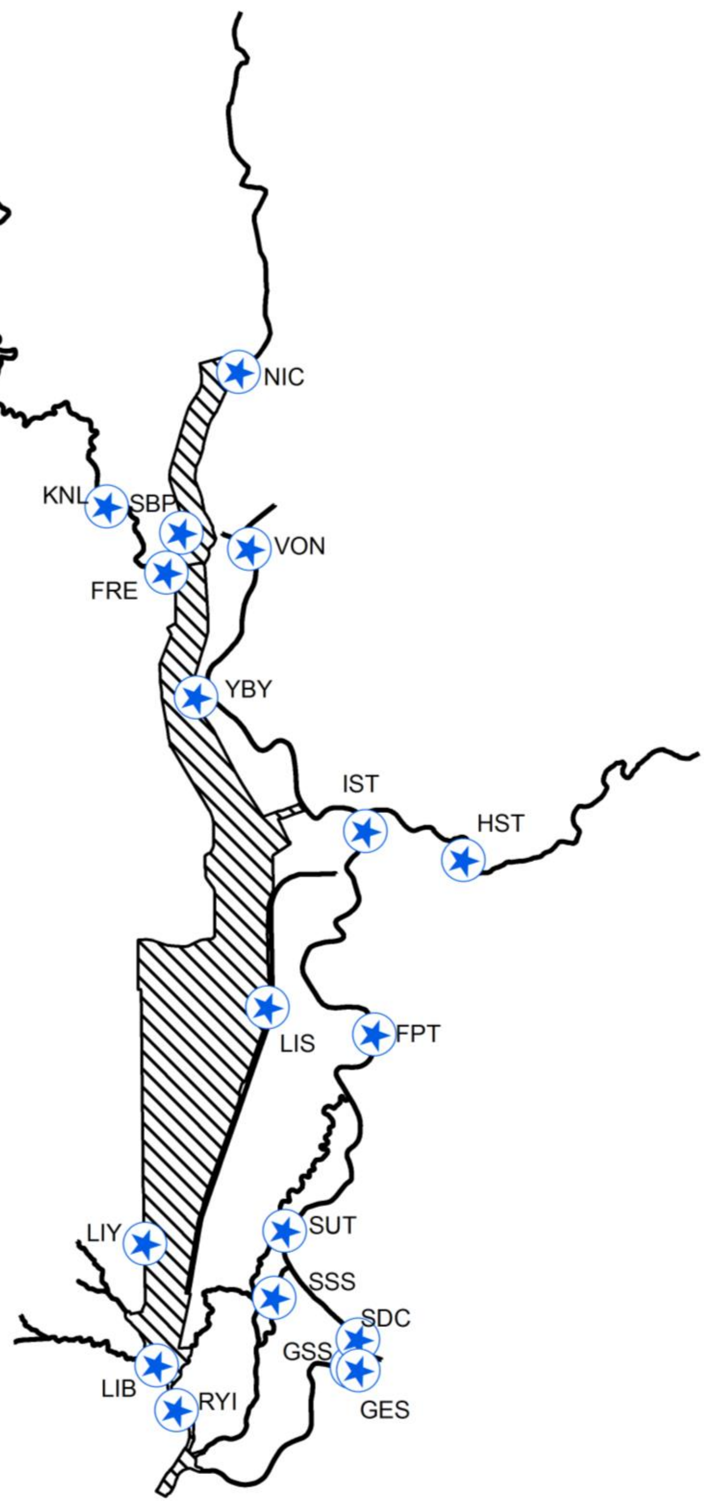

Figure 9 Internal gage locations for model calibration and validation

Appendix B - 2009 simulation results

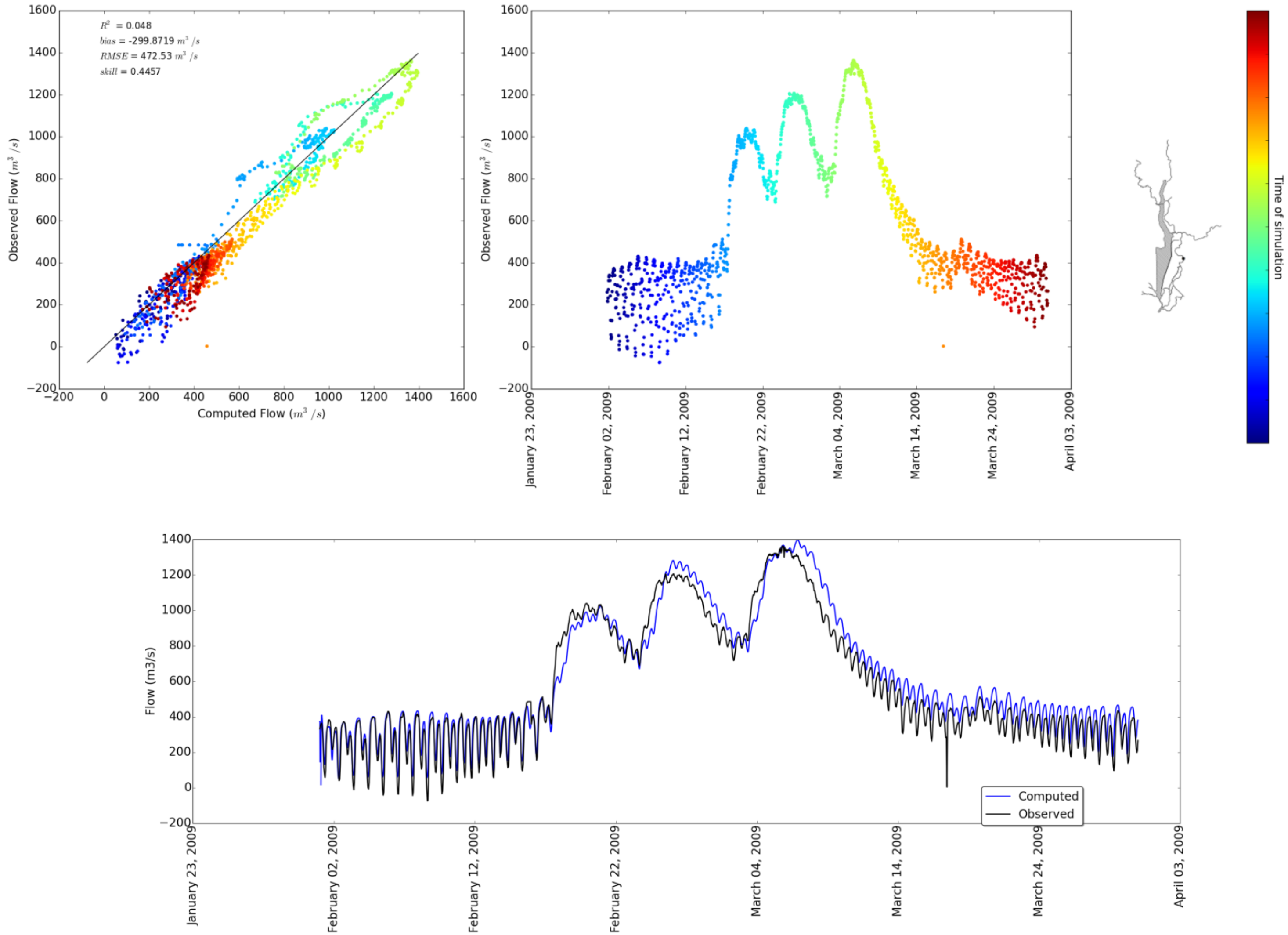

Figure 10 2009 Sacramento River at Freeport (FPT) gage flows

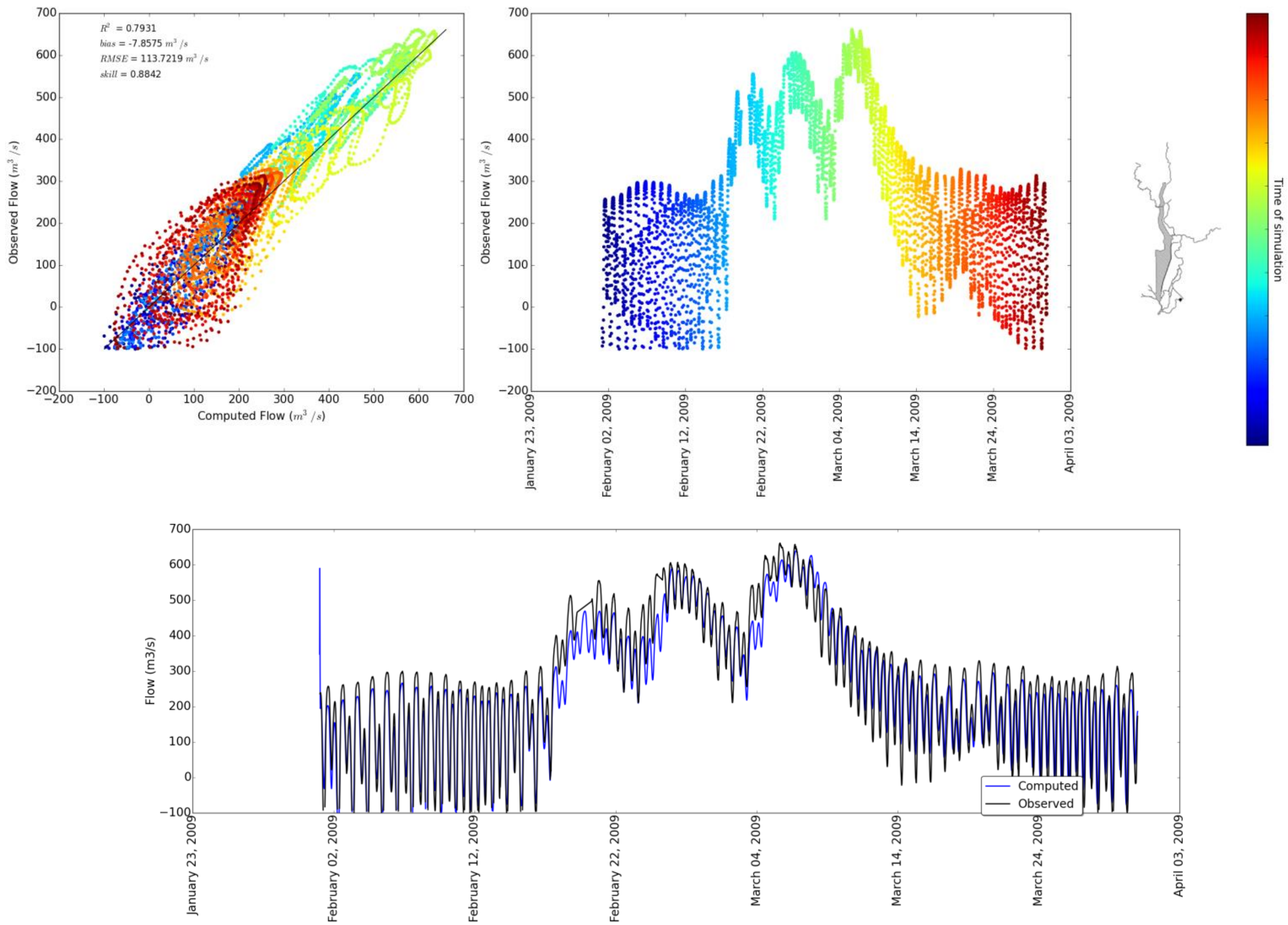

Figure 11 2009 Sacramento River below Georgiana Slough (GES) gage flows

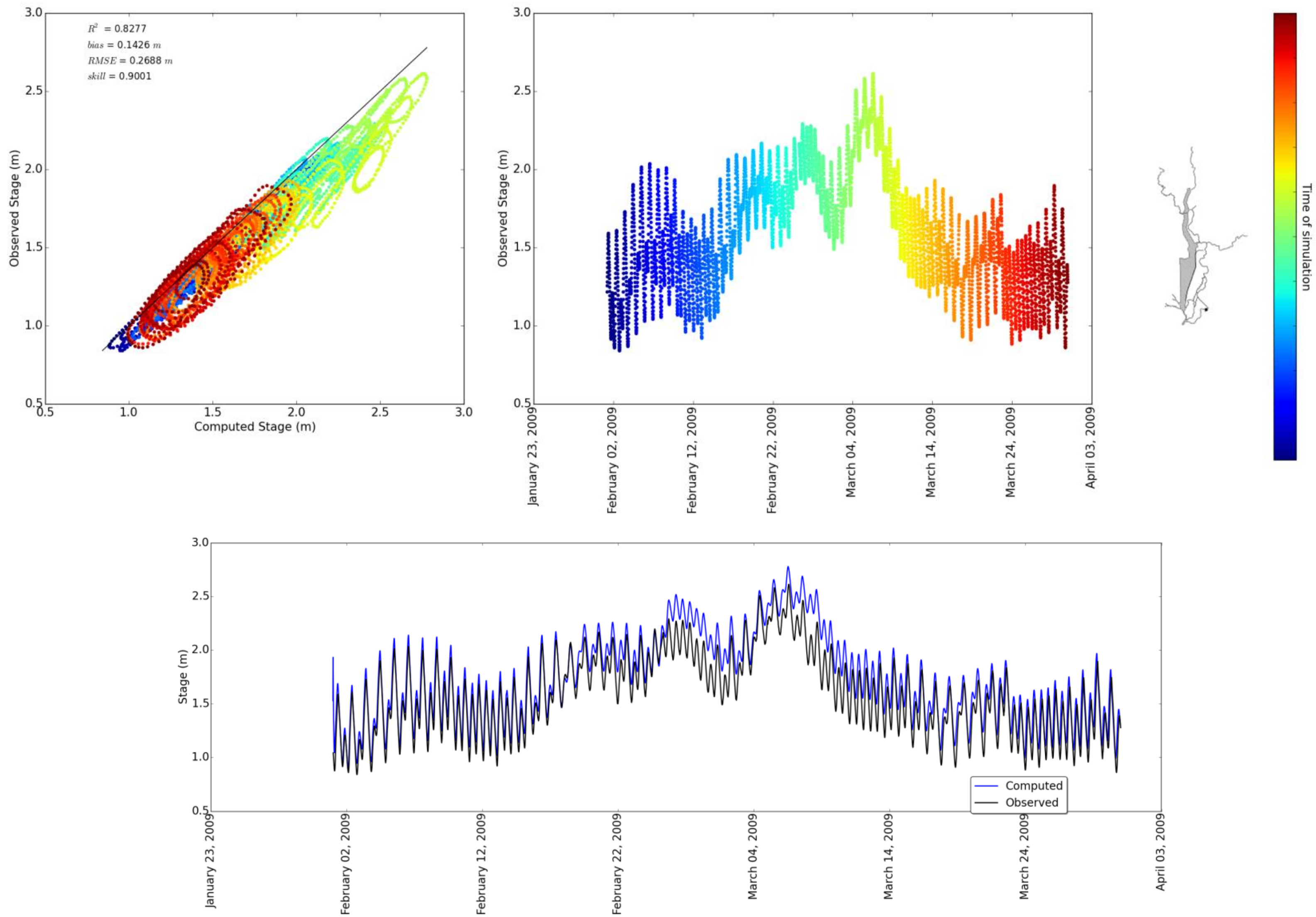

