Attachment 5
Hydrodynamics and Sediment Transport Discipline Report

CAPITOL LAKE – DESCHUTES ESTUARY

Long-Term Management Project Environmental Impact Statement

Hydrodynamics and Sediment Transport Discipline Report

Prepared for:

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This document and the methodology upon which the analysis was conducted has been reviewed by an independent third-party expert or experts. Third party reviews can be used in an EIS process to ensure technical analyses are conducted using industry-recognized best practices and include a reasonable level of analysis to allow for the comparison of alternatives, consistent with the requirements of the State Environmental Policy Act (SEPA). Third party review is not required under SEPA, but is considered an opportunity to provide independent review of the technical analyses conducted by the EIS project team that is also made up of members with expertise in the disciplines that are being studied.

Enterprise Services wishes to acknowledge the efforts of the following third-party experts that reviewed this document:

Alex Horner-Devine, PhD; Professor, Department of Civil and Environmental Engineering, University of Washington.

Ioannis Y. Georgiou, PhD; Director of Coastal and Deltaic Systems Modeling, Water Institute of the Gulf and Associate Professor, Department of Environmental Sciences, University of New Orleans.

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Executive Summary

Moffatt & Nichol (M&N), as a member of the Capitol Lake –Deschutes Estuary Long-term Management Environmental Impact Statement (EIS) project team, performed a numerical modeling study of hydrodynamics and sediment transport for the Capitol Lake –Deschutes Estuary for the project alternatives. These included a Managed Lake, Estuary, Hybrid, and a No Action Alternative.

The objective of this numerical modeling study is to compare the four alternatives quantitatively under analysis scenarios in terms of: (a) maximum water levels and depth-averaged flow velocities; (b) extent of potential upland flooding; and (c) cumulative erosion and deposition patterns within the study area. The model domain (study area) used in this study included the Capitol Lake Basin (South Basin, Middle Basin, and North Basin) as well as the East and West Bays of Budd Inlet extending to Gull Harbor.

The Capitol Lake – Deschutes Estuary includes the 260-acre Capitol Lake Basin, located on the Washington State Capitol Campus, in Olympia, Washington. Long-term management strategies and actions are needed to address issues in the Capitol Lake – Deschutes Estuary project area. The results of this numerical modeling study are documented as part of the EIS, which is being prepared to evaluate the potential environmental impacts of the project alternatives and determine how these alternatives meet the long-term management objectives identified for the waterbody.

The three-dimensional (3D) modeling was performed using the state-of-the-art process-based hydrodynamic-morphologic modeling system, Delft3D, developed by Deltares. Water level data measured at the 5th Avenue Dam during a low, a median, and a high flow period in 2017 were used to calibrate the hydrodynamic model. Pattern and rates of erosion and deposition obtained by comparison of bathymetric surveys in 2013 and 2020 were used to calibrate the sediment transport model. The model calibration showed that the model captured the main hydrodynamic-morphologic processes and model results agreed with field measurements. The model was then used to simulate the following scenarios for the four alternatives for two extreme storm events:

- 'Without relative sea level rise (RSLR)' conditions - The differences in maximum water levels, peak flow velocities, extent of upland inundation, and sediment erosion/deposition in the study area was determined for the project alternatives for two extreme storm events.

- 'With RSLR' conditions (includes a 0.61 m future increase in RSLR applied as a relative, i.e. local, upward shift in offshore water level boundary condition) – The differences in maximum water levels, peak flow velocities, extent of upland inundation, and sediment erosion/deposition in the study area were determined for the project alternatives for two extreme storm events.

Main findings of the hydrodynamic simulations are as follows:

- Under the Estuary and Hybrid Alternatives, the tidal connection with Budd Inlet is immediately restored after removal of the 5th Avenue Dam and water levels within the Capitol Lake Basin are mostly controlled by tidal fluctuations in Budd Inlet.
- With an extreme tidal level event, the maximum water levels will be higher for the Estuary and Hybrid Alternatives than the No Action and Managed Lake Alternatives. With a more extreme river inflow, the maximum water levels will be higher for the No Action and Managed Lake Alternatives than the Estuary and Hybrid Alternatives.
- Model results showed that incorporating 0.61 m of RSLR results in higher maximum water levels and greater extent of upland flooding under all four alternatives.

Main findings of the sediment transport and morphologic simulations are as follows:

- The Managed Lake Alternative can result in increased (4%) sediment deposition within the North Basin and small changes (< 4%) in sediment deposition within Budd Inlet under extreme hydrologic events, compared to the No Action Alternative. This is likely due to deepening of the North Basin under the Managed Lake Alternative, which would create a more effective settling basin for the sediments.
- The Estuary Alternative, compared to the No Action Alternative, can increase sediment deposition within Budd Inlet by up to 283% and decrease deposition within North Basin by approximately 64% under extreme hydrologic events. These changes in deposition rates and patterns occur because the river-borne sediments are transported into Budd Inlet instead of settling within the North Basin during extreme hydrologic events.
- To reduce sediment deposition on the east side of West Bay within Budd Inlet for the Estuary Alternative, various measures (including a sediment trap, a sediment control structure, dredging the river channel, and combination of these measures) as alterations to the Estuary Alternative were evaluated. The effectiveness of these measures at reducing sediment deposition in Budd Inlet were considered along with regulatory requirements and potential environmental impacts on aquatic habitat. Model results suggest that having an active monitoring/dredging program would be the most effective mitigation measure (it would not prevent sedimentation, but it could mitigate impacts to safe navigation). The location of long-term maintenance dredging must be considered relative to potentially impacted land uses, and occur at a frequency to avoid or minimize potential impacts to Olympia Yacht Club, Marinas, Port of Olympia, and the Federal Navigation Channel in Budd Inlet

- The Hybrid Alternative, similar to the Estuary Alternative, results in increased sediment deposition within Budd Inlet and a decrease in deposition within North Basin under extreme flow events. The Hybrid Alternative, compared to the Estuary Alternative, can result in higher (<23%) rates of deposition within Budd Inlet and an erosional pattern within North Basin instead of a depositional pattern. This is most likely due to acceleration of the flow within the North Basin as flow is forced to bend around the barrier wall of the reflecting pool. This acceleration of the flow results in increased erosion within the North Basin and increased deposition within Budd Inlet compared to the Estuary Alternative.
- Model results show that pre-dredging Capitol Lake Basin, before the 5th Avenue Dam is removed, is effective in reducing sediment deposition in Budd Inlet. Sediment deposition at the Olympia Yacht Club, for example, reduces by approximately 48% when pre-dredging is assumed. All project alternatives include pre-dredging.
- Numerical simulation of the four alternatives were conducted with 0.61 m (2 ft) of RSLR. Model results showed that the project alternatives generally perform similarly with and without 0.61 m of RSLR. However, the erosion/deposition rates are lower for simulations with RSLR. This is likely due to the higher water levels associated with RSLR resulting in reduced current velocities and reduced erosion of sediments in the Middle Basin.

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List of Acronyms and Abbreviations

Acronyms/ Abbreviations	Definition
ΔT	Time delay or lag
2D	Two-dimensional
3D	Three-dimensional
BNSF	Burlington-Santa Fe
City Datum	City of Olympia datum
CLAMP	Capitol Lake Adaptive Management Plan
CO-OPS	Center for Operational Oceanographic Products and Services
cy/yr	Cubic yards per year
DEM	Digital Elevation Model(s)
EIS	Environmental Impact Study
Enterprise Services	Washington State Department of Enterprise Services
ERDC	U.S. Army Engineer Research and Development Center
FEMA	Federal Emergency Management Agency
FRIS	Flood Risk Information System
I-5	Interstate 5
IOA	Index of Agreement
LiDAR	Light Detection and Ranging
M&N	Moffatt & Nichol
MAE	Mean Absolute Error
ME	Mean Error
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
MORFAC	Morphological Factor
MSL	Mean Sea Level
MTL	Mean Tide Level
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988

Acronyms/ Abbreviations	Definition
NGS	National Geodetic Survey
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
R	Correlation Coefficient
RMS	Root Mean Square
RMSE	Root Mean Square Error
RSLR	Relative Sea Level Rise
RTC	Real-Time Control
SLR	Sea Level Rise
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WDFW	Washington Department of Fish & Wildlife
WGS84	World Geodetic System 1984

1.0 Introduction and Project Description

1.1 PROJECT DESCRIPTION

The Capitol Lake – Deschutes Estuary includes the 260-acre Capitol Lake Basin, located on the Washington State Capitol Campus, in Olympia, Washington. The waterbody has long been a valued community amenity. Capitol Lake was formed in 1951 following construction of a dam and provided an important recreational resource. Historically, the Deschutes Estuary was used by local tribes for subsistence and ceremonial purposes. Today, the expansive waterbody is closed to active public use. There are a number of environmental issues including the presence of invasive species, exceedances of water quality (WQ) standards, and inadequate sediment management.

The Washington State Department of Enterprise Services (Enterprise Services) is responsible for the stewardship, preservation, operation, and maintenance of the Capitol Lake Basin. The 260-acre Capitol Lake Basin is maintained by Enterprise Services under long-term lease agreement from the Washington Department of Natural Resources.

In 2016, as part of Phase 1 of long-term planning, a diverse group of stakeholders, in collaboration with the state, identified shared goals for long-term management and agreed an Environmental Impact Statement (EIS) was needed to evaluate a range of alternatives and identify a preferred alternative. In 2018, the state began the EIS process. The EIS evaluates four alternatives, including a Managed Lake, Estuary, Hybrid, and a No Action Alternative.

The long-term management alternatives are evaluated against the shared project goals of: improving water quality; managing sediment accumulation and future deposition; improving ecological functions; and enhancing community use of the resource. Refer to Figure 1.1 for the project area for long-term management. The Final EIS will identify a preferred environmentally and economically sustainable long-term management alternative for the Capitol Lake – Deschutes Estuary.

The EIS process maintains engagement with the existing Work Groups, which include the local governments, resource agencies, and tribe. It also provides for expanded engagement opportunities for the public, such as a community sounding board.

Figure 1.1 Project Area

1.2 SUMMARY OF PROJECT ALTERNATIVES

1.2.1 Managed Lake Alternative

The Managed Lake Alternative would retain the 5th Avenue Dam in its existing configuration. The 5th Avenue Dam would be overhauled to significantly extend the serviceable life of the structure. The reflecting pool within the North Basin would be maintained, and active recreational use would be restored in this area. Sediment would be managed through initial construction dredging and recurring maintenance dredging in the North Basin only. Sediment from construction dredging would be used to create habitat areas in the Middle Basin to support improved ecological function, habitat complexity, and diversity. Sediment would continue to accumulate and over time would promote a transition to freshwater wetlands in the South and Middle Basins. Boardwalks, a 5th Avenue Pedestrian Bridge, a dock, and a boat launch would be constructed for community use.

If selected as the Preferred Alternative, adaptive management plans would be developed to maintain water quality, improve ecological functions, and manage invasive species during the design and permitting process.

1.2.2 Estuary Alternative

Under the Estuary Alternative, the 5th Avenue Dam would be removed, and an approximately 500-foot-wide (150-meter-wide) opening would be established in its place. This would reintroduce tidal hydrology to the Capitol Lake Basin, returning the area to estuarine conditions where saltwater from Budd Inlet would mix with freshwater from the Deschutes River. Sediment would be managed through initial construction dredging in the Capitol Lake Basin and recurring maintenance dredging within West Bay. Dredged materials from construction dredging would be used to create habitat areas in the Middle and North Basins to promote ecological diversity, though tideflats would be the predominant habitat type. Boardwalks, a 5th Avenue Pedestrian Bridge, a dock, and a boat launch would be constructed for community use. This alternative also includes stabilization along the entire length of Deschutes Parkway to avoid undercutting or destabilization from the tidal flow. Existing utilities and other infrastructure would be upgraded and/or protected from reintroduced tidal hydrology and saltwater conditions.

If selected as the Preferred Alternative, adaptive management plans would be developed to improve ecological functions and manage invasive species during the design and permitting process.

1.2.3 Hybrid Alternative

Under the Hybrid Alternative, the 5th Avenue Dam would be removed, and an approximately 500-foot-wide (150-meter-wide) opening would be established in its place. Tidal hydrology would be reintroduced to the western portion of the North Basin and to the Middle and South Basins. Within the North Basin, a curved and approximately 2,600-foot-long (790-meter-long) barrier wall with a walkway would be constructed to create an approximately 45-acre saltwater reflecting pool adjacent to Heritage Park. A freshwater (groundwater-fed) reflecting pool was also evaluated for this EIS. Construction and maintenance of this smaller reflecting pool, in addition to restored estuarine conditions in part of the Capitol Lake Basin, gives this alternative its classification as a hybrid. Sediment would be managed through initial construction dredging in the Capitol Lake Basin and recurring maintenance dredging within West Bay. In the Middle and North Basins, constructed habitat areas would promote ecological diversity, though tideflats would be the predominant habitat type. Boardwalks, a 5th Avenue Pedestrian Bridge, a dock, and a boat launch would be constructed for community use. This alternative also includes stabilization along the entire length of Deschutes Parkway to avoid scour or destabilization. Existing utilities and other infrastructure would be upgraded and/or protected from reintroduced tidal hydrology and saltwater conditions.

If selected as the Preferred Alternative, adaptive management plans would be developed before operation of the alternative to improve ecological functions and manage invasive species during the design and permitting process. Adaptive management would also be needed for a freshwater reflecting pool, but not for a saltwater reflecting pool.

1.2.4 No Action Alternative

The No Action Alternative represents the most likely future expected in the absence of implementing a long-term management project. The No Action Alternative would persist if a Preferred Alternative is not identified and/or if funding is not acquired to implement the Preferred Alternative. A No Action Alternative is a required element in a SEPA EIS and provides a baseline against which the impacts of the action alternatives (Managed Lake, Estuary, Hybrid) can be evaluated and compared.

The No Action Alternative would retain the 5th Avenue Dam in its current configuration, with limited repair and maintenance activities, consistent with the scope and scale of those that have received funding and environmental approvals over the past 30 years. In the last 30 years, the repair and maintenance activities have been limited to emergency or high-priority actions, which occur sporadically as a result of need and funding appropriations.

Although Enterprise Services would not implement a long-term management project, current management activities and ongoing projects in the Capitol Lake Basin would continue. Enterprise Services would continue to implement limited nuisance and invasive species management strategies.

In the absence of a long-term management project, it is unlikely that Enterprise Services would be able to procure funding and approvals to manage sediment, improve water quality, improve ecological functions, or enhance community use. The No Action Alternative does not achieve the project goals.

1.3 CONSTRUCTION METHODS FOR THE ACTION ALTERNATIVES

This impact analysis relies on the construction method and anticipated duration for the action alternatives, which are described in detail in Chapter 2 of the EIS.

1.4 MODELING STUDY OBJECTIVE

The objective of this numerical modeling study is to compare the four alternatives quantitatively under analysis scenarios in terms of: (a) maximum water levels and current flow velocities; (b) extent of potential upland flooding; and (c) cumulative erosion and deposition patterns.

The hydrodynamic and sediment transport model will be used to simulate alternatives without and with RSLR to represent future rise in sea levels. The EIS Project Team evaluated the best available science on sea level rise (SLR), including the City of Olympia Seal Level Rise Response Plan (City of Olympia 2019) as well as the latest projections developed for the State of Washington (Miller et al. 2018) to define the "future condition" to include 0.61 m (2 ft) of RSLR.

The study area for hydrodynamics and sediment transport is defined by the Capitol Lake Basin[1], which extends from the south end at Tumwater Falls in the City of Tumwater to the north end at the 5th Avenue Dam in the City of Olympia (**Error! Reference source not found.**). The study area continues d ownstream of the Capitol Lake basin (including both West and East Bays) to Gull Harbor to capture the area that may be affected by sediment transport under certain long-term management alternatives.

1.5 BACKGROUND STUDIES

The United States Geological Survey (USGS) previously conducted hydrodynamic and sediment transport numerical modeling studies using the Delft3D software package (George et al. 2006 and Stevens et al. 2008). These previous studies provided an in-depth understanding of the system and possible changes under an Estuary Alternative. These studies found that tidal hydrology was restored immediately after dam removal, while it took approximately three to five years for the morphological changes to reach an equilibrium state. During ebb or flood tides and periods of high river discharge, the maximum flow velocity could reach over 1.5 m/s at three constriction points – under the Interstate 5 (I-5) Bridge, through the Burlington-Santa Fe (BNSF) Railroad Trestle, and the 5th Avenue Dam. During slack tides and low river flow condition, current speeds were below 0.2 m/s in most of the basin.

For morphological changes, there were some consistent trends including more sand deposition in the river channel, more mud deposition in the flanks, and decreasing rates of sedimentation volume change after dam removal.

Another study focused on flood management is a hydraulic study performed by Moffatt & Nichol (M&N 2008). The study investigated the dam operation and the Managed Lake, Estuary, and Hybrid Alternatives in terms of peak water levels in the Capitol Lake Basin with and without SLR using the

[1] The Capitol Lake Basin was created from the Capitol Lake – Deschutes Estuary in southern Puget Sound by constructing an earthen dam, 80-foot-wide tide gate, and concrete spillways in 1951. The modern assembly consists of two radial gates to regulate lake level and a fish ladder to allow fish to pass the dam and access upstream habitat.

HEC-RAS software package. The alternatives evaluated in the (M&N 2008) hydraulic study were different from the alternatives evaluated here in this study.

This modeling effort will build upon and improve the previously conducted modeling work. The USGS team that conducted the previous studies has graciously offered to share their insights with the M&N team throughout the EIS project, as needed.

2.0 Existing Conditions and Data Sources

2.1 CAPITOL LAKE BASIN

There are three basins – North Basin, Middle Basin, and South Basin in Capitol Lake (**Error! Reference source not found.**). The North Basin is separated from Budd Inlet by the 5th Avenue Dam, constructed in 1951. The BNSF Railroad Trestle, which splits the North and Middle Basins, existed before the dam was constructed. The I-5 overpass bridge was completed in 1957 and splits the South Basin from the Middle Basin. Percival Creek flows into the Middle Basin at Percival Cove. The size of each basin (North, Middle -excluding Percival Cove, and South) is approximately 96 acres, 120 acres, and 30 acres, respectively; Percival Cove's size is approximately 16 acres. The total area of Capitol Lake Basin is approximately 260 acres.

The Capitol Lake Basin follows a north-south direction with the Deschutes River entering from the south via Tumwater Falls, and West Bay of Budd Inlet to the north (**Error! Reference source not found.**).

2.2 WATER LEVELS AND TIDAL DATUMS

2.2.1 Water Levels

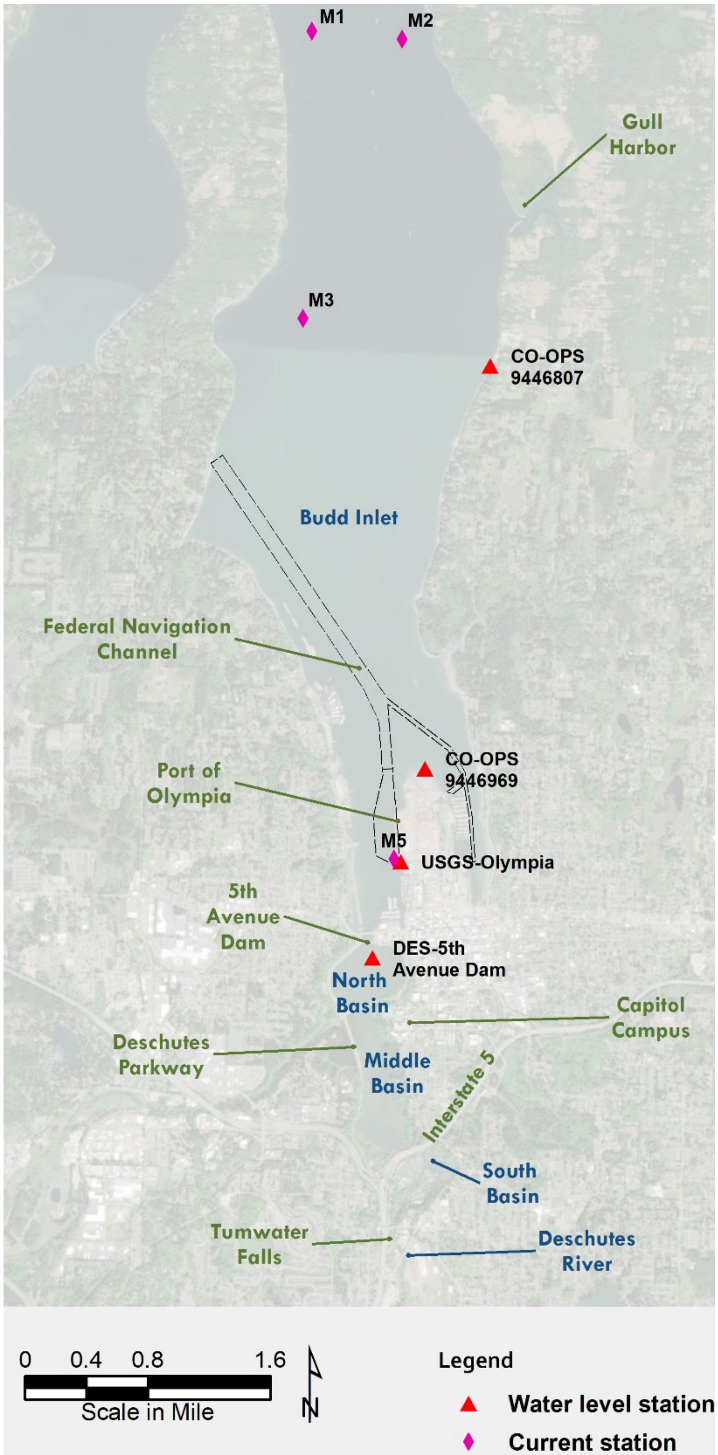
Water levels from three stations were collected in Budd Inlet and Capitol Lake from various resources including the National Oceanic and Atmospheric Administration's (NOAA's) Center for Operational Oceanographic Products and Services (CO-OPS), USGS, and Enterprise Services. Detailed information about the data is listed in Table 2-1 . The station locations are shown in Figure 2-1. Additionally, the Enterprise Services – 5th Avenue Dam Station contains two water level gages at the east and west gates upstream (south) of the dam with the same data coverage and reporting frequency.

Table 2-1 Water Level Gage Station Information

Source	Station	Start Date	End Date	Frequency
NOAA CO-OPS	9446807 Budd Inlet, South of Gull Harbor, WA	04/26/1996	12/03/1996	6-min
NOAA CO-OPS	9446807 Budd Inlet, South of Gull Harbor, WA	04/26/1996	12/03/1996	60-min
NOAA CO-OPS	9446969	04/01/1977	03/31/1978	Monthly
USGS	Olympia	11/05/2018	present	15-min
Enterprise Services†	5th Avenue Dam	04/27/2016	04/01/2019	5-min

† Water level measurements are available on the Capitol Lake side (upstream of the 5th Avenue Dam).

Figure 2-1 Location Map of Water Level and Current Measurement Stations



2.2.2 Vertical Datum

Vertical datum for this study was selected to be the North American Vertical Datum of 1988 (NAVD88). Tidal datums for Olympia referenced to NAVD88, Mean Lower Low Water (MLLW), and North American Geodetic Vertical Datum of 1929 (NGVD29) for the 1983-2001 tidal epoch are listed in Table 2-2. Extreme (1-, 10-, and 100-yr) water levels are listed in Table 2-2 as well, per AECOM (2019). These extreme water levels reflect a temporary increase in coastal water level due to a combination of high astronomical tide and storm surge due to low barometric pressure and local winds (not including wave effects at the shoreline).

Table 2-2 Water Levels and Tidal Datums for Olympia (NOAA Station 9446969, Olympia, WA)

Datum	NAVD88	MLLW	NGVD29
100-yr Water Level*	+4.3 m (+14.10 ft)	+5.5 m (+18.13 ft)	+3.3 m (+10.7 ft)
10-yr Water Level*	+4.1 m (+13.60 ft)	+5.4 m (+17.63 ft)	+3.1 m (+10.2 ft)
1-yr Water Level*	+3.8 m (+12.31 ft)	+5.0 m (16.34 ft)	+2.7 m (+8.9 ft)
Mean Higher High Water (MHHW)	+3.2 m (+10.5 ft)	+4.4 m (+14.6 ft)	+2.2 m (+7.2 ft)
Mean Sea Level (MSL)	+1.3 m (+4.3 ft)	+2.5 m (+8.4 ft)	+0.3 m (+0.9 ft)
Mean Tide Level (MTL)	+1.3 m (+4.3 ft)	+2.5 m (+8.4 ft)	+0.3 m (+0.9 ft)
NGVD29	+1.0 m (+3.4 ft)	+2.3 m (+7.4 ft)	0.0 m (0.0 ft)
NAVD88	0.0 m (0.0 ft)	+1.2 m (+4.0 ft)	-1.0 m (-3.4 ft)
MLLW	-1.2 m (-4.0 ft)	0.0 m (0.0 ft)	-2.3 m (-7.4 ft)

* Extreme water levels per AECOM (2019)

2.2.3 Key Elevations

Table 2-3 lists key elevations for reference to be used in this study.

Table 2-3 Key Elevations in Capitol Lake (Quantum Spatial 2017, M&N 2007, M&N 2008)

Element	Elevation (NAVD88)
Arc of Statehood Lake Wall Crest	+4.3 m (+14.1 ft)
Arc of Statehood Steps Crest	+4.0 m (+13.1 ft)
Top of Spillway	+1.2 m (-3.8 ft)

Element	Elevation (NAVD88)
Winter Lake Levels	+2.6 m (+8.6 ft)
Summer Lake Levels	+2.9 m (+9.6 ft)

2.3 PROJECT HORIZONTAL COORDINATE SYSTEM

Horizontal coordinate system for this study was selected to be the Washington State Plane South North American Datum of 1983 (NAD83) in meters.

2.4 BATHYMETRY/TOPOGRAPHY

Existing water depth within the basin ranges from approximately 0.8 to 21.6 feet during summer and 1.8 to 22.6 feet during winter. The deepest water depths are at the self-scouring hole in the North Basin immediately south of 5th Avenue, and shallowest water depths are in the South Basin south of the I-5 Bridge. The following bathymetry and topography data sets were identified:

- 2014 NOAA Puget Sound, WA 1/3 arc-second Digital Elevation Model (DEM) compiled from various sources (NOAA 2014);
- 2011, 2016, 2017, 2018, and 2019 United States Army Corps of Engineers (USACE) condition survey data in the federal channel and turning basin (USACE 2020);
- 2015 City of Olympia Light Detection and Ranging (LiDAR) survey by Quantum Spatial (Quantum Spatial 2015);
- 2004 USGS hydrographic survey of Capitol Lake Basin and southern Budd Inlet (USGS 2005). Detailed review of this survey data set and comparison with other data sets indicated that the vertical datum for this survey is incorrect. Therefore, this survey was discarded in this study;
- 2013 TerraSond hydrographic survey of Capitol Lake Basin (TerraSond 2013);
- 2015 NewFields hydrographic survey of North Basin (NewFields 2015); and
- 2020 eTrac hydrographic survey of Capitol Lake (eTrac 2020).

