Appendix P – Basis of Design Report – Tidal Hydrology and Hydraulic Analysis: Lookout Slough Restoration Project, Environmental Science Associates, January 2019.

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DRAFT BASIS OF DESIGN REPORT – TIDAL HYDROLOGY AND HYDRAULIC ANALYSIS

LOOKOUT SLOUGH RESTORATION PROJECT

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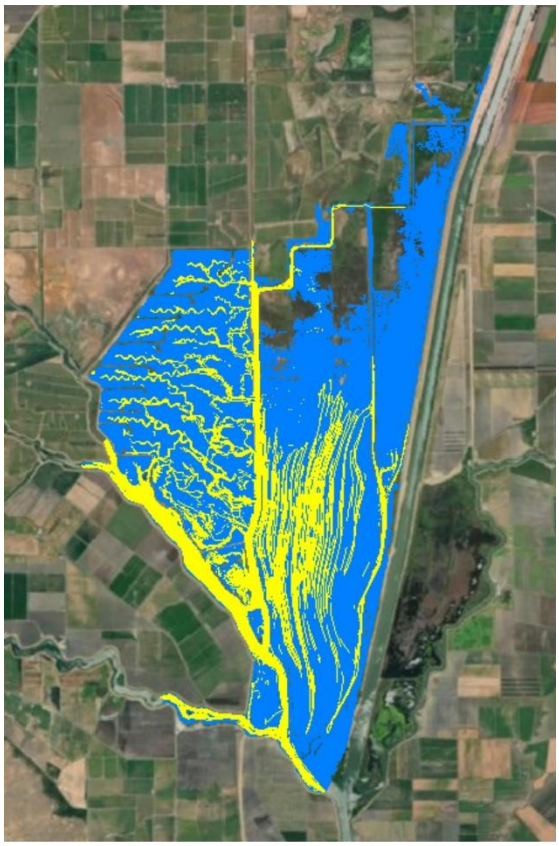

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LOOKOUT SLOUGH RESTORATION PROJECT

Basis of Design Report – Tidal Hydrology and Hydraulics

Introduction

The Lookout Slough Restoration Project (Project) will create approximately 3,000 acres of natural freshwater tidal marsh in the Cache Slough Complex in the northern Sacramento-San Joaquin Delta (**Figure 1**) and provide the co-benefit of increasing the regional flood conveyance capacity of the Yolo Bypass. The Project is being funded by the California Department of Water Resources (DWR) to meet multiple objectives:

- To meet goals outlined in the State of California's Bay Delta Conservation Plan (BDCP) as well as the U.S. Fish and Wildlife Service's (FWS) Biological Opinion (BiOp) issued as part of the Long-Term Operational Criteria and Plan (OCAP) for coordination of the Central Valley Project and State Water Project. The Project is within the priority habitat restoration areas delineated in the 2008 FWS BiOp Delta Smelt Crediting Decision Model, and will create creditable acres for Delta Smelt that will satisfy DWR's obligations under the Delta Smelt BiOp and salmonids under the Salmonid BiOp.

- To meet regional flood protection objectives to increase the conveyance capacity of the Yolo Bypass in a manner that is consistent with the 2017 DWR Sacramento Basin-Wide Feasibility Study (BWFS). By setting back the existing State-Federal levee along the west side of the Yolo Bypass, the Project will provide flood control storage and reduce upstream flood stages in the Yolo Bypass.

This report provides the hydrologic and hydraulic basis of design for the habitat restoration features of the Project. Hydrologic and hydraulic analysis of the flood control components of the Project are documented in a separate appendix of the Project's overall Basis of Design Report.

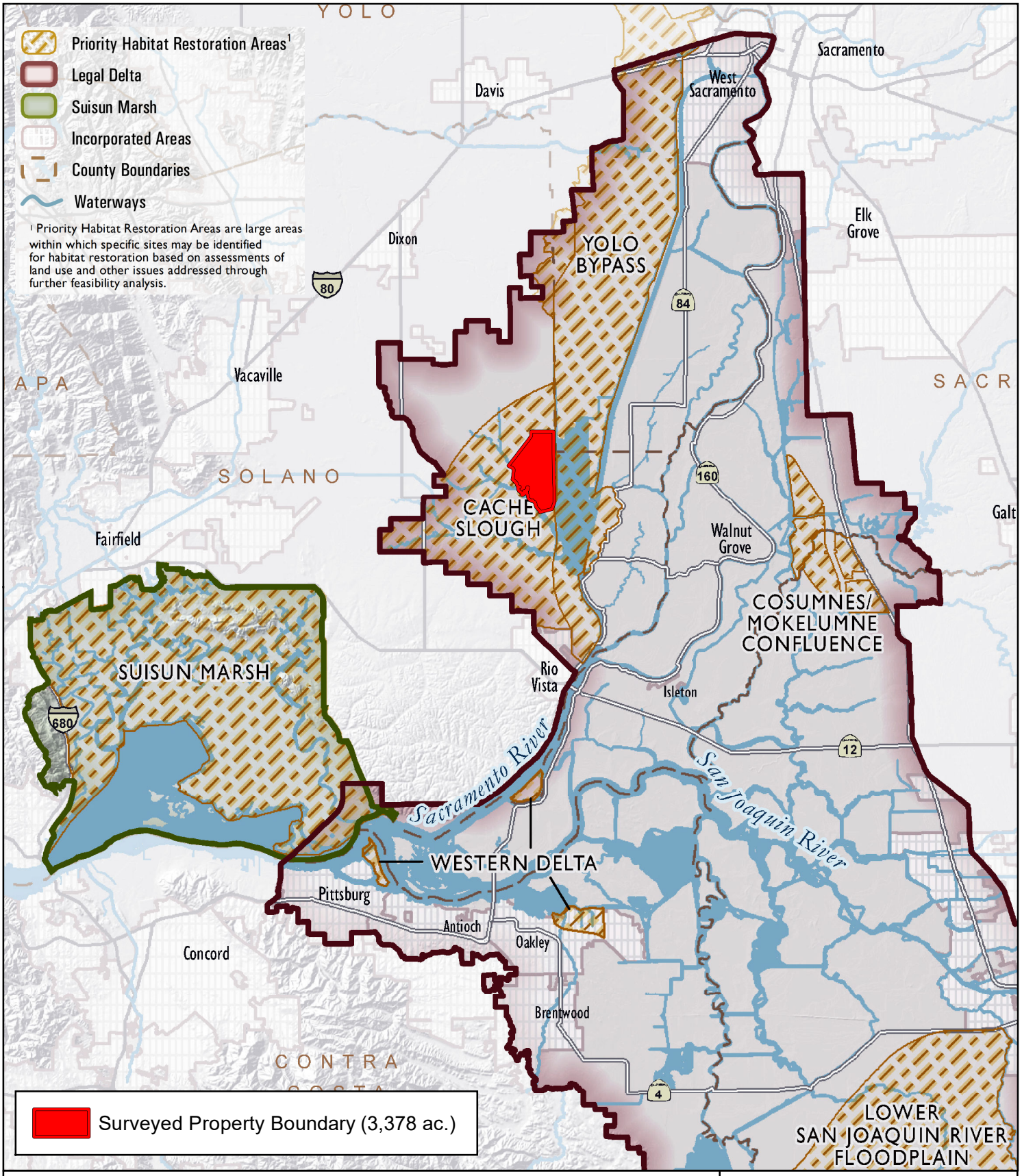

Figure 1
Location Map

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Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/29/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
Delta Stewardship Council, 2013

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Background

The Project is located within the Cache Slough Complex, in the northwest corner of the Sacramento-San Joaquin Delta in Solano and Yolo Counties. The Cache Slough Complex is considered ideal for tidal restoration by federal and state wildlife agencies as a result of its "connectivity to the Yolo Bypass floodplain, suitable elevations, high turbidity, high primary and secondary productivity, and use by Delta smelt, Chinook salmon, and other native fishes" (CDFW, 2017a).

The Project is bounded to the north by Liberty Island Road, to the east by the Yolo Bypass, to the south by Cache Slough, and to the west by Duck Slough. With the exception of the levee system, land on the Project site ranges between El. 4.5 feet (NAVD 88) and El. 8.0 feet (NAVD 88), and generally slopes from west to east. Precipitation at the site is derived from frontal storms originating from the Pacific Ocean during the primary wet season between the months of October and April. The site receives a mean annual rainfall of approximately 17 inches (Solano County, 1999) and is characterized by poorly drained clay soils, with high runoff potential (USDA, 2018).

Historic Landscape

Up to the early 20th century, the majority of the site was part of the historic tidal tule marsh complex (**Figure 2**) that formed the low-lying southern portion of the Yolo Basin. The upper portions of the Yolo Basin were formed by Holocene basin deposits laid down by the Sacramento River and the two major west side tributaries, Cache Creek and Putah Creek (**Figure 3**). These deposits grade basin-ward into the plains of the north Delta, which is characterized by peat-rich muds (Helley and Harwood, 1983). Flood-basin deposits in this region are typically firm to stiff silty clay, clayey silt, and silt (Atwater, 1982).

The Yolo Basin was largely cutoff from the Sacramento River, except in times when the natural levees along the banks of the river overtopped, similar to flows cresting Fremont Weir today (Opperman et al, 2017). The Yolo Basin received seasonal runoff from the west side tributaries, including Cache Creek and Putah Creek, as well as groundwater seepage from the Sacramento River. These sources combined with freshwater tidal inundation, fed the historic freshwater tidal marsh and channels where the Project is located (PWA, 2008).

The Project is located in what is understood to have been part of the historic tidally inundated marsh above Cache Slough. Vegetation on the majority of the Project site was tules (*Scirpus acutus,* also known as Hardstem Bulrush), a dense perennial wetland plant species which historically dominated the marshplains of the region. The density of tules and willows in the region are considered to be one of the reasons that these areas were not carefully surveyed prior to reclamation (Atwater, 1982). The site would have been relatively level, gradually draining southward into Cache Slough, with the marshplain edge dictated by elevation of the highest tides (PWA, 2008). As shown on Figure 2, a network of blind tidal channels formed along the banks of Cache Slough.

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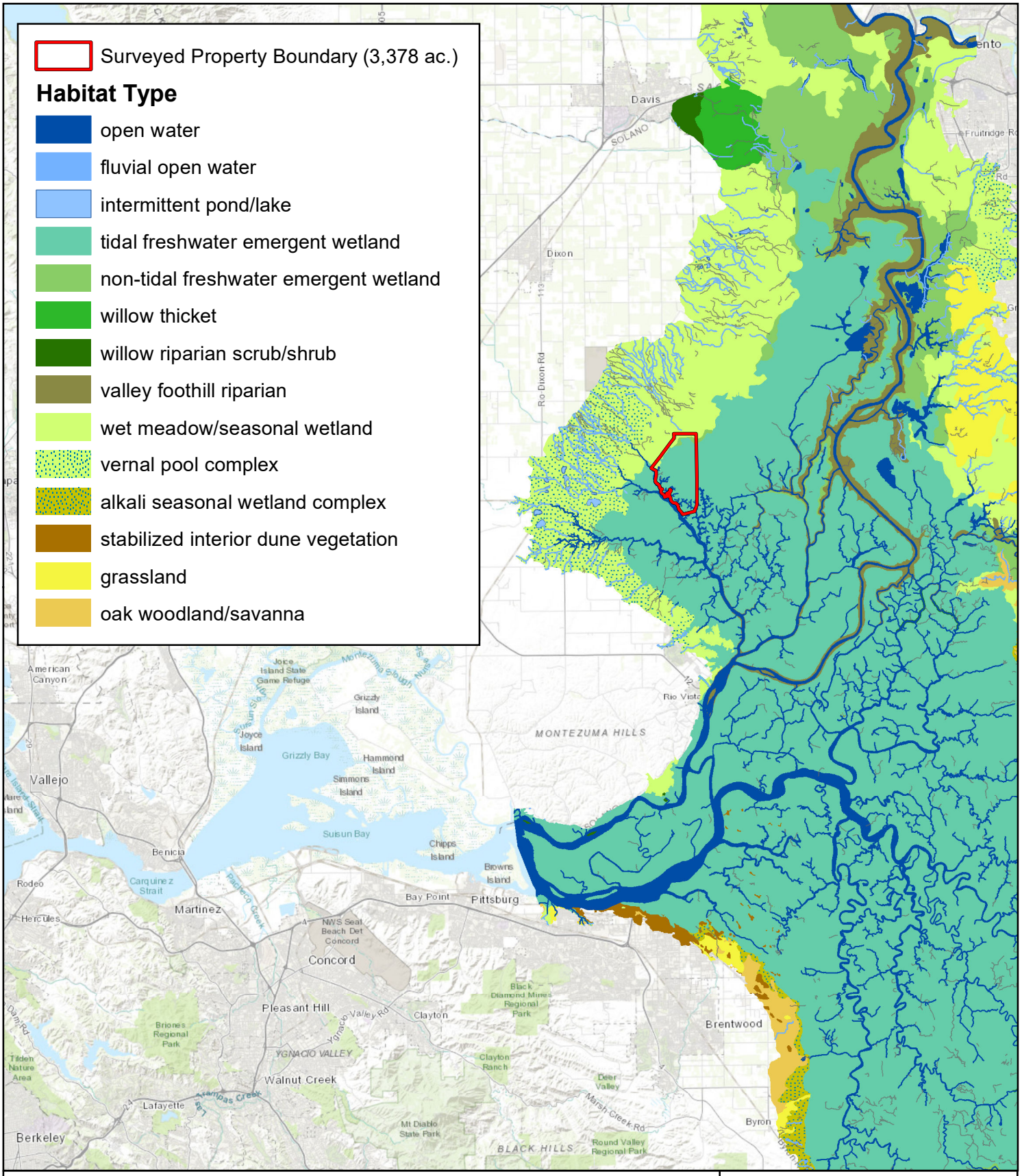

Figure 2
Historical Ecology

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Lookout Slough Restoration Project

Ecosystem Investment Partners

Map Prepared Date: 12/29/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
SFEI, 2012

Prepared by: ESA

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Figure 3
Geologic Map of Sacramento-San Joaquin Delta, California

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Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/29/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
Atwater, 1982

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Existing Conditions

Beginning in the 1930's and continuing through the 1960's, a series of levee improvements were constructed along the east side of Cache Slough and the west side Yolo Bypass as part of the Sacramento River Flood Control Project to develop and protect approximately 13,000 acres of agricultural land and associated structures and roads (U.S. Army Corps of Engineers [USACE], 1962). The levee system bounding the Project is currently maintained and operated by Reclamation District (RD) No. 2098. Until recently, the Project site was currently managed separately by three primary land owners (**Figure 4**):

- The Vogel Island portion of the project was originally purchased for use as a duck club, but in recent years has been primarily been operated as grazing land for sheep. Historically, the island drained by gravity through a gated outfall structure into Cache Slough. During winter flood season the berms forming the perimeter of Vogel Island often overtop, flooding the property. These same berms prevent flood waters from draining once the island is inundated, creating a condition where water and potentially fish are trapped inside a temporary lake.

- The Bowlesby Ranch property north and west of Lookout Slough has been operated and managed as irrigated pasture for livestock. The land is irrigated using water pumped from Cache Slough and drains generally from west to east to Lookout Slough through a network of agricultural ditches.

- The Liberty Farms property was used for agricultural production for many years before being converted to a duck club circa 2005. Although the northern portion of the property continues to be used for agricultural production, the majority of the site is seasonally flooded and drained through a series of artificial channels for vegetation management on the duck club. The property is irrigated using water sourced from Cache Slough and is drained via pumping to Shag Slough.

The State-Federal levee system ensures that the Project land is currently inaccessible to fishes, including Delta smelt, green sturgeon, Central Valley Spring Run Chinook salmon, Sacramento River Winter-run Chinook salmon, Central Valley steelhead, and longfin smelt, except during winter runoff events which periodically flood the Vogel Island tract. The Project will establish tidal hydraulic connectivity to all three pieces of land by breaching the levees at Cache Slough and at the Yolo Bypass along Shag Slough. The existing pumping and irrigation channel network will be decommissioned and replaced with a network of tidal channels which will allow the site to flood and drain by gravity with the tides. In doing so, the Project will have a continuous supply of fresh water and suspended sediment which will promote establishment of a mosaic of subtidal, intertidal, and uplands habitat types.

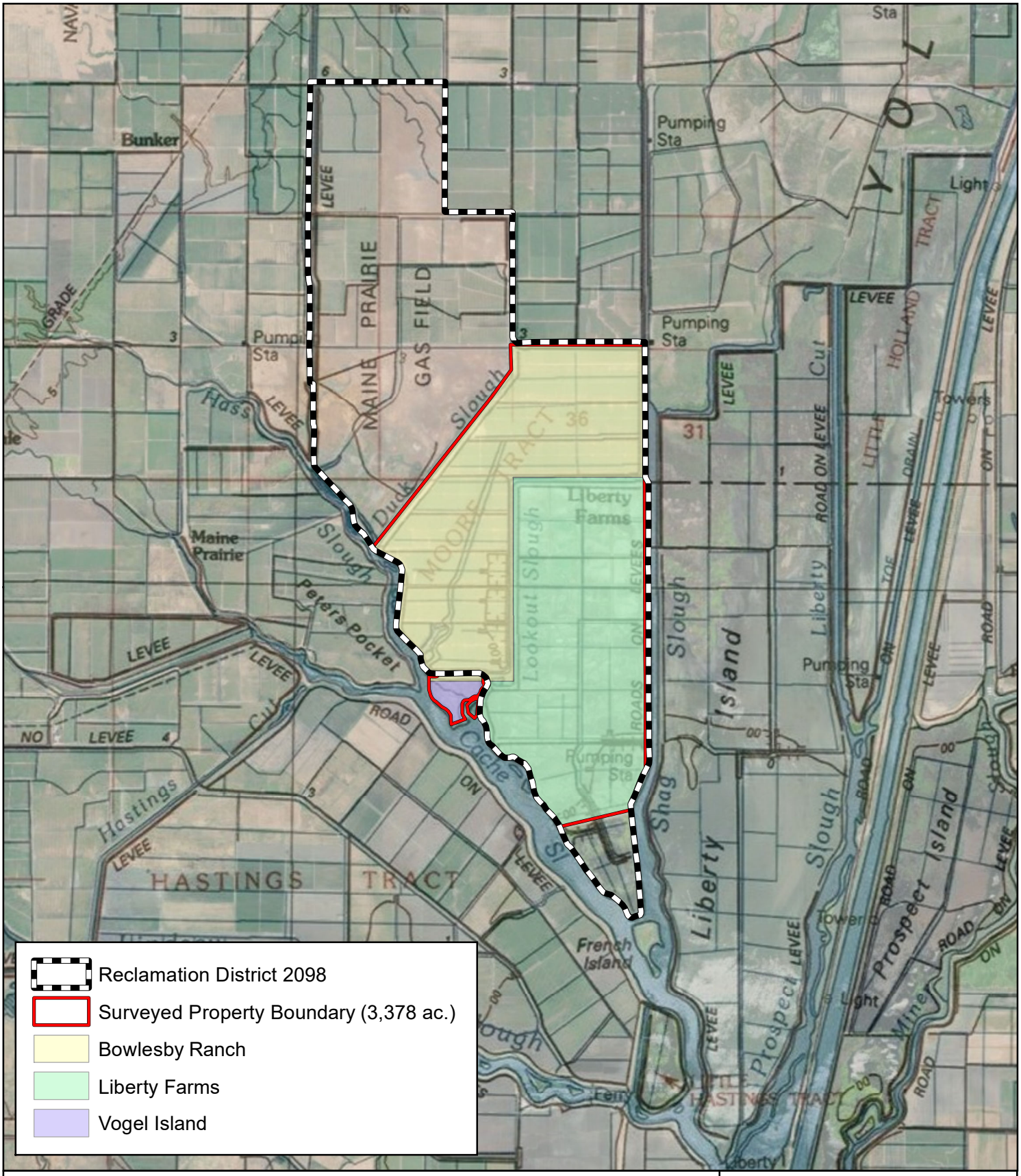

Figure 4
Land Ownership

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Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 1/2/2019
Map Prepared By: JPritchard
Base Source: Wood Rogers
Base Date: 10/24/2017
Data Source(s):

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The Project is anticipated to provide the following benefits for the target protected species (WRA, 2018):

- **Newly created and enhanced existing rearing habitat.** Subtidal dendritic channels bordered by tidal wetlands will provide foraging habitat and cover for juvenile salmonids and green sturgeon. A range of rearing habitat will be created by the Project, with deeper subtidal habitat being established in the southern portions of the Project and shallower subtidal and intertidal channels established in the northern portions of the Project. Breaching of the levees surrounding the Vogel Island tract will remove barriers which currently act as a potentially stranding area for native fish using this area for foraging habitat during high water conditions.

- **Added food web support.** Improved access to primary productivity and zooplankton, particularly during the summer and fall months, have been identified as necessary to recovering the Delta smelt (IEP, 2015). The Project is anticipated to serve as an exporter of nutrients and basal trophic level support during seasonal pulse flows and more extreme tidal periods, providing food web support to target species within the Cache Slough Complex, particularly the Delta smelt as a portion of the population is believed to reside there year-round (IEP, 2015).

- **Improved and new created spawning habitat.** The Cache Slough Complex contains suitable spawning habitat for Delta smelt and longfin smelt and the detection of larval smelt indicate these species use the area as a core portion of their remaining spawning grounds (Sommer and Meija, 2013; Young et al, 2015; Morris and Damon 2016; CDFW, 2017b). The creation of subtidal channels tidally connected to the Cache Slough Complex is anticipated to provide potentially suitable spawning habitat for Delta smelt and longfin smelt. While specific spawning habitat requirements for these two species are unknown, the restoration design will incorporate the current understanding of suitable spawning habitat. An approach including heterogeneous subtidal habitat, with seasonally deeper elevations occurring in the southeastern portion of the Project Area and shallower subtidal and intertidal channels occurring in the northwestern portion, is anticipated to provide a range of spawning sites under different tidal and flood flow conditions. Seasonal inundation of freshwater marsh habitat is also anticipated to provide habitat for other native fish species, including the California species of special concern Sacramento splittail (*Pogonichthys macrolepidotus*).

- **High flow refugia.** The Project is anticipated to provide shelter to juvenile fish from high velocities during seasonal flood events. Seasonal flooding of the Project site is also anticipated to increase access to high quality foraging habitat for out-migrating salmonids, which will benefit from access to high water refugia and access to food resources (Jeffres et al., 2008). Access to the large tidal marsh and floodplain will allow juvenile fish to move out of channelized flood conveyance areas into lower velocity tidal marshplains and channels, reducing the potential for them to be swept downstream and out of productive rearing habitat.

Project Datums

All data for the project is referenced to the North American Datum of 1983 and the California State Plane II (feet) coordinate system. All vertical elevations described in this report are referenced to the North American Vertical Datum of 1988 (NAVD 88) and are reported in units of feet.

Tidal datums for the project site were calculated using short-term records collected at several locations in the vicinity of the project (**Figure 5**). **Table 1** summarizes calculations for the Liberty Island at Yolo Bypass (LIY) stream gage operated by DWR, as well as four short-term gages that were deployed by ESA PWA as part of the BREACH III Project funded by the California-Federal (CALFED) Bay-Delta Program. Tidal datums were calculated independently at each gage using the methodology outlined in the National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) *Computational Techniques for Tidal Datums Handbook*, and referenced to the Port of Chicago control gage maintained by NOAA. The window of June through September 2010 was used as the basis of calculations at each gage, consistent with the period of deployment of the ESA PWA gage network. For purposes of design, the values computed at the Liberty Island at Yolo Bypass Gage have been used for estimating the vertical profile of habitat establishment on the Project site.

TABLE 1
TIDAL DATUM ESTIMATES IN VICINITY OF PROJECT (FEET, NAVD 88)

Datum	Liberty Island at Yolo Bypass Gage (LIY)[1]	ESA PWA Gages[1]			
		North	East	South	West
Mean Higher High Water (MHHW)	6.48	6.63	6.52	6.45	6.62
Mean High Water (MHW)	6.02	6.15	6.04	5.98	6.16
Mean Sea Level (MSL)	4.46	4.59	4.51	4.50	4.63
Mean Tide Level (MTL)	4.42	4.61	4.48	4.48	4.62
Mean Low Water (MLW)	2.82	3.07	2.91	2.98	3.08
Mean Lower Low Water (MLLW)	2.21	2.54	2.29	2.39	2.51
Diurnal Tidal Range (MHHW-MLLW)	4.27	4.09	4.23	4.06	4.11

[1] SOURCES: DWR Water Data Library Website, 2018; ESA PWA, 2013.

Hydraulic Design Criteria

The primary hydraulic design criteria used to assess the project design include tidal damping, channel stability, and exposure time, as described below.

Tidal Damping

Tidal drainage is necessary to develop conditions that result in establishment of vegetated tidal marsh habitat. Tidal damping, or reduction in the tidal range, occurs naturally due to dissipation of tidal energy in channels and over-marsh flow. If damping is too pronounced, low marsh vegetation may become stressed due to waterlogging. The spatial extent of marsh colonization is also closely tied to MHHW, which, if reduced, can result in a smaller marsh footprint and adversely affect crediting potential at the site. Tidal action can be significantly damped by hydraulic constrictions at breach openings or undersized tidal channels. Over time, scouring action tends to enlarge constrictions to the point where full tidal exchange is restored (PWA et al.,

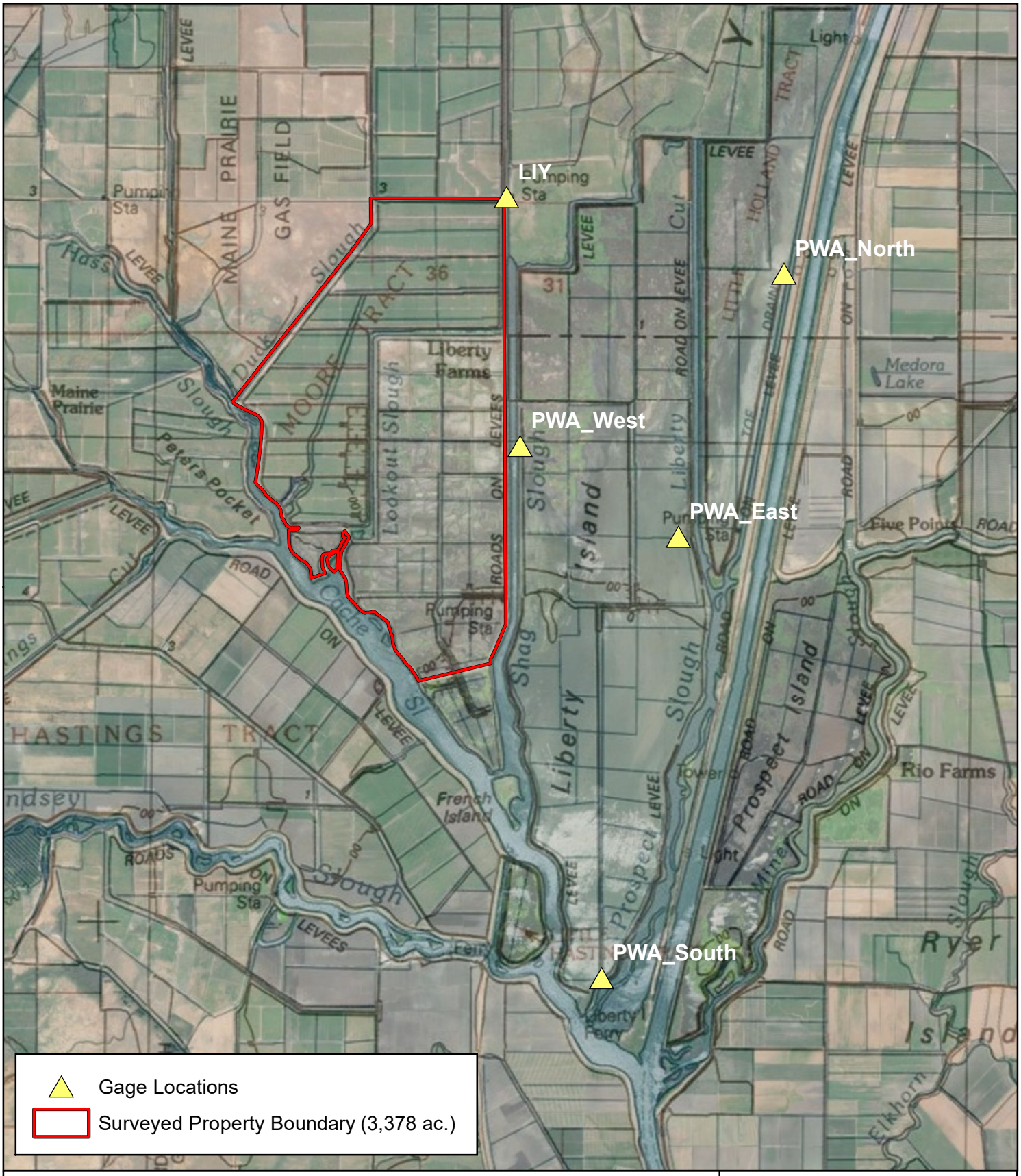

Figure 5
Stream Gages Used in Tidal Datum Calculations

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rogers
Base Date: 10/24/2017
Data Source(s):

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2004). However, it is preferred to design the site in a manner that does not adversely impact the evolution of the marsh following construction. To minimize tidal damping and promote circulation, the following design strategies were employed:

- Levee breaches and tidal channels have been sized to optimize exchange of the tidal prism.
- Thalwegs of the tidal channels have been designed to El. 0.0 feet (NAVD 88) or lower. This will provide over four feet of depth below the mean tide line to reduce potential for establishment of tule (hardstem bulrush) vegetation in the channel corridors (Tilley, 2012). Although tules provide desirable habitat throughout the rest of the marsh, they have the potential to greatly dampen the tidal energy needed to drive the tidal range in many parts of the site.

In general, the greatest potential for tidal damping occurs at the northern and western edges of the marsh due to their distance from Cache Slough and Shag Slough. In these areas, efforts have been made to ensure that damping of MHHW is less than 0.75 feet (or approximately El. 5.75 feet, NAVD 88).

Channel Stability

To reduce channel maintenance, channels that are self-scouring and require minimal maintenance are desirable. Preliminary geotechnical investigations have encountered clay material as deep as 30 feet in some areas of the site. Permissible shear thresholds for the type of floodplain deposits that characterize the majority of site are assumed to be similar to those of stiff clay or alluvial silt, which are generally 0.26 lbs/sf or less (Fischenich, 2001). Based on conversations with Blackburn Consulting, to provide a more conservative estimate of erosion potential it is also assumed that some firm loam may be present in the middle third of the site, and that silty loam may be present in the lower third. These soil types correlate to permissible shear stress thresholds of 0.075 lbs/sf and 0.05 lbs/sf, respectively (Fischenich, 2001). Bed shear stresses computed by the hydraulic model will be reviewed to identify whether these thresholds are exceeded as this may indicate locations vulnerable to erosion and instability. This would be an indication that channels or breach openings may be undersized relative to volume of the tidal prism exchange.

Exposure Time

An important restoration outcome of the Project is increased aquatic food web productivity within the Cache Slough Complex. The site design is being evaluated to understand potential for productivity of suspended biomass (organic detritus, phytoplankton, zooplankton, etc.). The time scale used for estimating food web productivity on the Project site is the exposure time, or total amount of time a particle spends inside the site, including exits and entrances through the levee breaches on the perimeter of the Project. This measure is used as it assumes that “growth dynamics in a tidal flow are a function of the total amount of time spent in a particular (e.g., high-growth) environment” (Monsen et al., 2002). For purposes of assessing productivity of the site, a neutrally buoyant particle tracking model was used in conjunction with the results of the two-dimensional hydrodynamic model to estimate exposure time. Particle exposure time computed by the model is used here as a proxy for biomass production.

Longer exposure times are generally considered good for beneficial productivity, but this may be complicated or in some cases reversed in the presence of grazing species, including invasive bivalves (Lucas and Thompson, 2012), such as the invasive overbite clam. While the particle tracking model cannot explicitly represent the effect of benthic grazing on productivity, Moyle (2015) suggested that a preferred exposure period of two weeks could potentially allow zooplankton to grow large enough to pass by the clams.

Longer exposure times also have the potential to produce harmful algal blooms. The classification scheme developed for the Prospect Island Tidal Habitat Restoration Project (WWR-Stillwater Sciences, 2014) was based on available literature values (Baxter et al., 2010) and is shown on **Table 2**.

TABLE 2
EXPOSURE TIME CLASSES

Number of Days	Description
< 1	Removal rate exceeds algal growth rates (productivity limited)
1-3 days	Target exposure time for diatom based productivity
3-5 days	Close to optimal
5-7 days	Low rates of tidal exchange, risk of domination of algal community by slower growing blue-green algae
7-25 days	
> 25 days	

Source: WWR-Stillwater Sciences, 2014.

Speaking to this balancing act with respect to residence time, Sherman et al. (2017) note that "it is currently not clear how restoration sites may be designed to optimize flow conditions in order to find the right balance to increase benefits and reduce potential negative effects." Given these uncertainties, the current analytical approach is to demonstrate a heterogeneity of residence times across the Project. This consists of a binning scheme which expands on that shown in Table 2 to include an additional bin to capture the two-week target recommended by Moyle (2015).

Restored Marsh Concept

The conceptual site design (**Figure 6**) was developed by WRA, Inc. (WRA) and Beaver Creek Hydrology, LLC (Beaver Creek Hydrology) to restore the full tidal range to as much of the site as is practical, and to limit tidal damping to less than 0.75 feet. Hydrology is considered to be the single most important determinant of for establishing and maintaining wetland processes (Mitsch & Gosselink, 2015). Restoring tidal exchange to the site will allow for establishment and growth of emergent vegetation such that ecological processes such as food web production occur naturally within the Project's tidal marsh areas.

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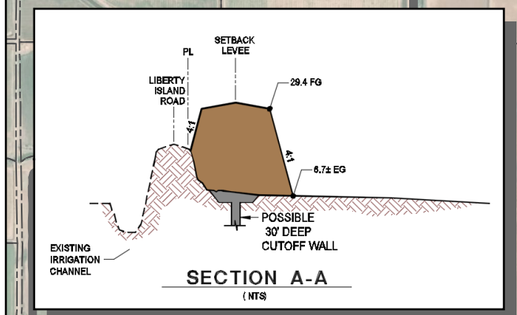

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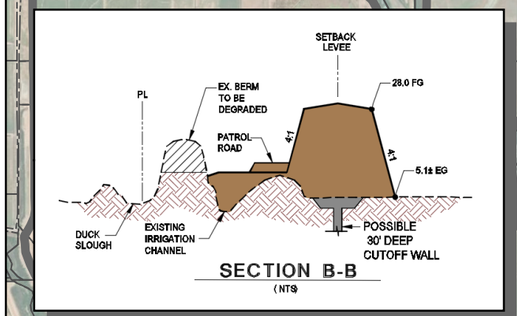

SECTION B-B
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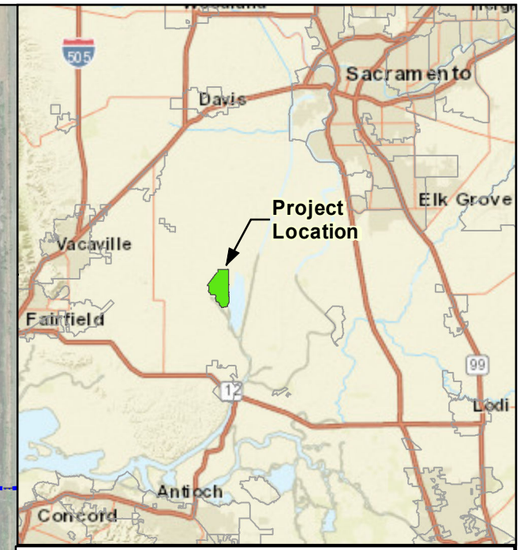

LOOKOUT SLOUGH SETBACK LEVEE

OVERALL PROJECT EXHIBIT

ECOSYSTEM INVESTMENT PATNERS

SOLANO COUNTY, CALIFORNIA

OCTOBER 2018

NORTH

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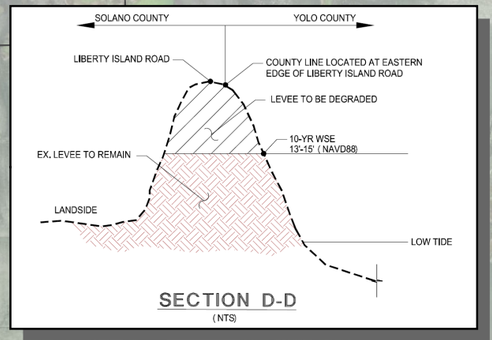
FEET

- Proposed Setback Levee Alignment
- Proposed Levee/Embankment Fill
- PG&E Access Road/GGS Habitat
- Project Site
- Property Line
- Existing Project Levee
- Existing Project Levee to be Degraded
- County Line
- Levee Breach Locations

PRELIMINARY

WOOD RODGERS



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(NTS)

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A number of functional design components such as habitat berms and refugia areas were incorporated into the design. These features are intended to address DWR's obligations in the respective BiOps, and many offer dual benefits in the form of flood protection. The major project features and their intended functions are described below (WRA, 2019).

Breach of Cache Slough and Shag Slough Levees

Prior to being developed for agriculture, the majority of the Bowlesby Ranch and Liberty Farms parcels were covered in tidal freshwater emergent wetlands which drained to Cache Sough (Whipple et al., 2012). Today, the existing State-Federal levee system currently prevents the site from flooding and draining with normal tides. Breaching the levee system is necessary to restore tidal exchange on the Project site.

Modification of the State-Federal levees requires careful consideration to ensure that risk is not transferred from one part of the system to another and constrains what modifications can be made to re-establish tidal processes on the site. Flood management considerations have been analyzed in parallel with the tidal marsh design, and have been documented in a separate Appendix to the overall Basis of Design Report. A brief description of the modifications of the Cache Slough and Shag Slough levees follows below.

Shag Slough Levee Improvements

The west (right bank) levee of Shag Slough and the Yolo Bypass will be breached at eight locations to provide hydraulic connectivity from the site to Shag Slough to restore normal tidal exchange to the majority of the site and habitat connectivity to Shag Slough. The remainder of the existing levee will be degraded to the match the elevation of the 10% AEP (10-year) design storm (elevations ranging between El. 14.7 and El. 11.8 feet, NAVD 88). During large flood events, the remnant levee segments will act as a weir, diverting additional flood overflows from the Yolo Bypass onto the Project site.

Cache Slough Levee Improvements

A single 100-foot wide breach opening will be created at the north (left bank) levee of Cache Slough at the southern terminus of the existing Lookout Slough alignment. This opening will re-establish the daily tidal exchange with Cache Slough and restore habitat connectivity to the marsh plain.

Tidal Channel Network

Tidal channel networks provide important low resistance pathways for distributing material and energy between the marsh habitat and adjacent bodies of water (Mitsch & Gosselink, 2015). In general, width and depth of the channel decrease between the channel inlets at Cache Slough and Shag Slough and the back of the site. Channel top widths will range from 60 feet to 200 feet, with channel invert elevations ranging between 1.0 and -1.0 feet (NAVD 88) to limit growth of

emergent vegetation. Channel side slopes would be set to a maximum of 3:1. Additional site grading will be performed to remove man-made berms and existing drainage canals (including the previously realigned Lookout Slough) throughout the site to prevent short-circuiting of the new channel network. The proposed network has been laid out to take advantage of the existing topography which drains primarily from west to east towards Shag Slough, with additional provisions to provide connectivity to Cache Slough. The performance of the Project channel network and marsh plain grading plan was tested and further refined by WRA and Beaver Creek Hydrology using results from the hydrodynamic modeling described in this report (WRA and Beaver Creek Hydrology, 2019).

Tidal Ponds

Foraging habitat for the endangered Giant Garter Snake (*Thamnophis gigas*) will be created by excavating a series of open water tidal ponds, which would provide habitat for food species such as tree frogs and juvenile fish. The foraging ponds will be located adjacent to upland habitat and emergent tidal marsh habitat (WRA, 2019).

Upland Giant Garter Snake Habitat and Refugia Areas

A series of raised peninsulas will be constructed to provide year-round access to the base of each PG&E tower on the Project Site. In addition to facilitating PG&E access to their on-site infrastructure, the peninsulas would be designed to provide summer basking sites and winter flood refugia for GGS. The elevation of the peninsulas would be at least 8.0 feet (NAVD 88), which is high enough to be above typical high tides. The majority of peninsula top elevations would be constructed at Elevation 11.5 feet (NAVD 88), with some portions as high as Elevation 13.5 feet (NAVD 88). These raised areas would provide refugia from flood events with a 2-year frequency (WRA, 2018).

Analysis

Model Selection

To address the complex interaction between Yolo Bypass flows and the tidal influences of the north Sacramento-San Joaquin Delta, a two-dimensional hydraulic model is necessary for supporting design of the Project.

Hydrodynamic Model

Parent-Child Model Nesting Concept

One cost-effective and computationally efficient technique that has been deployed successfully in numerical modeling applications is splitting computations between coarse, large scale region-wide models (parent models) and localized high-resolution subdomain areas (child models). It can often be useful to deploy this technique in series, whereby results from the parent model are used to define boundary conditions for the child model, particularly when the child model domain is defined appropriately so as to avoid erroneous biasing at the boundary conditions.

This report documents the development and analysis performed using a child model prepared specifically for on-site design of the Project. Documentation associated with development and deployment of the parent model for establishing boundary conditions in the child model have been referenced where applicable.

Parent Hydrodynamic Model

The RMA Delta model was utilized as the parent model for this study. The RMA Delta model was developed by Resource Management Associates (RMA) using the RMA2 two-dimensional depth-averaged finite element hydrodynamic model. The RMA Delta Model extends from Martinez at the west end of Suisun Bay to the Sacramento River, upstream of the confluence with the American River, and to the San Joaquin River near Vernalis. The RMA Delta model domain includes the Cache Slough Complex, and was refined and calibrated in that region of the model in 2012 in support of the Prospect Island Tidal Restoration Project (RMA, 2012b). The model's geographic coverage and quality of calibration make it well suited as a source for establishing boundary conditions for a localized site-specific model.

Child Hydrodynamic Model

For on-site design, a high resolution two-dimensional child model was developed using the TUFLOW HPC commercial software package. TUFLOW HPC simulates depth-averaged, one and two-dimensional unsteady-state free-surface flow such as occurs from floods and tides, using a two-dimensional finite volume solution occurring over a regular grid of square elements. TUFLOW HPC was selected specifically for its ability to run simulations on NVidia GPU hardware, facilitating rapid simulation times. This is particularly advantageous for projects requiring long simulation periods (one or more months), or in cases where large numbers of alternatives need to be considered.

The relative extents of the parent and child models are shown on **Figure 7**. A detailed description of the on-site TUFLOW HPC model development, including calibration and verification is included in subsequent sections of this report.

Particle Tracking Modeling

The Particle Tracking Model (PTM) software developed by USACE Engineer Research and Development Center (ERDC) is a Lagrangian particle tracker designed to simulate particle transport processes. The software models sediment discretized into a finite number of particles that are followed as they are transported by the flow, providing insight for modeling transport from specified sources. PTM uses waves and currents developed through other models (in this case, TUFLOW HPC) and input directly to PTM as forcing functions. PTM includes the option to model particles in a neutrally-buoyant state, making it useful for simulating loose flocs in cases where fall velocity is considered negligible (USACE, 2006). These capabilities make the software useful for investigating site exposure times and food export pathways.