Figure 12 2009 Georgiana Slough at Sacramento River (GSS) gage stage

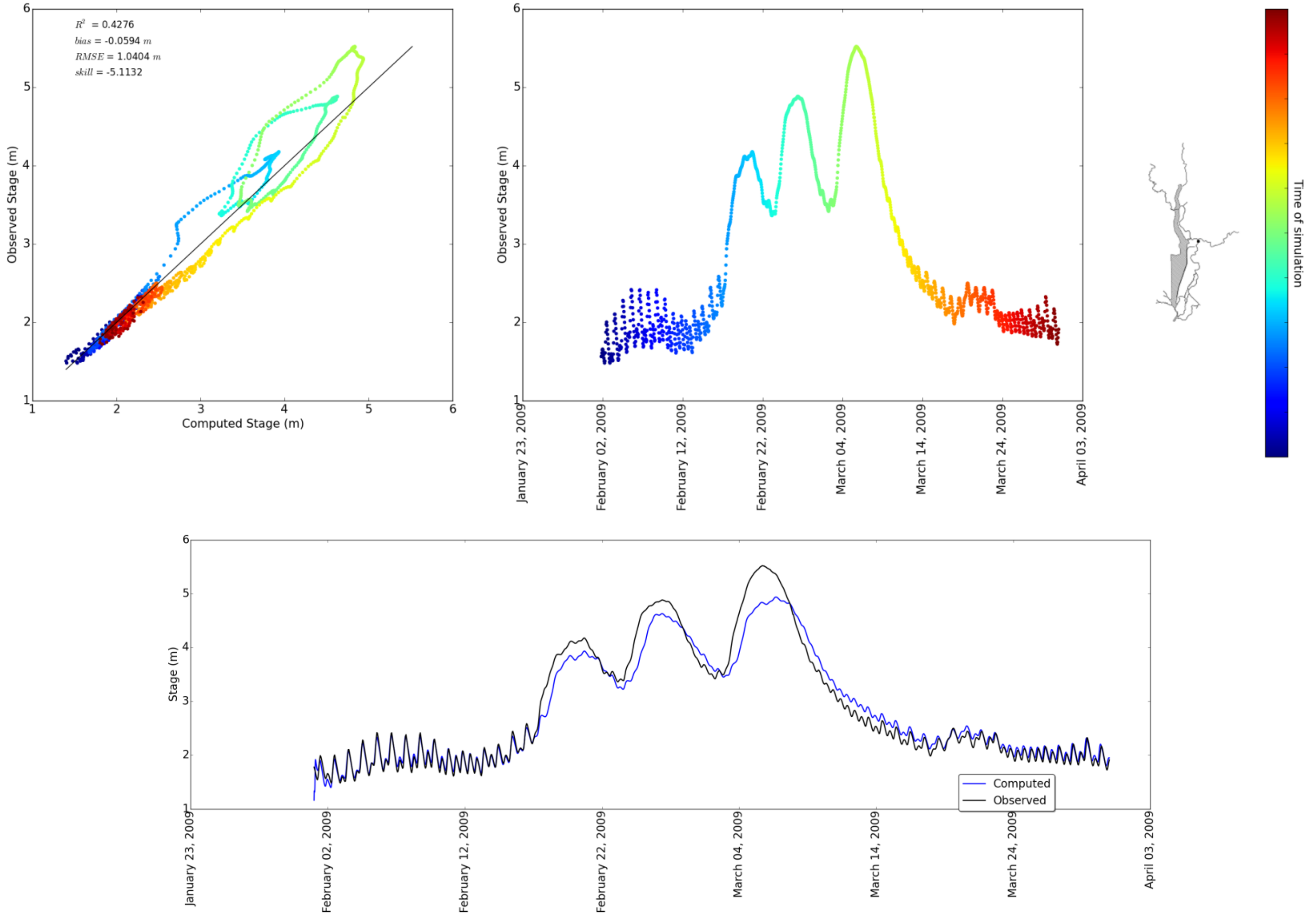

Figure 13 2009 Sacramento River at I Street (IST) gage stage

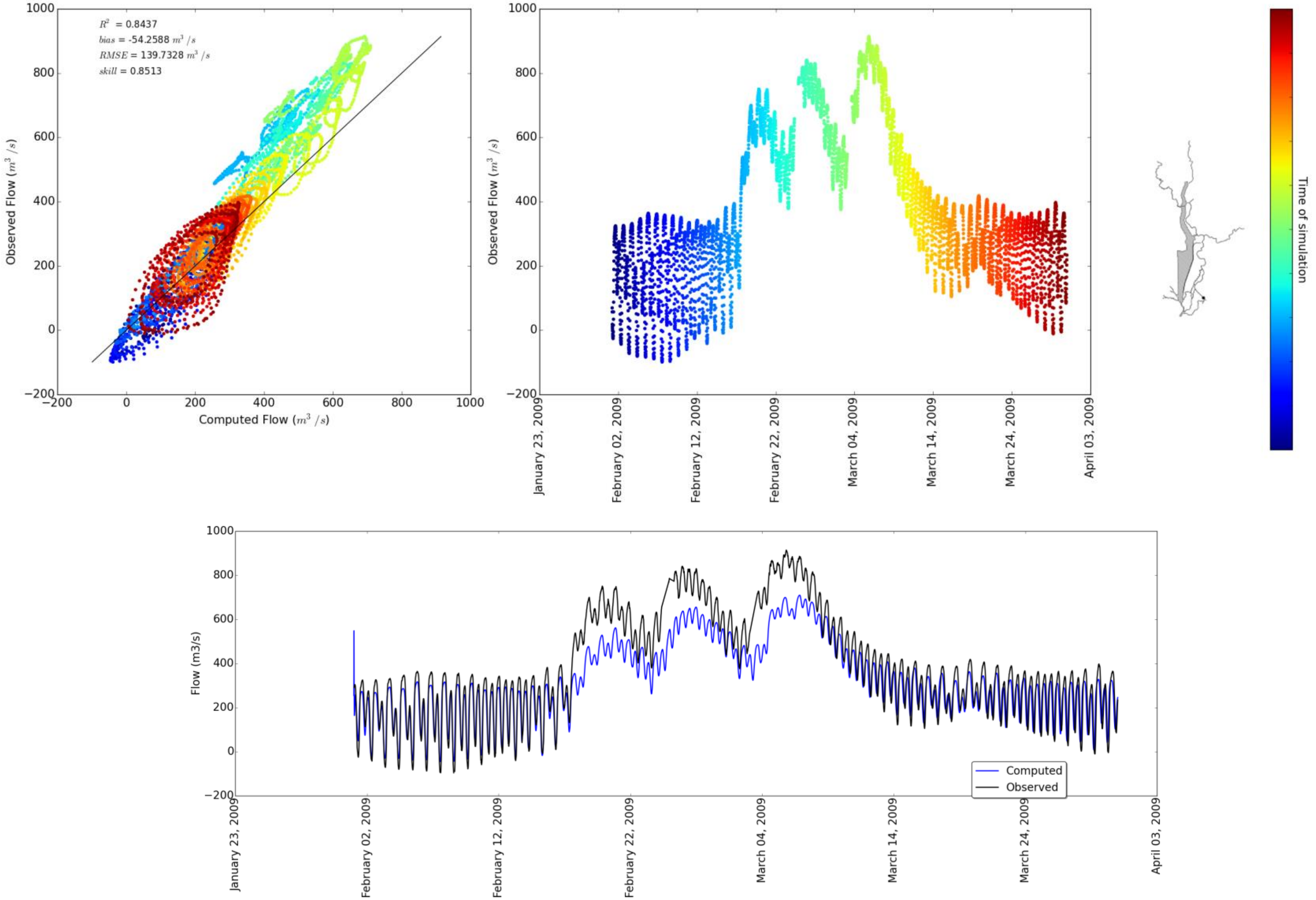

Figure 14 2009 Sacramneto River above Delta Cross Channel (SDC) gage flows

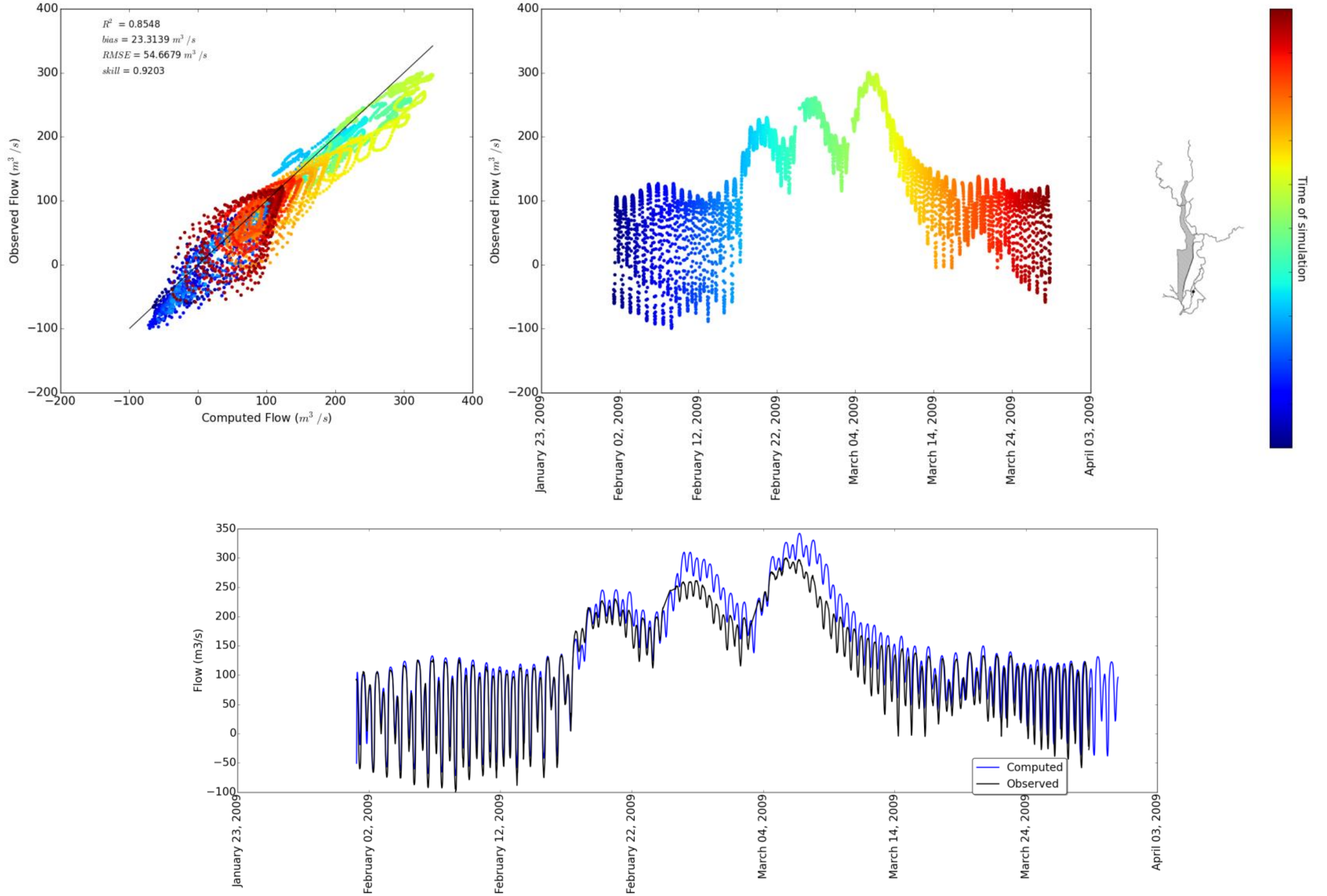

Figure 15 2009 Steamboat Slough between Sacramento River and Sutter Slough (SSS) gage flows