Original horizontal coordinate system and vertical datum information of these data sets are listed in Table 2-4. All datasets were converted to project horizontal coordinate system of Washington State Plane South in meters and vertical datum of NAVD88 in meters.

Table 2-4 Horizontal and Vertical Reference Information of Bathymetric and Topographic Datasets

Source	Survey Type/Name	Survey Time	Horizontal Reference	Vertical Datum – Unit
NOAA	Puget Sound DEM	2014+	WGS84 Lat/Lon	NAVD88 – meters
USACE	Bathymetric	12/2011, 02/2016 to 01/2019	NAD83 Washington State Plane South – feet	MLLW – feet
Quantum Spatial	LiDAR	02/2015	NAD83 Washington State Plane South – feet	NAVD88 – feet
TerraSond	Bathymetric	03/2013	NAD83 Washington State Plane South – feet	NAVD88 – feet
NewFields	Bathymetric	04/2015	NAD83 Washington State Plane South – meters	NAVD88 – meters
eTrac	Bathymetric	01/2020	NAD83 Washington State Plane South – feet	NAVD88 – feet

+ NOAA DEM was compiled from NOAA NOS (1984-2011), USACE (2008-2014), PSLC-Tenix LADS (2001), PSLC (1996-2012), and USGS NED (1999-2015).

WGS84=World Geodetic System 1984

Coverages of the elevation datasets are shown in Figure 2-2 through Figure 2-7.

Figure 2-2 Elevation Dataset Coverage of NOAA DEM 2014

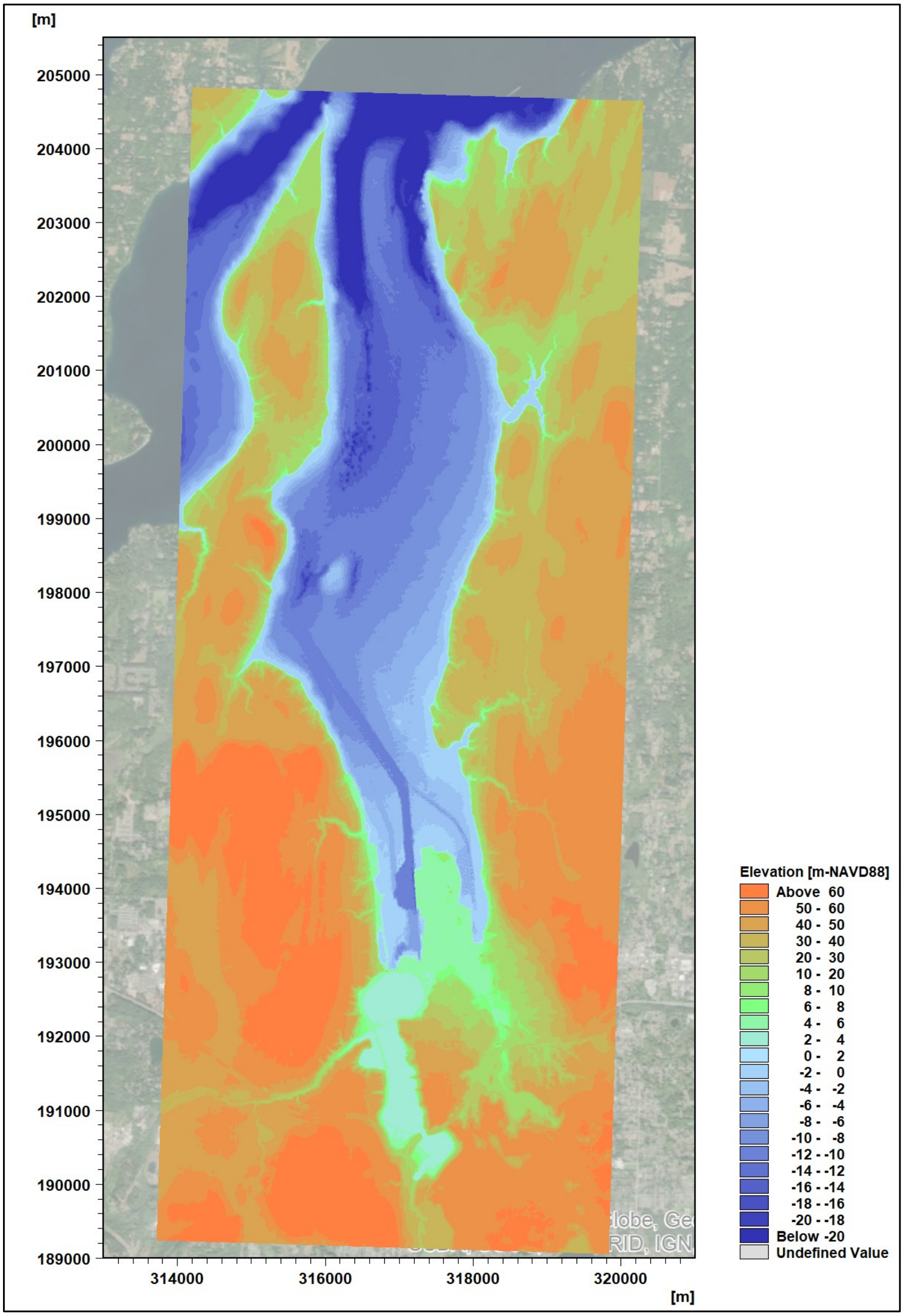


Figure 2-3 Coverage of USACE 2019 Hydrographic Dataset

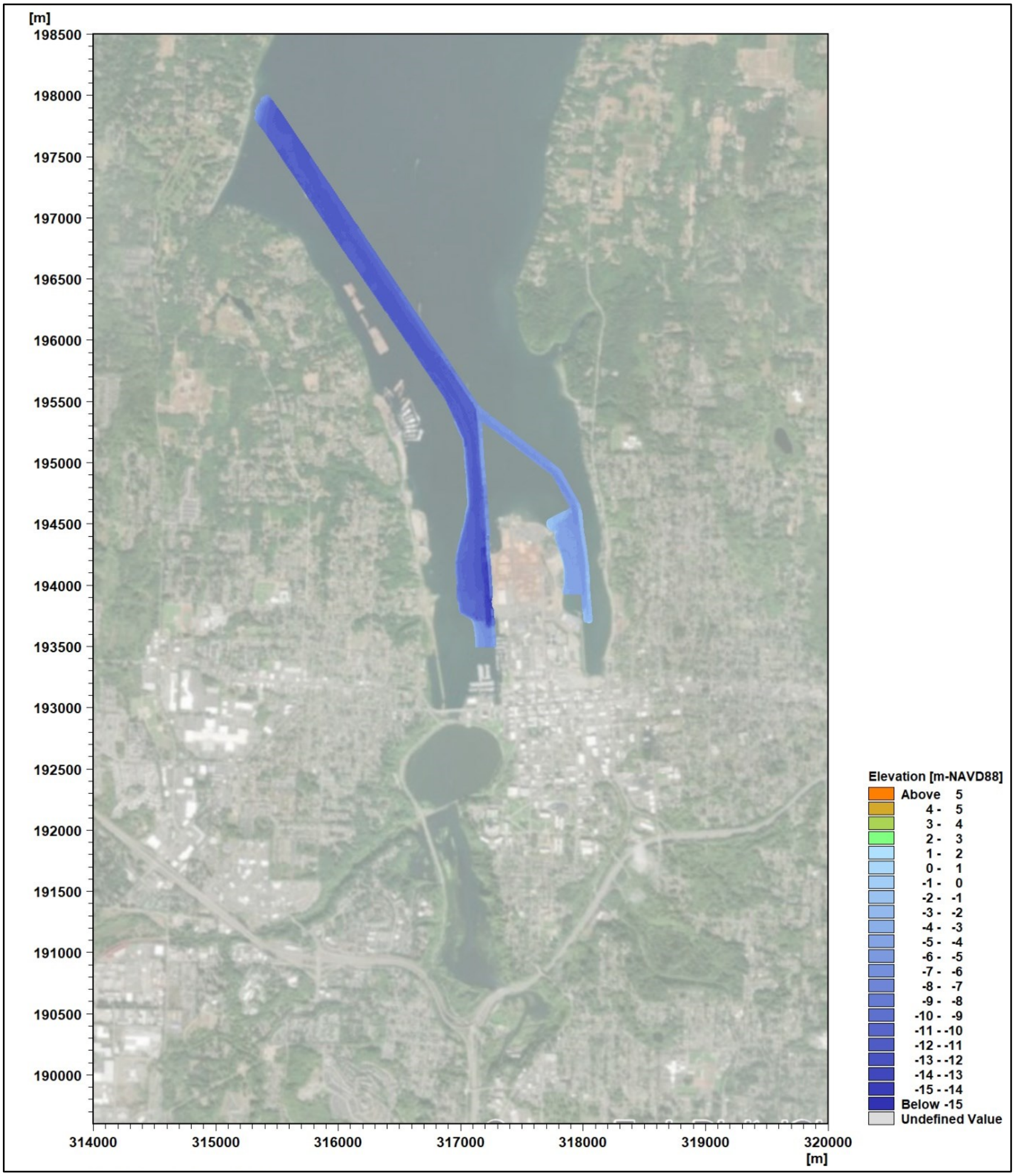


Figure 2-4 Coverage of Quantum Spatial 2015 LiDAR Dataset

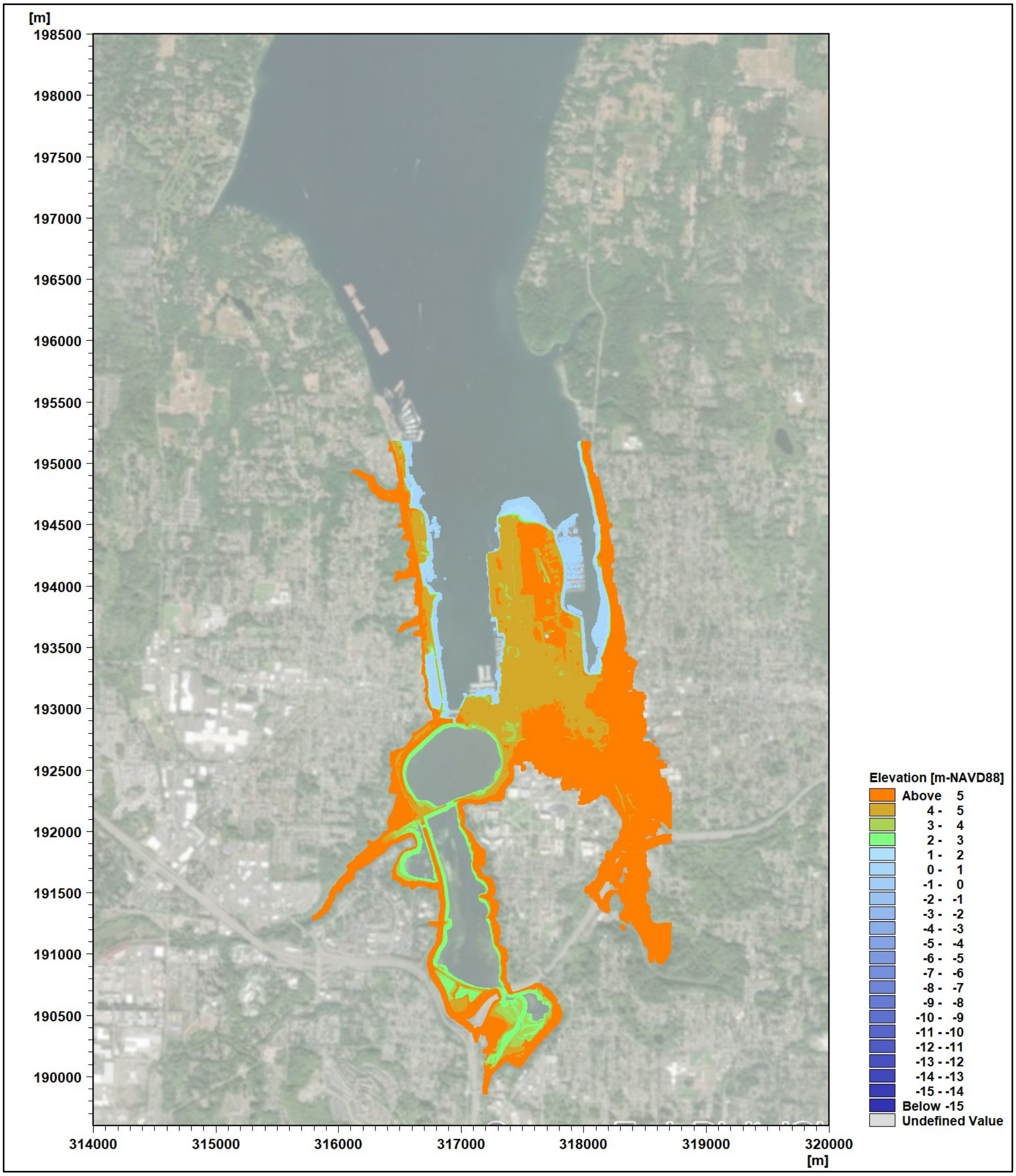


Figure 2-5 Coverage of TerraSond 2013 Hydrographic Survey Data Set

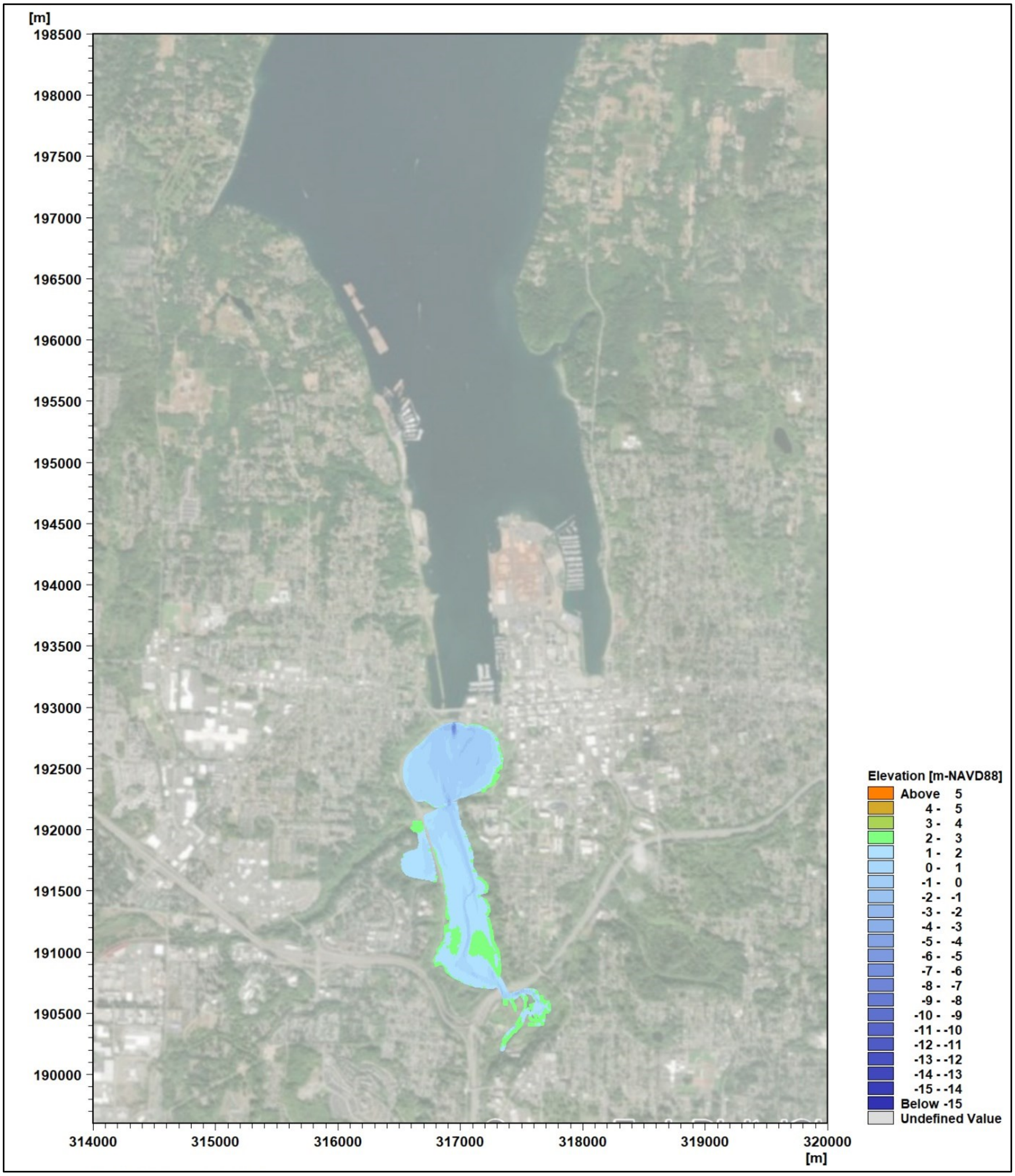


Figure 2-6: Coverage of the NewFields 2015 Hydrographic Survey Dataset

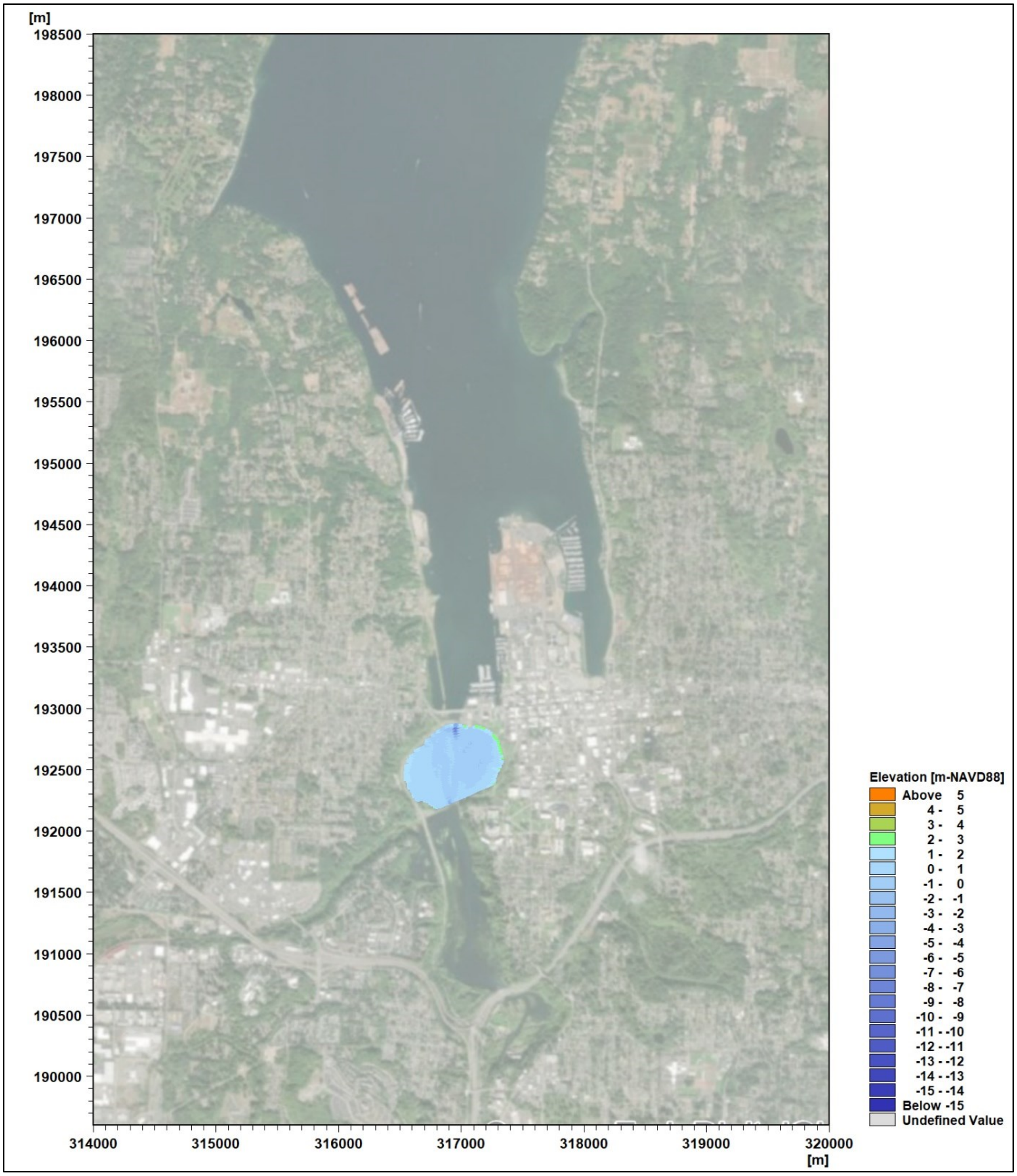
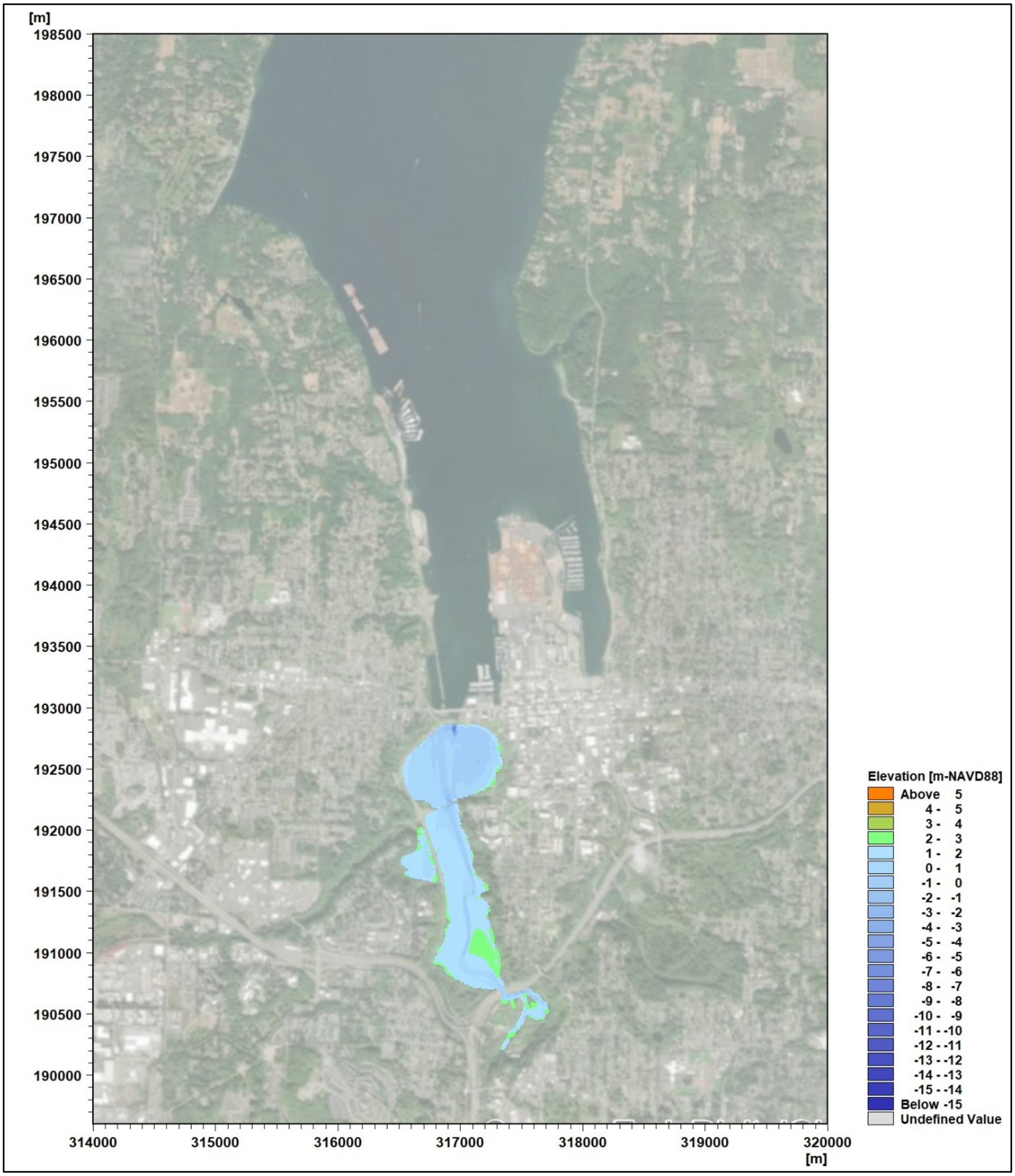


Figure 2-7 Coverage of eTrac 2020 Hydrographic Dataset



2.5 FRESHWATER INFLOW

The Deschutes River flows into Capitol Lake, which empties into Budd Inlet. Deschutes River discharge data from two stations were collected from the USGS National Water Information System. The station locations, Deschutes River watershed, and un-gaged small watersheds from the Thurston County GeoData Center and Thurston County Resource Stewardship are shown in Figure 2-8. Discharge observations with 15-min and daily intervals are available at the four stations. Detailed information about the data is listed in Table 2-5, and 15-min and daily discharge time series are shown in Figure 2-9 through Figure 2-12.

Table 2-5 USGS River Gage Station Information

Stream Gage ID#	Start Date	End Date	Sampling Rate
12079000 Deschutes River Near Rainier, WA	10/06/1987	present	15-min
12079000 Deschutes River Near Rainier, WA	06/01/1949	present	daily
12080010 Deschutes River at E St Bridge At Tumwater, WA	10/01/1990	present	15-min
12080010 Deschutes River at E St Bridge At Tumwater, WA	05/01/1945	present	daily
12078720 Black Lake Ditch Near Olympia, WA	02/23/1988	03/19/1990	15-min
12078720 Black Lake Ditch Near Olympia, WA	02/22/1988	03/18/1990	daily
12078730 Percival Creek Near Olympia, WA	03/01/1988	03/01/1990	15-min
12078730 Percival Creek Near Olympia, WA	03/01/1988	02/28/1990	daily

Extreme statistics of the Deschutes River flow were developed using extreme value analysis based on both the daily and 15-min discharge data and are shown in Figure 2-10 and listed in Table 2-6. Previous estimates of extreme statistics by FEMA (2018) and CLAMP (2000) are listed in Table 2-6 as a reference as well.