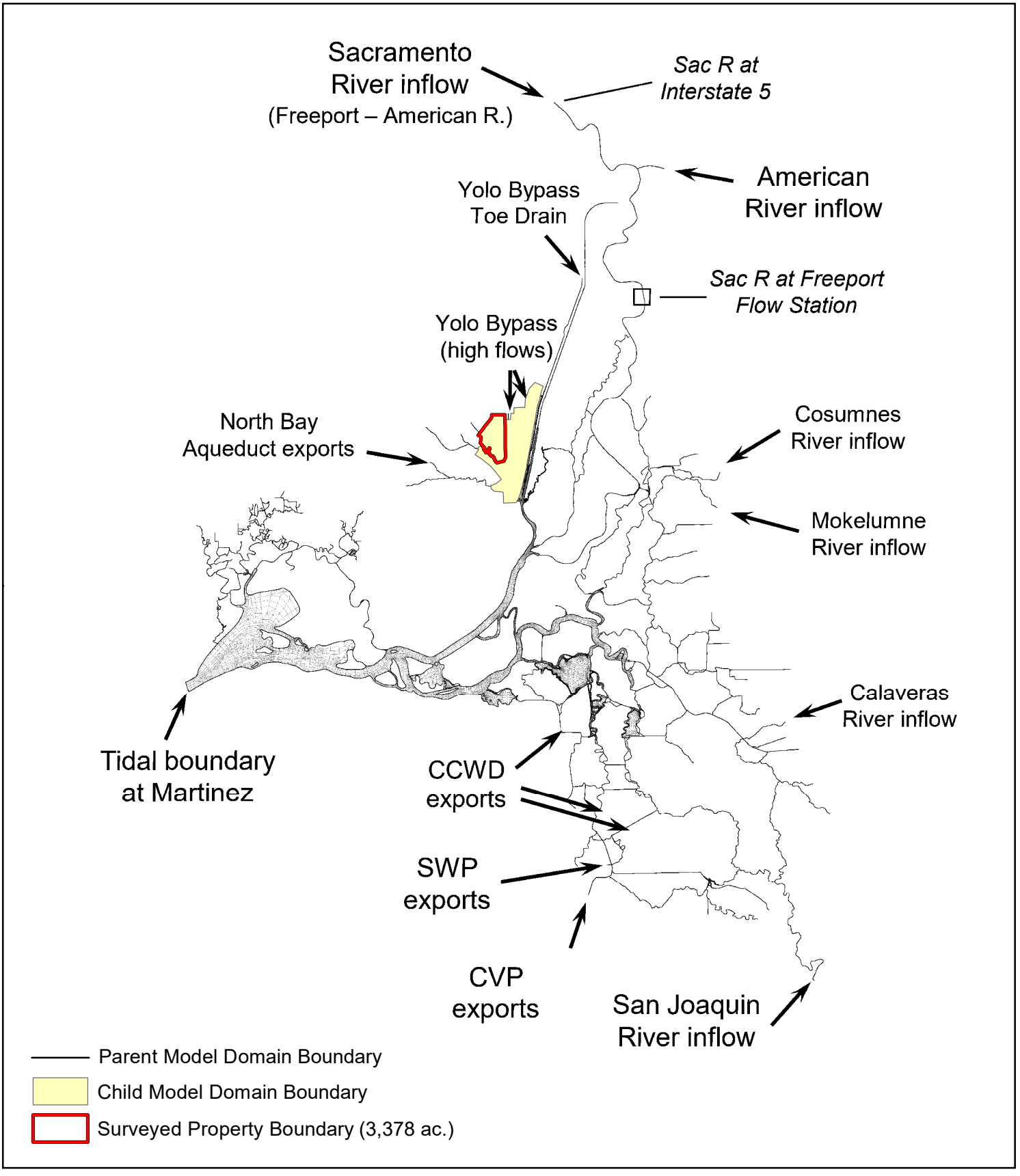

Figure 7
Parent-Child Model Schematic

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Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Map Prepared Date: 1/2/2019
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
RMA, 2012

Prepared by: ESA

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Hydrology

Data Sources and Design Events

Boundary conditions hydrology for the on-site analysis was sourced primarily from the RMA Delta model, which includes the tidal boundary, river inflows, as well as North Bay Aqueduct exports and other regional flow withdrawals and returns outside of the TUFLOW HPC model domain extents. Localized agricultural diversions and returns within the TUFLOW HPC model domain boundary were represented using data estimated by DWR for use in DWR's DSM2 modeling (DWR, 1995) at geographic locations consistent with the appropriate DSM2 node location. A detailed summary of the application of model boundary conditions is described in a subsequent section of this report.

A series of simulation events were selected in an effort to encompass a full range of normal tidal and hydrologic conditions. Three event periods were selected consistent with the work performed for the Prospect Island Tidal Restoration Project to represent summer, winter, and fall conditions during below normal water years. In this manner, estimates of potential tidal marsh establishment and food export productivity are considered to be conservative.

Summer 2010

The first simulation event encompasses the June 1, 2010 through July 31, 2010 period, during a year considered below normal for the Sacramento Valley. This period consisted of moderate to low flows in the Sacramento River (14,000 – 30,000 cfs), high Delta flow exports and Delta Island Consumptive Use (DICU), and operation (opening and closing) of the Delta Cross Channel gates. This period overlaps deployment of ESA PWA stage gages (ESA PWA, 2012) and DWR Acoustic Doppler Current Profiler (ADCP) measurements in the Cache Slough Complex, making it ideal for use in calibrating the without-Project baseline condition (RMA, 2012b). This period also overlaps the period of interest for most rapid growth in juvenile delta smelt (Moyle, 2002), making it useful for evaluation of food export production.

Winter 2010

The second simulation event encompasses the January 10, 2010 through March 31, 2010 period. During this period, flows in the Sacramento River were high to moderate (9,000 – 58,000 cfs), flows in the Yolo Bypass were relatively low (400 – 3,000 cfs) and the Delta Cross Channel gates were closed (RMA, 2012b). It is noted that the 2010 peak flow in the Sacramento River at Freeport occurred during this period, but was less than the 50% Annual Exceedance Probability (or 2-year) flow of 70,650 cfs at this location (PWA, 2006).

Fall 2008

The final simulation event encompasses the October 1, 2008 through November 30, 2008 period. This period overlaps deployment of stage gages by Metropolitan Water District (MWD) in the Cache Slough Complex. During this period flows in the Sacramento River were relatively low (8,000 – 13,000 cfs), and follow the low flow period from water year 2008 classified as "critical"

for the Sacramento Valley (RMA, 2012b). For purposes of evaluating the establishment of marsh habitat for crediting purposes, this scenario is considered to provide the most conservative estimate of the limits of viable marsh habitat.

Hydraulic Model Development

Hydraulic analysis was performed using a high resolution two-dimensional hydrodynamic model built using the TUFLOW HPC commercial software package. The following section describes the model extents, general construction of the model and input data sources, calibration and validation of the model to observed data, and application of the model for evaluating the project design.

Geographic Extents

The TUFLOW HPC model domain boundary is shown in **Figure 8**. The upstream end of the model domain begins approximately one mile north of the Holland Tract on the eastern side of the Yolo Bypass, and tracks along the Liberty Island step levees and includes a short portion of Shag Slough north of Liberty Island Road (near the northeastern corner of the project). The eastern edge of the model domain is bounded by the east levee of the Yolo Bypass, which forms the west levee of the Sacramento River Deep Water Ship Channel. The western edge of the model domain covers the Project boundary up to Duck Slough; lower Hass Slough and Cache Slough up to approximately 1,500 feet above where these streams form a confluence at the southeastern tip of the Peters Pocket track; and also includes the lower portion of Lindsey Slough beginning approximately 4,000 feet above Hastings Island Bridge. The model extends to the south, with the downstream boundary located just above the confluence of Cache Slough with the Sacramento River Deep Water Ship Channel and Miner Slough.

The model domain extents have been defined sufficiently far from the area of interest to avoid the influence of numerical artifacts at the model domain boundaries. Care has been taken to avoid setting the model domain boundary beyond the extents of regional parent model (the RMA Delta model), and to avoid excessively complicating the model boundary set up by reaching further than necessary into the confluence with the Sacramento River Deep Water Ship Channel and Miner Slough.

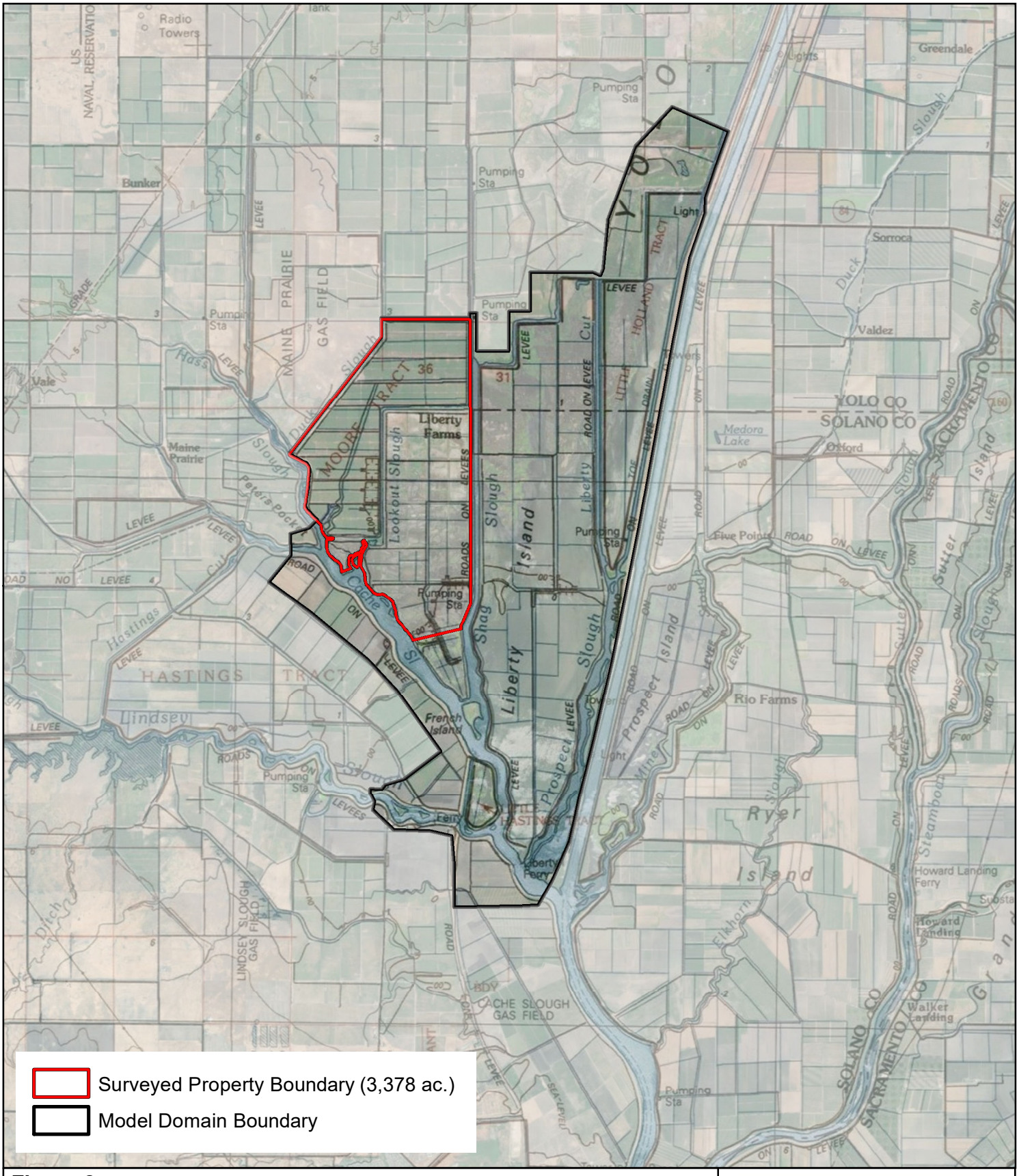

Figure 8
TUFLOW HPC Model Domain Extents

N
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0 0.75 1.5 3
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/29/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
RMA, 2012

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Boundary Conditions

Figure 9 shows the locations of the model boundary conditions. The model boundary conditions can be generally summarized as follows:

- Tidal boundary at Cache Slough
- Inflow at Shag Slough (west side of Yolo Bypass)
- Inflow at Yolo Bypass Toe Drain (east side of Yolo Bypass)
- Inflow at Yolo Bypass near Liberty Cut (high flow only, applicable to January through March 2010 simulation)
- Inflow at Hass Slough
- Inflow at Cache Slough
- Inflow at Lindsey Slough (note: during summer months, net flux is often negative due to withdrawals to the North Bay Aqueduct via the Barker Slough Pumping Plant)
- Delta Island Consumptive Use (DICU) agricultural withdrawal/return locations (DSM2 nodes 317, 318, and 321)

With the exception of the DICU locations, time series data at the tidal boundary and inflow boundary locations was extracted from the RMA Delta parent model by RMA and provided in *.dss database format. DICU flow rates were extracted independently from DWR's DSM2 model input and applied at the respective node locations as summarize in **Table 3**.

TABLE 3
DICU FLOW SUMMARY (MONTHLY FLOW RATE, CFS)

	Scenario:	CAL01		CAL02			VER01	
DSM2 Node ID	TUFLOW BC Database ID	Jun. 2010	Jul. 2010	Jan. 2010	Feb. 2010	Mar. 2010	Oct. 2008	Nov. 2008
317	DICU_317	-21.15	-31.08	1.25	-0.86	-5.65	-10.97	-8.44
318	DICU_318	-110.22	-137.34	121.66	90.4	-0.19	-6.22	1.46
319	DICU_319	-31.42	-61.95	15.80	8.52	-7.74	-19.48	-13.48
321	DICU_321	-11.58	-21.57	15.54	7.78	-0.03	-8.75	-5.45

SOURCE: DWR, 2013. Note that DSM2 diversion rate, drainage rate, and seepage rate are aggregated as a single withdrawal rate in the model simulation.

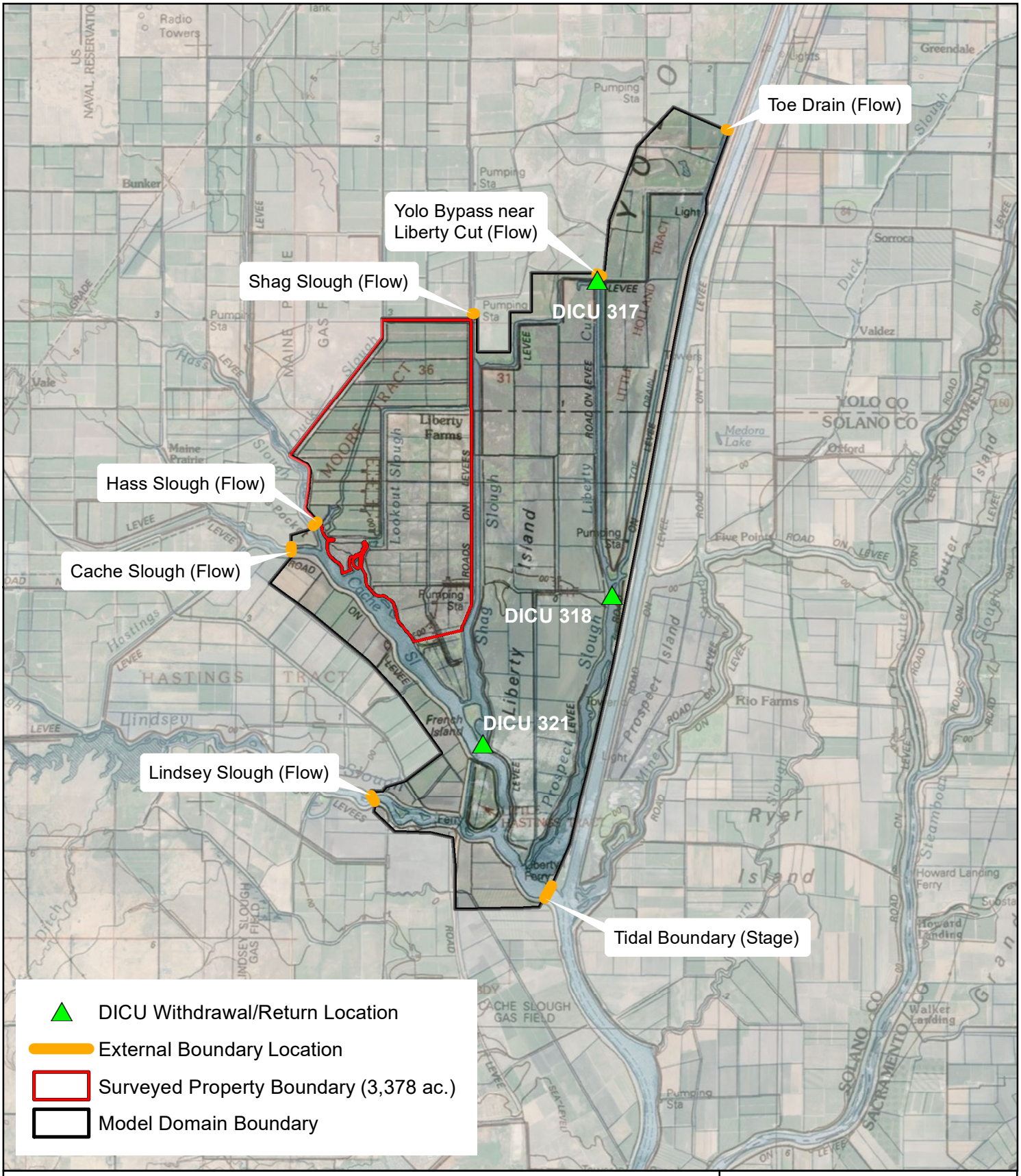

Figure 9
TUFLOW HPC Model Boundary Conditions

0 0.75 1.5 3
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
Esri Service Layers (2018)

Prepared by: ESA

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Topographic and Bathymetric Survey Data

Terrain data for this modeling is based on the following data sources, which are layered in the TUFLOW HPC model input to build a composite bathymetric and terrain surface:

- The primary terrain data source representing existing terrain and bathymetry for the southern portion of the model domain is based on the DWR San Francisco Bay and Sacramento-San Joaquin Delta Digital Elevation Model, or DEM (Wang & Ateljevich, 2012), which aggregates a number of data sources. In the vicinity of the Project, coverage consists primarily of Delta Risk Management Strategy (DRMS) LiDAR data (Dudas, 2010) and the Liberty Island single beam bathymetric surveys prepared by cbec/EDS in 2006, 2009, and 2010. The elevation data was aggregated by DWR into a seamless 10m DEM format (Esri Grid) in units of centimeters, referenced to NAVD 88 and projected in NAD 83 UTM Zone 10 coordinates in meters, and clipped to a smaller extent to reduce the overall data footprint and terrain processing overhead.

- The DRMS LiDAR dataset (Dudas, 2010) was used to fill in gaps in some of the low confidence marsh areas on Liberty Island as well as portions of the Yolo Bypass north of Liberty Island and west of the Yolo Bypass Toe Drain. DRMS LiDAR tiles that were post-processed as part of DWR's Central Valley Floodplain Evaluation and Delineation (CVFED) Program were utilized to create "patch" areas to improve terrain representation in these areas. The CVFED post-processed tiles incorporate breaklines to enforce edges of water bodies and avoid undesired interpolation across large flat area.

- The U.S. Geological Survey (USGS) collected detailed bathymetric surveys of the Little Holland Tract area in 2015 (Snyder et al., 2016). Data was provided in NAD 83 UTM Zone 10 coordinates in units of meters, with elevations provided in units of meters and referenced to NAVD 88. For purposes of preparing the model input, the elevation data was converted to units of feet and re-projected to California State Plane II FIPS 0402 (US Feet) for consistency with the Project datum.

- DWR's North Central Regional Office (NCRO) provided bathymetric survey data collected in 2015 along the northern "steps" of Liberty Island. This data was provided in NAD83, California State Plane II FIPS 0402 (US Feet) coordinates and referenced to NAVD 88 in units of feet. No additional processing was required.

- To correct for isolated issues identified in the San Francisco Bay and Sacramento-San Joaquin Delta DEM surface, some locations were replaced with data from the DWR Bay-Delta Office Cross Section Development Program (CSDP).

At the project site, new topographic surveys collected by Wood Rodgers were used to define without-project conditions. This data was collected and mapped in NAD 83, California State Plane II FIPS 0402 (US Feet) and referenced to NAVD 88 in units of feet, consistent with the Project datums. Field surveys were also performed as part of this effort to rectify aerial survey data in marsh areas within the Liberty Farms tract.

The TUFLOW topographic layering hierarchy was input as follows (layers listed in order from "bottom" of stack, to "top"):

- San Francisco Bay and Sacramento-San Joaquin Delta DEM (Wang & Ateljevich, 2012)

- DRMS LiDAR DEM (Dudas, 2010)
- Little Holland Tract DEM (Snyder et al., 2016).
- Liberty Cut March 2015 Survey DEM (DWR NCRO, 2015)
- CDSP Bathymetry for localized bathymetry corrections (DWR Bay-Delta Office, 2001)
- On-site topography (aerial and bathymetry) collected in Fall 2017 by Wood Rodgers. For the with-Project scenarios, a preliminary grading surface prepared by Wood Rodgers reflecting the proposed marsh grading plan and tidal channel network replaces the onsite topography.

The geographic distribution of the respective terrain layer datasets is shown on **Figure 10**.

Terrain Enforcement

The DWR Delta DEM surface exhibits areas with erroneous elevations or missing data. These areas are filled/cleaned using TUFLOW's topographic layering tools to generate TIN surfaces which eliminate gaps and clean up erroneous data values in the terrain.

Using the 3D breaklines prepared previously as part of DWR's CVFED LiDAR surveying efforts and data contained in the DWR California Levee Database (DWR, 2010) as a base, a comprehensive breakline dataset was developed to enforce the tops of levees and embankments within the domain area. In some cases, manual edits were made to better align the line work with tops of embankments considered hydraulically significant. The California Levee Database line work was then densified to intervals of 30 feet (roughly half the cell size of the computational grid) and converted to points using ArcGIS, which were then assigned elevations using the SF Bay SJ Delta DEM surface. The CVFED 3D breaklines already contained elevation values and were converted to points accordingly. The respective breakline datasets used to enforce terrain in the model are shown on Figure 10. The resultant composite terrain and bathymetry surface utilized by the model is shown on **Figure 11**.

Bed Roughness

Land use classifications derived from mapping prepared by the California Department of Fish and Game (now Fish and Wildlife, CDFW) in 2007 were aggregated into general land cover (materials) types for input into the baseline hydraulic model: subtidal, mudflats, low and middle marsh, upland, and cropland. With the exception of cropland, these are generally associated with vegetation densities and depths that will be associated with different portions of the tidal prism (**Figure 12**), which are expected to be representative of conditions in the north Delta and lower Yolo Bypass. The crosswalk between CDFW vegetation and the model material type reclassification scheme used is summarized in **Table 4**.

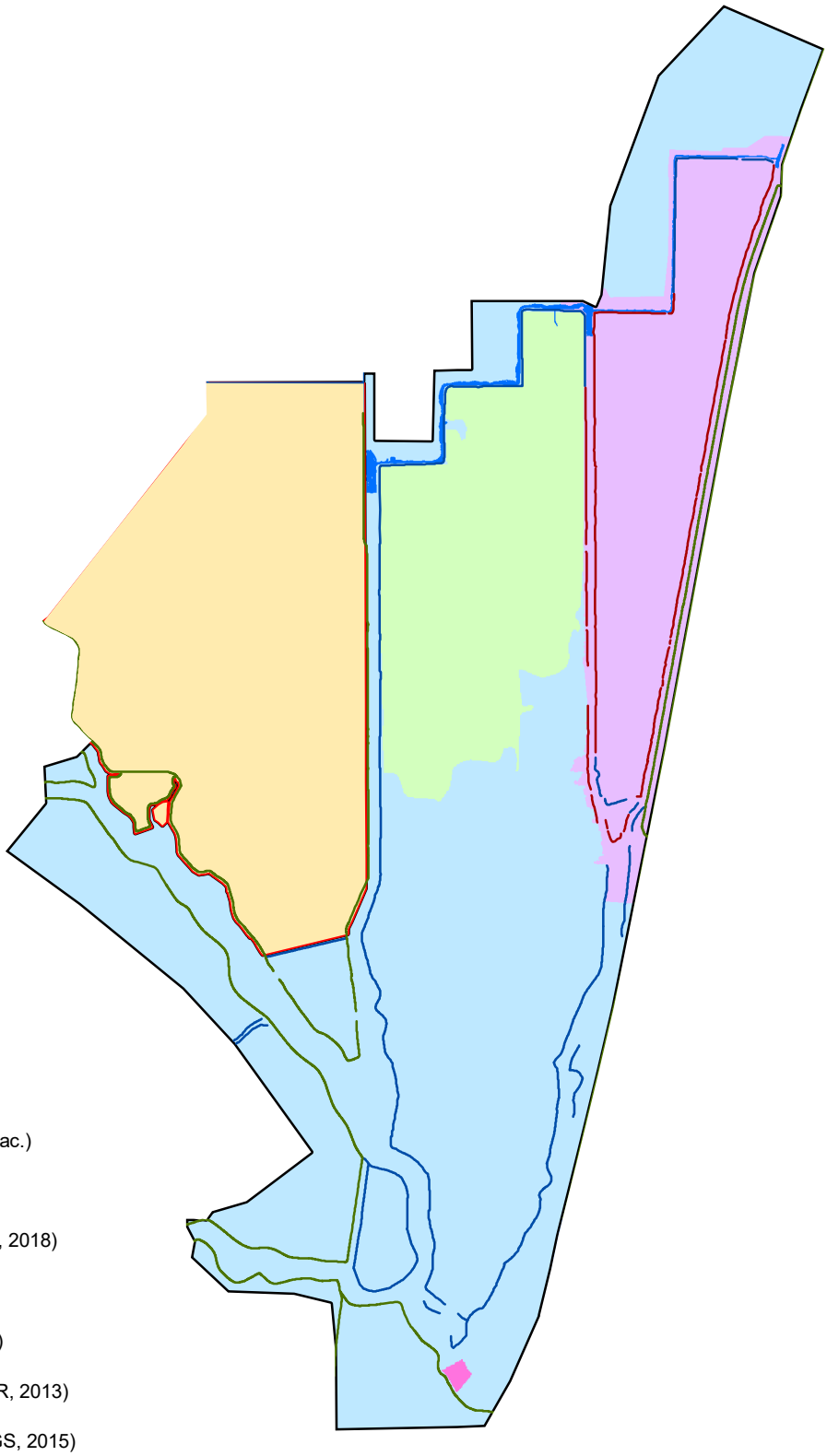

Figure 10
TUFLOW HPC Topographic and Bathymetric Data

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Feet

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
Esri Service Layers (2018)

Lookout Slough Restoration Project

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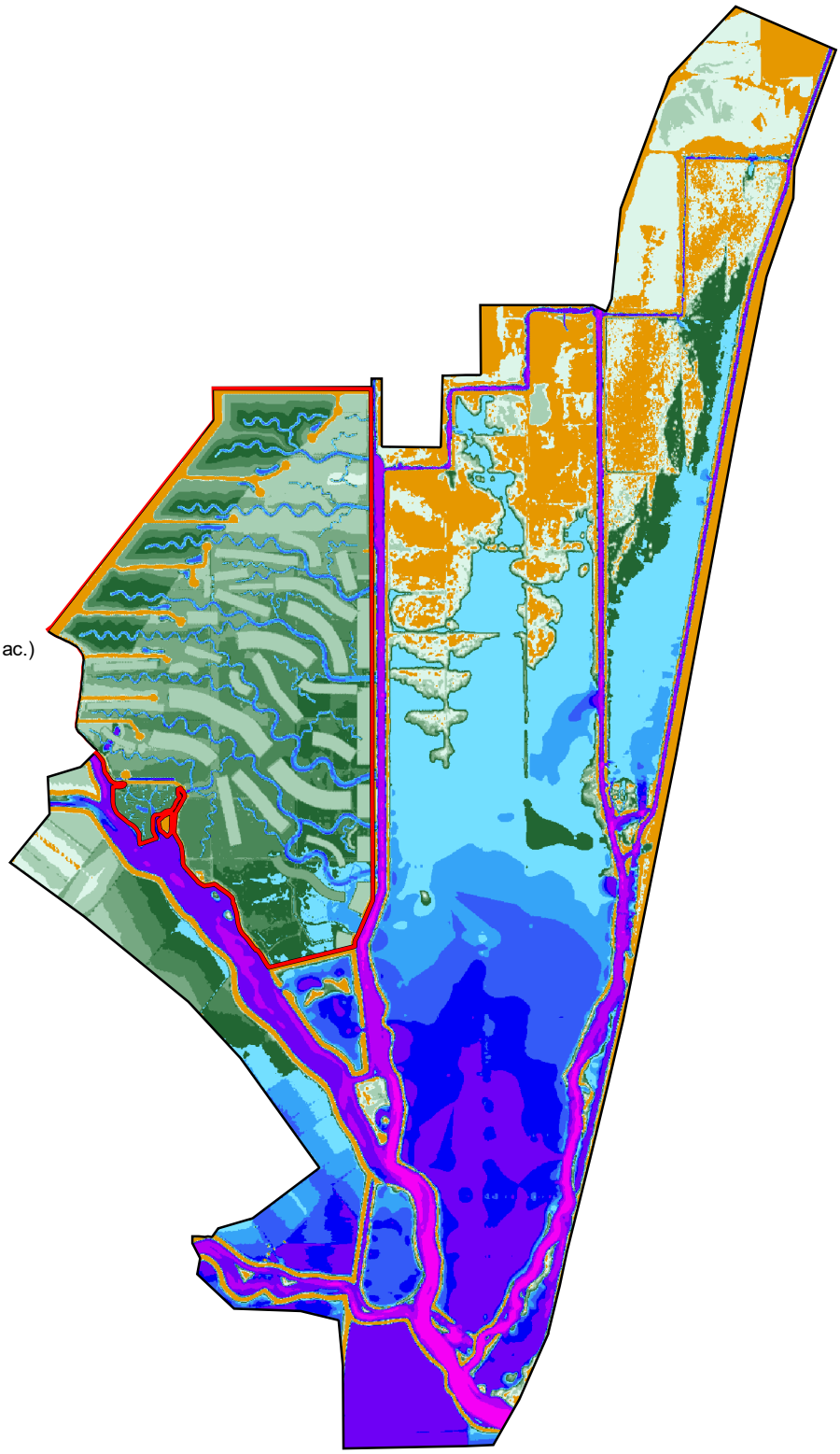

Surveyed Property Boundary (3,378 ac.)

Model Domain Boundary

Elevation (feet, NAVD 88)

Subtidal Zone

- < - 20
- -20 - -10
- -10 - -2
- -2 - -1
- -1 - 0
- 0 - 1
- 1 - 2

Emergent Tidal Marsh Zone

- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7

Upland Zone

- > 7 feet

Figure 11
TUFLOW HPC Composite Digital Elevation Model

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Feet

Lookout Slough Restoration Project

Ecosystem Investment Partners

Map Prepared Date: 1/2/2019
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
USGS, DWR, Wood Rodgers

Prepared by: ESA

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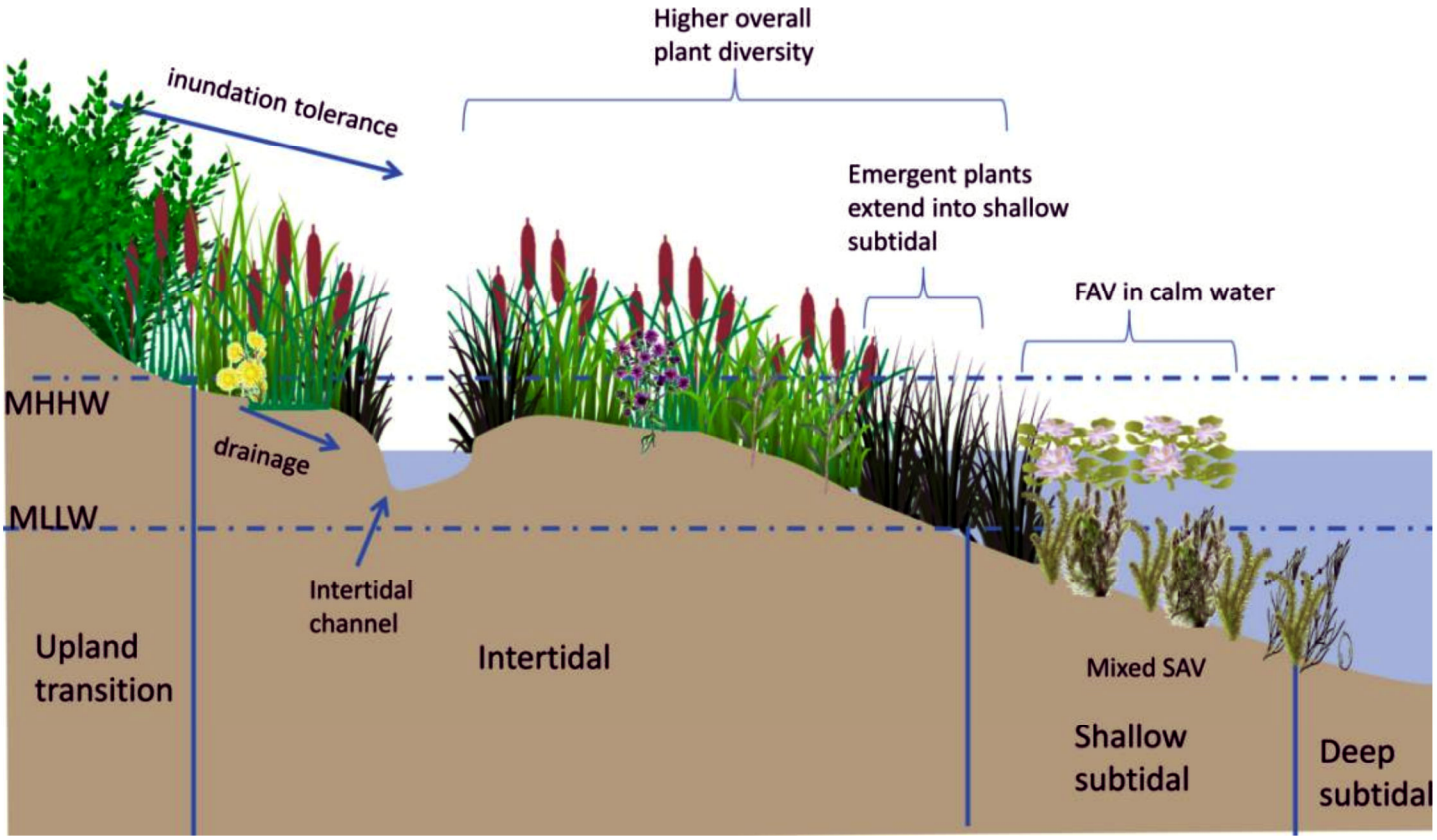

Figure 12
General Factors Controlling Vegetation Zonation
in Freshwater Marshes (Sherman et al, 2017)

Ecosystem Investment Partners

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Data Source(s):
Sherman et al (2017)

Prepared by: ESA

Lookout Slough Restoration Project

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TABLE 4
MODEL MATERIAL CLASSIFICATION KEY

California Wildlife Habitat Relationship[1]	TUFLOW Model Material Type
Unclassified	Upland
Annual Grassland	Mudflat/Grassland
Barren	Mudflat/Grassland
Coastal Oak Woodland	Upland
Coastal Scrub	Low and Middle Marsh
Cropland	Upland
Deciduous Orchard	Upland
Eucalyptus	Upland
Fresh Emergent Wetland	Low and Middle Marsh
Riverine	Riverine
Saline Emergent Wetland	Low and Middle Marsh
Urban	Upland
Valley Foothill Riparian	Upland
Vineyard	Upland

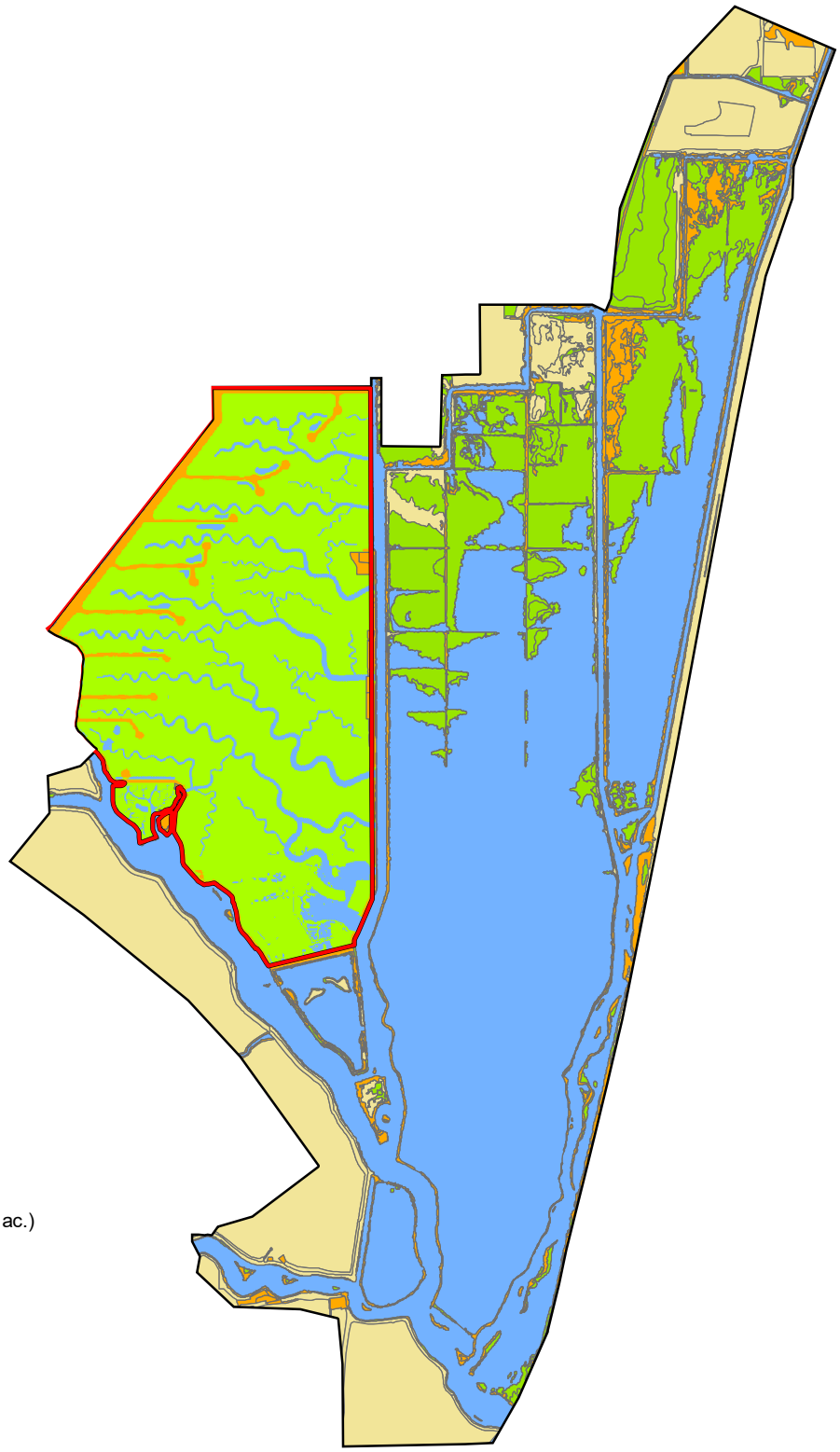
[1] SOURCE: CDFW, 2007.

In the hydraulic model, the default material assignment to the 2D domain is material ID 1 (Subtidal), representing a roughness coefficient of 0.030 (consistent with the RMA Delta Model). Roughness coefficient values for the Mudflat and Upland materials types were developed estimated using the procedure for floodplains described in USGS Water Supply Paper No. 2339 (USGS, 1989). Roughness coefficient values for the Low and Middle Marsh material type were estimated using values reported for bulrush environments by the USACE Waterways Experiment Station (USACE, 1994), and refined during model calibration. **Table 5** summarizes the model material classification scheme and associated roughness coefficient estimates. To be conservative, it has been assumed that stands of tules will colonize the Project site at and above Elevation 2.0 feet (NAVD 88), encompassing elevation ranges which might otherwise be characterized as mudflats. The resultant baseline materials input file is shown as a map on **Figure 13**.

TABLE 5
TIDAL DATUM ESTIMATES IN VICINITY OF PROJECT (FEET, NAVD 88)

Material Class	Vegetation Complex Type	Typical Vegetation	Manning's Roughness[1]	Elevation Range (feet, NAVD 88)
1	Riverine	Negligible (primarily open water)	0.030	< 2.0 (MLLW)
2	Mudflat/Grassland	Minor	0.035	2.0 – 3.5 (MTL)
3	Low and Middle Marsh	Perennial vegetation, dense stands of bulrushes (tules and cattails)	0.270	3.5 – 7.0 (MHHW)
4	Upland	Dense emergent vegetation	0.060	> 7.0 (Maximum Tide)

SOURCES: USGS, 1989; Chow, 1959; RMA, 2012; USACE, 1994.



Surveyed Property Boundary (3,378 ac.)

Model Domain Boundary

Material Classification

Riverine

Mudflat / Grassland

Low and Middle Marsh

Upland

Figure 13
TUFLOW HPC Materials Classification

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Feet

Lookout Slough Restoration Project

Ecosystem Investment Partners

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
CDFG, Wood Rodgers

Prepared by: ESA

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Model Calibration and Verification

Three simulation periods were used as the basis for calibrating and verifying the performance of the TUFLOW HPC hydrodynamic model for without-Project conditions, consistent with the approach documented in the Prospect Island EIR (RMA, 2012b):

- Calibration Simulation 1 (CAL01), consisting of the June 1, 2010 through July 18, 2010 period. The RMA Delta model calibration was limited to this period due to unrealistic or missing stage observations at Martinez during the summer months of 2010. The calibration analysis of the TUFLOW HPC child model was limited to same window as that of the RMA Delta parent model to facilitate direct comparison between the parent and child model results.
- Calibration Simulation 2 (CAL02), consisting of the January 10, 2010 through March 31, 2010 period. This represents a second calibration run.
- Verification Simulation 1 (VER01), consisting of the October 1, 2008 through November 30, 2008 period.

Calibration and verification of the TUFLOW HPC model performance was evaluated against both observed data, as well as against documented performance of the RMA Delta model to ensure that the quality of the model results was not significantly affected by handoff between the parent and child models. To that end, the following tidal system calibration metrics were utilized to assess the quality of fit between the modeled and observed data (RMA, 2012b):

- **Mean**. Comparison of mean values between computed values and measured time series data (stage or flow) provides a measure of how well the model results correlate to net observed flow or average stage at a monitoring station.
- **Phase Shift**. The average shift in time (or lag) between the computed and observed tidal signals determined from a cross-correlation analysis.
- **Linear Regression**. After the phase shift is removed, a linear regression analysis is performed to compare the modeled data with observations collected at monitoring stations.
- **Tidal Amp Ratio**. This is computed using the slope of the regression line derived from a second linear regression analysis where the tidally averaged signal is removed from the observed and computed records, generating a time series that is more representative of the daily tides.

Locations and of stage and flow measurement stations and their corresponding period of record are shown on **Figure 14**, and are summarized within **Table 6**. Plots depicting computed and observed stage/flow, tidally averaged stage/flow computed using a two-pass moving average window, and a linear regression scatter plot for each gage location and corresponding simulation period of interest are presented in **Appendix A**.