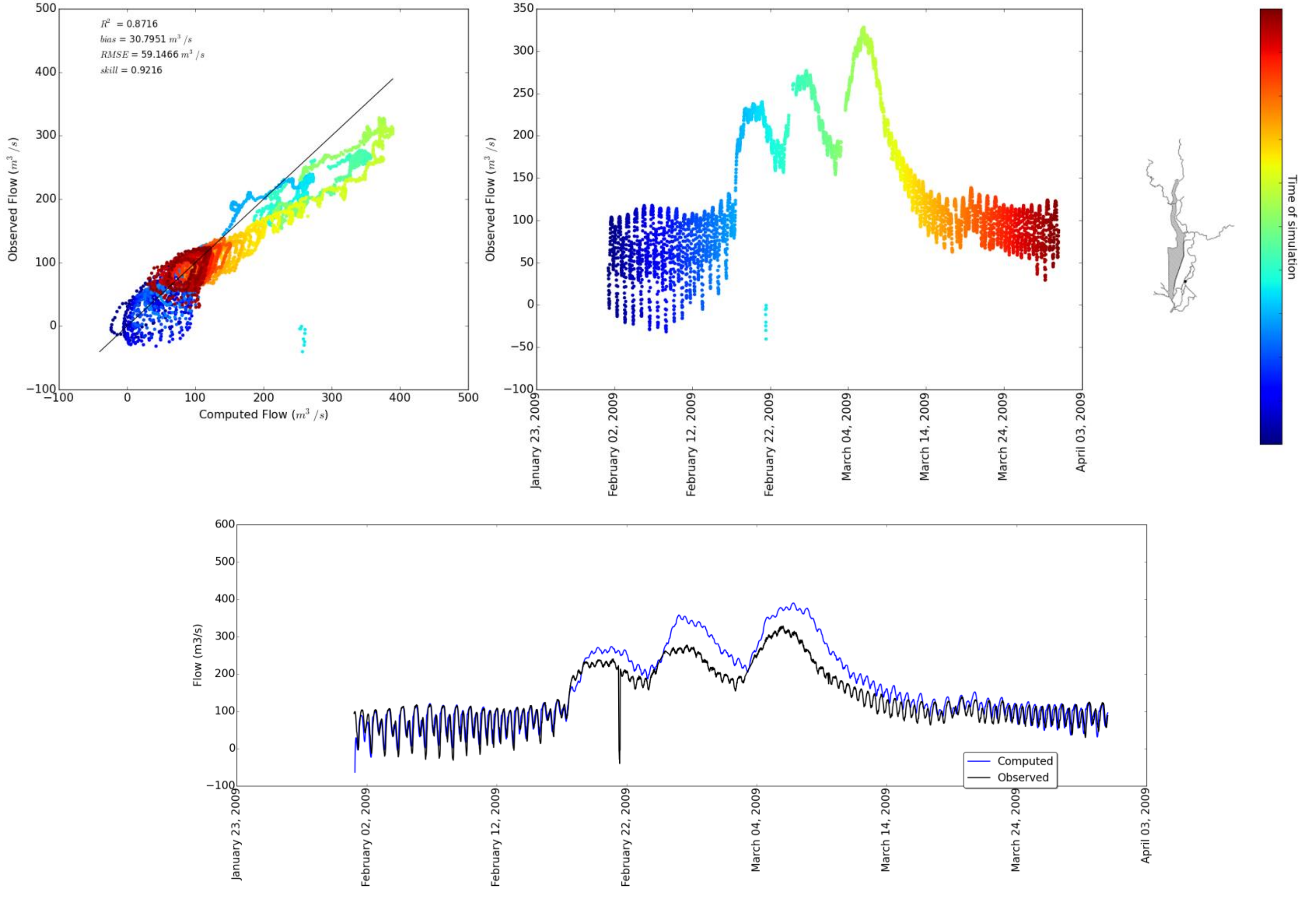

Figure 16 2009 Sutter Slough (SUT) gage flows

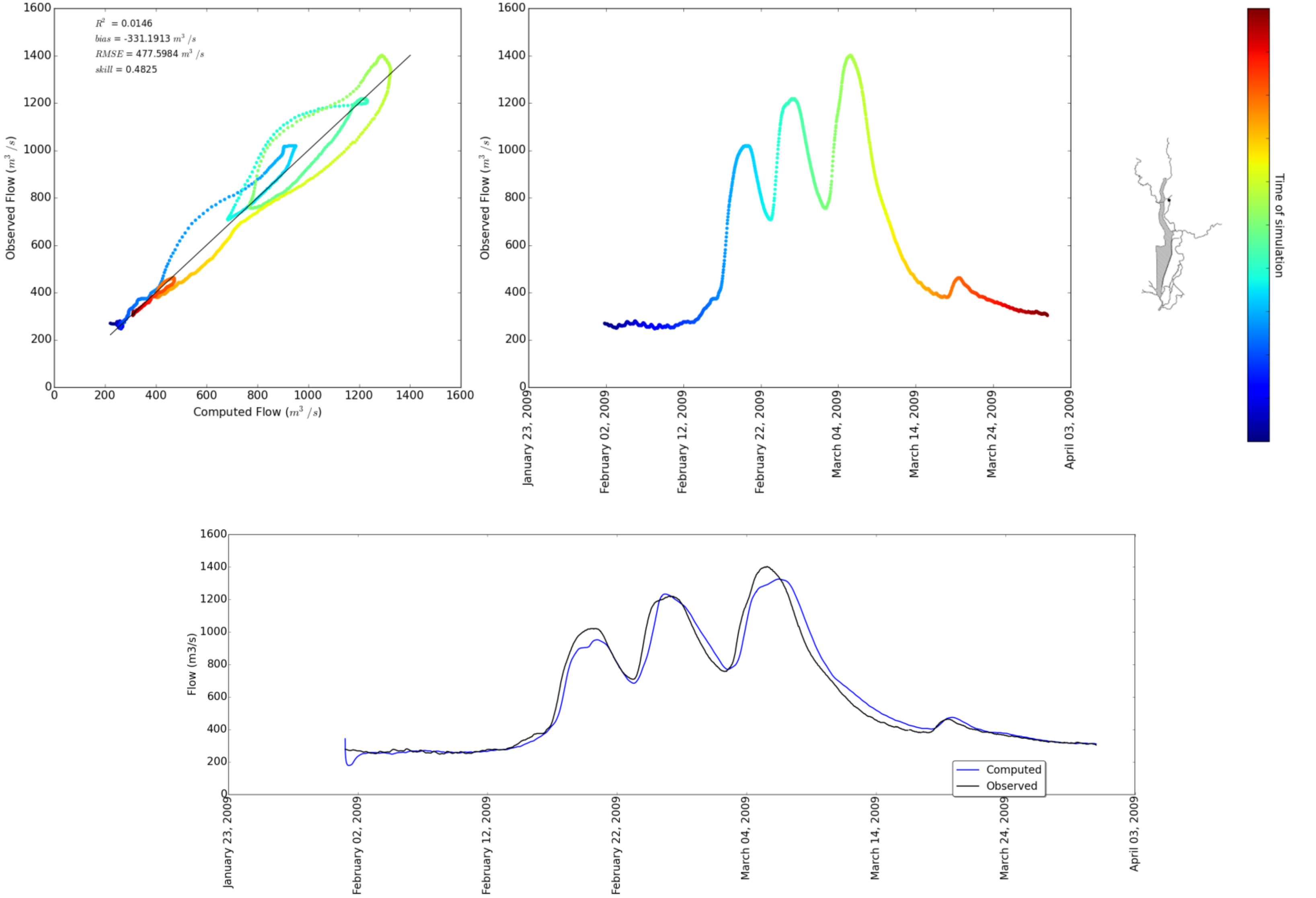

Figure 17 2009 Sacramento River at Verona (VON) gage flows

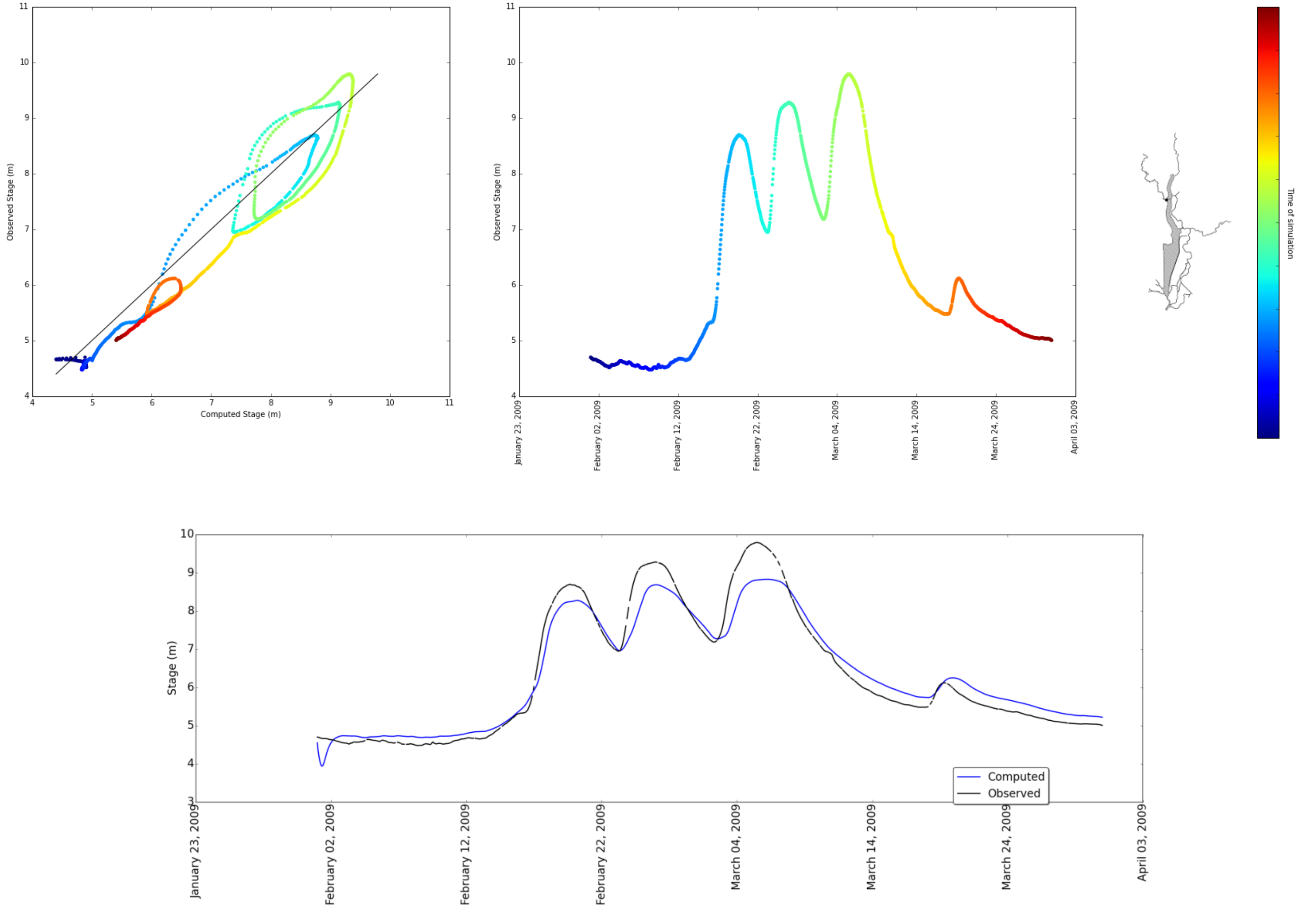

Figure 18 2009 Fremont Weir (FRE) gage stage

Appendix C - 2006 simulation results

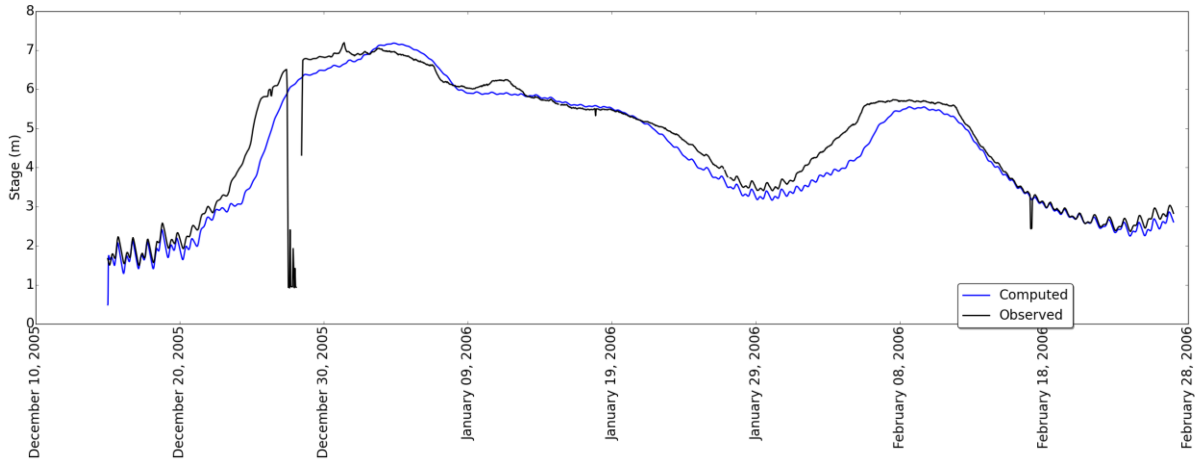

Figure 19 2006 Sacramento River at Freeport (FPT) gage stage

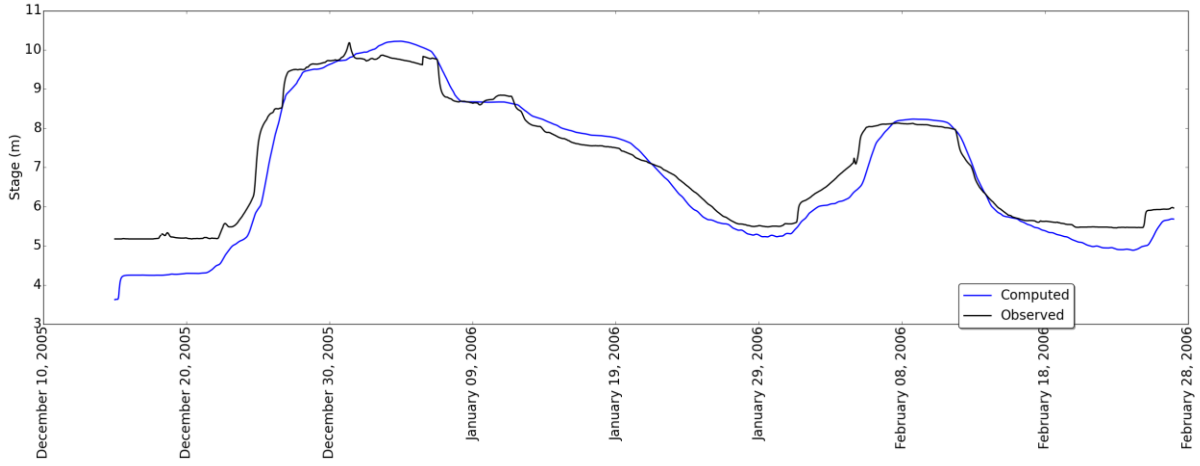

Figure 20 2006 American River at H Street (HST) gage stage

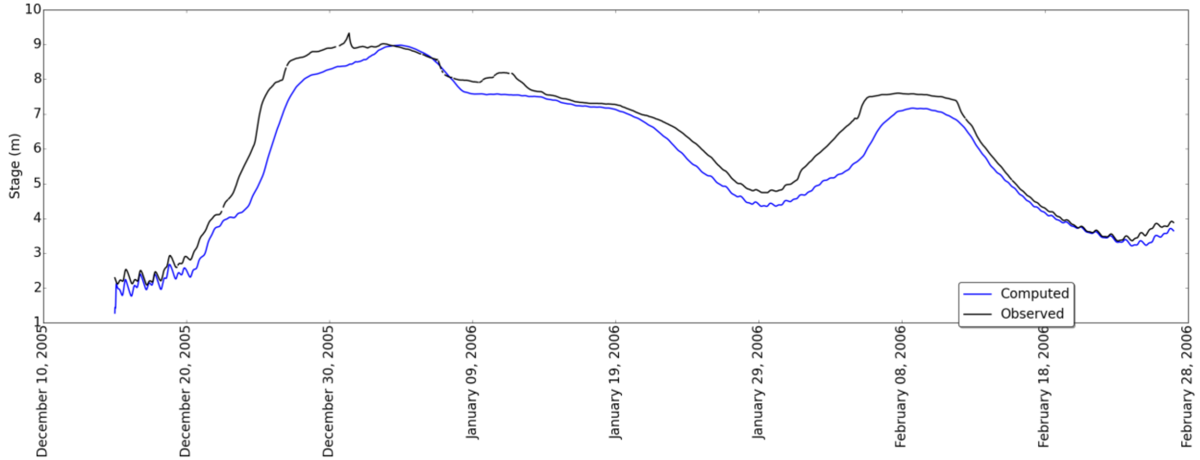

Figure 21 2006 Sacramento River at I Street (IST) gage stage

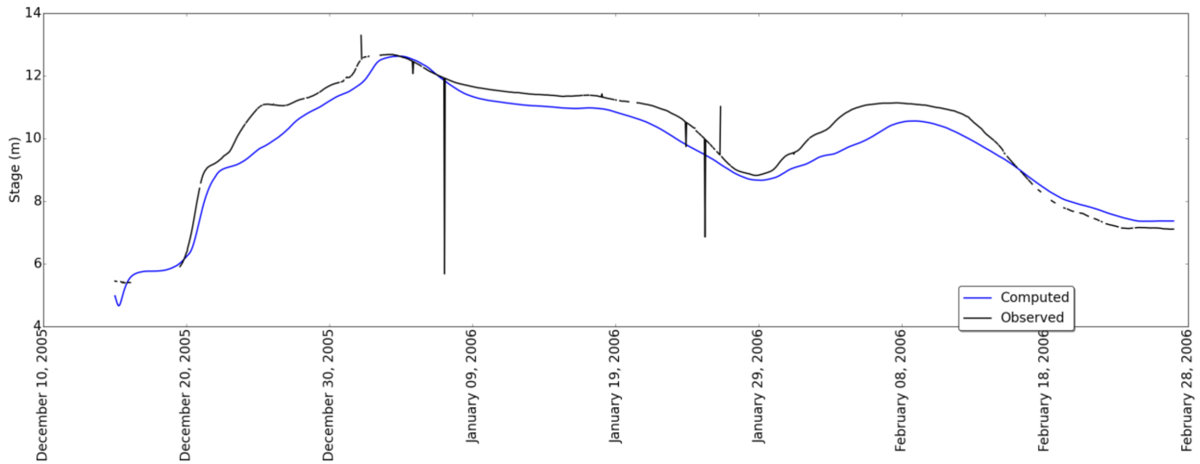

Figure 22 2006 Knights Landing Ridge Cut (KNL) gage stage

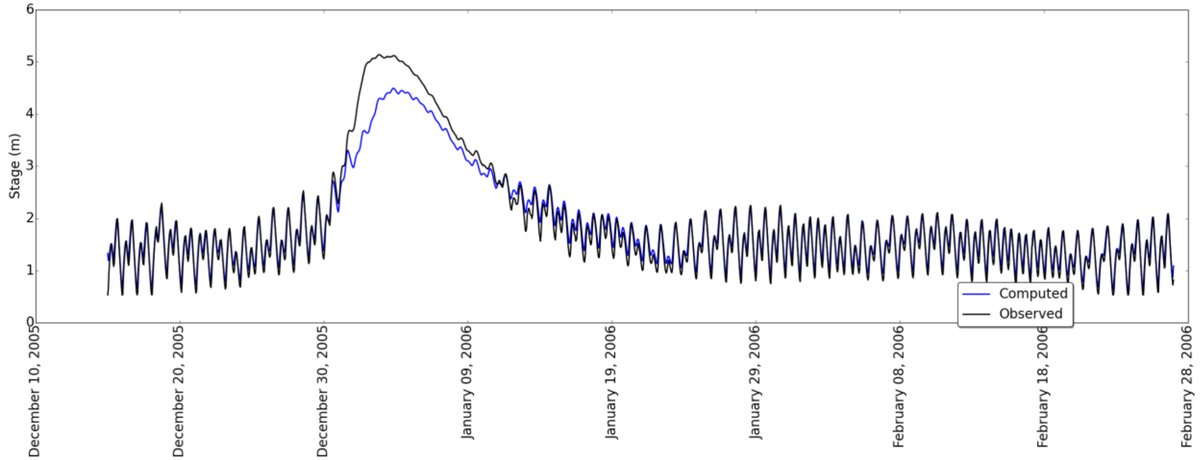

Figure 23 2006 Liberty Island at Yolo Bypass (LIY) gage stage