The most severe floods for Deschutes River, as recorded at the USGS Station 12080010 on Deschutes River near E Street, is 231 cms (8,150 cfs) (daily discharge) in February 1996. FEMA (2018) notes that on January 15, 1974 a flood with a recurrence interval of approximately 100 years occurred on the Deschutes River. The Tumwater Valley Golf Course was inundated and the Olympia Brewing Company incurred some property damage during this flood.

Figure 2-8 USGS Stream Gages and Watersheds

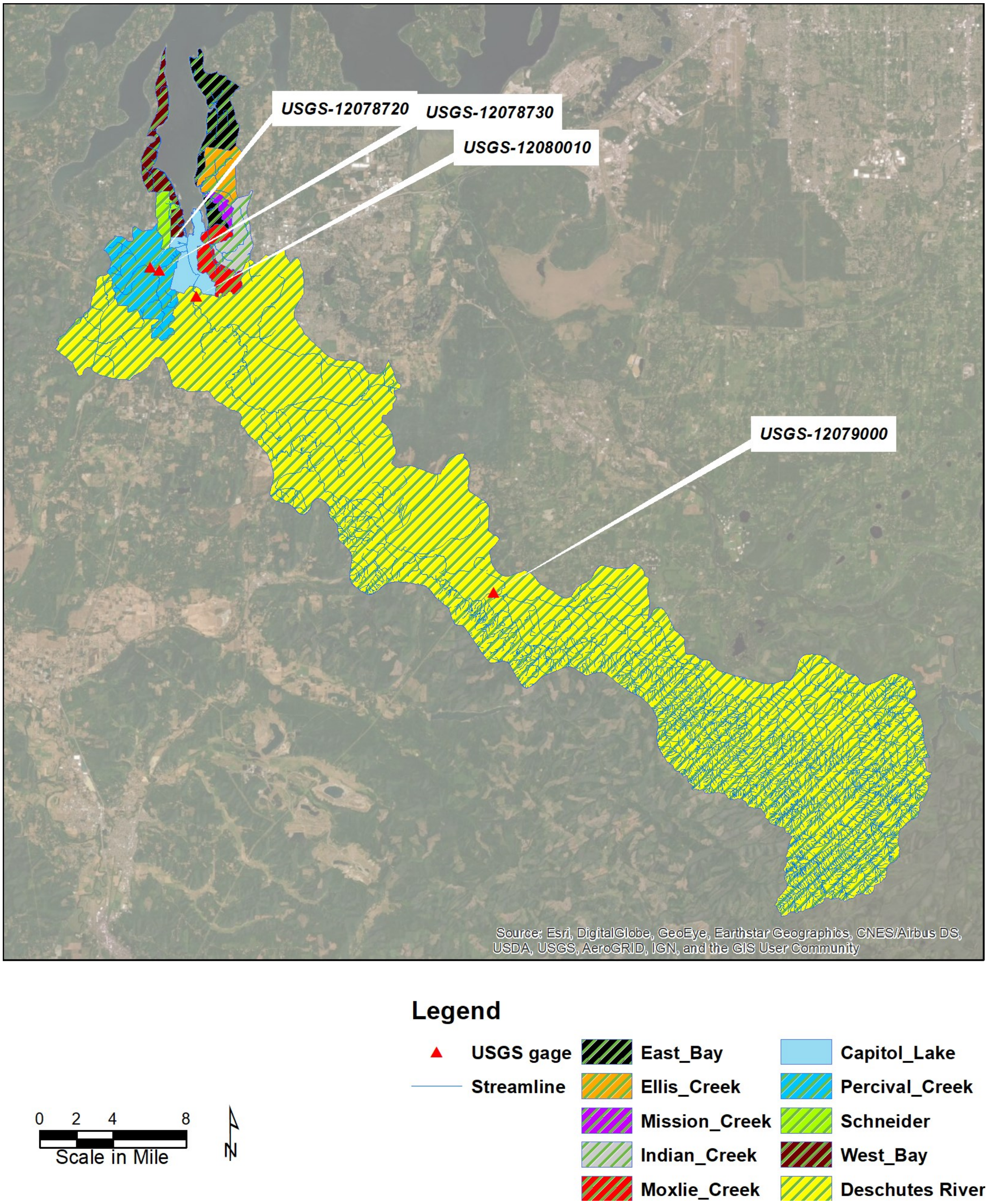


Figure 2-9 Time Series of 15-min and Daily Discharges at USGS Gage 12079000

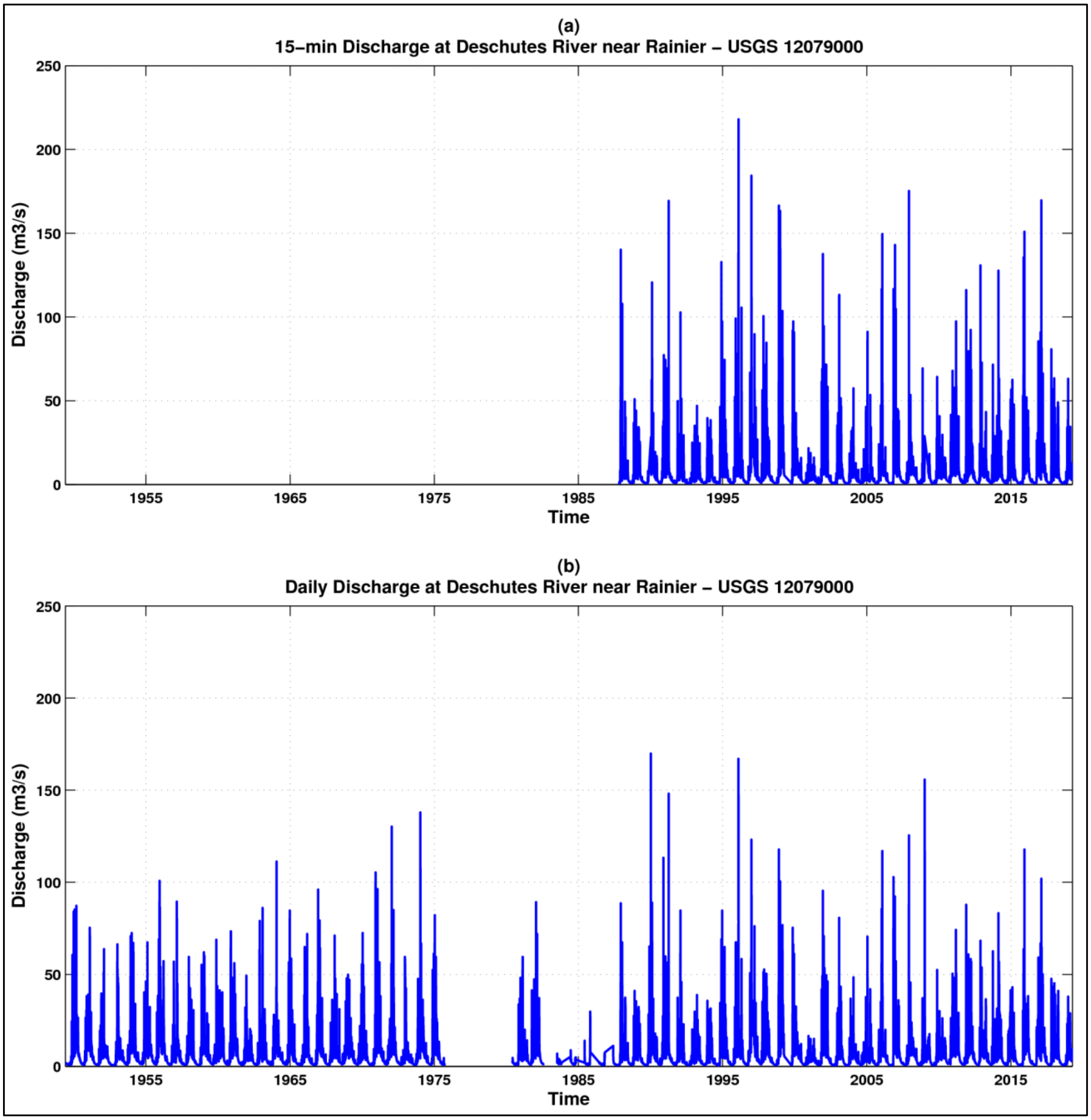


Figure 2-10 Time Series of 15-min and Daily Discharges at USGS Gage 12080010

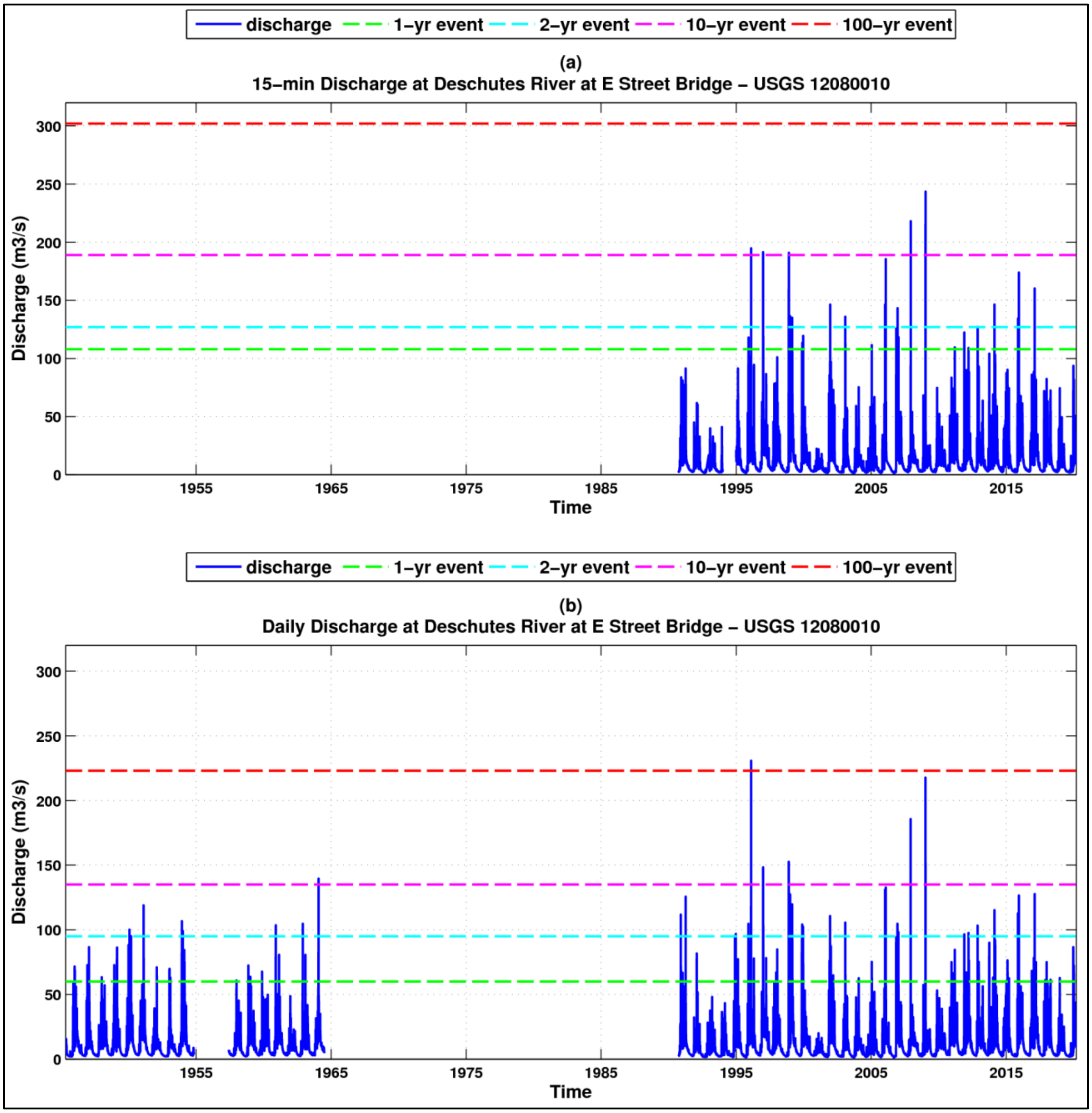


Figure 2-11 Time Series of 15-min and Daily Discharges at USGS gage 12078720

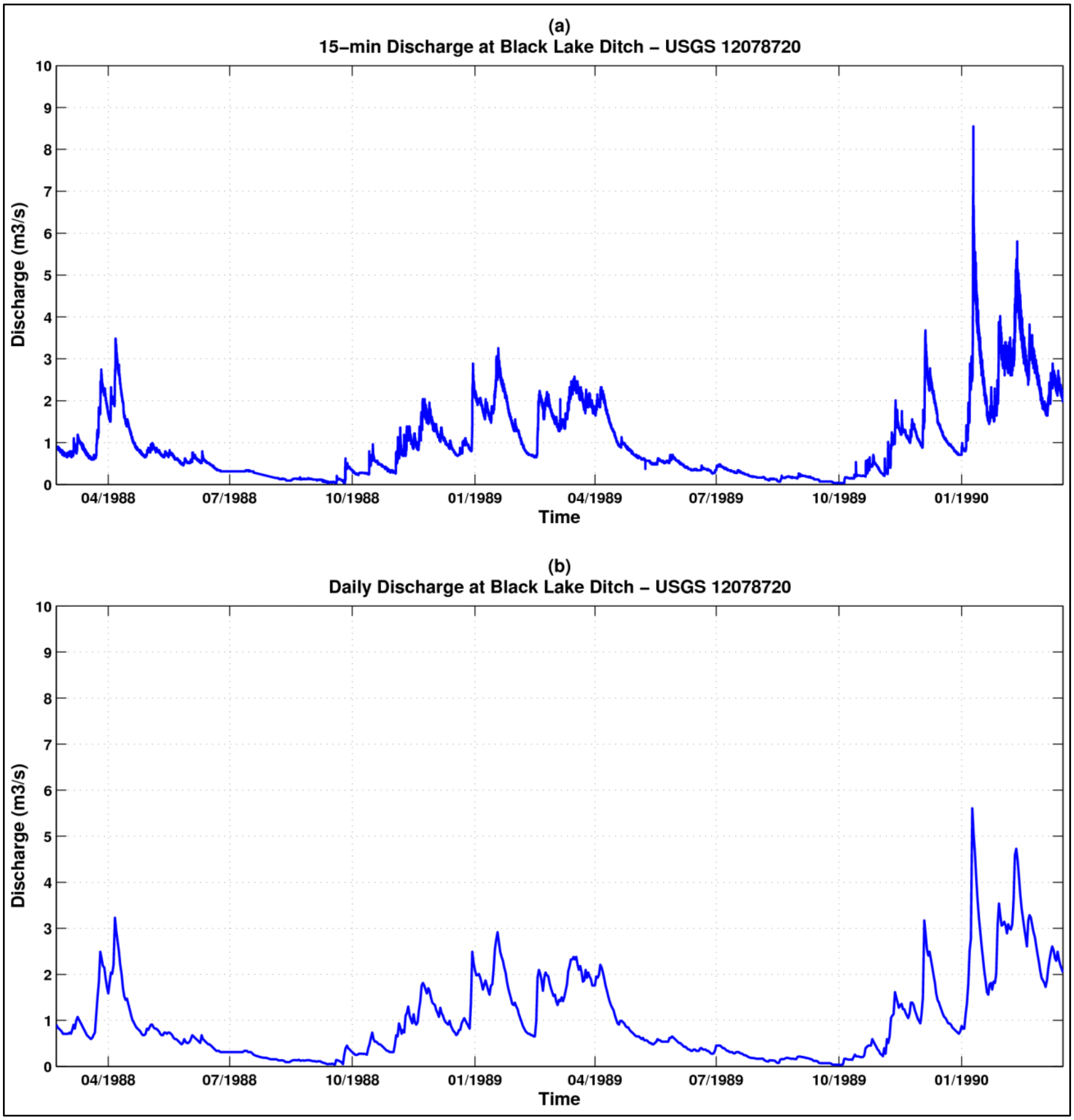


Figure 2-12 Time Series of 15-min and Daily Discharges at USGS Gage 12078730

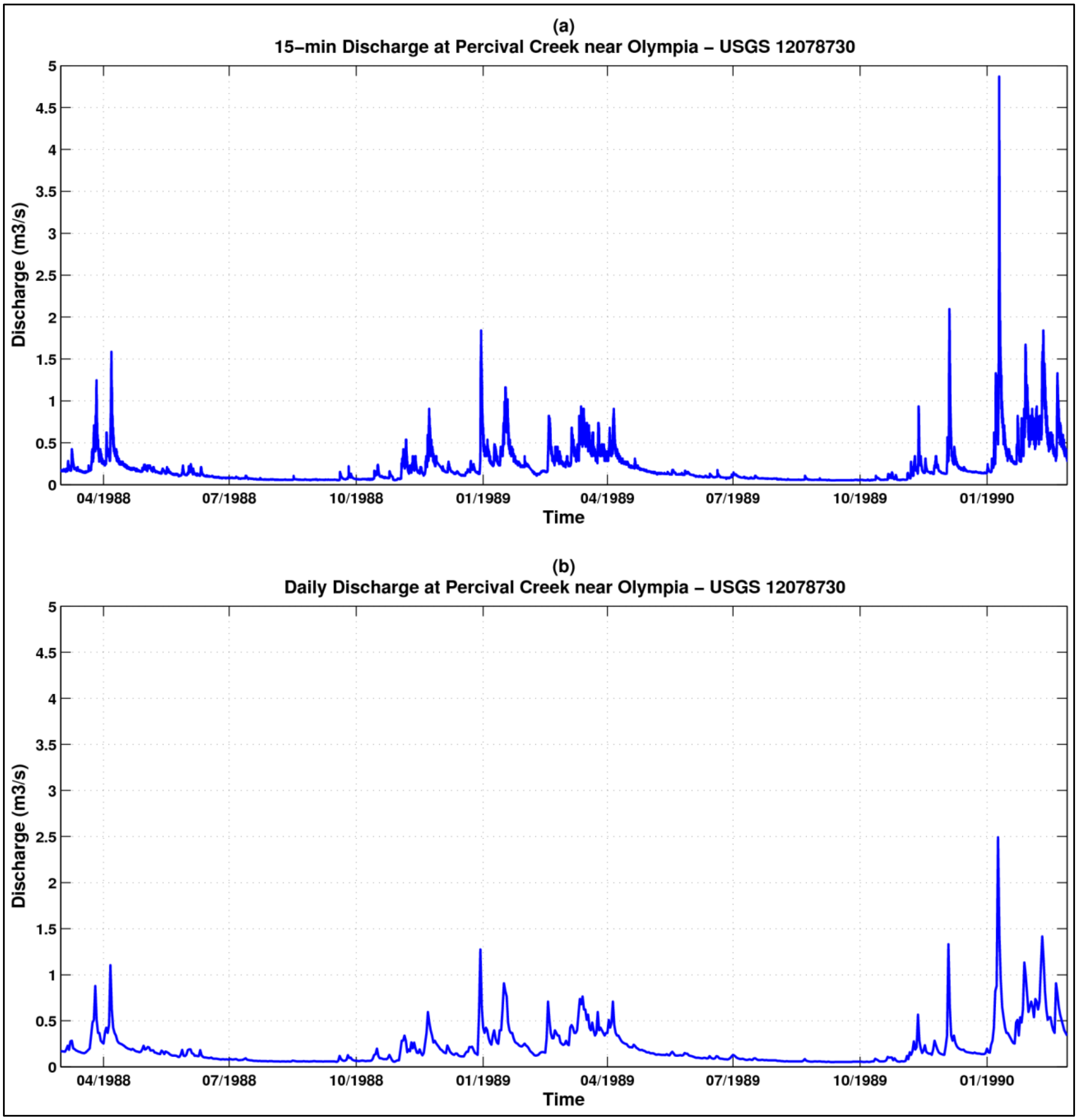


Table 2-6: Deschutes River Flow Return Period Events for USGS Station 12080100

Return Period	15-min Discharge	Daily Discharge	CLAMP (2000)	FEMA (2018)
1	108	60	41	N/A
2	127	95	113	N/A
5	160	114	167	N/A
10	189	135	205	212
25	231	167	257	258
50	265	194	298	294
100	302	223	341	329
500	393	297	449	417

2.6 CURRENTS

Depth-averaged currents were collected at four stations in Budd Inlet by Washington State Department of Ecology (Ecology). Detailed information about the data is listed in Table 2-7. The locations of current measurement stations are shown in Figure 2-1.

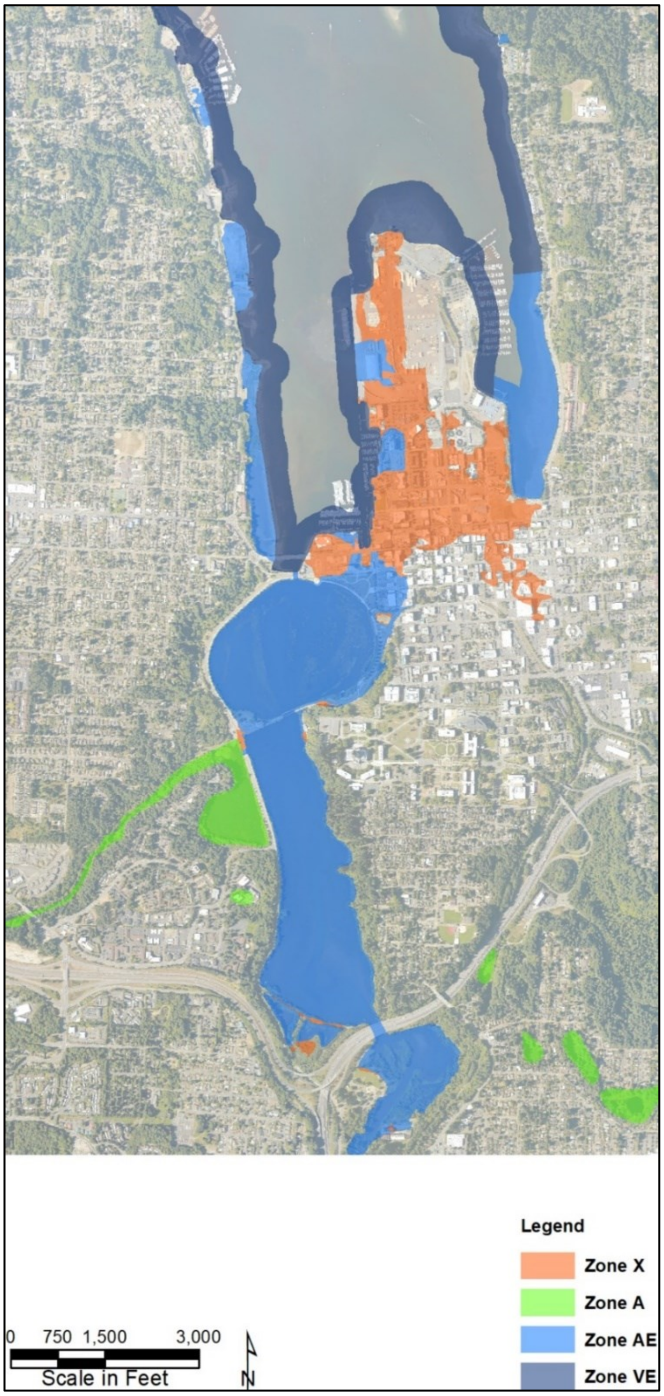
Table 2-7 WA State Department of Ecology 1997 Current Measurement Information

Station	Period of Record	Sampling Frequency
M1	10/30/1996 – 12/10/1996 01/17/1997 – 08/13/1997 08/21/1997 – 10/01/1997	15-min
M2	01/17/1997 – 02/19/1997 02/28/1997 – 10/03/1997	15-min
M3	10/30/1996 – 12/14/1996 01/17/1997 – 10/01/1997	15-min
M5	10/30/1996 – 12/13/1996 01/17/1997 – 10/03/1997 11/26/1997 – 02/20/1998	15-min

2.7 FLOODING

Flooding hazard information was collected from Federal Emergency Management Agency (FEMA) Flood Risk Information System (FRIS). Figure 2-13 shows the flood hazard line and flood hazard areas. Most of the lines and areas indicate the 100-yr flood boundary, except areas with note X which are either the 500-yr flood boundary or the 100-yr flood boundary with average depth less than 1 foot or with drainage area less than 1 square mile.

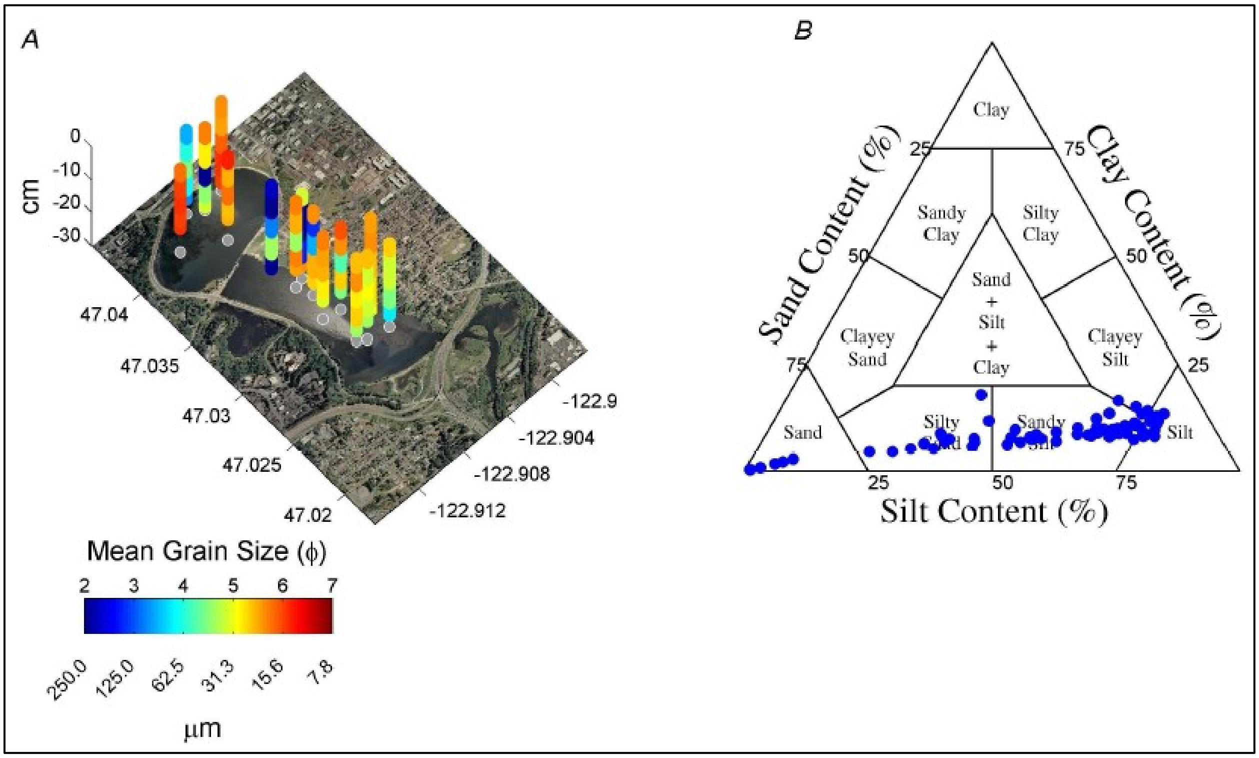
Figure 2-13 FEMA Flood Hazard Map



2.8 SEDIMENTS

Previous studies by USGS collected sediment cores and analyzed sediment data within Capitol Lake, which included grain size, dry sediment density, critical shear stress for erosion, and erodibility (Stevens et al. 2008). Results show that the mean grain size ranges from 13 to 578 µm in Capitol Lake, with variation both spatially and vertically (Figure 2-14). In the North Basin, the eastern and western sides are characterized by fine sediment deposits, while coarser sediments are observed near the dam. Coarse sandy sediments are observed in the Middle Basin near the BNSF Railroad Trestle located between the Middle and North Basins. Other sediment parameters are also highly variable. The dry sediment density in Capitol Lake varies between 250 and 1,400 kg/m^3, and the critical shear stress for erosion is from 0.06 to 1.84 Pa. Erosion rate measurements show results vary from 4×10^{-4} to 1.2 kg m^{-2} s^{-1} for shear stresses between 0.1 and 10 Pa.

