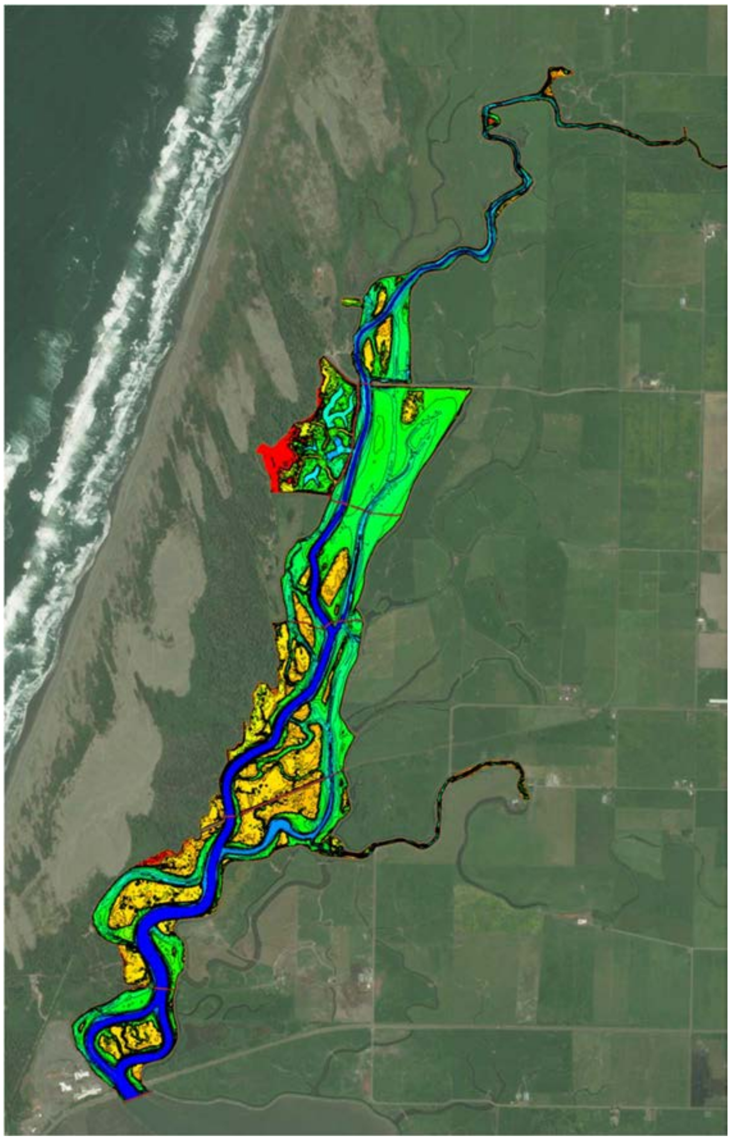
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT
HYDRODYNAMIC AND SEDIMENT TRANSPORT ANALYSIS



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EXECUTIVE SUMMARY

The Wadulh Lagoon Tidal Wetland Enhancement Project (Project) is located on the west side of Mad River Slough, just south of the Lanphere Road Bridge. The Project is located within the Wadulh Unit of the Humboldt Bay National Wildlife Refuge (Refuge). The Wadulh Lagoon Project Area consists of former tide lands that were converted to agricultural pastureland in the 1930's by construction of a dike on Mad River Slough. The Project will restore tidal hydrology to the diked agricultural pasture. The project will create a combination of estuarine and palustrine wetland habitats, including salt marsh, brackish marsh, mudflat, subtidal/intertidal eelgrass habitat, while enhancing and protecting existing forested wetlands.

The Project is being developed by the U.S. Fish and Wildlife Service (USFWS) Coastal Program and the Refuge. The Project will be implemented using a National Coastal Wetland Conservation Grant and funding from the California State Coastal Conservancy.

This report documents development and testing of two-dimensional hydrodynamic and sediment transport modeling prepared to evaluate effects of the Project on tidal stages, flow velocities, and sedimentation within Mad River Slough.

USFWS developed a hydrodynamic and sediment transport model of Mad River Slough from the head of the slough downstream to the mouth of the slough at the Samoa Boulevard Bridge. The model was developed using the TUFLOW-FV hydrodynamic model and the associated Sediment Transport Module. Topographic surface models were developed using the 1986-2019 USGS CoNED Topobathy DEM. USFWS set initial model parameter values for hydrodynamics and sediment transport using standard values supplemented by locally available field measurements. USFWS calibrated and validated the model using available observations of water levels and suspended sediment concentration.

USFWS performed a paired set of six-week duration simulations for Existing Conditions and Proposed Conditions. The Proposed Conditions model simulated a levee breach after two weeks and included proposed Project grading. Model results were analyzed for changes in water levels, changes in suspended sediment concentration, cumulative sediment flux, and discharge.

Model findings are that there are negligible changes to tidal stages, there are minor reductions in suspended sediment concentrations, and there are minor changes in erosion and deposition. Erosion increases in the main navigation channel indicating no risk to existing boat navigation. Changes in erosion and deposition are on order of millimeters and unlikely to be discernible. The Wadulh Lagoon Project Area will trap sediment and performed as designed.

INTRODUCTION

PROJECT PURPOSE

The Wadulh Lagoon Tidal Wetland Enhancement Project (Project) is located on the west side of Mad River Slough, just south of the Lanphere Road Bridge, west of Arcata, CA (Figure 1). The Project is located within the Wadulh Unit of the Humboldt Bay National Wildlife Refuge (Refuge). The Wadulh Lagoon Project Area consists of former tide lands that were converted to agricultural pastureland in the 1930's by construction of a dike on Mad River Slough. The Project will restore tidal hydrology to the diked agricultural pasture. The project will create a combination of estuarine and palustrine wetland habitats, including salt marsh, brackish marsh, mudflat, subtidal/intertidal eelgrass habitat, while enhancing and protecting existing forested wetlands. Proposed restoration actions include:

- breaching and lowering of the Mad River Slough Levee;
- excavating low-elevation pasture areas that are less than 3.0 feet in elevation[1] to elevations that will support eelgrass (Zostera marina);
- using excavated fill to raise selected areas to elevations that will sustain salt marsh colonization;
- construction of two set-back levees to maintain existing flood protection for adjacent landowners from twice-daily tidal flooding; and
- removal of invasive plant species.

The Project is being developed by the U.S. Fish and Wildlife Service (USFWS) Coastal Program and the Refuge. The Project will be implemented using a National Coastal Wetland Conservation Grant and funding from the California State Coastal Conservancy.

The purpose of this report is to document hydrodynamic and sediment transport modeling and analyses prepared to evaluate effects of the Project on tidal stages, flow velocities, and sedimentation within Mad River Slough.

PROJECT BACKGROUND

Project Location

The Wadulh Lagoon Project Area is located within a 76-acre parcel (Caltrans Parcel) purchased by the California Department of Transportation (Caltrans) in 2010. Caltrans intended to use the parcel to develop a wetland mitigation project. Caltrans eventually determined that the wetland mitigation project would not provide the required mitigation and terminated development of their project. Subsequentially, Caltrans donated the parcel to the Refuge, a process that was completed in early 2023.

[1] All elevations in this report are referenced to the NAVD 1988 datum.

Predevelopment Conditions

The Wadulh Lagoon Project Area was mapped in 1870 by the U.S. Coast Survey (Figure 2). The overlay of the Project boundary on the 1870 map indicates that the eastern portion of the Wadulh Lagoon Project Area was originally intertidal mud flat or sub-tidal (clear area on map) prior to diking and draining. The current bathymetry of Mad River Slough suggests that most of the area was mudflat. The 1870 map indicates that there was a band of salt marsh vegetation adjacent to the forested wetlands. The boundary between salt marsh and the forested wetlands is similar to the location of the current eastern edge of the forested wetlands.

Existing Conditions

Present day land cover in the Wadulh Lagoon Project Area consists of an abandoned agricultural pasture bordered by a strip of forested wetlands transitioning into coastal dunes (Figure 3). Groundwater seeps from the dunes maintaining freshwater wetland conditions within the forested area. The western end of Lanphere Road forms the north border of the Wadulh Lagoon Project Area. The Refuge Access Road runs along the west side of the Wadulh Lagoon Project Area. A cross levee runs along the south side of the Wadulh Lagoon Project Area and separates the Refuge lands from a privately owned parcel. Grazing of the pasture was abandoned by Caltrans when they purchased the property in 2010. Fencing and other infrastructure were not maintained and have fallen into disrepair.

Caltrans contracted with AECOM, Inc. and ICF International (ICF) to conduct environmental and engineering studies of the Caltrans parcel. ICF (2018a) assessed vegetation patterns within the Wadulh Lagoon Project Area. Vegetation in the former pasture areas consists of mixture of native and non-native grasses. Areas adjacent to the borrow ditch at the levee consist of brackish adapted species because of saltwater leakage through the tide gate and groundwater infiltration. The western edge of the Wadulh Lagoon Project Area consists of herbaceous plants transitioning to woodland vegetation. There are patches of invasive and non-native species that include manna grass, Reed canary grass, and Himalayan blackberry. USFWS characterizes the strip of woodland and herbaceous plants as having high conservation value because it supports neotropical migrant birds. The abandoned pasture has low conservation value.

The former pastureland has subsided several feet in elevation due to grazing compaction and decay of organic soil components. Much of the pasture area is below an elevation (6.0 feet) that will support salt marsh vegetation under an unrestricted tidal regime.

Levee Condition

The Mad River Slough Levee bordering the east side of the Wadulh Lagoon Project Area was constructed in the 1930's (AECOM, 2015a). The levee extends upstream and downstream of the Refuge property. The levee prevents tidal flooding of adjacent properties as well as the Refuge property.

AECOM, Inc. evaluated the condition and stability of the Refuge's portion of the Mad River Slough Levee (AECOM, 2015a). They determined that the levee has undergone long-term progressive erosion on the east (slough) side. Erosion has caused block failures, slumping, and over steepening of the levee face, and significant loss of the original levee cross section. AECOM judged that there had been sufficient loss of the levee to create a "relatively high extant risk of breaching or overtopping in the near future." Overtopping occurs frequently during spring tides. Overtopping is eroding the surface of the levee. The hydraulic infrastructure is in poor condition. The tide gated culvert passing through the levee collapsed and caused a levee breach in 2019. The levee was repaired, but the Refuge's expectation is that the levee will eventually breach catastrophically if no remedial actions are taken.

Alternatives Analysis

USFWS is concerned about the potential failure of the Mad River Slough Levee. Uncontrolled breaching of the levee would flood adjacent properties, hinder access to the Refuge's Lanphere Unit, and negatively impact the valuable woodland and herbaceous plants located along the western edge of the Wadulh Lagoon Project Area.

USFWS prepared an alternatives analysis to guide the planning of management actions for the parcel (USFWS 2023a). USFWS evaluated five action alternatives for the site which included taking no action, attempting to maintain existing conditions through levee repair, creating a muted tidal regime, and two alternatives restoring full tidal exchange.

USFWS judged that the no action was not a feasible alternative because the levee is likely to fail causing flooding of adjacent properties and disrupting Refuge access. USFWS did not consider maintaining the status quo as an acceptable alternative because of the cost associated with rehabilitation of the Mad River Slough levee, lack of long-term viability due to sea level rise, and because the abandoned pasture area has little conservation value under existing conditions. Implementing a muted tidal regime did not appear viable because of the cost required to rehabilitate the Mad River Slough Levee and would produce only small gains in desirable habitat for avian and aquatic species. USFWS selected the alternative of restoring full tidal with a natural shoreline as it will provide the maximum habitat gains, will provide protection for the freshwater wetlands along the west edge of the Wadulh Lagoon Project Area, will restore historic tidal conditions, and will provide resilience to sea level rise.

Project Goals

USFWS identified the following Habitat Improvement Goals for the Project:

- Restore full tidal hydrology to the Project area and re-establish ecological connectivity between Mad River Slough and the forested wetlands at the base of the Lanphere Dunes.
- Improve habitat conditions for resident and migratory neotropical birds and shorebirds.
- Improve habitat for aquatic species.
- Promote conversion of low-lying areas to salt marsh and minimize conversion to intertidal mudflat.
- Encourage suitable hydrologic conditions to support eelgrass.
- Protect loss of forested wetlands from saltwater impacts.
- Promote long-term sustainability of fringing salt marsh.
- Maintain existing flood protection for adjacent properties.
- Prevent nuisance flooding of the Refuge Access Road.

USFWS prepared a Basis of Design report (USFWS 2023a)and developed 30% design plans (USFWS 2023a) for the selected alternative.

Public Comment and Response

USFWS conducted both a formal and informal notification process to advise the public about the proposed project. The formal process consisted of a published public notification with a 30-day period to submit comments. The informal process consisted of meetings with adjacent landowners and tenants (two oyster growing companies) to inform them about the proposed project and to respond to questions. Six set of comments were received during the formal notification process, including several from the adjacent landowner and tenants.

The comments included both those supporting Project implementation and those with concerns about the Project. Concerns fell into several categories: (1) concerns about increase in public access; (2) concerns about the condition of Lanphere Road; (3) concerns about specific project elements; (4) concerns about potential changes to Mad River Slough tidal stages, water quality, and sedimentation patterns; and (5) concerns about changes in depth for the navigation channel in Mad River Slough that runs from north of Lanphere Road down to Samoa Boulevard.

USFWS modified the 30% plans to address several of the comments regarding public access and location of several project features. The Lanphere Road levee was set back from the edge of Lanphere Road to limit public access to the Wadulh Lagoon Project Area and to relocate a proposed drainage culvert to Refuge property. The limit of Mad River Slough Levee lowering was moved south 200 feet from the Lanphere Road Bridge to prevent changes in erosion potential at the Lanphere Road bridge. USFWS is unable to address the condition of Lanphere Road as the road is owned and maintained by Humboldt County.

The purpose of this report is to investigate concerns about changes to tidal stages, water quality, and sedimentation patterns resulting from the project implementation. The report documents development and calibration of a two-dimensional hydraulic and sediment transport model for Mad River Slough and application of the model to evaluate changes in tidal stages, sedimentation patterns, and depth of the navigation channel after project implementation.

MODEL DEVELOPMENT

MODEL REQUIREMENTS

The purpose of the hydrodynamic and sediment transport modeling is to evaluate changes in water levels, flow velocities, pattern and timing of flow, and patterns of sediment transport, erosion, and deposition. This requires a model capable of efficiently performing long-term dynamic (time-varying) hydrodynamic and sediment transport computations and simulating bed erosion and deposition. USFWS selected TUFLOW-FV to perform the analysis. TUFLOW-FV is a sophisticated model with many capabilities for evaluating hydrodynamics, water quality and sediment transport in coastal and riverine settings. (TUFLOW, 2020). Model features important to this analysis include:

- TUFLOW-FV, is a numerical hydrodynamic model for solving the one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) Non-Linear Shallow Water Equations (NLSWE). The model is suitable for solving a wide range of hydrodynamic systems ranging in scale from the open channels and floodplains, through estuaries to coasts and oceans.

- The Finite Volume (FV) numerical scheme employed by TUFLOW FV solves the NLSWE on unstructured meshes comprised of triangular and quadrilateral elements. The flexible mesh allows for seamless boundary fitting along complex coastlines or open channels as well as accurately and efficiently representing complex bathymetries with a minimum number of computational elements. The flexible mesh capability is particularly efficient at resolving a range of scales in a single model.

- The TUFLOW Sediment Transport Module (STM) is designed to work in conjunction with TUFLOW-FV to model sediment transport processes. STM is versatile and contains both cohesive and non-cohesive sediment transport routines which handle both bed and suspended load mechanisms. STM can perform dynamic morphology updating to reflect changes upon the underlying topography due to sediment deposition and erosion.

- TUFLOW-FV program runs are very stable and computation speeds are rapid.

TUFLOW-FV's sediment transport functions require the use of SI units. Model results in this report are given in SI units of meters (m) for lengths and elevations, cubic meter per second (m^3/sec) for discharge, kilograms (kg) for mass, Pascals (Pa) for force, milligrams per liter (mg/l) for sediment concentration, etc.

TUFLOW-FV HYDRODYNAMIC MODEL DEVELOPMENT

Work Tasks

USFWS developed the hydrodynamic model of Mad River Slough first. Development of the sediment transport model was conducted after completing development and testing of the hydrodynamic portions of the model. Development of the TUFLOW-FV hydrodynamic model for Mad River Slough involved the following tasks:

- Cataloging and assessment of available monitoring data for developing modeling scenarios, boundary conditions, and model calibration;

- Determining model extent (solution domain);

- Development of topographic surface models representing Existing and Proposed Conditions;

- Development of the finite element meshes for Existing and Proposed conditions;

- Development of hydrodynamic model boundary conditions;

- Initial assignment of hydrodynamic roughness parameters;

- Preparation of TUFLOW-FV input files; and

- Model calibration and validation.

Water Level Monitoring Data

There are several water level monitoring data sets available for Mad River Slough.

NOAA

NOAA maintains a control water level gage on Humboldt Bay's North Spit (Station ID: 9418767). Gage records are available at 6-minute intervals. NOAA established a tertiary water level station on Mad River Slough at the Samoa Boulevard bridge (Station ID: 9418865) (Figure 4). The gage operated from 12/1/1978 to 3/31/1979.

NOAA calculated time and stage offsets for the Mad River Slough gage based on comparison of water levels at the North Spit and Mad River Slough gages using standard NOAA techniques (NOAA, 2003). High and low water stages at the Mad River Slough gage occur 43 and 35 minutes later than the high and low water stages at the North Spit gage. High water stages above Mean High Water (MHW) are 12% higher at the Mad River Slough gage than high water stages at North Spit. Low water stages below Mean Low Water (MLW) are 7% lower than low water stages below MLW at North Spit.

AECOM

AECOM conducted field investigations to establish tidal datums at the Lanphere Road Bridge over Mad River Slough (AECOM, 2015a). AECOM deployed a water level recording gage (Figure 4) for 76 days in spring 2015. Water levels were recorded at 10-minute intervals. The sensor elevation was below the elevation of the lowest tides observed (-2.39 feet).

USGS

The Unites State Geological Survey (USGS) maintained a water level recording gage in Mad River Slough about 2,500 feet north of the Samoa Boulevard Bridge (Curtis et al. 2022). The gage was operated from March 16, 2016 to September 10, 2019. Water levels were recorded at six-minute intervals. The gage was located in a shallow area that was exposed at low tides. The sensor elevation was 0.79 feet. Low water levels below 0.79 feet were not recorded.

Tidal Datums

Mad River Slough tidal datums are listed in Table 1. The tidal range is amplified (i.e., the tidal range increases) moving north from the Samoa Boulevard Bridge to the Lanphere Road Bridge. This is consistent with observations by Northern Hydrology and Engineering (2009). Humboldt Bay tides typically show some amplification and phase lag with distance from the Humboldt Bay entrance (Costa and Glatzel, 2002). Friedrichs and Aubrey (1988) demonstrated that tidal range increases as distance from estuary mouth increases and as flow depth decreases.

TABLE 1
MAD RIVER SLOUGH TIDAL DATUMS

LOCATION	SAMOA BOULEVARD (NOAA 9418767)	MARSH ISLAND (USGS)	LANPHERE ROAD BRIDGE (AECOM 2015a)
PERIOD OF RECORD	9/14/1977 – 2/13/1980	3/16/2016 – 9/10/2019	3/17/2015 – 6/1/2015

TIDAL DATUM ELEVATION (FEET – NAVD 1988)			
MAXIMUM OBSERVED WATER LEVEL	N/A	9.45	8.63
MEAN HIGHER HIGH WATER (MHHW)	6.63	6.91	7.05
MEAN HIGH WATER (MHW)	5.90	6.43	6.33
MEAN TIDE LEVEL (MTL)	3.13	N/A	3.21
MEAN LOW WATER (MLW)	0.34	N/A	0.10
MEAN LOWER LOW WATER (MLLW)	-1.00	N/A	-1.15

Solution Domain

The purpose of USFWS hydrodynamic modeling is to evaluate effects of the Wadulh Lagoon Restoration Project on flows and sediment movement within Mad River Slough. The limits of Mad River Slough are well defined. Levees were constructed along most of Mad River Slough including the entire eastern bank, the western bank from a point approximately 0.8 miles downstream of the Lanphere Road Bridge, and the former sawmill at the mouth of Mad River Slough. Portions of the western bank may have been modified to support a now abandoned railroad. There is fringing tidal marsh along the western bank of Mad River Slough where levees are not present. There are several tidal marsh islands within the slough. Except for the lower end of Liscom Slough, all tributary channels are equipped with one-way tide gates and are physically separated from Mad River Slough.

USFWS set the limits of the hydrodynamic model (solution domain) of the Existing Conditions Mad River Slough hydrodynamic model to include Mad River Slough from the head downstream to just below the Samoa Boulevard Bridge (Figure 5). The model extends to the top of the levees where present or to elevation 11.0 feet where there is natural shoreline on the west bank. The model includes the lower portion of Liscom Slough extending from the tide gate located east of Jackson Ranch Road to Mad River Slough.

Boundary conditions for the model consists of estimated water surface elevations and suspended sediment concentrations at the Samoa Boulevard Bridge. The model does not simulate inflow of water or suspended sediment entering Mad River Slough from drainages ditches and channels located behind tide gates. Model application should be limited to dry season conditions when there is no inflow to the slough through tide gates from areas behind dikes.

The solution domain for the Proposed Conditions Mad River Slough model consists of the extent of the Existing Conditions model with the addition of the Wadulh Lagoon Project Area.

Topographic Surface Models

Existing Conditions Topographic Surface Model
Topographic surface models are used to map surface elevations at each node within the finite element network. The primary source of data used to prepare the topographic surface models is the USGS Coastal National Elevation Database). The 1986-2019 USGS CoNED Topobathy DEM (Compiled 2020): Northern California dataset (CoNED dataset) was prepared by USGS in 2020. The CoNED dataset consists of the best available multi-source topographic and bathymetric elevation data for the onshore and offshore areas in Northern California. It includes LIDAR data collected between 2009 and 2019 by various government agencies, and bathymetric sounding data collected between 1986 and 2019. The CoNED dataset was downloaded from the NOAA Digital Coastal Data Access Viewer in the form of a digital elevation model (DEM) with 1m x 1m cell size.

Bathymetry for upper Mad River Slough has not been surveyed. The CoNED data for Mad River Slough from the mouth up to the second large island above the Samoa River Bridge is based on NOAA soundings and LIDAR data. Above the second large island, there is no data for bed elevations less than 1.3 feet. This was the water surface elevation when the LIDAR data was collected. Channel bed elevations below -1.3 feet have not been surveyed. USFWS developed an estimated DEM for the missing channel bathymetry below elevation -1.3 feet using methods similar to those employed by PWA 2014 to prepare a bay-wide bathymetric map of Humboldt Bay. USFWS prepared a channel thalweg profile assuming a linear change in maximum channel depth between soundings in lower Mad River Slough, soundings at the Lanphere Road Bridge, and the upper end of Mad River Slough. USFWS developed a Triangulated Irregular Network (TIN) for the missing channel below -1.3 feet using the thalweg profile and assuming a parabolic channel shape (typical of tidal channels) tying into the outer edges of the-1.3-foot contour. USFWS combined the TIN with the CoNED dataset to create the Existing Conditions Topographic Surface Model (Figure 6).

Proposed Conditions Topographic Surface Model
The topographic surface model for proposed conditions was developed by combining the existing conditions topographic surface model with the proposed 65% grading plan for the Wadulh Lagoon Restoration project (Figure 7).

Finite Element Network Development

TUFLOW FV employs unstructured finite elements meshes comprised of interconnected triangular and quadrilateral elements. Individual finite elements are defined by corner nodes that are assigned X-, Y-, and Z- coordinates and assigned hydrodynamic and sediment characteristic parameters. USFWS developed an Existing Conditions finite element network and a Proposed Condition finite element network using the Surface Water Modeling System (SMS) following recommended practices for constructing finite element networks (TUFLOW, 2020a). An unstructured mesh allows element sizes to vary. Larger elements are used in areas of low flow diversity. Smaller element sizes are employed in areas where rapid flow variations occur or in areas of specific interest. The average element size for the network was 36 square meters.

Tidal Boundary Condition

The finite element network for Mad River Slough has only one open boundary which is located at the Samoa Boulevard Bridge. Flow into and out of the model is controlled by the level of tides at the bridge. Water level monitoring data for this location is limited to observations made 9/14/1977 to 2/13/1980. USFWS employed a computational procedure to transform water level observations from the North Spit NOAA gage to the Samoa Boulevard Bridge location to provide boundary conditions for the more recent USGS and AECOM gaging records. USFWS obtained North Spit water level data for AECOM or USGS periods of observation. USFWS employed a computer program that identified high and low water events, and then computed Samoa Boulevard Bridge water levels by first adjusting the time of the observations using the NOAA gage offsets for the Samoa Boulevard Bridge. Because the time offsets differ between low and high tides, the time offsets were proportionally adjusted based on the length of time between tide extremes. Similarly, water level heights relative to mean tide level at the Samoa Boulevard Bridge were computed by proportionally adjusting the observed water levels relative to mean tide level at the North Spit Gage. Figure 8 shows an example set of observed North Spit water levels and the corresponding computed water levels at the Samoa Boulevard Bridge.

Bed Resistance

Bed resistance is the primary parameter used to calibrate the TUFLOW-FV hydrodynamic model. USFWS chose to represent bed resistance using Manning's 'n' roughness values. USFWS developed a set of land cover types for the Existing and Proposed Conditions models (Table 2). Manning's n values were assigned to each land cover type (Table 2). Initial Manning's n values were established using standard recommended values (U.S. Army Corps of Engineers, 2021) and professional experience with modeling tidal systems. Manning's n values were adjusted slightly during model calibration. USFWS developed a shape file representing land cover boundaries. The shape file was mapped to the finite element networks using SMS tools.

TABLE 2: LANDCOVER TYPES AND MANNING'S n VALUES

LAND COVER	MANNING'S n	MODEL
SLOUGH	0.035	EXISTING/PROPOSED
ISLAND	0.040	EXISTING/PROPOSED
BANK	0.050	EXISTING/PROPOSED
MARSH	0.045	EXISTING/PROPOSED
PIPELINE CROSSING	0.060	EXISTING/PROPOSED
TIDAL CREEK	0.037	EXISTING/PROPOSED
BRIDGE	0.060	EXISTING/PROPOSED
LEVEE	0.045	EXISTING/PROPOSED
TIDAL FLAT	0.037	EXISTING/PROPOSED

TRANSITION CHANNEL	0.035	EXISTING/PROPOSED
SILL	0.037	PROPOSED
LOWERED LEVEE	0.045	PROPOSED
LAGOON	0.037	PROPOSED
NEW LEVEE	0.045	PROPOSED
TIDAL RIDGE	0.035	PROPOSED

TUFLOW-FV Input File Development

TUFLOW-FV modeling simulations are run using a text input file that specifies hydrodynamic model parameters, simulation options, and model output options. The input files allow specification of parameters to simulate hydrodynamic processes including turbulence, diffusivity, friction, and momentum. USFWS selected standard values for most parameters based on professional judgement and recommended valued from TUFLOW-FV documentation.