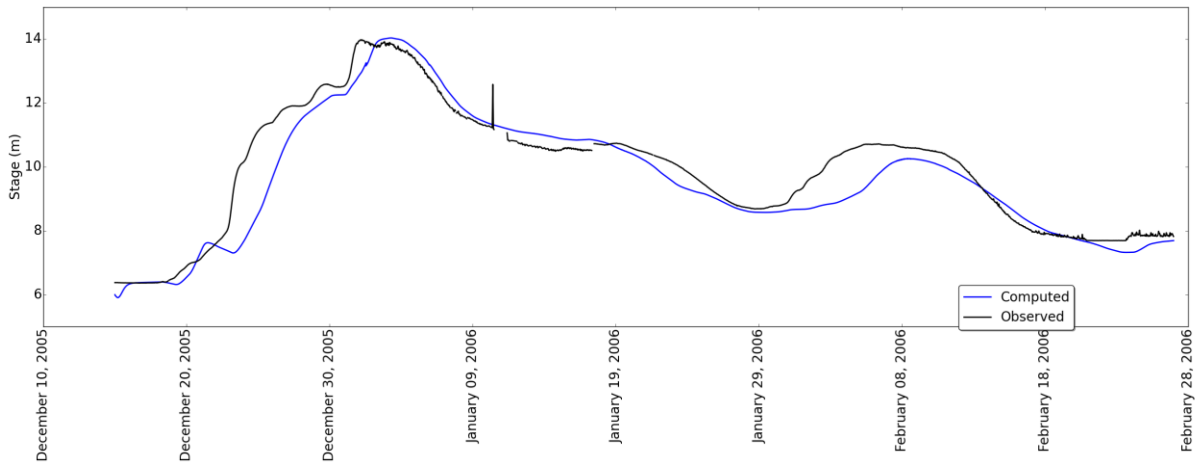

Figure 24 2006 Liberty Island at Yolo Bypass (LIY) gage stage

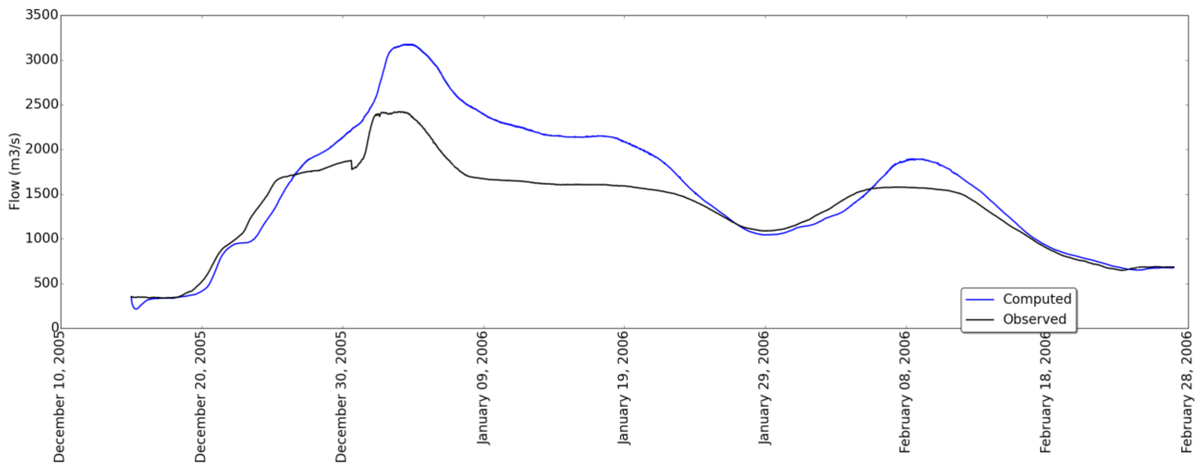

Figure 25 2006 Sacramento River at Verona (VON) gage flow

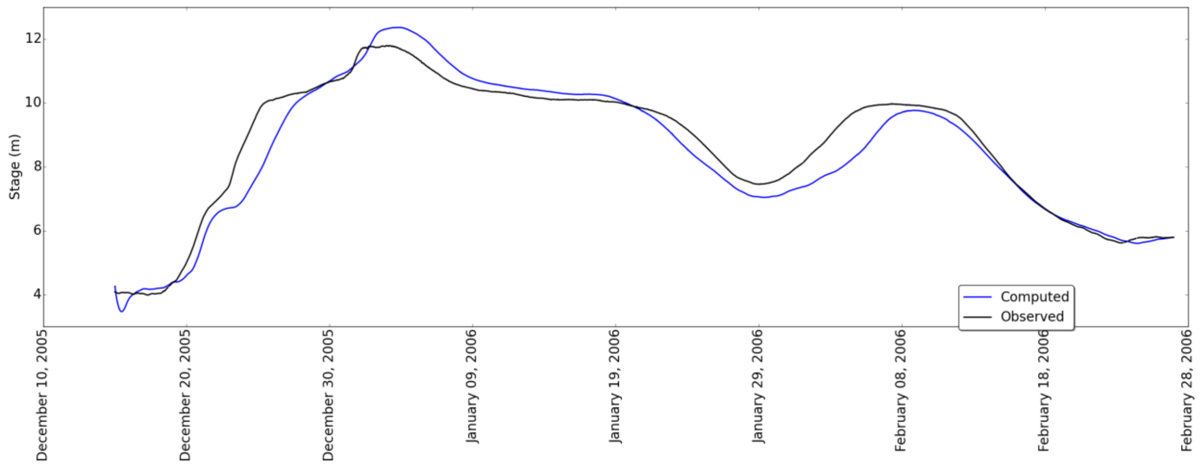

Figure 26 2006 Sacramento River at Verona (VON) gage stage

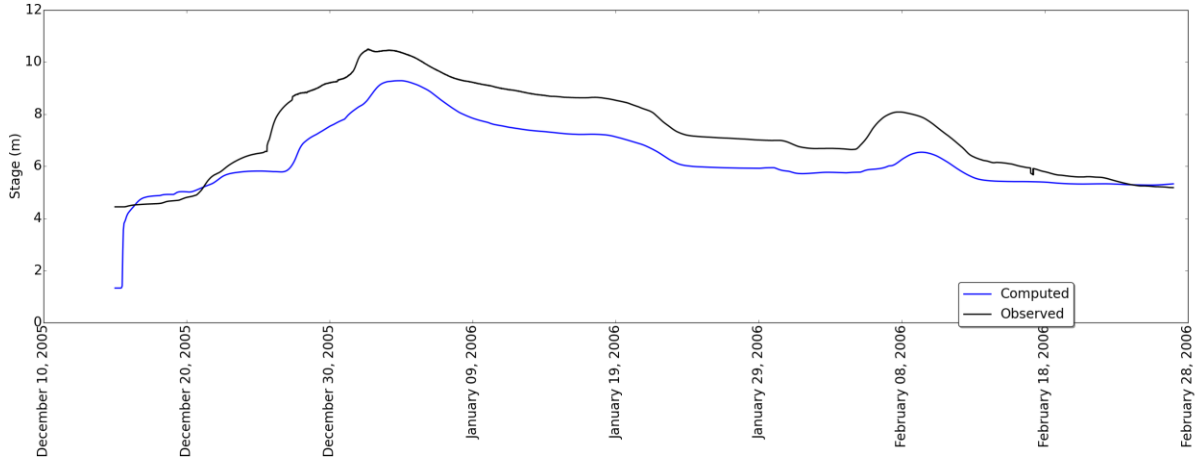

Figure 27 2006 Yolo Bypass near Woodland (YBY) gage stage

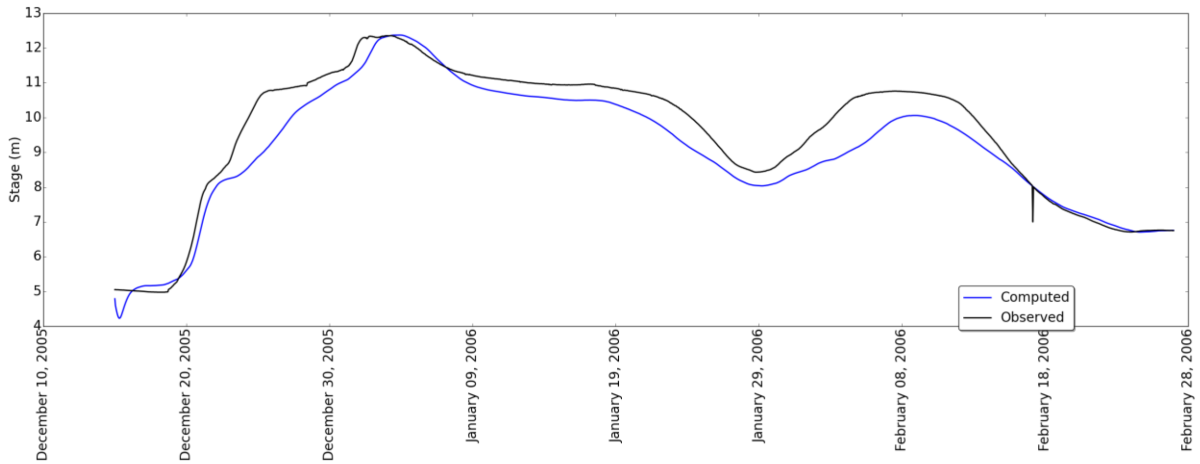

Figure 28 2006 Fremont Weir (FRE) gage stage

Appendix D - 2011 simulation results

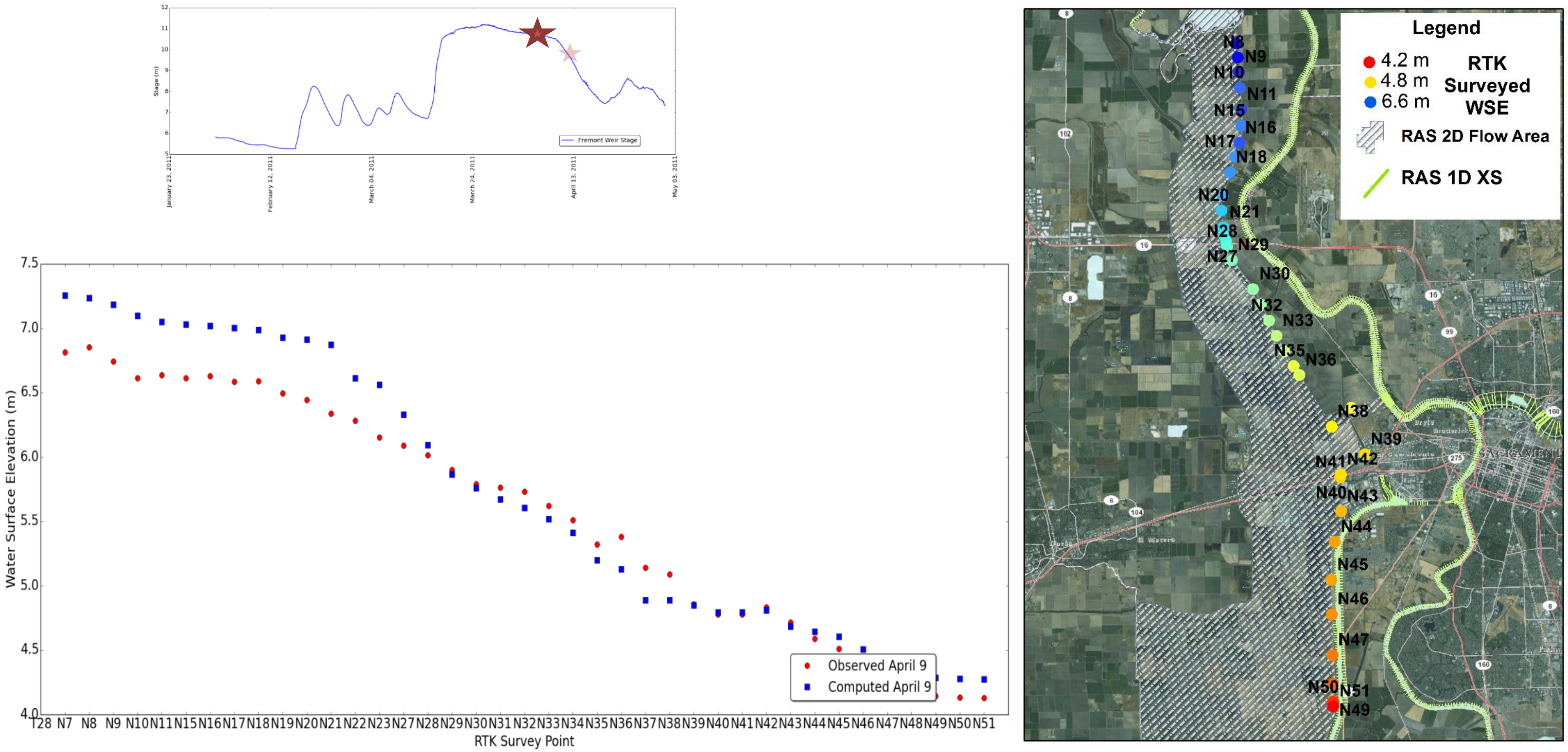

Figure 29 Water surface elevation (WSE) point comparison from real time kinetic (RTK) survey on April 9, 2011. (A) The point on the hydrograph where the survey was taken. (B) The graphical comparison of the surveyed WSEs. (C) The locations and WSE of the survey points shown in color.