Figure 2-14 Sediment Composition within Capitol Lake (Stevens et al. 2008)



In A, mean grain size with depth in the core, the z-axis is positive upward, and 0 indicates the sediment-water interface. In B, the relative percentages of sand, silt, and clay in each of the sub-samples analyzed are given.

2.9 SEDIMENT LOAD

2.9.1 Deschutes River

Annual sediment load to Capitol Lake has significant inter-annual variability according to previous studies (Entranco 1984, Entranco 1990, Entranco, 1997). The 2000 Capitol Lake Adaptive Management Plan (CLAMP) Report summarizes the annual sediment load from Deschutes River from previous studies from 1952 to 1996, see Table 2-8. The estimated annual sediment load to the lake is between approximately 22,200 m^3/yr (29,000 cubic yards per year [cy/yr]) and 42,050 m^3/yr (55,000 cy/yr).

The method used to calculate the sediment load in Table 2-8 is based on changes in lake volume from repeat bathymetry surveys. According to Entranco (1984), estimates of sediment load listed in Table 2-8 should be increased by 20-40% to account for suspended sediment transported into Budd Inlet and not trapped by the lake.

Table 2-8 Deschutes River Annual Sediment Load, Dredge Volume, and Accumulation in Capitol Lake Since 1952 (Modified from CLAMP 1999)

Time frame (yrs)	Sediment load m^3/yr (cy/yr)	Accumulation m^3 (cy)	Dredging m^3 (cy)	Net accumulation m^3 (cy)
1952-1974 (23)	23,000 (30,000)	505,000 (660,000)	-	505,000 (660,000)
1975-1979 (5)	42,000 (55,000)	210,000 (275,000)	-191,000 (-250,000)	524,000 (685,000)
1980-1983 (4)	42,000 (55,000)	168,000 (220,000)	-	692,000 (905,000)
1984-1986 (3)	27,000 (35,000)	80,000 (105,000)	-44,000 (-57,000)	729,000 (953,000)
1987-1990 (4)	27,000 (35,000)	107,000 (140,000)	-	835,000 (1,093,000)
1991-1996 (6)	22,000 (29,000)	133,000 (174,000)	-	969,000 (1,267,000)
Total (45)	-	1,203,410 (1,574,000)	-235,000 (-307,000)	969,000 (1,267,000)

Combining the repeat survey results and contribution of sediments deposited in Budd Inlet, the total annual sediment load from Deschutes River ranges from 26,600 m^3/yr (34,800 cy/yr) to 58,870 m^3/yr (77,000 cy/yr).

2.9.2 Percival Creek

The annual sediment load in Percival Creek is estimated from historical surveys (George et al. 2006) as 1,070 m^3/yr (1,400 cy/yr).

2.9.3 Sediment Rating Curve

The existing sediment rating curve for Deschutes River dates back to 1974 (Mih and Orsborn 1974). They used field measurements gathered by Nelson (1974) to extrapolate a suspended sediment rating curve for the Deschutes River at Olympia. This power relation has been applied since 1974 and most recently in the hydrodynamic and sediment transport study (George et al. 2006).

$C_s = 0.0797 * Q^{1.93}$

where Q is the river discharge (m^3/s) and C_s is sediment concentration (mg/L or g/m^3)

Sediment rating curves are established based on limited field measurements and there are inherent limitations and uncertainties associated with these curves. Based on conversations with USGS scientists, it is understood that the existing sediment rating curve is a reasonable representation of sediment input into the system. In lieu of long-term and more recent measurements of sediment load, the existing rating curve is the best available information to be used.

To better evaluate sediment load to the system, comparison of available bathymetric surveys within Capitol Lake Basin and Budd Inlet were conducted. And existing information on sediment deposition rates within Budd Inlet using sediment cores (Anchor QEA 2013) were evaluated, see Sections 2.10 and 2.11 for further details. Additionally, an empirical formulation was used to develop an envelope for transport rates into the lake from the Deschutes River and Percival Creek, see Herrera (2019). It was observed that the sediment load into the system is generally consistent across the data (old sediment rating curve, bathy comparison, sediment cores) but not with the empirical formula.

For sediment transport modeling purposes, sediment load into the system was treated as a calibration parameter to match modeled vs. measured rates and spatial patterns of sediment erosion/deposition within the modeled area, see Section 5.0 for further details.

2.10 SEDIMENTATION PATTERNS IN CAPITOL LAKE BASIN

Detailed information about spatial patterns of erosion/deposition within the Capitol Lake Basin are not available to the best of our knowledge. Previous estimates were focused on lake-wide values of erosion and deposition only. Entranco (1984) estimated average deposition rates of 0.3 m (1 ft) in 11 to 13 years, which translates into 2.3 cm/yr (0.9 inch/yr) to 2.7 cm/yr (1.0 inch/yr). From 1952 to 1996, average deposition rate in terms of volume and thickness in the Capitol Lake from Table 2-8 was 26,800 m^3/yr (35,000 cy/yr) and 3.0 cm/yr (1.2 inch/yr), respectively.

Two bathymetry surveys conducted in 2013 and 2020 were used as the primary bathymetry data to compute the sedimentation rate in the Capitol Lake in recent years. Bathymetry data extracted from USGS model were also utilized as a reference for pre-dam condition. Information of the two bathymetry surveys and the USGS modeled bathymetry (design elevation for pre-dam condition by George et al. 2006) are listed in Table 2-9. The USGS model bathymetry coverage is shown in Figure 2-15 and the survey data coverages for the 2013 survey and 2020 survey are shown in Figure 2-17 and Figure 2-19 with the black line indicating the 2013 survey coverage extension. The 1949 bathymetry data has a sparser coverage than the other two survey data, and there is a clear channel migration from east to west in the South Basin compared to the 2013 survey extension and the background image (Figure 2-16). The 2013 survey has a dense coverage for the North Basin, the Middle Basin, and Percival Cove, and the coverage for the South Basin is sparse (Figure 2-18). The 2020 survey has a denser coverage than 2013, especially in the South Basin (Figure 2-20) and along the river channel.

Table 2-9 Bathymetry Survey Information

Source	Start Date	End Date
USGS (George et al. 2006)	1949 (date not available)	1949 (date not available)
TerraSond (2013)	03/12/2013	03/15/2013
eTrac (2020)	01/15/2020	01/17/2020

Figure 2-15 USGS (1949) Modeled Data Points and Coverage

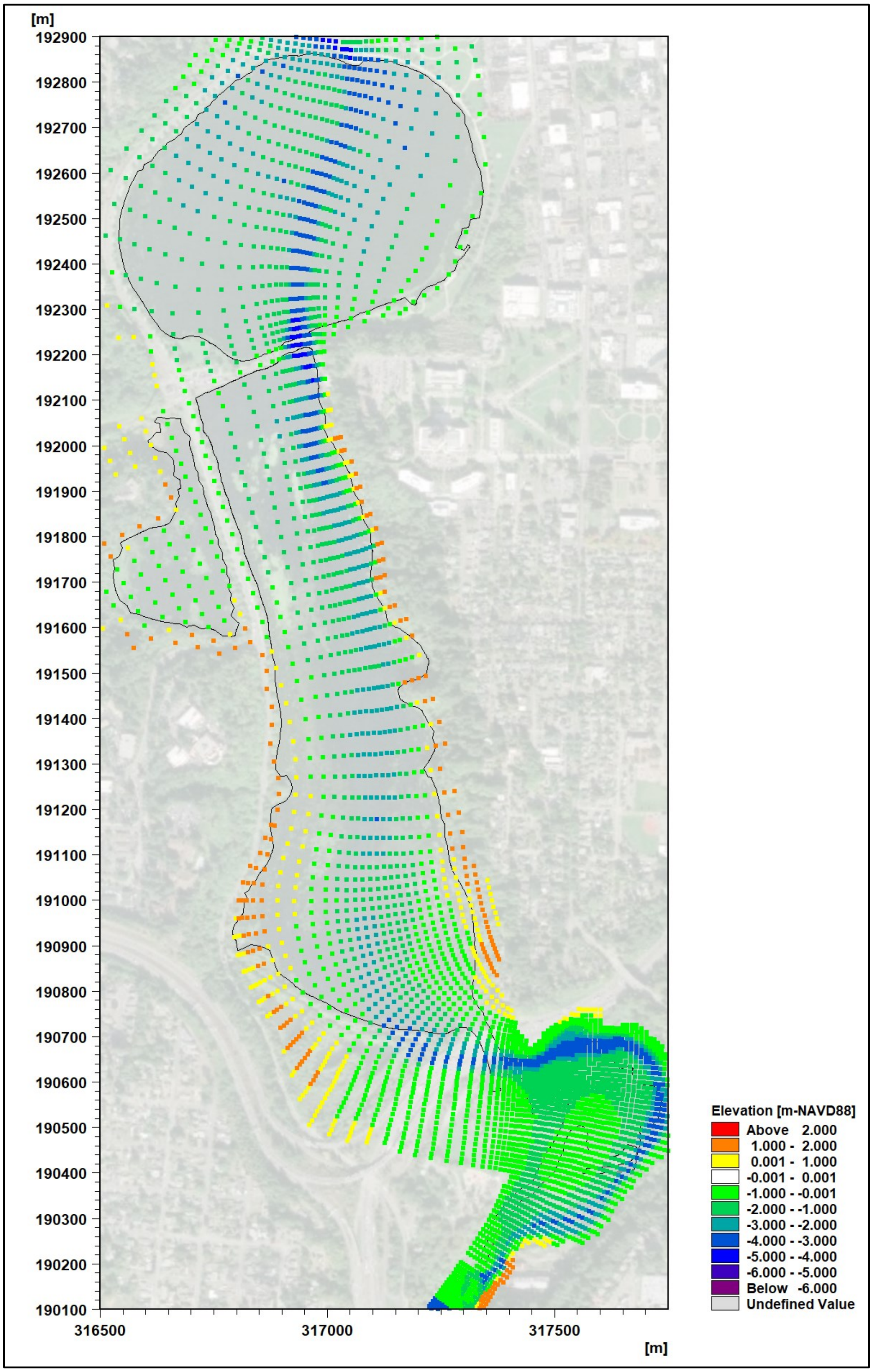


Figure 2-16 USGS (1949) Modeled Data Points and Coverage Zoomed into South Basin

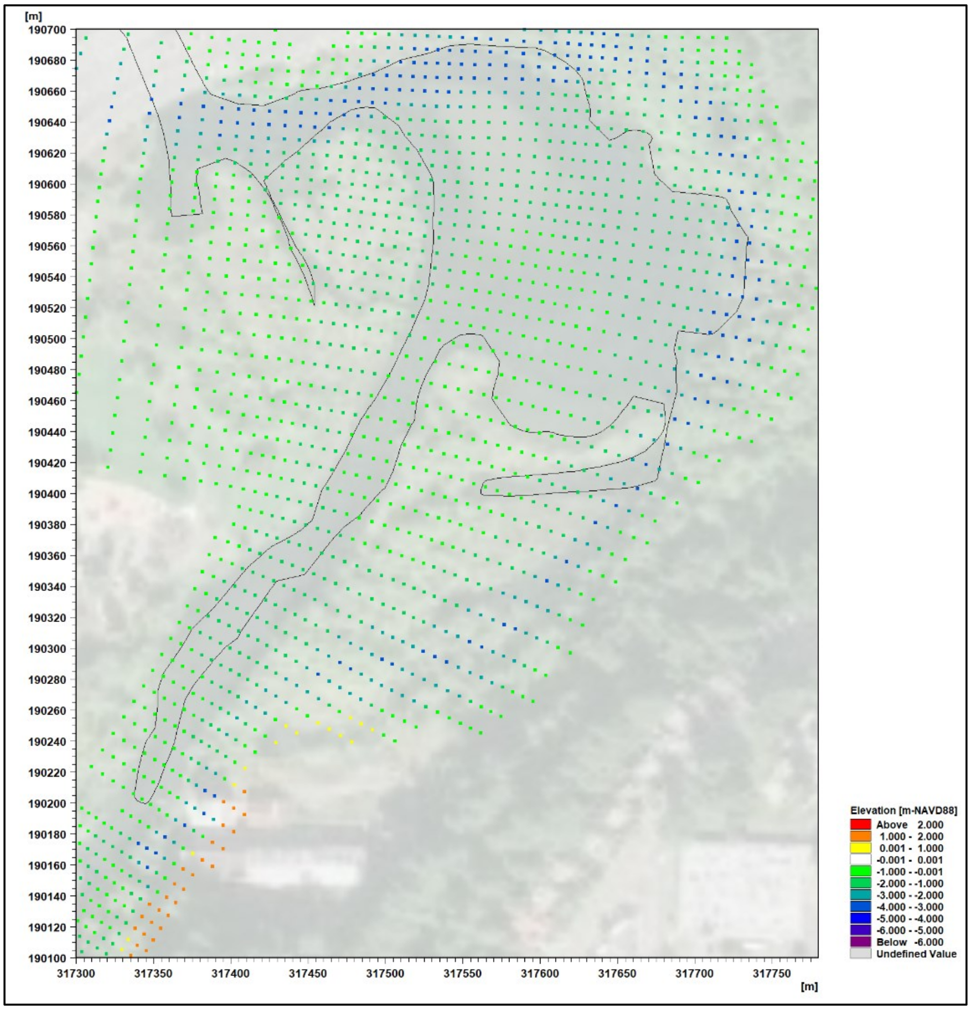


Figure 2-17 TerraSond (2013) Survey Data Points and Coverage

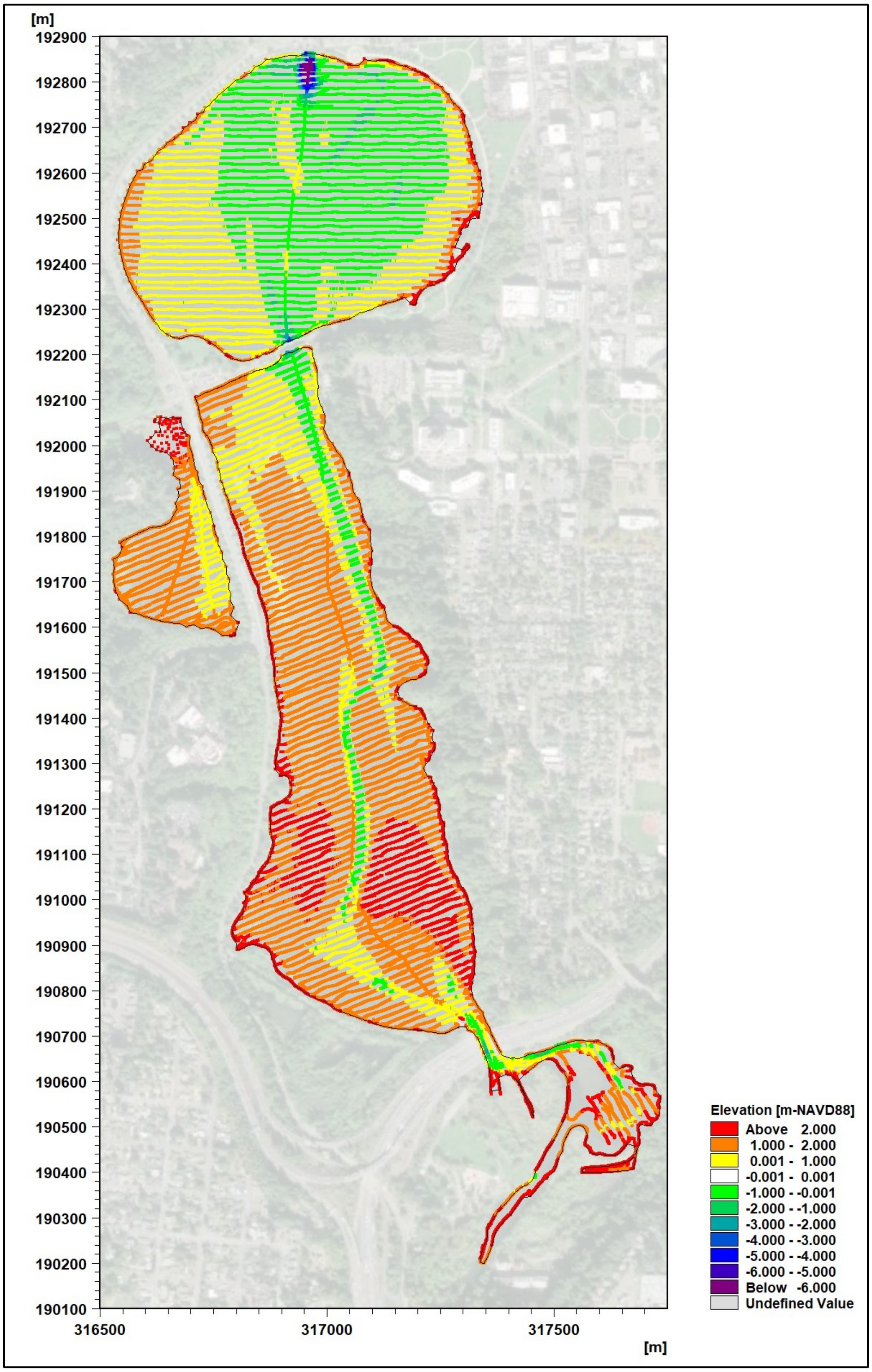


Figure 2-18 TerraSond (2013) Survey Data Points and Coverage Zoomed Into South Basin