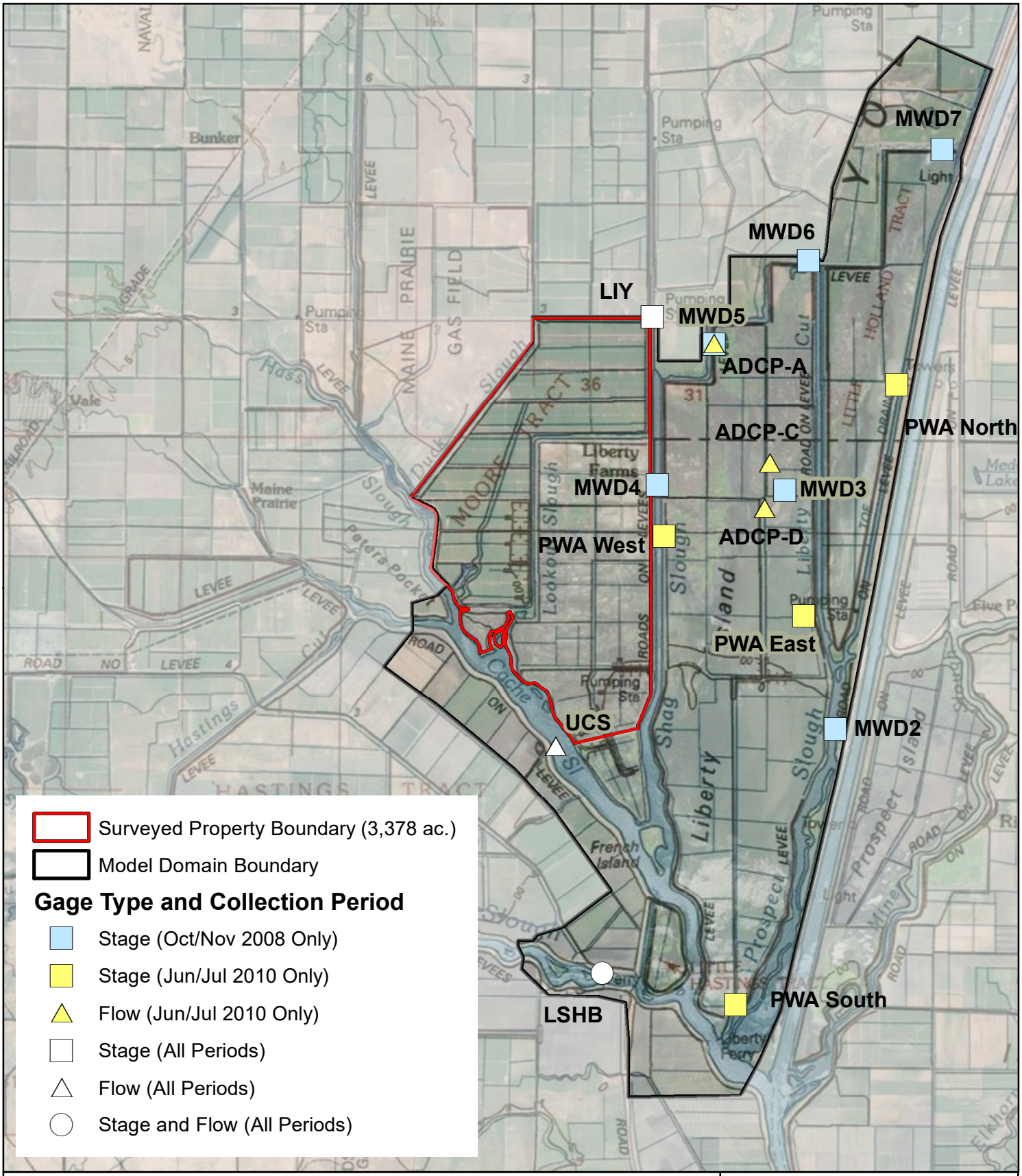

Figure 14
Calibration Stage and Flow Locations

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Feet

Lookout Slough Restoration Project

Ecosystem Investment Partners

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
DWR, ESA PWA, MWD, SCWA

Prepared by: ESA

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TABLE 6
CALIBRATION STAGE AND FLOW MONITORING STATIONS

Station ID	Description	Stage	Flow	Data Source
LSHB	Lindsey Slough at Hastings Bridge	•	•	Solano County Water Agency
UCS	Upper Cache Slough		•	DWR North Central Region Office
LIY	Yolo Bypass at Liberty Island	•		DWR California Water Data Library
PWA East	Liberty Island	•		PWA ESA
PWA North	Liberty Island	•		PWA ESA
PWA South	Liberty Island	•		PWA ESA
PWA West	Liberty Island	•		PWA ESA
ADCP-A	Liberty Island		•	DWR North Central Region Office
ADCP-C	Liberty Island		•	DWR North Central Region Office
ADCP-D	Liberty Island		•	DWR North Central Region Office
MWD2	Liberty Island	•		cbec
MWD3	Liberty Island	•		cbec
MWD4	Liberty Island	•		cbec
MWD5	Liberty Island	•		cbec
MWD6	Liberty Island	•		cbec
MWD7	Liberty Island	•		cbec

Calibration typically involves adjustment of parameters and refinement to model geometry to reduce residual errors between the model predictions and observed results. For the TUFLOW HPC model, this primarily involved inspection at the observed data locations to identify localized corrections in the terrain and bathymetry surfaces. Sensitivity analysis was performed at a global level to adjust Manning's roughness coefficients (primarily the Low and Middle Marsh material type) to perform a final fitness correction when evaluating water levels throughout the domain. In general, the Manning's roughness refinements were considered minor and conform to literature values for tidal marsh environments under non-flood conditions.

Stage and flow statistics for the respective calibration and verification simulations are summarized in **Table 7** through **Table 12**. Although deviation varies from station to station, comparisons between the TUFLOW HPC child model and RMA Delta parent model indicate that both models are performing similarly within the region of interest, and that the tidal signal is well represented in both models. The modeled flow results at the ADCP-C and ADCP-D gage locations on Liberty Island do, however, show significant variation from the observed data. These differences are most likely the result of poor representation in the bathymetry data and resolution of the model grid at these locations. The ADCP-D gage for instance, was deployed in an old irrigation canal that appears to be poorly represented in the bathymetry data. DWR staff also noted in personal communication that GPS was not used to record the locations of the ADCP reference transects, casting uncertainty on the orientation and length of the transect when extracting results from the model. Both the ADCP-C and ADCP-D gages were deployed in a

region that is hydraulically isolated from the Project, and the uncertainty at these locations is considered to be localized and will not adversely impact the performance of the model in the region of interest.

TABLE 7
STAGE ERROR STATISTICS FOR JUNE 1 – JULY 18, 2010 CALIBRATION PERIOD

Station ID	Mean Observed (feet, NAVD 88)	Mean Computed (feet, NAVD 88)	ΔMean (feet)	Lag (minutes)	Tidal Amp Ratio	R^2
LSHB	4.72	4.40	0.32	4.00	1.02	0.93
LIY	4.57	4.40	0.17	0.00	1.03	0.98
PWA East	4.74	4.52	0.22	-7.00	0.98	0.97
PWA North	4.82	4.55	0.27	-13.00	0.93	0.94
PWA South	4.71	4.50	0.21	0.00	1.02	0.97
PWA West	4.83	4.51	0.32	-5.00	1.00	0.93

TABLE 8
FLOW ERROR STATISTICS FOR JUNE 1 – JULY 18, 2010 CALIBRATION PERIOD

Station ID	Mean Observed (cfs)	Mean Computed (cfs)	ΔMean (cfs)	Lag (minutes)	Tidal Amp Ratio	R^2
LSHB	-385.61	-385.64	0.03	16.00	0.99	1.00
UCS	-569.79	-568.67	-1.12	-4.00	1.16	0.97
ADCP-A	-17.96	9.09	-27.05	2.00	0.88	0.98
ADCP-C	-3.84	-0.76	-3.08	22.00	0.40	0.63
ADCP-D	38.81	-0.13	38.95	-3.00	0.27	0.43

TABLE 9
STAGE ERROR STATISTICS FOR JANUARY 10 – MARCH 31, 2010 CALIBRATION PERIOD

Station ID	Mean Observed (feet, NAVD 88)	Mean Computed (feet, NAVD 88)	ΔMean (feet)	Lag (minutes)	Tidal Amp Ratio	R^2
LSHB	5.10	4.86	0.24	11.00	1.02	0.96
LIY	4.86	4.88	-0.02	5.00	1.01	1.00

TABLE 10
FLOW ERROR STATISTICS FOR JANUARY 10 – MARCH 31, 2010 CALIBRATION PERIOD

Station ID	Mean Observed (cfs)	Mean Computed (cfs)	ΔMean (cfs)	Lag (minutes)	Tidal Amp Ratio	R^2
LSHB	-298.38	-297.42	-0.96	24.00	1.01	1.00
UCS	384.37	386.27	-1.89	19.00	1.11	0.99

TABLE 11
STAGE ERROR STATISTICS FOR OCTOBER 1 – NOVEMBER 30, 2008 VERIFICATION PERIOD

Station ID	Mean Observed (feet, NAVD 88)	Mean Computed (feet, NAVD 88)	ΔMean (feet)	Lag (minutes)	Tidal Amp Ratio	R^2
LSHB	4.26	4.29	-0.03	4.00	1.00	1.00
LIY	4.10	4.29	-0.19	0.00	1.02	0.97
MWD2	4.04	4.29	-0.25	-7.00	0.99	0.96
MWD3	4.15	4.31	-0.16	-5.00	1.13	0.96
MWD4	4.25	4.29	-0.05	0.00	1.00	1.00
MWD5	4.00	4.36	-0.35	-12.00	0.93	0.90
MWD6	4.04	4.30	-0.27	-14.00	0.95	0.95
MWD7	4.00	4.31	-0.31	-43.00	0.86	0.91

TABLE 12
FLOW ERROR STATISTICS FOR OCTOBER 1 – NOVEMBER 30, 2008 VERIFICATION PERIOD

Station ID	Mean Observed (cfs)	Mean Computed (cfs)	ΔMean (cfs)	Lag (minutes)	Tidal Amp Ratio	R^2
LSHB	-393.86	-395.42	1.56	11.00	1.01	1.00
UCS	-182.40	-203.24	20.84	-5.00	1.07	1.00

Particle Tracking Model Development

The primary purpose of the particle tracking simulation is to model onsite exposure time. The ability to track the transport of the particles in the simulation is limited to the extents of the hydrodynamic model domain. Particles leaving the simulation at the model domain boundaries are assumed to leave the domain area without returning. Although limited in geographic scope, the resultant transport pathways can be visualized and used to inform general trends regarding export pathways within the region of interest.

Particle tracking simulations were performed for using June through July 2010 simulation period. This simulation period was selected as it includes the period of most rapid growth in juvenile Delta smelt (Moyle, 2002), and overlaps one of the model calibration simulation periods. This simulation period is consistent with the exposure time analysis performed as part of the Prospect Island Restoration Project (SWS-WWR, 2012).

A grid pattern of particle release locations was developed to provide a relatively uniform spatial distribution of particles across the project site, including Vogel Island (**Figure 15**). For the current phase of analysis, the approximate spacing of the particle release grid was approximately 1,000 feet. The current model configuration was considered appropriate for evaluating broad-scale exposure time patterns within the Project area. Refinements to the grid spacing may be warranted for analysis of specific regions or design features within the project site.

Individual particles were released every two hours over a two-week period during the June 20 to July 4, 2010 window and tracked through the end of July 2010. This release schedule is designed to remove bias arising from the timing of the daily and spring-neap tidal cycles (RMA, 2012a).

During the simulation, approximately 25,000 particles were released and tracked through the model domain. Several trap polygons (**Figure 16**) were defined in the model to record the movement of particles in and out of regions of interest within the model domain. In this manner, the time spent inside a region can be determined to compute exposure time within a region, or alternatively to identify particles exiting the open boundaries of the model domain.

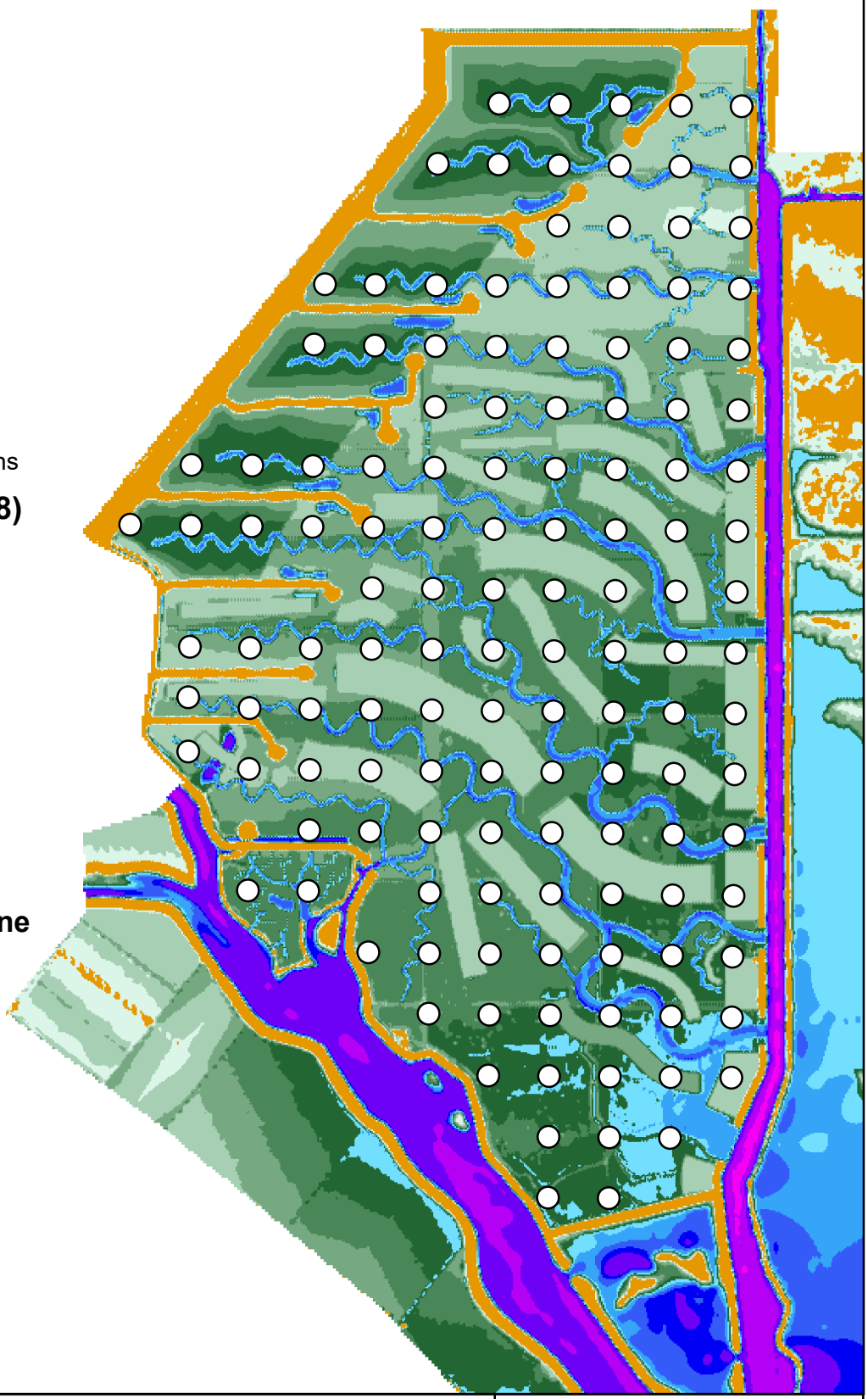
With-Project Condition Assessment

The project design was evaluated using the aforementioned criteria for tidal damping, channel stability, and exposure time. The modeled performance of the project for the respective criteria is discussed below.

Tidal Damping Assessment

For evaluating the potential for tidal damping across the project site, a general threshold for maximum reduction in MHHW was set to 0.75 feet, relative to reference water levels in Cache Slough and Shag Slough. Some tidal damping will inevitably occur due to dissipation of tidal energy in the channel network and dense tule marsh plains that bound it. To the extent practical, refinements were incorporated into the design to reduce damping as much as possible. This was accomplished primarily by development of a tidal channel network and through refinements in site grading design to remove physical barriers and promote drainage off of the marsh plain towards the channel system (WRA and Beaver Creek Hydrology, 2019).

MHHW values were computed across the site using output from the two-dimensional hydrodynamic model for the October through November 2008 simulation period. This period represents a relatively dry period during a critical water year, and is expected to produce a conservative estimate of the MHHW levels on the site once the Project is constructed. The



Particle Release Locations

Elevation (feet, NAVD 88)

Subtidal Zone

- < - 20
- -20 - -10
- -10 - -2
- -2 - -1
- -1 - 0
- 0 - 1
- 1 - 2

Emergent Tidal Marsh Zone

- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7

Upland Zone

- > 7 feet

Figure 15
Particle Release Grid

N
W E
S

0 0.25 0.5 1
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
DWR, USGS, Wood Rodgers

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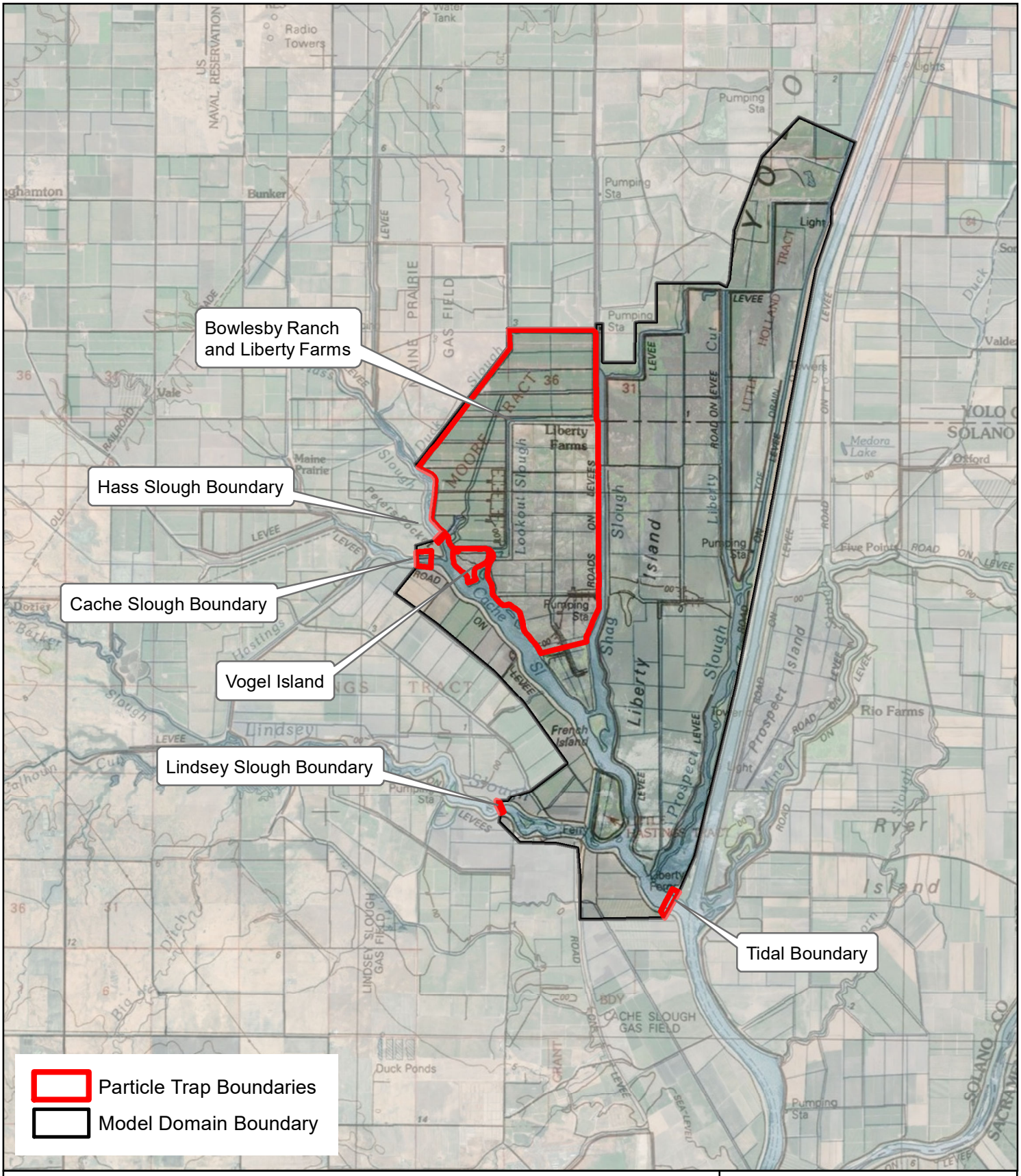

Figure 16
Particle Trap Locations

0 0.75 1.5 3
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
Esri Service Layers (2018)

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modeled reduction in MHHW elevation across the project site relative to the reference value at the confluence of Cache Slough and Shag Slough is shown on **Figure 17**. Detailed time series plots at key locations across the site are presented in **Appendix B** for reference.

In general, the model results indicate that damping effects increase relative to the distance from the levee breach openings on the project perimeter. This is not expected given the hydraulic roughness of the tidal channels and vegetated marsh plain. Dissipation of tidal energy is particularly pronounced in the vicinity of the line of PG&E towers that cross the site on the Bowlesby tract, as evidenced by the density of the damping isolines shown on Figure 16. The access roads leading to the towers act as hydraulic barriers in some locations, further dissipating the tidal energy on the western edge of the site. Modifications to the access road alignments may reduce the degree to which damping occurs at these locations. Additional refinements to portions of the channel network geometry and site grading may also yield some localized improvements. The feasibility of further reducing tidal damping through additional refinements will be investigated in the 60% design phase.

Channel Stability Assessment

Maximum bed shear stress was computed using the TUFLOW HPC hydrodynamic model for the three simulation periods. In general, January through March 2010 period yielded the highest bed shear stress values in the channel network. Although this period represents a relatively mild winter storm season, it does provide an indication of the types of conditions the site would be exposed to in most water years.

As shown on **Figure 18**, bed shear stress values computed within the channel corridors are generally less than 0.05 lbs/sf, indicating minimal potential for erosion given the geology of the site. Sediment deposition potential within the channel network is not considered to be significant. Drainage to and from the marshplain is expected to create sufficient tidal prism to discourage deposition of suspended sediment in the channels. The Project channel network is also shallow relative to the deep perimeter channels at Cache Slough and Shag Slough, and largely isolated from bedload sediment transport by these deeper exterior channels (WRA and Beaver Creek Hydrology, 2019).

Exposure Time Assessment

Results of the particle tracking analysis were binned and mapped spatially to characterize the distribution of exposure times across the site (**Figure 19**). In general, the Project is able to realize a broad range of exposure times across the site. Shorter exposure times are observed on Vogel Island and in proximity to the levee breach openings on Shag Slough. Exposure times increase moving from southeast to northwest across the site, correlating to the increased travel distance and dissipation of tidal energy towards the back of the site. There are also several areas immediately adjacent to the levee and between breaches that exhibit high exposure times, likely due to the hydraulic shadow formed behind the remnant levee embankment.

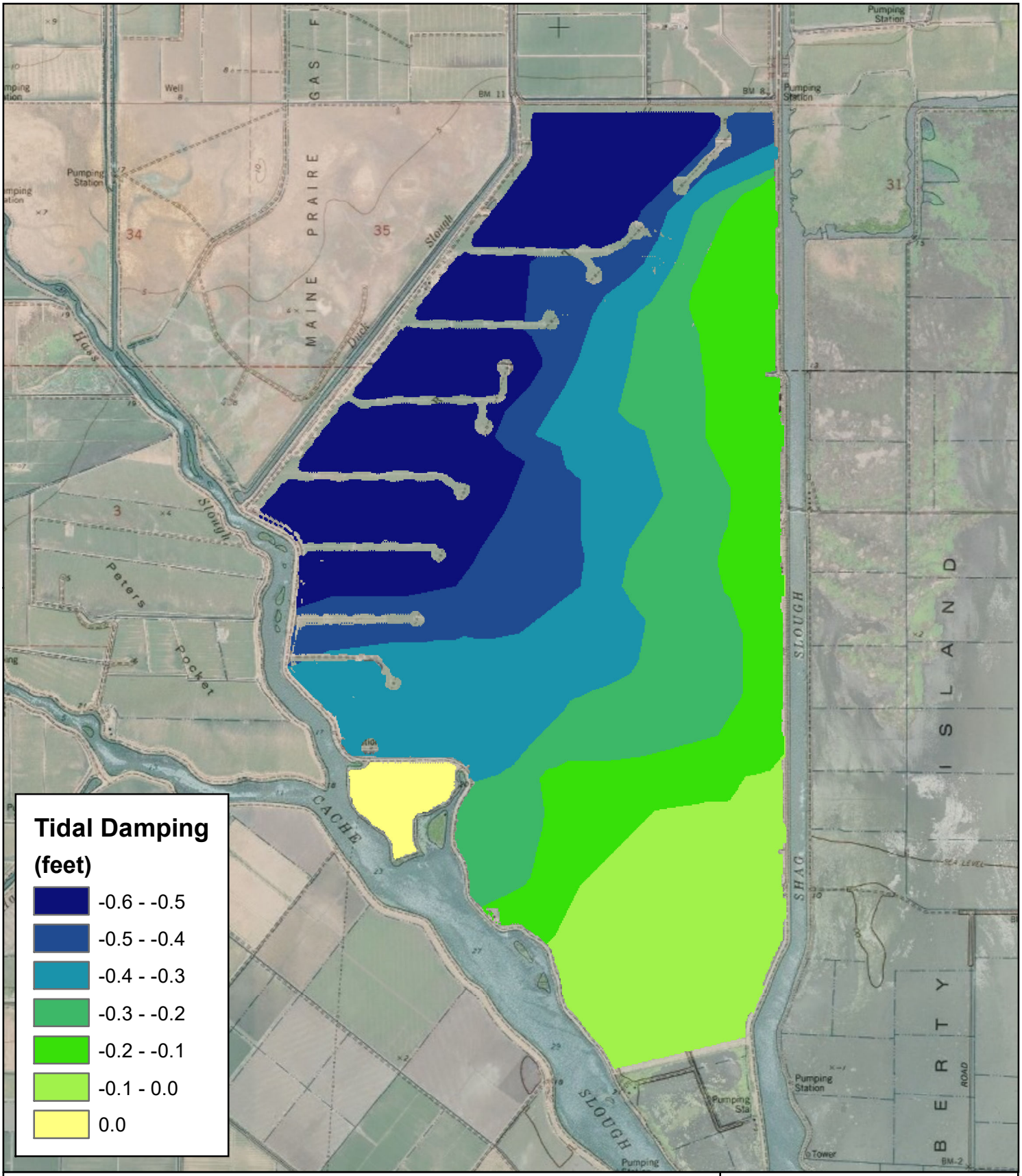

Figure 17
Onsite Tidal Damping

N
W E
S

0 0.25 0.5 1
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

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Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rogers
Base Date: 10/24/2017
Data Source(s):

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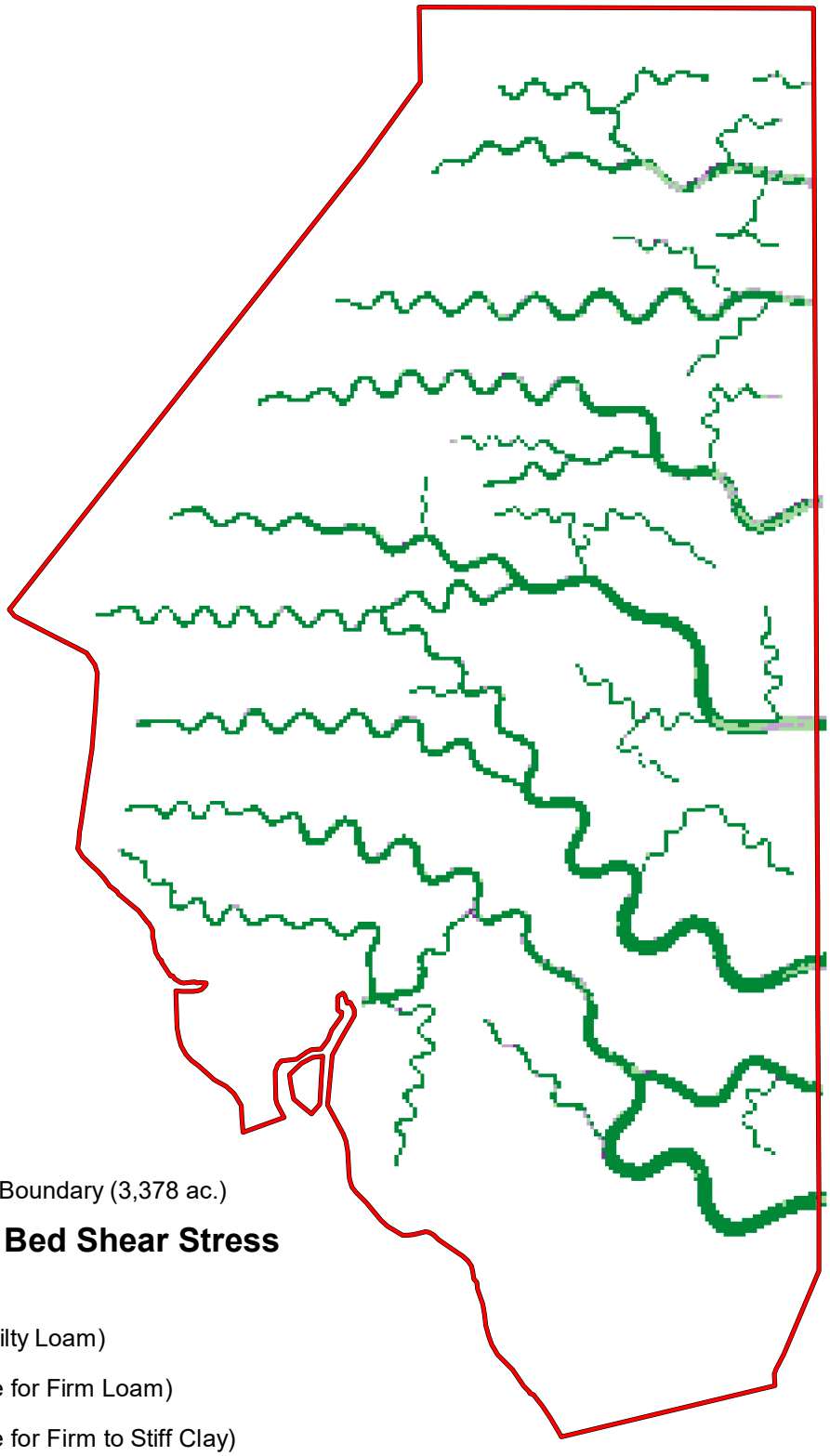

Surveyed Property Boundary (3,378 ac.)

Maximum Channel Bed Shear Stress

(lbs/sf)

- < 0.05 (Stable for Silty Loam)
- 0.05 - 0.075 (Stable for Firm Loam)
- 0.075 - 0.26 (Stable for Firm to Stiff Clay)
- > 0.26 (Potential Scour for Clay)

Figure 18
Channel Bed Shear Stress

N
W E
S

0 0.25 0.5 1
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/30/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
DWR, USGS, Wood Rodgers

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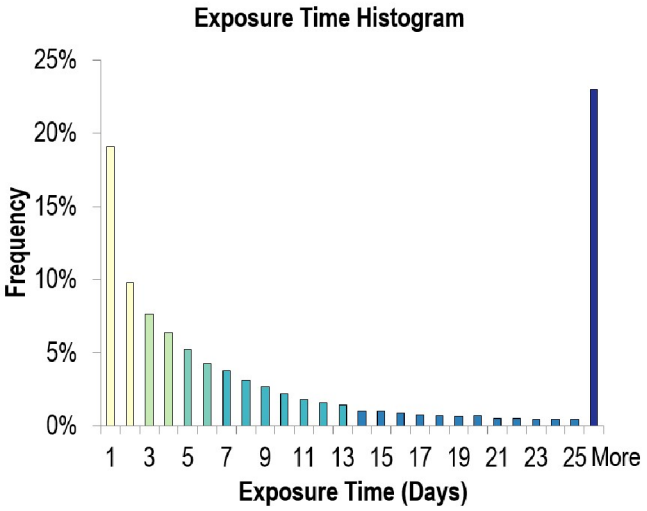

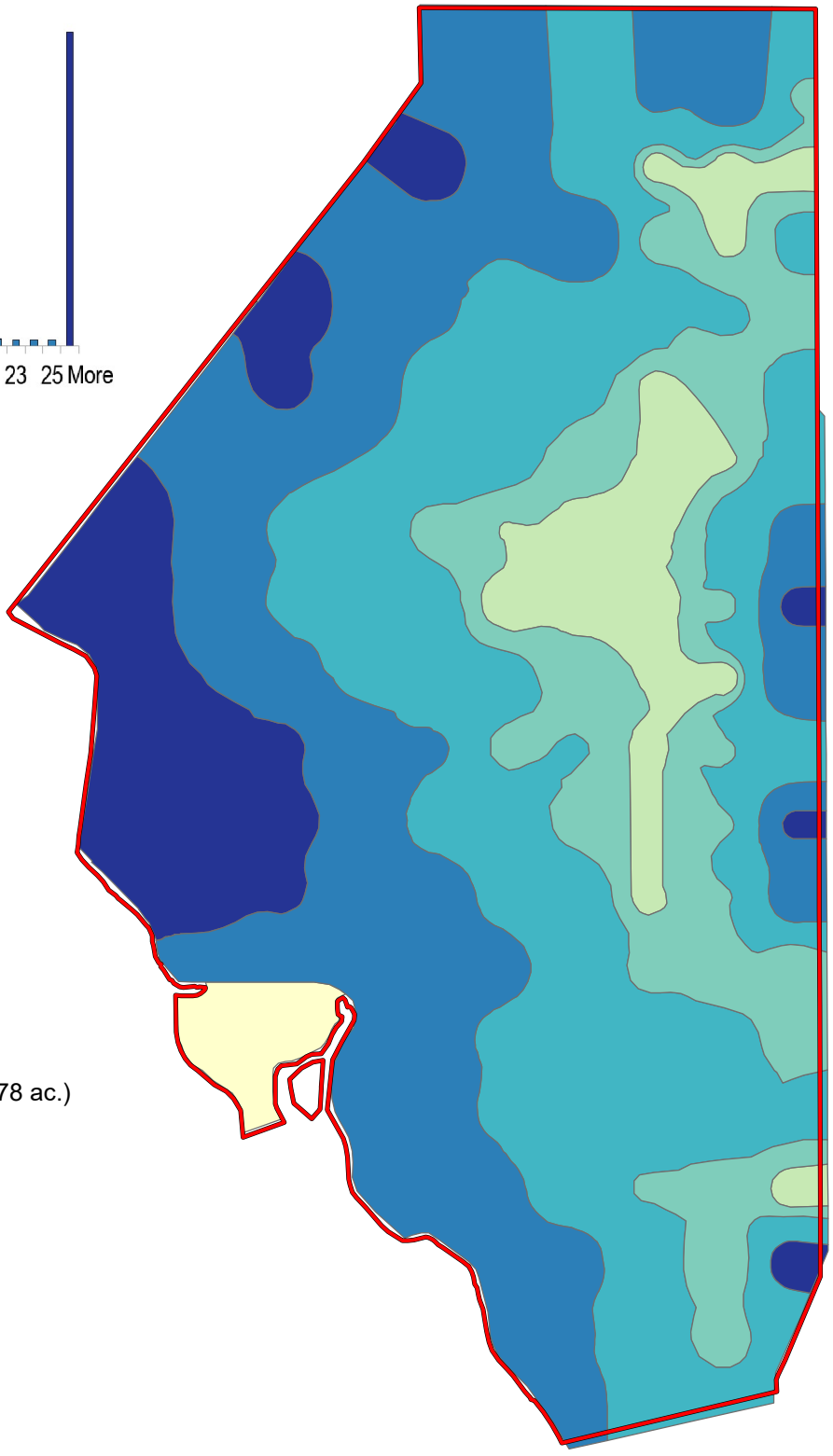

Surveyed Property Boundary (3,378 ac.)

Exposure Time (Days)

- 1-3
- 3-5
- 5-7
- 7-14
- 14-25
- >25

Figure 19
Exposure Time Assessment

N
W E
S

0 0.25 0.5 1
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/31/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s):
DWR, USGS, Wood Rodgers

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The rate of movement of shallow water across the dense marsh plain areas is largely fixed, and is unlikely to change significantly through modification of the design. Exposure time on the site is largely governed by the location and orientation of levee breaches around the perimeter of the site. Due to flood control considerations, the Project is constrained from modifying the breach opening at Cache Slough. Although there is some flexibility to modify the breaches along Shag Slough and at Vogel Island, alteration of the current site design is likely to only have localized effects on exposure time. Review of individual particle pathways may highlight opportunities for modifying the grading plan to improve export from the site on a localized basis.

The general pattern of particle transport pathways in the simulation is shown on **Figure 20**. For clarity, only five percent of the particles in the simulation are displayed on Figure 20. In general, as particles exit the site, they enter Shag Slough and Cache Slough. Although some particles migrate to Liberty Cut and Liberty Island, the majority stay within the primary conveyance corridors of Shag Slough and Cache Slough. **Table 13** summarizes the number of particles exiting the model domain at the respective boundaries.