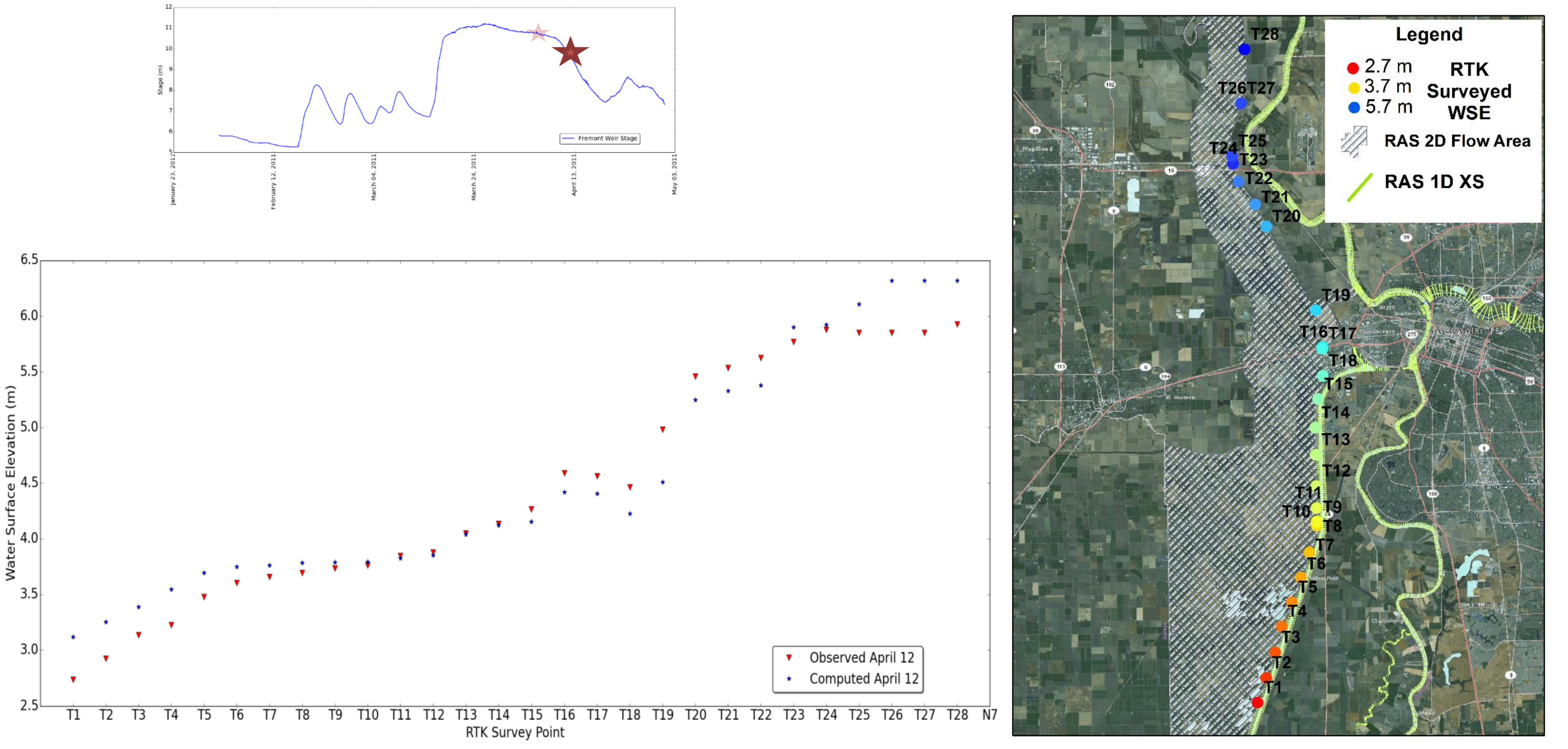

Figure 30 Water surface elevation (WSE) point comparison from real time kinetic (RTK) survey on April 12, 2011. (A) The point on the hydrograph where the survey was taken. (B) The graphical comparison of the surveyed WSEs. (C) The locations and WSE of th

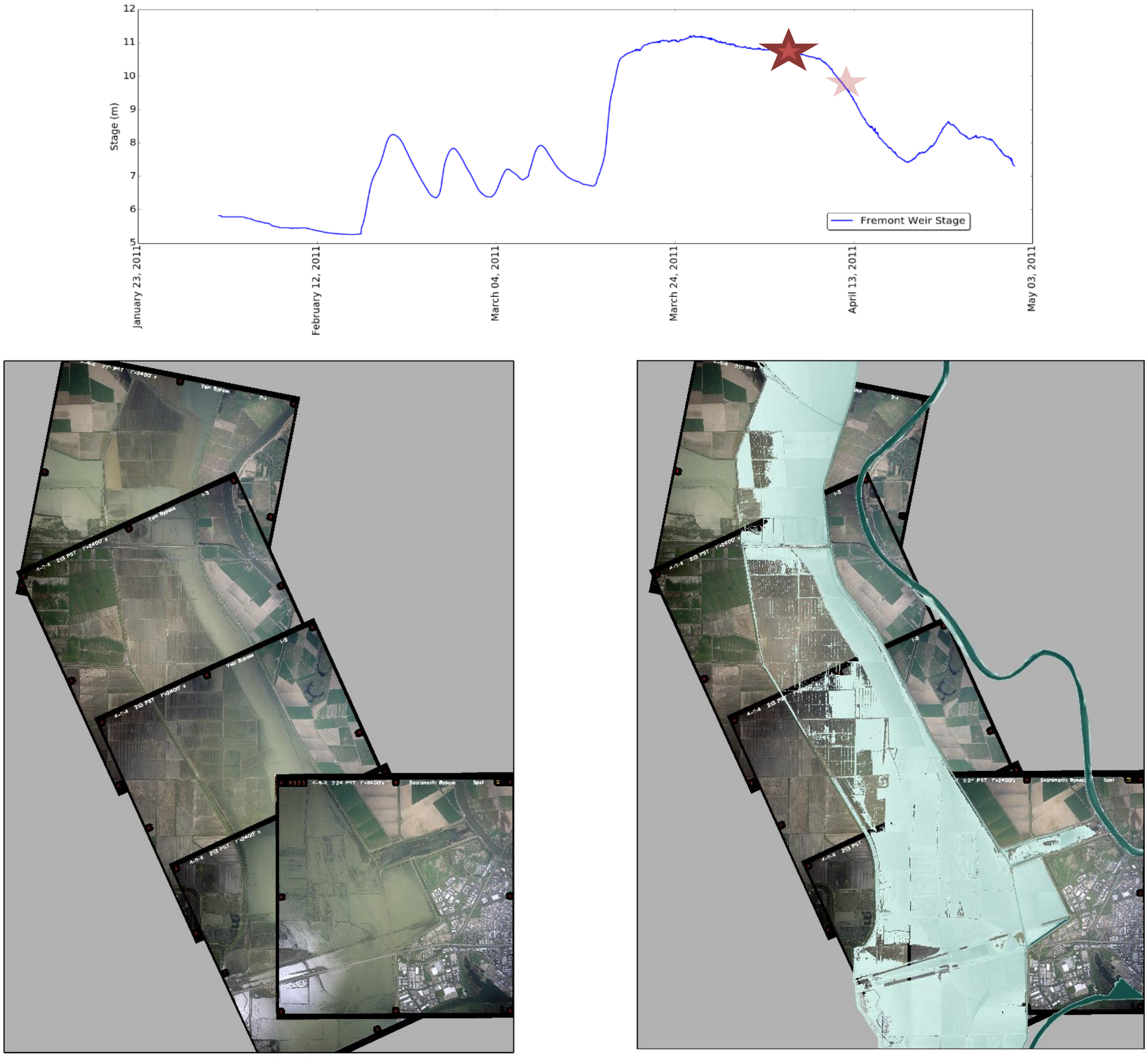

Figure 31 Aerial imagery comparison of the Yolo Bypass on April 9, 2011. Aerial imagery (left) compared to the modeled results (right), and the time the photo was taken is shown in the hydrograph (above).

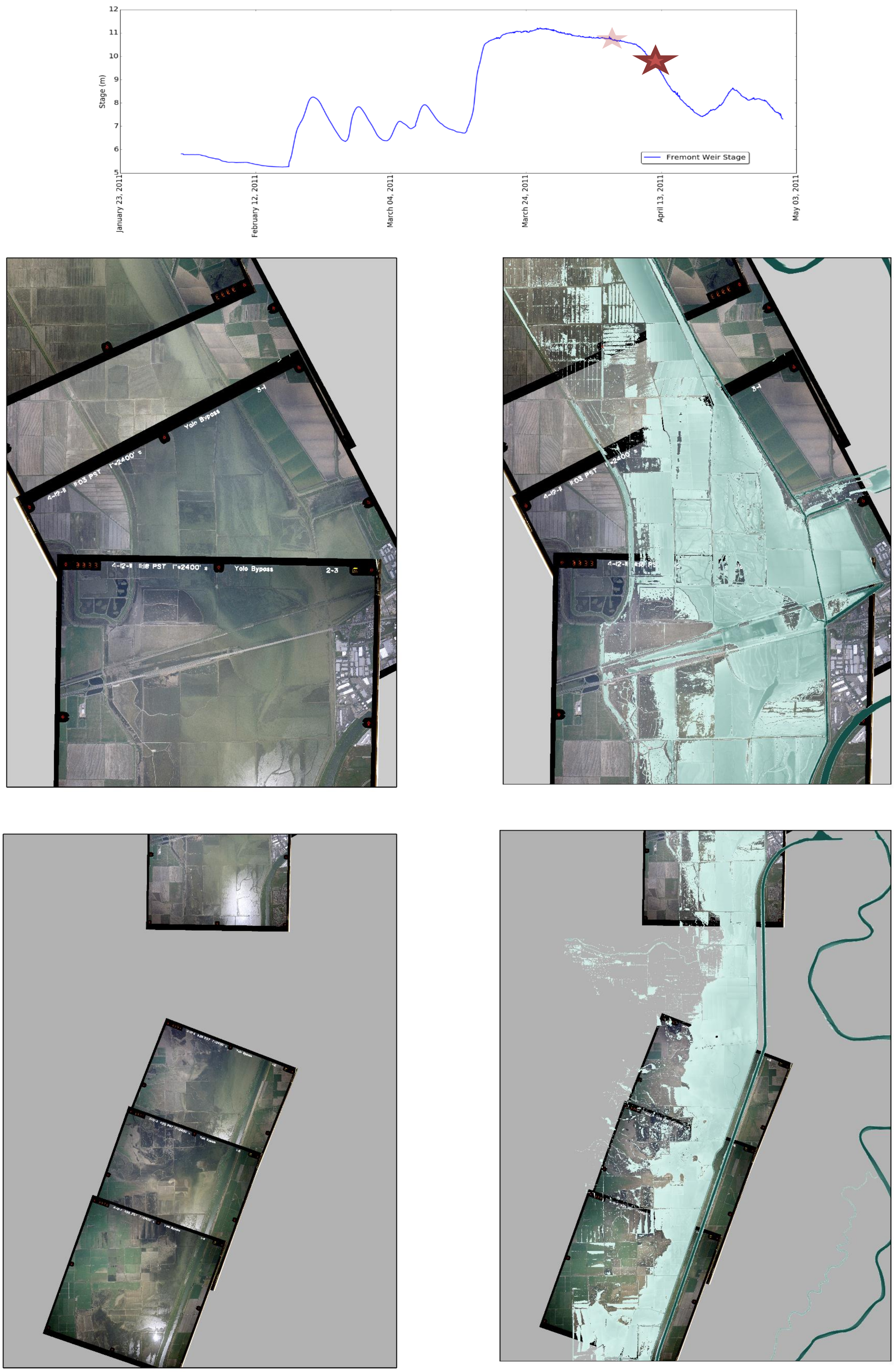

Figure 32 Aerial imagery comparison of the Yolo Bypass on April 12, 2011. Aerial imagery (left) compared to the modeled results (right), and the time the photo was taken is shown in the hydrograph (above).