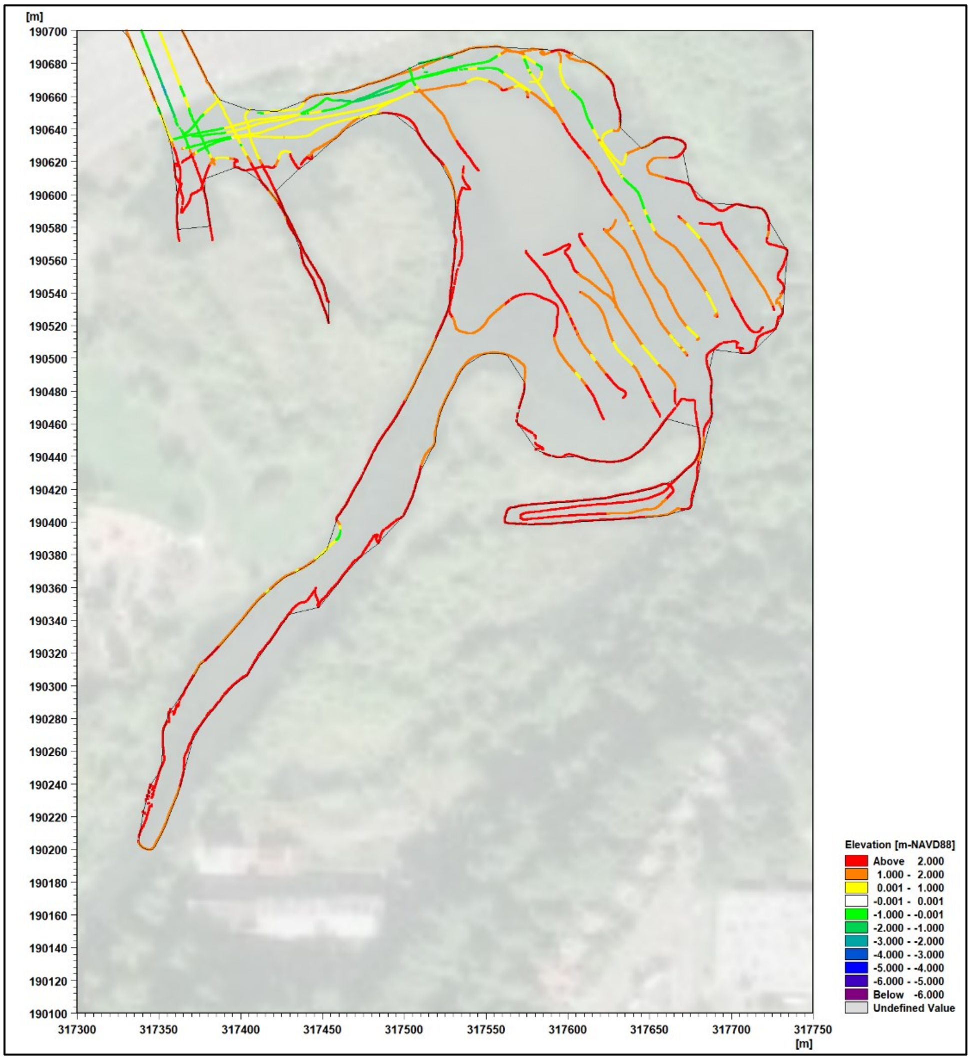


Figure 2-19 eTrac (2020) Survey Data Points and Coverage

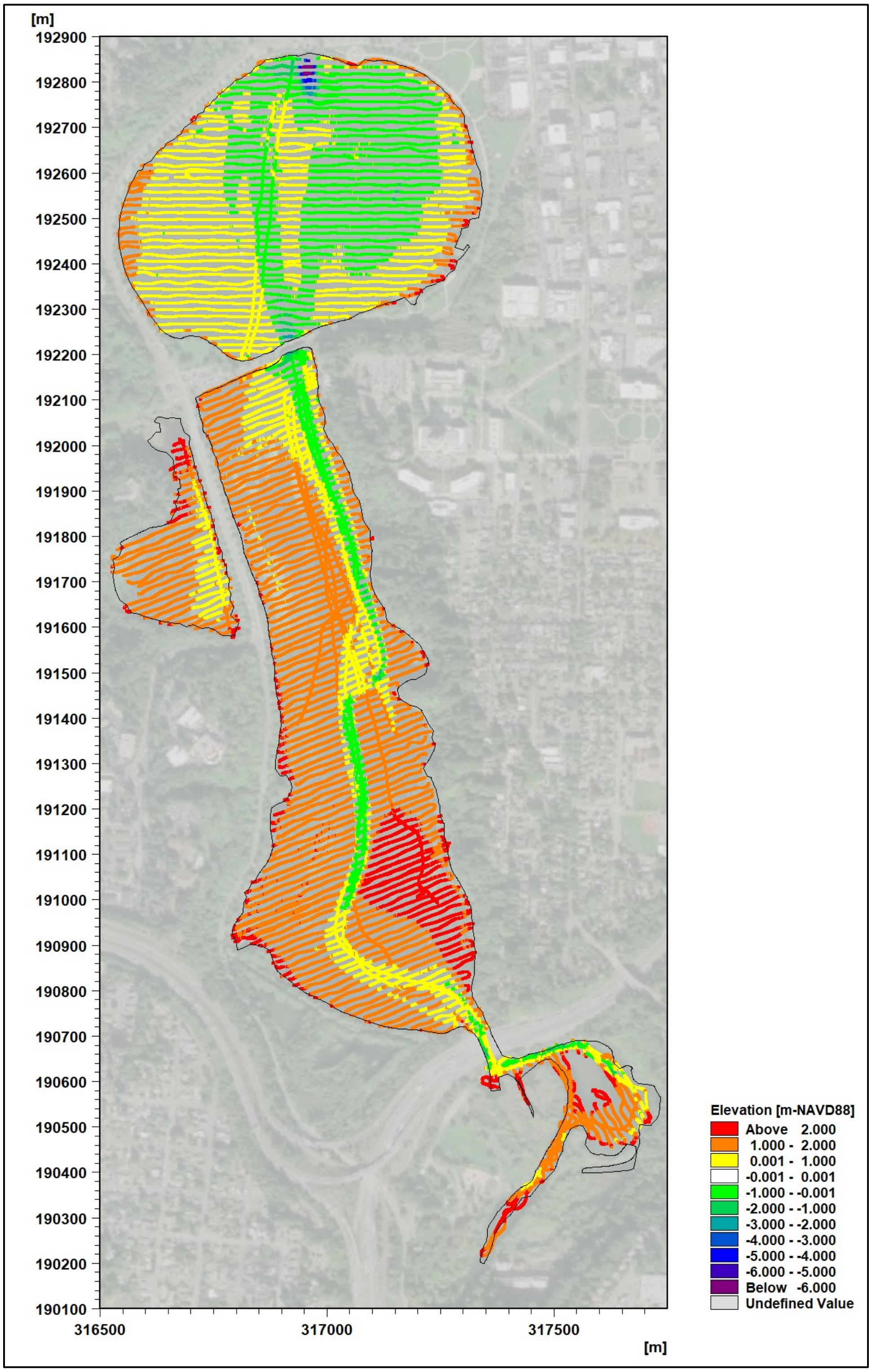
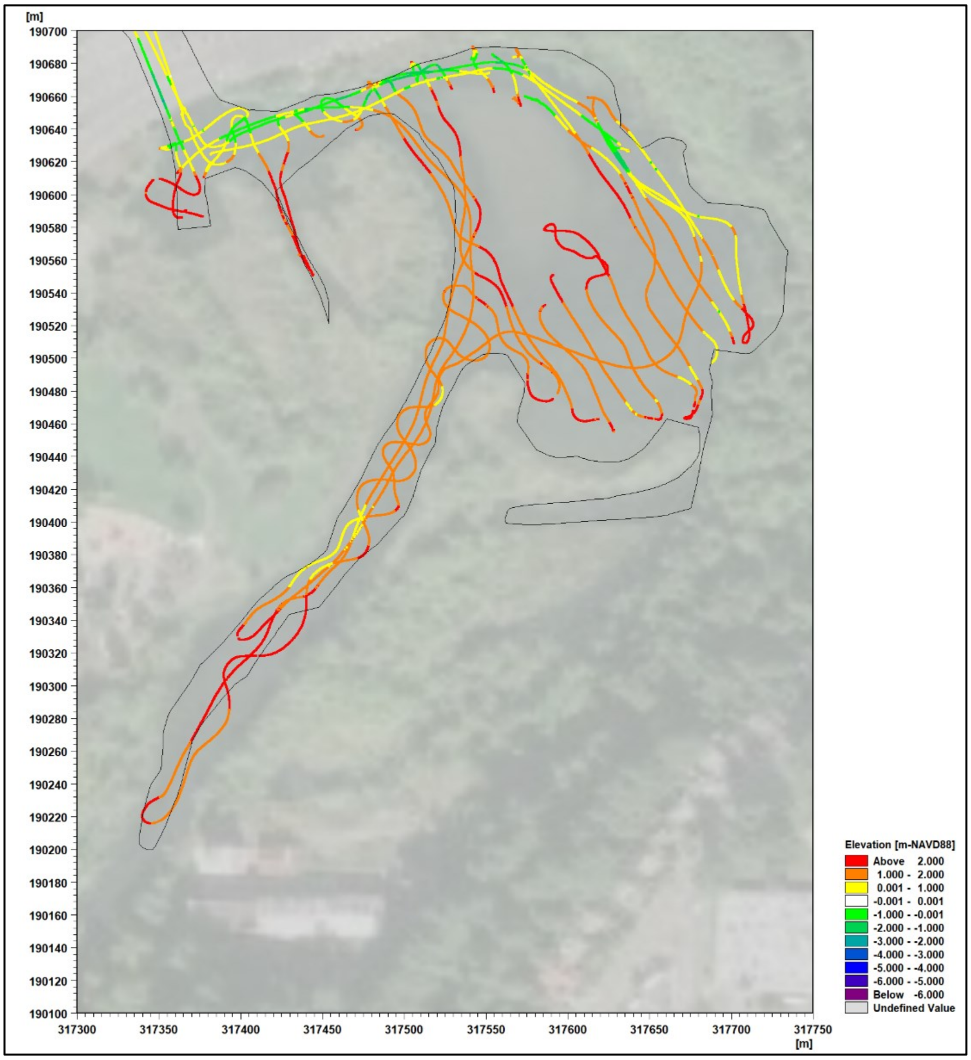
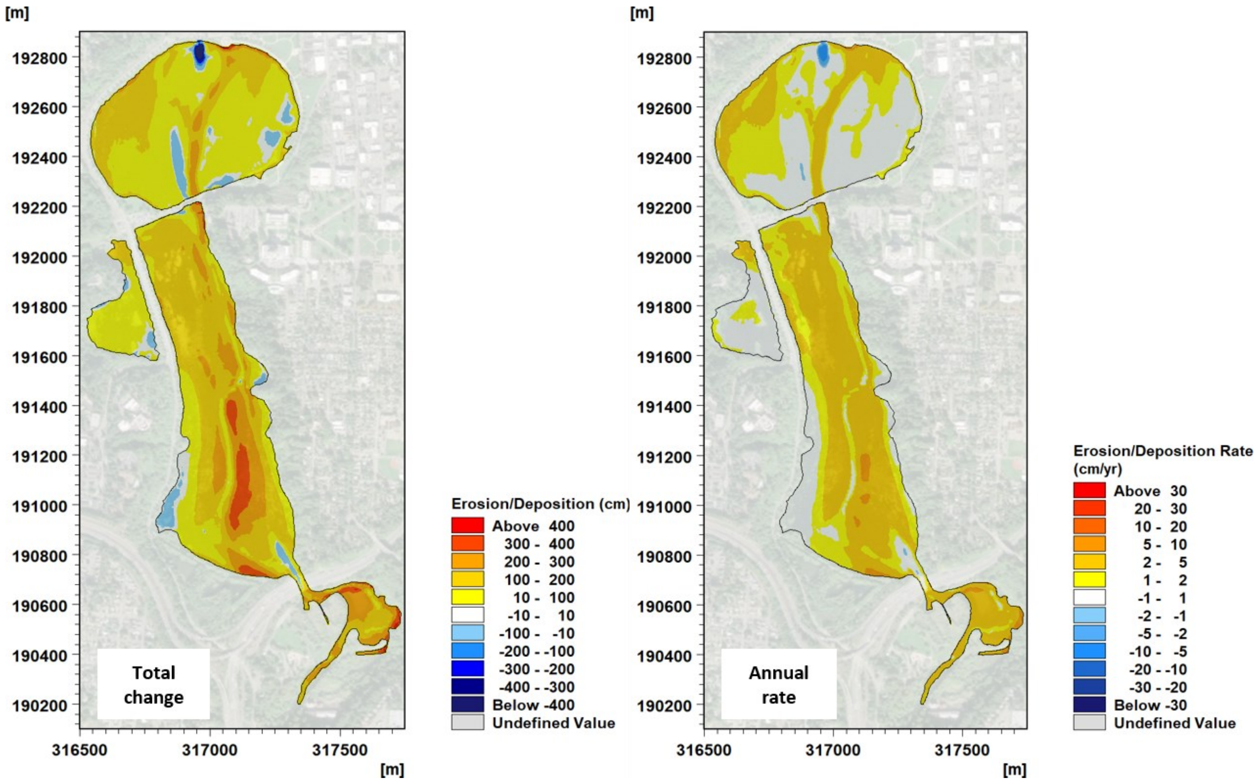


Figure 2-20 eTrac (2020) Survey Data Points and Coverage Zoomed Into South Basin



Morphological change maps were generated from the three bathymetry data sets discussed above. Figure 2-21 shows the morphological changes from 1949 (pre-dam condition) to 2013 with a total 64 years. After the dam construction, deposition occurred in most of Capitol Lake. The largest deposition thickness of over 4 m occurred in the South Basin due to channel migration. Most of the Middle Basin had deposits of approximately 2 m sediment, with some spots reaching 3 m. In the North Basin, the original channel was filled with 1-2 m sediment, a scouring hole was observed with over 4 m erosion, and most of the North Basin had a deposition amount between 0.5 m and 1 m.

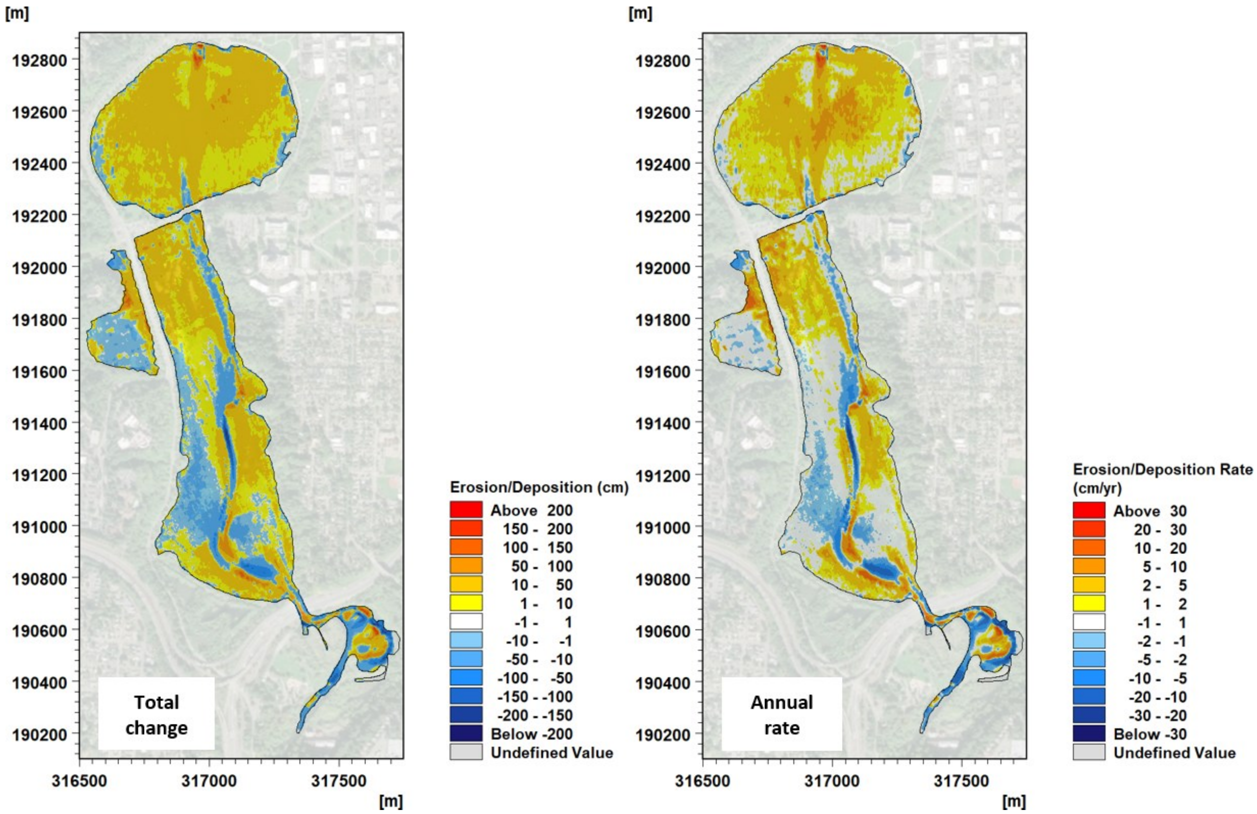
Figure 2-21 Morphological Change within Capitol Lake Basin From 1949 to 2013d



Red represents deposition and blue represents erosion

Figure 2-22 shows the morphological changes from 2013 to 2020, for a total 7 years. In the North Basin, a general depositional pattern can be observed with total sediment deposition ranging from 0.05 m to 1 m, with greater deposition in the central part than closer to the shoreline. The total deposition in the North Basin translates to 0.7 to 14.2 cm/yr. In the Middle Basin, erosion occurred along the river channel (could be attributed to channel migration) and the flanks of the channel in the southwest corner of Middle Basin. The rest of the Middle Basin experienced deposition from 0.05 m (most riverbanks) to 1 m (downstream to the I-5 Bridge). The South Basin appears to have experienced more erosion when comparing to long-term changes observed between 1949 to 2013. This is mostly attributed to inadequate coverage of the South Basin in the 2013 survey that did not capture the main channels in South Basin (Figure 2-18).

Figure 2-22 Morphological Change within Capitol Lake Basin from 2013 to 2020



Red represents deposition and blue represents erosion

From the morphological change maps, annual sedimentation volumes were estimated, and the results are listed in Table 2-10. The total annual sedimentation volume dropped 32% from 21,647 cy to 13,994 cy based on the 1949-2013 and 2013-2020 data. During the course of the survey years, the sedimentation patterns in the three basins were switched. From 1949-2013 to 2013-2020, the South Basin changed from net deposition to net erosion, the Middle Basin changed from relatively large deposition to small deposition, and the North Basin changed from relatively small deposition to large deposition. As a result, the deposition center has migrating from south to north following dam closure.

Table 2-10 Annual Sedimentation Volume in the Capitol Lake

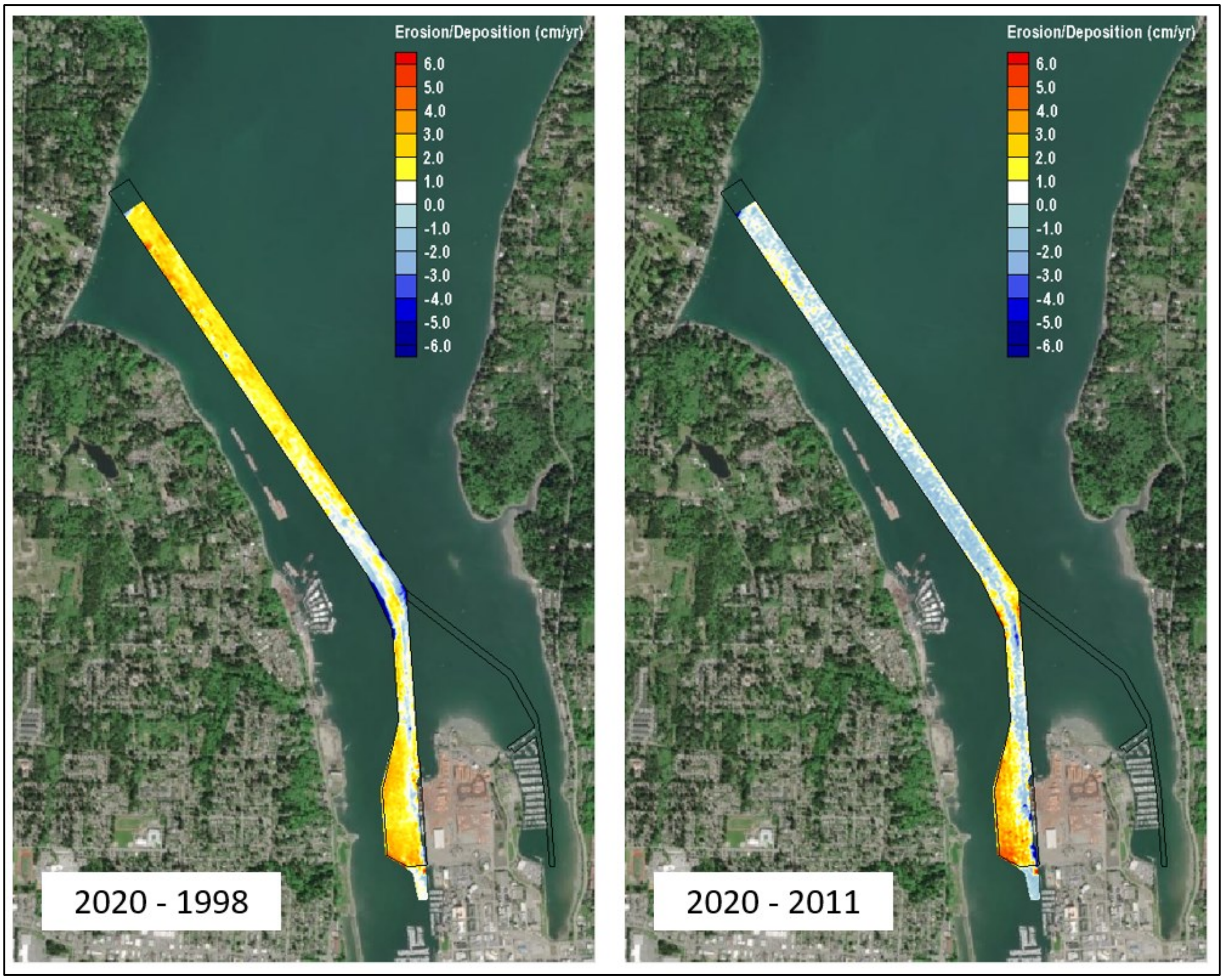
	South Basin m^3/yr (cy/yr)	Middle Basin m^3/yr (cy/yr)	North Basin m^3/yr (cy/yr)	Percival Cove m^3/yr (cy/yr)	Sum m^3/yr (cy/yr)
1949-2013	2,408 (2,191)	14,061 (14,553)	4,869 (6133)	489 (639)	21,647 (28,313)
2013-2020	-967 (-1265)	2,741 (3,586)	8,414 (11,005)	511 (668)	10,699 (13,994)

2.11 SEDIMENTATION PATTERNS IN BUDD INLET

US Army Corps of Engineers (USACE) conducts periodic condition surveys of the Federal Navigation Channel. The bathymetric conditions surveys are available dating back to 1998. These surveys were used to establish long-term spatial patterns of rates of sediment erosion/deposition. Three sets of surveys have been compared to establish sediment erosion/deposition pattern in the Federal Navigation Channel in Budd Inlet, see Figure 2-23.

The survey comparisons show that for 1998-2020 (22 years), majority of the federal navigation channel has experienced sediment deposition ranging from 2 to 3 cm/yr. On the other hand, in the last nine years (2011-2020), majority of the federal navigation channel, excluding the turning basin, has experienced erosion of approximately less than 1 cm/yr. The turning basin has experienced sediment deposition of approximately 3 cm/yr in 2011-2020 period, similar to the long-term trend observed for 1998-2020.

Figure 2-23: Erosion/Deposition (cm/yr) in Budd Inlet for 1998-2020 and 2011-2020



Sedimentation rate studies were carried out in Port of Olympia and Budd Inlet to estimate the sedimentation rate from high-resolution sediment cores in 1993 (Landau 1993), 2008 (SAIC 2008), and 2013 (Anchor QEA 2013). Locations of these sediment cores are shown in Figure 2-24; Table 2-11 summarizes the study information and results.

Figure 2-24 Location of Sediment Cores From Previous Studies

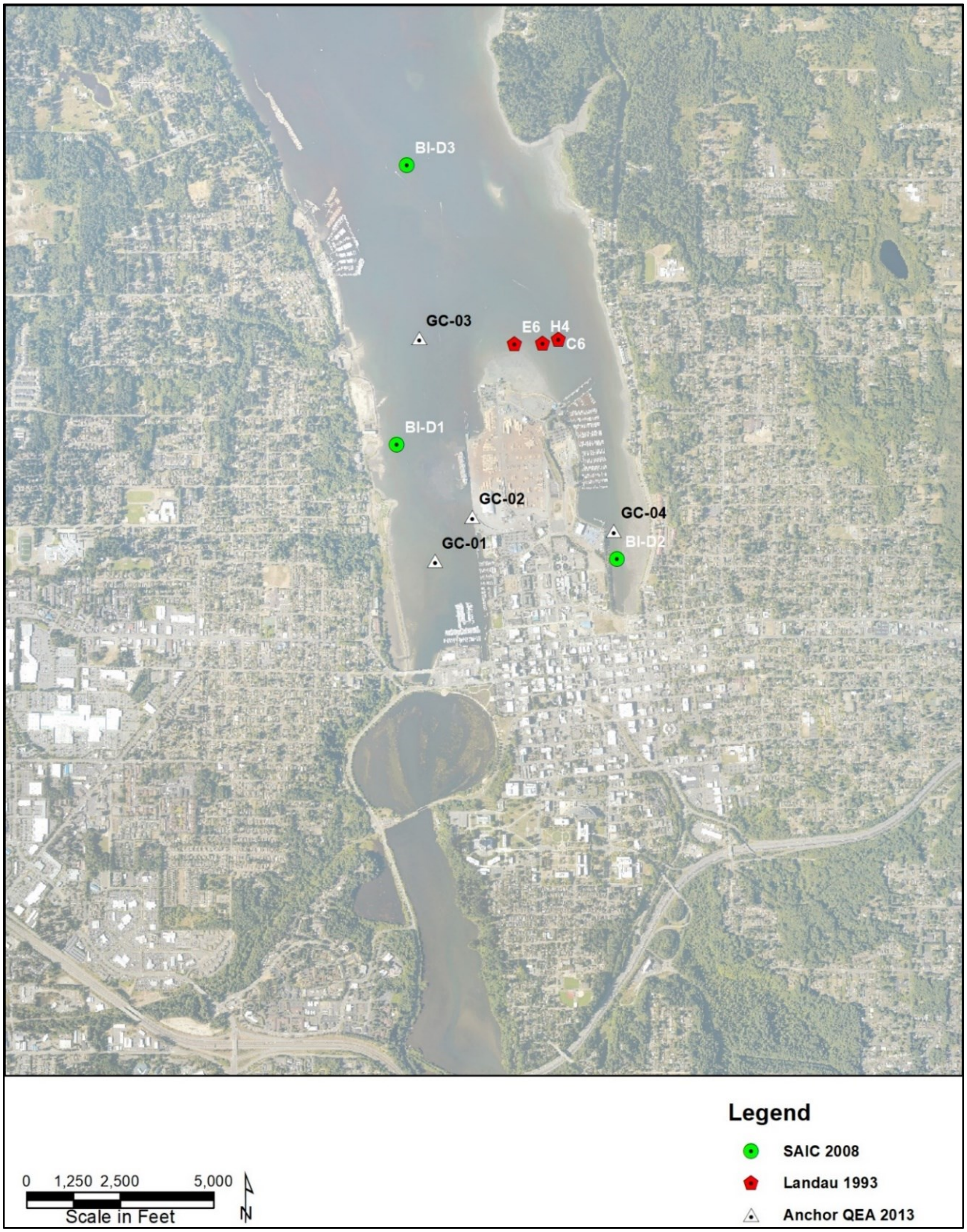


Table 2-11 Summary of Sedimentation Rate Results from Previous Studies (Anchor QEA 2016)

Station ID	Study	Sedimentation Rate (cm/yr)	Mass Sedimentation Rate ($g/cm^2/yr$)
GC-01	Anchor QEA 2013	1.0	1.6
GC-02	Anchor QEA 2013	1.1	1.8
GC-03	Anchor QEA 2013	0.7	1.1
GC-04	Anchor QEA 2013	0.9	1.5
C6	Landau 1993	0.13	0.21
E6	Landau 1993	0.12	0.19
H4	Landau 1993	0.13	0.20
BI-D1 (post-1951)	SAIC 2008	0.26	0.45
BI-D1 (pre-1951)	SAIC 2008	0.39	0.68
BI-D2	SAIC 2008	0.35	0.60
BI-D3 (post-1951)	SAIC 2008	0.14	0.24
BI-D3 (pre-1951)	SAIC 2008	0.17	0.29

The 1993 study (Landau 1993) was conducted in the Cascade Pole cleanup area north of the Port, and the sedimentation rates are 0.12 cm/yr (0.049 in./yr) to 0.13 cm/yr (0.051 in./yr).

The range of sedimentation rates in the 2008 study (SAIC 2008) are from 0.14 cm/yr (0.055 in./yr) to 0.39 cm/yr (0.15 in./yr) for three locations in Budd Inlet. Rates were higher in the southern areas than the northern areas of the inlet and higher in East Bay than West Bay. Additionally, the 2008 study investigated potential impacts from the 5th Avenue Dam on sedimentation rates in Budd Inlet. At BI-D1 near the Port, the sedimentation rate reduced 33% from pre-dam condition to post-dam condition. At BI-D3 further downstream in Budd Inlet, the sedimentation rate reduced 18%.

The most recent study in 2013 (Anchor QEA 2013) estimated sedimentation rates of 1.0 cm/yr (0.39 in./yr) to 1.1 cm/yr (0.43 in./yr) at GC-01 and GC-02 near the Port, 0.7 cm/yr (0.28 in./yr) at GC-03 further downstream, and 0.9 cm/yr (0.35 in./yr) at GC-04 in the East Bay.

The estimated range of sediment deposition from these studies (Landau 1993, SAIC 2008, and Anchor QEA 2013) is equal to 0.12 to 1.1 cm/yr, which is within the range of long-term rates obtained from USACE survey comparisons (-1.0 to +3.0 cm/yr).

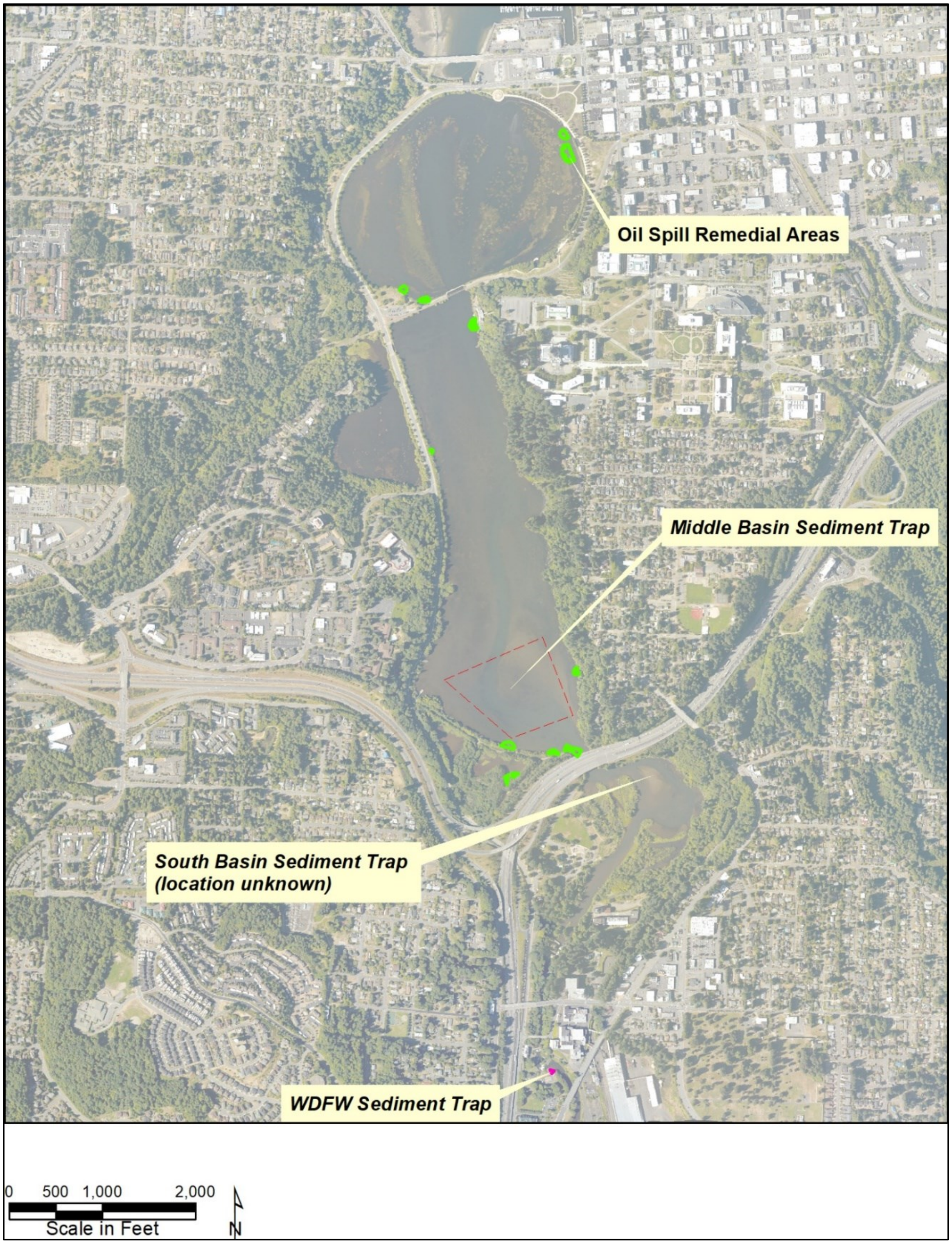
2.12 DREDGE RECORDS

To address sediment accumulation in Capitol Lake, two sediment traps were constructed in 1978. The traps were built by removing 200,000 cy (152,910 m^3) of sediment in the South Basin (location unknown) and the Middle Basin north of the I-5 Bridge (location shown as red polygon with an area of 75,500 m^2 in Figure 2-25). However, the South Basin trap was not functioning very well and was abandoned and is no longer maintained. The only maintenance dredging of the Middle Basin trap since 1978 occurred in 1987, when 57,000 cy (43,580 m^3) of sediment were dredged, with an accumulation rate of 4,800 m^3/yr (6,300 cy/yr) or a 6 cm/yr (2.36 in./yr) increase in thickness in this trap (Entranco 1990).