The model simulations for Mad River Slough are run in a dynamic (i.e., time-varying) mode. An important simulation parameter is the time step. TUFLOW-FV uses an adaptive time step that is controlled by the Courant-Friedrich-Lewy criterion (CFL) to ensure model stability. The CFL number is a function of the cell size and shape, water depth, flow velocity and the model timestep. The maximum value of CFL for a stable time step must be less than 1.0. USFWS set the maximum value of CFL to 0.9 to ensure model stability.

HYDRODYNAMIC MODEL VERIFICATION

Procedure

After initial hydrodynamic model development, best practices call for model testing to ensure that the hydrodynamic model accurately predicts site specific hydrodynamic conditions. Verification of the Mad River Slough hydrodynamic and sediment transport model consisted of several steps. The hydrodynamic model was validated first through initial evaluation of model results, model calibration, and model validation. Then the sediment transport portions of the model were evaluated and tested.

Initial Model Evaluation

Initial model evaluations were made using a two-week tidal simulation. The purpose of the initial evaluation was to examine the finite element mesh for poor network construction. Model results were examined graphically using SMS by reviewing TUFLOW-FV output files to identify locations where poor finite element construction produced poor representation of bathymetry or flow. The finite element network was refined to correct all issues.

Model Calibration and Validation

Model calibration is a procedure to compare model results with observed conditions and to adjust model parameters to produce simulations which match observations. After a model is calibrated to one or more set of observations, model validation is performed by comparing simulation results to observations for a different period or for different stage conditions. Model validation is considered successful if the model accurately simulates conditions other than those used to calibrate the model.

Calibration Procedure and Results

USFWS calibrated the Existing Conditions hydrodynamic model by simulating a two-week period from 9/1/2016 to 9/15/ 2016. A two-week period was selected so that the simulation contained both spring tides (high tide range) and neap tides (low tide range). Model results were compared to water level observations at the USGS Mad River Slough gage. Initial model runs were reviewed. Model roughness values were adjusted slightly to produce a better match to observed conditions. The final calibrated Manning's n values are listed Table 2. Sensitivity analyses performed during the calibration indicated low model sensitivity to selected model roughness values. Figure 9 compares the model water level results with the water levels observed at the USGS Mad River Slough gage. Figure 10 is a plot of modeled values versus observed values. The points are tightly grouped around a perfect line of fit. The correlation coefficient between the modeled results and observed results is 0.99 indicating a very high positive correlation.

Validation Procedure and Results

The model was validated using a separate set of water level observations from the AECOM gaging at the Lanphere Road Bridge for the period 3/17/2015 to 3/31/2015. This is a good test of model performance because it is in a separate location from the calibration data set and at a different time of the year. The validation simulation uses the adjusted parameters developed from the calibration simulation. Figure 11 compares the model water level results with the water levels observed at the AECOM gage. Figure 12 is a plot of modeled values versus observed values. The correlation coefficient between the modeled results and observed results for the validation simulation is 0.98. The validation results demonstrates that the hydrodynamic model can successfully replicate physical processes of tidal flows in Mad River Slough.

SEDIMENT TRANSPORT MODELING

TUFLOW-FV SEDIMENT TRANSPORT MODULE

The TUFLOW-FV Sediment Transport Module (STM) uses input from the hydrodynamic model to evaluate erosion of sediment from the bed, transport as either bedload or suspended sediment, deposition, and sediment consolidation of sediment on the bed. Results of the STM are used to update the hydrodynamic model bed elevations on a user selected time step. Thus, the combined modules can simulate changes in bed composition, bed erosion and deposition.

Sediment characteristics may be assigned to individual sediment fractions represented by average grain diameters. Sediment fractions are assigned appropriate transport models for the fraction size on a fraction-by-fraction basis. Full details on the STM are provided in the TUFLOW STM User Manual (TUFLOW 2020b).

Development of the input data for STM requires knowledge of the model area's sediment properties and the mode of sediment transport within the model area. USFWS collected and reviewed available data sources for characterizing sediment properties. Pertinent findings are described below. The development of STM model inputs appropriate for sediment conditions found in Mad River Slough is discussed next, followed by a summary of model calibration results,

SEDIMENT DATA

Suspended Sediment Monitoring Data

AECOM

AECOM (2015a) evaluated the availability of sediment in Mad River Slough through use of previously collected turbidity data. AECOM obtained turbidity data from the Wiyot Tribe and the Central and Northern California Ocean Observing System (CeNCOOS). The Wiyot tribe data was collected at four locations including the mouth of Mad River Slough. The Wiyot Tribe date was collected as discrete samples on a two-week basis. The CeNCOOS data was collected continuously at three stations in Humboldt Bay.

AECOM made the following observations on sediment availability from their analysis of the sediment data:

- Total Suspended Solids (TSS) concentrations were extremely variable in space and time in Humboldt Bay
- TSS concentrations peaked in the winter months (December-February) and generally declined through spring, summer, and fall, reaching minimums in October-November
- Hookton Slough exhibited the highest TSS concentrations within Humboldt Bay. Mad River Slough at the Samoa Boulevard bridge exhibited the second highest TSS concentrations.
- Elevated TSS concentrations in Arcata Bay and South Bay likely corresponded to wind wave resuspension on mudflats and/or precipitation events in local watersheds.

USGS

USGS maintained a recording turbidity meter in Mad River Slough from March 5, 2016 to September 9, 2019 (Curtis et al. 2022). The gage was mounted on a barge (used for oyster storage) anchored in the main channel of Mad River Slough about 2500 feet north of the Samoa Boulevard Bridge (Figure 4). The meter recorded turbidity, salinity, and water temperature at 15-minute intervals.

USGS used turbidity measurements to develop estimates of suspended sediment concentrations (SSC[2]). USGS collected 131 discrete water samples at the turbidity gage throughout the duration of the monitoring periods. USGS performed SSC lab analyses to determine the level of suspended sediment in the samples. USGS developed a linear regression relation between observed turbidity and SSC (Curtis 2021). Although the Mad River Slough regression model is statistically significant ($p<0.0001$), the R^2

[2] Two laboratory analytical methods are used to measure the concentration of suspended solid material in flowing waters: (1) suspended-sediment concentration (SSC); and (2) total suspended solids (TSS). USGS employs the SSC test because it produces more accurate results overall than the TSS test particularly when sand content is greater than 25% (Gray et al. 2000).

value (0.408) is low, indicating variability in the relation between turbidity and SSC observations. The model's root mean squared error (RMSE) is 6.83 mg/l and mean squared percent error (MSPE) is 38.9%.

A portion of the variability in the USGS relation data may be due to turbidity measurement accuracy. Variability in turbidity measurements is caused by variation in particle size, color and shape, presence of fine organic material, incident light, and air bubbles (Lewis and Eads, 2009). Particle size variations can be caused by variations in flow energy at differing tidal stages and flow direction, and seasonal variations. Another contributor to the variation between turbidity and SCC measurements are that point measurements exhibit significant spatial and temporal variability in natural water bodies versus stream-wide averages (Jastram et al. 2010). Despite these variations, turbidity measurements remain the most widely adopted methods for estimating SCC levels in natural waters (Matos et al. 2024).

The Mad River Slough turbidity-SCC linear regression model met USGS standards for publication. USGS computed SSC values for the period of observation based on the regression model. Computed SSC values ranged between 6.7 and 58.3 mg/l, with an average of 16.9 mg/l. The SSC estimates provide a strong means for calibrating sediment transport relations in Mad River Slough.

Figure 13 shows a typical two-week period of SSC at the USGS gage. The interval-to-interval SCC estimates exhibit fluctuations. The fluctuations are partially caused by measurement error. The fluctuations also reflect the natural spatial and short-term variability in suspended sediment concentrations.

There is a general trend of rising SSC with flood tides and falling turbidity levels with ebb tides. This indicates that resuspended sediment from Arcata Bay is a larger source of suspended than upper Mad River Slough. There is also a general trend that SSC levels are elevated during spring tides and lower than average during neap tides.

Sediment Properties

<u>Humboldt Bay SEDFlume Study</u>
The Humboldt County Department of Public Works developed a concept plan for marsh restoration on the Humboldt Bay shoreline between Arcata, and Eureka, CA (GHD et al., 2022). As part of the study, three sediment cores were collected from bay mudflats. The cores were evaluated using SEDFlume analysis methodology (Integral Consulting, Inc., 2021). SEDFlume analyses evaluate the relationship between erosion rates and applied shear stress. The erosion relationships developed from SEDFlume testing provide the basis for setting the values of erosion model parameter used in the sediment transport modeling. SEDFlume analyses also evaluated sediment properties including median grain size, wet bulk density, dry bulk density, and critical shear stress and how the properties vary with depth. The sediment cores were dominated by fine silt particles.

<u>Brown (2019)</u>
In work associated with USGS investigations, Brown (2019) collected 12 sediment cores from marshes located at the mouth of Mad River Slough and from within Mad River Slough. Grain size analysis yielded an average of 10.6% sand, 73.7% silt, and 15.5% clay sized particles. From this distribution, USFWS estimated the median grain size for marsh sediment to be 38 μm based on the relationship developed by Yao et al. (2021).

SHN (2024)

SHN (2024) collected seven borings within the Wadulh Lagoon project footprint to aid final design. SHN lab tests evaluated geotechnical properties of the borings including wet and dry bulk density. Notably, the mean bulk density of soil in the Wadulh Lagoon Project Area was higher than the mean bulk density in the undisturbed marshes sampled by Brown (2019). USFWS interprets this as an indication of compaction from cattle when the Wadulh Lagoon Project Area was used for pastures.

Discussion

Slough channel and overbank sediment in the Mad River Slough is dominated by silt with small fractions of clay and sand. The primary mode of sediment transport for particles in this size range is as suspended sediment.

STM MODEL DEVELOPMENT

Introduction

TUFLOW-FV's Sediment Transport Module (STM) possesses a suite of routines for simulating sediment transport processes for multiple sediment classes. STM model development consists of selecting an appropriate set of models based on the characteristics of the modeled area's hydrodynamics, sediment supply, and sediment transport processes. STM contains several global models which simulate transport processes for all sediment fractions, and individual fraction models which may employ different transport functions and parameters for individual sediment fractions. STM simulations are run by developing a Sediment Control File that specifies the parameter values for global models and the transport functions and parameters for individual sediment fractions.

Global Models

The Mad River Slough model employs the following STM models (i.e., models that are applied across the entire network for all sediment fractions):

- Sediment Concentration Profile: USFWS used STM's default concentration profile model. The concentration profile is used to calculate the net vertical exchange fluxes between the bed and water column. Using the STM results, TUFLOW-FV computes an analytical concentration profile for each computational cell as a function of an assumed vertical diffusivity and calculated settling velocity.

- Bed Roughness Model (separate from the hydrodynamic model): The bed roughness model is used to represent the bed friction created by bed sediment. USFWS used the STM Nikuradse roughness height model.

- Bed Shear Model: The bed shear model evaluates the amount of erosive force applied to the bed as a function of water depth and velocity. The default STM shear model was used which is based on the formulation by Soulsby (1997).

- Bed Slumping Model: Material deposited on the bed may move after deposition due to gravity forces. The slumping model is used to represent this process. The STM Simple model was used which is based on the angle of repose.

Refer to the TUFLOW STM User Manual (TUFLOW 2020b) for more details on individual models.

Sediment Fractions

USFWS developed a set of five sediment fractions to represent sediment properties in the Mad River Slough model (Table 3). The fractions are based on the distribution of sediment grain sizes identified by sediment sampling and how they are modified by land cover properties.

TABLE 3: MAD RIVER SLOUGH SEDIMENT FRACTIONS ,PROPERTIES, AND MODELS					
SEDIMENT FRACTION NAME	CHARACTERISTICS	D_{50} - MEDIAN GRAIN DIAMETER (mm)	SETTLING MODEL	DEPOSITION MODEL	DEPOSITION PARAMETER
WASH_LOAD	SUSPENDED SEDIMENT WITH LONG DURATION SETTLING TIME	0.002	VAN RIJN (1984)	KRONE	0.03
BAY	BAY MUD BED MATERIAL FOUND IN SLOUGH CHANNELS AND MUD-FLATS	0.014	VAN RIJN (1984)	KRONE	0.10
MARSH	EXISTING VEGETATED MARSHES	0.038	VAN RIJN (1984)	KRONE	0.10
PASTURE	UNDISTURBED PASTURE AREAS WITHIN WADULH LAGOON PROJECT AREA	0.038	VAN RIJN (1984)	KRONE	0.10
DISTURBED	DISTURBED AREAS OF LOOSE SURFACE SEDIMENT FOLLOWING WADULH LAGOON CONSTRUCTION	0.038	VAN RIJN (1984)	KRONE	0.10

There are several sediment transport process models applied to individual sediment fractions:

- Settling Model: The settling model specifies the rate of vertical settling for suspended sediment fractions. The Van Rijn (1984) relation is used for all sediment fractions. In this modeling, settling velocity is based on grain size, grain density, and the kinematic viscosity of water.

- Deposition Model: The deposition model represents transfer of suspended sediment to the bed. The Krone model is used for all sediment fractions. In the Krone model, no deposition occurs if bed shear stress is greater than a user supplied critical shear stress value. When bed shear stress is less than the critical shear stress, deposition is reduced based on a calculated deposition factor which varies from 0 to 1 depending on the ratio bed shear stress to critical shear stress.

- Bed Erosion Model: The bed erosion model computes the amount of sediment transferred from the bed to suspended sediment as a function of the applied shear stress. The Mehta model was used for all sediment fractions. The form of the model is:

$$F_e = E_r \left(\frac{\tau_b}{\tau_{ce}} - 1\right)^{\alpha} \quad (1)$$

where:

F_e is the erosion flux from the bed;

E_r is the erosion rate constant (g/m^2s);

τ_b is the shear stress;

τ_{ce} is the critical shear stress for erosion to occur; and

α is an exponent.

The values for the input parameters should be calibrated based on experimental data and field observations. The values for modeling Mad River Slough were first estimated using the erosion relationships developed by Integral Consulting (2021) from the SEDFlume test results. The initial estimates were modified to best fit values based on STM model calibration. Calibrated erosion parameter values are listed in Table 4.

The erosion rate for the Disturbed soil fraction was set to twice the values for the Marsh soil fraction to simulate high erodibility for graded areas within the Wadulh Lagoon Project Area immediately following construction.

- Particle Dry Density: The particle dry density is the mass of material found per unit volume in the soil. Particle dry density values for the Bay and Wash_Load sediment fractions are based on the bay core samples collected by Integral Consulting, Inc. (2021). The particle dry density value for the Marsh sediment fractions is based on cores collected by Brown (2019). The particle dry density values for Pasture and Disturbed sediment fractions are based on the sediment core samples collected by SHN (2024). Particle dry density values are also listed in Table 4.

TABLE 4: MAD RIVER SLOUGH SEDIMENT FRACTION EROSION PARAMETERS

SEDIMENT FRACTION NAME	Er - EROSION RATE (g/m^2s)	τ_{ce} -CRITICAL SHEAR STRESS (Pa)	α - EXPONENT	DRY PARTICLE DENSITY (kg/m^3)
WASH_LOAD	0.00025	0.025	1.0	520

BAY	0.001	0.040	1.2	523
MARSH	0.003	0.042	1.2	840
PASTURE	0.002	0.042	1.2	1009
DISTURBED	0.006	0.042	1.2	600

Sediment Mix

The final STM model development task is to assign sediment fraction mixes to the model landcover types. The sediment mix represent the mass and sediment properties of the ground covered by the finite element network. STM operates by evaluating the amount and types of sediment transferred to the bed by deposition and the amount and types of sediment eroded from the bed based on the applied shear stress. Bed composition and elevation is updated so the processes of scour, deposition, and bed armoring are simulated.

Sediment mixes for each landcover type are based on the sediment cores collected from the bay floor (integral Consulting, Inc, 2021), existing marshes (Brown, 2019), and the Wadulh Lagoon Project Area (SHN, 2024). Multiple sediment layers are used where sediment cores possessed changing properties with depth (typically an increase in erosion resistance and bulk density). USFWS developed an initial set of sediment mixes. The mixes were adjusted during calibration to produce a better simulation of observed suspended sediment. The final set of calibrated mixes is listed in Table 5.

TABLE 5: SEDIMENT MIXES							
LAND COVER	MODEL	THICKNESS (m)	SEDIMENT MIX (%)				
			WASHLOAD	BAY	MARSH	PASTURE	DISTURBED
SLOUGH LAYER 1	EXISTING & PROPOSED	0.05	1.8	98.2			
SLOUGH LAYER 2	EXISTING & PROPOSED	3.00		100.0			
ISLAND	EXISTING & PROPOSED	3.00			100.0		
BANK	EXISTING & PROPOSED	5.00		100.0			
MARSH	EXISTING & PROPOSED	3.00			100.0		
PIPELINE CROSSING	EXISTING & PROPOSED	3.00		100.0			

TIDAL CREEK LAYER 1	EXISTING & PROPOSED	0.05	20.0	80.0			
TIDAL CREEK LAYER 2	EXISTING & PROPOSED	3.00		100.0			
BRIDGE	EXISTING & PROPOSED	3.00		100.0			
LEVEE	EXISTING & PROPOSED	3.00		100.0			
TIDAL FLAT	EXISTING & PROPOSED	0.05	20.0	80.0			
TRANSITION CHANNEL LAYER 1	EXISTING & PROPOSED	3.00		100.0			
TRANSITION CHANNEL LAYER 1	EXISTING & PROPOSED	0.05	5.0	95.0			
SILL	PROPOSED	3.00		100.0			
LOWERED LEVEE	PROPOSED	1.00				100.0	
LAGOON LAYER 1	PROPOSED	0.15		50.0			50.0
LAGOON LAYER 2	PROPOSED	3.00		100.0			
NEW LEVEE	PROPOSED	0.15				50.0	50.0
TIDAL RIDGE	PROPOSED	1.00				100.0	

STM MODEL TESTING

STM Model Calibration

The STM model was calibrated by simulating sediment transport with the Existing Conditions Model for the four-week period 9/1/2016 to 9/29/2016. A four-week period was selected to allow for a two-week warm-up period from initial conditions. Model results were compared to the total suspended sediment (SSC) estimates at the USGS Mad River Slough gage. STM model parameters were adjusted to produce a better fit to the SSC magnitude and to the pattern of changes in SSC in response to flood and ebb tides cycles; and to neap and spring tide cycles. Modeled SSC levels were most sensitive to the parameter values for the Bed Erosion model and the amount of Wash_Load sediment included in the sediment mixes for Slough Channel, Transition Channel, and Tidal Creek land cover types. Flow velocities are generally too low to generate sufficient shear stress to erode the bed from other areas.

Figure 14 compares the modeled SSC with the observed SSC at the USGS Mad River Slough gage. The model results replicate the decreases in SSC levels with neap tides and increases with spring tides. Physically, this pattern reflects that spring tides have higher velocities and greater shear stress, resulting in higher rates of bed erosion. Figure 15 is a plot of modeled values versus observed values. The points are grouped around a perfect line of fit. The correlation coefficient between the modeled results and observed results is 0.74 indicating a high positive correlation. The average percent error between modeled and observed SSC level is 0.2%. The standard deviation is 4.1%. The root mean square error (RSME) between mean and observed values is 0.41 mg/l. Recall that RSME for USGS measurements is 6.83 mg/l. Because the error in modeled values is less than potential measurement error, USFWS judged that the calibration results were acceptable for the STM model.

STM Validation Procedure and Results

The STM was validated using a separate set of SSC from the USGS gaging station. The time period for the validation simulation was for two-week from 8/12/2017 to 8/26/2016. The validation simulation uses the calibrated STM model parameters developed from the calibration simulation. Figure 16 compares the modeled SSC values with USGS SSC values. Figure 17 is a plot of modeled values versus observed values. The correlation coefficient between the modeled results and observed results for the validation simulation is 0.83 indicating a high positive correlation and which is better than the calibration results. The validation results demonstrates that the STM model can successfully replicate observed patterns of SSC at the USGS Mad River Slough gage.

Discussion

USFWS developed and tested a dynamic two-dimensional model of Mad River Slough that replicated observed water level stages and observed SSC at the USGS Mad River Slough gage. The model may be used to evaluate change in conditions resulting from construction of the Wadulh Lagoon Restoration Project. Model testing was conducted for periods in August and September when inflow of water and sediment from local drainage is minimal. The model is not intended for use during wet season periods.

WADULH LAGOON RESTORATION PROJECT EVALUATION

SIMULATION

USFWS developed the Mad River Slough TUFLOW-FV model to evaluate changes to tidal stages, water quality, and sedimentation patterns resulting from the implementation of the Wadulh Lagoon Restoration Project. To evaluate changes, both the Existing Conditions model and the Proposed Conditions model are run for the same simulation period and boundary conditions using the calibrated hydrodynamic and STM (Sediment Transport Module) parameters. Model results are compared to identify changes in flow, stage, and sediment erosion and deposition.

The simulation period for the evaluation is a six-week period extending from 9/1/2016 to 10/13/2016. The Existing Conditions model is run using the calibrated hydrodynamics and sediment transport parameters. Figure 18 depicts the tidal boundary condition at the Samoa Boulevard Bridge used for the mode simulation.

The Proposed Conditions model is run for the initial two-weeks with the Mad River Slough levee intact at the Wadulh Lagoon Project Area. No flow is allowed to enter the Wadulh Lagoon Project Area, essentially representing pre-construction conditions. After two weeks on 9/15/2016, the Mad River Slough levee is breached and removed allowing the model to simulate flow entering and flooding the Wadulh Lagoon Project Area. The simulation then continues for another four weeks simulating conditions that will occur when the Project is completed.

RESULTS

Introduction

TUFLOW-FV and STM model results are computed for each node in the finite element network. Results are written to data files at user-selected time intervals. USFWS selected to output results on a 12-minute time interval. The results may be mapped and reviewed visually using SMS. The amount of data is extensive, however, and difficult to convey in a written report. This report focuses on presenting analysis of tidal stage changes, changes in SSC levels, and change in flow at several key locations that address the specific study questions of how the Wadulh Lagoon Restoration Project might change tidal stages, water quality, and sedimentation patterns in Mad River Slough. Analysis locations are shown on Figure 19. Readers may contact the report author if there is interest in examining model results beyond the material presented here.

Lanphere Road Bridge

The Lanphere Road Bridge is located uptide from where the Wadulh Lagoon Project will connect to Mad River Slough. Landowners adjacent to the Project have expressed concerns that the Project might negatively impact water quality in this area.

- Water Levels: There are minor changes of less than 0.05m (0.16 feet) in water levels following the breach (Figure 20). Water levels are slightly higher at low tides and slightly lower at high tides.

- Discharge: Figure 21 shows the total flow rate passing the Lanphere Road Bridge under Existing and Proposed Conditions. Proposed Conditions will lower the peak flood and ebb discharge slightly. Proposed Conditions will also delay the occurrence of peak discharges by approximately 15 minutes.

- Suspended Sediment Concentration (SSC): Generally, changes in SSC levels are minor and on average the SCC levels are lower at Lanphere Road following the breach (Figure 22). The maximum increase is 0.5 mg/l. The maximum decrease is 1.6 mg/l.

- Cumulative Sediment Flux: Sediment flux is the mass of sediment moving across a cross section at a point of time. Cumulative sediment flux is a running total of the mass transfer of sediment. Figure 23 shows the cumulative sediment flux at the Lanphere Road Bridge. There is a net transfer of sediment moving uptide past the bridge under both Existing and Proposed Conditions. This reflects that sediment is transported into Mad River Slough from Arcata Bay where sediment is resuspended by wind and waves on mudflats. Sediment deposition occurs in the slack water areas north of the bridge. There are minor differences in the timing of sediment movement between Existing and Proposed Conditions, but overall, there are negligible differences in the total sediment movement.

Wadulh Lagoon Confluence

The Wadulh Lagoon Confluence analysis point is in the deepest part of the main channel opposite the point where the Wadulh Lagoon levee breach will occur.

- Water Levels: Water level changes at the Wadulh Lagoon Confluence are similar to the Lanphere Road Bridge. There are minor changes of less than 0.05m (0.16 feet) in water levels following the breach (Figure 24). There is a reverse in the pattern from Lanphere Road Bridge. Water levels are slightly higher at high tides and slightly lower at low tides.

- Suspended Sediment Concentration (SSC): On average, changes in SSC levels decrease about 0.5 mg/l. There are decreases in SSC up to 2.0 mg/l at mid-tides. (Figure 25).

Wadulh Entrance

The Wadulh Entrance Flux Line measured flow and sediment movement through the levee breach in the Wadulh Lagoon Project Area.

- Discharge: Figure 26a shows the total flow rate entering the Wadulh Lagoon Project Area under Proposed Conditions. Peak inflow rates are higher than peak outflow rates indicating that sediment transport into the lagoon will be higher in flood tides than on ebb tides.

- Cumulative Sediment Flux: Figure 26b shows the cumulative sediment flux into the Wadulh Lagoon Project Area. Sediment is deposited in the lagoon on each tidal cycle. Four weeks after the breach, approximately 10,000 kg of sediment are projected to deposit within the lagoon. Project plans include large lagoon areas that were specifically intended to create quiescent areas which would trap suspended sediment (USFWS 2023a).

Lower Wadulh

The Lower Wadulh analysis point is in the main channel opposite the southern boundary of the Wadulh Lagoon Restoration Project.

- Water Levels: There are minor changes of less than 0.05m (0.16 feet) in water levels following the breach (Figure 27). There is a reverse in the pattern of changes from the Lanphere Road Bridge. At this location, the lower water levels are slight lower (< 0.05m) at low tides and the higher water levels are slightly higher (<0.05m) at high tides.

- Discharge: Figure 28 shows the total flow rate passing the south boundary of the Wadulh Lagoon Project Area under Existing and Proposed Conditions. Under Proposed Conditions, there are increases in peak flood and ebb discharge. The increases reflect increases in tidal prism created by opening up the Wadulh Lagoon Project Area to full tides.

- Suspended Sediment Concentration (SSC): SSC levels decrease on average less than 1.0 mg/l. (Figure 29).