TABLE 13
SUMMARY OF PARTICLES EXITING THE MODEL DOMAIN

Location	Total Number Leaving	% of Particles Leaving
Cache Slough	1,097	4.5%
Hass Slough	3,396	14.0%
Lindsey Slough	323	1.3%
Cache Slough Tidal Boundary (to Delta)	1,915	7.9%

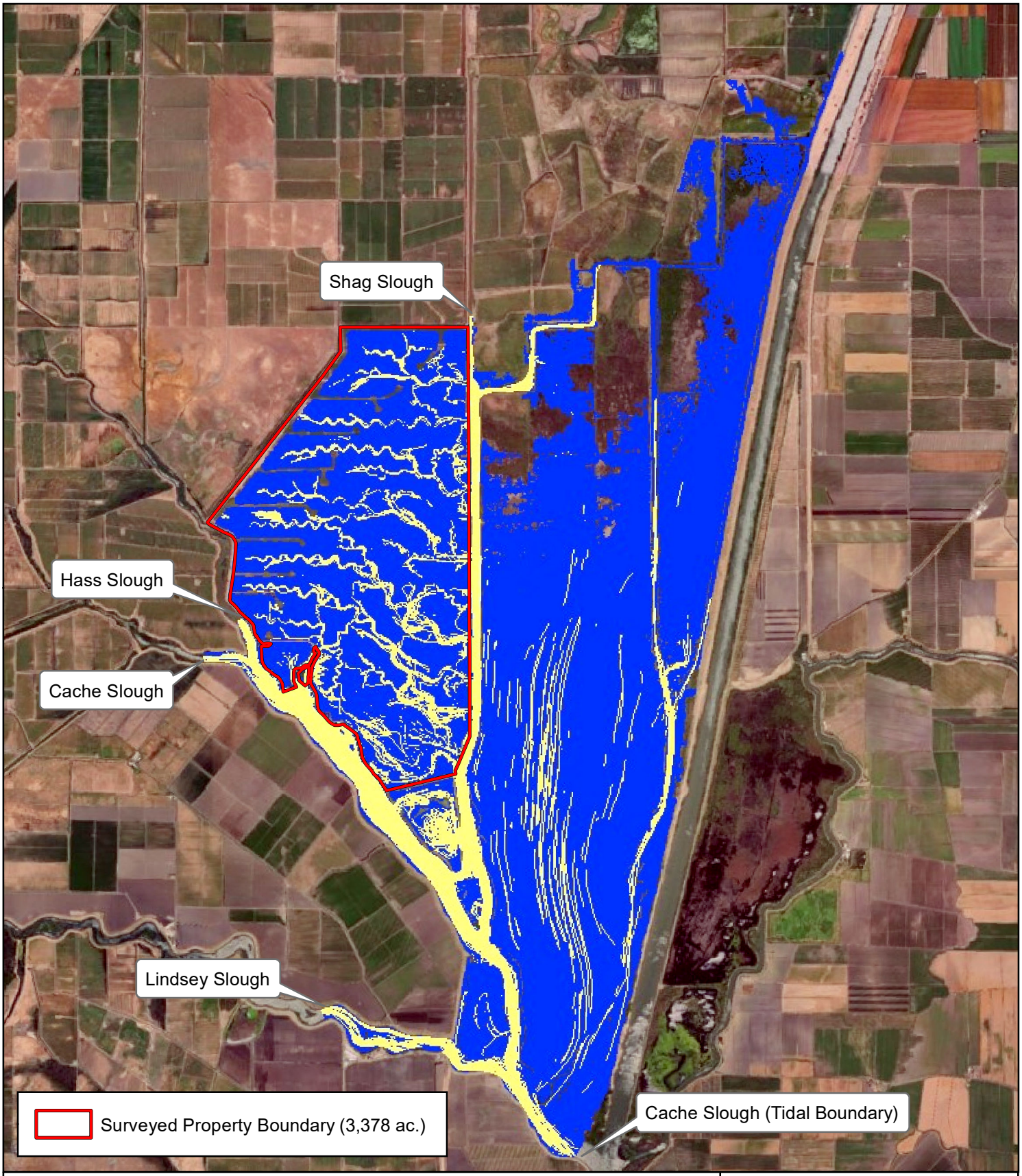

Figure 20
Particle Pathways

N
W E
S

0 0.5 1 2
Miles

Lookout Slough Restoration Project

Ecosystem Investment Partners

Prepared by: ESA

Map Prepared Date: 12/31/2018
Map Prepared By: JPritchard
Base Source: Wood Rodgers
Base Date: 10/24/2017
Data Source(s): DWR, USGS, Wood Rodgers

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Appendix A

Model Calibration and Verification Summary Plots

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APPENDIX A

Model Calibration and Verification Summary Plots

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1. Calibration Period 1: June-July 2010

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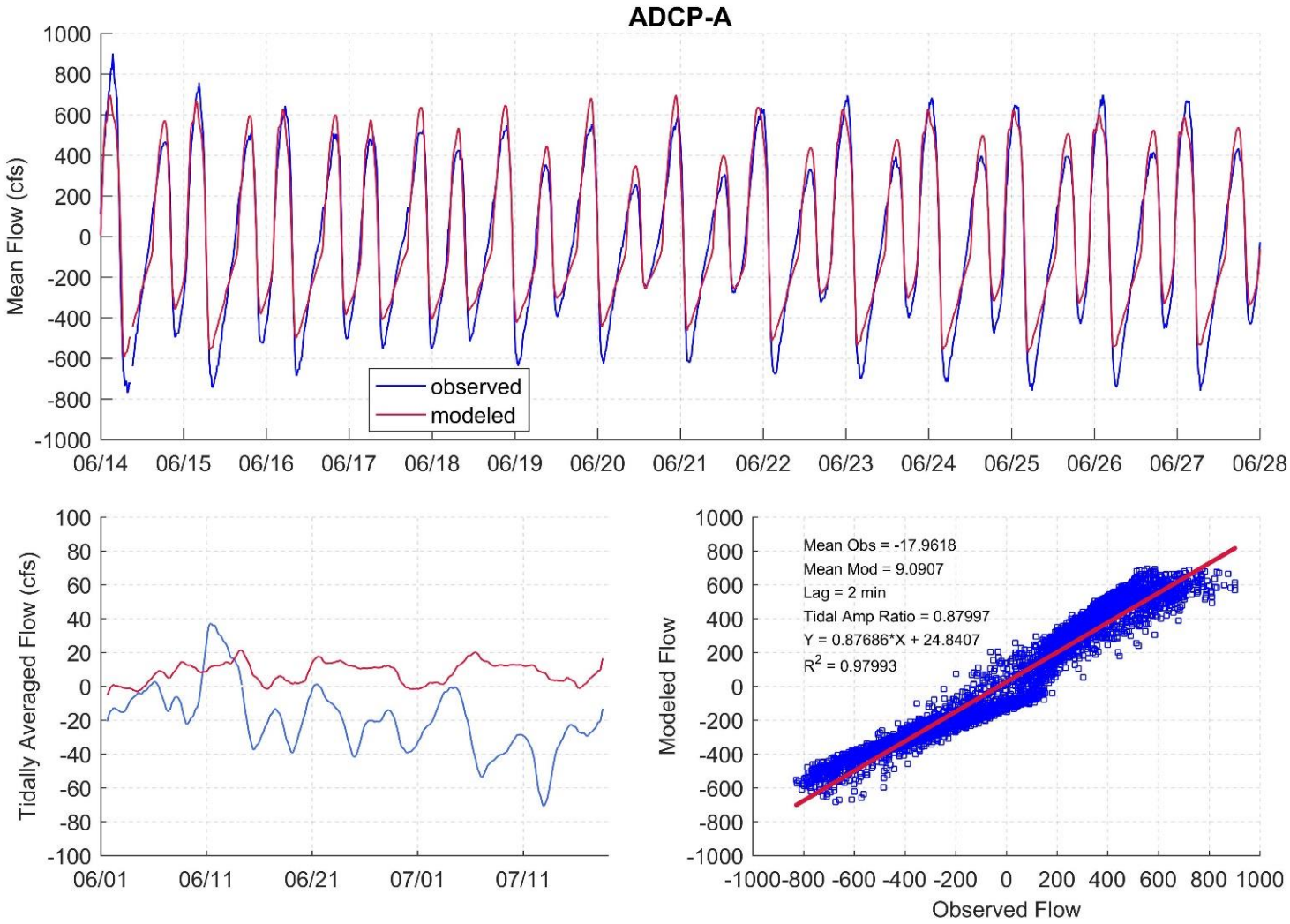
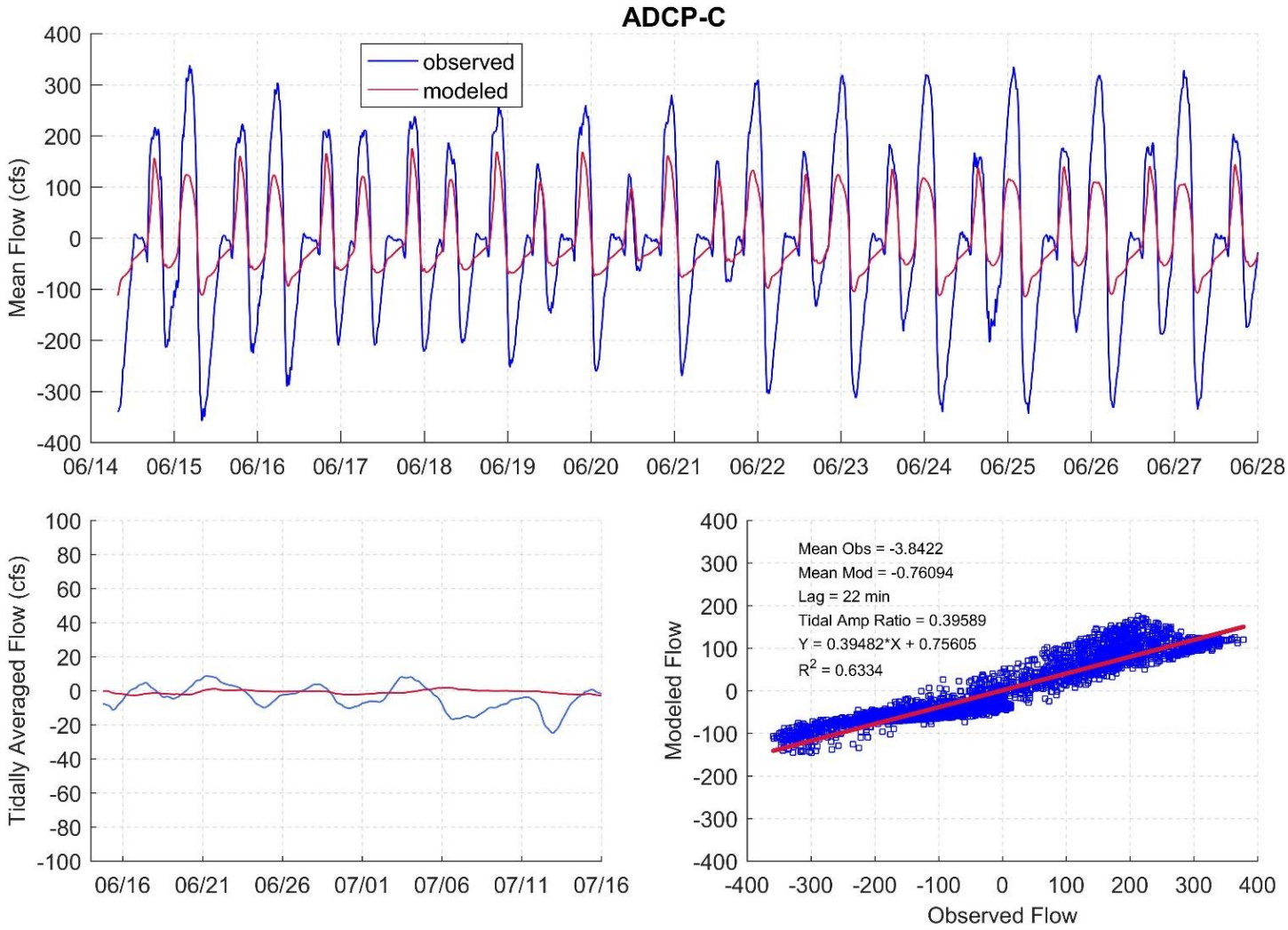


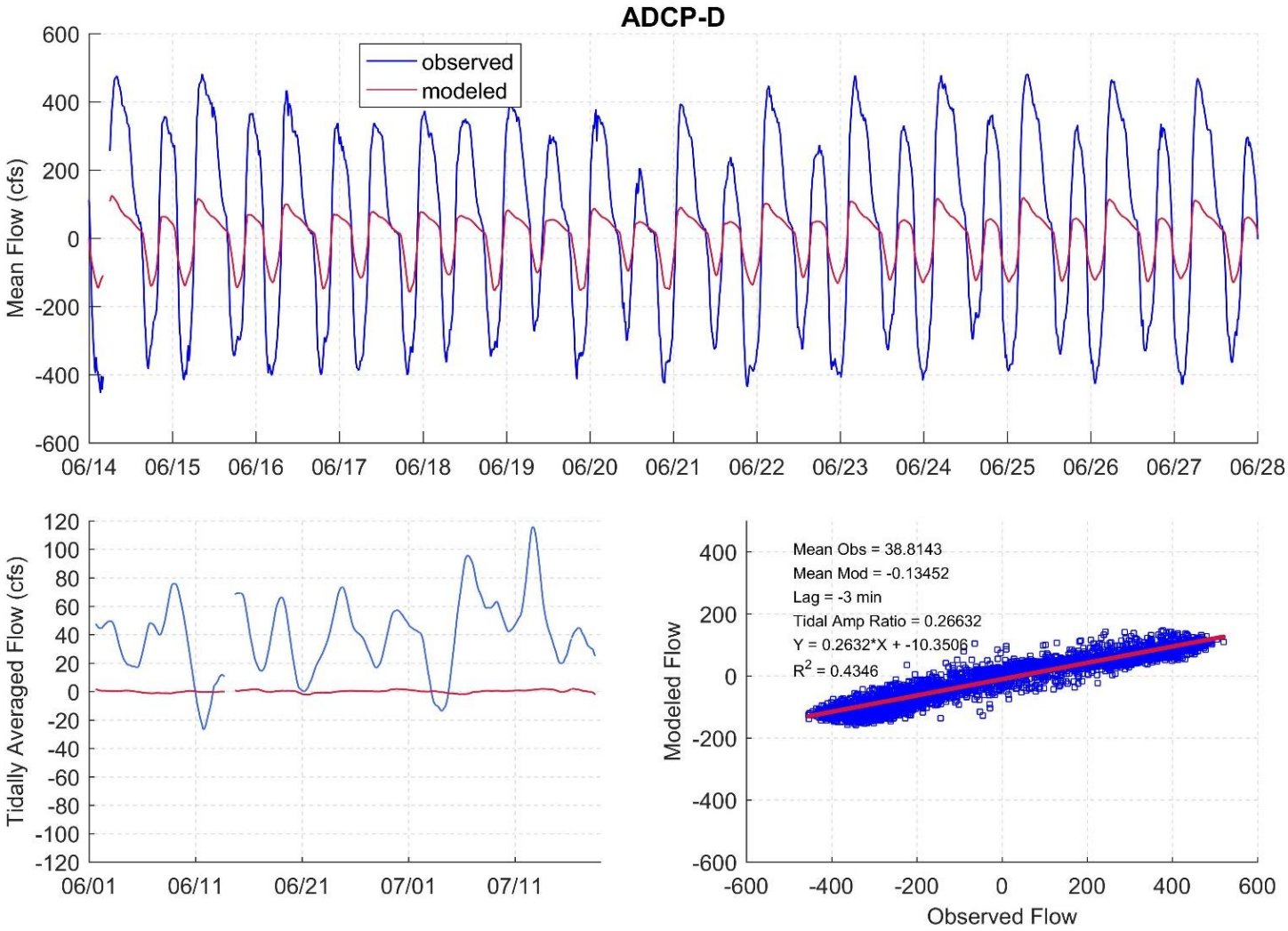
D181197.00 Lookout Slough Restoration

Figure A1
Mean flows at ADCP A: June-July 2010



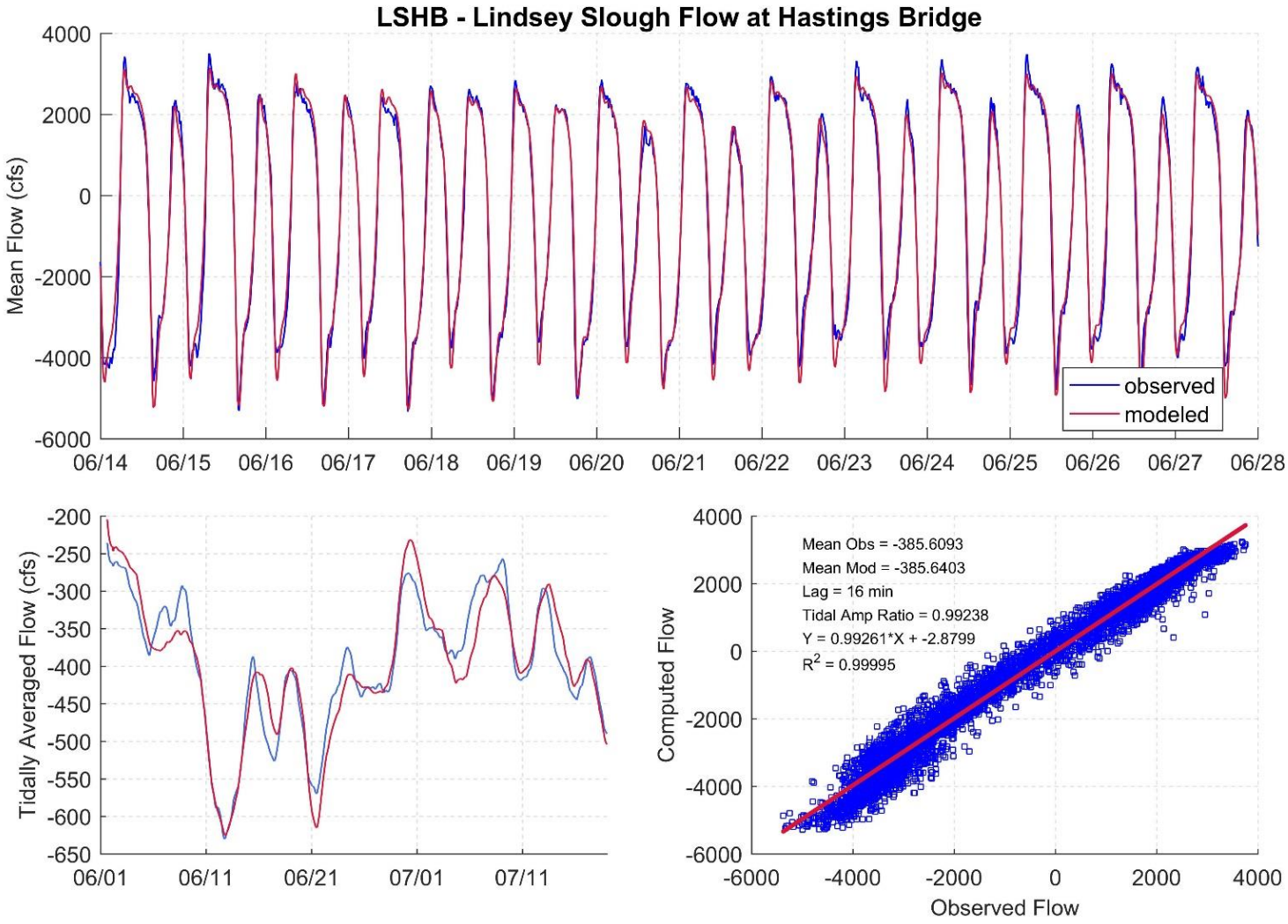
D181197.00 Lookout Slough Restoration

Figure A2
Mean flows at ADCP C: June-July 2010



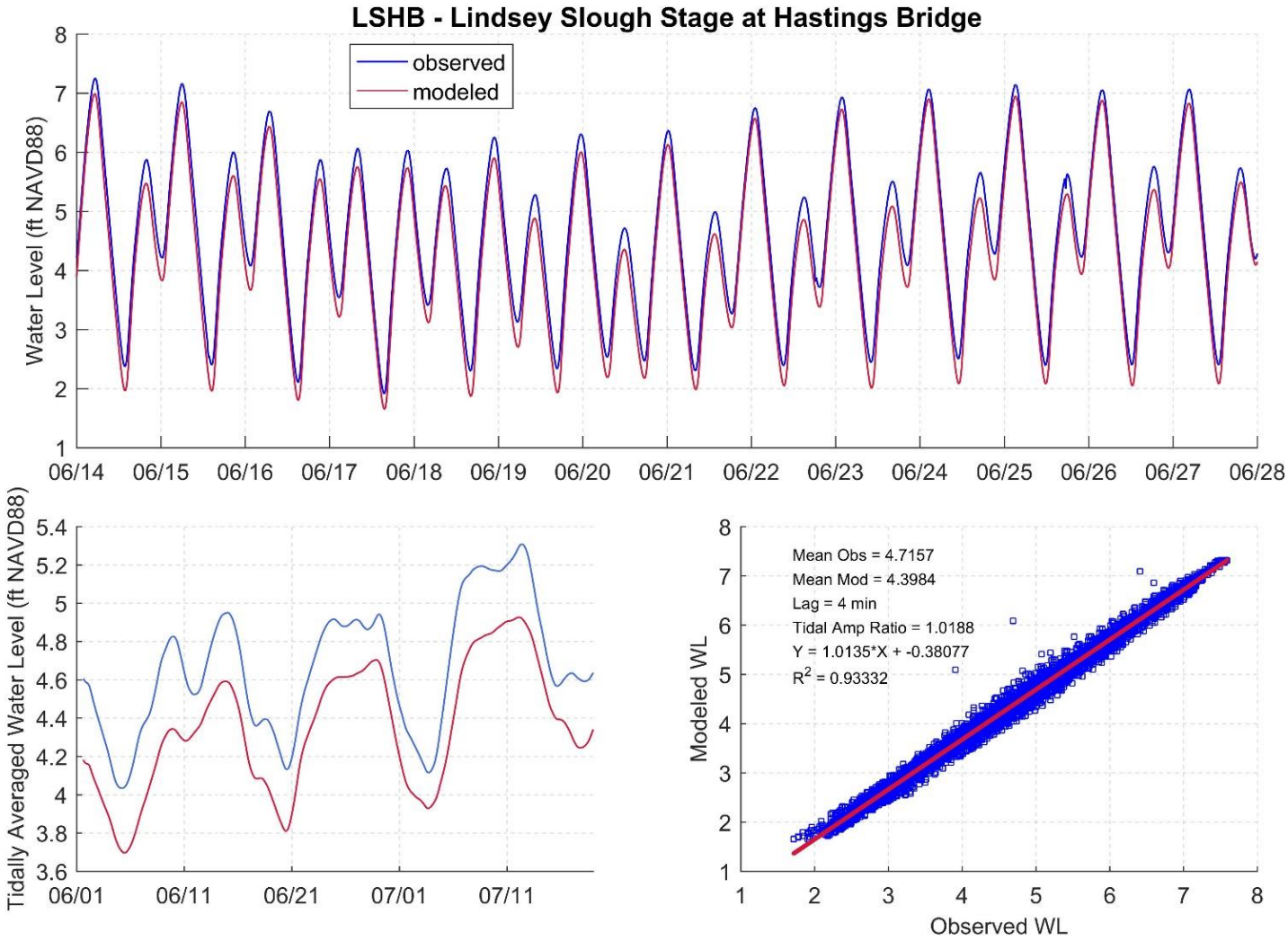
D181197.00 Lookout Slough Restoration

Figure A3
Mean flows at ADCP D: June-July 2010



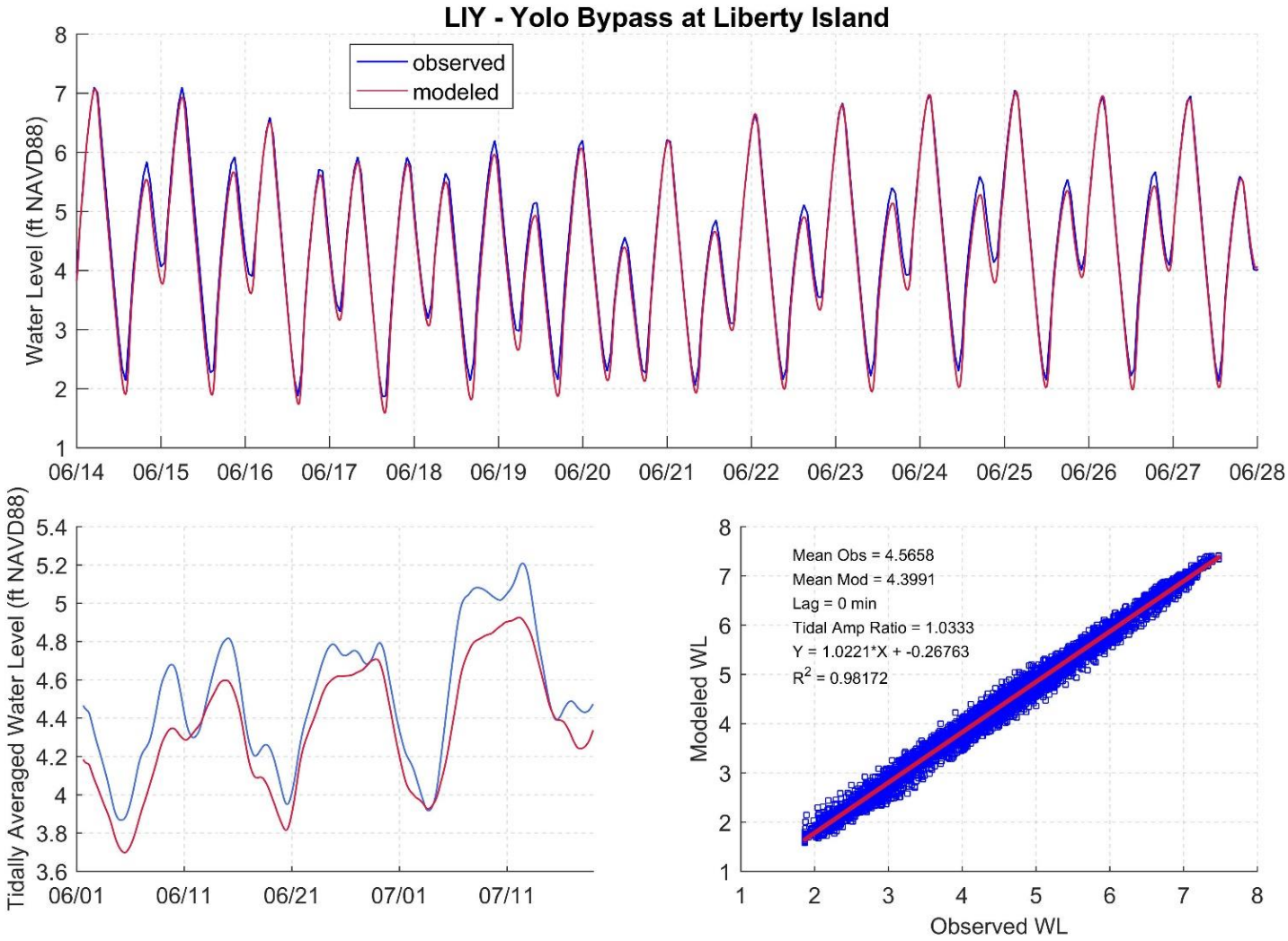
D181197.00 Lookout Slough Restoration

Figure A4
Mean flows at LSHB: June-July 2010



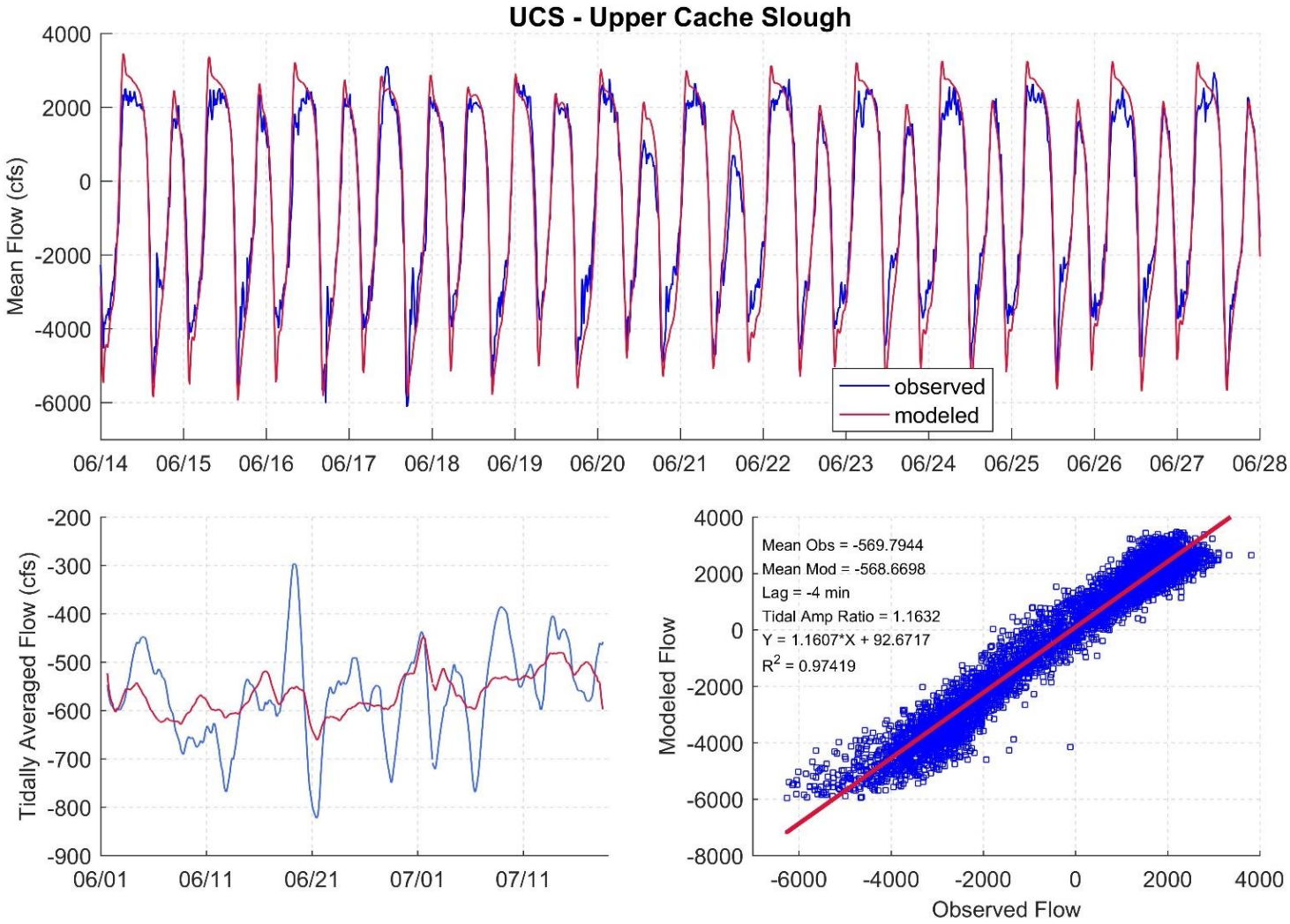
D181197.00 Lookout Slough Restoration

Figure A5
Water levels at LSHB: June-July 2010



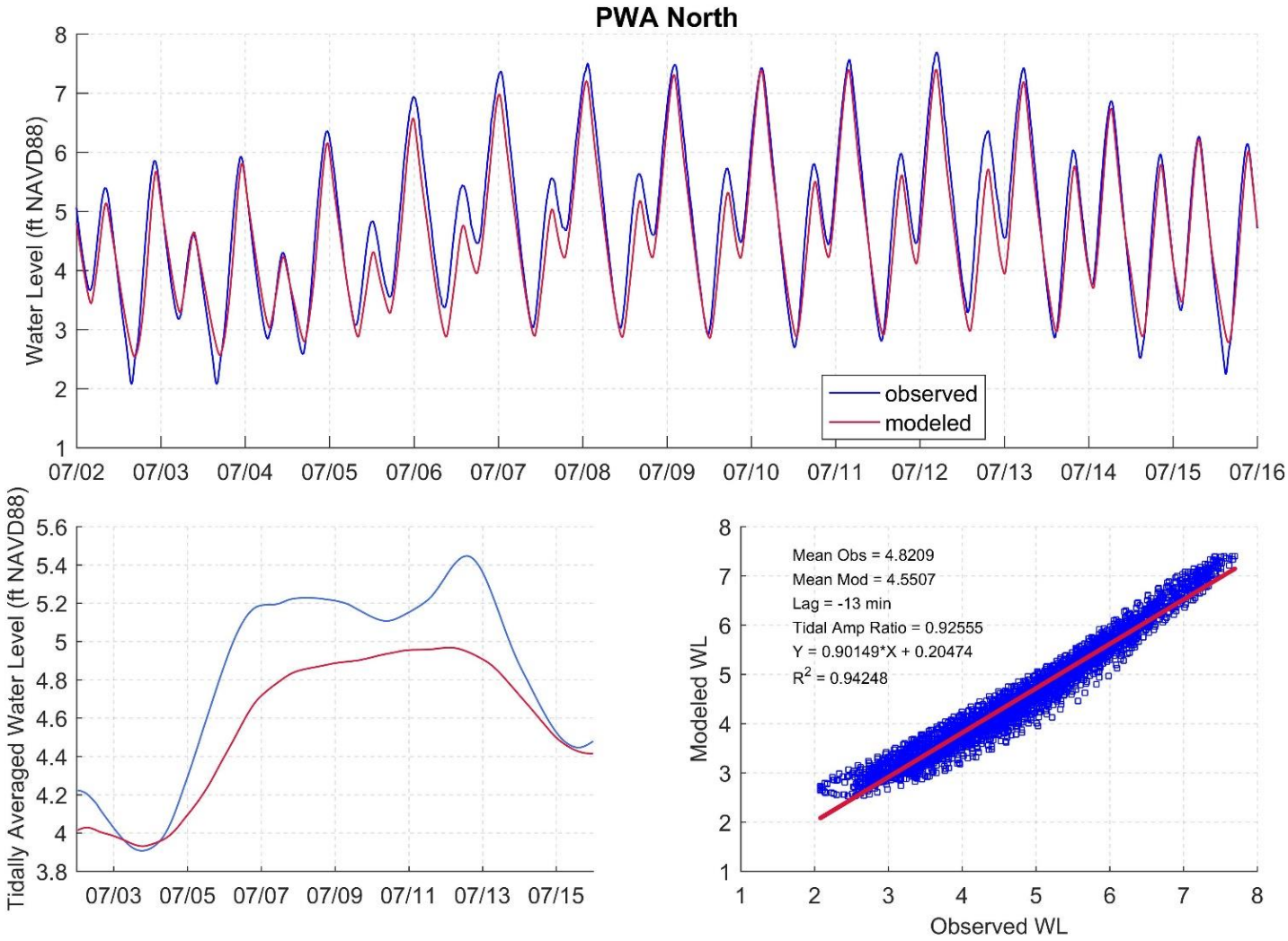
D181197.00 Lookout Slough Restoration

Figure A6
Water levels at LIY: June-July 2010



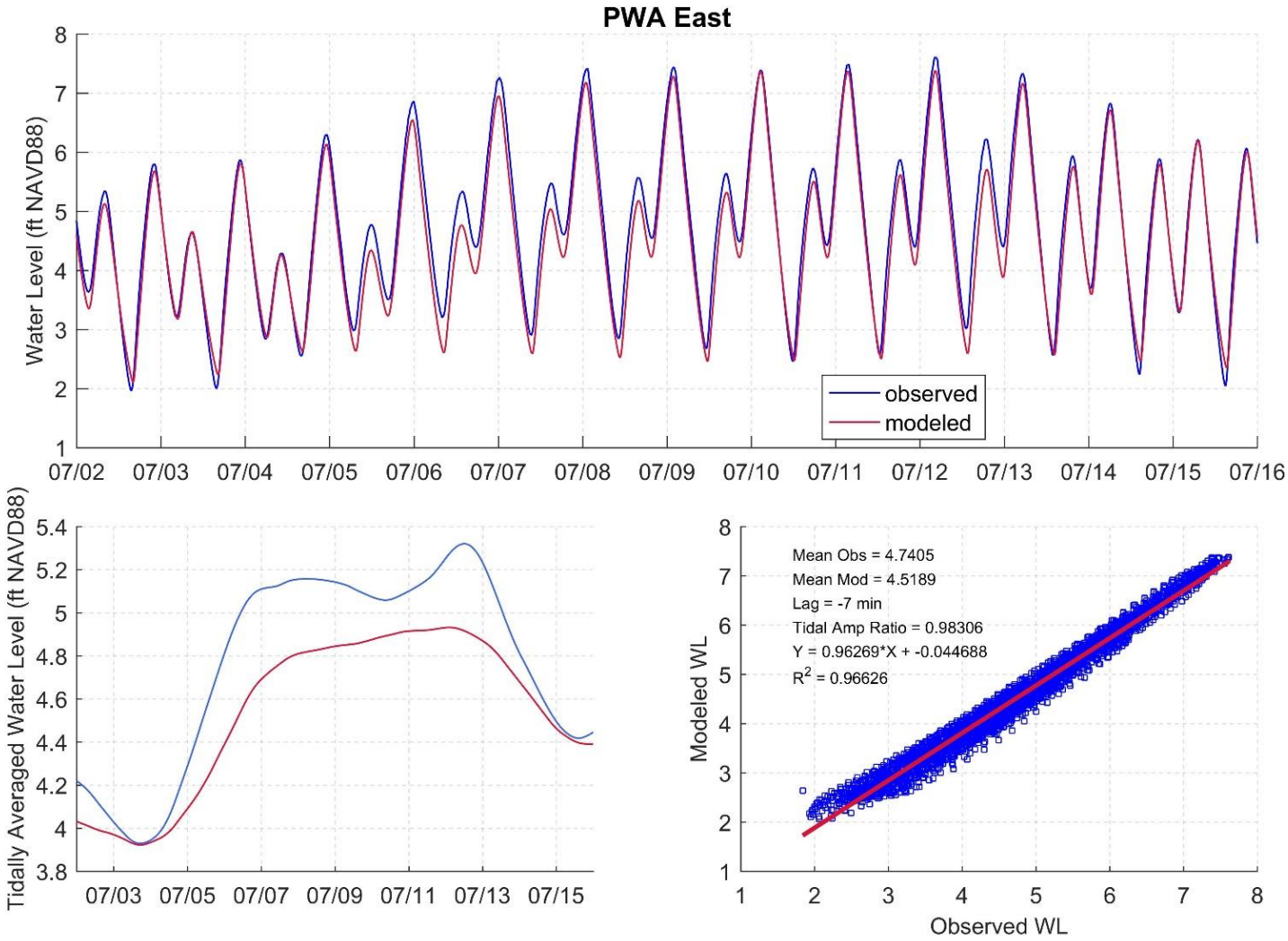
D181197.00 Lookout Slough Restoration

Figure A7
Mean flows at UCS: June-July 2010



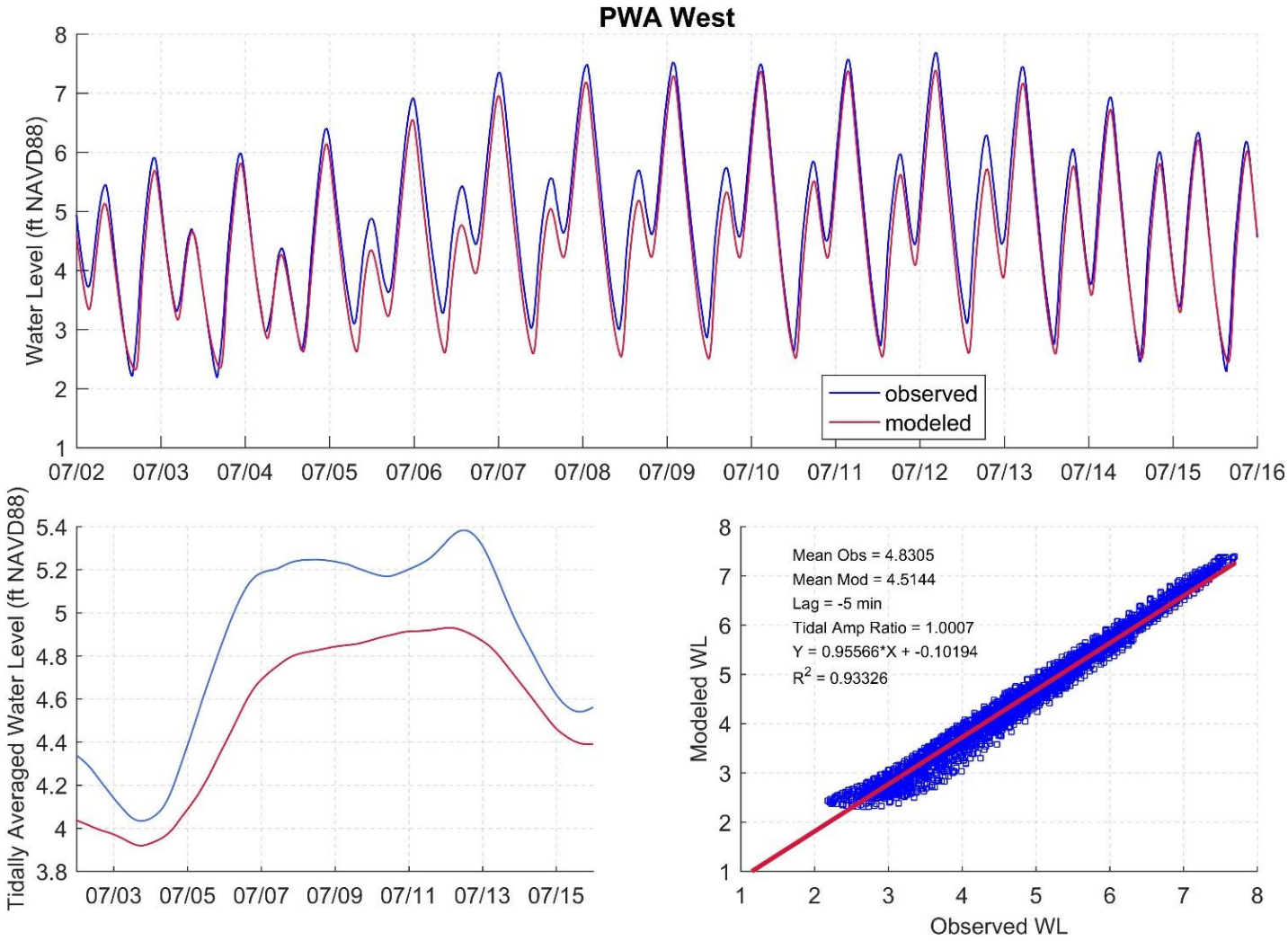
D181197.00 Lookout Slough Restoration

Figure A8
Water levels at PWA North: June-July 2010



D181197.00 Lookout Slough Restoration

Figure A9
Water levels at PWA East: June-July 2010



D181197.00 Lookout Slough Restoration

Figure A10
Water levels at PWA West: June-July 2010

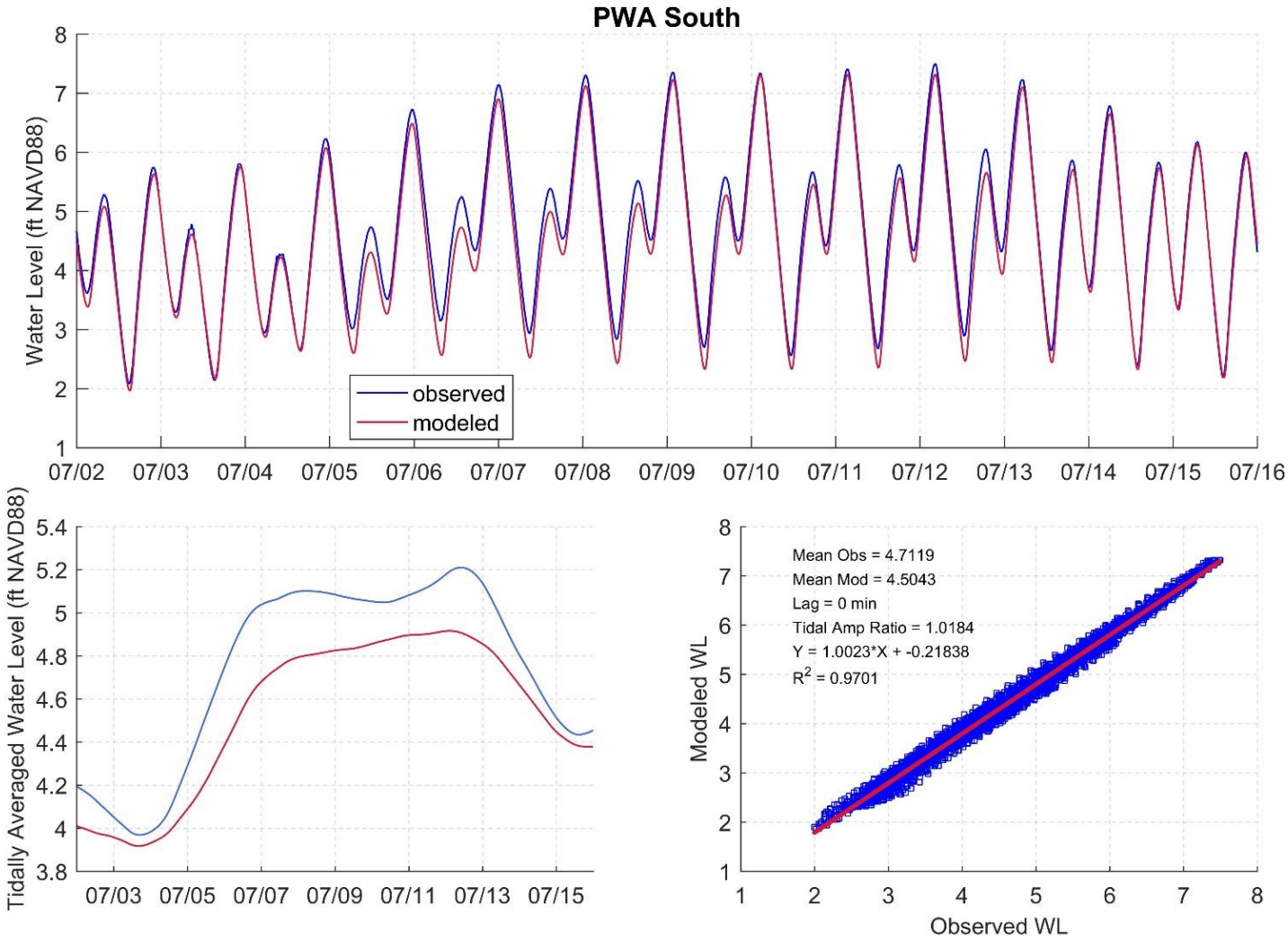


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Figure A11
Water levels at PWA South: June-July 2010

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2. Calibration Period 2: January-March 2010