In 2019, some areas in the lake were dredged during the oil spill cleanup by ECY (locations shown as green polygons in Figure 2-25).The dredged sediment thickness in these areas ranged from 6 inches to 4 feet.

In the upstream river near Tumwater Falls Park, an annual maintenance dredging of approximately 76 m^3/yr (100 cy/yr) for the hatchery upstream of Tumwater Falls was operated by the Washington Department of Fish & Wildlife (WDFW) (personal communication with WDFW 2019; location shown as magenta polygon in Figure 2-25).

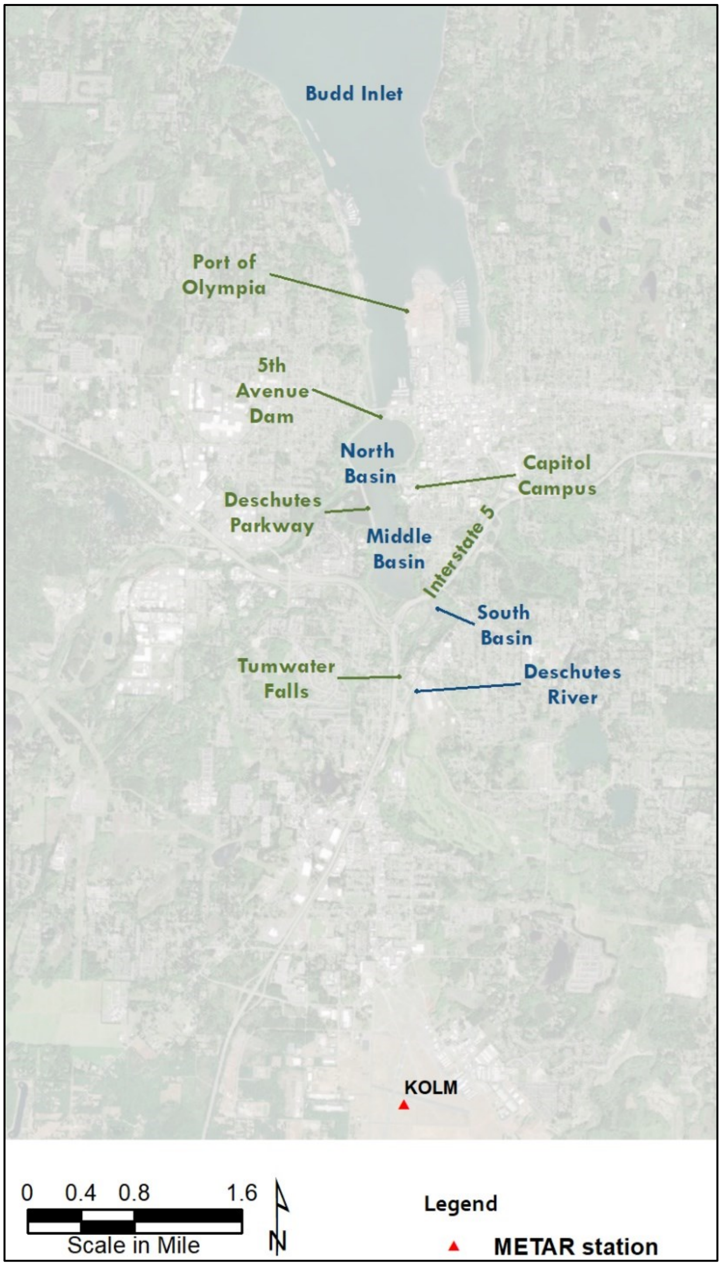
Figure 2-25 Locations of Sediment Traps



2.13 METEOROLOGICAL DATA

Wind and precipitation measurements in the proximity of Capitol Lake were obtained from Olympia Regional Airport weather station (METAR Station KOLM), shown in Figure 2-26.

Figure 2-26 Location of METAR station KOLM at Olympia Regional Airport



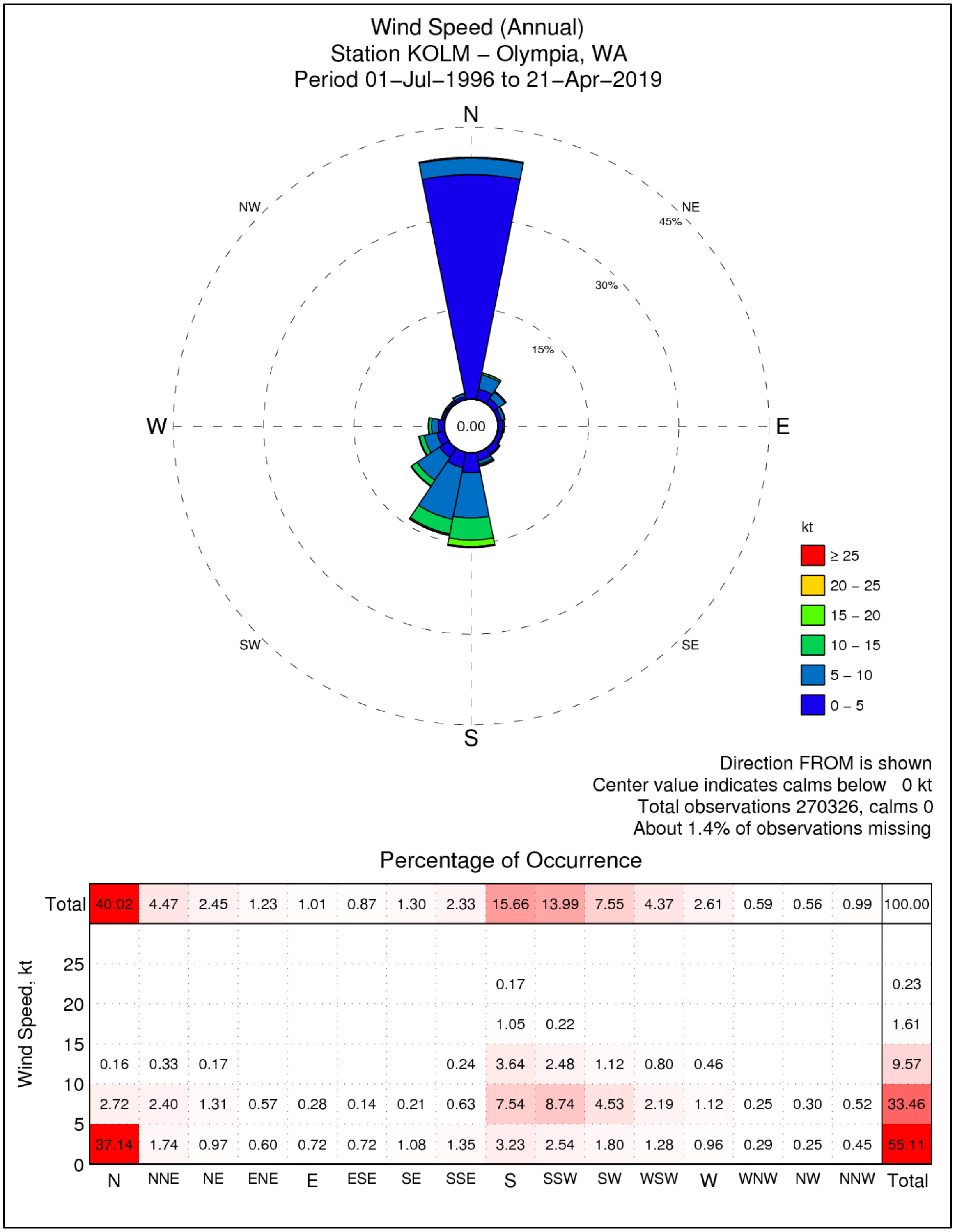
2.13.1 Wind

The information pertaining to the wind station is listed in Table 2-12. Data analyses were done for wind measurements at station KOLM. The annual wind roses are shown in Figure 2-27. From the results, it can be seen that the dominant wind directions are from southwest, south, and north. Northerly winds are more frequent (approximately 40% of the wind comes from north direction), with wind speeds typically below 5 knots. On the other hand, southerly winds are less frequent but stronger, with wind speed often reaching 15-20 knots.

Table 2-12 Wind Station Information

Source	Station	Anemometer Elevation (m)	Start Date	End Date	Frequency
METAR	KOLM	10	07/01/1996	Present	1 hr

Figure 2-27 Annual Wind Rose and Heat Map for Station KOLM



2.13.2 Precipitation

Olympia experiences an average annual rainfall of 50 inches/year (NOAA 2019). Precipitation data is available at METAR Station KOLM. Precipitation information for this station is listed in Table 2-13.

Table 2-13 Precipitation Station Information

Source	Station	Start Date	End Date	Sampling Frequency
METAR	KOLM	07/01/1996	Present	1 hr

2.14 5TH AVENUE DAM

Capitol Lake was created in 1951 through the construction of the 5th Avenue Dam, which disconnected the Deschutes River from Budd Inlet.

The 5th Avenue Dam consists of two radial gates to regulate water level within Capitol Lake along with a fish ladder. The side view of the dam and radial gate is shown in Figure 2-28; Figure 2-29 presents the schematic diagram and dimensions of the gate structure and the fish ladder.

Figure 2-28 Side Views of 5th Avenue Bridge and the 5th Avenue Dam (George et al. 2006)

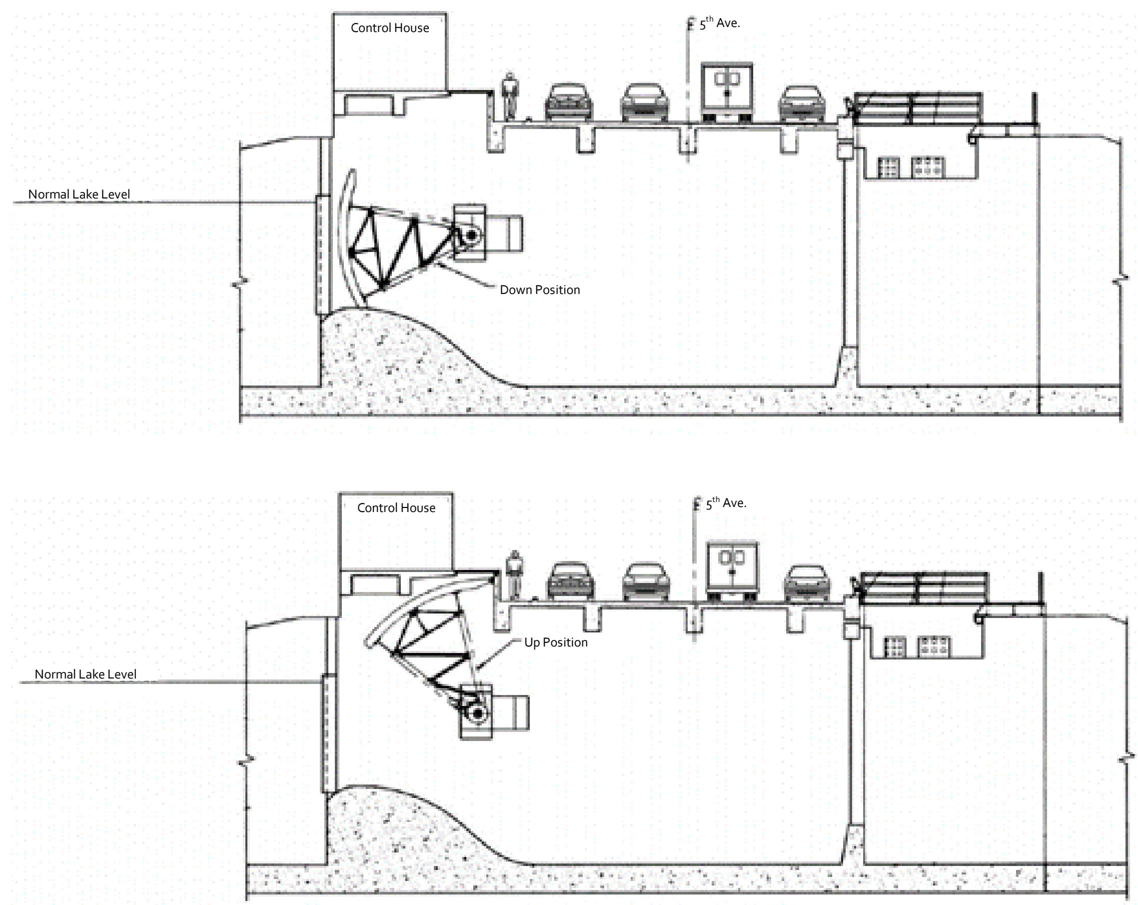
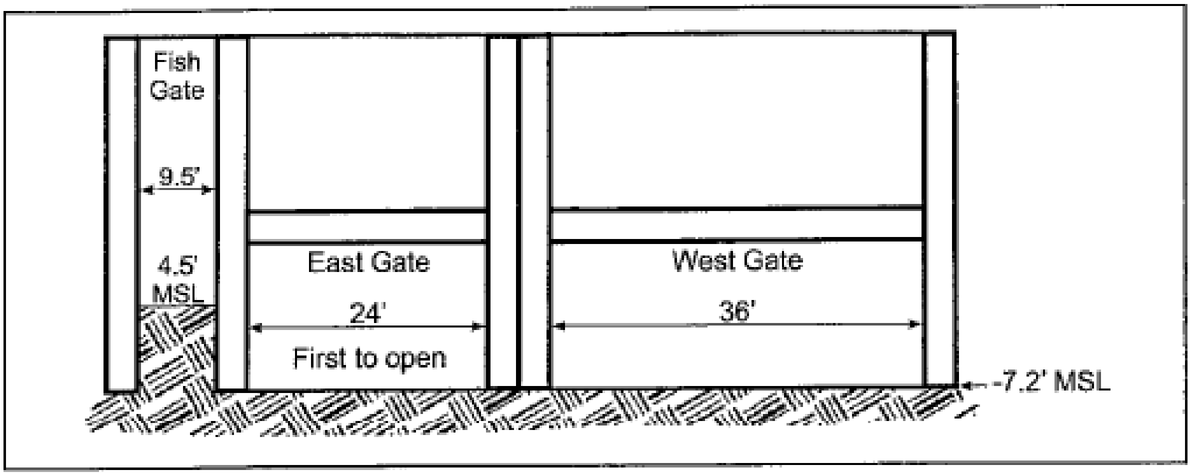


Figure 2-29 Schematic Diagram of 5th Avenue Dam Structures (URS & Dewberry 2003)



The 5th Avenue Dam operation details have been documented by M&N (2008) and NHC (2016). Photographs taken from downstream and upstream (at the radial gates) are shown in Figure 2-30 and Figure 2-31, respectively. The three openings, from left to right looking from the downstream (north) side (Figure 2-30) are: the fish ladder; the 24-foot-wide East Gate; and the 36-foot-wide West Gate. The gate operation logic based on a lower and an upper setpoint for the lake level is as follows:

- The first priority is to close both gates if the tide level (downstream of the gate) is at or above the lake level – this avoids flow from Budd Inlet into Capitol Lake. A very small buffer of 1.5 inches is applied to this rule; that is, the gate is only open if the lake level is at least 1.5 inches above the tide level. A larger buffer may have been applied in different time periods.
- The second priority is to close the gate if the lake level is below the lower setpoint.
- The third priority is to open the gate if the lake level is above the upper setpoint.

Setpoints for the East Gate and the West Gate are defined in Table 2-14. The West Gate is normally closed unless the additional opening is needed to drain the lake during a high river flow event. Additionally, different setpoints are used for winter (October through March) and summer (April through September) months. The fish ladder is always open in the summer and always closed in the winter. Details of the dam geometry and logic setpoints are given in Table 2-14 (M&N 2008).

Table 2-14 5th Avenue Dam Geometry and Logic Setpoints

Quantity	Fish Ladder	East Gate	West Gate
Bottom elevation (ft-NAVD88)	8.9^{+}	-2.8^{+}	-2.8^{+}
Width (ft)	9.5	24	36
Maximum gate opening (ft)	12.5	11.9	11.9

Quantity	Fish Ladder	East Gate	West Gate
Upper setpoint: summer (ft-NAVD88)	Always open	9.9	10.1
Lower setpoint: summer (ft-NAVD88)	Always open	9.1	9.1
Upper setpoint: winter (ft-NAVD88)	Always closed	8.9 *	9.1 *
Lower setpoint: winter (ft-NAVD88)	Always closed	8.1 *	8.1 *
Opening rate (ft/min)	NA	0.4	0.4
Closing rate (ft/min)	NA	0.6	0.6

+ Bottom elevation values were modified based on URS & Dewberry 2003 and NHC 2016

* Winter setpoints can vary in response to predicted river flows according to dam management practice

Figure 2-30 Photo of the North Side of the 5th Avenue Dam Looking South (M&N 2008)

Figure 2-31 Photograph of 5th Avenue Dam Looking Northward (M&N 2008)

2.15 AERIAL IMAGERY

Aerial images of the Capitol Lake area are available through various sources. The most recent aerial images include:

- Shoreline photos (oblique aerial images) from 1976, 1972, 2000, 2006, and 2016 provided by Washington State Coastal Atlas Map (https://fortress.wa.gov/ecy/coastalatlas/tools/Map.aspx).
- NOAA National Geodetic Survey (NGS) aerial image, 2017 (https://inport.nmfs.noaa.gov/inport/item/50857).
- NearMap imagery, 2019 (https://www.nearmap.com/us/en).

2.16 CLIMATE SCIENCE

2.16.1 Water Level and Relative Sea Level Rise

The science associated with projections of sea level change is continuously being developed and advanced. Although there is no doubt that sea levels have risen historically and will continue to rise at an accelerated rate over the coming century, it is difficult to predict with certainty what amount of sea level rise will occur over a given time frame.

Sea level rise projections were developed for the State of Washington by the Washington Coastal Resilience Project (Miller et al. 2018). These projections incorporated new science, accounting for local dynamics (such as subsidence and uplift) and providing information on the likelihood of different amounts of sea level rise under two future emissions scenarios. The new projections also extend to 2150.

Through a separate initiative, the City, LOTT, and Port of Olympia have developed a SLR Response Plan (and have identified physical and operational adaptation strategies to implement; some of which are within the project area (AECOM 2019).

2.16.2 Rainfall and Deschutes River Flow

There is considerable uncertainty surrounding the effects of climate change on precipitation. Local precipitation projections are one of the least certain aspects of global climate models, as the models do not resolve many of the fine-scale and complex interactions that produce spatially variable rainfall.

Researchers evaluate future precipitation trends using General Circulation Models (GCM) that capture relevant ocean, terrestrial, and atmosphere processes and their response to increased atmospheric greenhouse gas concentrations. An increase in the frequency and intensity of downpours is one of the clearest historical precipitation trends related to climate change in the United States and one that is expected to continue in the future (USGCRP 2017). However, there are important regional differences in trends.

Within the Puget Sound region, the exact changes in future precipitation patterns will vary by watershed, and natural year-to-year variations in precipitation patterns will remain a primary driver in observed precipitation (Mauger et al. 2015). Furthermore, the linkages between increased precipitation and increased streamflow are not necessarily linear, and depend on many factors including watershed land use, topography, surface water management structures, groundwater conditions, and snowpack hydrology.

GCM results for the Puget Sound region indicate that Olympia and the Deschutes River watershed may experience a 10 to 30% increase in extreme 24-hour precipitation by mid-century and a 10 to 30% increase by end-of-century, depending on storm event and emissions scenario. Results also indicate that moderate intensity events (such as the present day 20-year rainfall event) could occur more frequently (AECOM 2019).

Atmospheric rivers, bands of moisture that transport large amounts of water vapor from the tropics, are also projected to increase in frequency and duration. Atmospheric rivers can deliver a substantial amount of precipitation over the course of several days, amplifying storm conditions and elevating local water levels. Increases in precipitation intensity could cause more frequent urban flooding in Olympia and require increased capacity or more active management of increasing peak flows entering the Budd Inlet Treatment Plant.

Future discharge rates from the Deschutes River are uncertain; however, adjacent watersheds show projected increases in total winter runoff and peak discharge events such as the 10-year, 50-year, and 100-year discharges (Mauger et al. 2015). Increases in peak discharge events may cause more frequent and higher magnitude flooding along the Capitol Lake shoreline and adjacent low-lying areas.

3.0 Project Alternatives

This study evaluated the No Action Alternative and the three action alternatives in terms of hydrodynamics and sediment transport, as described in Section 4.6 and Section 5.9, respectively. The alternatives and a brief description of initial implementation and dredging activities are as follows.

- **No Action Alternative:** The No Action Alternative is intended to represent the likely future for the project area if the project is not implemented. Bathymetry within the Capitol Lake Basin was captured by the 2020 eTrac survey data (eTrac 2020), see Section 2.3 and Figure 2-7. Model elevation for the No Action Alternative within Capitol Lake Basin is shown in Figure 3-1.
- **Managed Lake Alternative:** This alternative is similar to the current configuration of Capitol Lake but includes an initial dredging of sediments in the North Basin of Capitol Lake. No changes to existing infrastructure will be made. For this alternative, the North Basin is dredged to -0.91 m (-3.0 ft) NAVD88, and several habitat areas are created in the Middle Basin with the highest elevation at approximately +4.27 m (+14.0 ft) NAVD88. Model elevation for the Managed Lake Alternative within Capitol Lake Basin is shown in Figure 3-2.
- **Estuary Alternative:** Under the Estuary Alternative, full tidal hydrology would be restored throughout the entire basin. This alternative creates an approximately 500-foot opening at the 5th Avenue Dam and related modifications to the existing infrastructure. The main river channel passing through the North Basin and the Middle Basin is dredged to -1.83 m (-6.0 ft) NAVD88, and several habitat areas are created in the Middle Basin with the highest elevation at approximately +3.66 m (+12.0 ft) NAVD88. The model elevation for the Estuary Alternative within Capitol Lake Basin is shown in Figure 3-3.
- **Hybrid Alternative:** This alternative includes the same elements as the Estuary Alternative, but a barrier wall would be constructed at approximately the centerline of the North Basin to develop a reflecting pool on the east side of the basin. The bed elevation of the basin under the Hybrid Alternative is shown in Figure 3-4. The design features and key elevations for each alternative for Middle and North Basins is listed in Table 3-1.