- Cumulative Sediment Flux: Figure 30 shows the cumulative sediment flux moving past the southern boundary of the Wadulh Lagoon Project Area. There is a net transfer of sediment moving uptide under both Existing and Proposed Conditions reflecting that Arcata Bay is supplying sediment to Mad River Slough. The cumulative amount of sediment flux (kg) increases under Proposed Conditions. After four weeks, the total increase is approximately 8000 kg, which is less than the 10,000 kg depositing in the Wadulh Lagoon Project Area. This indicates that the flow into the Wadulh Lagoon Project Area is entraining sediment from mudflats between the Lower Wadulh flux line and the Wadulh entrance.

Lower Lagoon

The Lower Lagoon analysis point is located in the main channel at the point where Mad River Slough changes from an unconfined channel flowing through extensive mudflats to a more-confined channel bounded by marsh islands and minor side channels.

- Water Levels: Changes in water level are less than 0.04m (0.13 feet) in water levels following the breach (Figure 31). At this location, the lower water levels are slight lower (< 0.04m) at low tides and the higher water levels are slightly higher (<0.4m) at high tides.

- Discharge: Figure 28 shows the total flow rate passing the south boundary of the Wadulh Lagoon Project Area under Existing and Proposed Conditions. Under Proposed Conditions, there are increases in peak flood and ebb discharge. The increases reflect increases in tidal prism created by opening up the Wadulh Lagoon Project Area to full tides.

- Suspended Sediment Concentration (SSC): There are increases and decreases in the SSC levels under Proposed Conditions, but changes average to zero (Figure 33).

- Cumulative Sediment Flux: Figure 34 shows the cumulative sediment flux moving past the Lower Lagoon Flux line. There is a net transfer of sediment moving uptide under both Existing and Proposed Conditions reflecting that Arcata Bay is supplying sediment to Mad River Slough. The cumulative amount of sediment flux (kg) increases under Proposed Conditions. There is less increase in total sediment flux (4000 kg) than at the Lower Lagoon flux line (8000 kg), indicating that additional sediment is being entrained between the two flux lines under Proposed Conditions.

Bed Elevation Change

The bed elevation changes in the vicinity of the Wadulh Lagoon Project area are shown in Figure 35 for Existing and Proposed Conditions. The bed elevation changes are the net erosion and deposition that occurred over the six-week model simulation period. The amounts of deposition and erosion are small - on the order of millimeters. Tidal flow velocities are low in Mad River Slough and do not generate sufficient shear to erode the Bay sediment fraction except for short periods of time in main channel areas. The fine material comprising the Wash_Load sediment fraction requires long settling time and is easily resuspended even by low flow velocities. Thus, the rates of erosion and deposition are low.

Model results indicate a minor amount of erosion in the main channel and that deposition occurs on the mudflats under both Existing and Proposed Conditions. Model results indicate that the constructed lagoons in the Wadulh Lagoon Project Area will experience deposition. This is consistent with cumulative sediment flux through the Wadulh Entrance Channel (Figure 26b). Model results indicate that Proposed Conditions will result in increased deposition or erosion in some areas (Figure 36), but that these changes are small. It would be difficult to measure changes of this size in the field. Erosion will increase in the main channel and in the mudflats in the south half of the large lagoon below Lanphere Road. Increased deposition will occur on the mudflats in the north half of the large lagoon and on some of the marsh islands.

Tidal Prism

Tidal prism is defined as the volume of water exchanged upstream of a point in an estuary during a tidal cycle. Over long periods of time, estuaries develop adjust their form in response to sediment supply and tidal prism to reach a dynamic equilibrium between erosional and depositional processes (Williams et al. 2002). Table 6 lists the mean diurnal tidal prisms calculated from the Existing and Proposed Conditions hydrodynamic model results at several points within Mad River Slough. There is an increase of approximately 80,000 m^3 in tidal prism in the slough channels downstream of the Wadulh Lagoon Project Area. The percent increase is 11.6% at the Lower Wadulh flux line and drops to 3.8 at Samoa Boulevard.

TABLE 6: MAD RIVER SLOUGH TIDAL PRISM

	TIDAL PRISM (1,000 m^3)				
	LOCATION				
	SAMOA BLVD.	RAIL BRIDGE	LOWER WADULH	LANPHERE ROAD	WADULH ENTRANCE
EXISTING CONDITION	2138	1372	691	334	0
PROPOSED CONDITIONS	2219	1452	771	335	114
CHANGE	81	80	80	1	0
% CHANGE	3.8%	5.8%	11.6%	0.3%	--

DISCUSSION

Model Findings

USFWS developed and tested a hydrodynamic and sediment transport model of Mad River Slough. The model was used to simulate a six-week period of tidal flows for Existing Conditions and for Proposed Conditions following breaching of the levee at the Wadulh Lagoon Project Area. The purpose of the modeling is to evaluate changes in water levels, flow velocities, pattern and timing of flow, and patterns of sediment transport, erosion, and deposition resulting from implementation of the Wadulh Lagoon Tidal Wetland Enhancement Project. Model results indicate the following:

- There were changes in the timing and elevation of high and low tides in the vicinity of the Wadulh Lagoon Project Area under Proposed Conditions. High and low tides occurred later under Proposed Conditions. Delays were less than 15 minutes. Changes in high and low tide elevations under Proposed Conditions range between increases of 0.05m and decreases of 0.05m.

- Under Proposed Conditions, the levels of suspended sediment concentration (SSC) decreased between 0.5 to 2.0 mg/l in Mad River Slough in the vicinity of the Wadulh Lagoon Project Area. The changes are small relative to Existing Conditions in the simulation period where SSC levels range between 10 and 30 mg/l.

- The Wadulh Lagoon Project Area will serve as a sediment sink for Mad River Slough. During the simulated four-week period following levee breaching, 10,000 kg of sediment were projected to settle within the Wadulh Lagoon Project Area.

- Modeling of sediment conditions within the Wadulh Lagoon Project Area under Proposed Conditions assumed a loose surface mixture of erodible soil following project construction. Shear forces within the Wadulh Lagoon Project Area were insufficient to entrain the loose soil into the water column.

- There are differences in erosion and deposition patterns between Existing and Proposed Conditions. The maximum difference in erosion and deposition over the four-week period following breaching was less than 0.4 mm. The largest increases in erosion under Proposed Conditions occurred in the main channel of Mad River Slough from upstream of Lanphere Road downstream to Samoa Boulevard. Erosion potential also increased for the mudflats in the southern half of the large lagoon below Lanphere Road.

Uncertainties

Modeling sediment transport processes in a tidal estuary is a complex undertaking. Uncertainties in model predictions can result from how sediment transport processes are modeled, uncertainties in parameter selection, uncertainties in field measurements of physical sediment properties, and uncertainties in observation data. USFWS acted to reduce uncertainties by use of a sophisticated sediment transport model developed for use in tidal estuarine environments. USFWS selected parameter values based on recommended model values and grounded by comparison to locally field measured values. USFWS calibrated and validated the hydrodynamic and sediment models successfully, but there was limited data available to calibrate the sediment transport models. Observed SSC values were limited to a single location within Mad River Slough. The reported SSC data has uncertainty due to spatial and temporal variability in SSC levels.

While there are uncertainties in the sediment transport models, there is confidence in the model findings because the calibrated models were used in a paired simulation of Existing and Proposed Conditions. Model findings are also consistent with the Project engineering analysis and design (USFWS 2023a) used to develop Project Design Plans (USFWS 2023b). The design intent was to construct the

Project to act as a sink for suspended sediment in Mad River Slough and to limit impacts to off-site areas. It was foreseen that the Project would increase tidal prism within Mad River Slough, but that the increased tidal prism would not create negative impacts to surrounding areas. The pattern of changes in sediment transport are also consistent with the increase in tidal prism and the results of the hydrodynamic simulations.

Conclusions

The purpose of the modeling was to evaluate potential changes to tidal stages, water quality, and erosion and deposition resulting from Project implementation. Model findings are that there are negligible changes to tidal stages, there are minor reductions in suspended sediment concentration, and there are minor changes in erosion and deposition. Erosion increases in the main navigation channel indicating no risk to existing boat navigation. Changes in erosion and deposition are on order of millimeters and unlikely to be discernible. The Wadulh Lagoon Project Area will trap sediment and performed as designed (USFWS 2023a).

REFERENCES

Anderson, J. K. 2018. Sea-Level Rise in the Humboldt Bay Region - Update 2, Local Reports and Publications. https://digitalcommons.humboldt.edu/hsuslri_local/5.

AECOM. 2015a. Mad River Slough (Lanphere Parcel) Restoration Project Concept Design Report (Draft). Prepared for Caltrans, November 2015.

AECOM., 2015b. Mad River Slough (Lanphere Parcel) Restoration Project Draft Site Evolution Appendix Prepared for Caltrans, November 2015.

AECOM. 2015c. Mad River Slough (Lanphere Parcel) Restoration Project DRAFT Topographic and Vegetation Survey and Hydrologic Monitoring Report.

BakerAECOM. 2013. Intermediate Data Submittal #2 – Offshore Water Levels and Waves for Central and Northern California. California Coastal Analysis and Mapping Project Open Pacific Coast Study. Prepared for the Federal Emergency Management Agency.

Borgeld, J. C., and A. W. Stevens. 2004. Humboldt Bay, California: Surface Sediments 2000–2001, Current Perspectives on the Physical and Biological Processes of Humboldt Bay, 51.

Brown, L.N. 2019. California Salt Marsh Accretion, Ecosystem Services, and Disturbance Responses in the Face of Climate Change, A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Geography, University of California Los Angeles, 238 p.

Costa, S. L. and K.A. Glatzel. 2002. Humboldt Bay, California, Entrance Channel, Report 1: Data Review. US Army Corps of Engineers. ERDC/CHL CR-02-1.

Curtis, J.A., C. Freeman, and K.M. Thorne. 2019. Early results – salt marsh response to changing fine-sediment supply conditions, Humboldt Bay, CA. In SEDHYD 2019. https://www.sedhyd.org/2019/openconf/modules/request.php?module=oc_program&action=view.php&id=80&file=1/80.pdf.

Curtis, J.A., L. E. Flint, M. A. Stern, J. Lewis, and R. D. Klein. 2021. Amplified Impact of Climate Change on Fine-Sediment Delivery to a Subsiding Coast, Humboldt Bay, California, Estuaries and Coasts, 44:2173–2193.

Curtis, J.A., 2021, Model archive summary for a suspended-sediment concentration surrogate regression model for station 405219124085601; Mad River Slough near Arcata, CA: U.S. Geological Survey data release, accessed June 1, 2021, at https://doi.org/ 10.5066/ P9TVX0Z8.

Curtis, J.A., Thorne, K.M., Freeman, C.M., Buffington, K.J., and Drexler, J.Z., 2022, A summary of water-quality and salt marsh monitoring, Humboldt Bay, California: U.S. Geological Survey Open-File Report 2022–1076, 30 p., https://doi.org/ 10.3133/ ofr20221076.

Friedrichs C.T. and D.G. Aubrey. 1988. Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. Estuarine, Coastal and Shelf Science 27(5):521-545.

GHD, Inc., Northern Hydrology and Engineering, and C. Shea. 2002. Natural Shoreline Infrastructure in Humboldt Bay for Intertidal Coastal Marsh Restoration and Transportation Corridor Protection: 50% Design Report.

Gray, J.R., G.D. Glysson, L.M. Turcios, and G. E. Schwarz. 2000. Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data, U. S. Geological Survey Water-Resources Investigations Report 00-4191, Reston, VA.

ICF International. 2018a. Humboldt Bay Area Mitigation Project – Lanphere Parcel, Humboldt County, CA Wetland & Waters of the U.S. Delineation Report, prepared for California Department of Transportation.

ICF International. 2018b. Lanphere Parcel Restoration Project, Modified Full Tidal Alternative, Biological Assessment, prepared for California Department of Transportation.

Integral Consulting, Inc. 2021. Humboldt Bay SED flume Study, prepared for GHD, Inc. and Humboldt County for Natural Shoreline Infrastructure in Humboldt Bay for Intertidal Coastal Marsh Restoration and Transportation Corridor Protection: 50% Design Report.

Jastram, J.D., C.E. Zipper, L.W. Zelanzny, and K. Hyer. 2010. Increasing precision of turbidity-based suspended sediment concentration and load estimates, J. Environ. Qual. 39:1306–1316, doi:10.2134/jeq2009.0280, Published online 15 Apr. 2010.

Matos, T., M.S. Martins, R. Henriques, and L.M. Goncalves. 2024. A review of methods and instruments to monitor turbidity and suspended sediment concentration, Journal of Water Process Engineering, https://doi.org/10.1016/j.jwpe.2024.10562.

NOAA National Ocean Service. 2003. Computational Techniques for Tidal Datums Handbook.

Northern Hydrology and Engineering. 2009. Tidal Wetland Geometric Relations in Humboldt Bay, Mad River Slough Pilot Study, prepared for U.S. Fish and Wildlife Service Coastal Program, Arcata, CA.

Pacific Watershed Associates (PWA). 2014. Humboldt Bay Sea Level Rise Vulnerability Assessment: DEM Development Report, Final Draft. Prepared for Northern Hydrology & Engineering. Prepared by PWA, McKinleyville, CA. PWA Report No. 14100351, dated February 2014.

SHN. 2024. Geotechnical Investigation Report for Wadulh Lagoon Tidal Wetland Enhancement Project, prepared for Humboldt County Resource Conservation District, Eureka, CA.

Soulsby, R. 1997. Dynamics of marine sands. Thomas Telford Publications, London.

Takekawa, J.Y., Thorne, K.M., Buffington, K.J., Freeman, C.M., Powelson, K.W., and Block G. 2013. Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge. Unpubl. Data Summary Report. USGS Western Ecological Research Center, Vallejo, CA. 45pp + Appendices.

TUFLOW. 2020a. TUFLOW-FV- User Manual, Build 2020.02, BMT Commercial Australia Pty Ltd, Brisbane, AU.

TUFLOW. 2020b. TUFLOW-FV- User Manual, Build 2020.01 Sediment Transport and Particle Tracking Modules, BMT Commercial Australia Pty Ltd, Brisbane, AU.

USFWS. 2023a. Wadulh Lagoon Tidal Wetland Enhancement Project Basis of Design, prepared by Conor Shea, U.S. Fish and Wildlife Service Coastal Program, Arcata, CA.

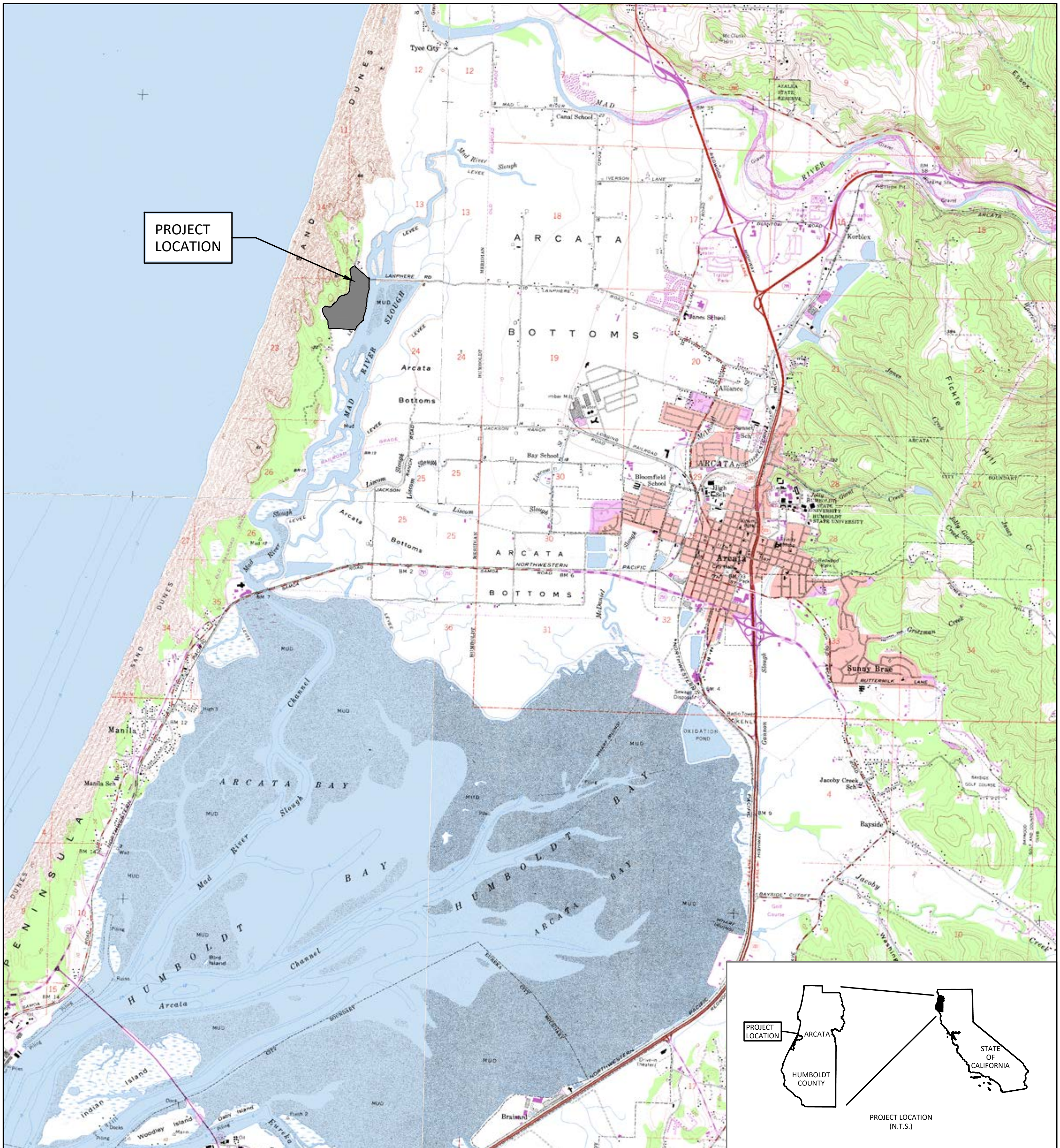
USFWS. 2023b. Wadulh Lagoon Tidal Wetland Enhancement Project 30% Design Plans, prepared by Conor Shea, U.S. Fish and Wildlife Service Coastal Program, Arcata, CA.

Van Rijn, L.C. 1984. Sediment Transport, Part II: Suspended Load Transport. Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 11, pp1613-41.

Yao, P., Su, M., Z. Wang, L.C. van Rijn, M.J.F. Stive, C. Xu, and Y. Chen. 2022. Erosion behavior of sand-silt mixtures: Revisiting the erosion threshold. Water Resources Research,58, e2021WR031788. https://doi.org/10.1029/2021WR031788.

Williams, P.B., M.K. Orr, and N.J. Garrity. 2002. Hydraulic Geometry: A Geomorphic Design Tool for Tidal Marsh Channel Evolution in Wetland Restoration Projects, Restoration Ecology, 10(3): 577-590.

FIGURES



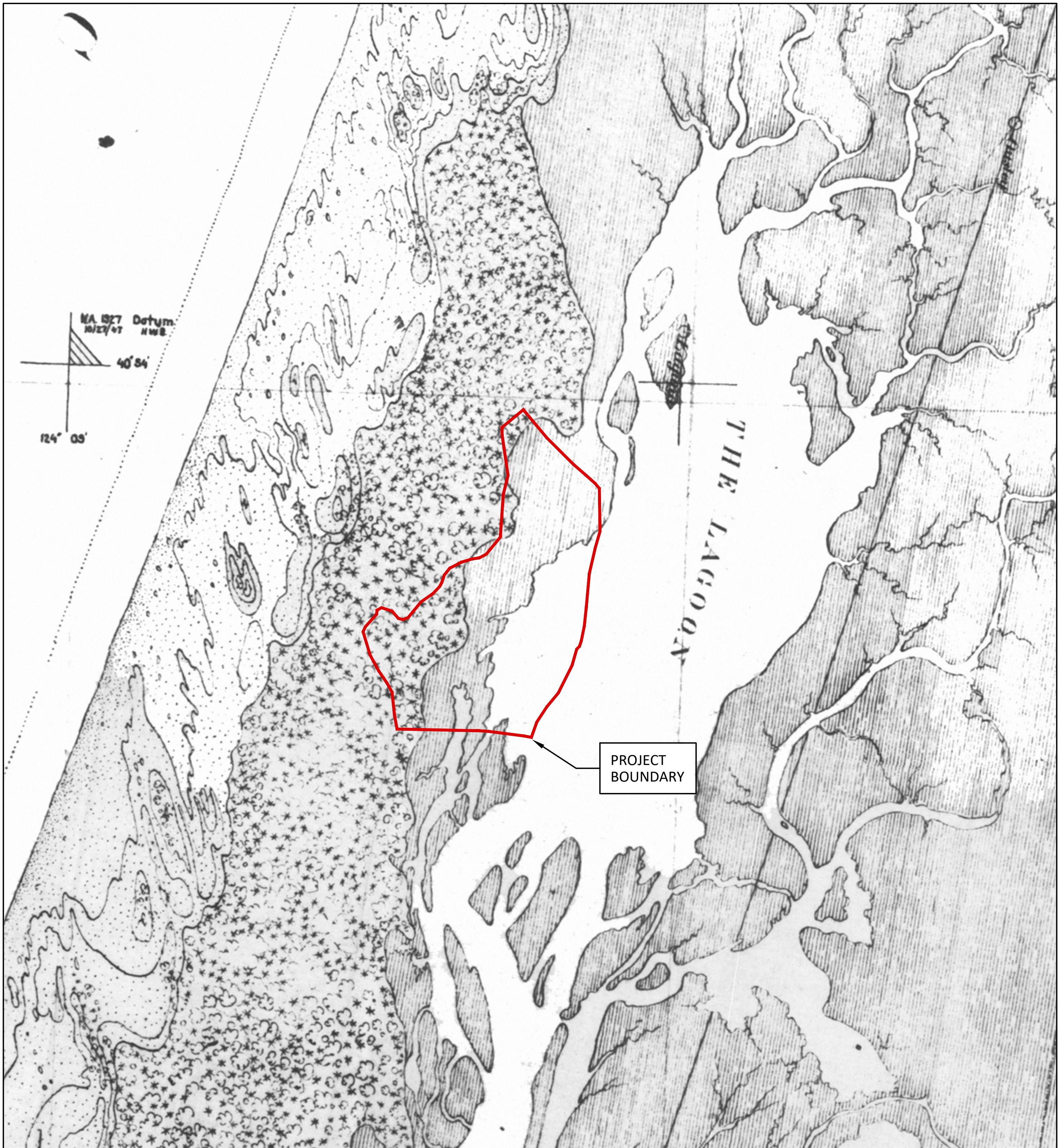
0 5000'

WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

PROJECT LOCATION

MAP SOURCE: USGS 7-1/2" QUADRANGLES: ARCATA NORTH, ARCATA SOUTH, TYEE CITY, AND EUREKA

FIGURE 1



0 1000'

WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

PROJECT BOUNDARY OVERLAY ON 1870 USCGS MAP

IMAGE SOURCE: LAIRD, 2007.