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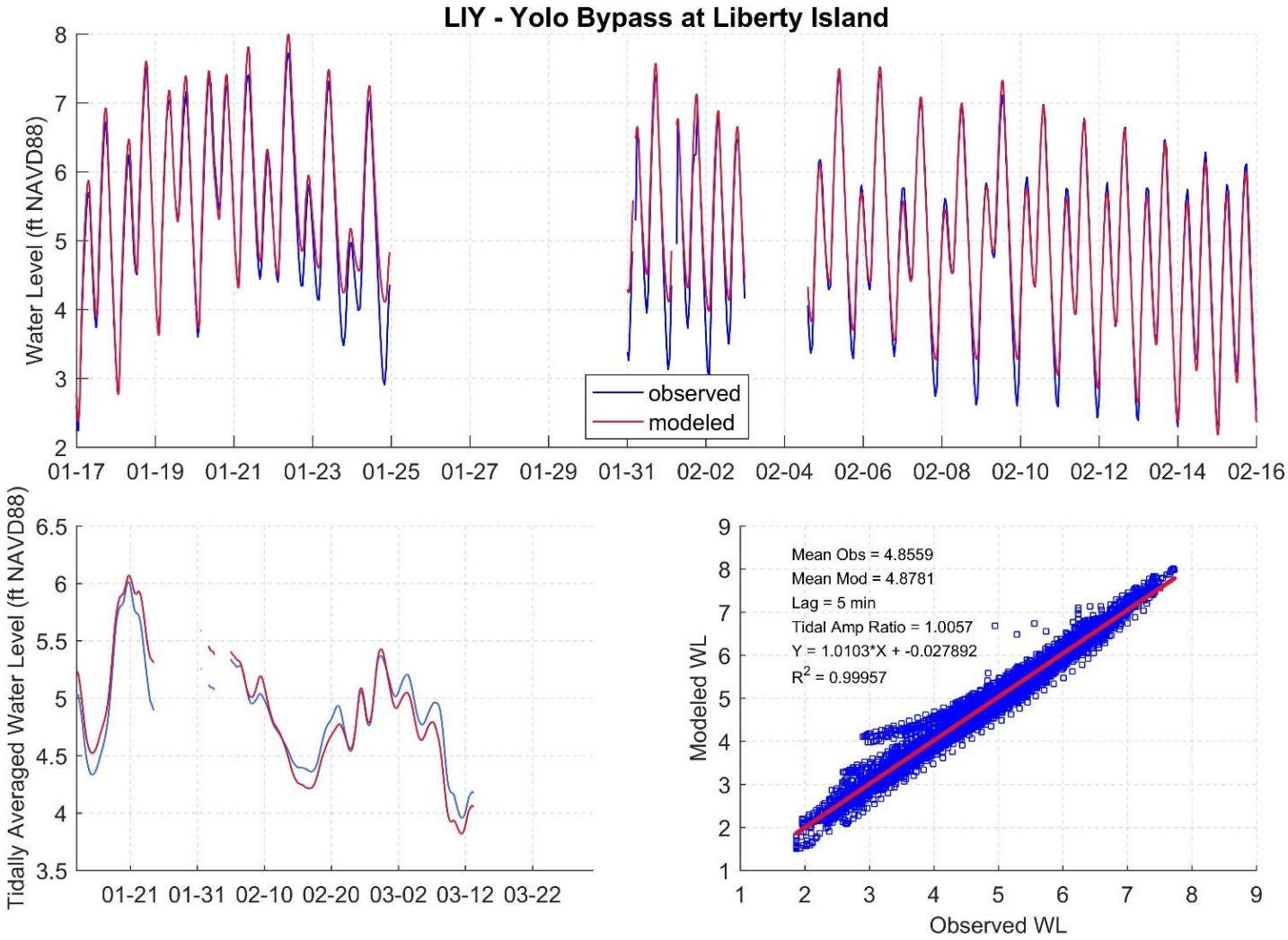
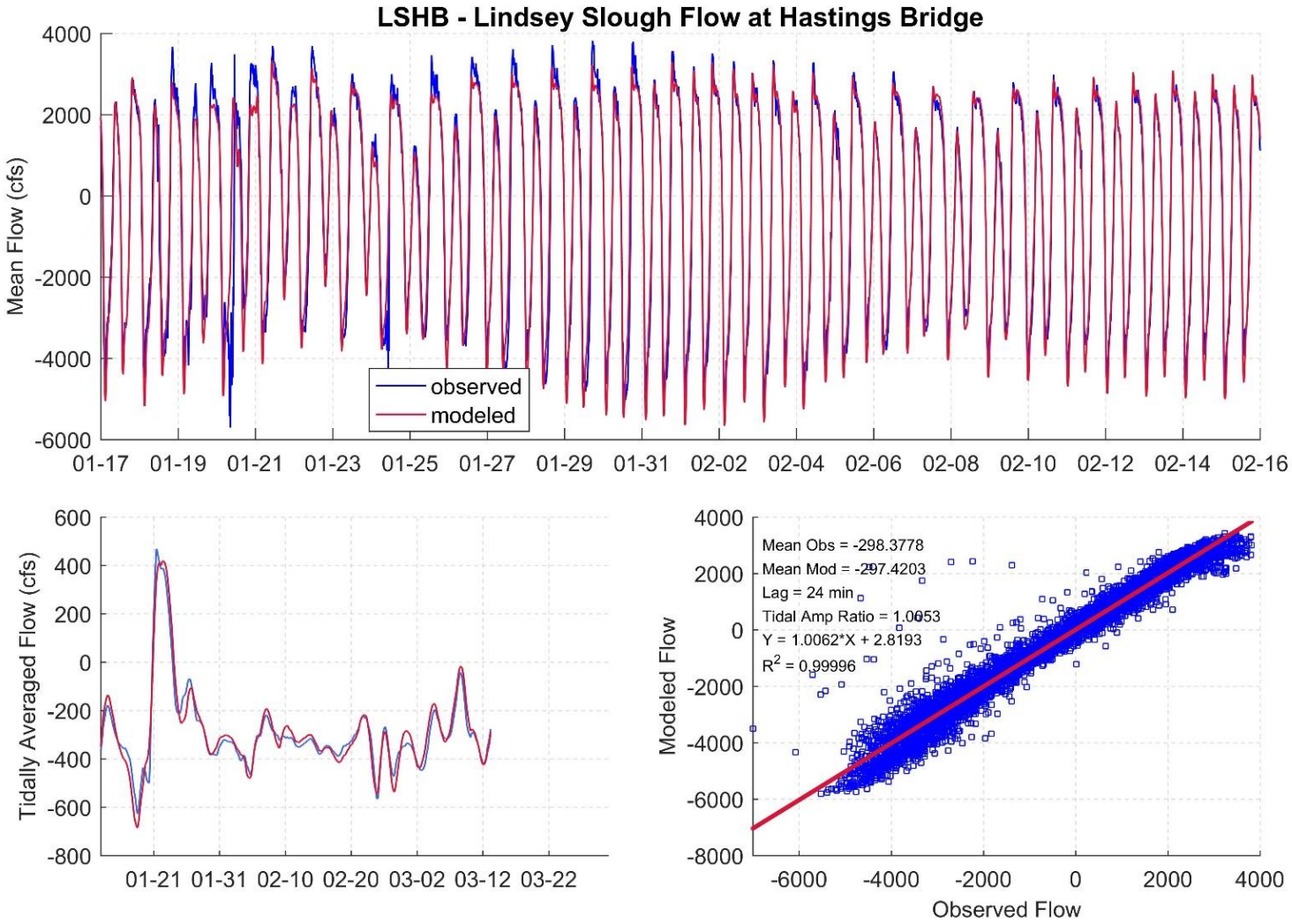


D181197.00 Lookout Slough Restoration

Figure A12
Water levels at LIY: January-March 2010



D181197.00 Lookout Slough Restoration

Figure A13
Mean flows at LSHB January-March 2010

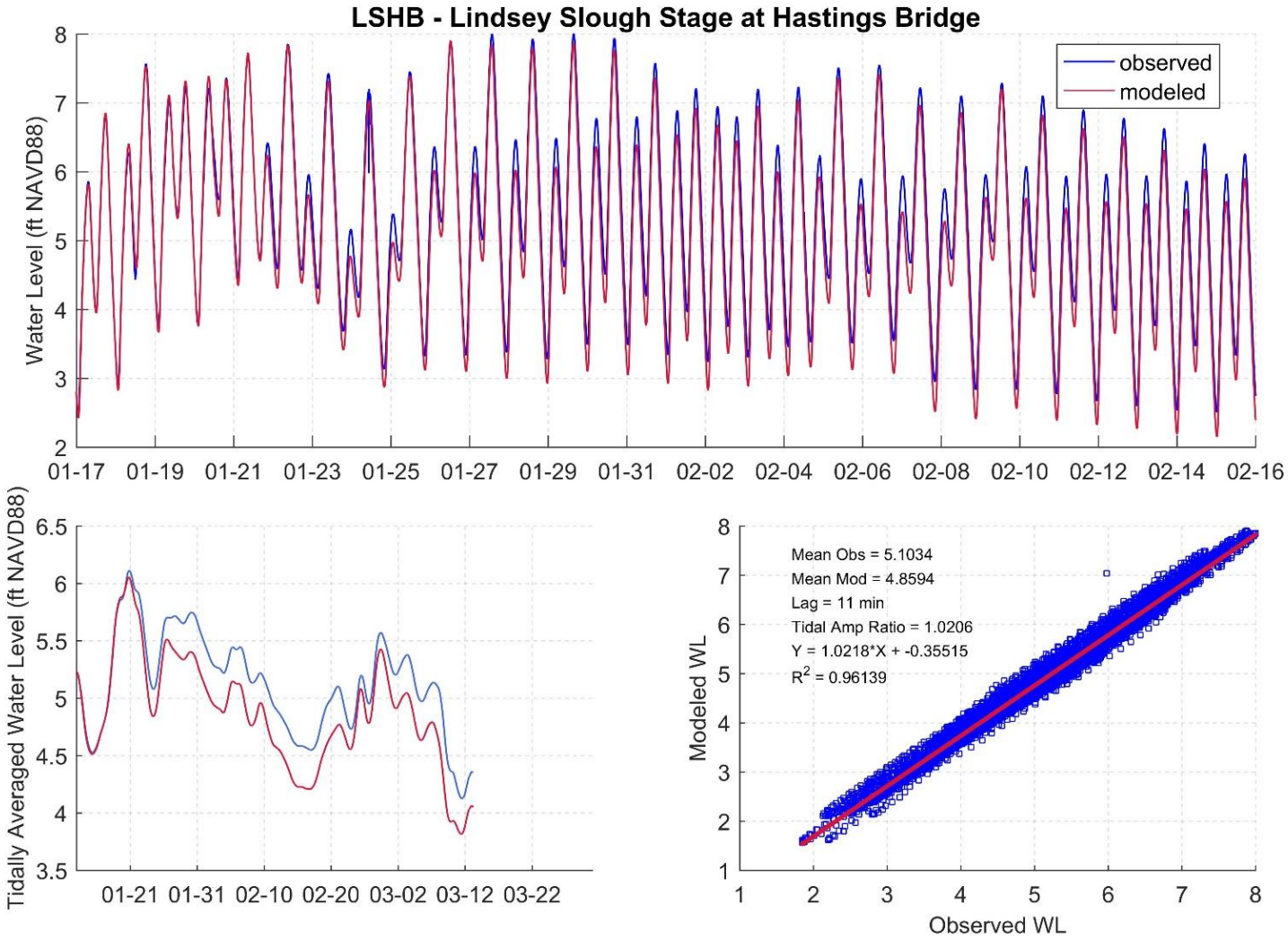


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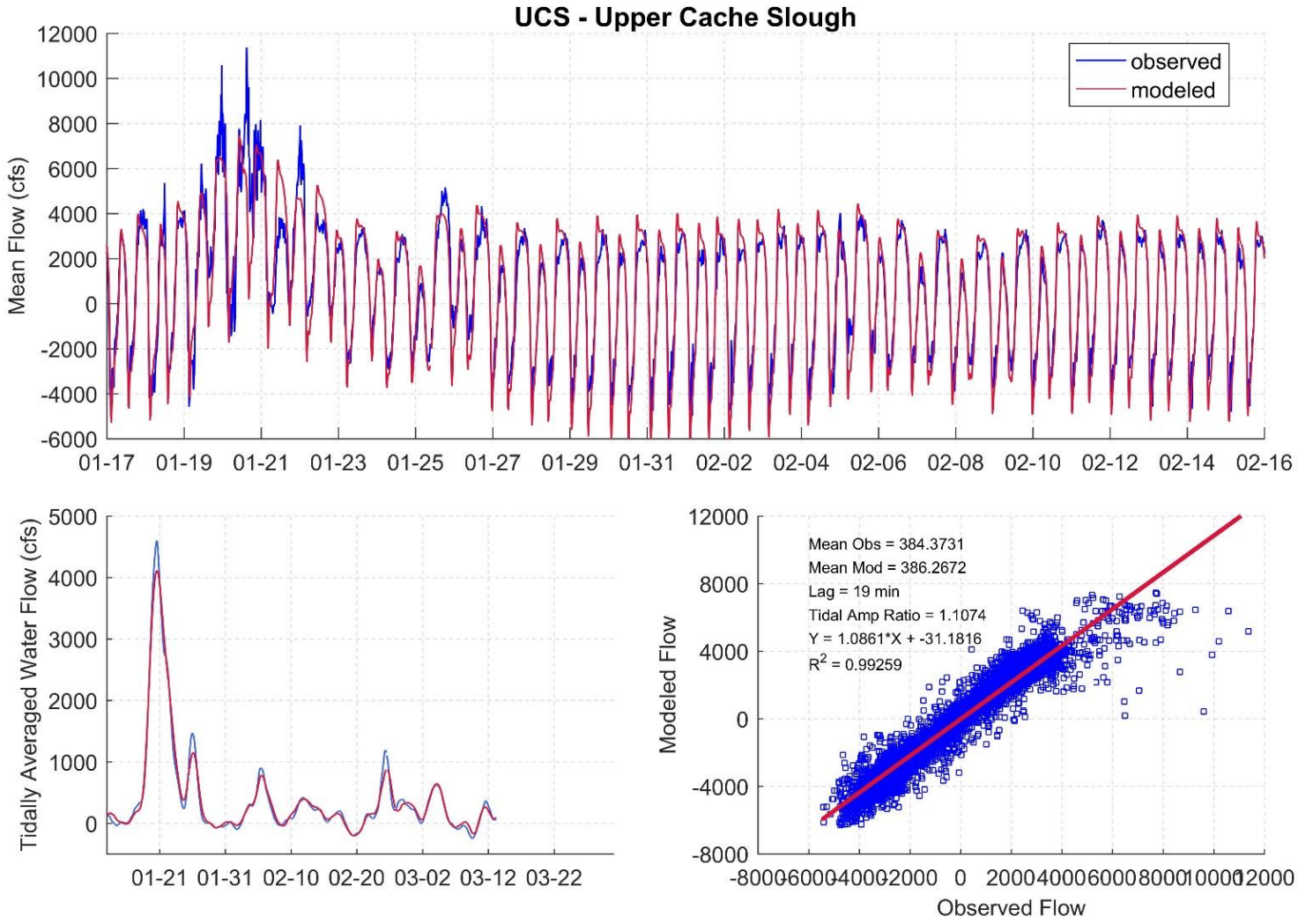
Figure A14
Water levels at LSHB January-March 2010



D181197.00 Lookout Slough Restoration

Figure A15
Mean flows at UCS January-March 2010

3. Verification: October-November 2008

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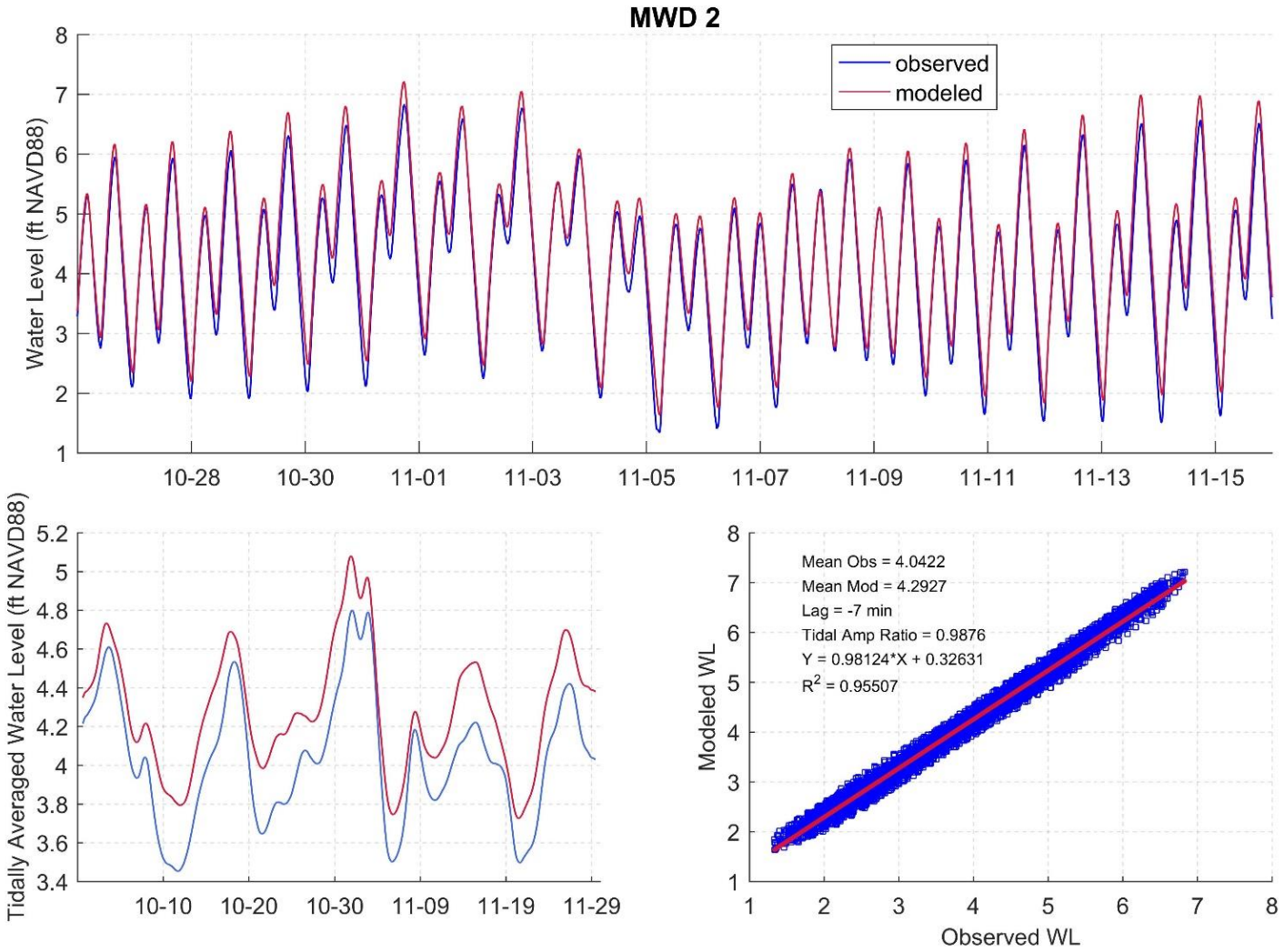
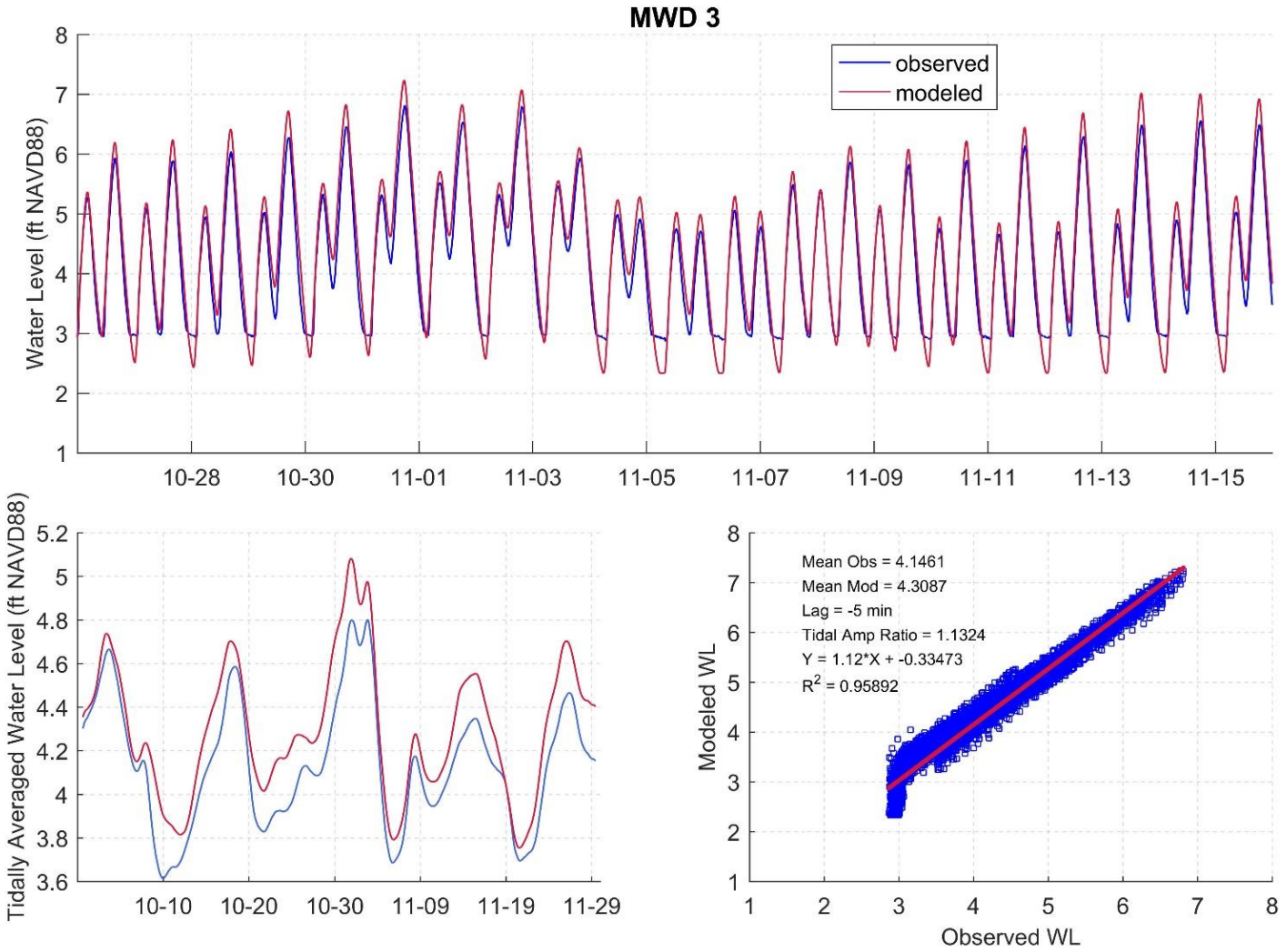


D181197.00 Lookout Slough Restoration

Figure A16
Water levels at MW2: October-November 2008.



D181197.00 Lookout Slough Restoration

Figure A17
Water levels at MW3: October-November 2008

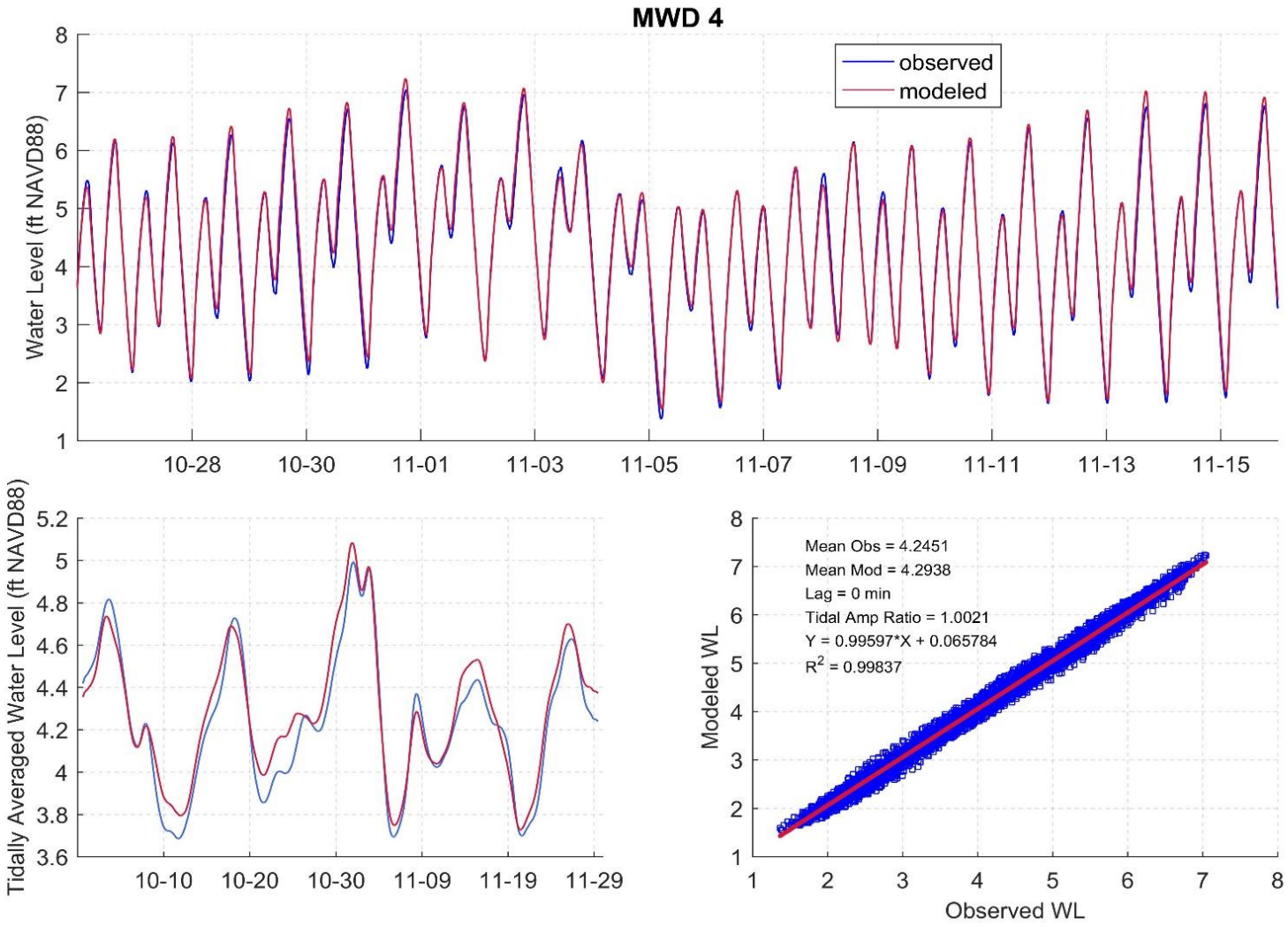


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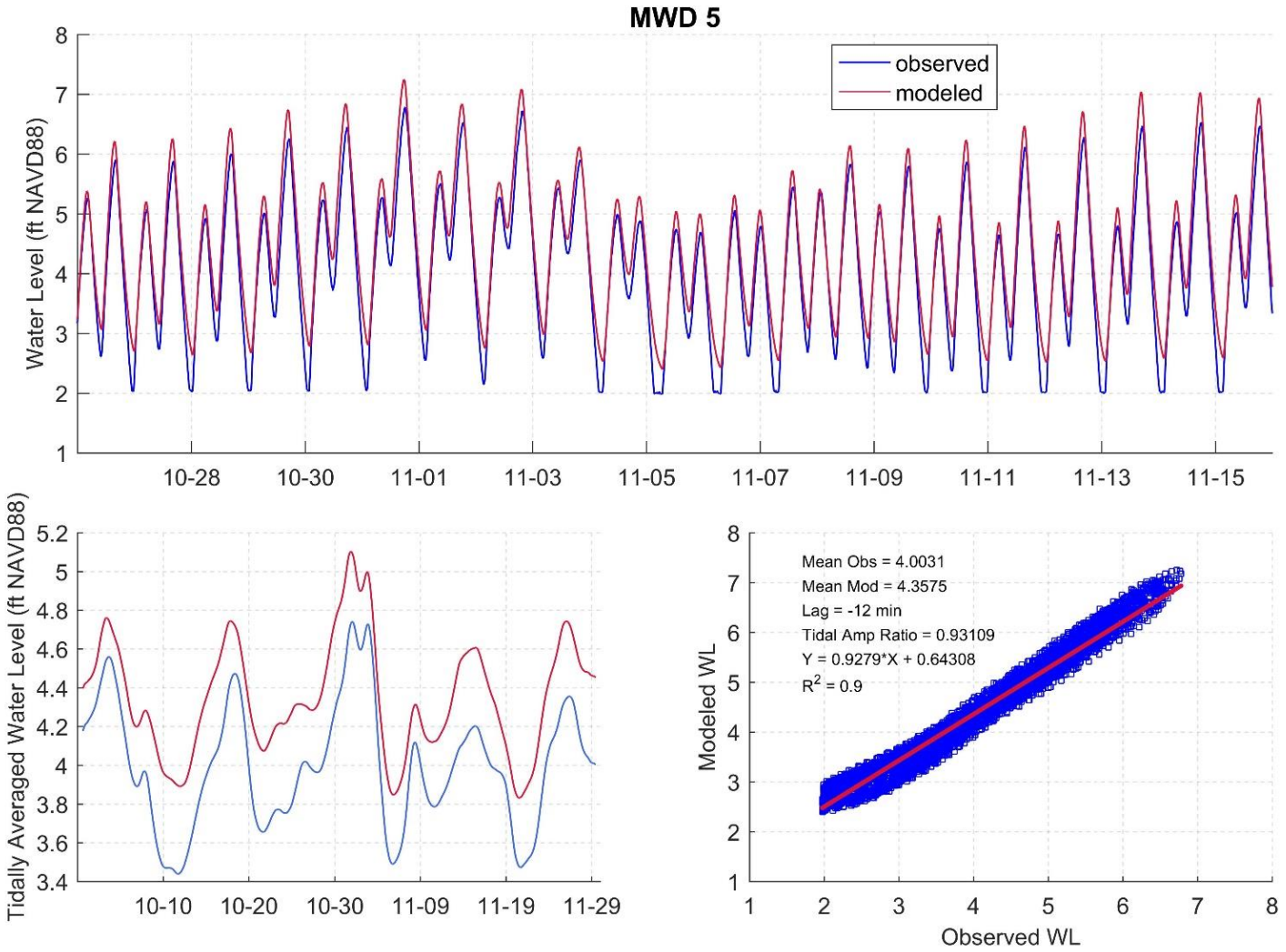
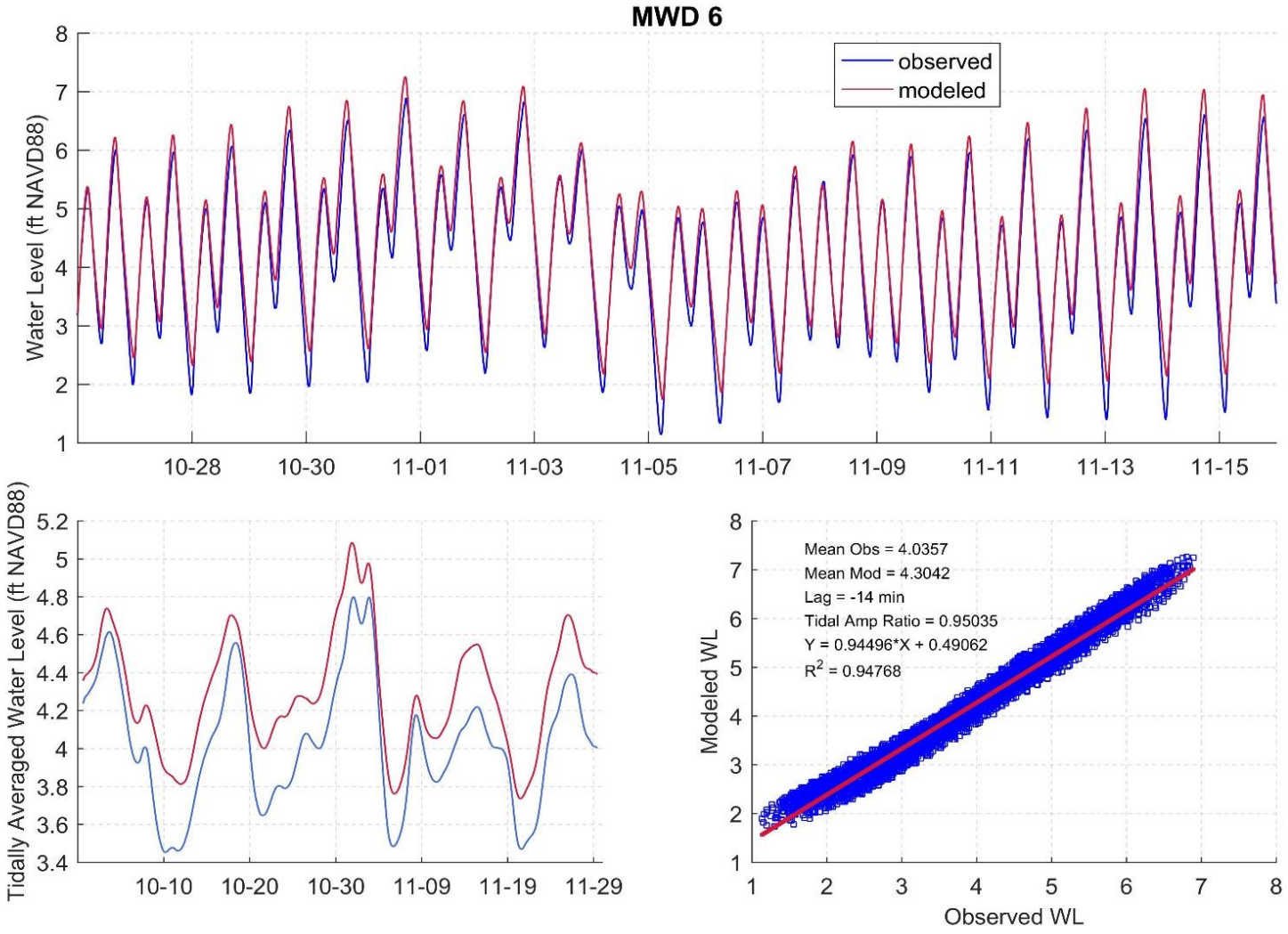
Figure A18
Water levels at MW4: October-November 2008