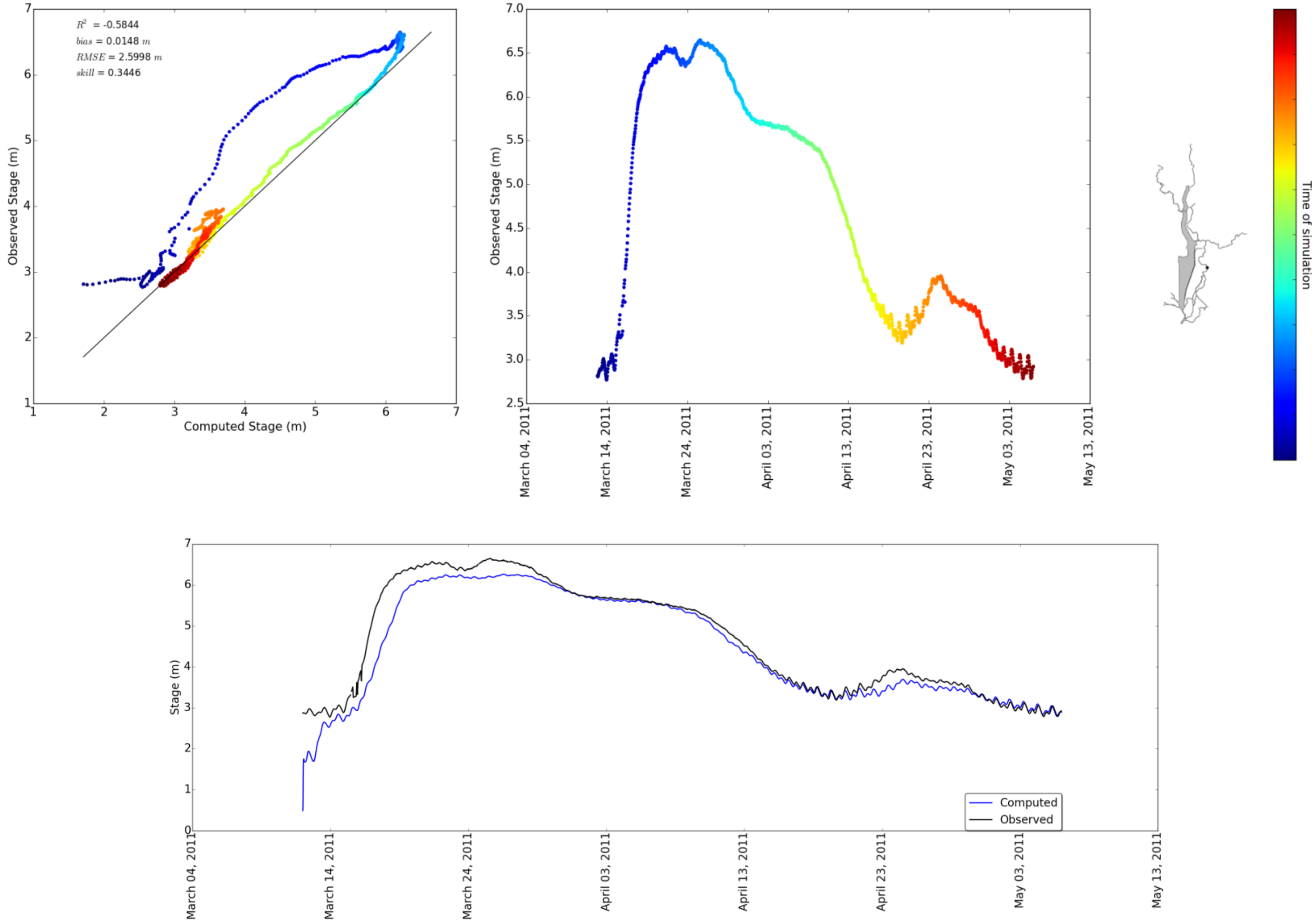

Figure 33 Sacramento River at Freeport (FPT) gage stage

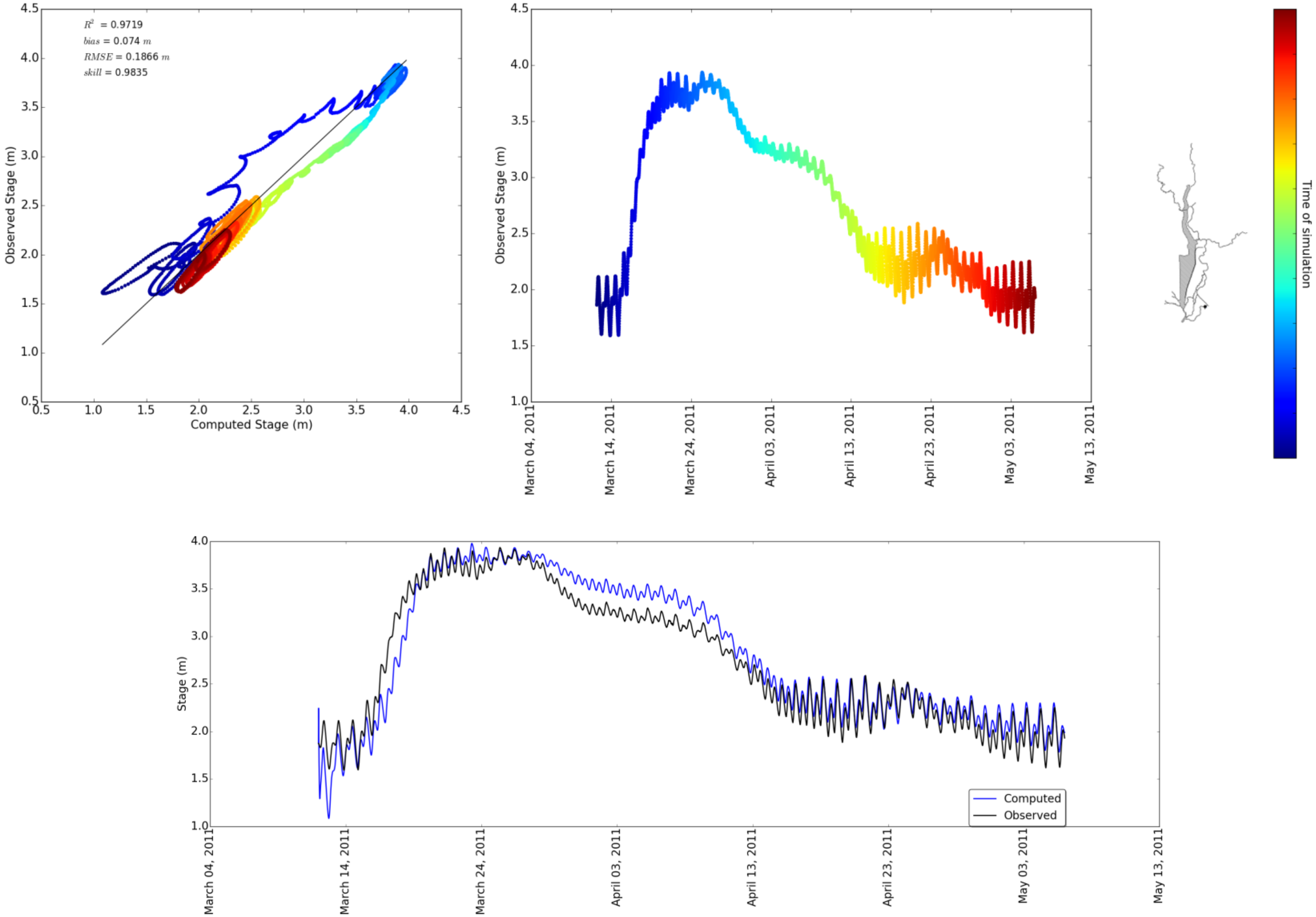

Figure 34 Georgiana Slough at Sacramento River (GSS) gage stage

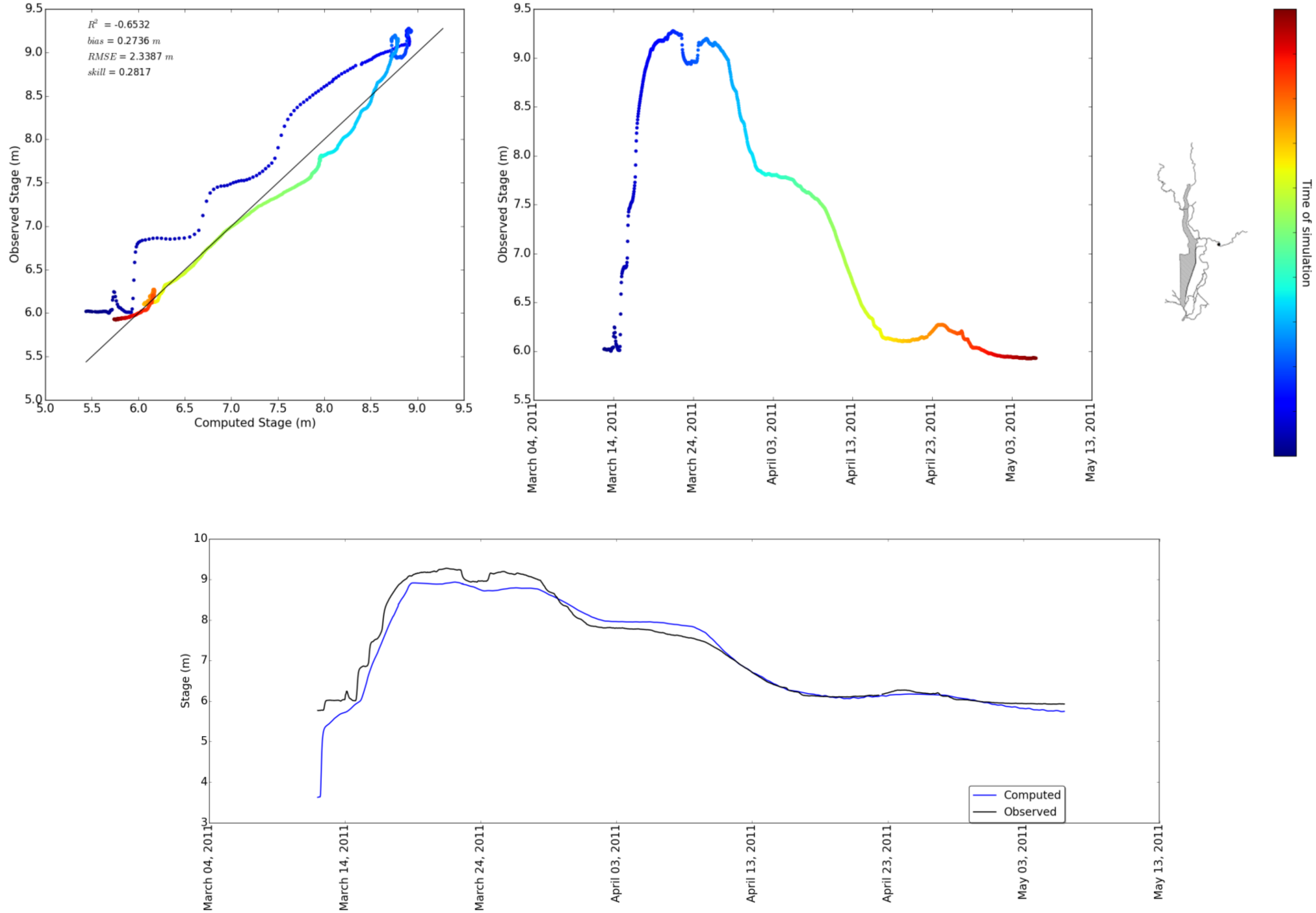

Figure 35 American River at H Street (HST) gage stage

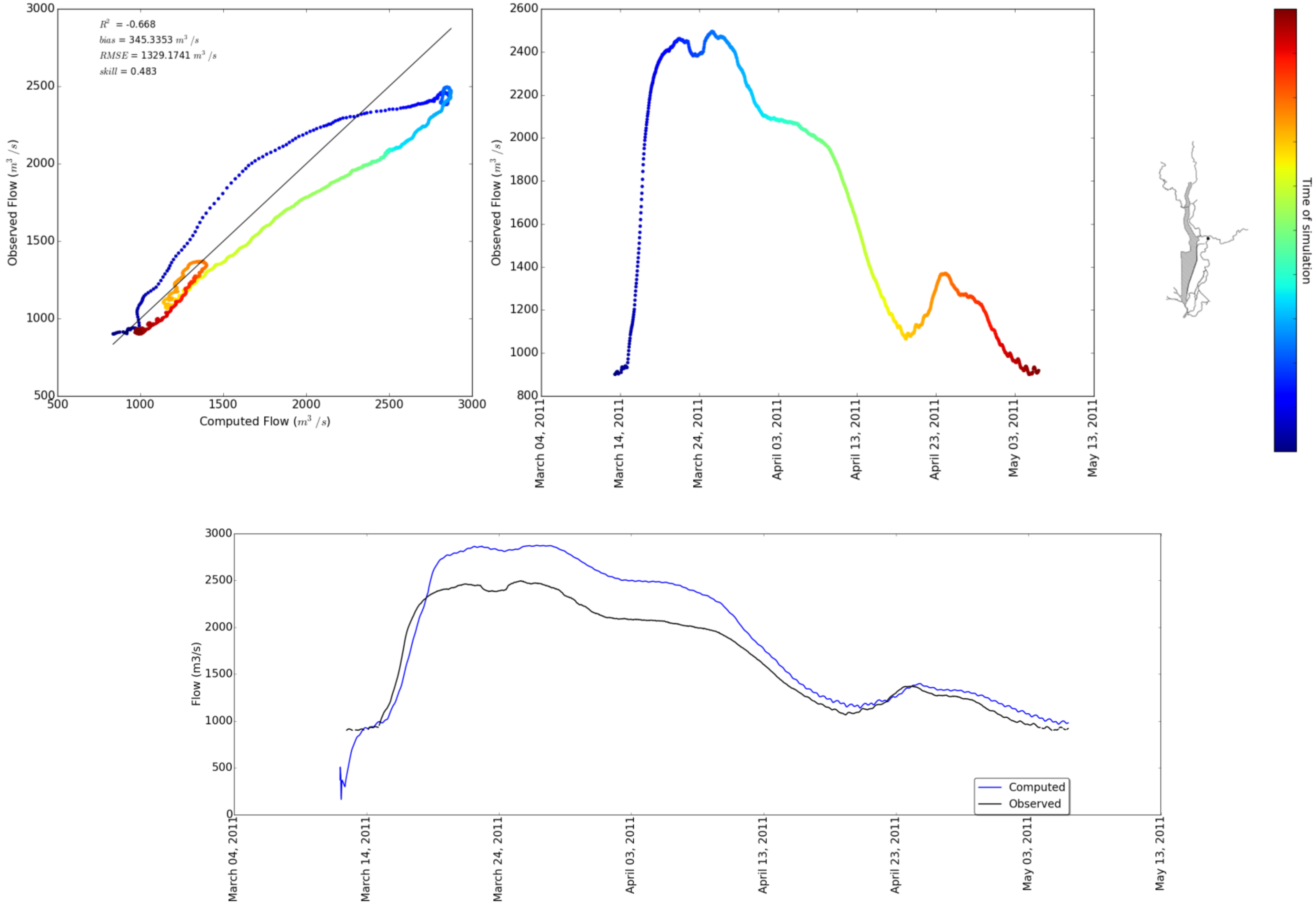

Figure 36 Sacramento River at I Street (IST) gage flow

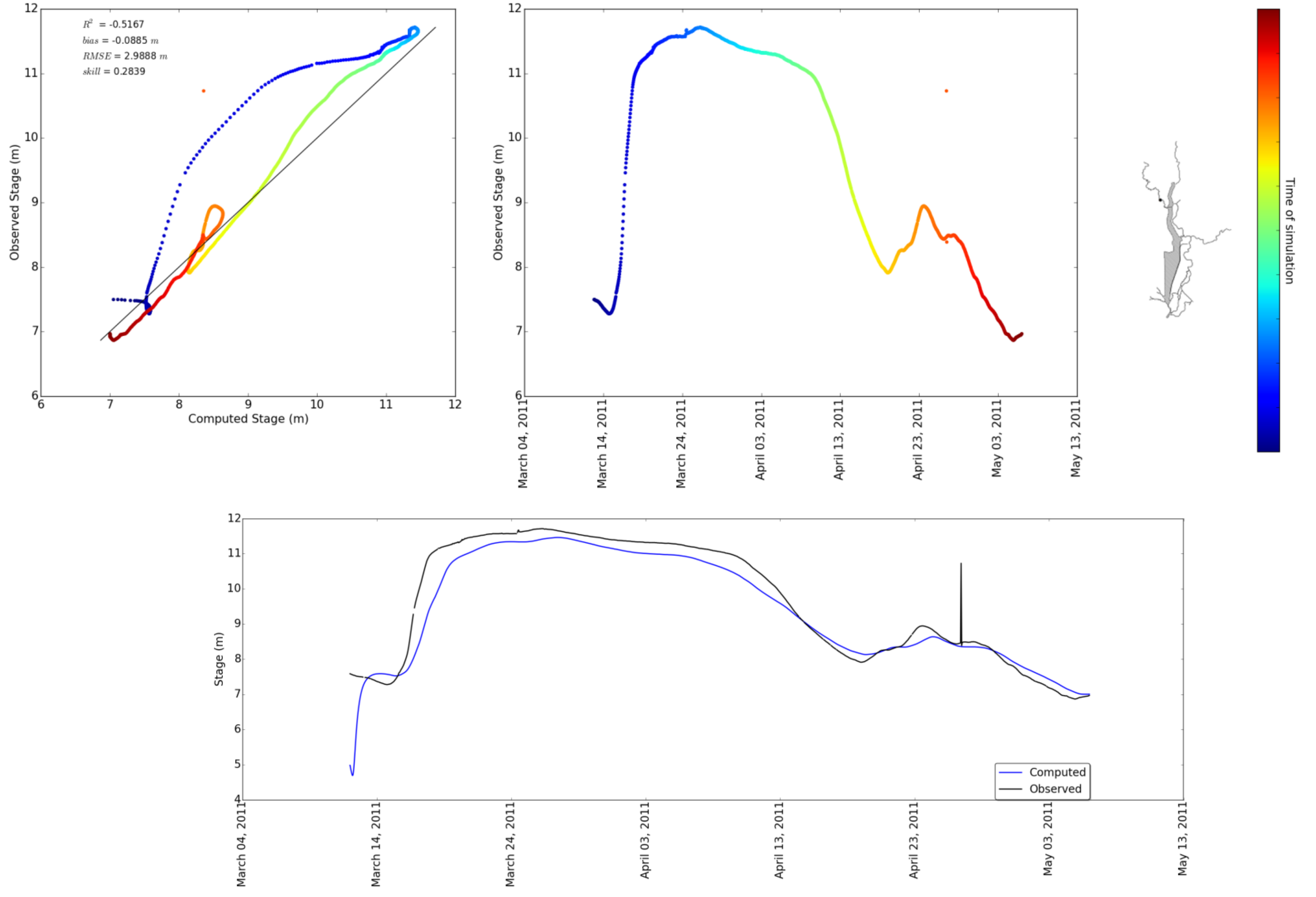

Figure 37 Knights Landing Ridge Cut (KNL) gage stage

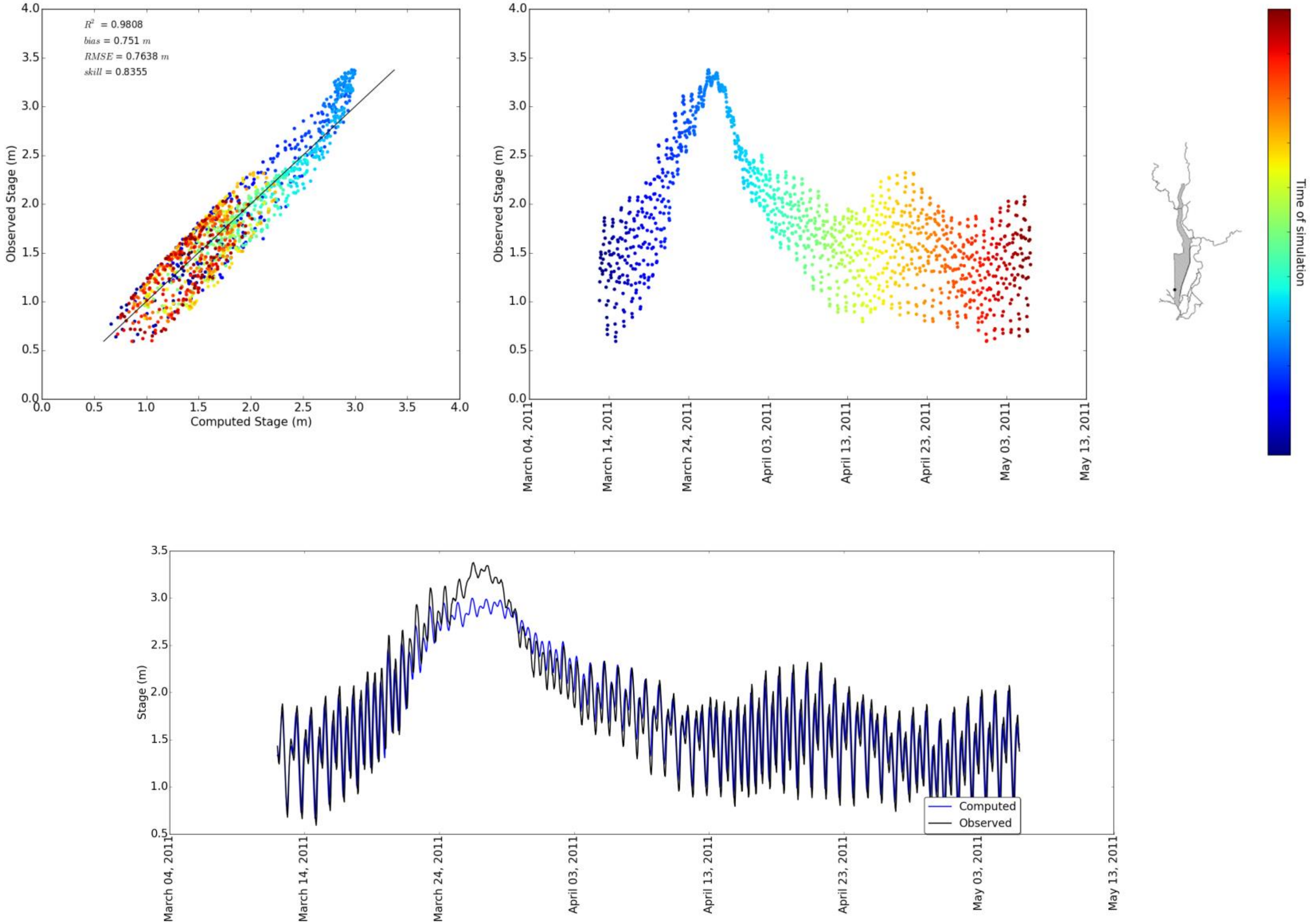

Figure 38 Liberty Island at Yolo Bypass (LIY) gage stage

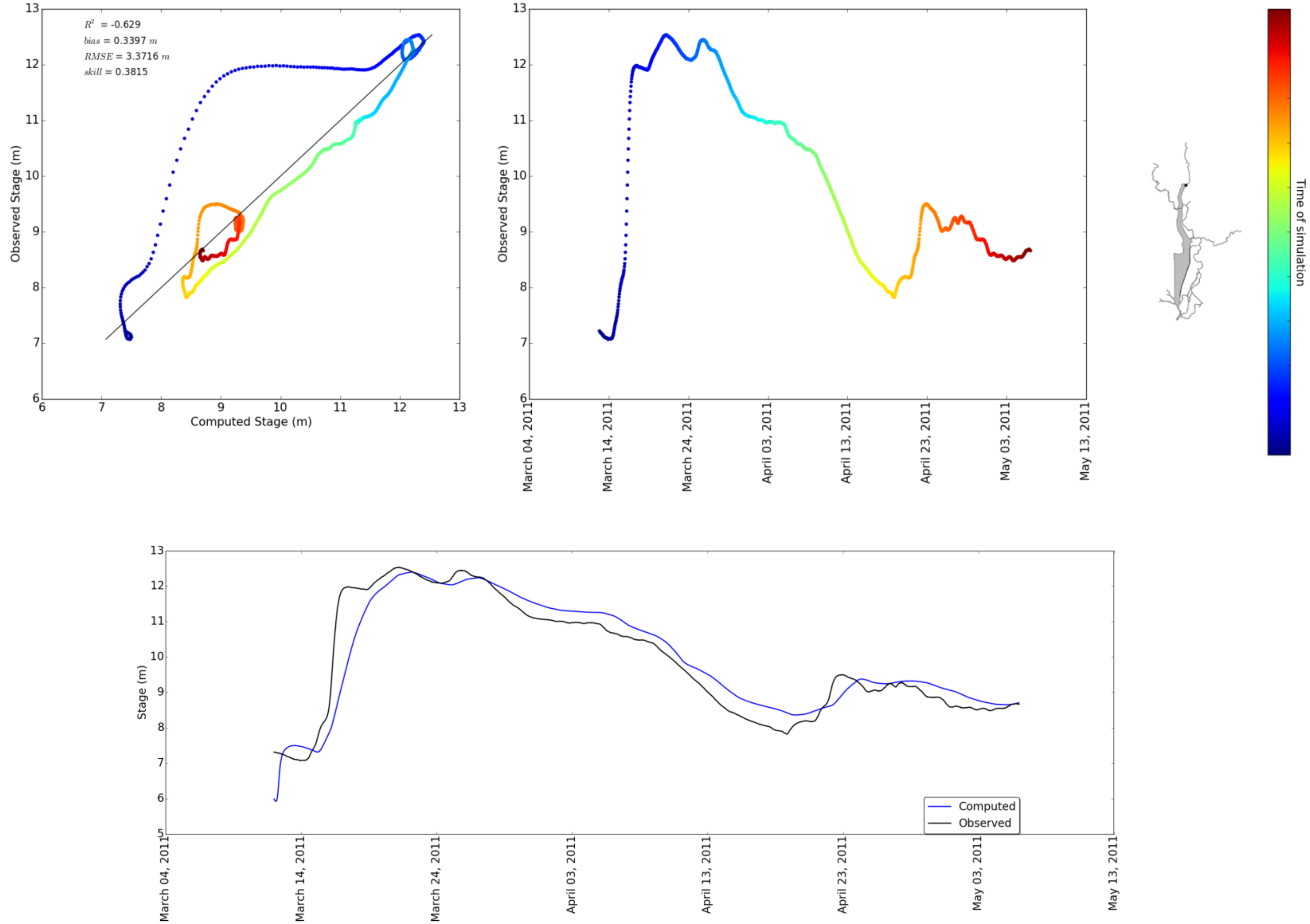

Figure 39 Feather River at Nicolaus (NIC) gage stage

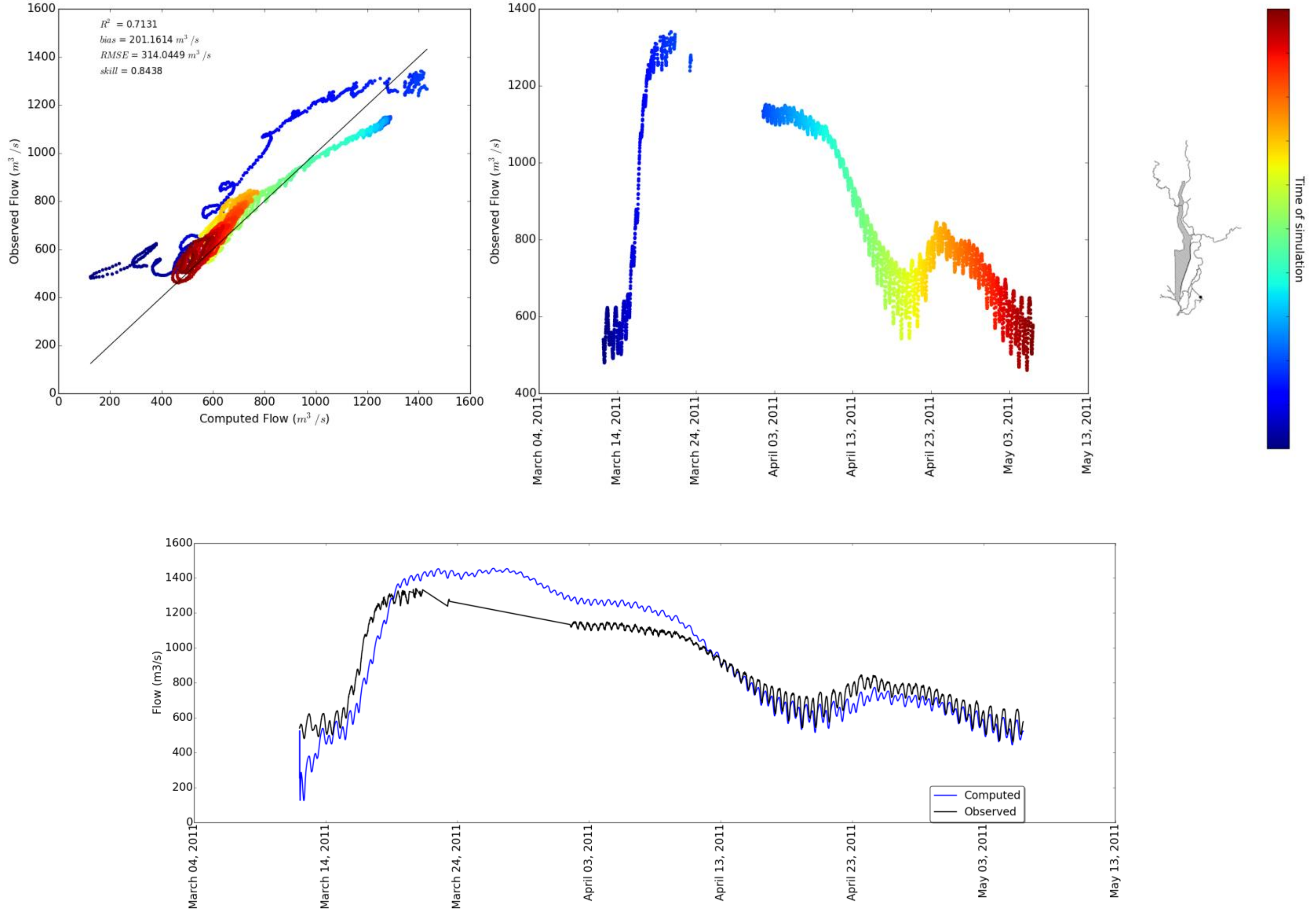

Figure 40 Sacramento River above the Delta Cross Channel (SDC) gage flow

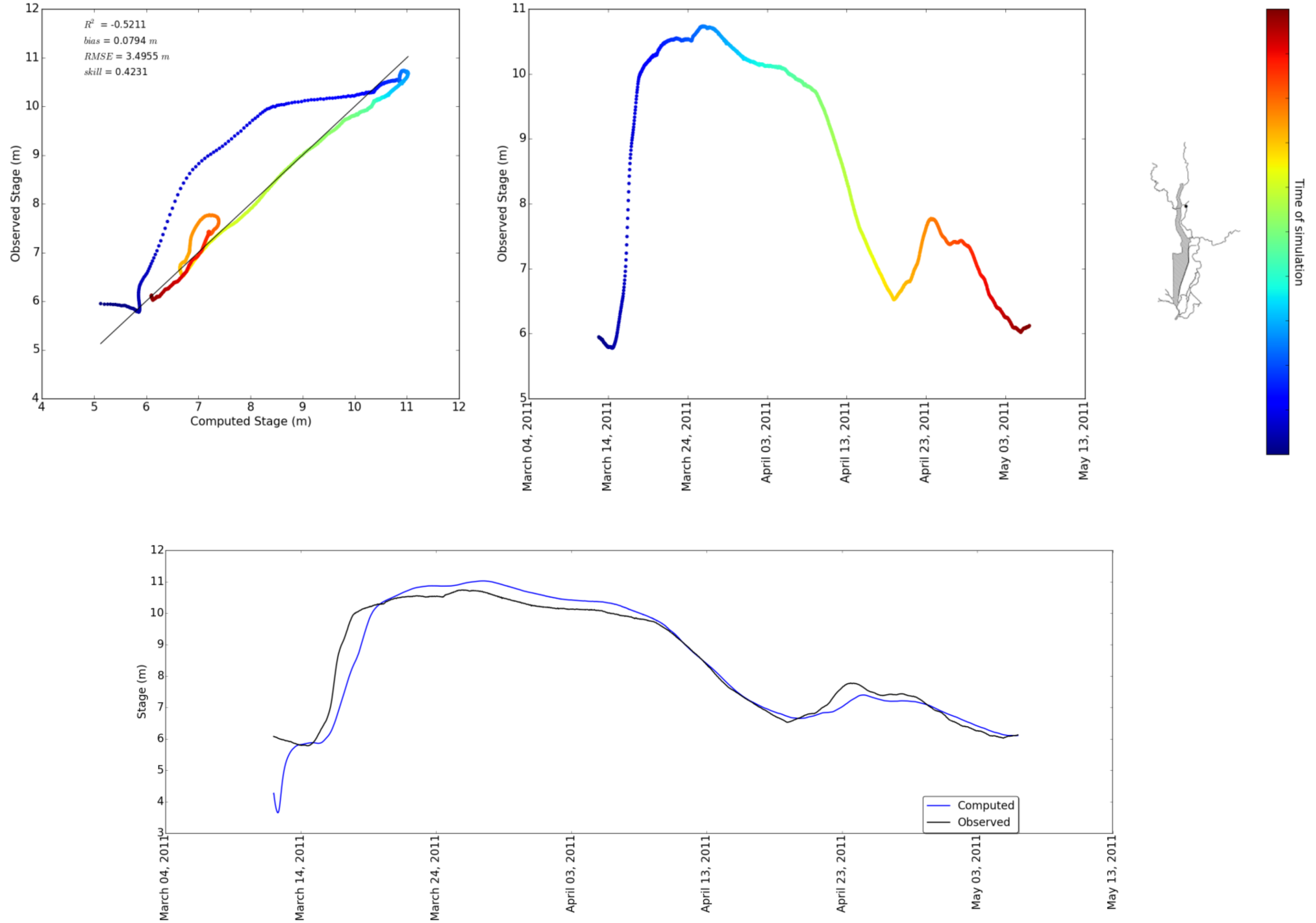

Figure 41 Sacramento River at Verona (VON) gage stage

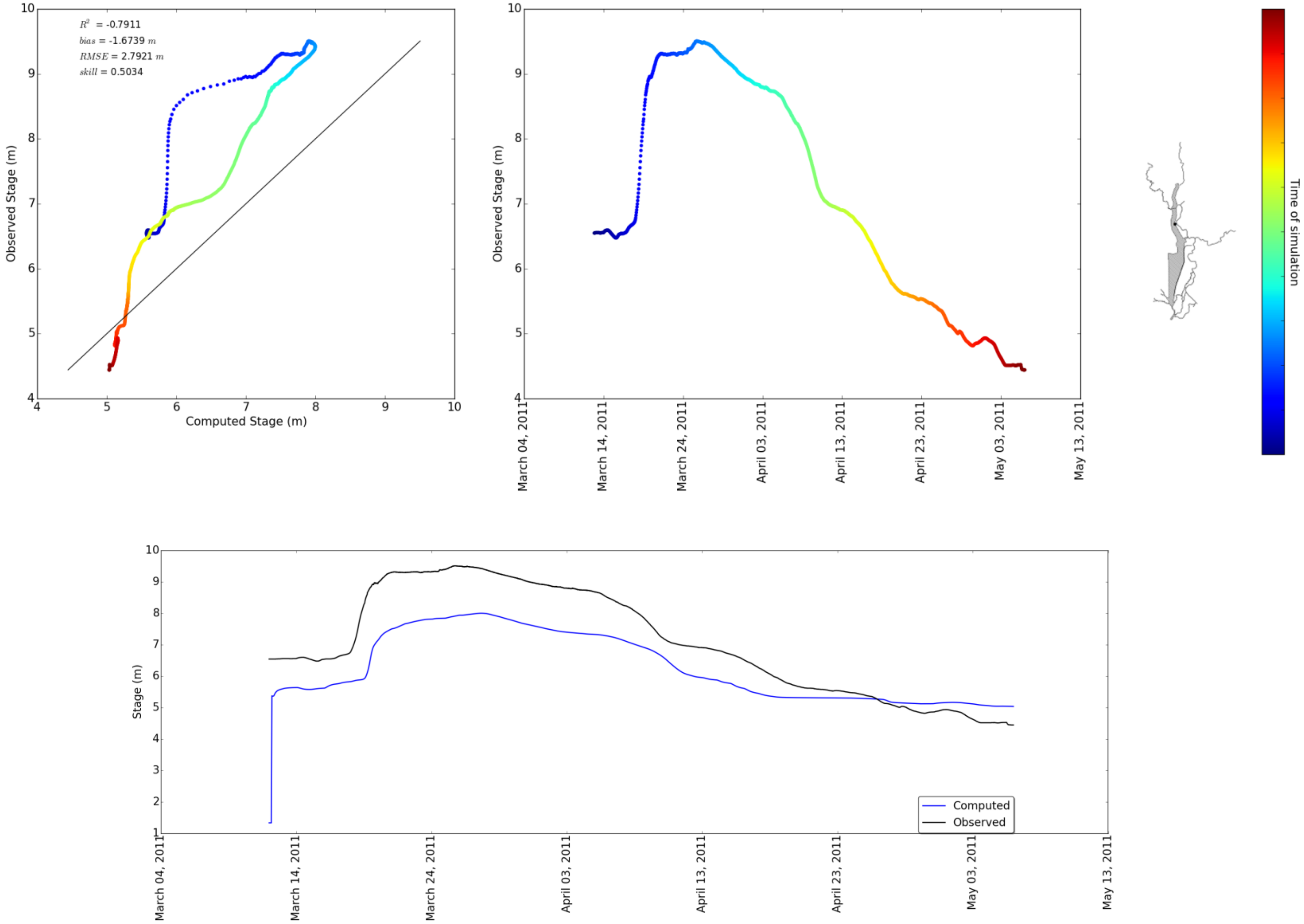

Figure 42 Yolo Bypass near Woodland (YBY) gage stage

Appendix E Tabulated model performance metrics