FIGURE

2

0 400'

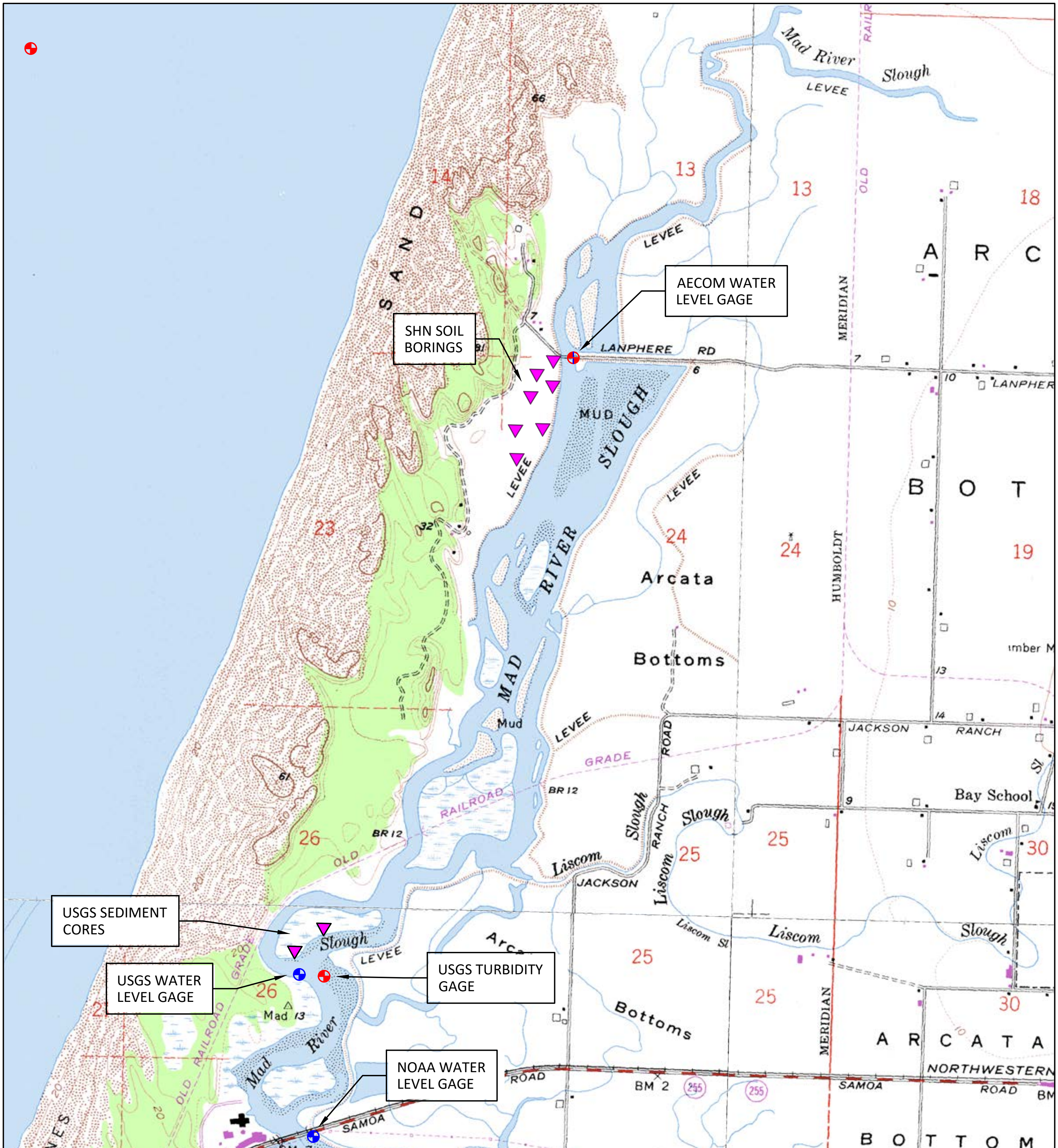
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

PROJECT EXISTING CONDITIONS

IMAGE SOURCE: DIGITAL GLOBE 2022

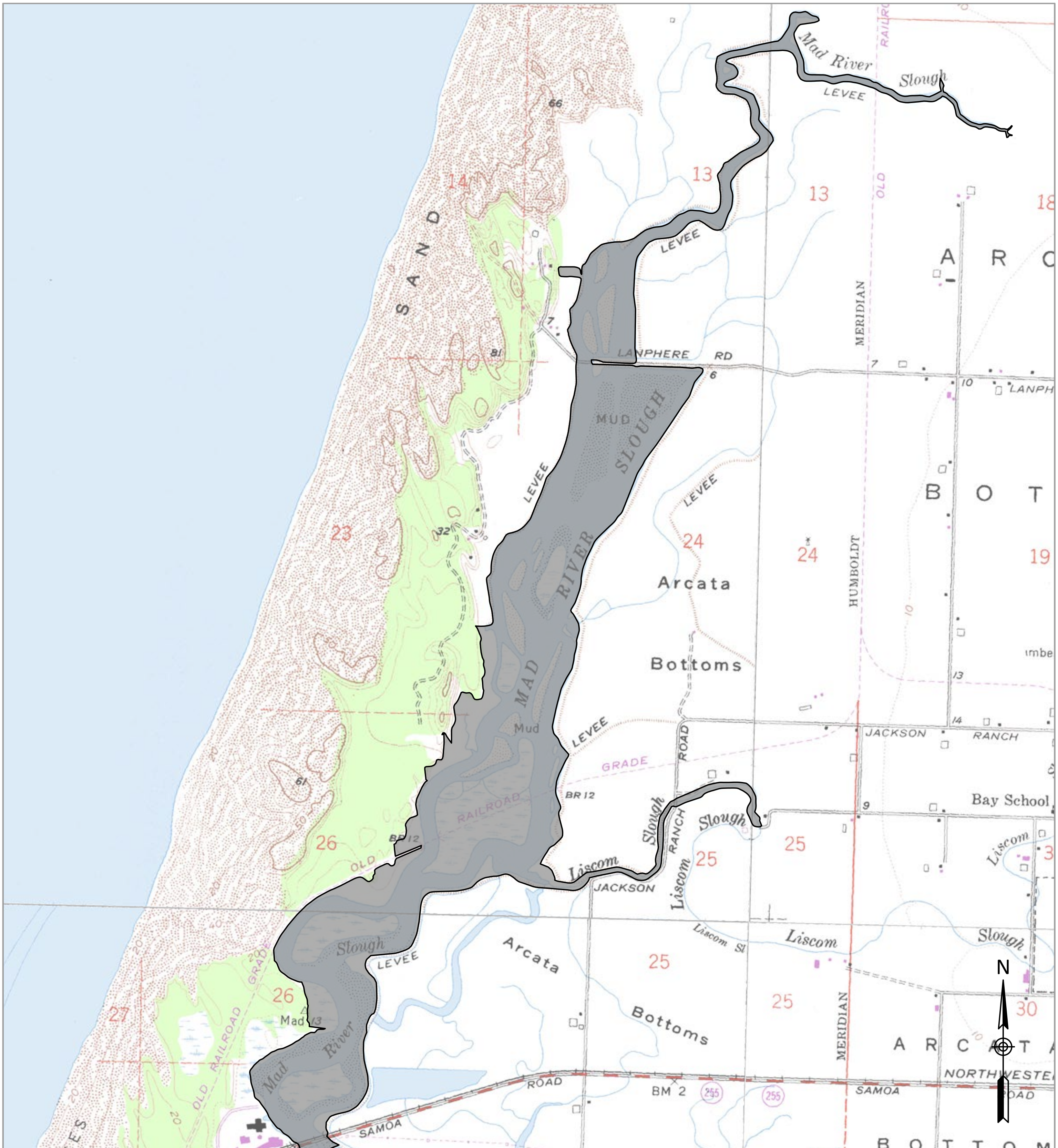
FIGURE

3



WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT
WATER LEVEL, WATER QUALITY, AND SEDIMENT SAMPLING LOCATIONS
MAP SOURCE: USGS 7-1/2" QUADRANGLES: ARCATA NORTH, ARCATA SOUTH, TYEE CITY, AND EUREKA

FIGURE 4



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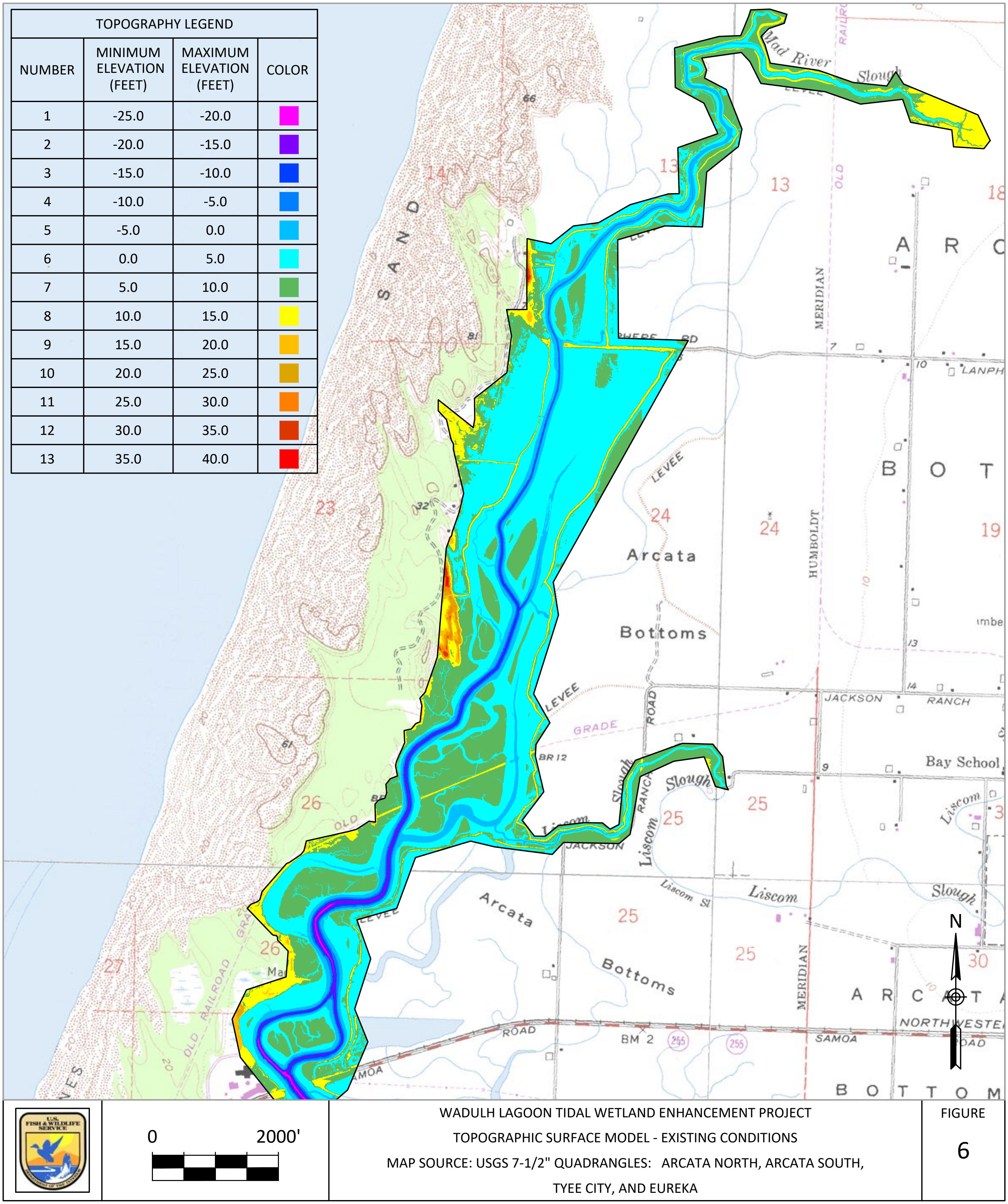
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

TUFLOW-FV MODEL SOLUTION DOMAIN

MAP SOURCE: USGS 7-1/2" QUADRANGLES: ARCATA NORTH, ARCATA SOUTH, TYEE CITY, AND EUREKA

FIGURE 5

TOPOGRAPHY LEGEND			
NUMBER	MINIMUM ELEVATION (FEET)	MAXIMUM ELEVATION (FEET)	COLOR
1	-25.0	-20.0	
2	-20.0	-15.0	
3	-15.0	-10.0	
4	-10.0	-5.0	
5	-5.0	0.0	
6	0.0	5.0	
7	5.0	10.0	
8	10.0	15.0	
9	15.0	20.0	
10	20.0	25.0	
11	25.0	30.0	
12	30.0	35.0	
13	35.0	40.0	

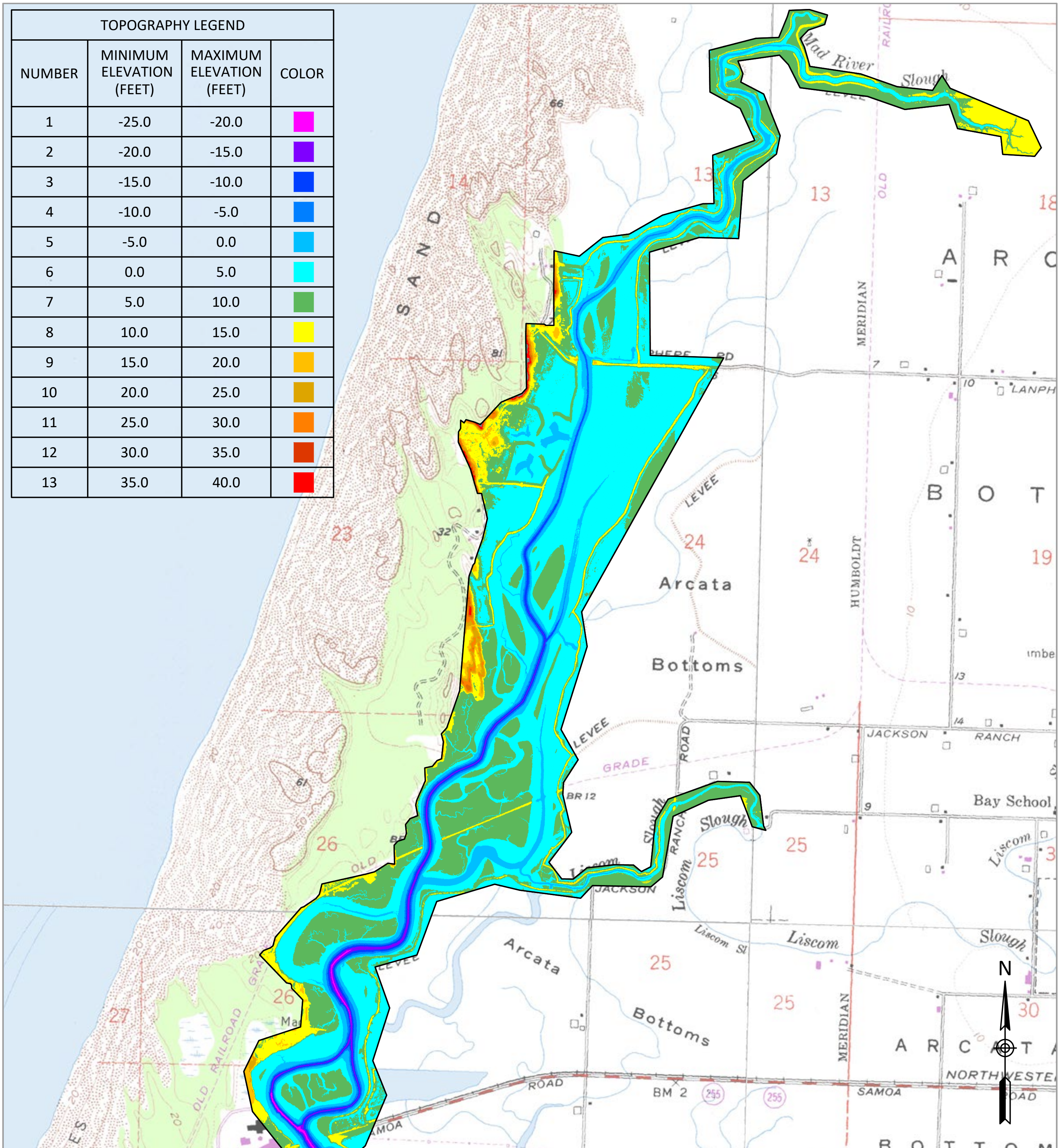


WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

TOPOGRAPHIC SURFACE MODEL - EXISTING CONDITIONS

MAP SOURCE: USGS 7-1/2" QUADRANGLES: ARCATA NORTH, ARCATA SOUTH, TYEE CITY, AND EUREKA

FIGURE 6



TOPOGRAPHY LEGEND			
NUMBER	MINIMUM ELEVATION (FEET)	MAXIMUM ELEVATION (FEET)	COLOR
1	-25.0	-20.0	
2	-20.0	-15.0	
3	-15.0	-10.0	
4	-10.0	-5.0	
5	-5.0	0.0	
6	0.0	5.0	
7	5.0	10.0	
8	10.0	15.0	
9	15.0	20.0	
10	20.0	25.0	
11	25.0	30.0	
12	30.0	35.0	
13	35.0	40.0	

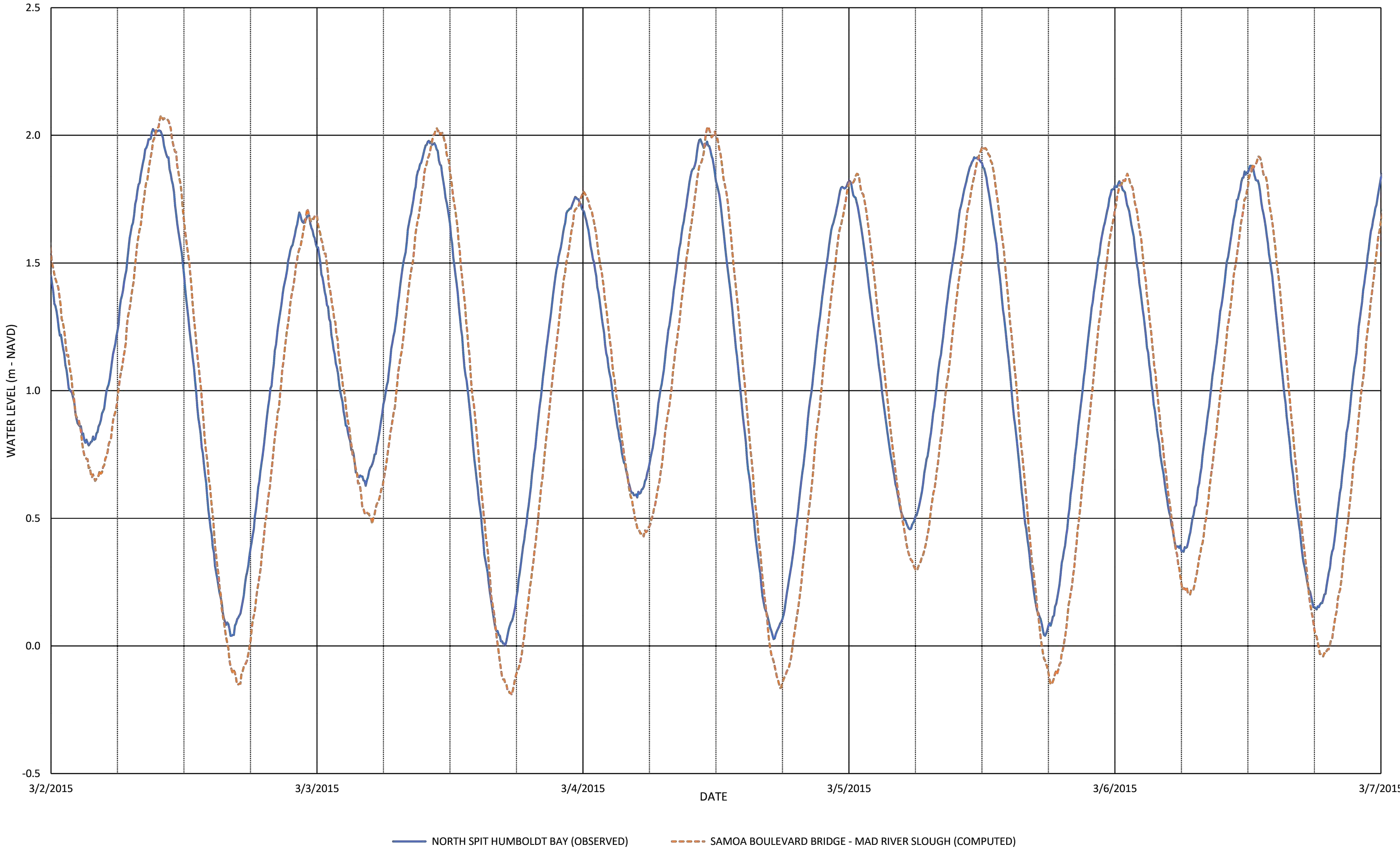
0 2000'

WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

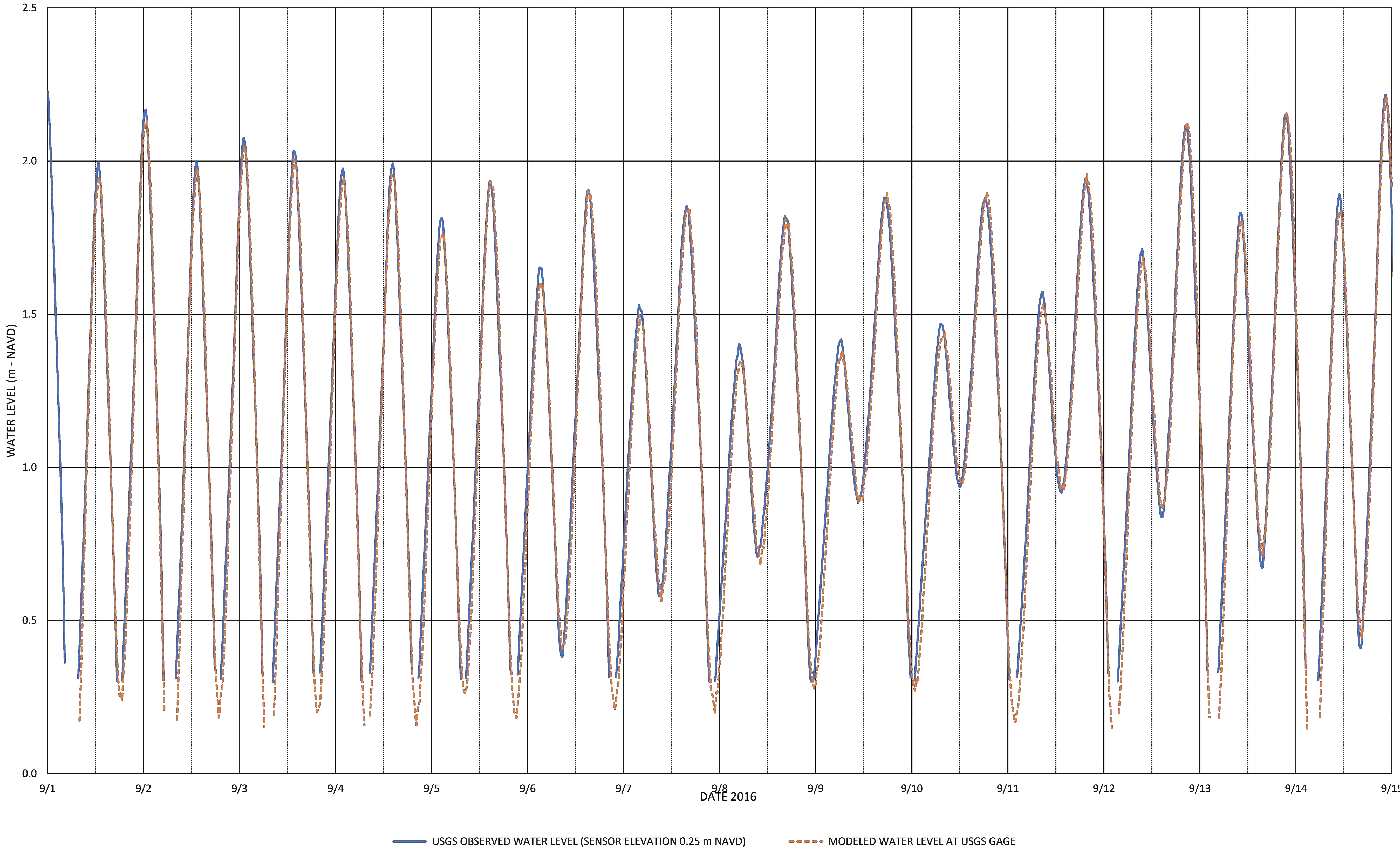
TOPOGRAPHIC SURFACE MODEL - PROPOSED CONDITIONS

MAP SOURCE: USGS 7-1/2" QUADRANGLES: ARCATA NORTH, ARCATA SOUTH, TYEE CITY, AND EUREKA

FIGURE 7



U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT EXAMPLE TRANSFORMATION OF NORTH SPIT WATER LEVEL RECORD TO MAD RIVER SLOUGH AT SAMOA BOULEVARD		FIGURE 8



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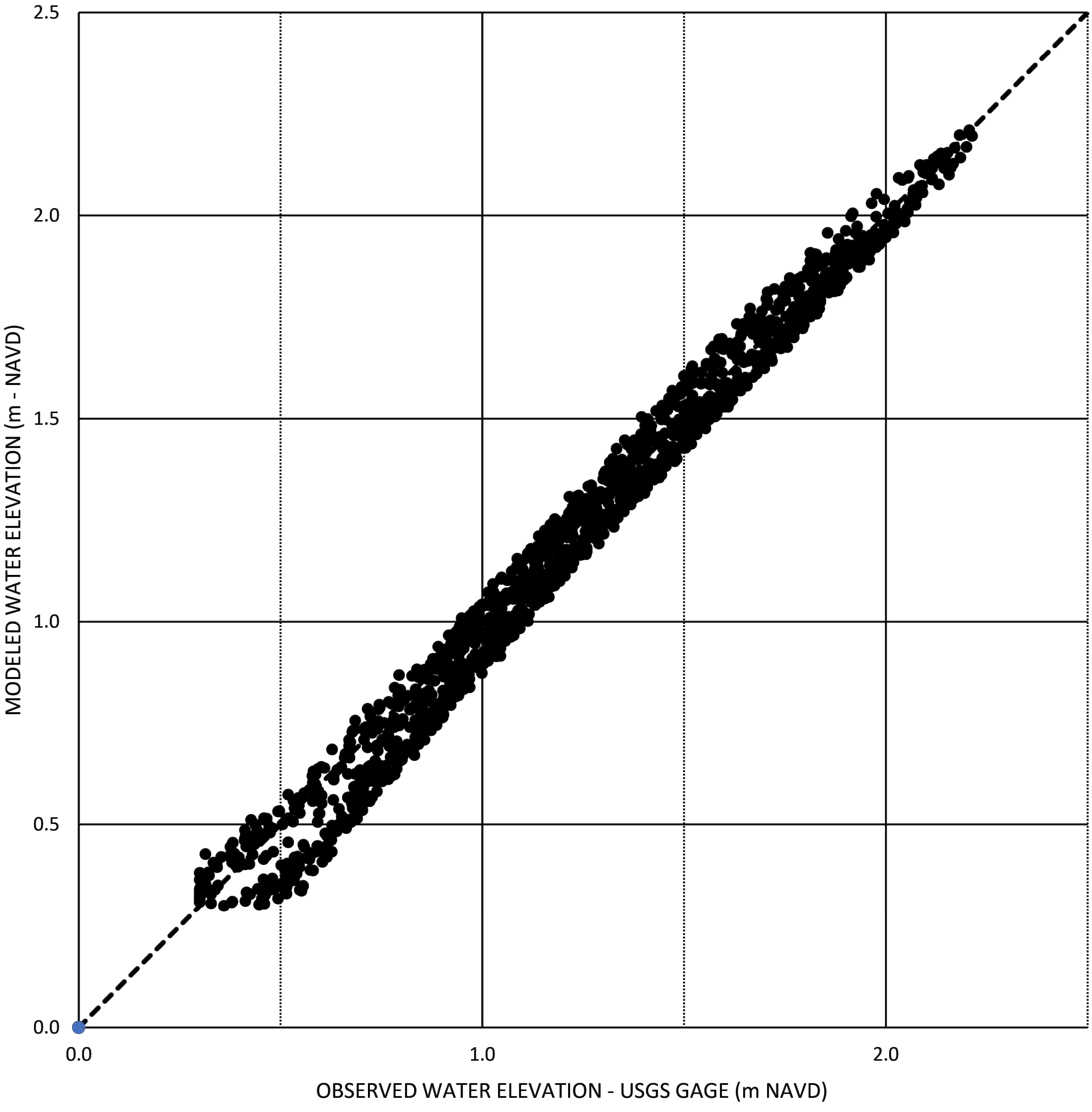
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