Table 3-1 Design Features and Key Elevations for Each Alternative

Feature	No Action	Managed Lake	Estuary	Hybrid
Middle Basin – Dredged Channel Elevation	N/A	N/A	-1.83m	-1.83m
Middle Basin – Dredged Channel Width	N/A	+85.00 - +110.00 m	+85.00 - +110.00 m	+85.00 - +110.00 m
Middle Basin – Habitat Area Highest Elevation	N/A	+4.27m	+3.66m	+3.66m
North Basin – Channel Dredge Elevation	N/A	-0.91m	-1.83m	-1.83m
North Basin – Habitat Area Highest Elevation	N/A	N/A	N/A	N/A
North Basin – Barrier Wall	N/A	N/A	Yes	N/A

Figure 3-1 Model Elevation – No Action Alternative

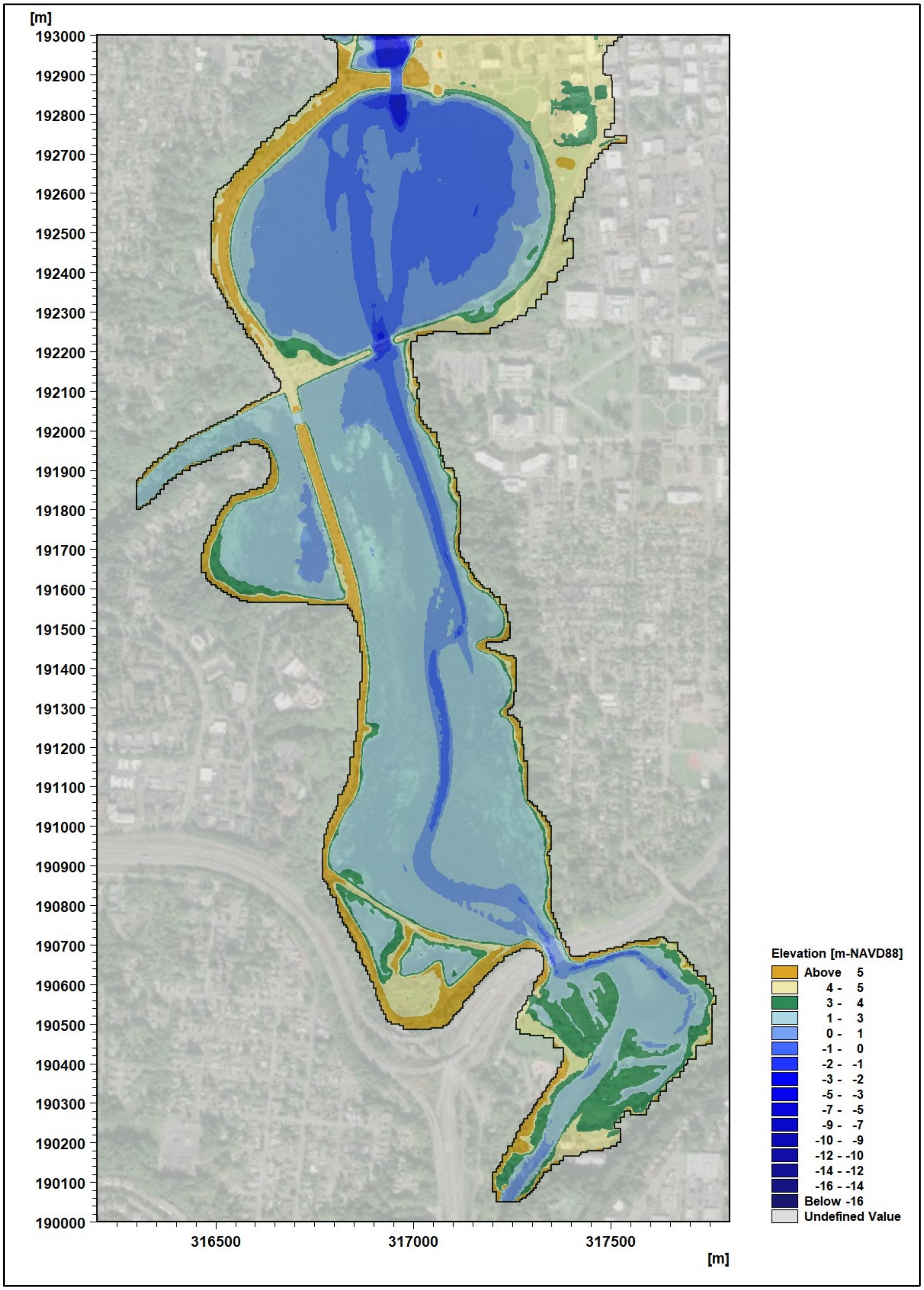


Figure 3-2 Model Elevation – Managed Lake Alternative

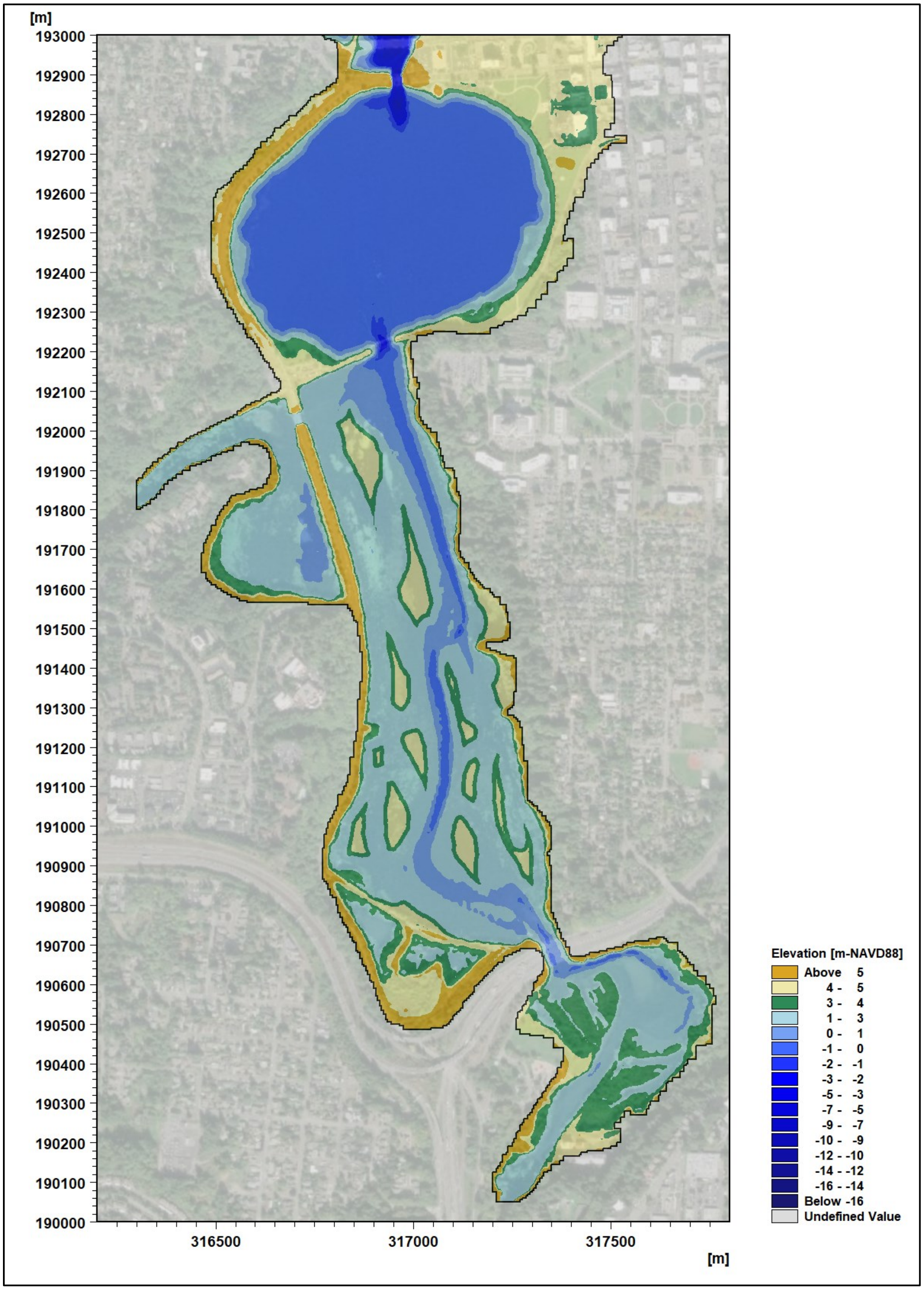


Figure 3-3 Model Elevation – Estuary Alternative

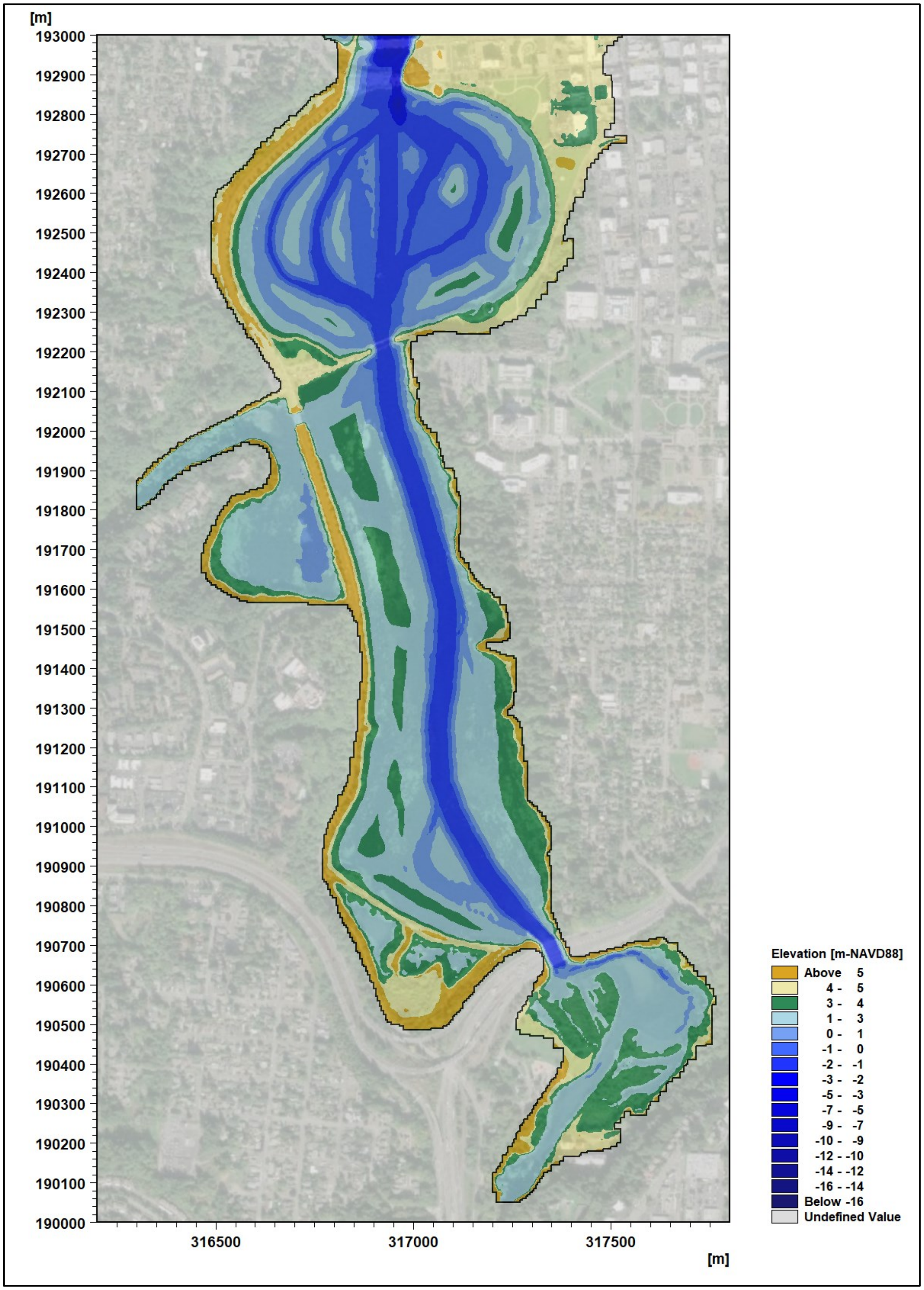
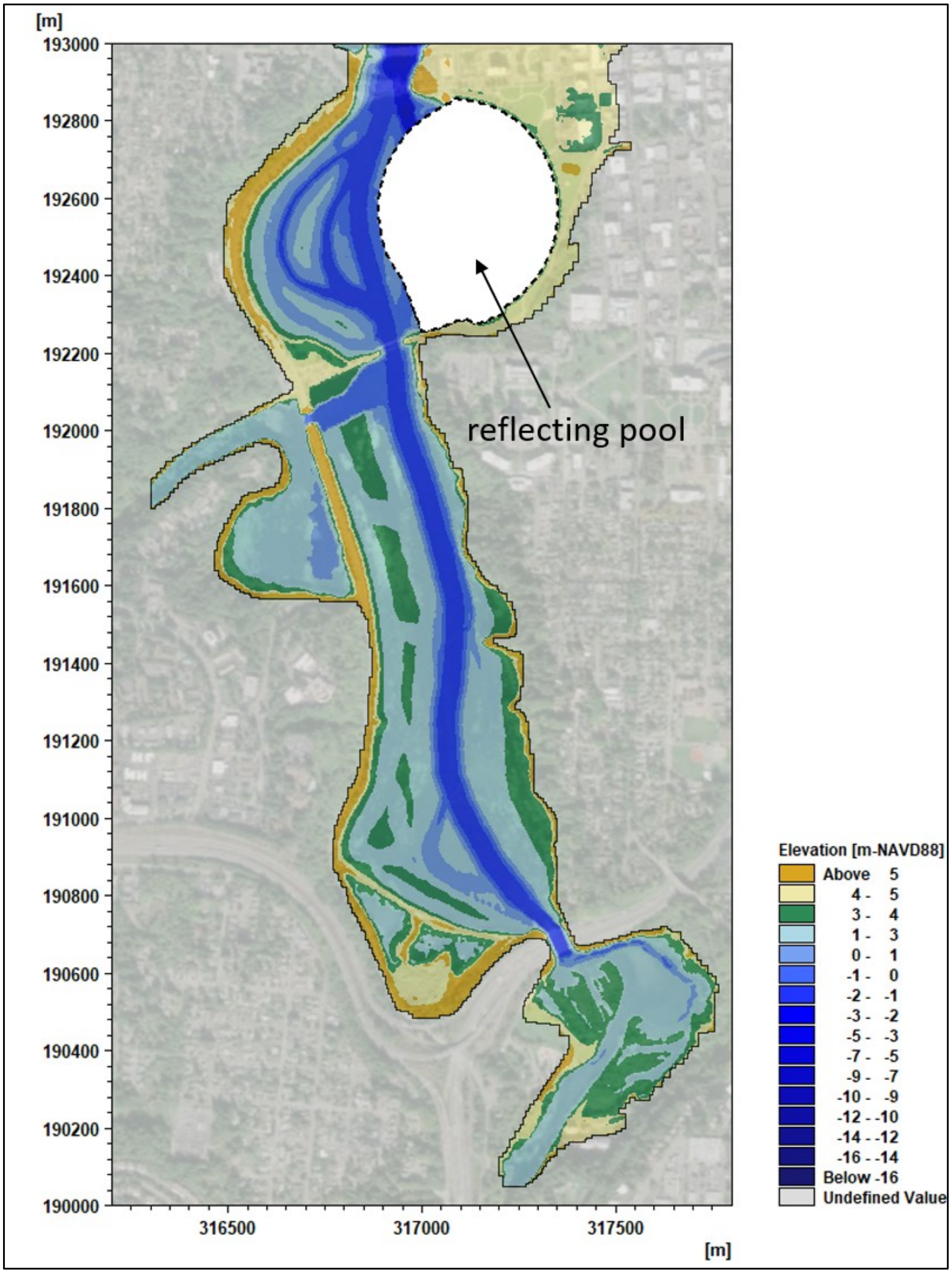


Figure 3-4 Model Elevation – Hybrid Alternative



4.0 Hydrodynamic Modeling

This section summarizes the numerical modeling work completed, including hydrodynamic model development and calibration/validation. A state-of-the-art surface water modeling system, Delft3D, developed at the Delft University of Technology (Deltares 2018), was used to simulate hydrodynamics in the study area.

4.1 MODEL DESCRIPTION

The Delft3D hydrodynamic-morphological modeling system, developed at Delft University of Technology in Netherlands, integrates the effects of waves, currents, sediment transport, and salinity on morphological changes, see Deltares (2018) for further details. This modeling system can simulate the morphodynamic behavior of rivers, estuaries, and coastal areas incorporating complex interactions between waves, currents, sediment transport, and bathymetry.

The hydrodynamic module Delft3D-FLOW was used to model hydrodynamics herein. Delft3D-FLOW can simulate two-dimensional (2D, depth averaged) or three-dimensional (3D) unsteady flow and transport resulting from tidal and/or meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). The flow can be forced by tide at the open boundaries, wind stress at the free surface, and pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). The 3D version of the Delft3D-FLOW was used herein.

The Delft3D-FLOW solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumption. Delft3D uses a fully implicit method to solve the equations in the vertical axis. The model allows the wetting and drying of tidal flats, which is a very common phenomenon in tidal estuaries.

4.2 MODEL DEVELOPMENT

4.2.1 Horizontal Coordinate System and Vertical Datum

The horizontal coordinate system for the hydrodynamic and sediment transport modeling was the Washington State Plane South NAD83 in meters. Vertical datum and units for the modeling were NAVD88 and meters, respectively.

4.2.2 Model Grid

The model domain extends from the Deschutes River mouth near Tumwater Falls to Budd Inlet near Gull Harbor, WA, approximately 4.5 miles north (downstream) of the 5th Avenue Dam (see Figure 4-1).

The model was built on a curvilinear computational grid. Over 100,000 computational grid points define the model. The grid resolution is variable to resolve details of the flow in different regions, to represent the dam structure in the domain, and to use coarser resolution to save computational time where fine resolution is not needed. Inside the Capitol Lake Basin, the grid cell resolution is close to uniform with a grid spacing of approximately 5 m. In the offshore area, the grid spacing increased from approximately 5 m spacing downstream of the lake to approximately 40 m spacing at Gull Harbor. The model domain and grid is shown in Figure 4-1; Figure 4-2 shows the finer model grid in the Capitol Lake Basin near the dam.