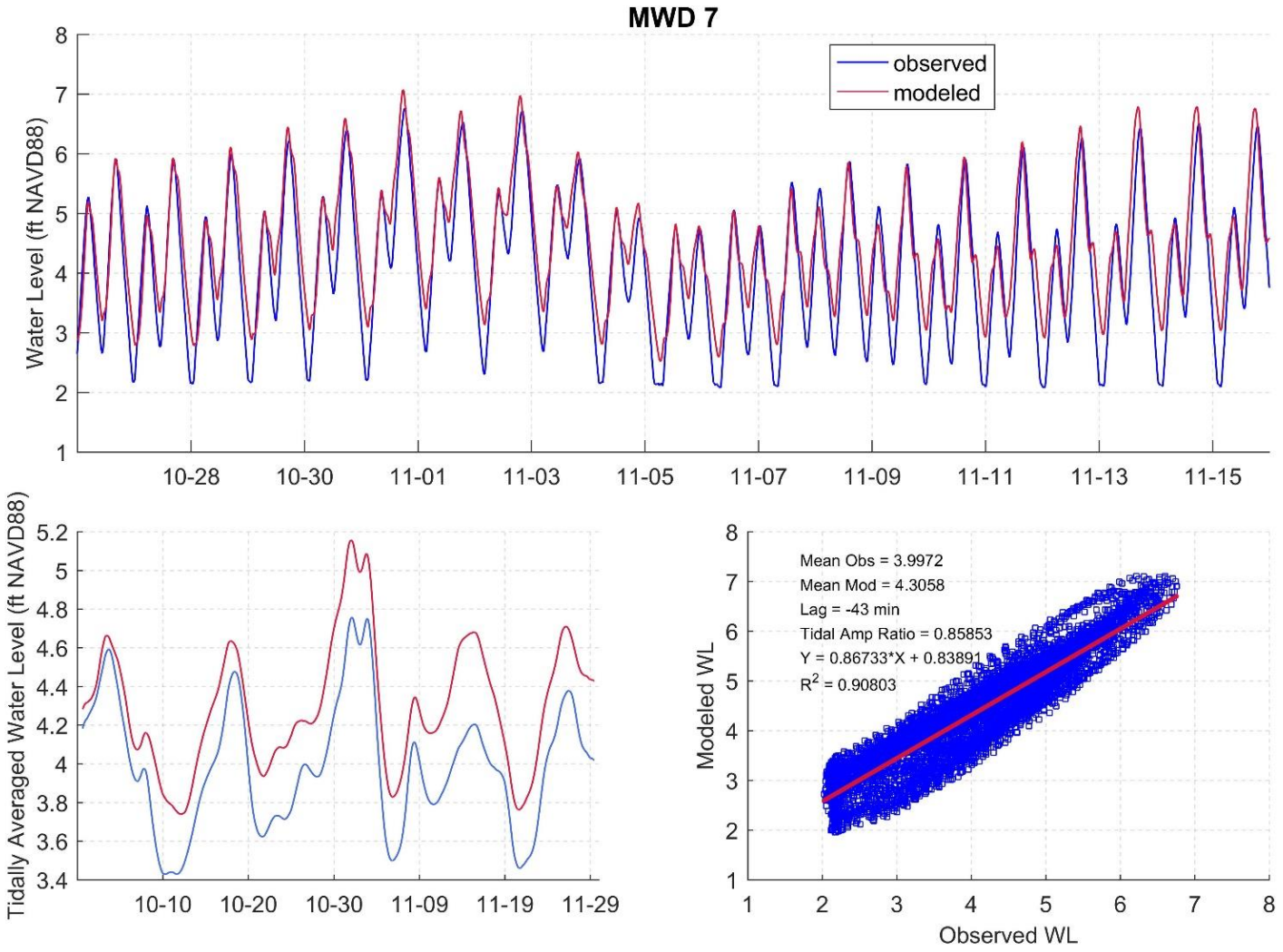
D181197.00 Lookout Slough Restoration

Figure A19
Water levels at MW5: October-November 2008



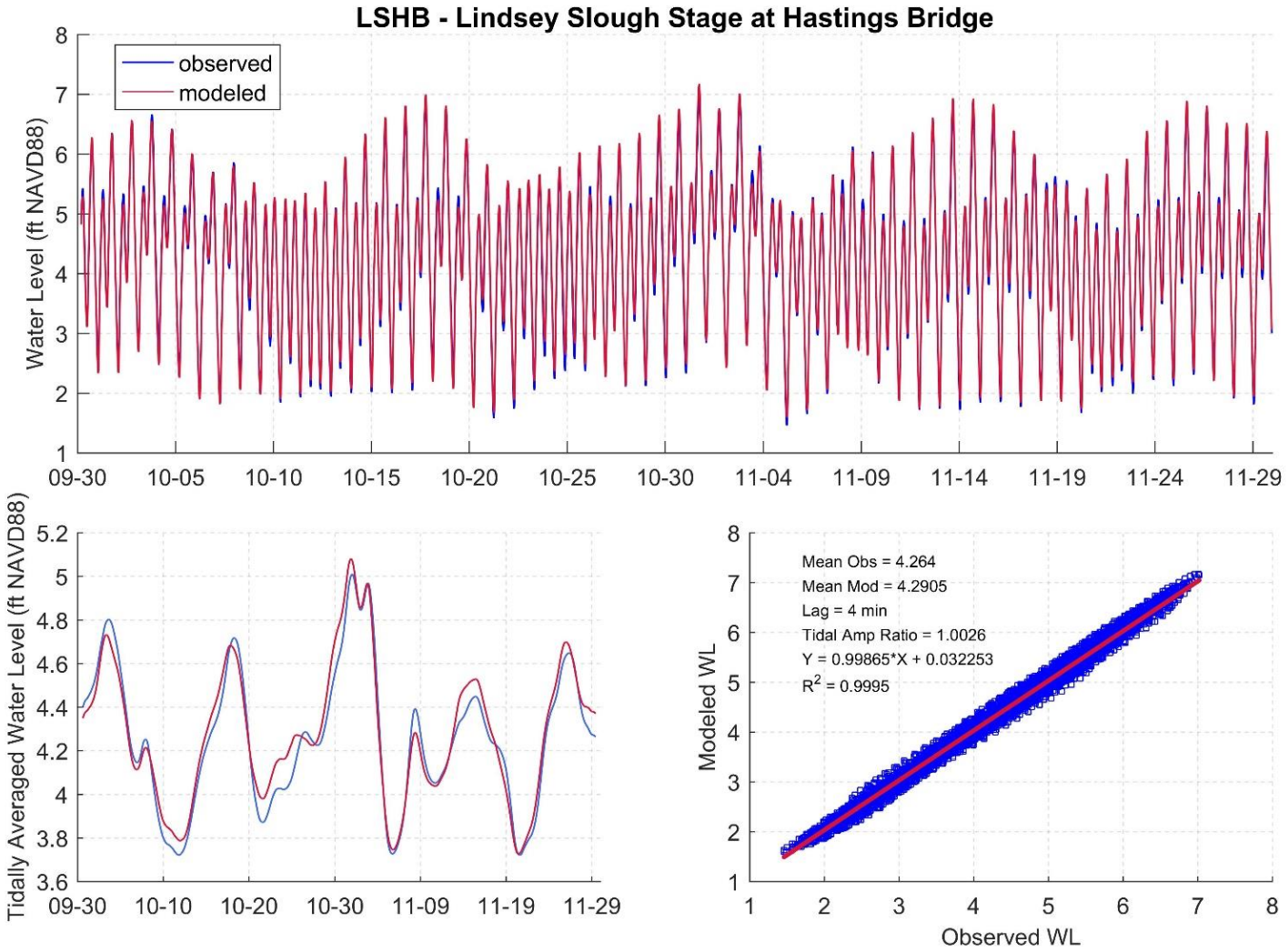
D181197.00 Lookout Slough Restoration

Figure A20
Water levels at MW6: October-November 2008



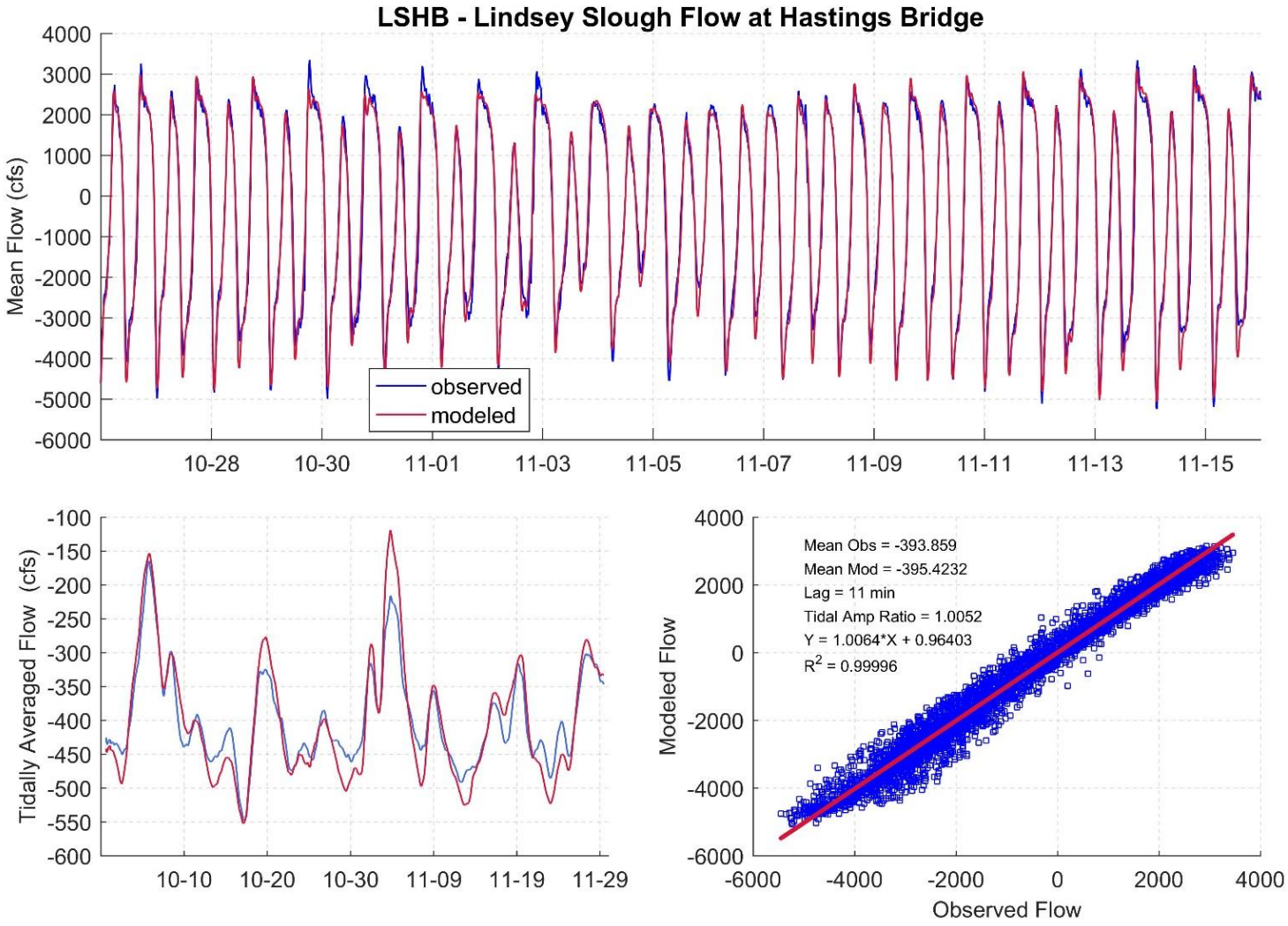
D181197.00 Lookout Slough Restoration

Figure A21
Water levels at MW7: October-November 2008



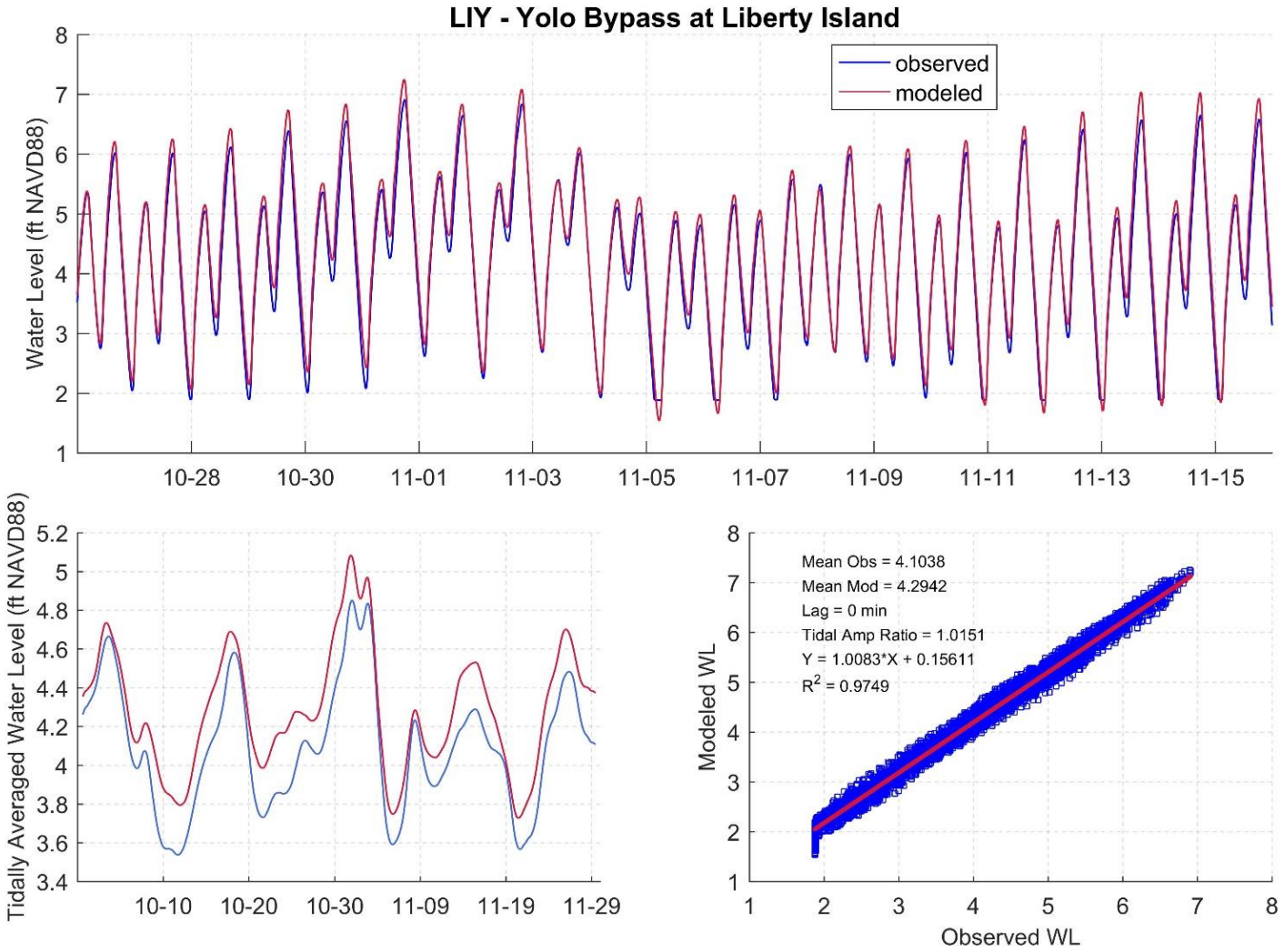
D181197.00 Lookout Slough Restoration

Figure A22
Water levels at LSHB: October-November 2008



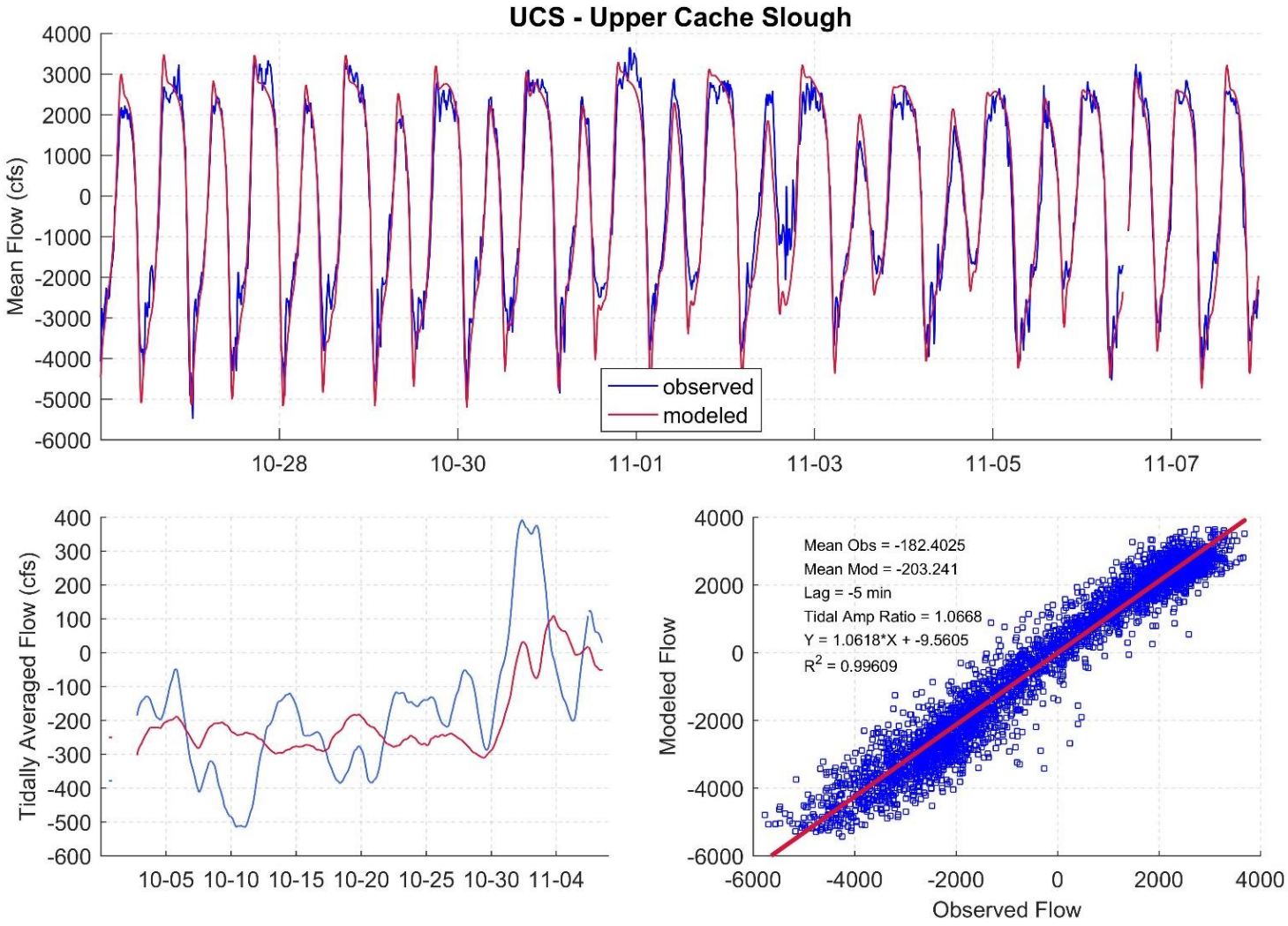
D181197.00 Lookout Slough Restoration

Figure A23
Mean flows at LSHB: October-November 2008



D181197.00 Lookout Slough Restoration

Figure A24
Water levels at LIY: October-November 2008



D181197.00 Lookout Slough Restoration

Figure A25
Mean flows at UCS: October-November 2008

Appendix B

Tidal Damping Analysis Summary Plots

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APPENDIX B
Tidal Damping Analysis Summary Plots

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Stage Hydrograph Location Map

N
W E
S

0 0.25 0.5 1
Miles

Ecosystem Investment Partners

Lookout Slough Restoration Project

Map Prepared Date: 12/27/2018
Map Prepared By: cmilligan
Base Source: Wood Rogers
Base Date: 10/24/17
Data Source(s):

Prepared by: WOOD RODGERS

Path: J:\3000-s\3487_Ecosystem_Invest_Partners\3487002 Lookout Slough Prelim Hydraulic Analysis\GIS\Tasks\20181227_Fish_BOD_Appendix\Fish_BOD_Stage_Hydrograph_Appendix_OA_Exhibit_20181227_V1.mxd

FIGURE B1

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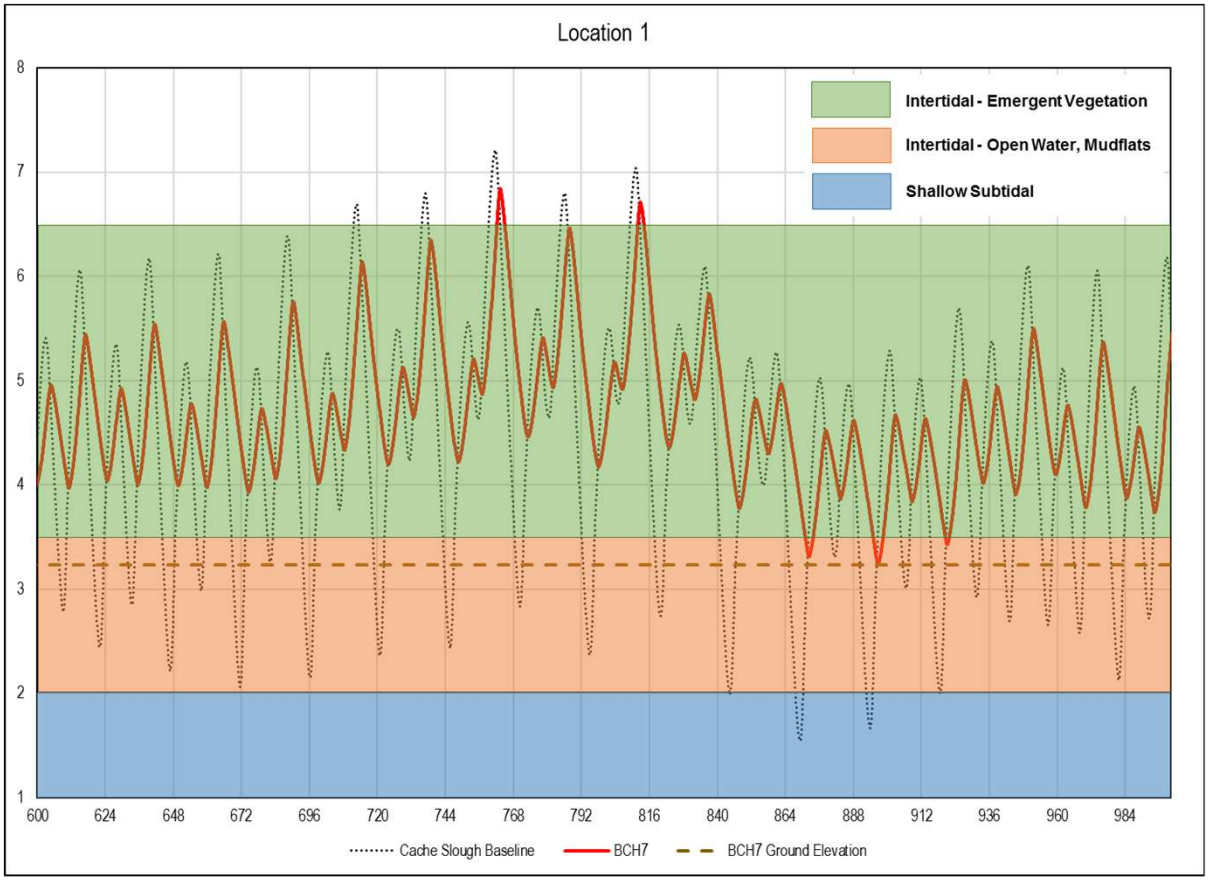
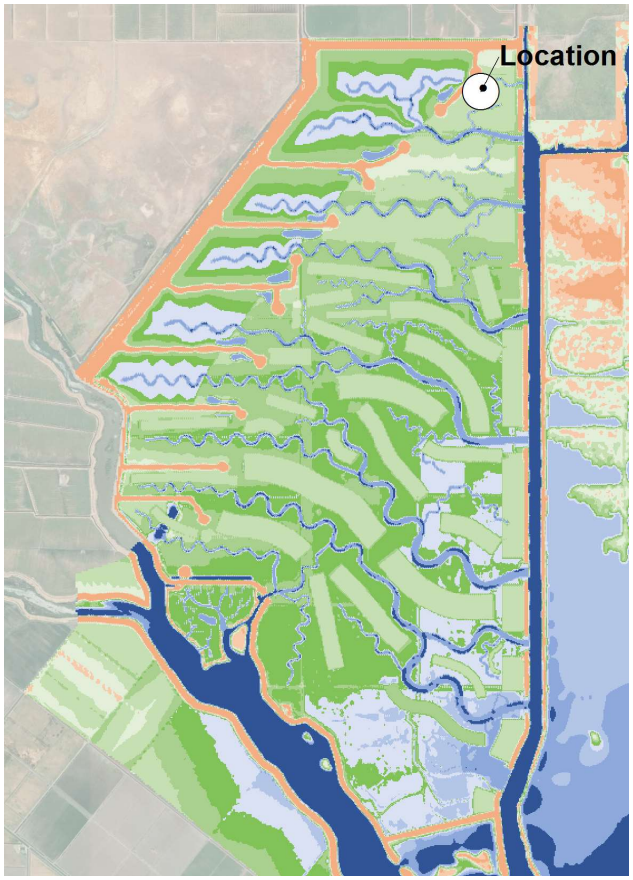


Ecosystem Investment Partners

WOOD RODGERS
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B2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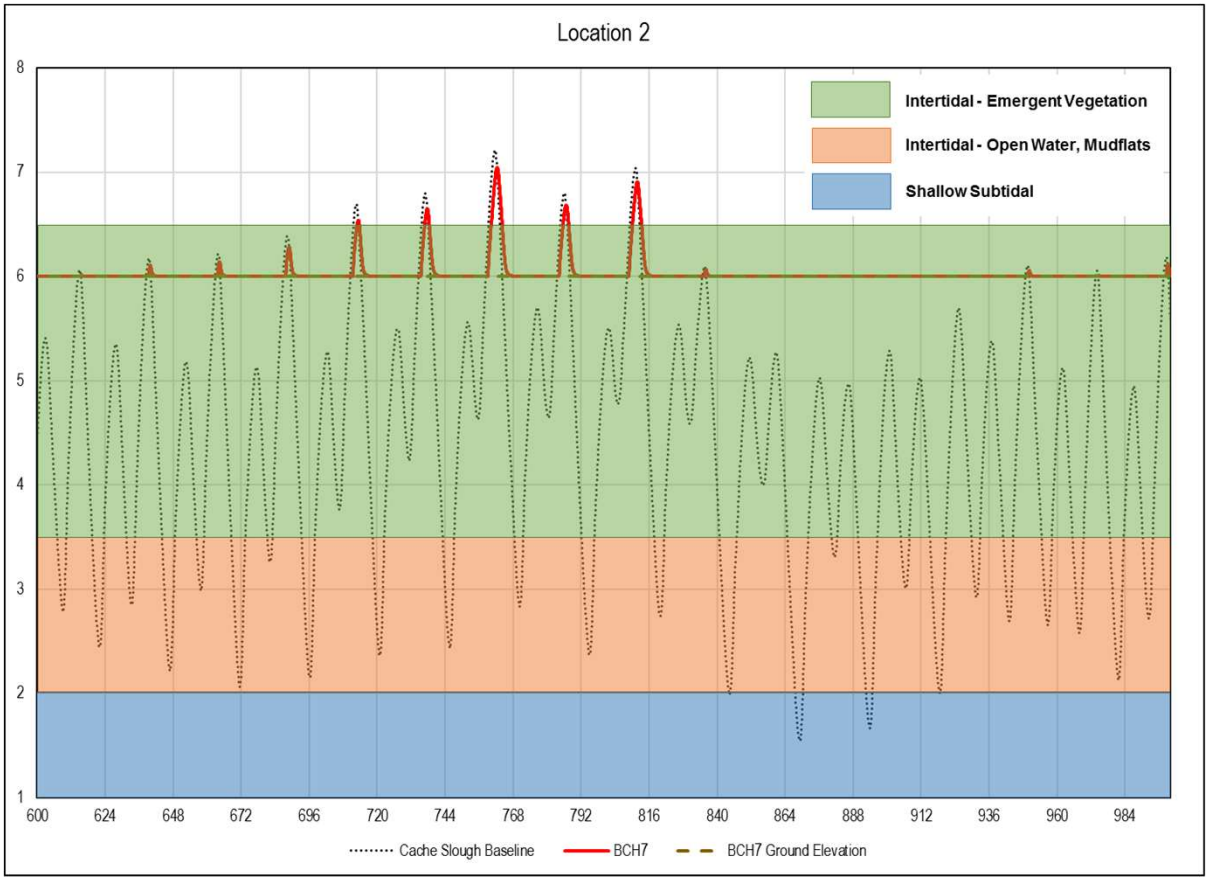
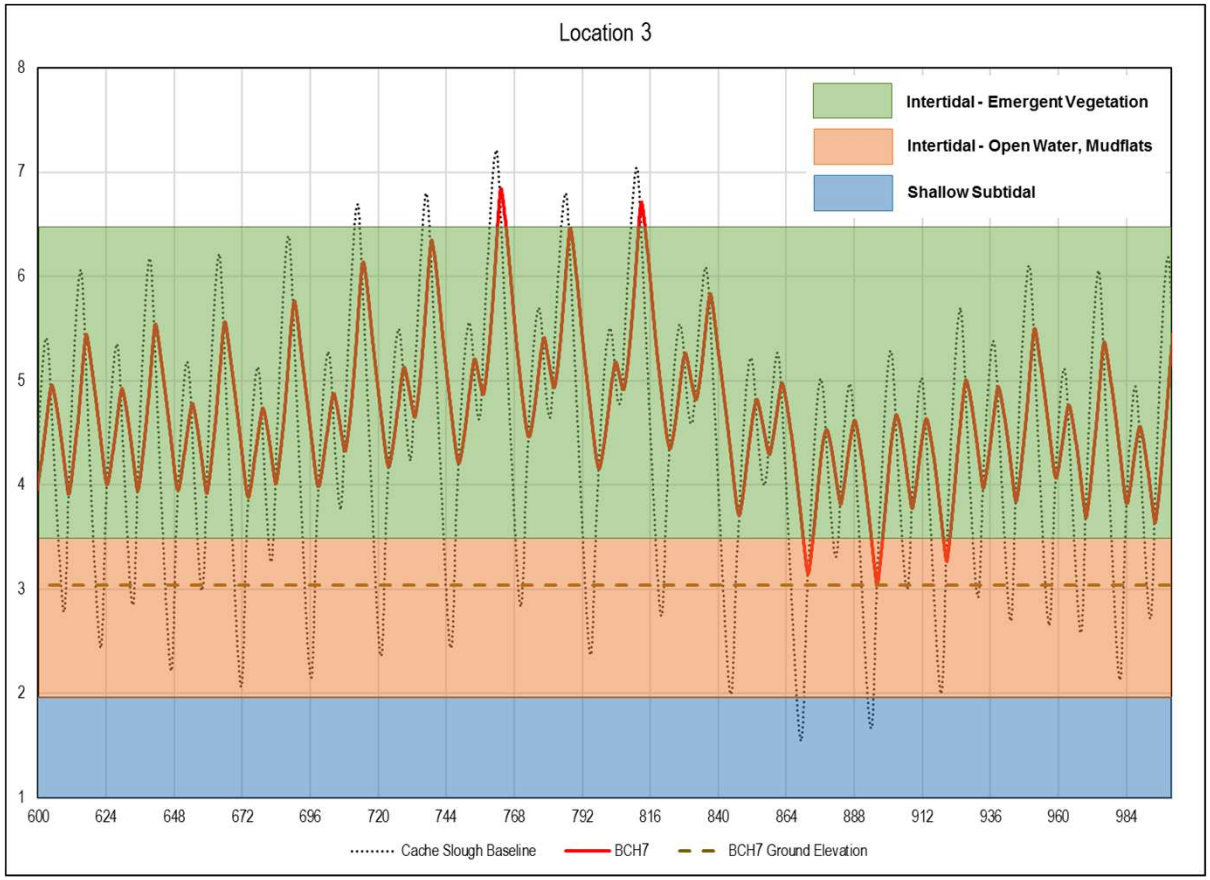

Location 2
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation

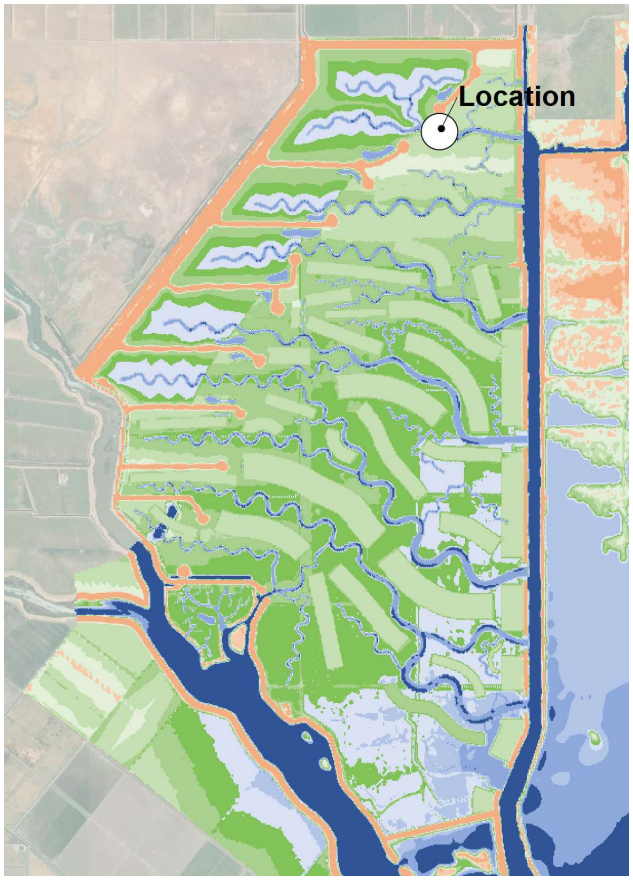




Ecosystem Investment Partners

WOOD RODGERS
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure 4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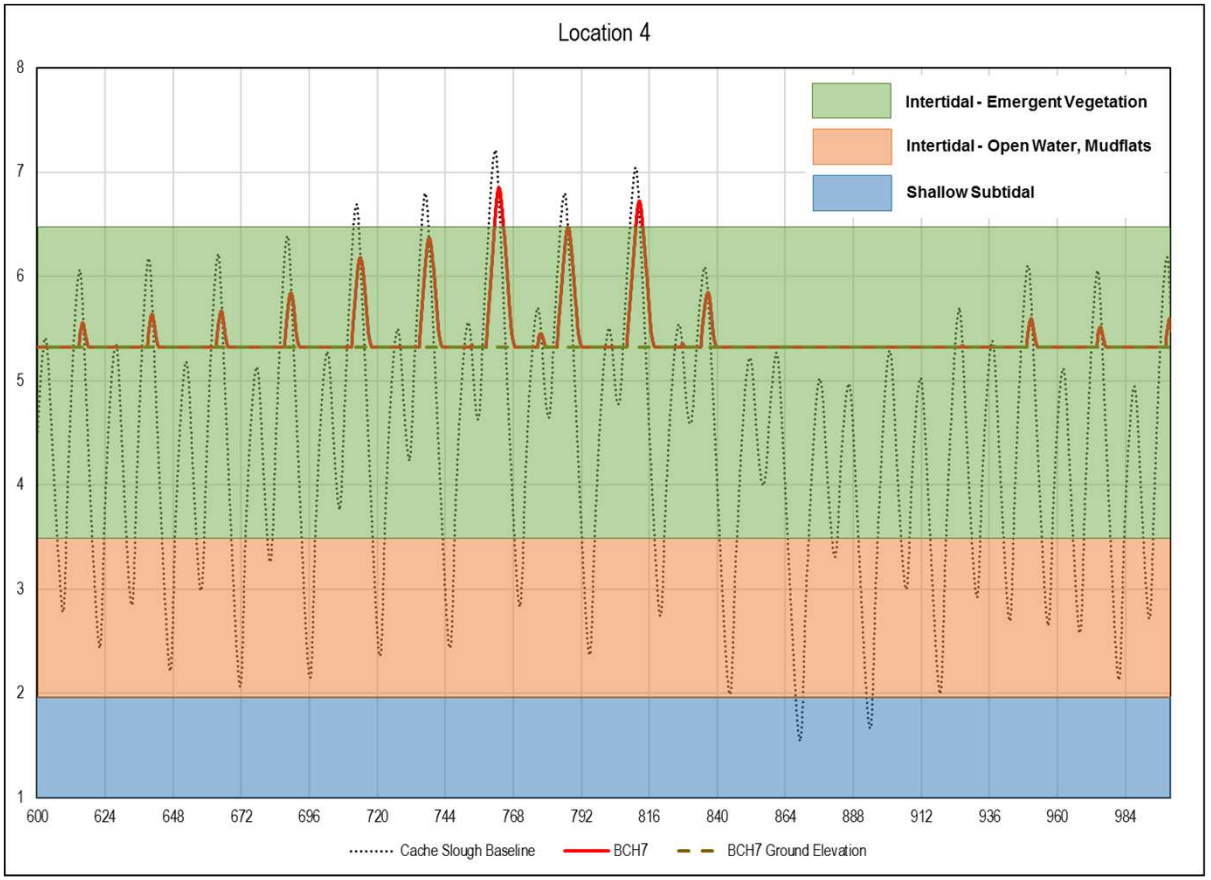
Location 4
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
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624
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672
696
720
744
768
792
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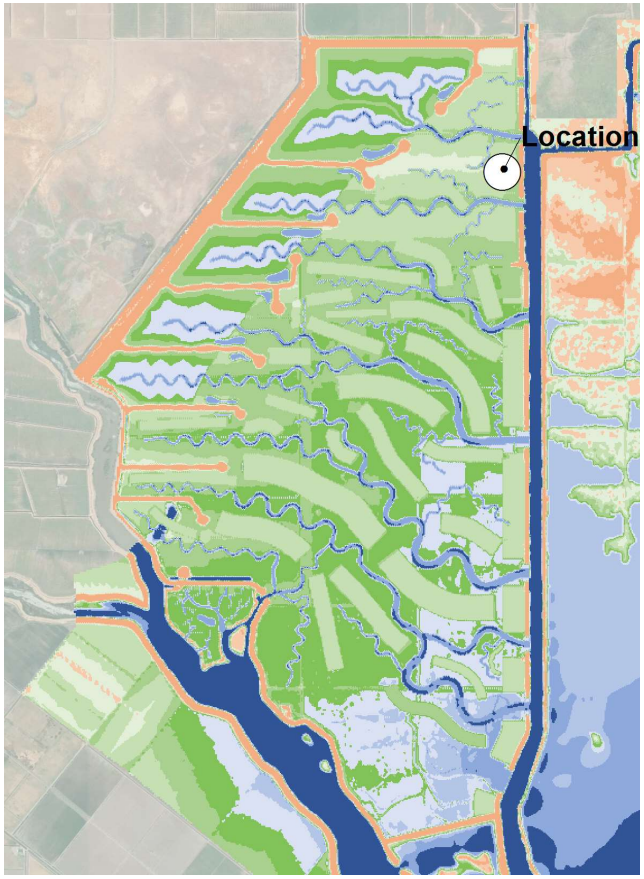
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation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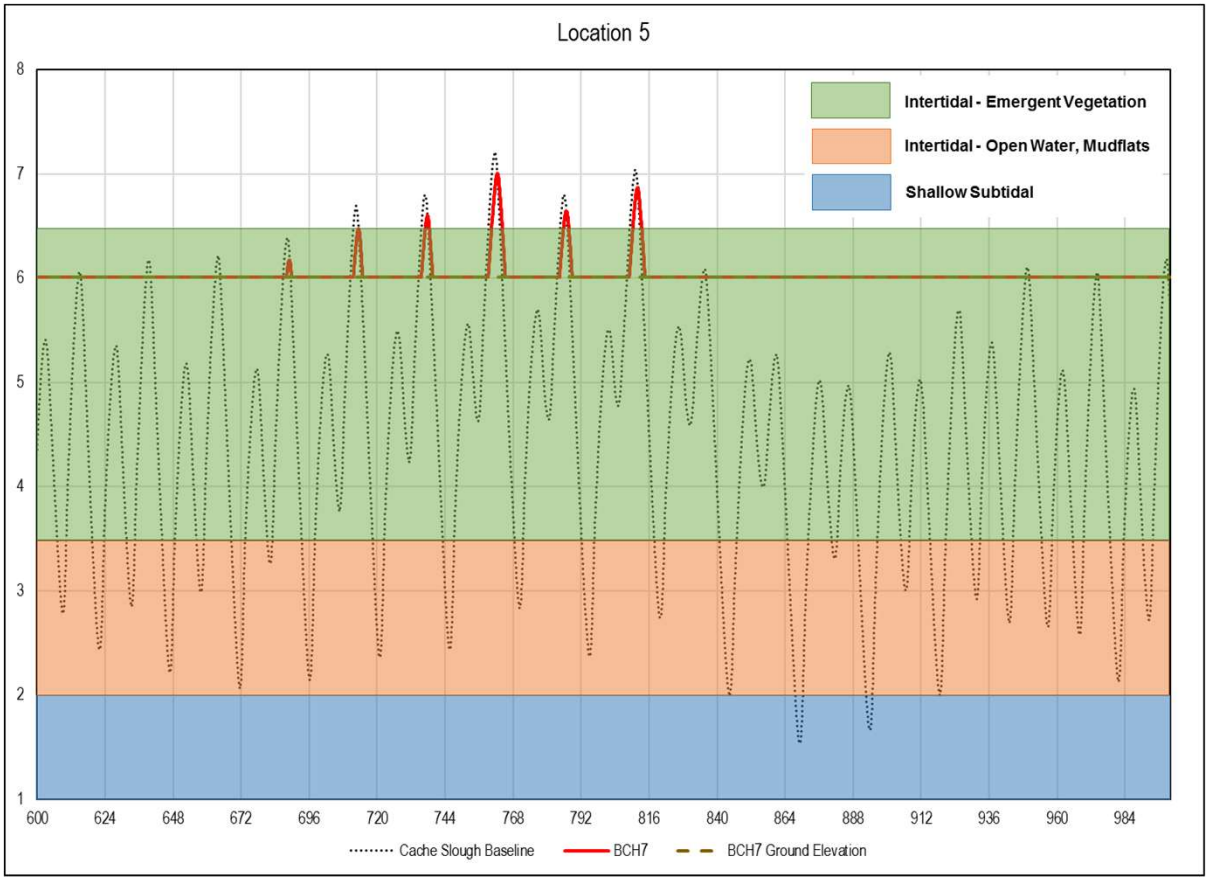
Location 5
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
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7
6
5
4
3
2
1
600
624
648
672
696
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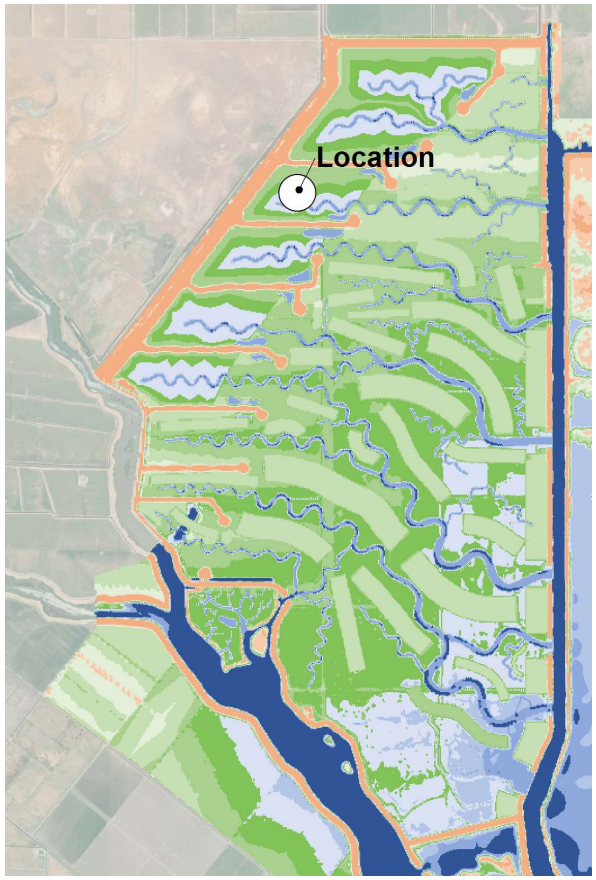
Cache Slough Baseline
BCH7
BCH7 Ground Elevation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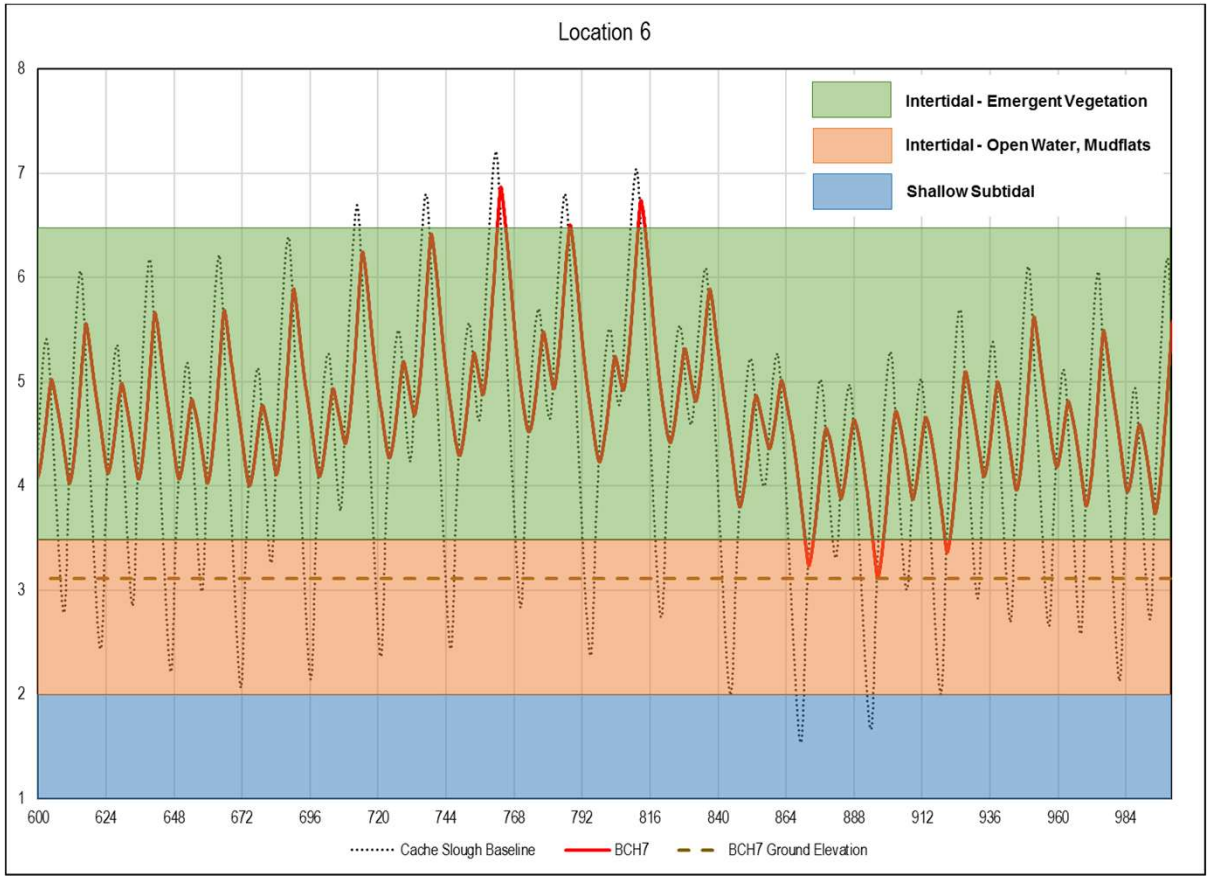
Location 6
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
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4
3
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672
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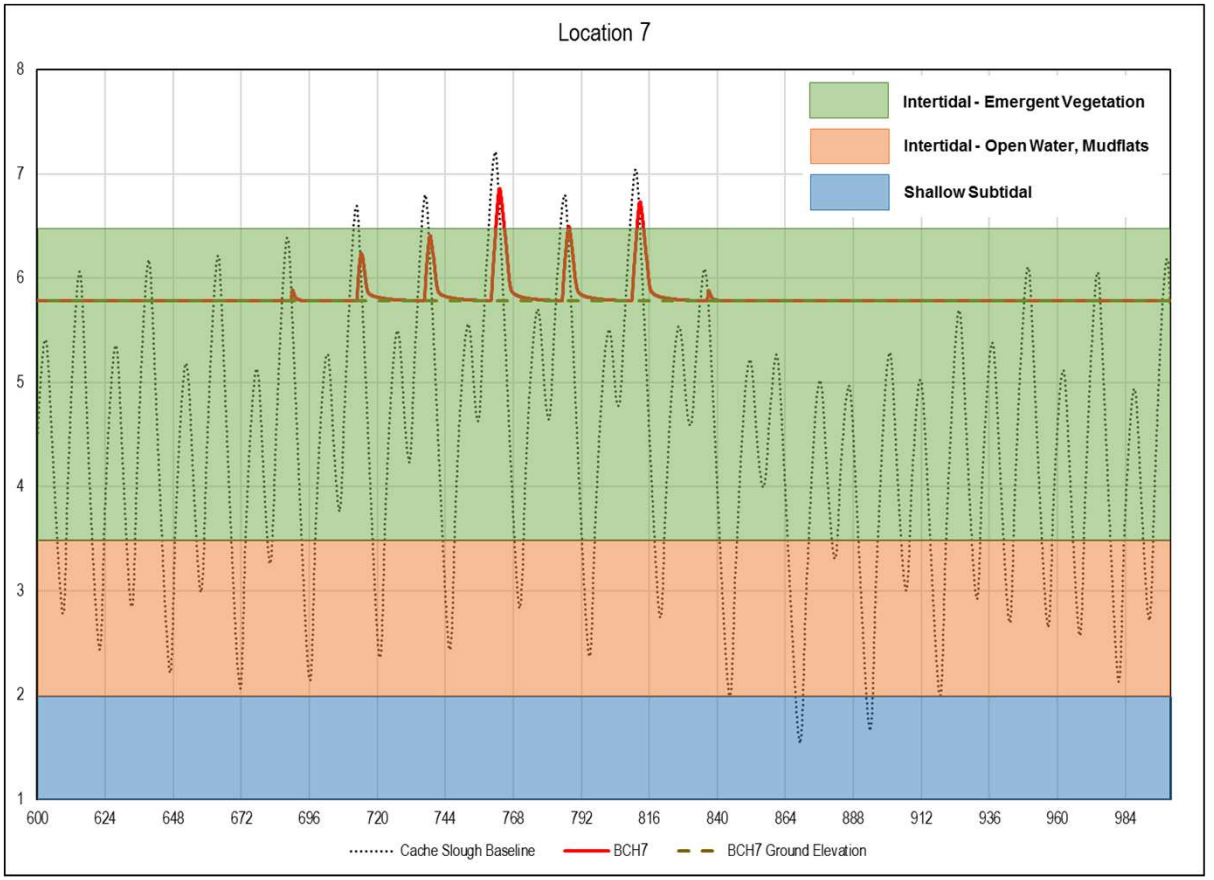
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation


Location


Location 7
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
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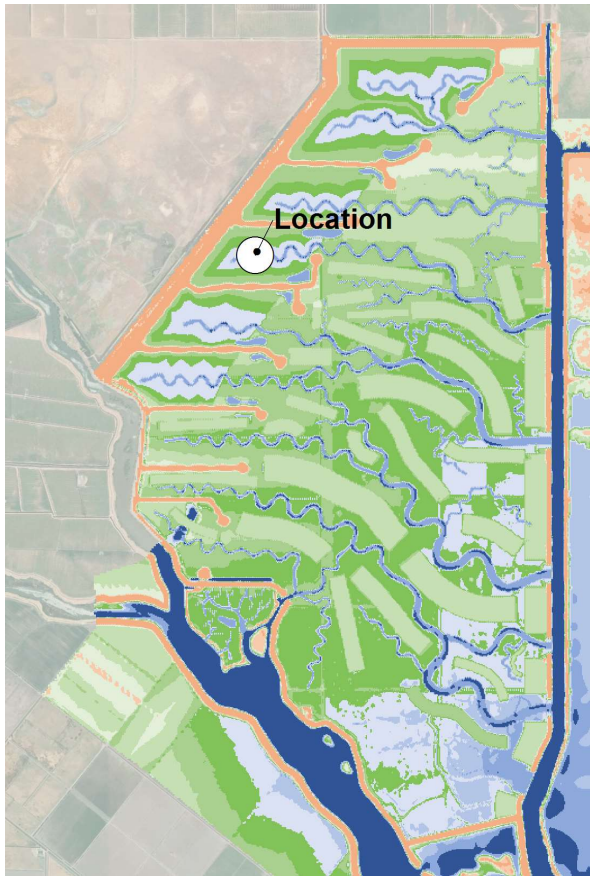
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation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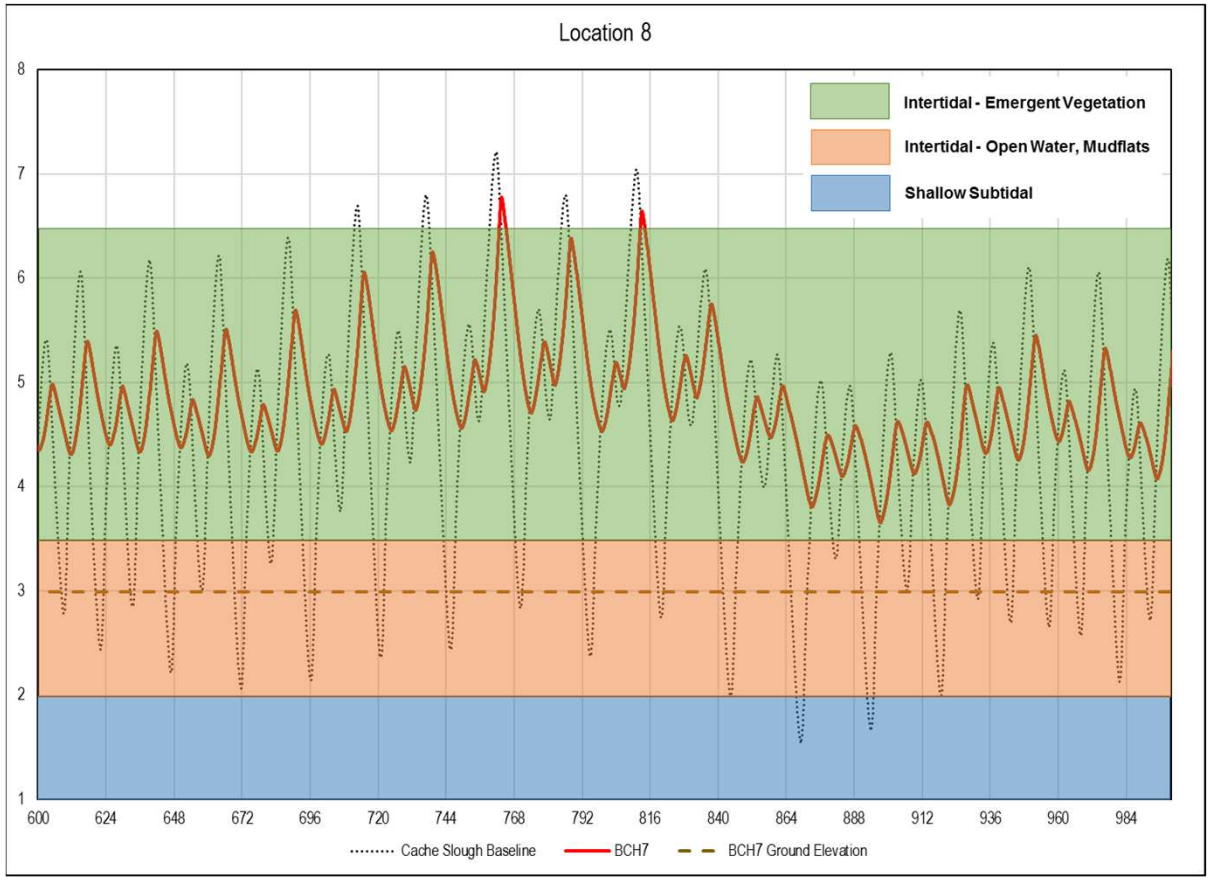
Location 8
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
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672
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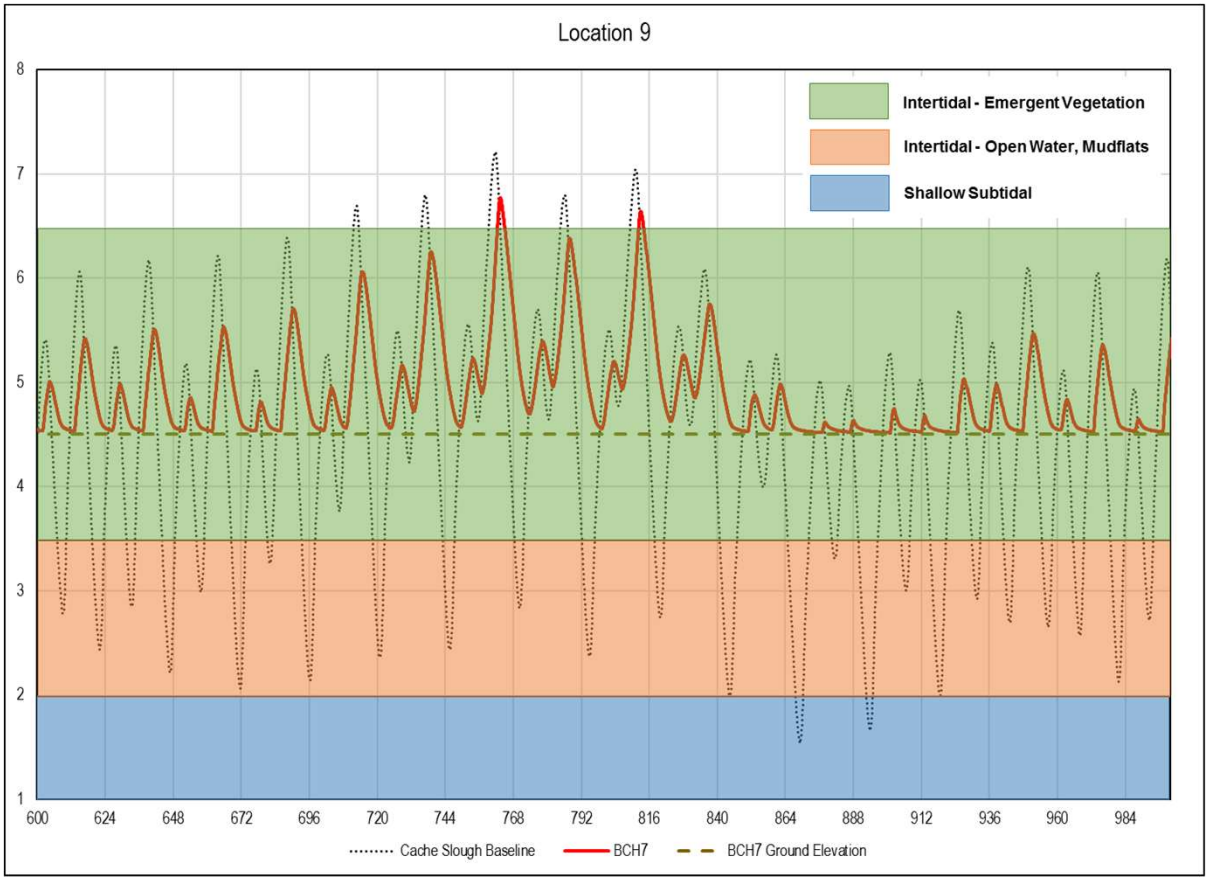
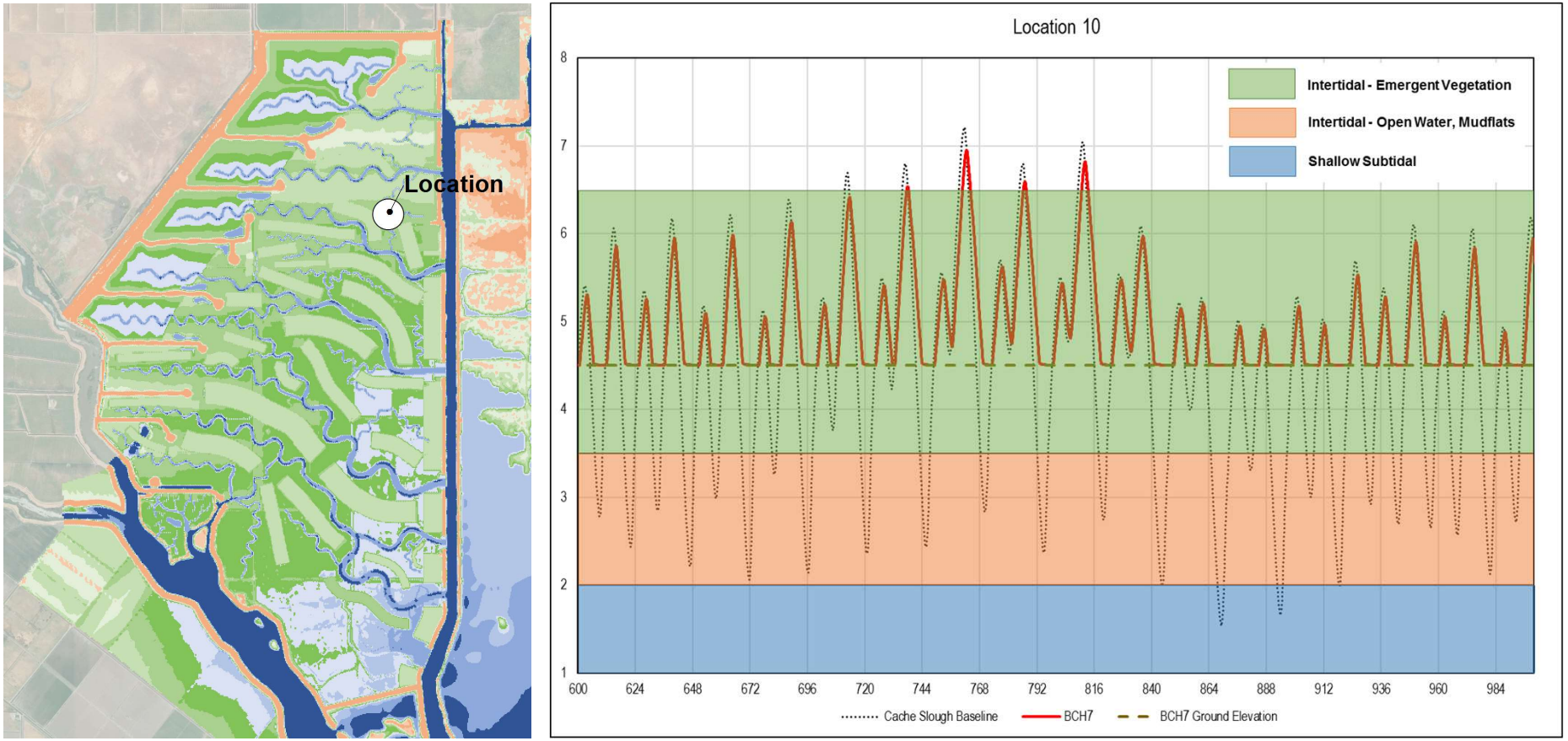
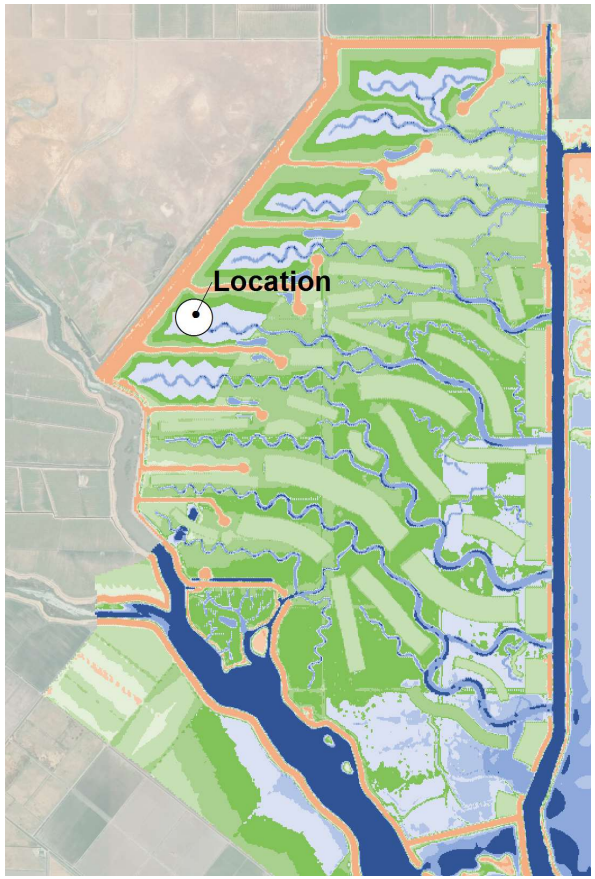
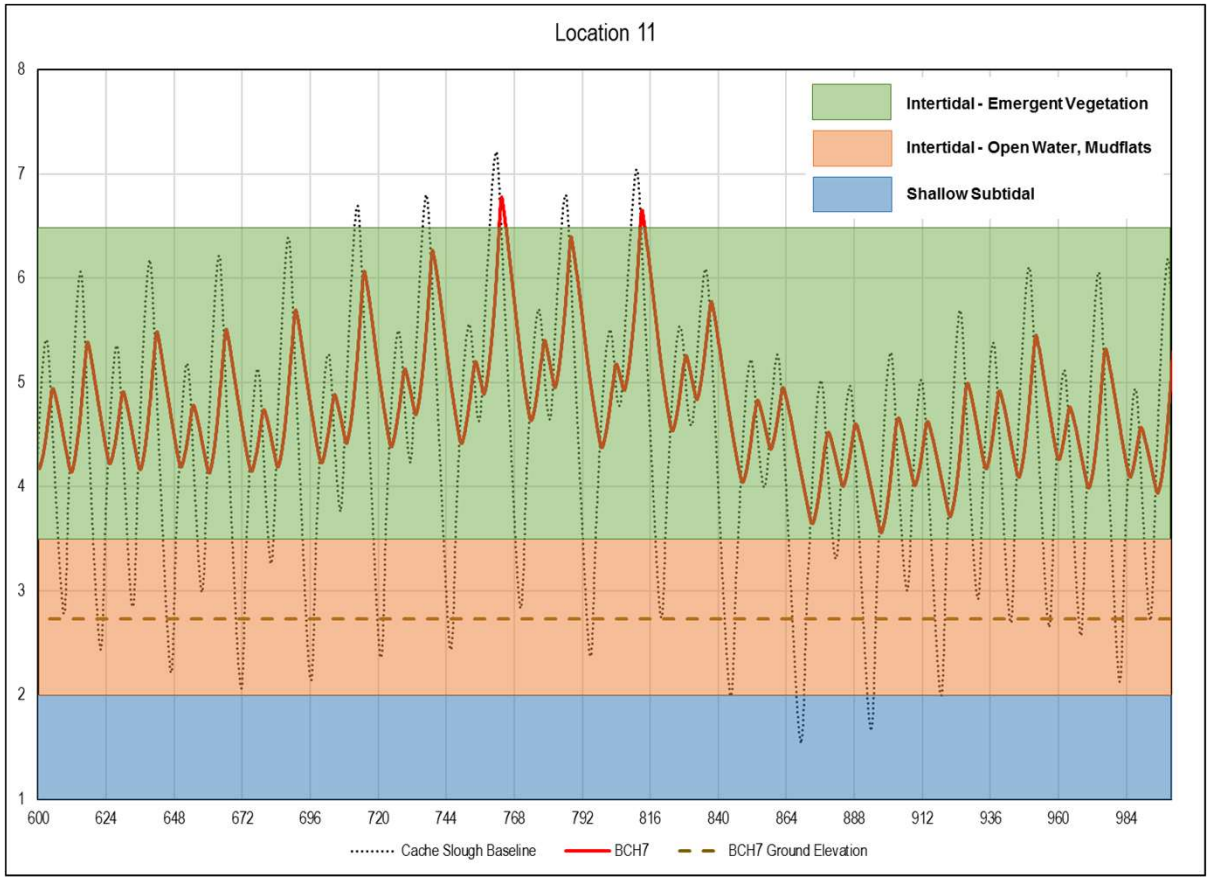
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation

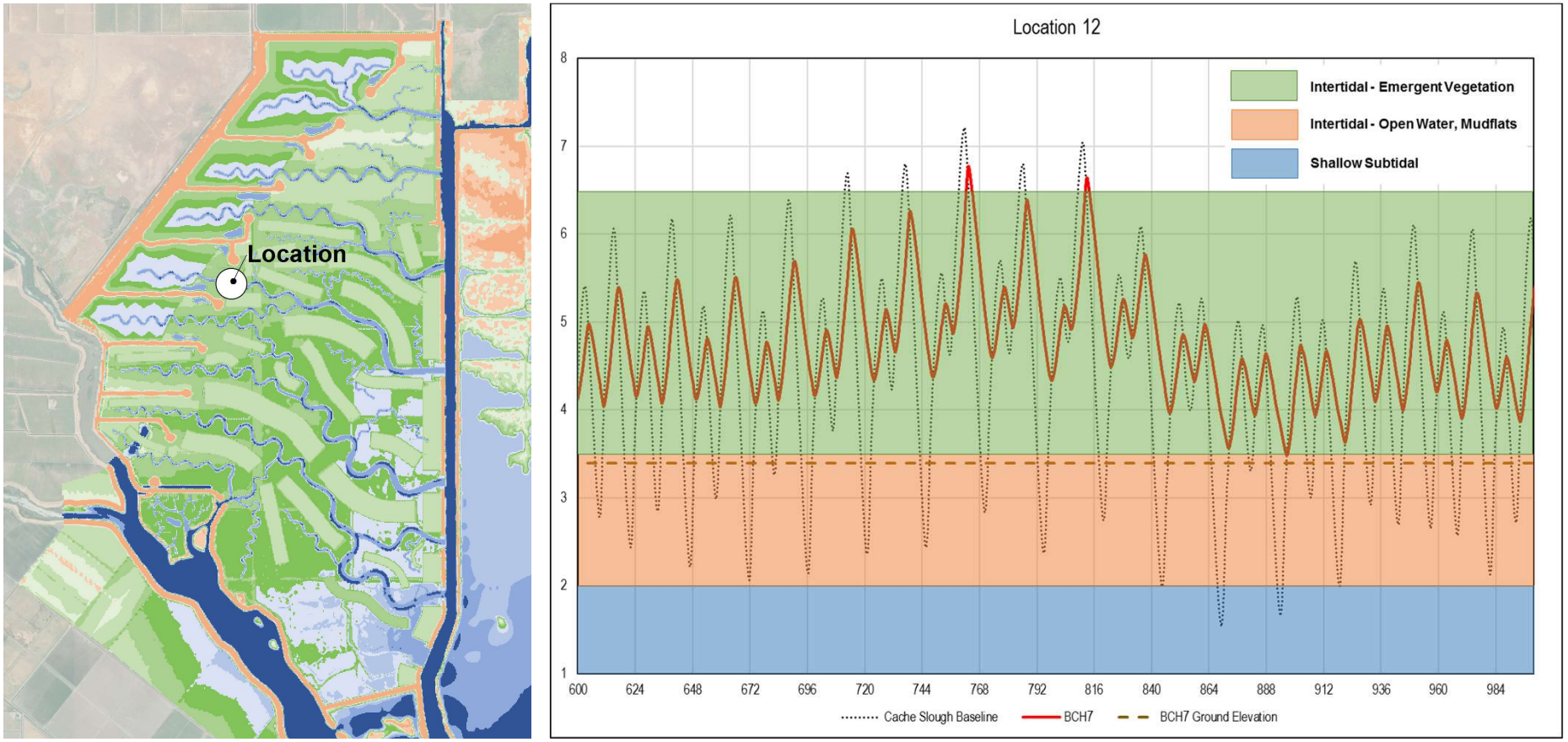

Location


Location 9
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation


Location
Location 10
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation


Location


Location 11
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation



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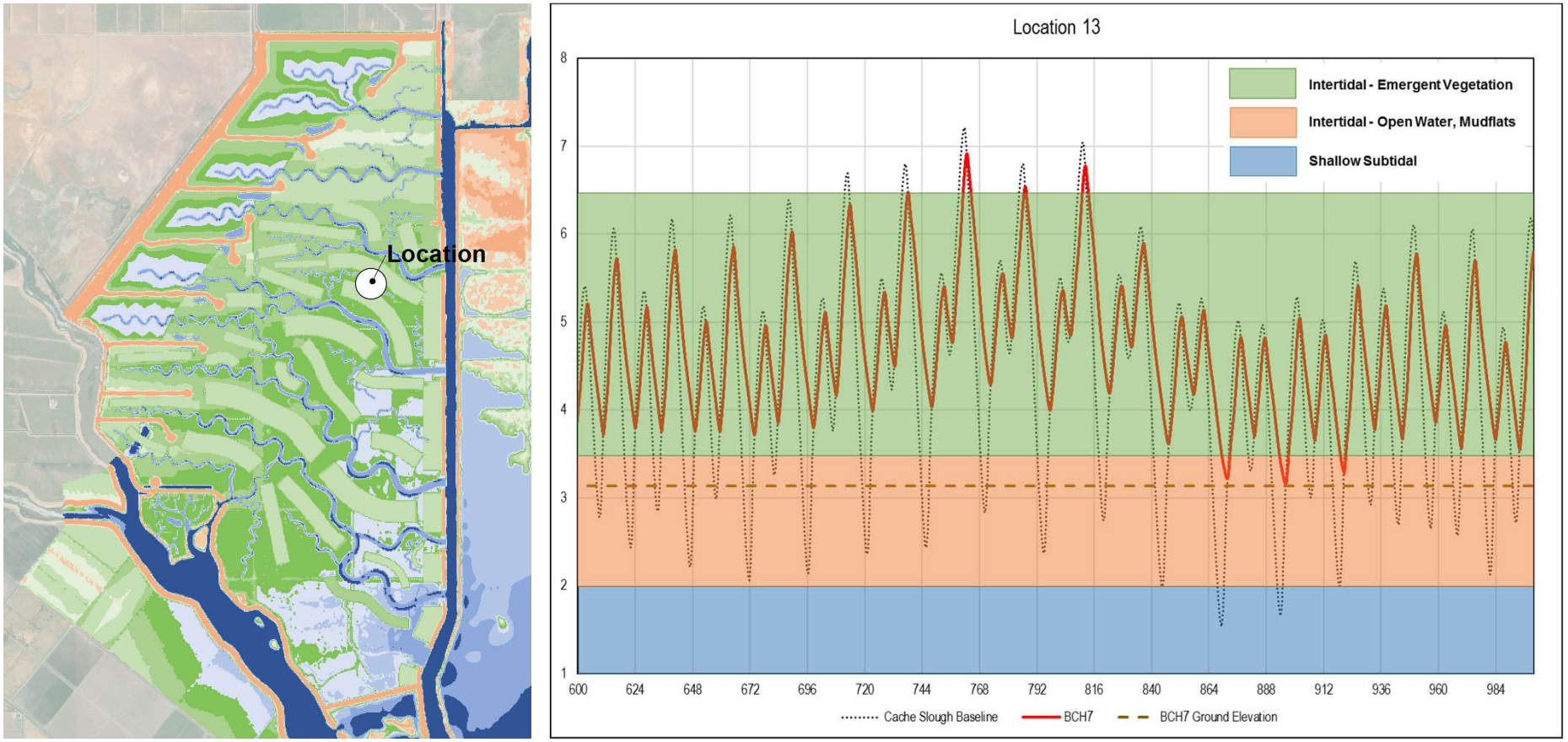
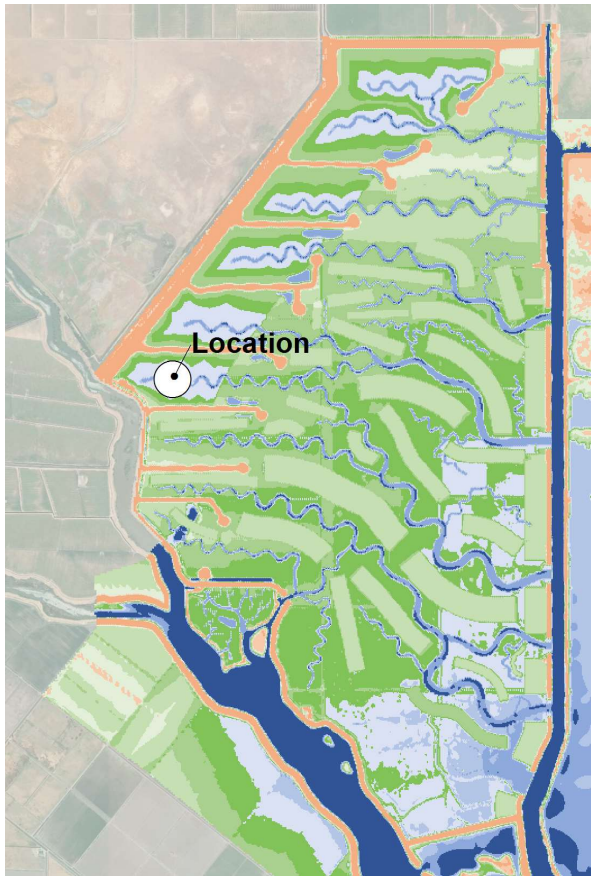
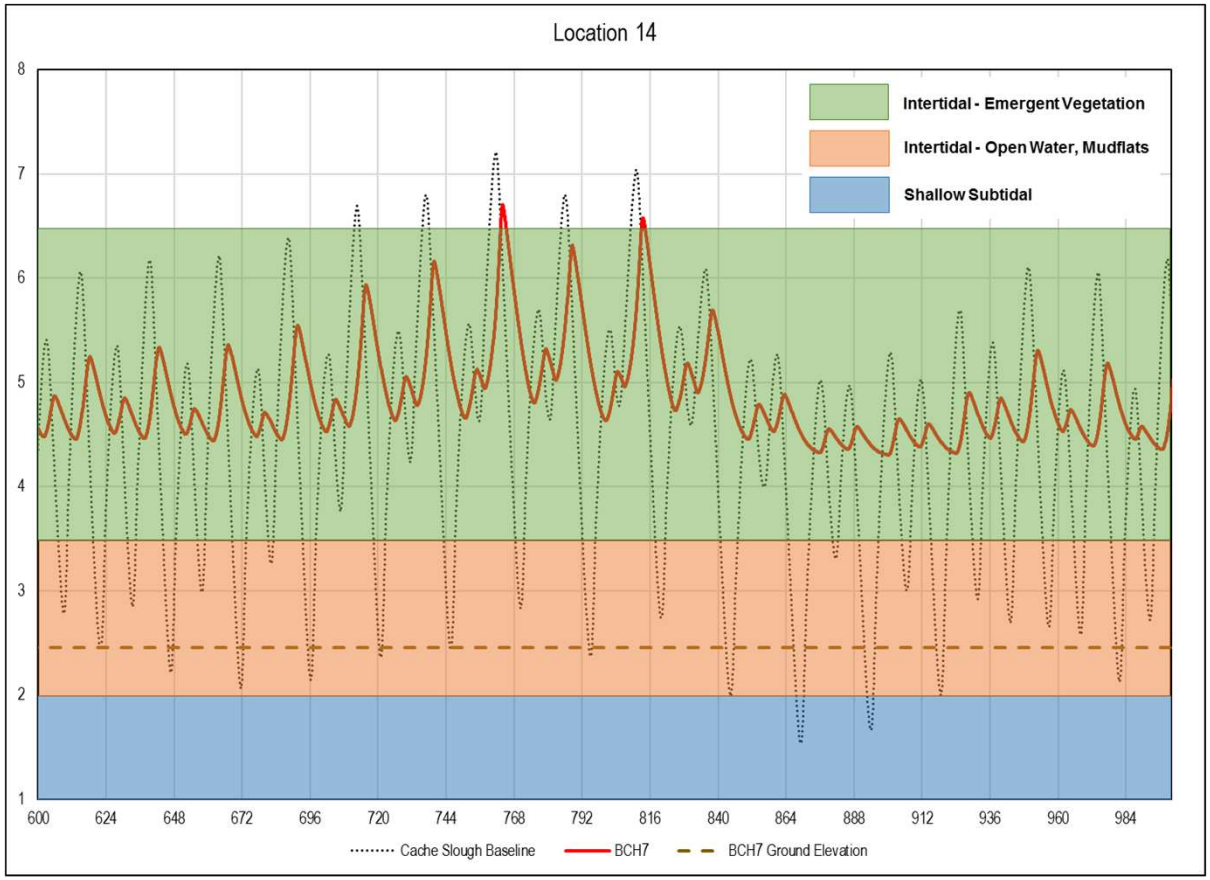
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B13


Location
Location 13
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation





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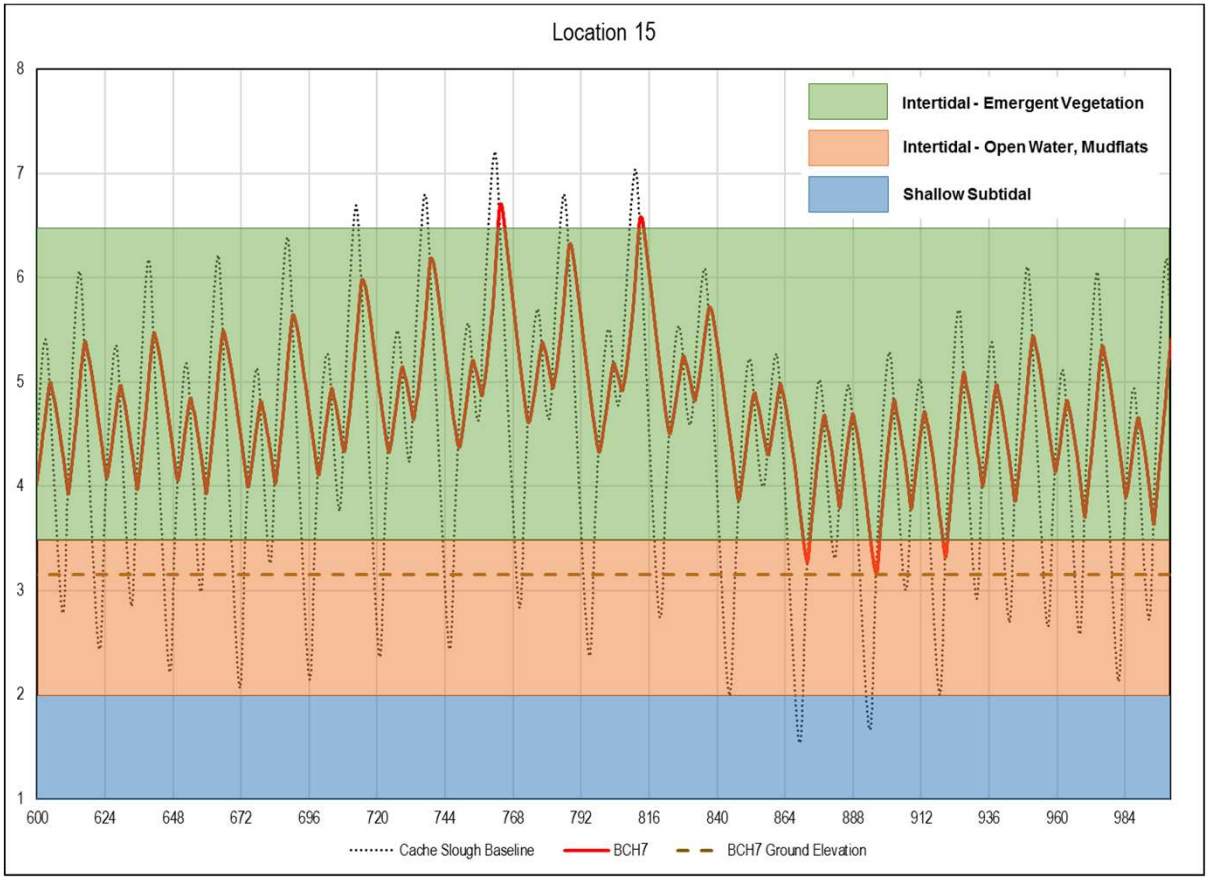
WOOD RODGERS
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B15





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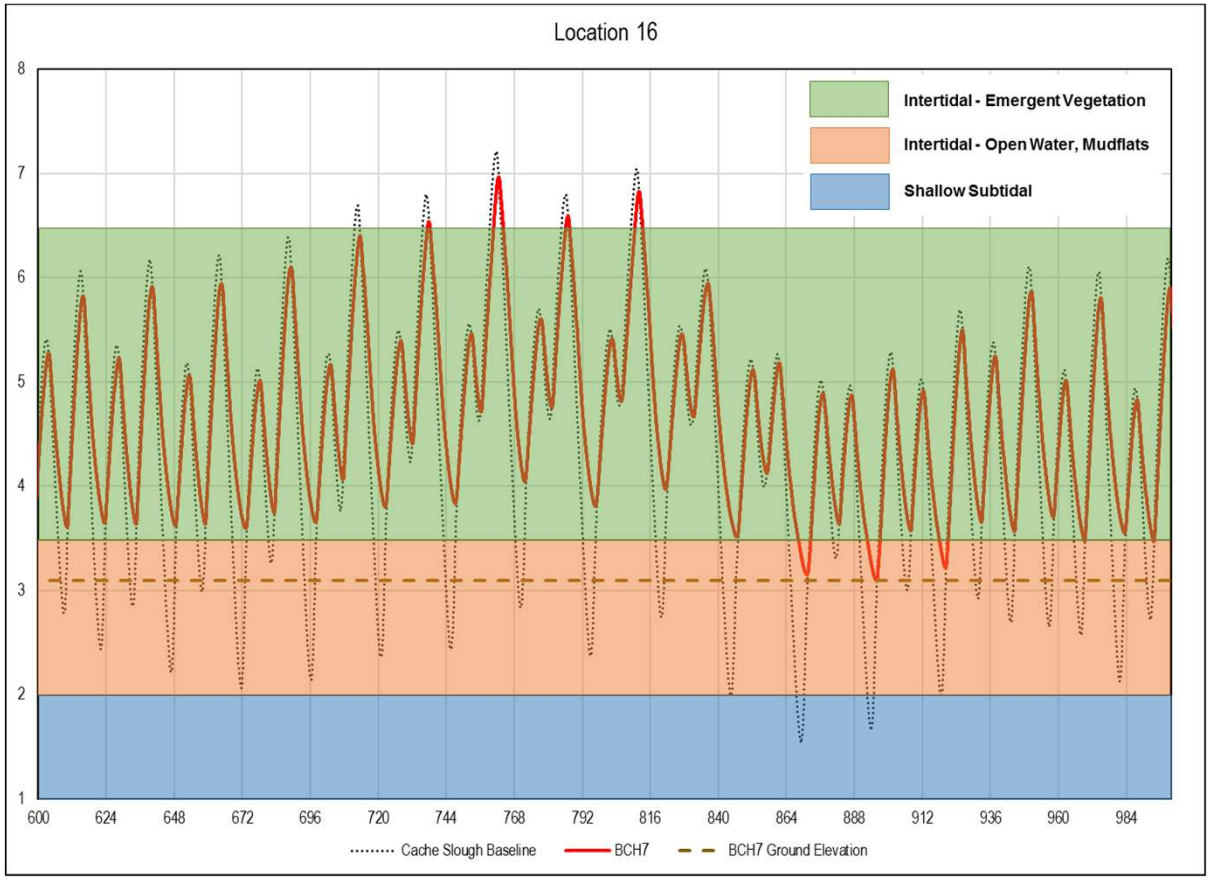
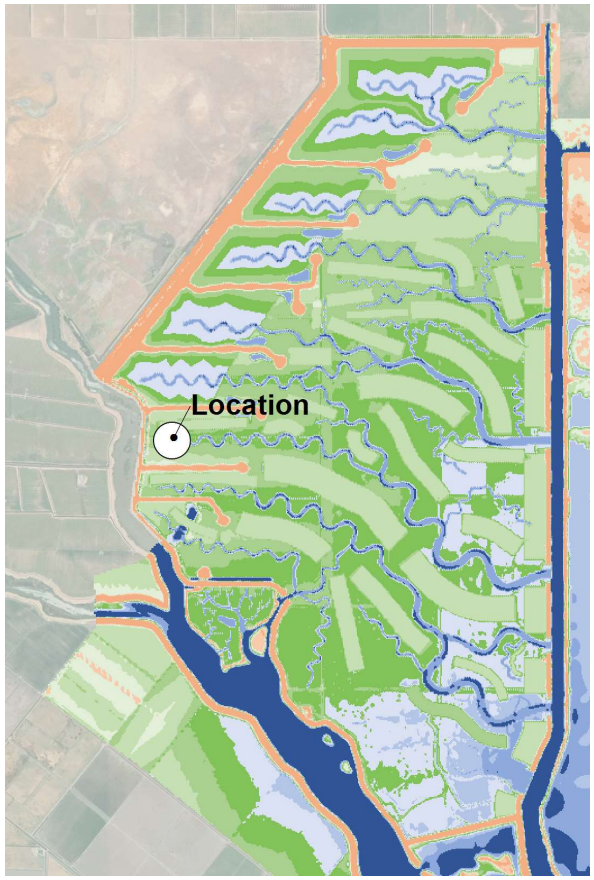
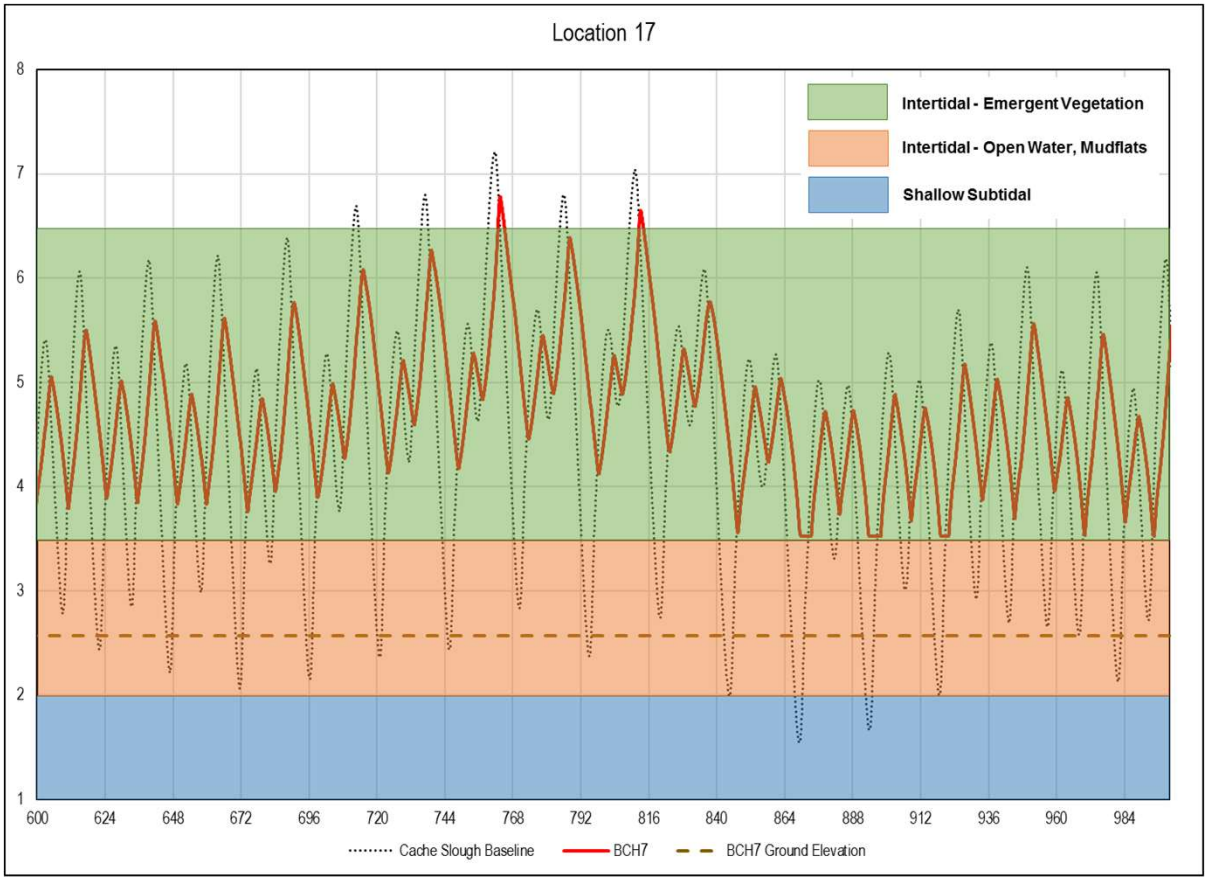
WOOD RODGERS
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B16


Location


Location 16
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation





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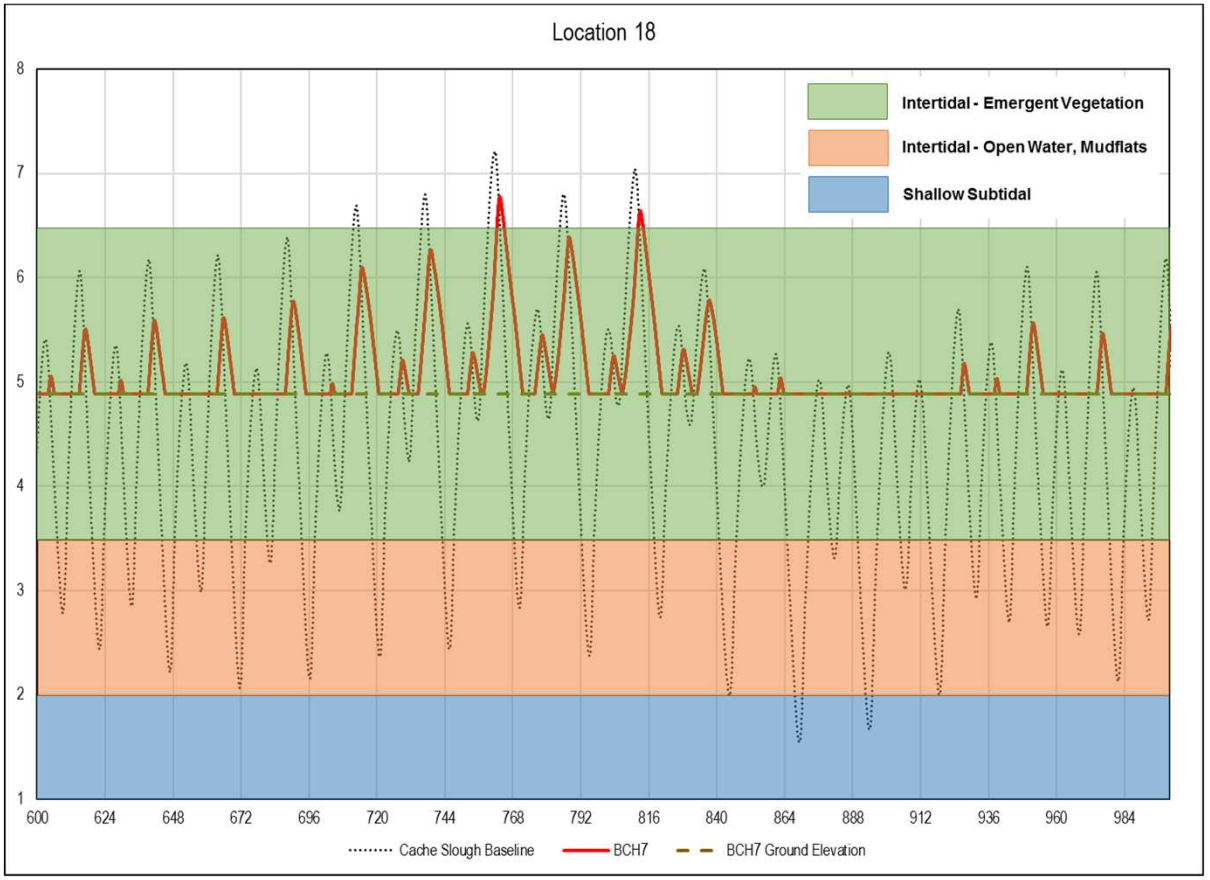
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B18