HYDRODYNAMIC MODEL CALIBRATION RESULTS

FIGURE

9



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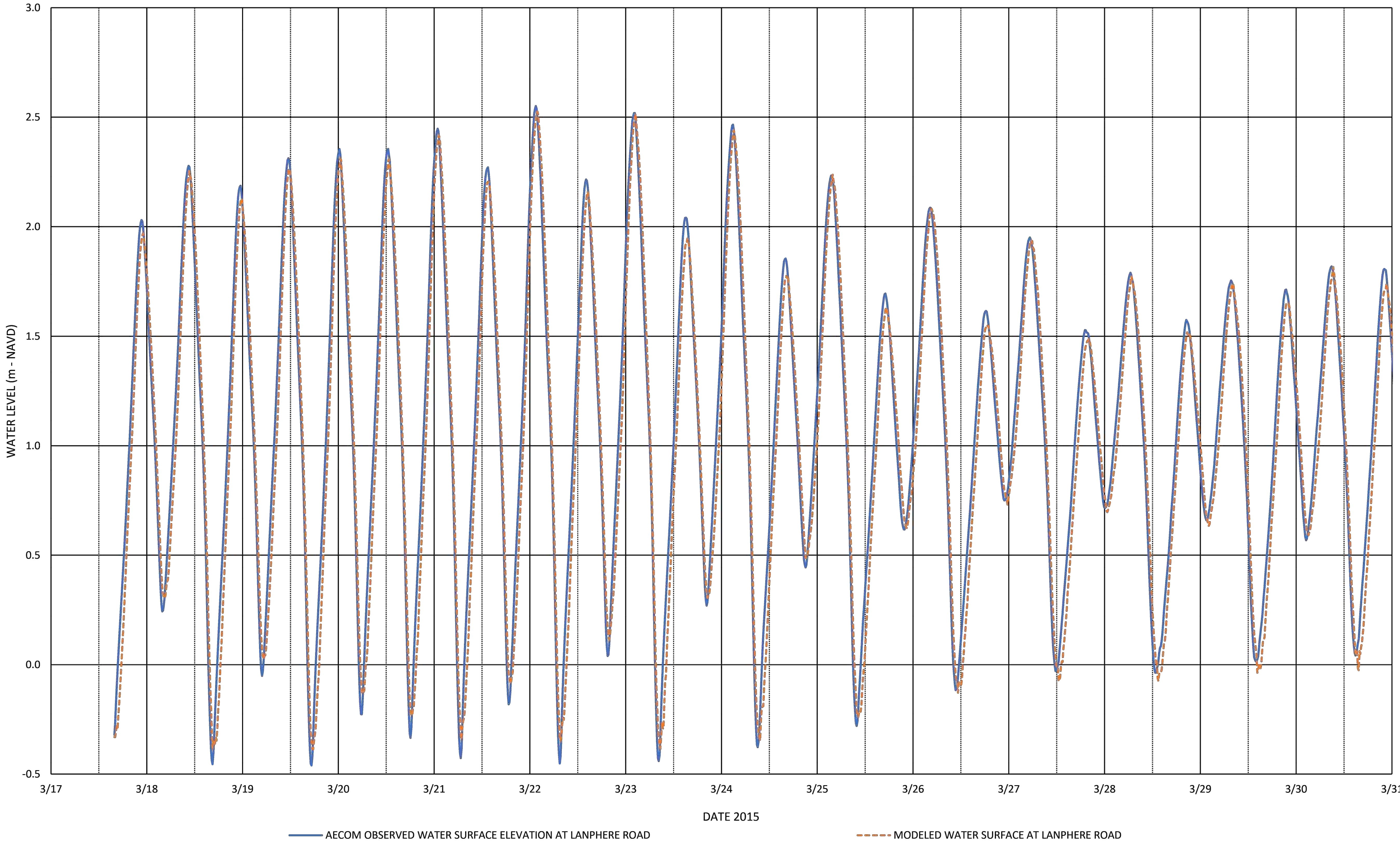
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

CALIBRATED MODELED WATER LEVEL VERSUS OBSERVED WATER LEVEL - USGS GAGE

FIGURE

10



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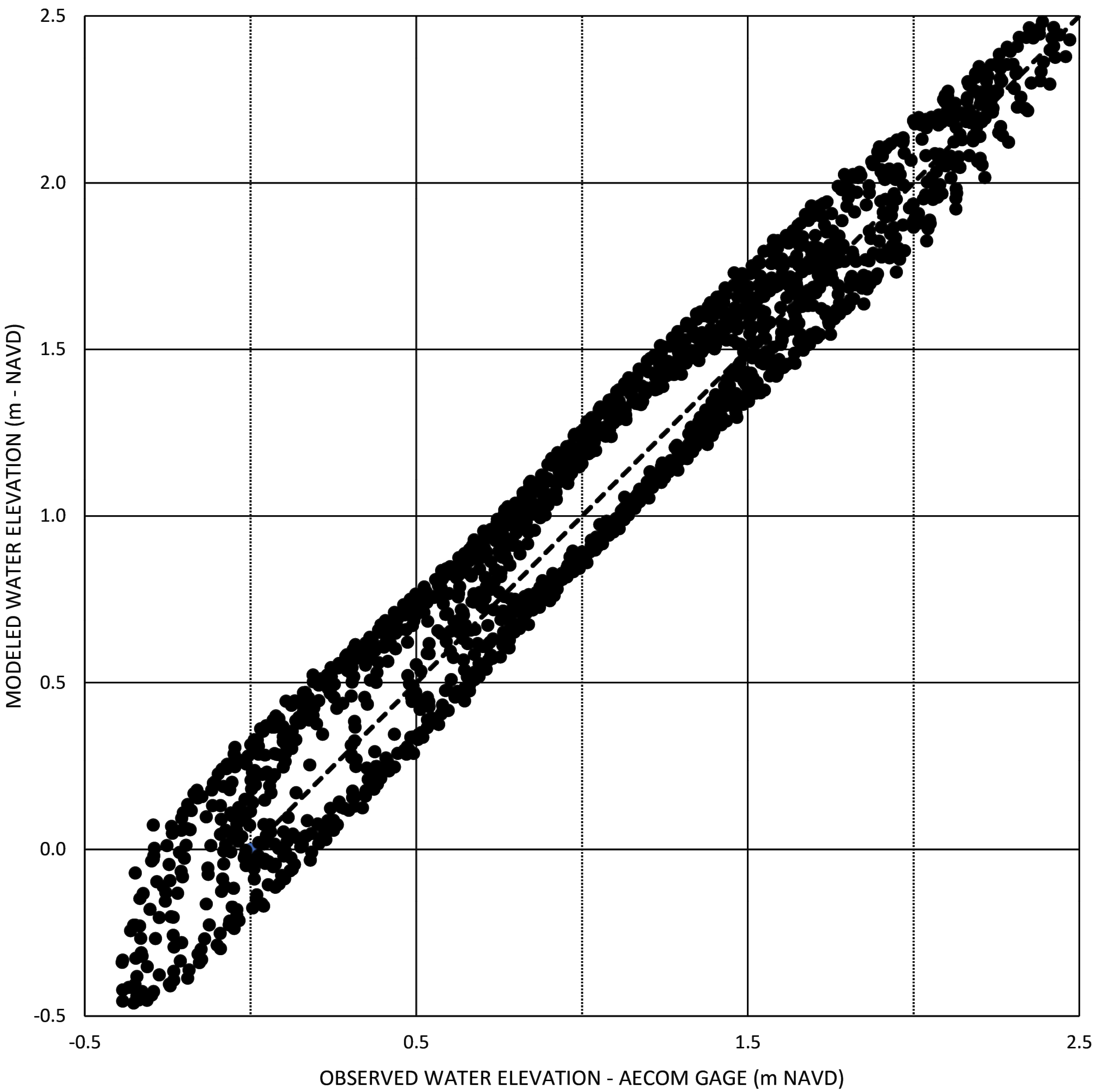
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

HYDRODYNAMIC MODEL VALIDATION RESULTS

FIGURE

11



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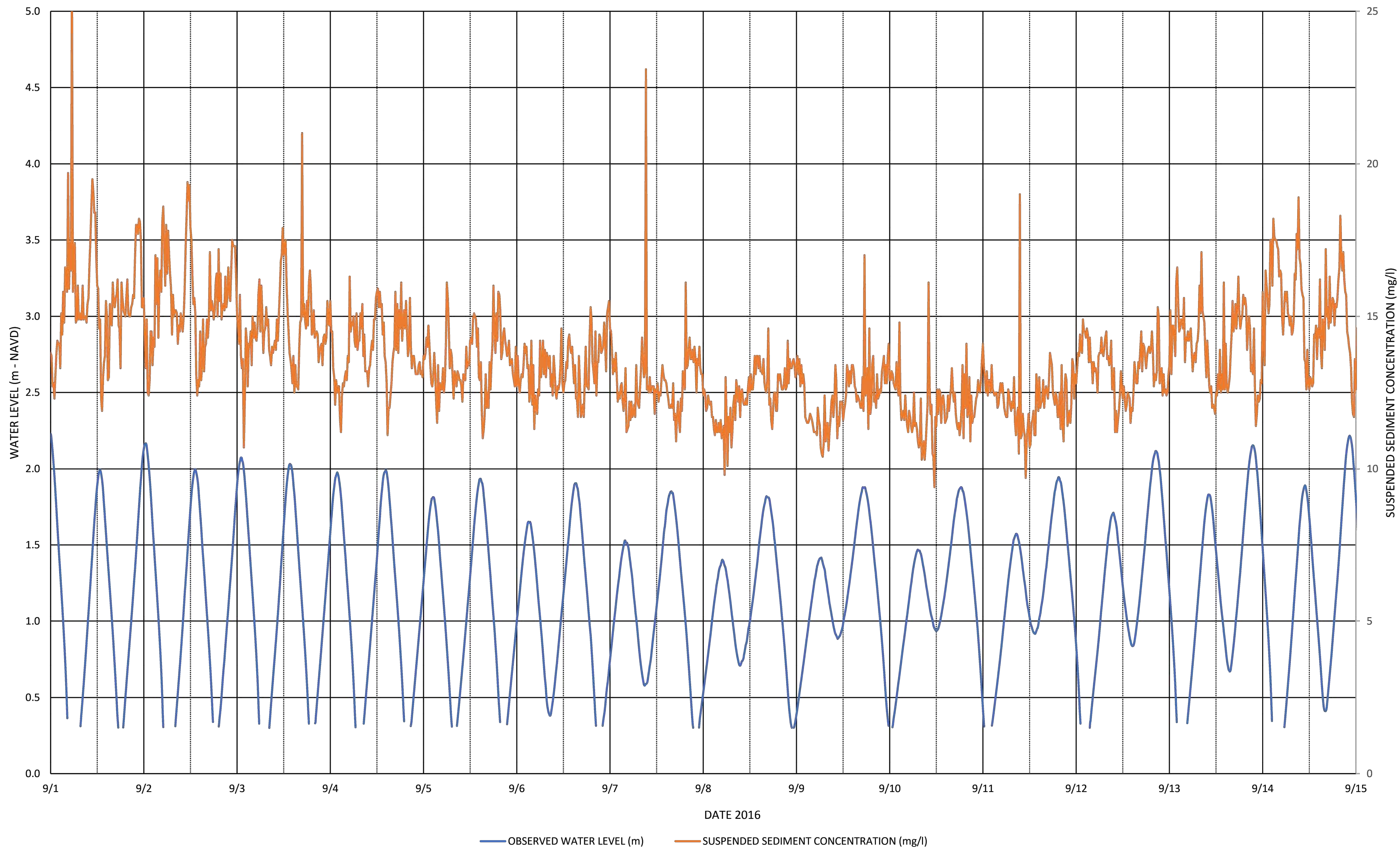
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

VALIDATED MODELED WATER LEVEL VERSUS OBSERVED WATER LEVEL - AECOM GAGE

FIGURE

12



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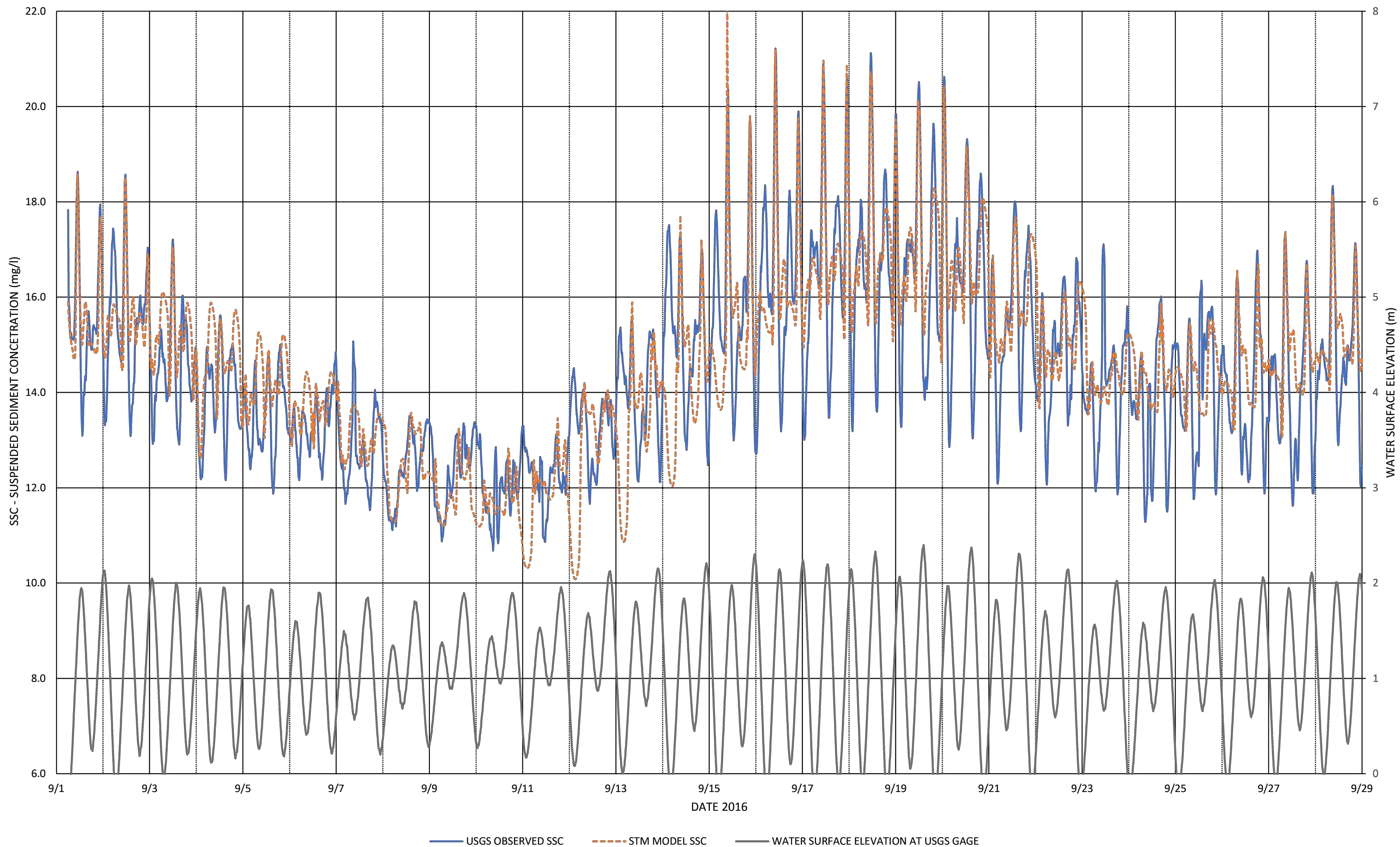
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

SAMPLE USGS WATER LEVEL AND TOTAL SUSPENDED SEDIMENT MEASUREMENTS

FIGURE
13



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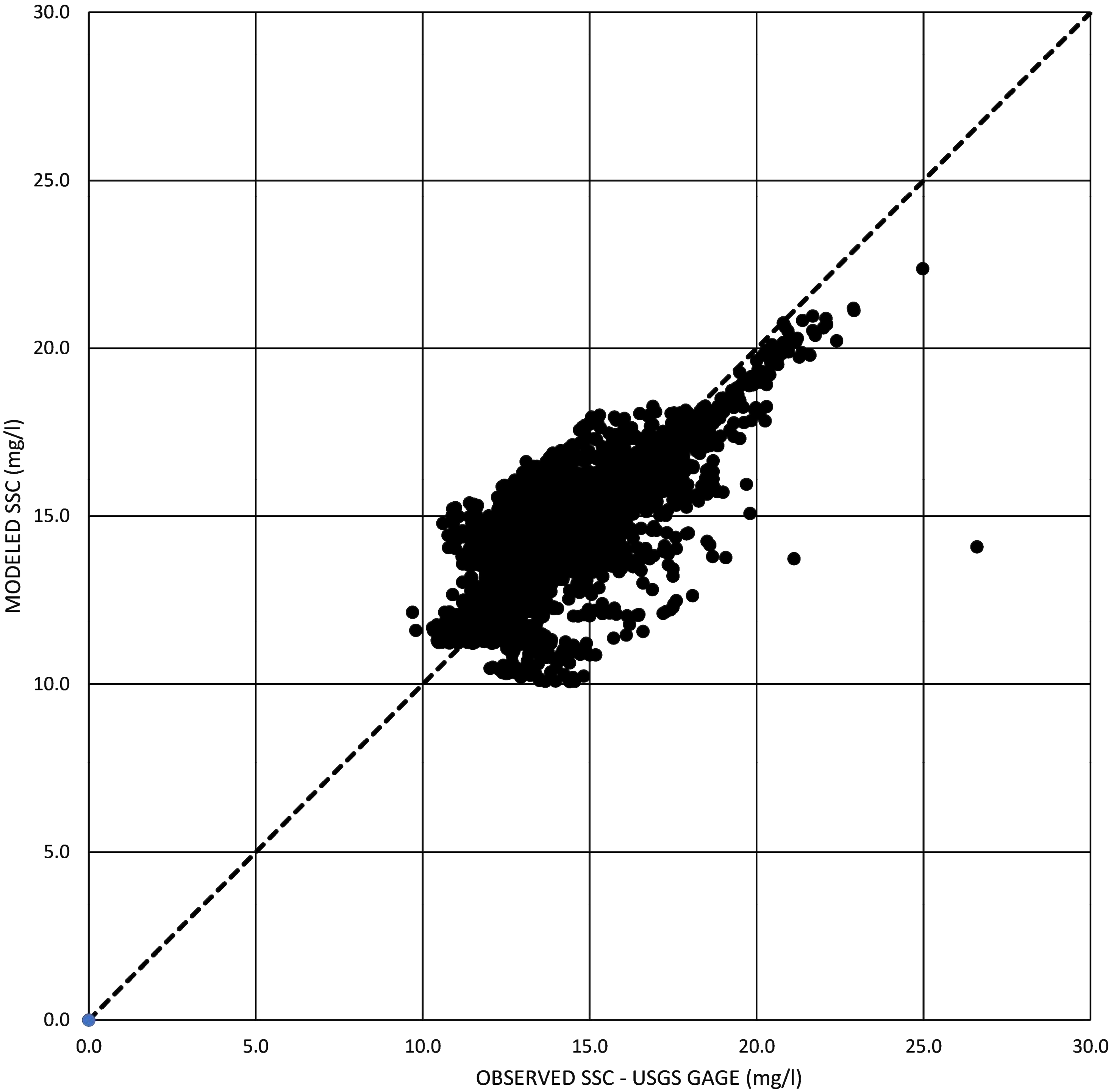
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

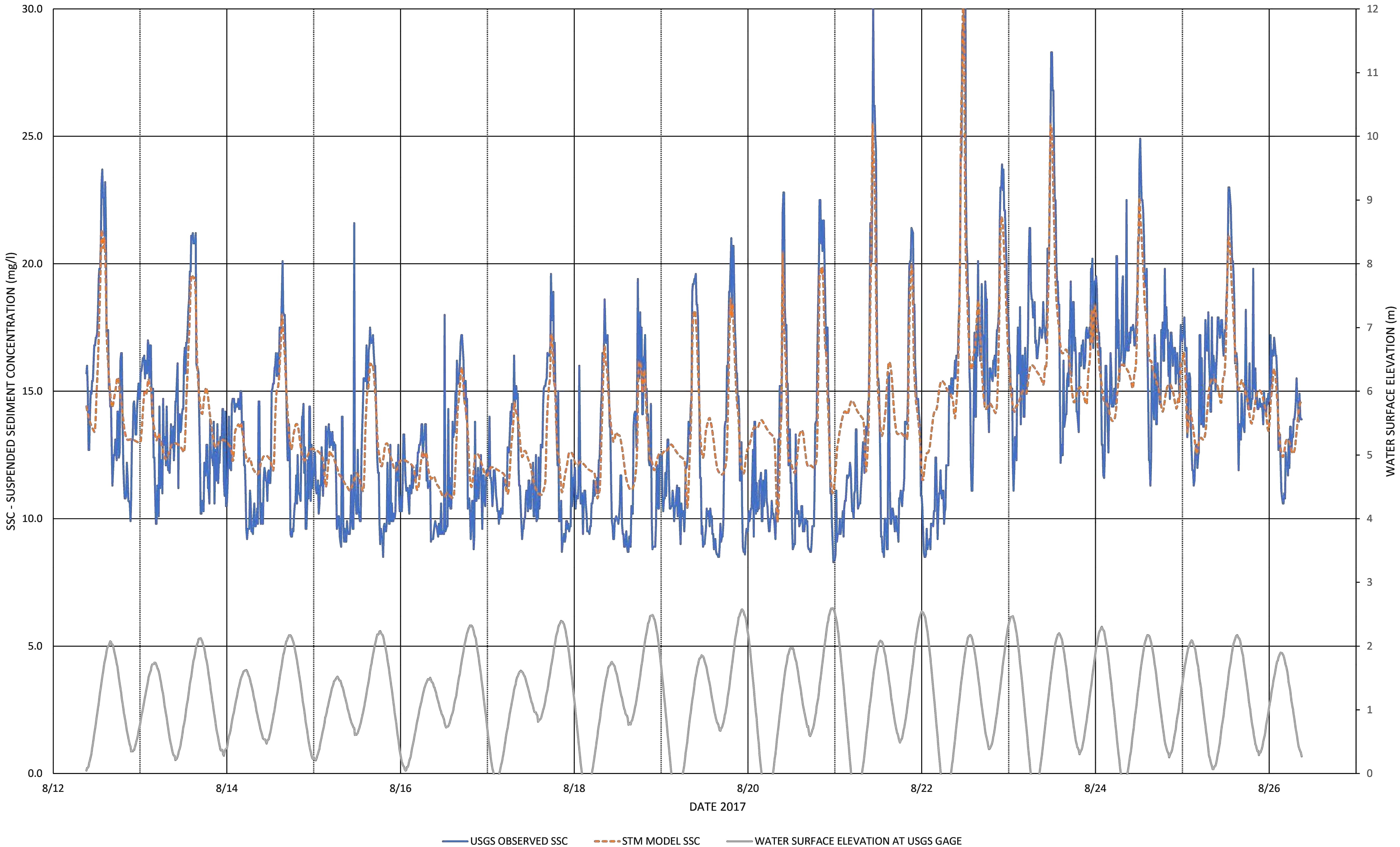
SEDIMENT TRANSPORT MODEL CALIBRATION RESULTS

FIGURE

14



	U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT CALIBRATED MODELED SSC VERSUS OBSERVED SSC - USGS GAGE	FIGURE 15



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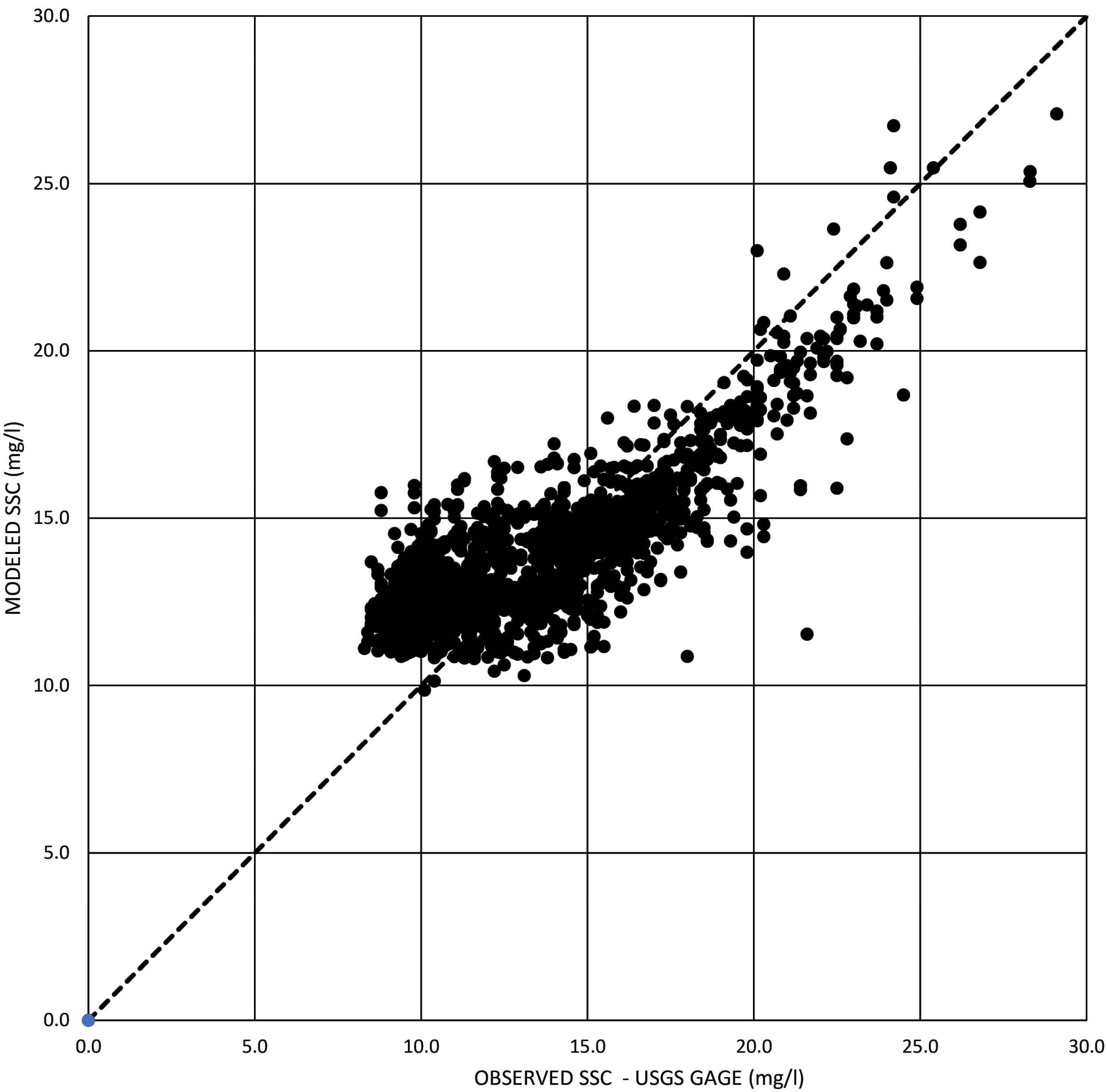
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