Table 7 Model performance metrics for flow in various stations over the simulated 2006, 2009, and 2011 flood events

		Station							
		FPT	GES	GSS	IST	SDC	SSS	SUT	VON
2006	R^2	0.05	0.82	0.26	0.84	0.86	0.87	0.01	0.05
	Bias	-299.87	-5.31	-884.85	-54.08	23.32	30.80	-331.19	-299.87
	RMSE	223284.58	12673.77	803708.62	19502.40	2988.20	3498.32	228100.27	223284.58
	Skill	0.46	0.90	0.22	0.88	0.91	0.89	0.47	0.46
2009	R^2	0.60	0.95	0.67	0.71	0.97	0.97	0.62	0.60
	Bias	379.73	11.23	345.34	201.16	77.46	136.54	163.88	379.73
	RMSE	1654749.56	11470.05	1766703.73	98624.21	12222.71	27268.37	1164737.77	1654749.56
	Skill	0.15	0.94	0.13	0.73	0.84	0.77	0.15	0.15
2011	R^2			0.51		0.40		0.39	
	Bias			-584.49		-28.66		-72.07	
	RMSE			1929590.92		19521.43		1221294.14	
	Skill			0.18		0.09		0.25	

Table 8 Model performance metrics for stage in various stations over the simulated 2006, 2009, and 2011 flood events.

		Station																	
		FPT	**FRE**	**GES**	**GSS**	**HST**	**IST**	**KNL**	**LIB**	**LIS**	**LIY**	**NIC**	**RYI**	**SBP**	**SDC**	**SSS**	**SUT**	**BON**	**YBY**