Location


Location 18
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation



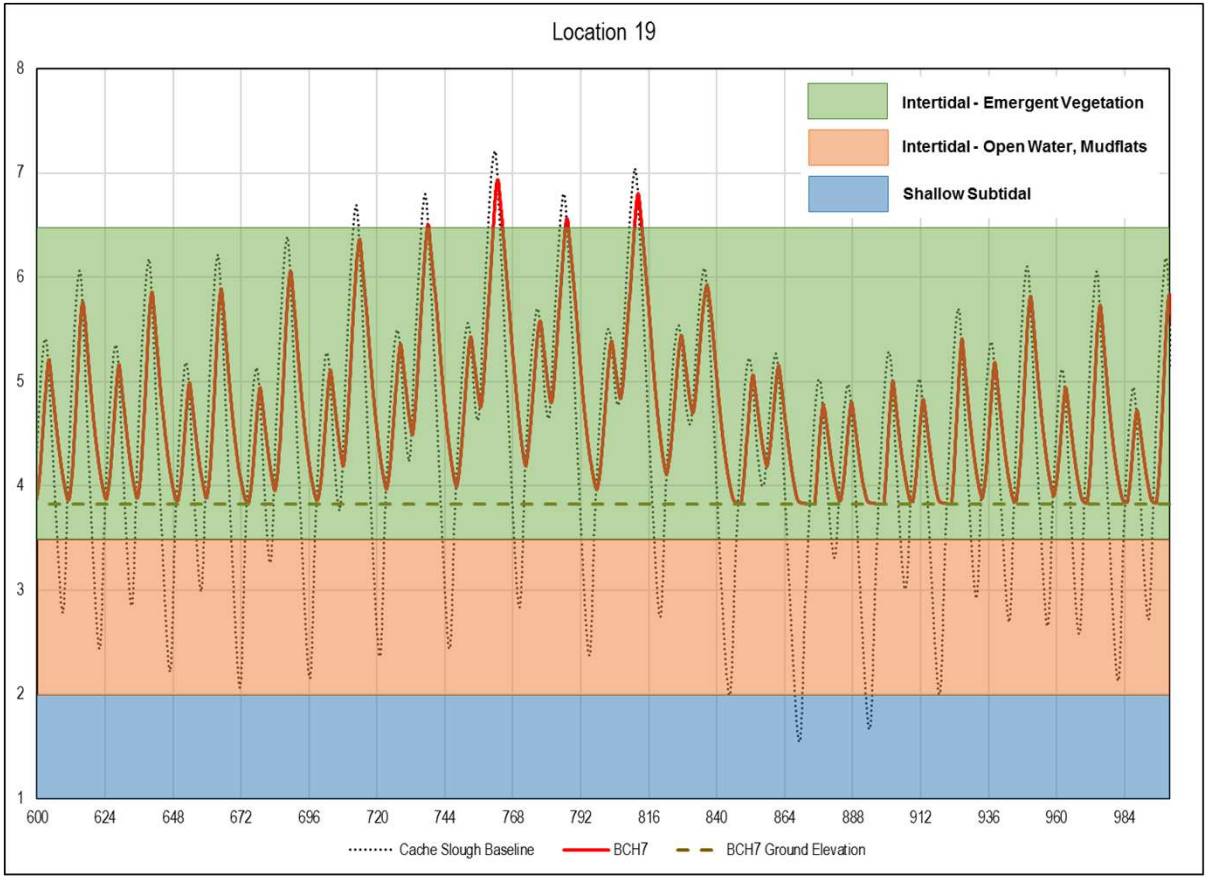


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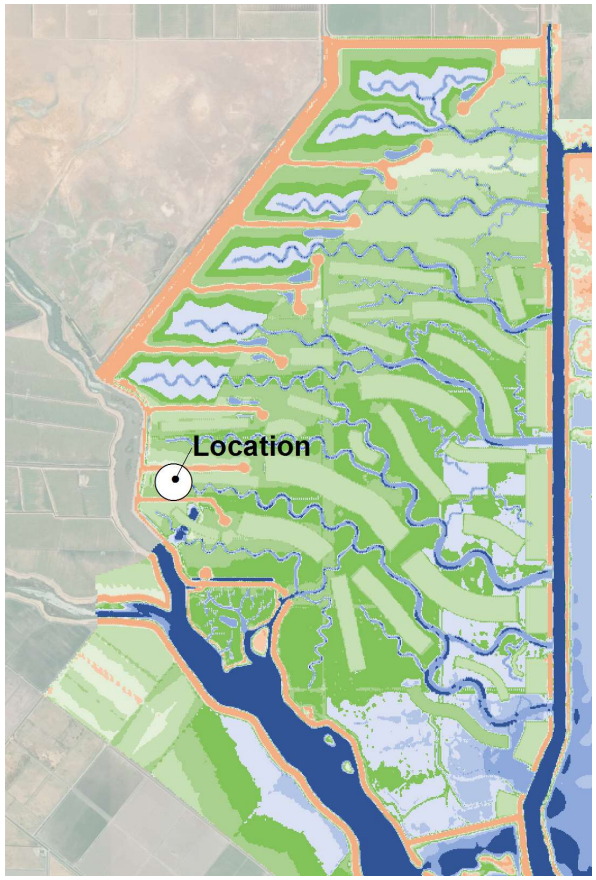
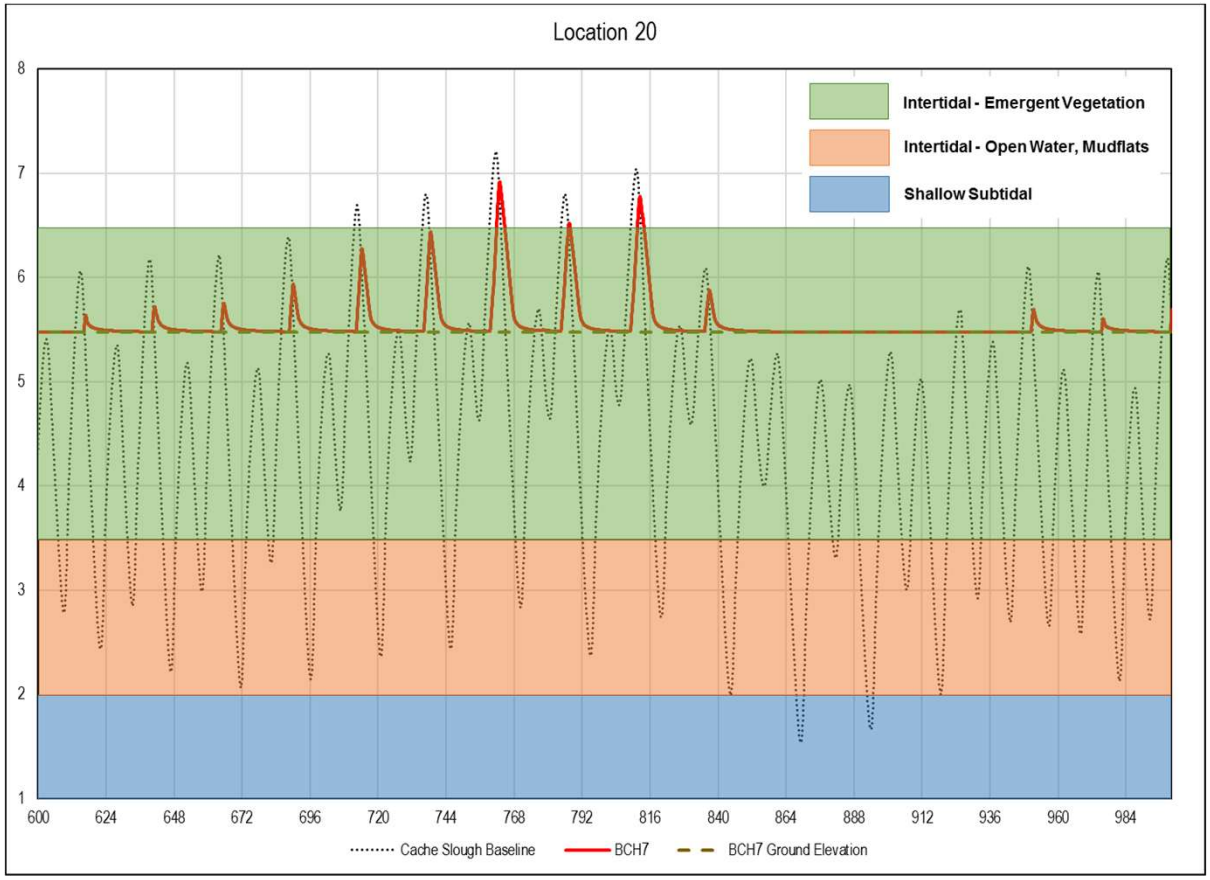
Figure B20





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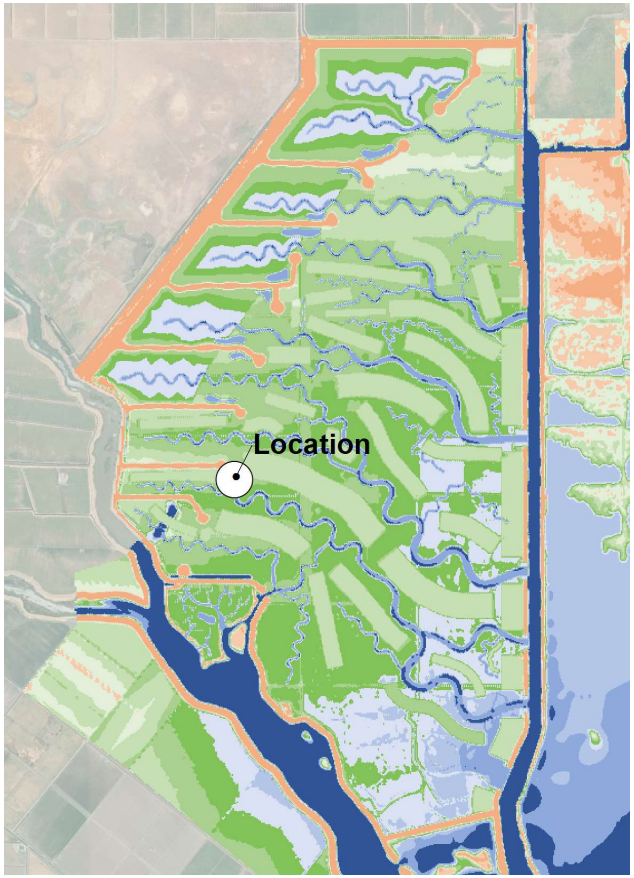
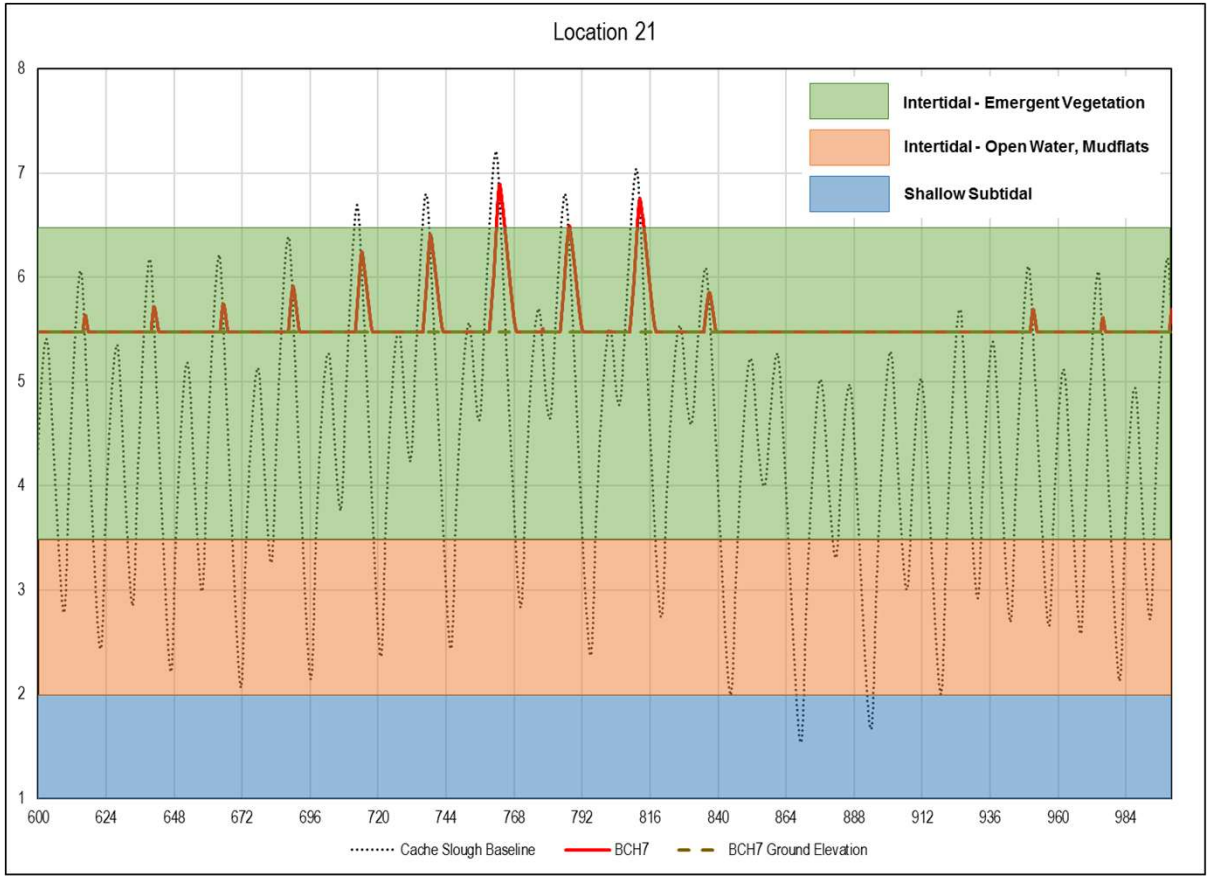
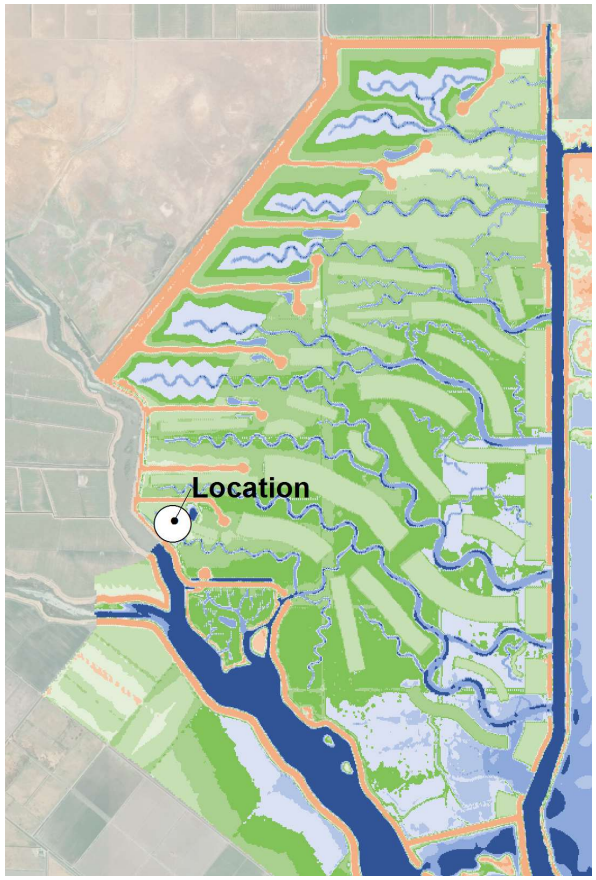
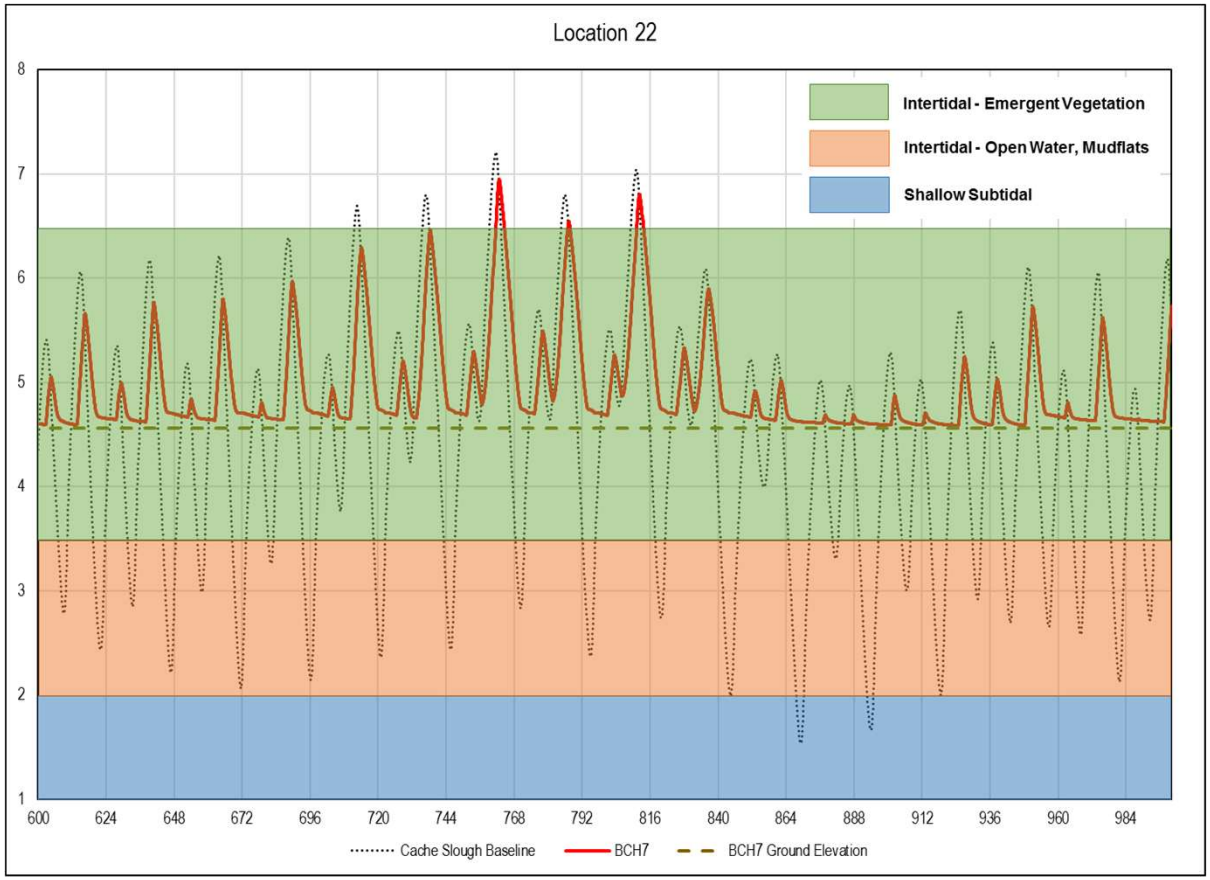
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B21


Location


Location 21
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation





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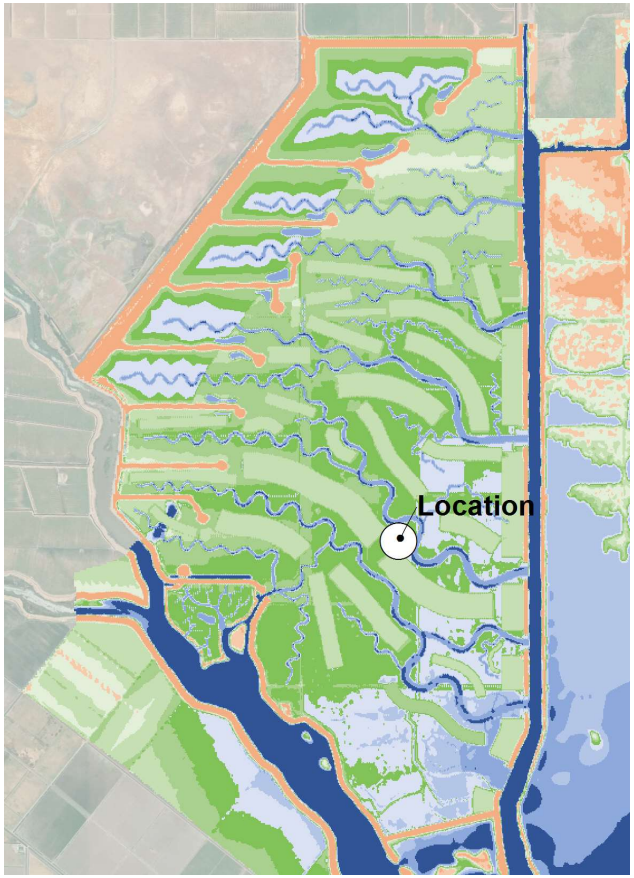
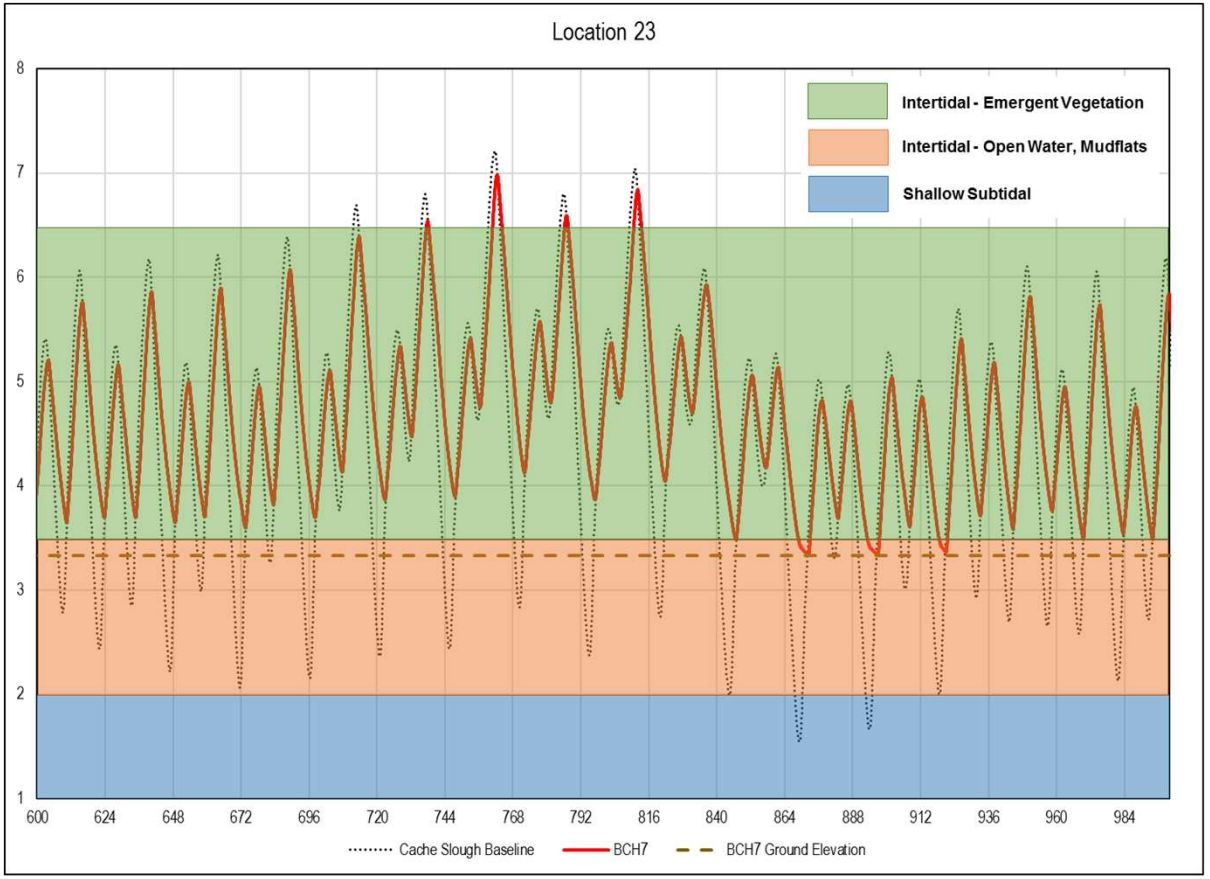
WOOD RODGERS
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B23





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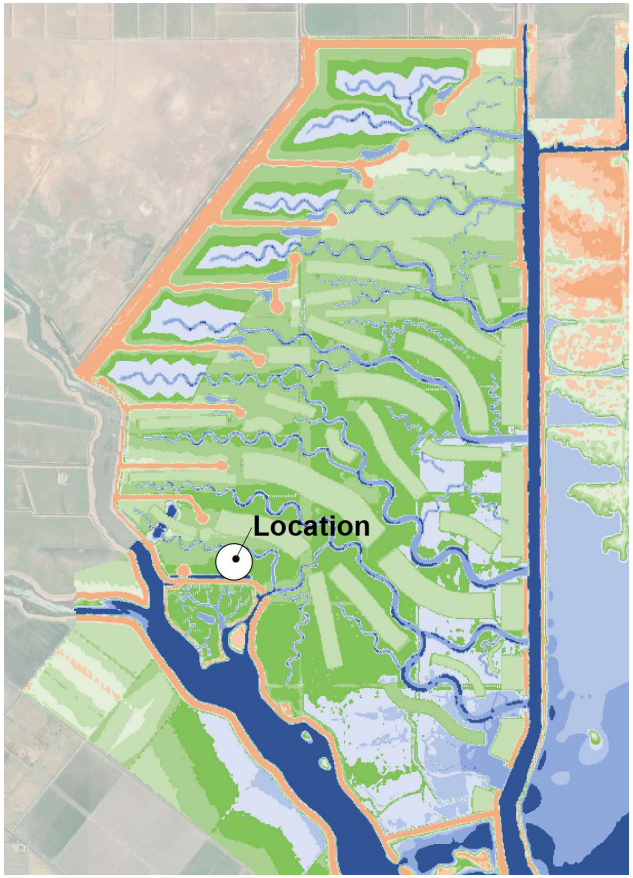
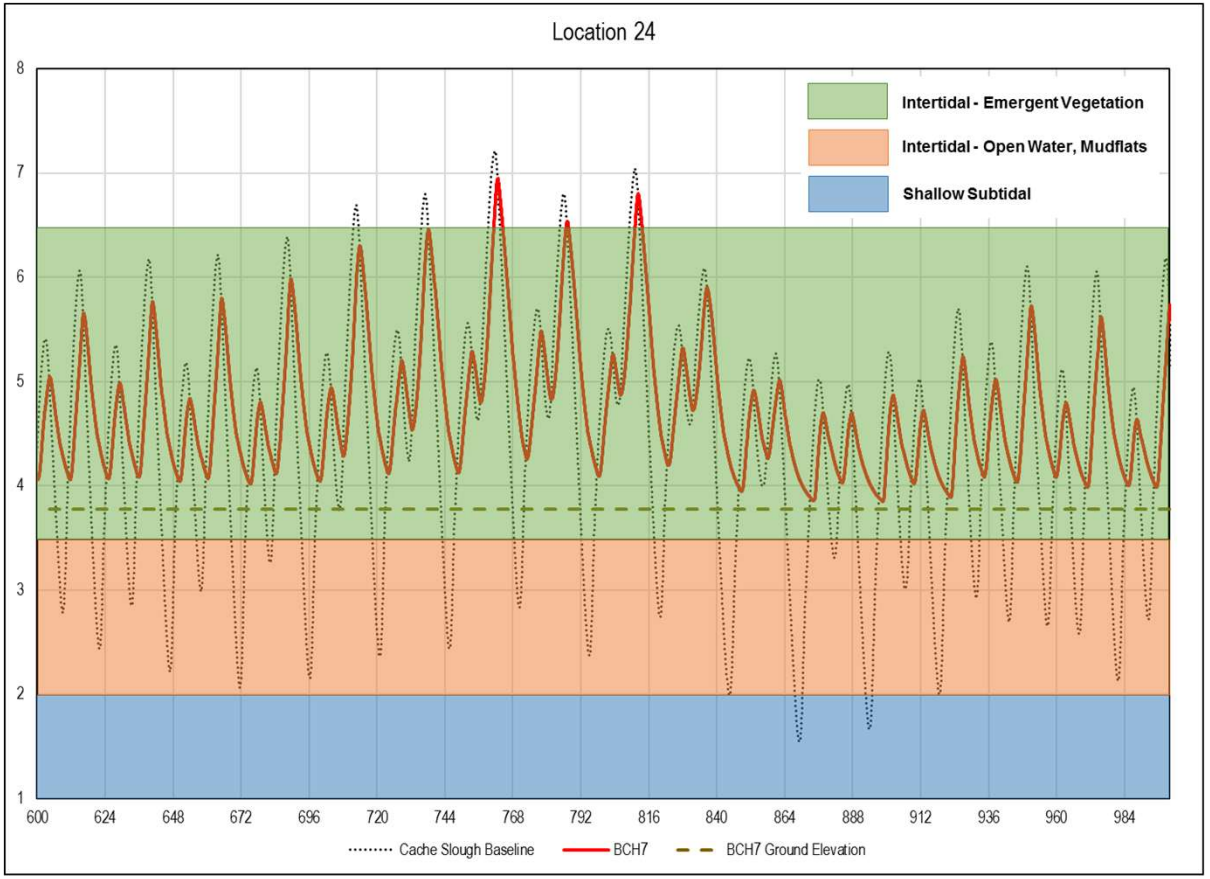
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B24





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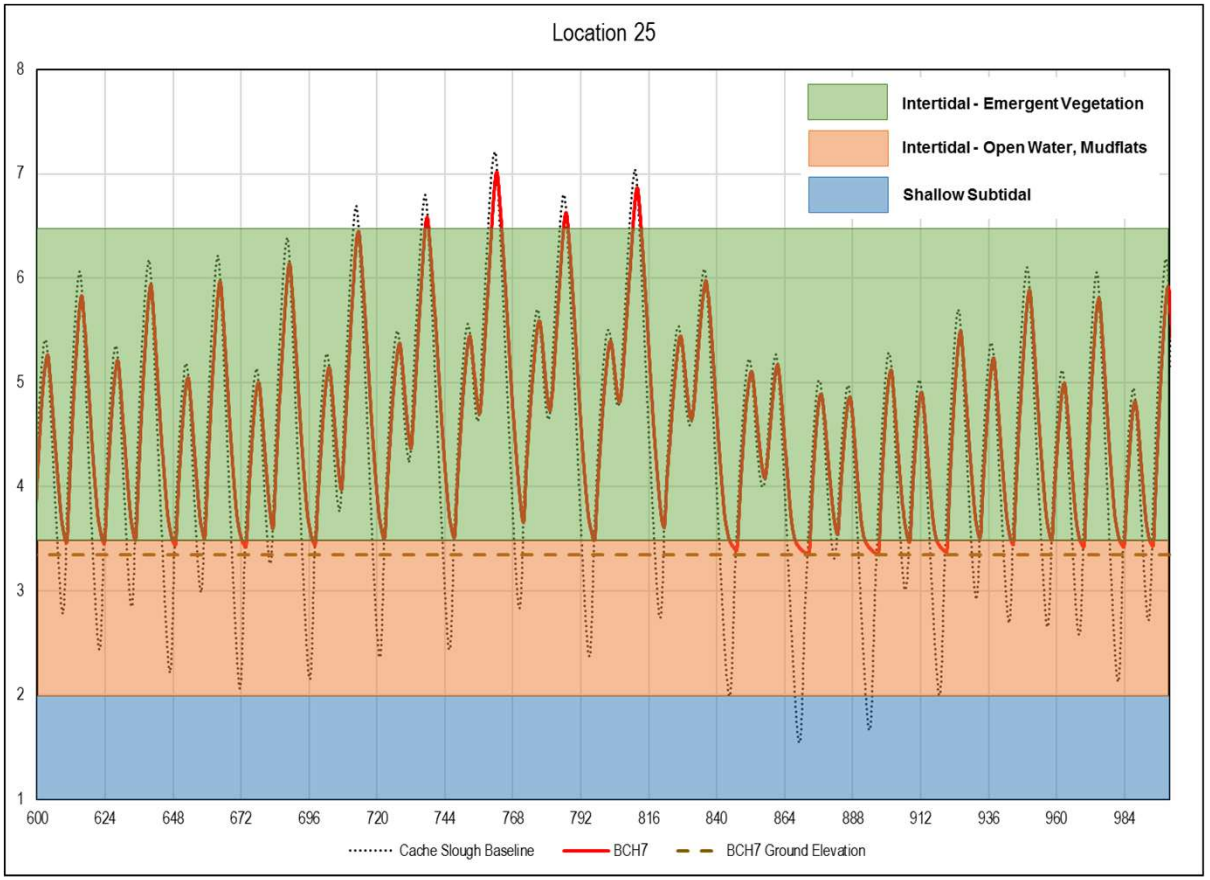
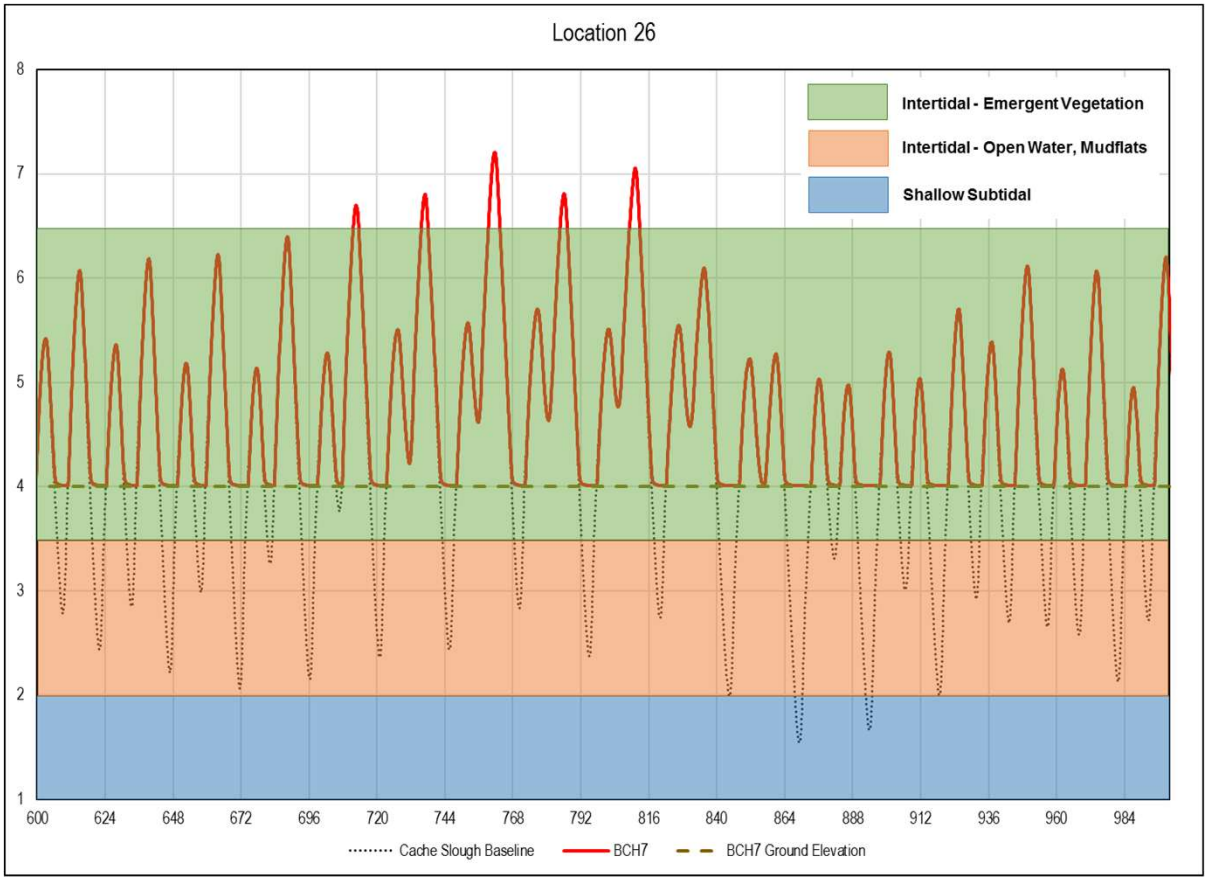
BUILDING RELATIONSHIPS ONE PROJECT AT A TIME

Figure B25

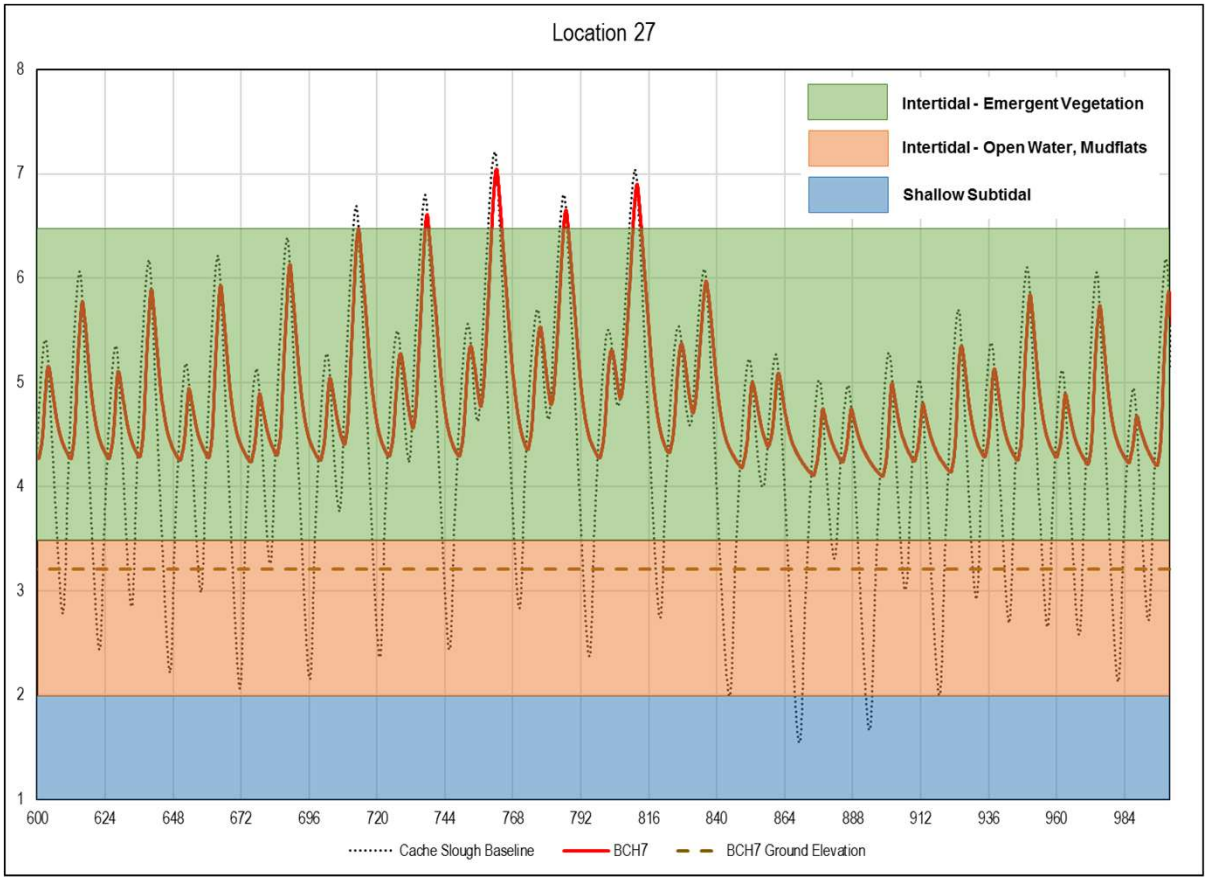

Location

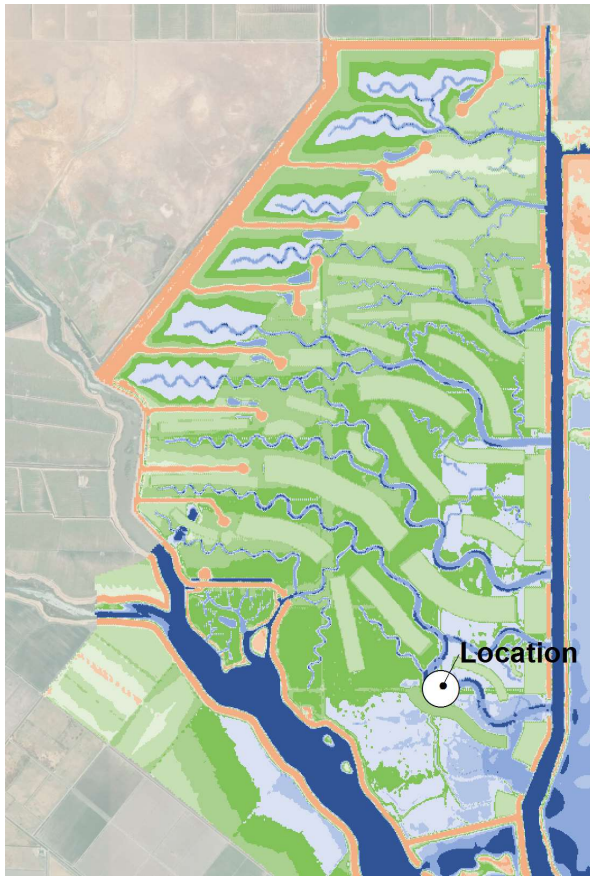

Location 25
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation


Location


Location 26
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation


Location


Location 27
Intertidal - Emergent Vegetation
Intertidal - Open Water, Mudflats
Shallow Subtidal
8
7
6
5
4
3
2
1
600
624
648
672
696
720
744
768
792
816
840
864
888
912
936
960
984
Cache Slough Baseline
BCH7
BCH7 Ground Elevation



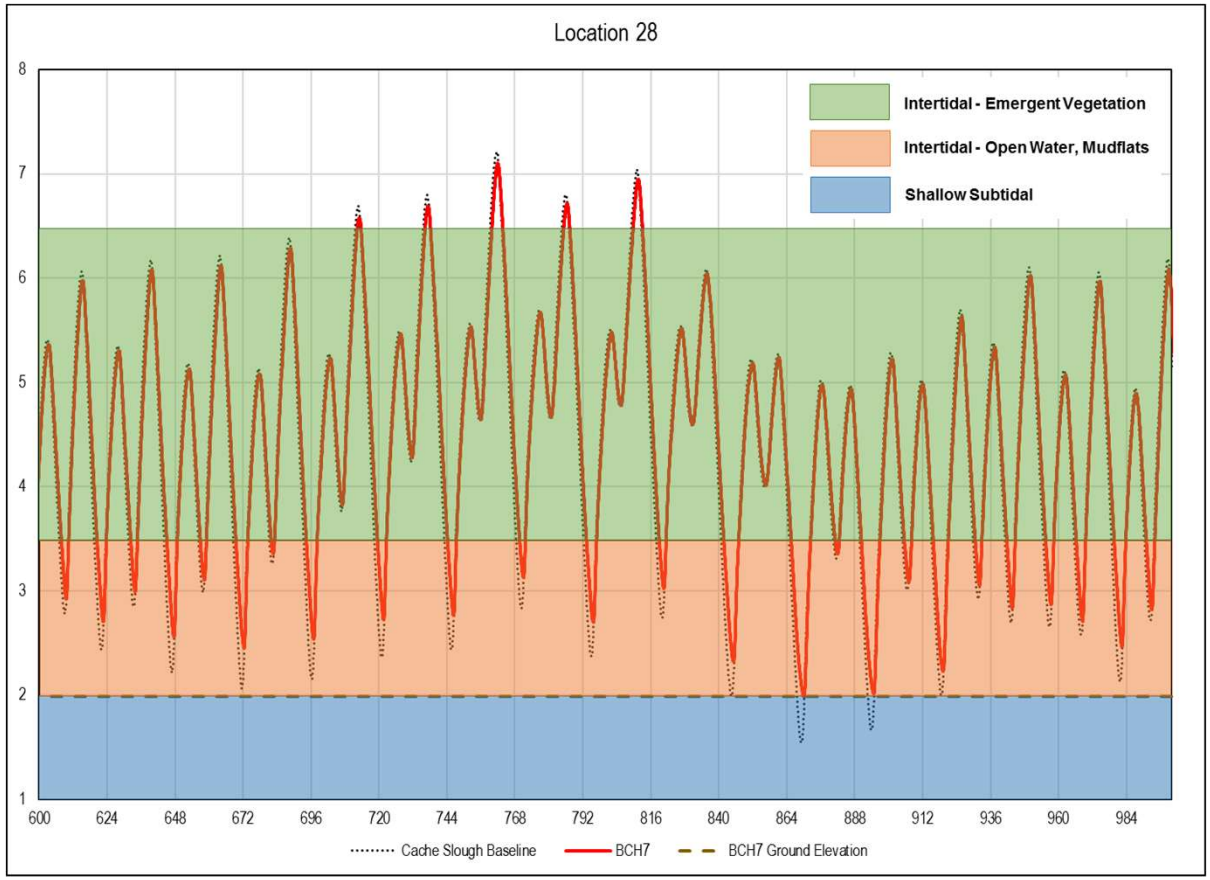


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Figure B29