SEDIMENT TRANSPORT MODEL VALIDATION RESULTS

FIGURE

16



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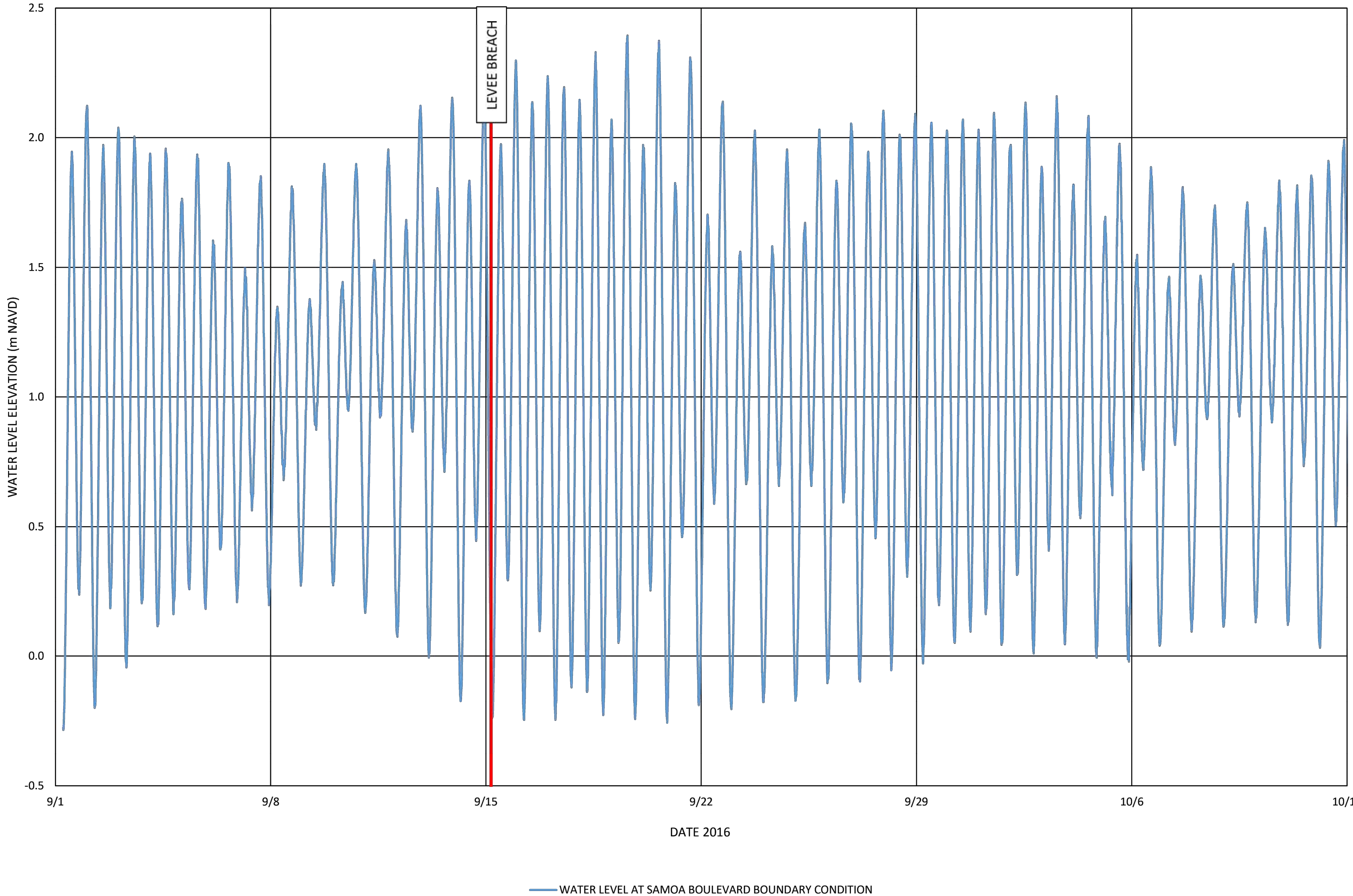
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

VALIDATED MODELED SSC VERSUS OBSERVED SSC - USGS GAGE

FIGURE

17



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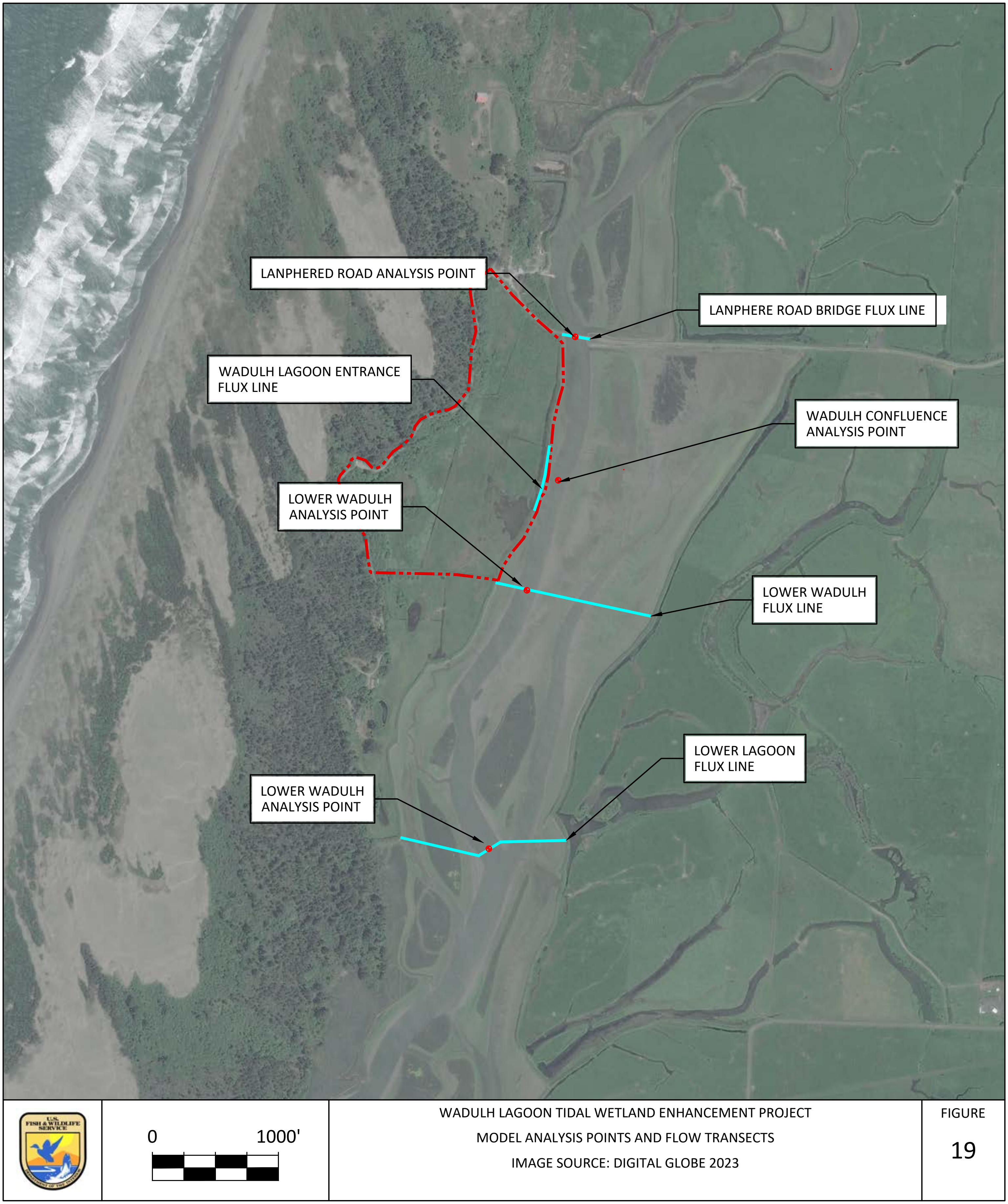
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

BREACH SIMULATION WATER LEVEL BOUNDARY CONDITION

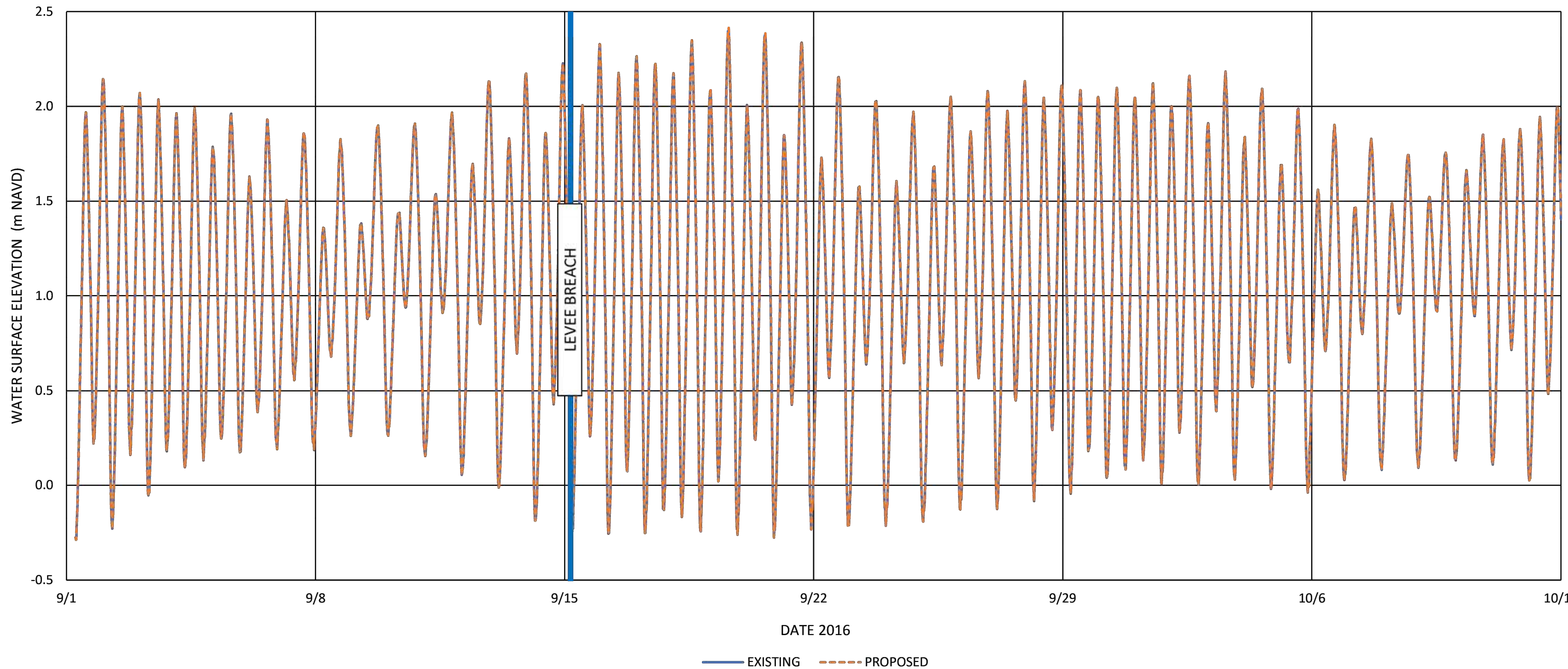
FIGURE

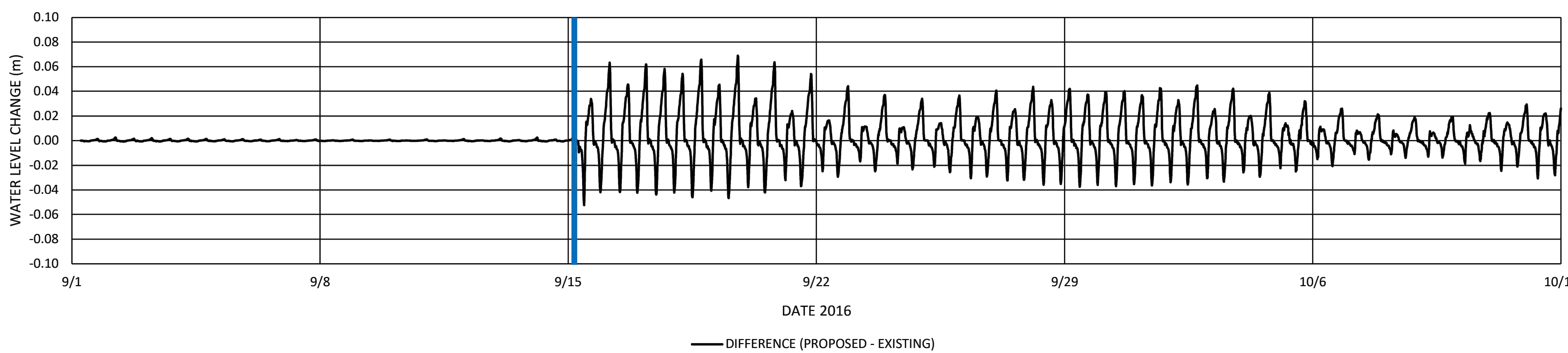
18



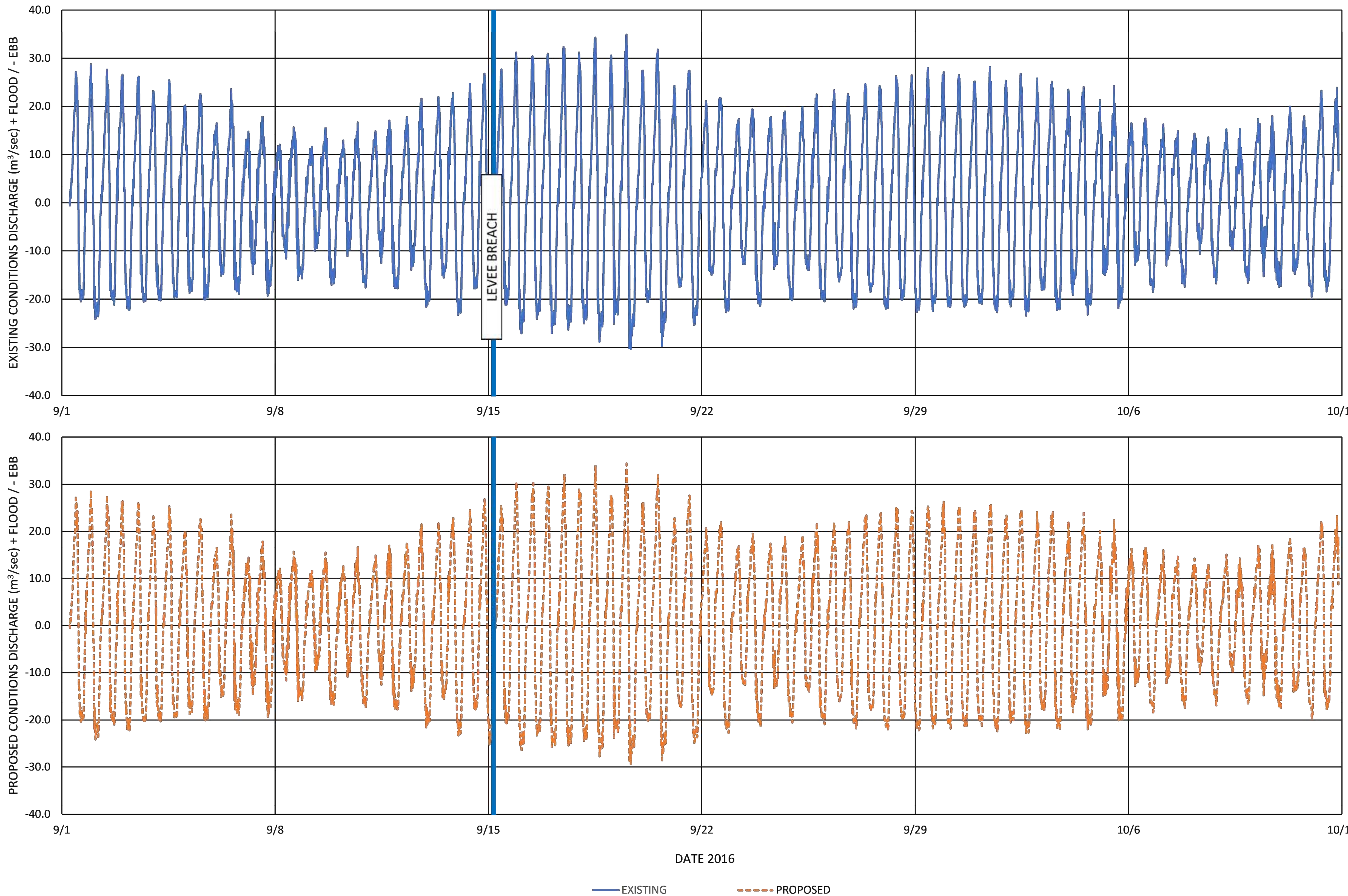
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT
MODEL ANALYSIS POINTS AND FLOW TRANSECTS
IMAGE SOURCE: DIGITAL GLOBE 2023

FIGURE 19





U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT EXISTING AND PROPOSED WATER SURFACE ELEVATION AT LANPHERE ROAD BRIDGE		FIGURE 20



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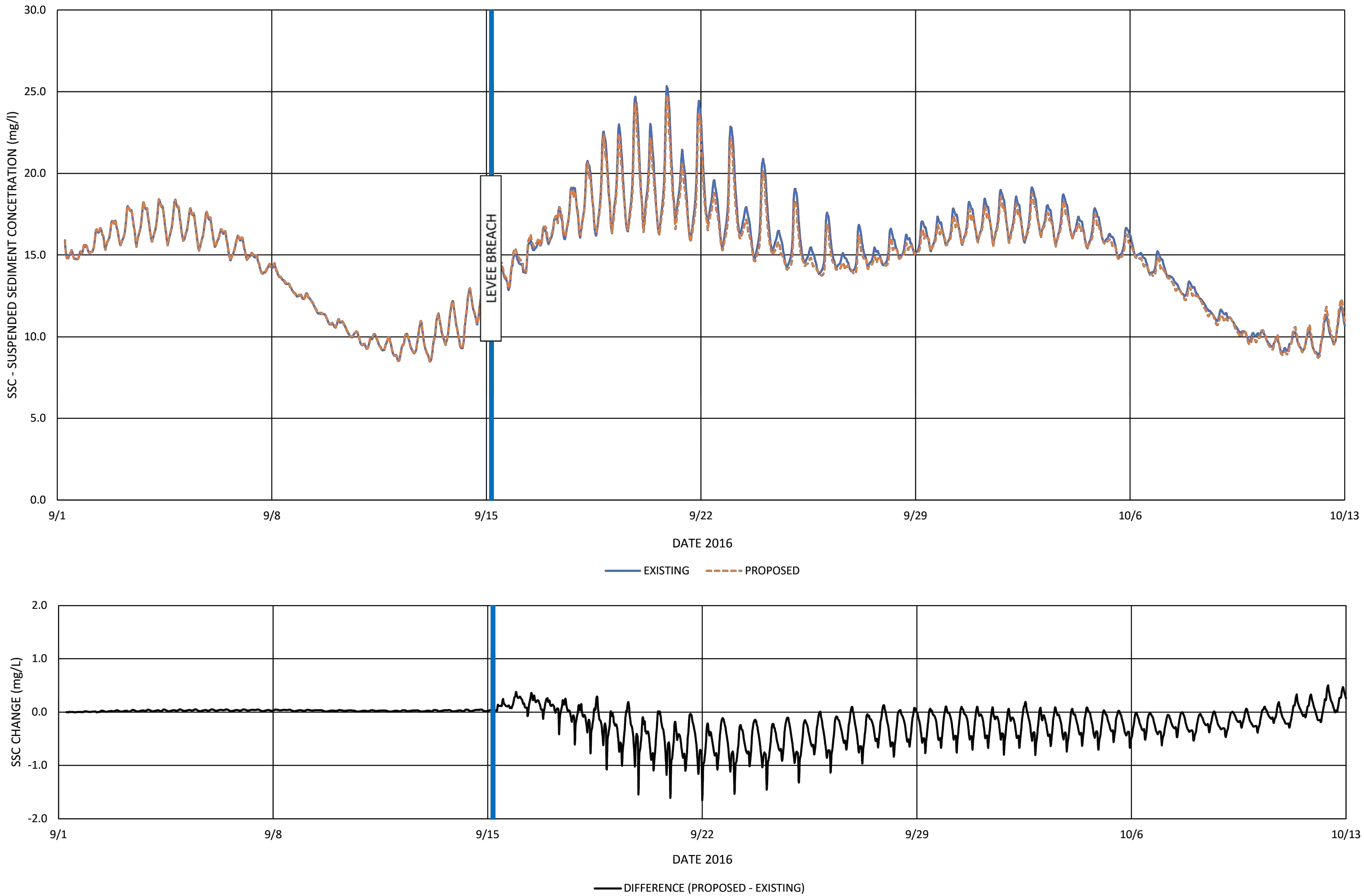
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED DISCHARGE AT LANPHERE ROAD BRIDGE

FIGURE

21



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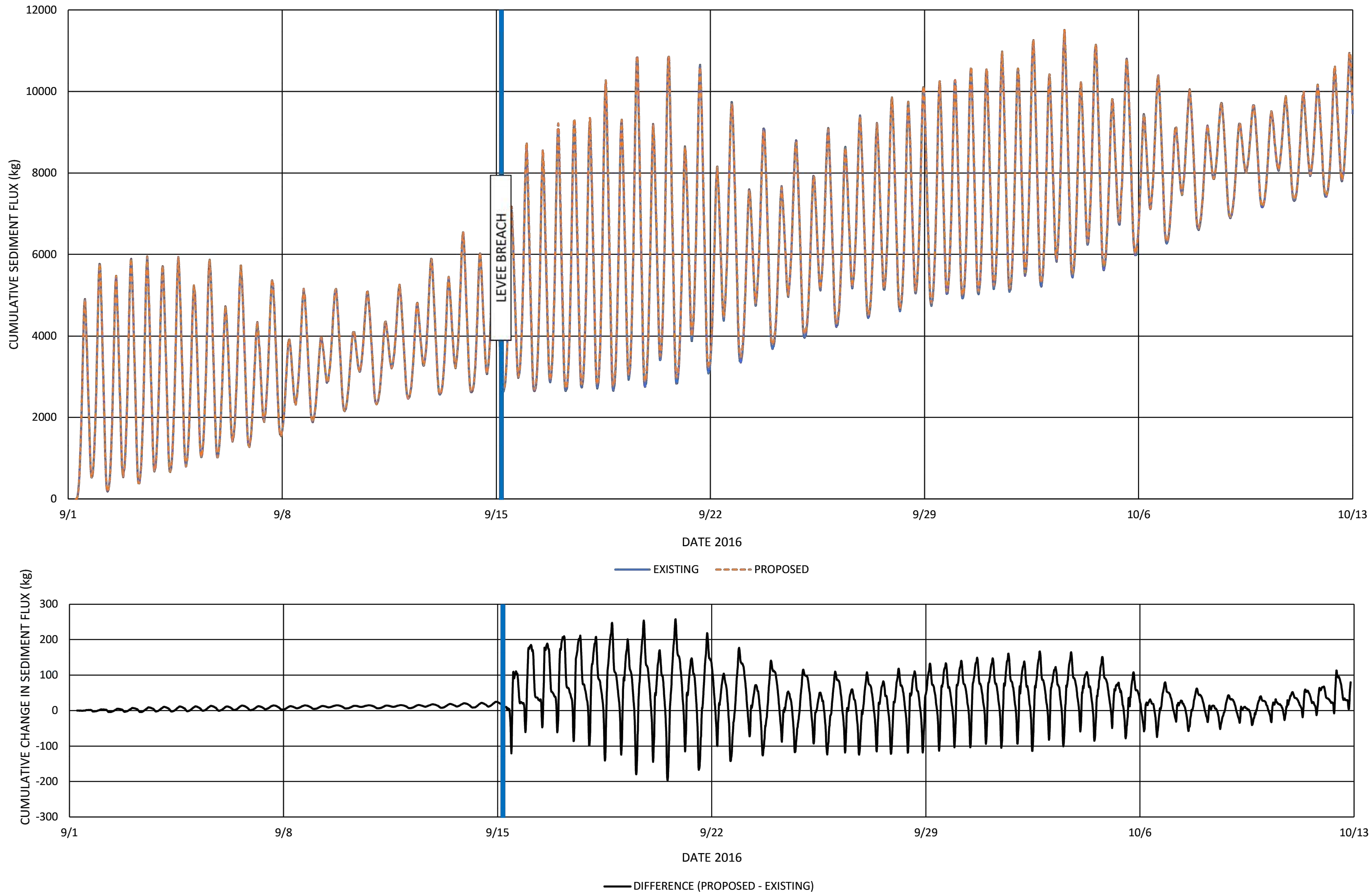
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED SUSPENDED SEDIMENT CONCENTRATION BRIDGE