2006	R^2	0.36	0.98	0.76	0.83	0.02	0.43	0.08		0.60	0.89	0.40	0.05	0.94	0.79	0.79	0.84	0.18	0.71
	Bias	-0.62	0.00	0.12	0.14	-1.30	-0.99	-1.54		1.34	0.00	-0.78	0.12	1.25	0.08	0.11	0.04	-1.42	0.63
	RMSE	0.83	0.15	0.08	0.07	1.72	2.07	5.52		2.05	0.03	1.57	0.26	2.28	0.07	0.08	0.07	4.57	0.48
	Skill	0.51	0.98	0.85	0.88	0.13	0.50	0.46		0.46	0.94	0.46	0.44	0.79	0.88	0.87	0.91	0.48	0.10
2009	R^2	0.58	0.98	0.97	0.97	0.65	0.55	0.52	0.38	0.94	0.98	0.63	0.33	0.96	0.96	0.98	0.97	0.52	0.79
	Bias	0.01	-0.38	0.07	0.10	0.55	-0.13	-0.09	0.00	0.78	0.00	0.34	0.00	0.13	-0.01	0.04	-0.06	0.08	-1.67
	RMSE	6.76	0.26	0.03	0.04	5.69	10.15	8.93	0.54	0.96	0.02	11.37	0.45	0.25	0.05	0.03	0.05	12.22	7.80
	Skill	0.17	0.97	0.98	0.98	0.12	0.19	0.20	0.19	0.87	0.99	0.16	0.21	0.98	0.98	0.99	0.98	0.20	0.22
2011	R^2	0.31	0.97			0.44	0.30	0.39		0.96	0.99	0.41		0.95		0.03		0.27	0.48
	Bias	-0.62	-0.46			-0.49	-0.99	-1.34		0.28	0.00	-0.77		0.00		-0.01		-1.15	-0.55
	RMSE	8.87	0.41			11.84	14.44	11.61		0.27	0.06	14.97		0.85		0.27		16.09	8.26
	Skill	0.32	0.97			0.23	0.32	0.22		0.97	0.98	0.26		0.96		0.30		0.34	0.24