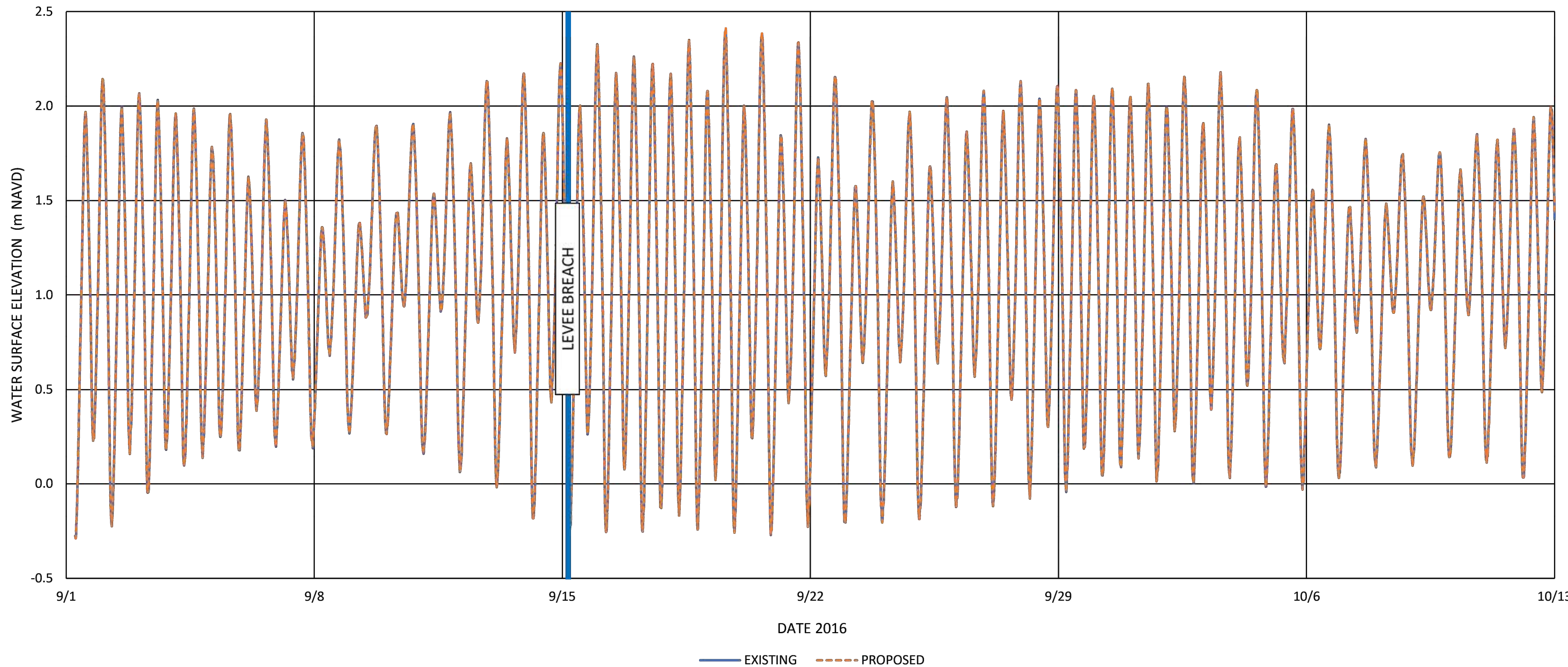
AT LANPHERE ROAD BRIDGE

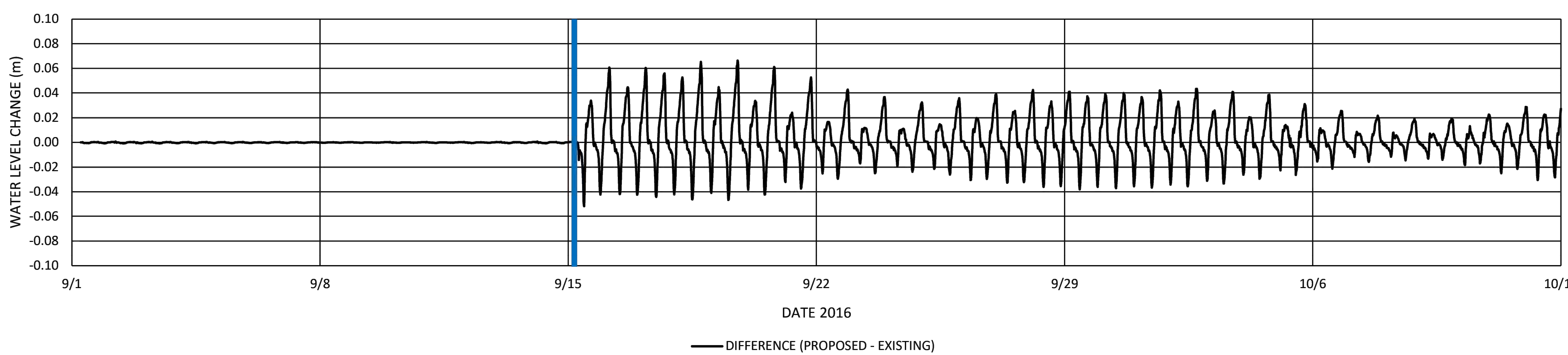
FIGURE

22

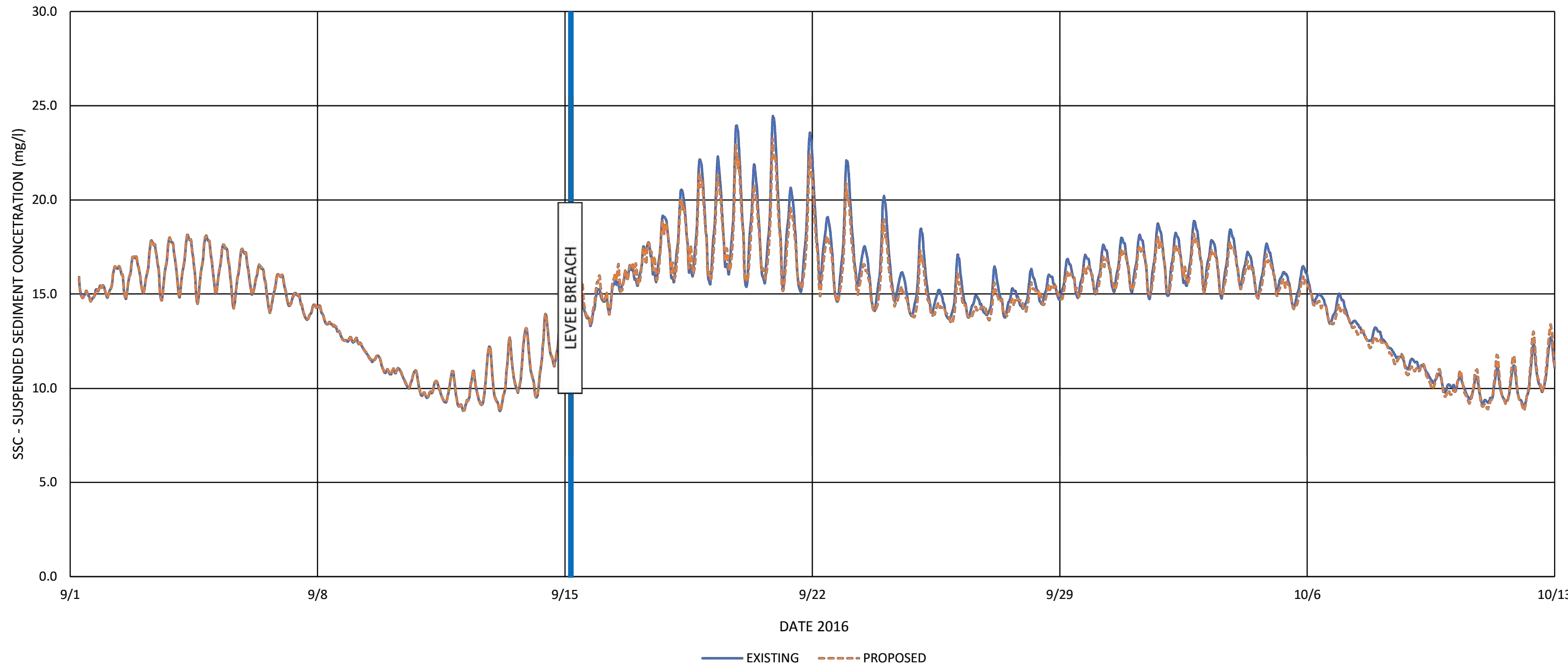


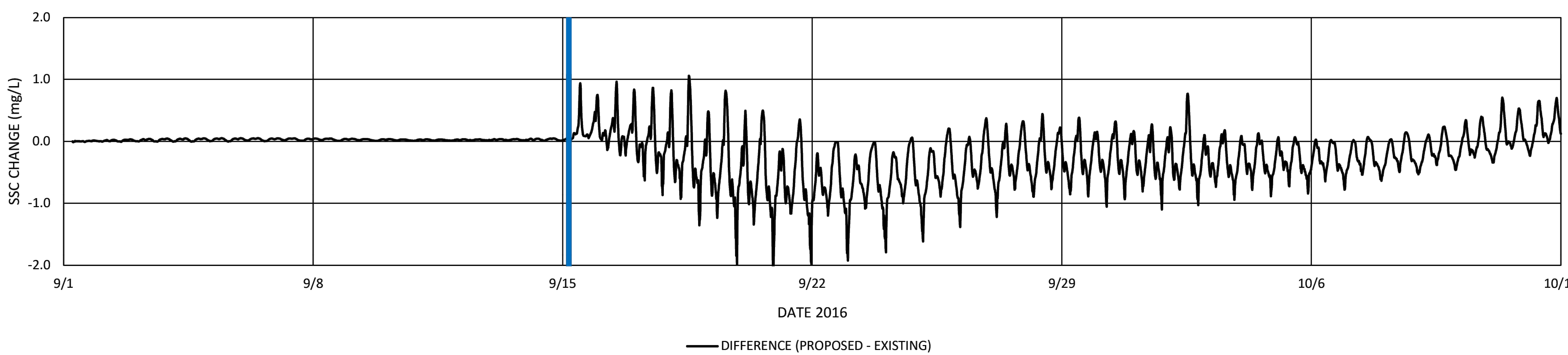
U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT EXISTING AND PROPOSED CUMULATIVE SEDIMENT FLUX AT LANPHERE ROAD BRIDGE		FIGURE 23





U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT EXISTING AND PROPOSED WATER SURFACE ELEVATION AT WADULH CONFLUENCE		FIGURE 24





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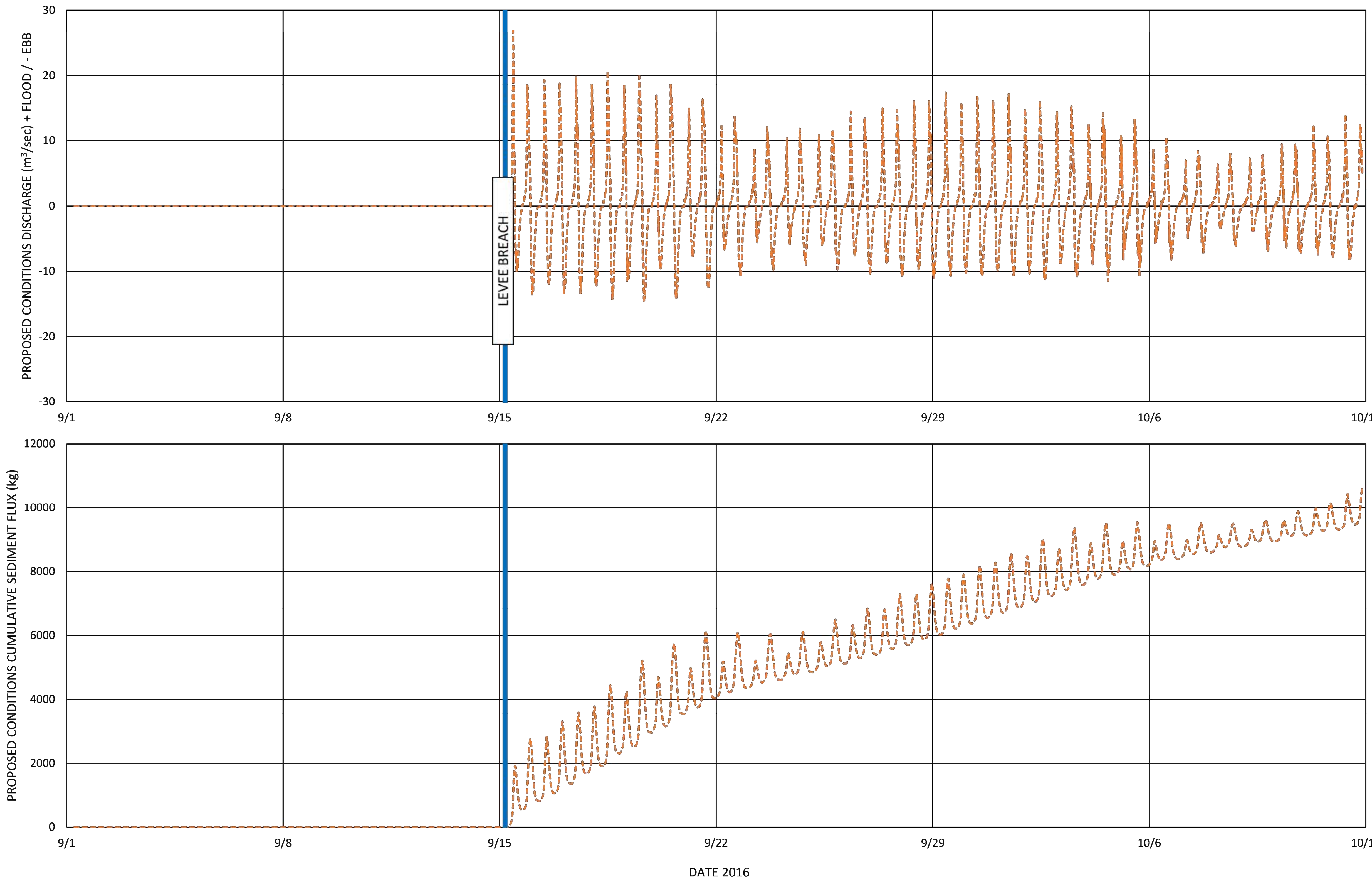
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED SUSPENDED SEDIMENT CONCENTRATION

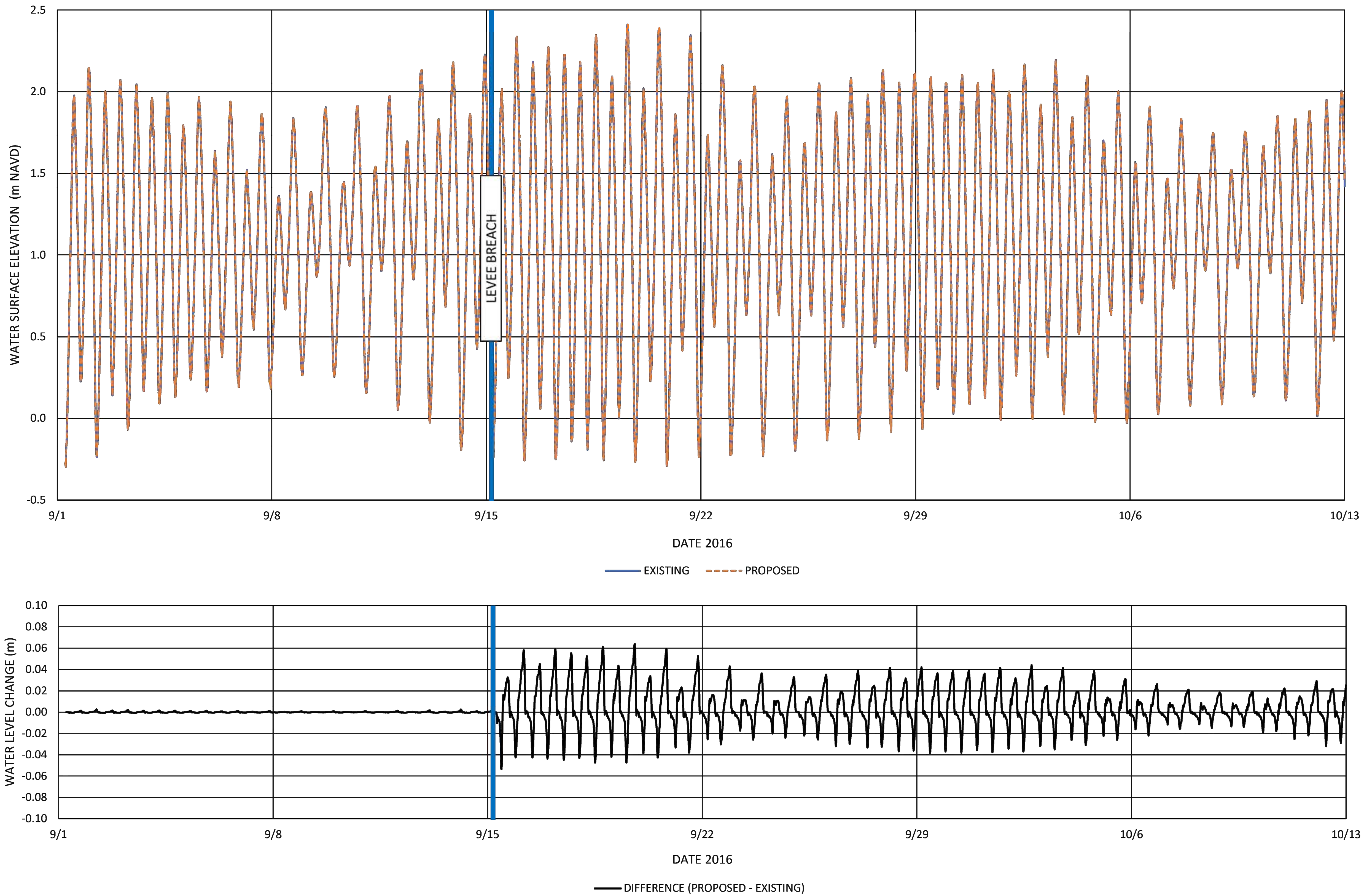
AT WADULH CONFLUENCE

FIGURE

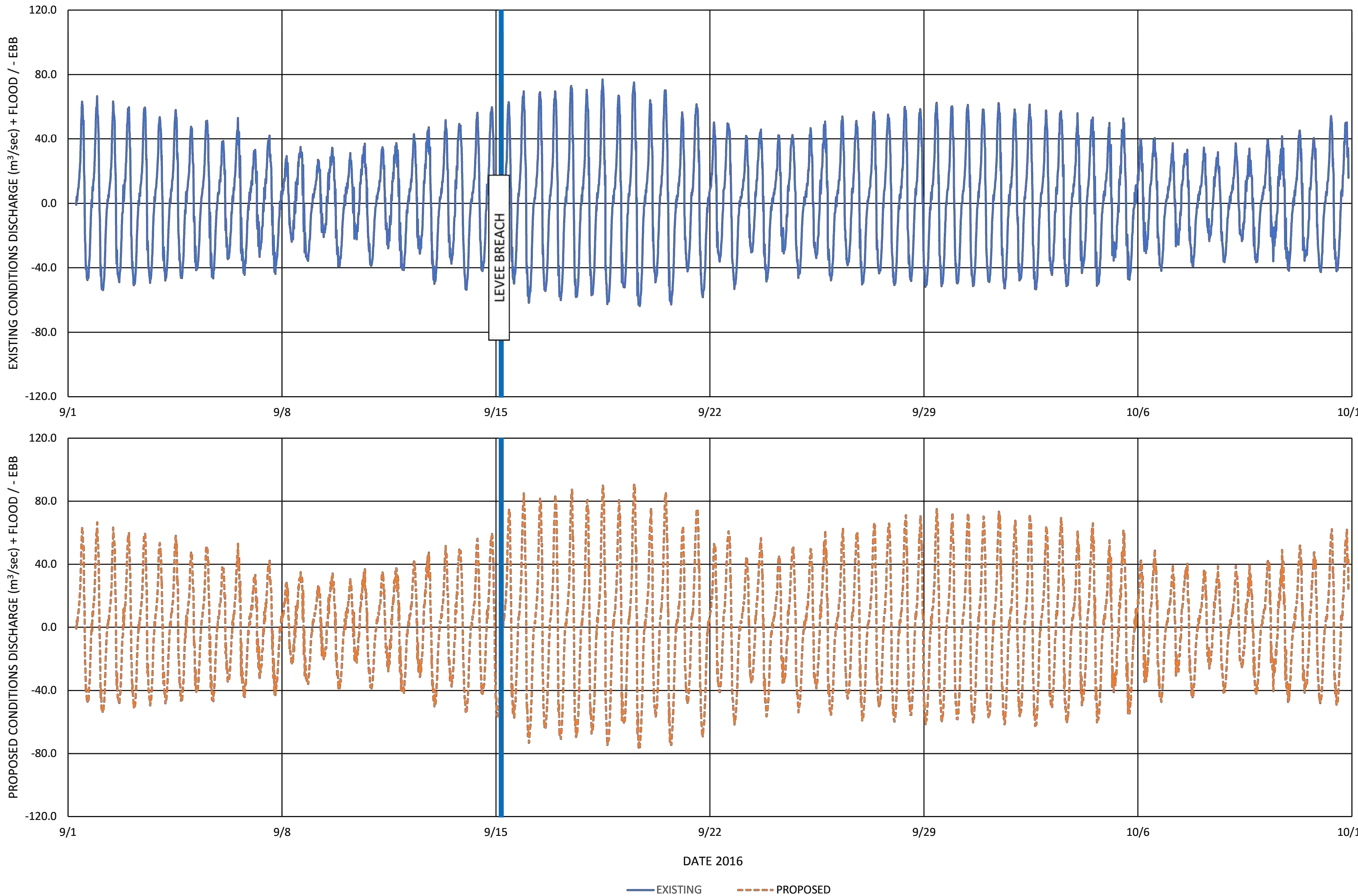
25



U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT PROPOSED DISCHARGE AND CUMULATIVE SEDIMENT FLUX AT WADULH LAGOON ENTRANCE		FIGURE 26



U.S. FISH AND WILDLIFE SERVICE ARCATA FISH AND WILDLIFE OFFICE COASTAL PROGRAM ARCATA, CA 95519	WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT EXISTING AND PROPOSED WATER SURFACE ELEVATION AT LOWER WADULH		FIGURE 27



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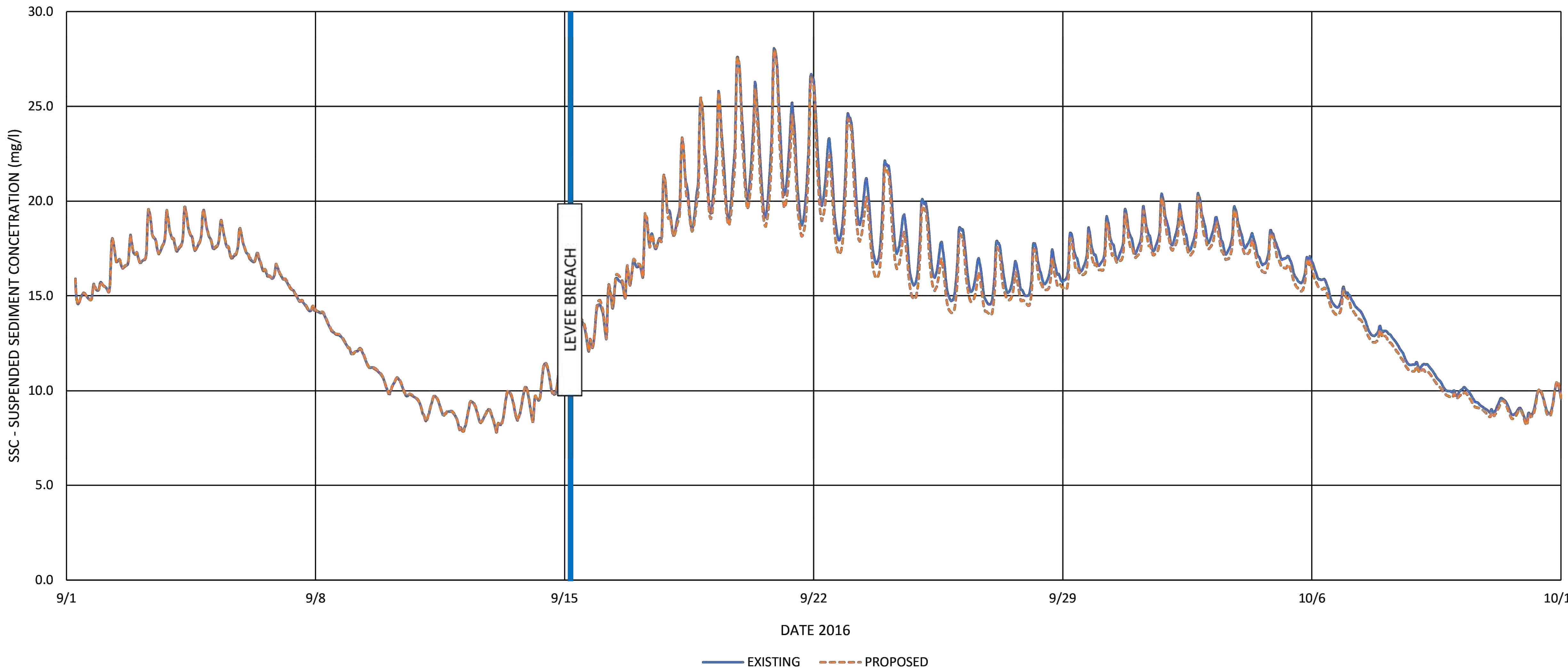
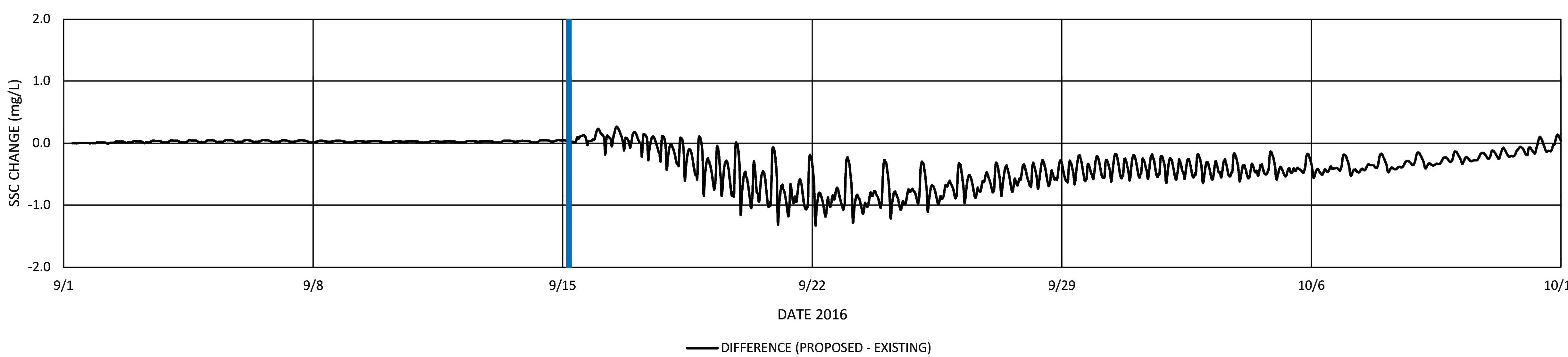
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED DISCHARGE AT LOWER WADULH

FIGURE

28





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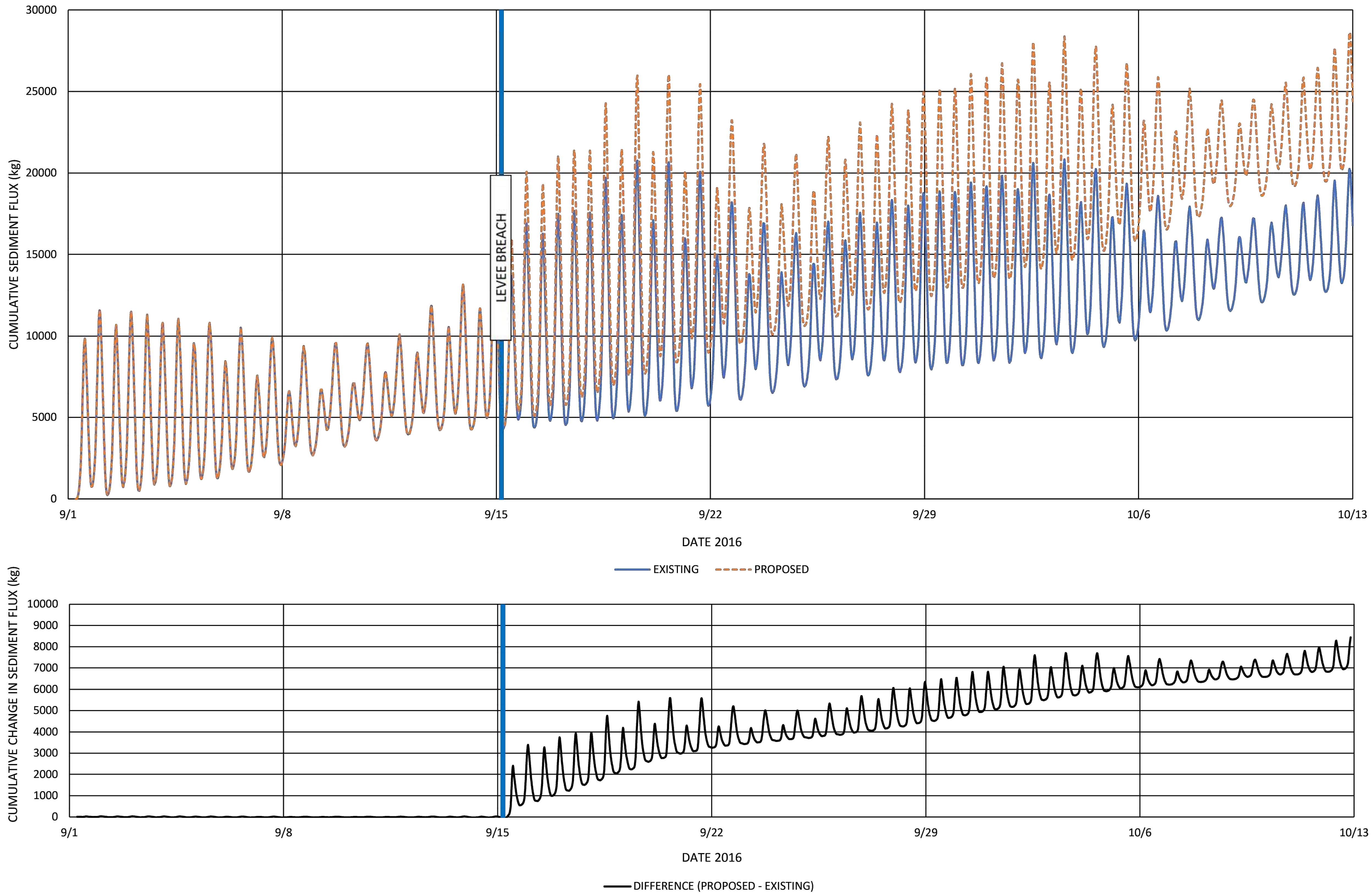
ARCATA, CA 95519

WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT
EXISTING AND PROPOSED SUSPENDED SEDIMENT CONCENTRATION
AT LOWER WADULH

FIGURE
29



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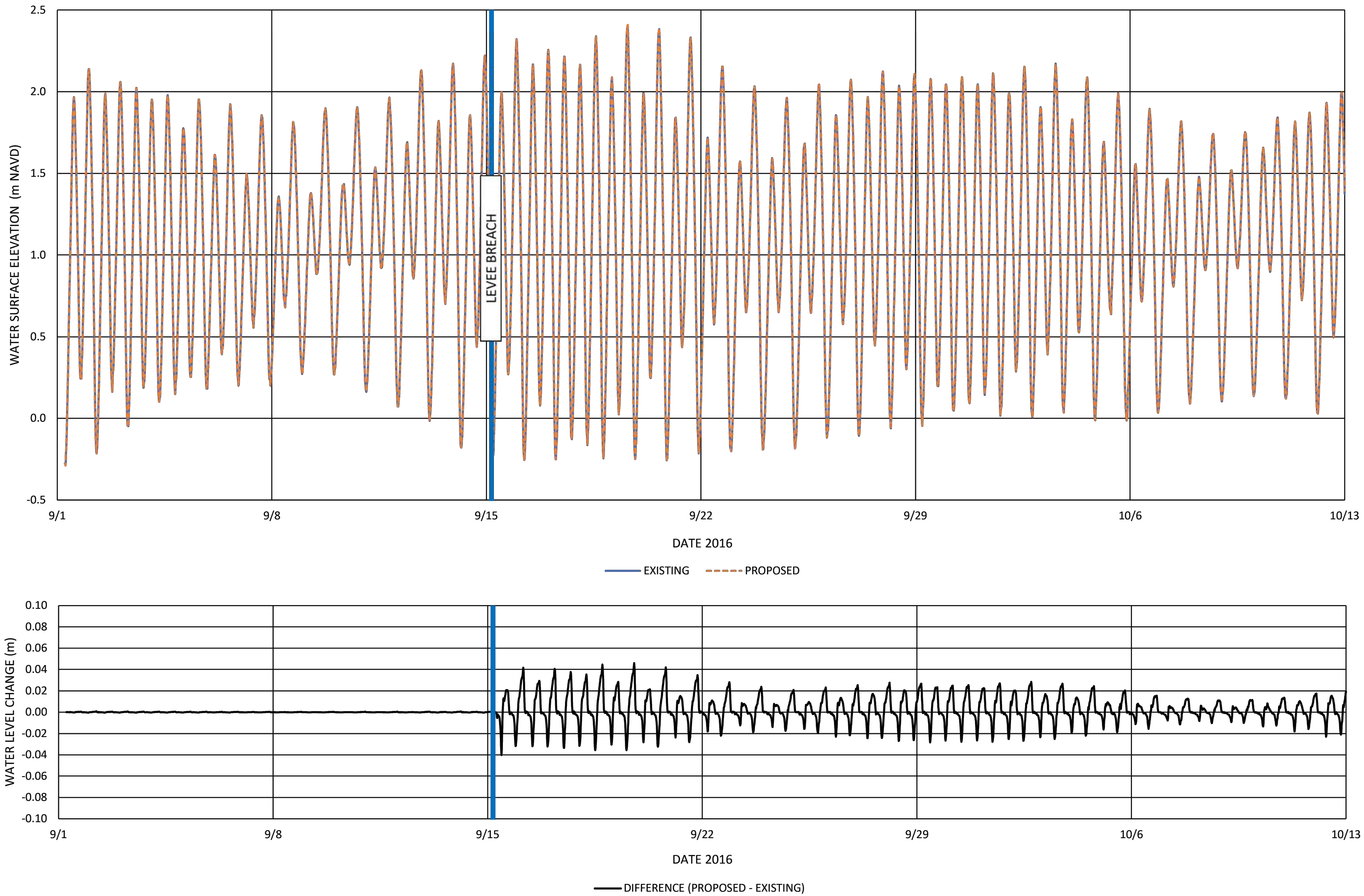
ARCATA, CA 95519

WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED CUMULATIVE SEDIMENT FLUX AT LOWER WADULH

FIGURE

30



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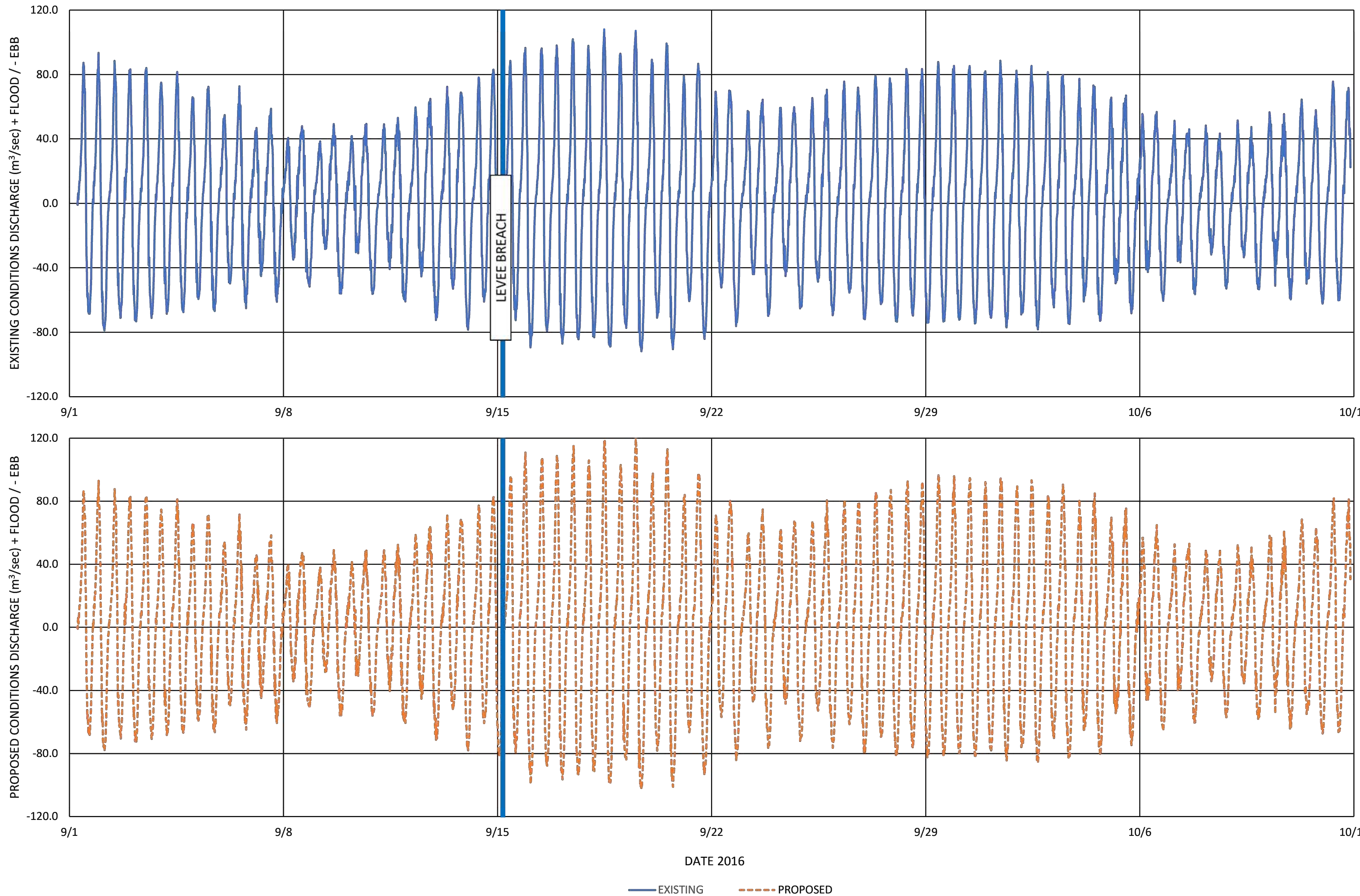
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED WATER SURFACE ELEVATION AT LOWER LAGOON

FIGURE

31



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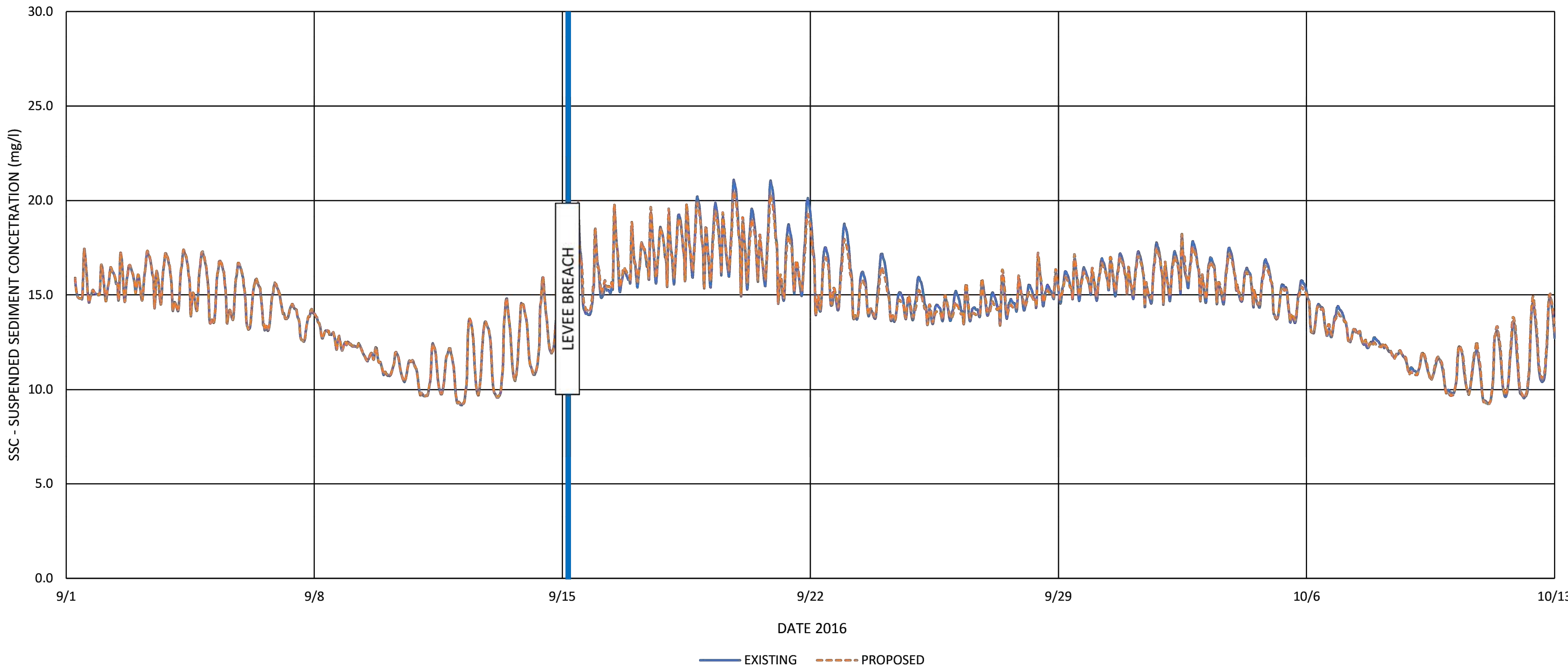
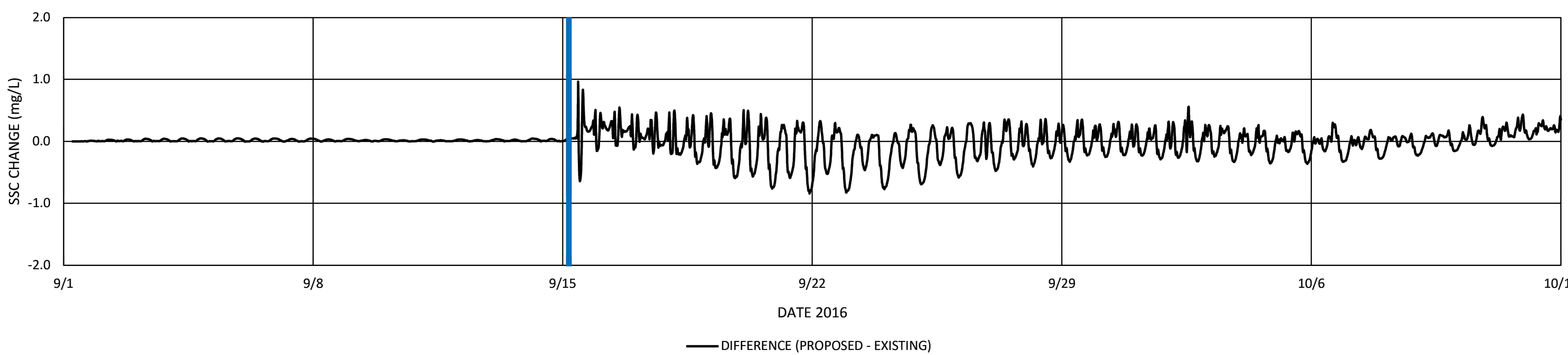
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED DISCHARGE AT LOWER LAGOON

FIGURE

32





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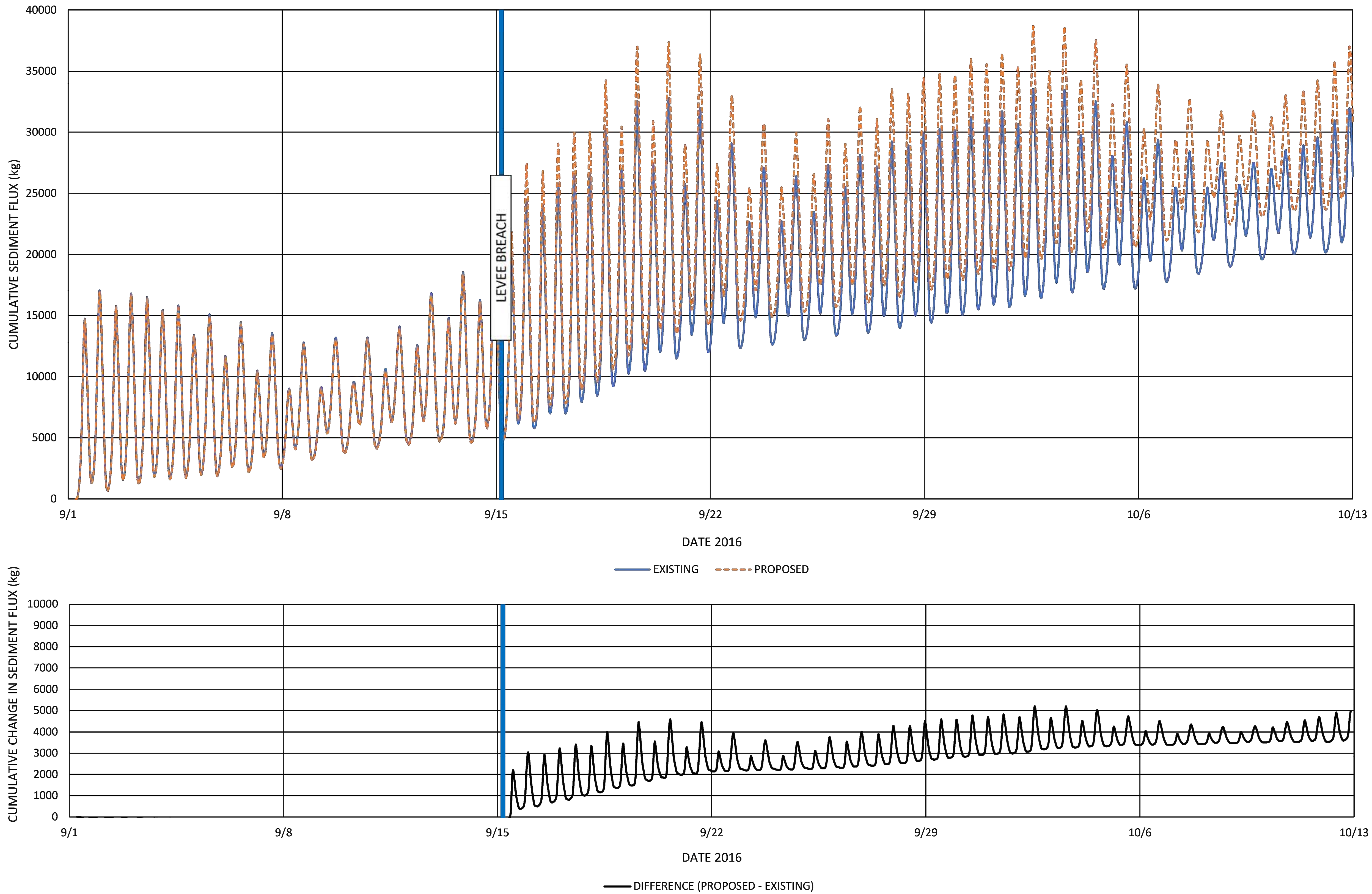
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED SUSPENDED SEDIMENT CONCENTRATION AT LOWER LAGOON

FIGURE

33



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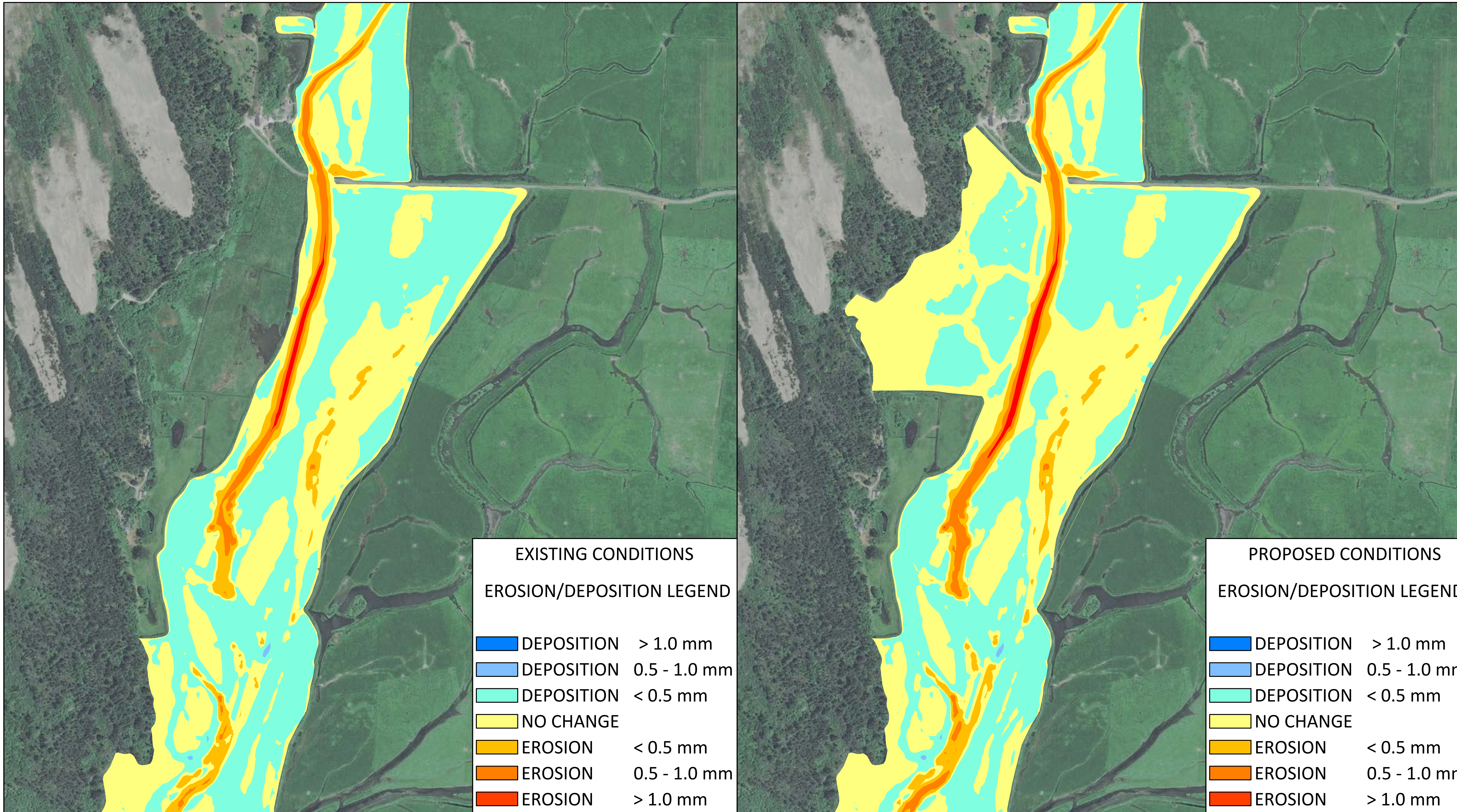
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

EXISTING AND PROPOSED CUMULATIVE SEDIMENT FLUX AT LOWER LAGOON

FIGURE

34



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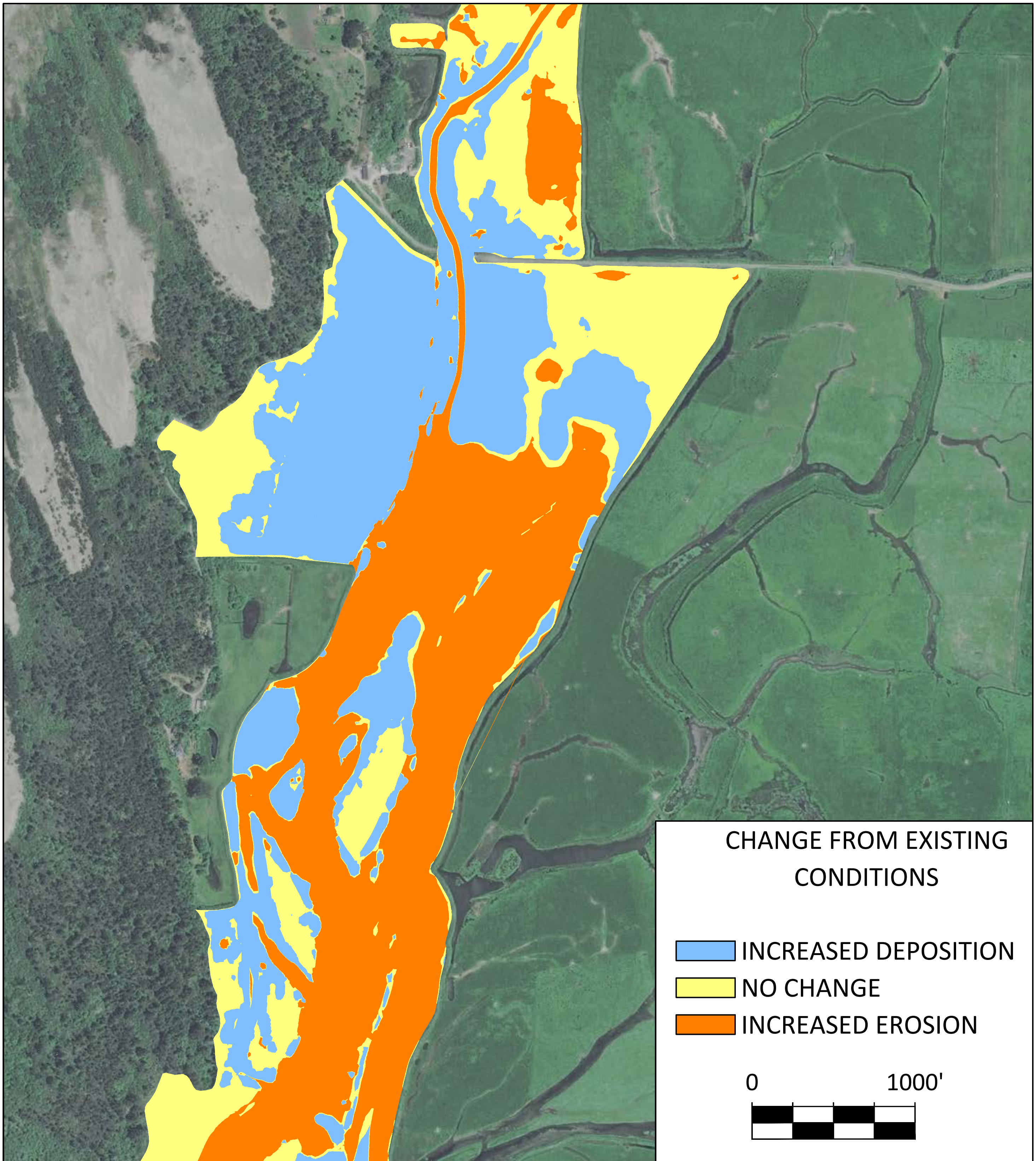
WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT
EXISTING AND PROPOSED BED ELEVATION CHANGE NEAR PROJECT AREA
IMAGE: DIGITAL GLOBE 1983

0 1000'

FIGURE
35



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WADULH LAGOON TIDAL WETLAND ENHANCEMENT PROJECT

CHANGE IN EROSION AND DEPOSITION FROM EXISTING CONDITIONS

IMAGE: DIGITAL GLOBE 2023

FIGURE

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