Figure 4-1 Model Grid

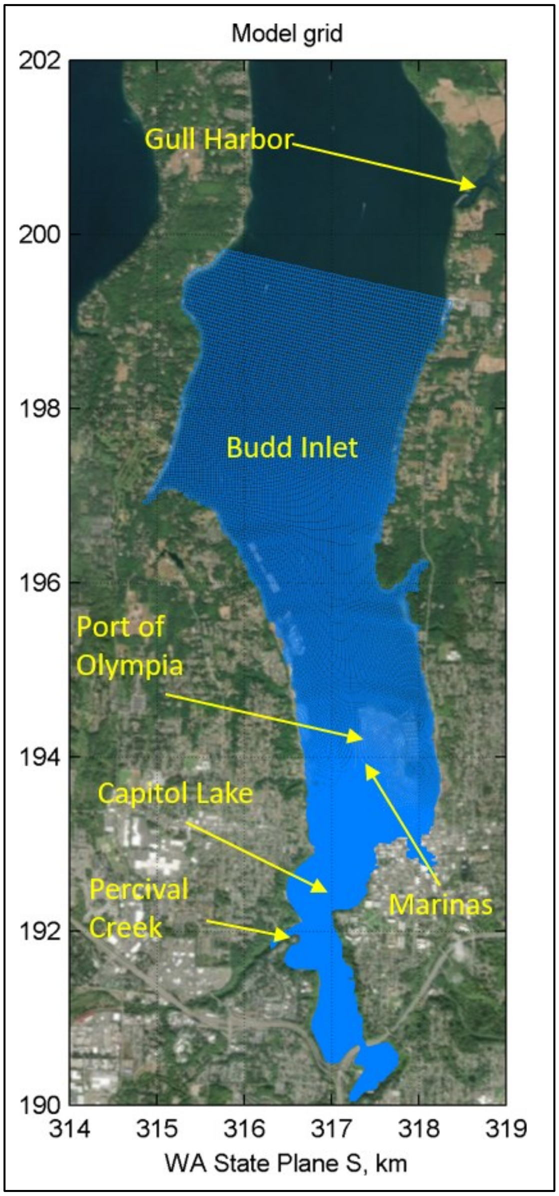


Figure 4-2 Model Grid in the South Basin

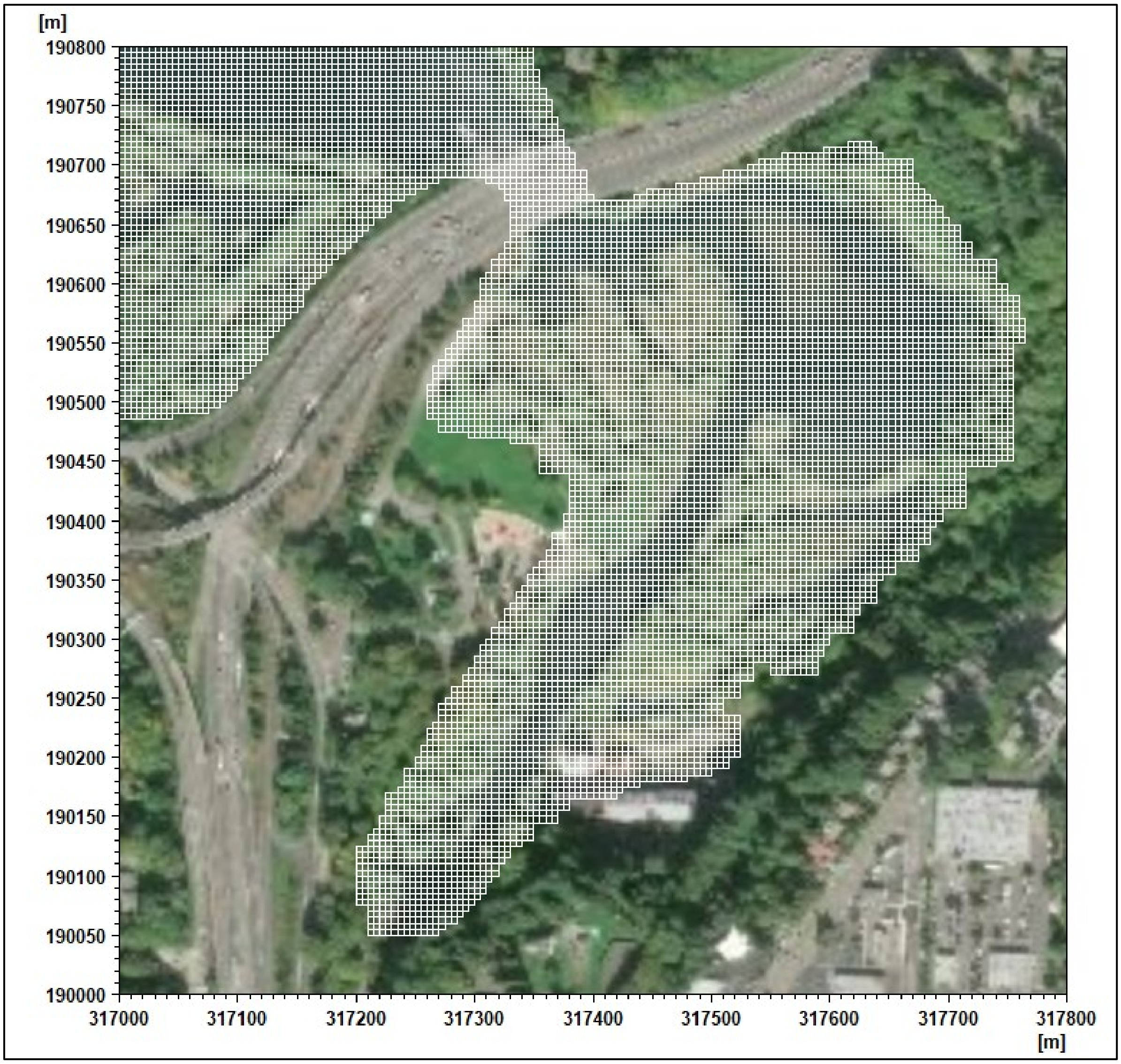


Figure 4-3 Model Grid in the Middle Basin and Percival Creek and Cove

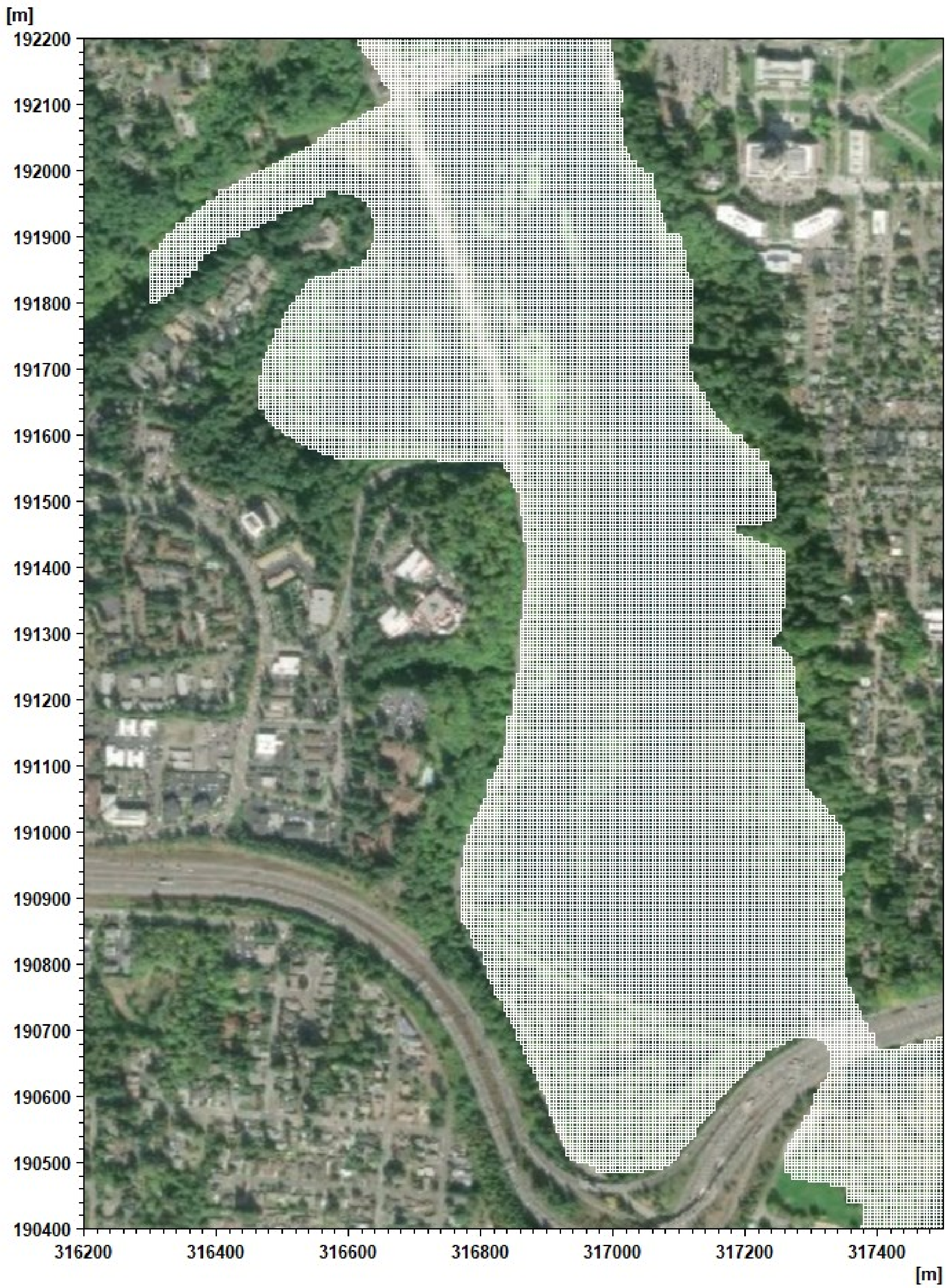


Figure 4-4 Model Grid in the North Basin

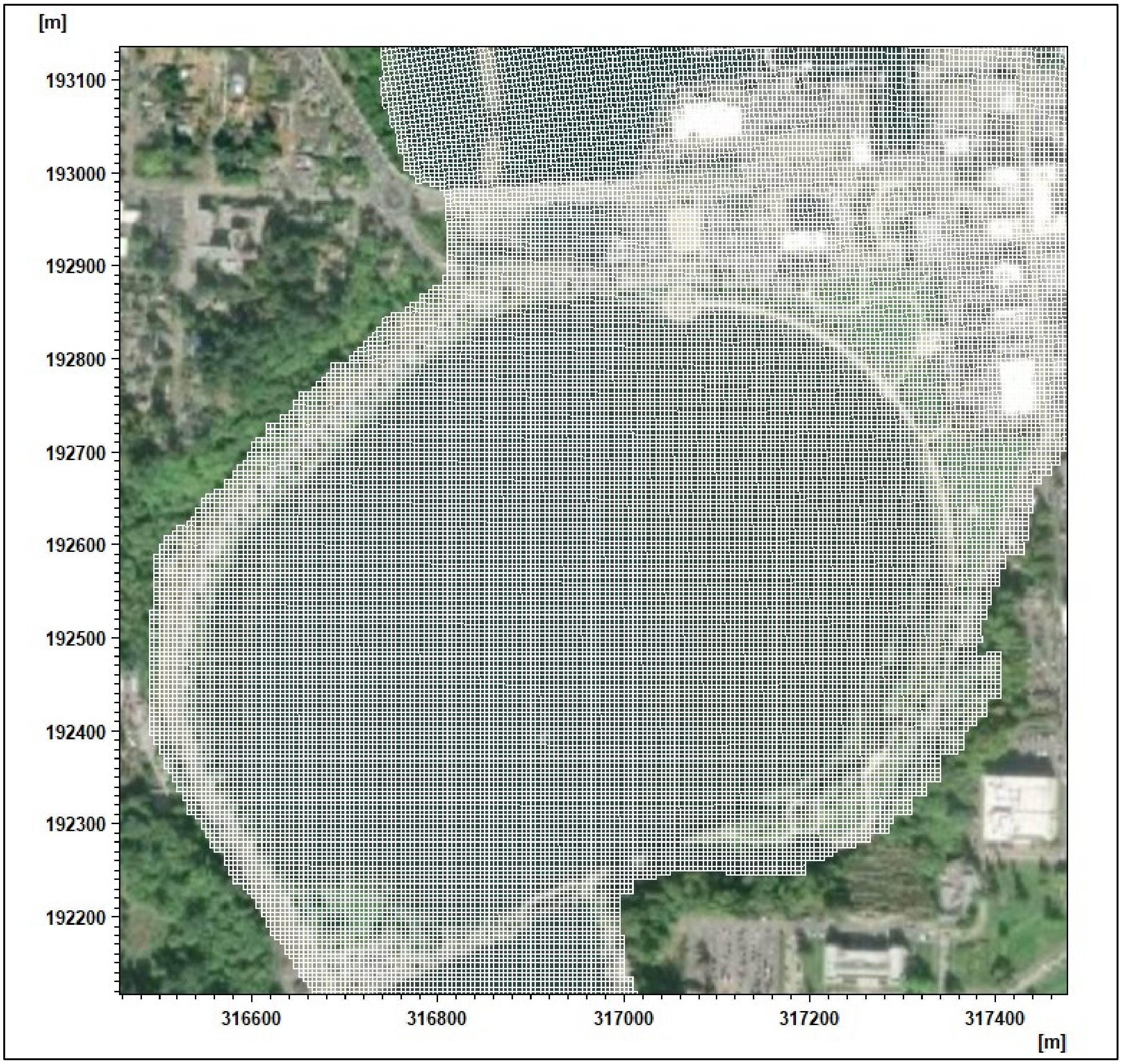


Figure 4-5 Model Grid in Budd Inlet from Yacht Club to Port of Olympia

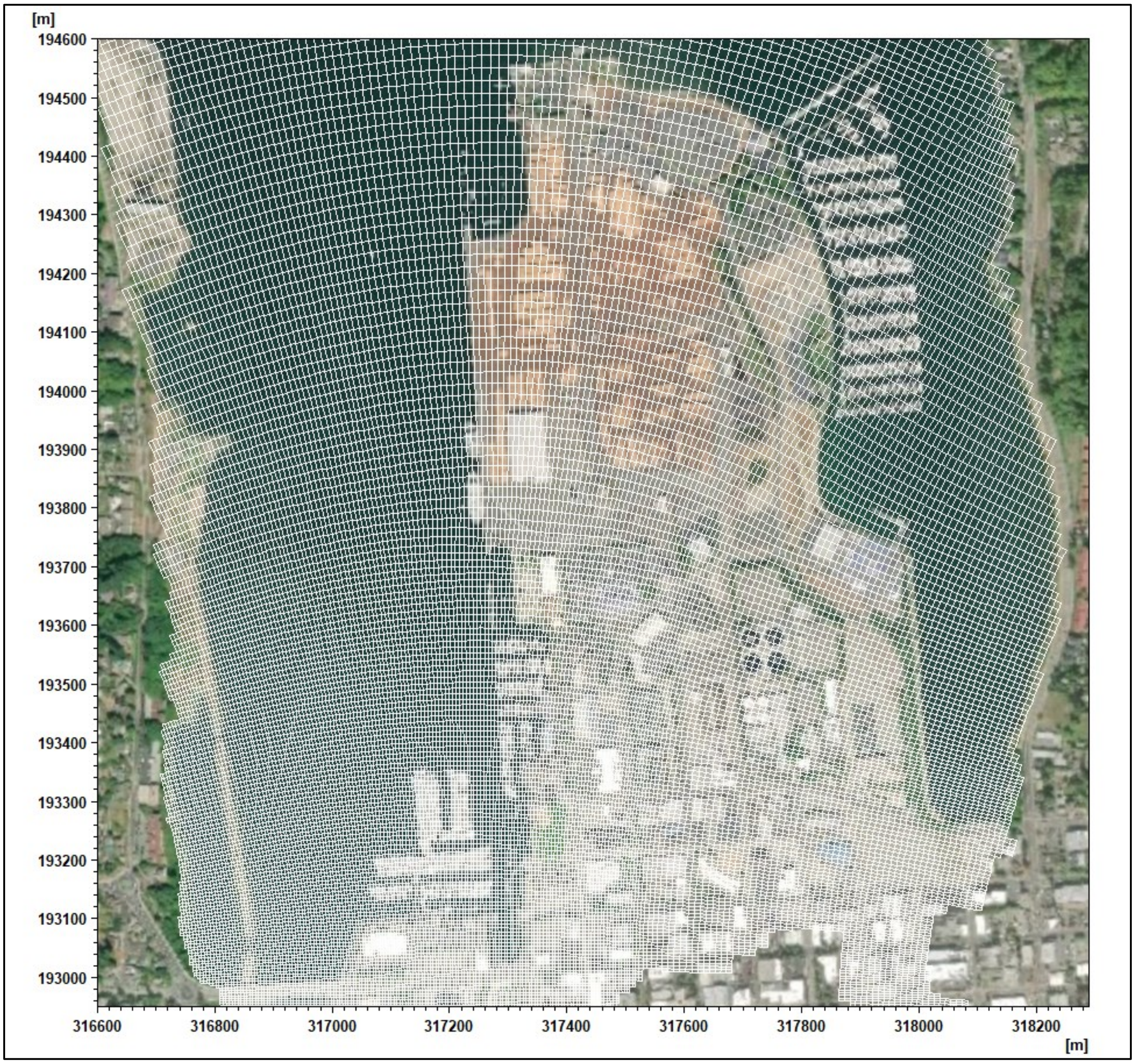
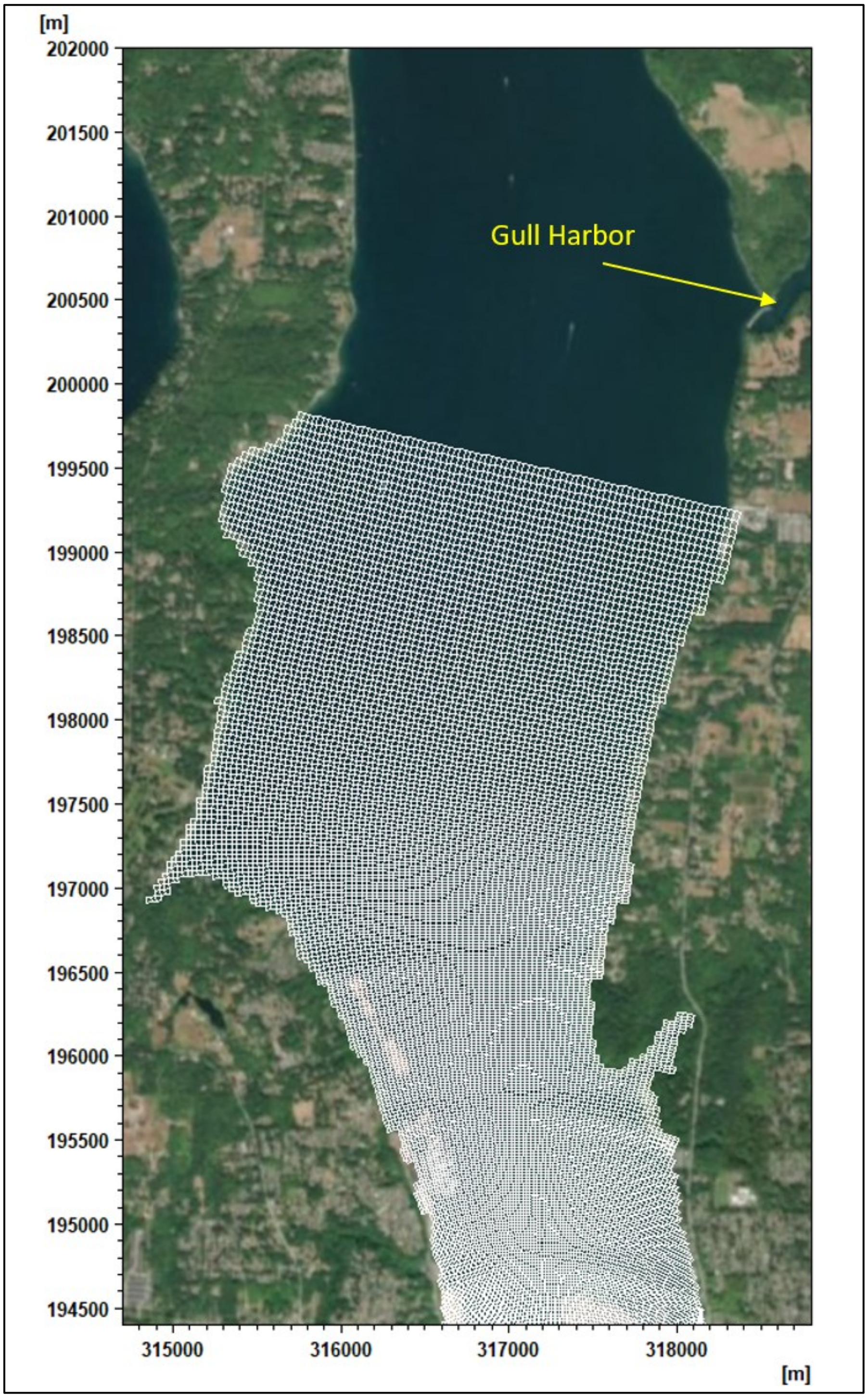


Figure 4-6 Model Grid in Budd Inlet Downstream to Port of Olympia



4.2.3 Model Elevation

Model elevation was developed by combining bathymetric and topographic survey data from five datasets, discussed in Section 2.3. All datasets were converted to project horizontal coordinate system (Washington State Plane South in meters) and vertical datum of NAVD88 in meters before model elevation development. The five datasets, listed in the order of increasing priority as datasets overlap in some areas, are as follows:

- 2014 NOAA Puget Sound, WA 1/3 arc-second DEM;
- 2015 Olympia City LiDAR data;
- 2019 USACE survey data of Budd Inlet;
- 2013 TerraSond survey of Capitol Lake;
- 2020 eTrac survey of Capitol Lake

Model elevation for calibration/validation process (associated with the No Action Alternative) is shown in Figure 4-7.

For production runs, the model elevations were based on the model elevations from the calibration process with existing elevations in Capitol Lake replaced for each project alternative, as discussed in Section 3.0. Model elevations for the No Action Alternative, Managed Lake Alternative, Estuary Alternative, and Hybrid Alternative used in the production runs are shown in Figure 4-8.

Figure 4-7 Model Elevation for Calibration Process (m-NAVD88)

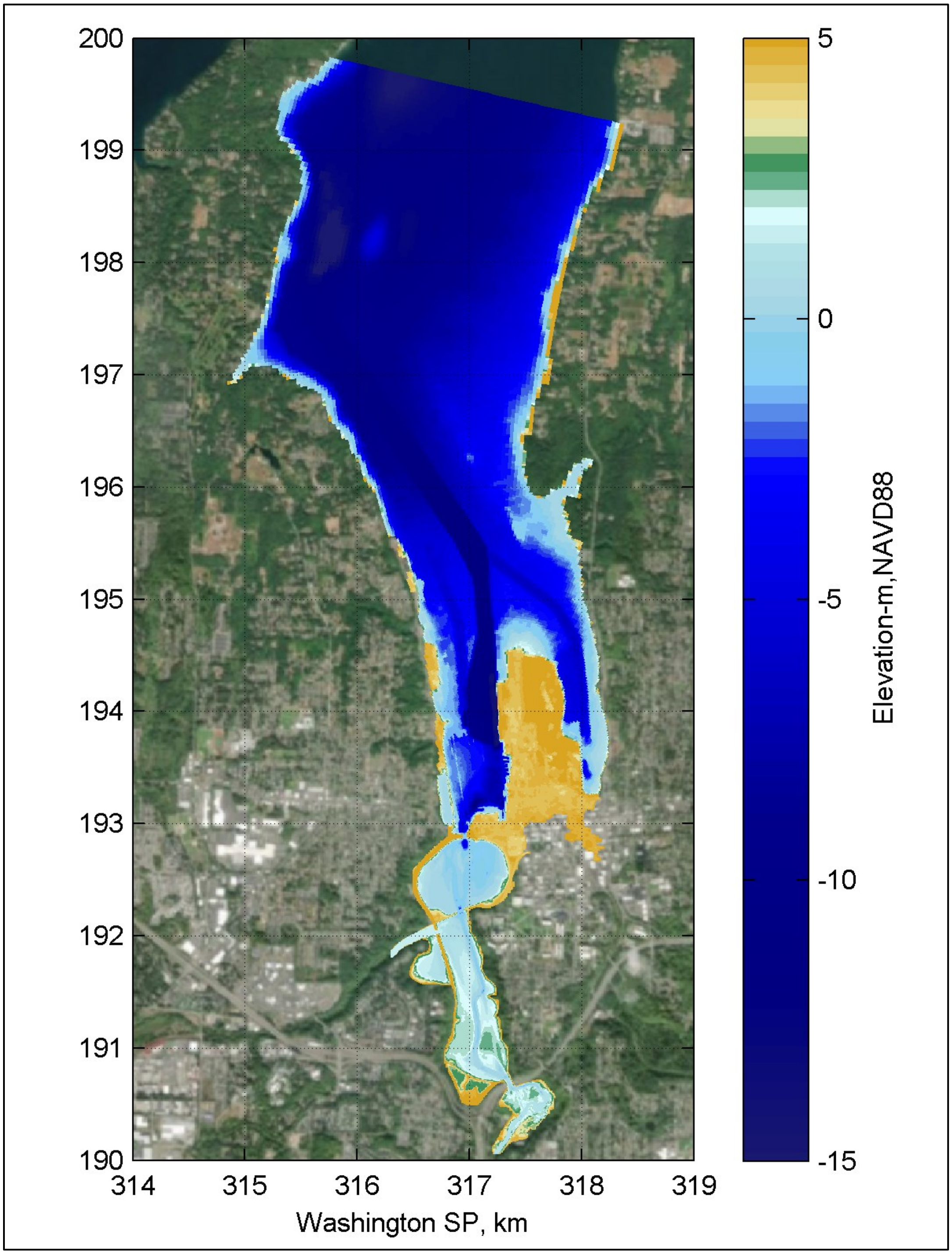
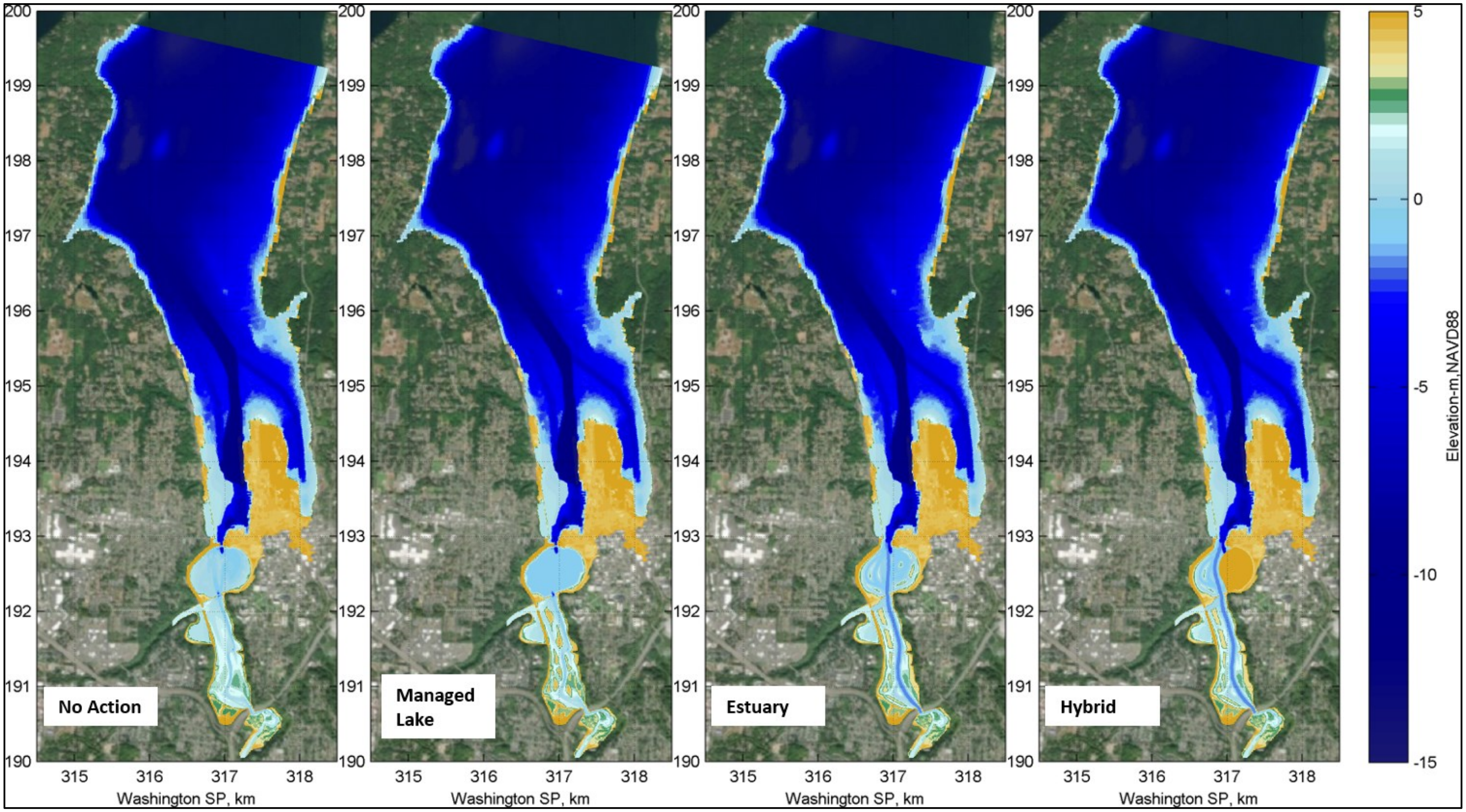


Figure 4-8 Model Elevation for Four Alternatives (m-NAVD88)

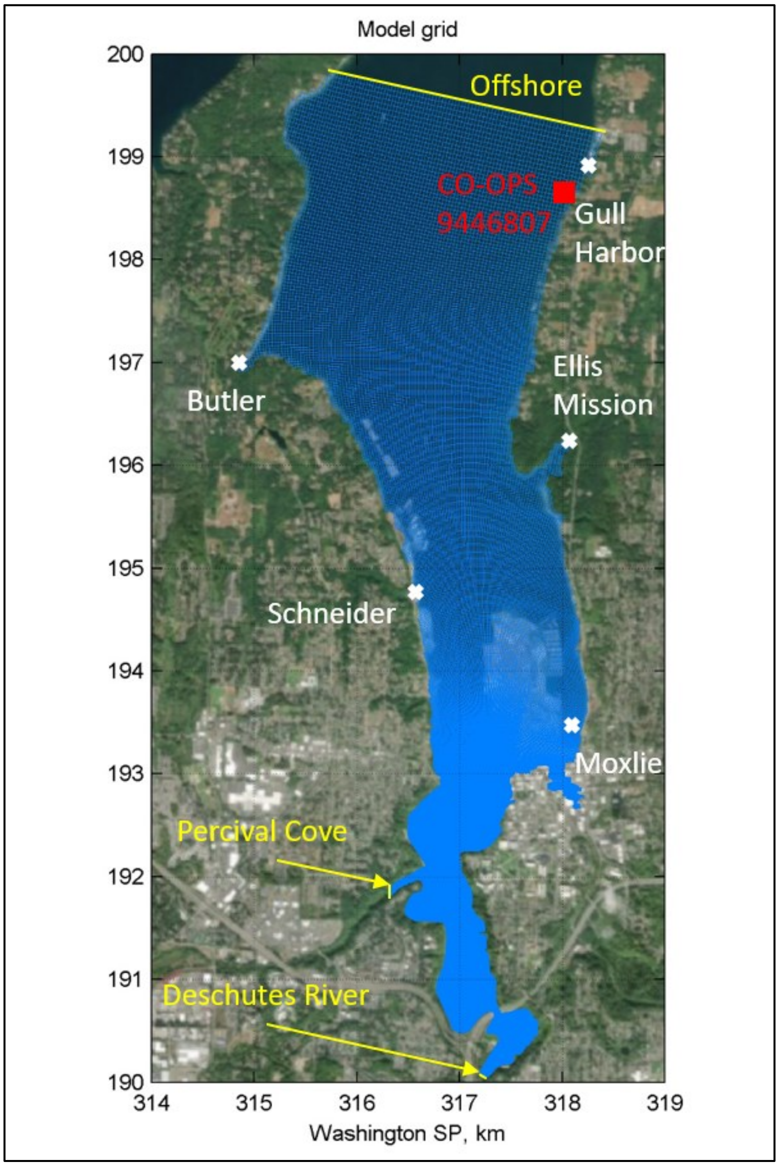


4.3 MODEL BOUNDARY CONDITIONS

Hydrodynamic models compute water surface elevations and current velocities over an area of modeled water body. The water levels and currents are primarily driven by variations of tide levels and inflows or outflows at the model boundaries and are influenced by bathymetry and roughness. These variations are referred to as boundary conditions. These conditions may include ocean tides and currents, and freshwater inflows from surrounding rivers and creeks.

There are three open boundaries in the model: (a) two upstream boundaries with freshwater inflow from the Deschutes River and Percival Creek and (b) the offshore boundary in Budd Inlet. The boundary locations are shown in Figure 4-9. There are five ungaged watersheds that discharge into Budd Inlet, see Figure 4-9 for their locations. The flow from these watersheds was not incorporated into the model because of their relatively small contribution.

Figure 4-9 Model Boundaries

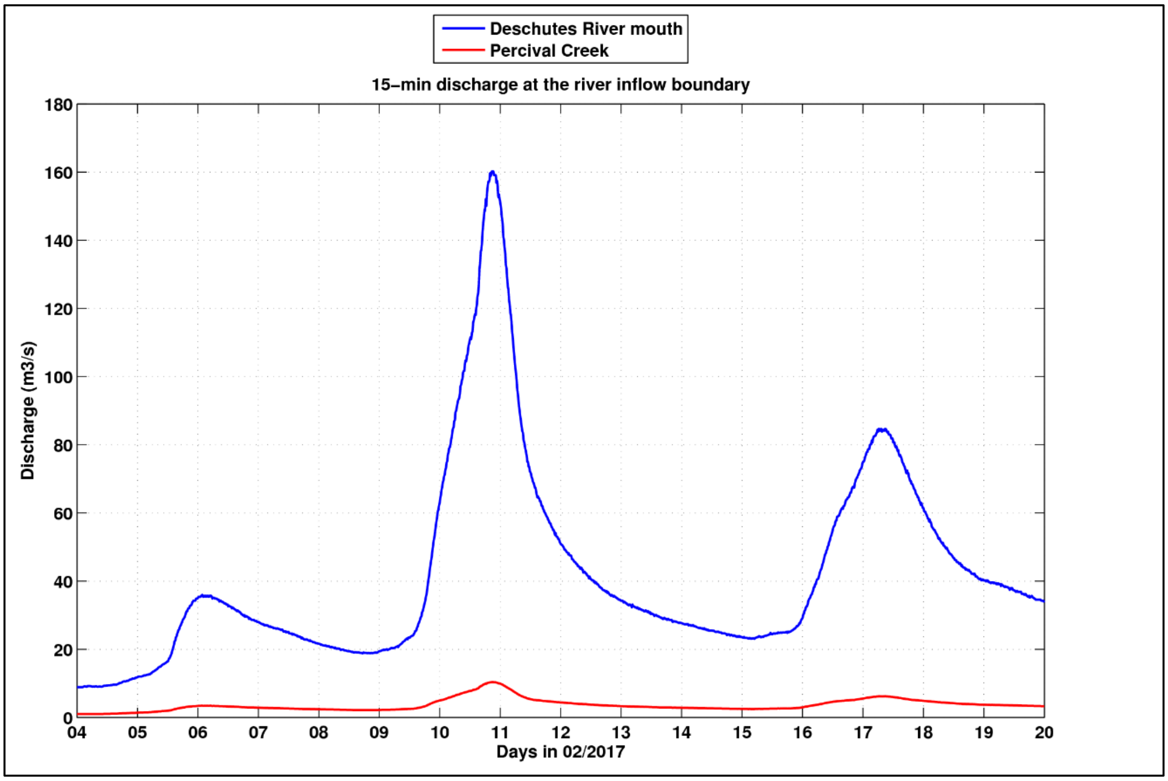


4.3.1 River/Creek Inflow Boundary

Two inflow boundaries were applied at the Deschutes River and Percival Creek, see Figure 4-9.

For the calibration process, time histories of discharge sampled at 15-min intervals at the USGS stream gage at E Street Bridge in Tumwater (Stream Gage 12080010) were used in the Deschutes River boundary. Time histories of discharge at the Percival Creek boundary were calculated from the Deschutes River boundary scaled using the watershed area approach (Archfield and Vogel 2010). Time series of discharge at the Deschutes River boundary and Percival Creek boundary for the calibration period (described in Section 4.4.2) are shown in Figure 4-10.

Figure 4-10 Time History of 15-min Discharge at the River Inflow Boundaries for Calibration Run



For the production runs, river discharges from the 100-yr flood event were applied at the Deschutes River boundary and the Percival Creek boundary. The 100-yr discharge (15-min average) value analyzed from measurements at Deschutes River at E Street Bridge (USGS Stream Gage 12080010) is 302 m^3/s, while the 100-yr discharge acquired from a previous study and the published flood analysis report was 341 m^3/s (CLAMP 2000) and 329 m^3/s (FEMA 2018). To represent a more conservative scenario (and capture possible increase in extreme flow events resulting from climate change), a 100-yr (15-min average) discharge of 341 m^3/s was used as a constant inflow value at the Deschutes River boundary and a 100-yr discharge of 15 m^3/s calculated from the Deschutes River boundary with the scaling factor approach described in Section 2.5 applied at the Percival Creek boundary as a constant inflow value.

4.3.2 Offshore Water Level Boundary

Astronomical tidal constituents[2] from Gull Harbor in eastern Budd Inlet (NOAA Station 9446807) were used to construct water level time series with a 15-min interval at the offshore boundary. The amplitude and phase for twelve main tidal constituents are listed in Table 4-1.

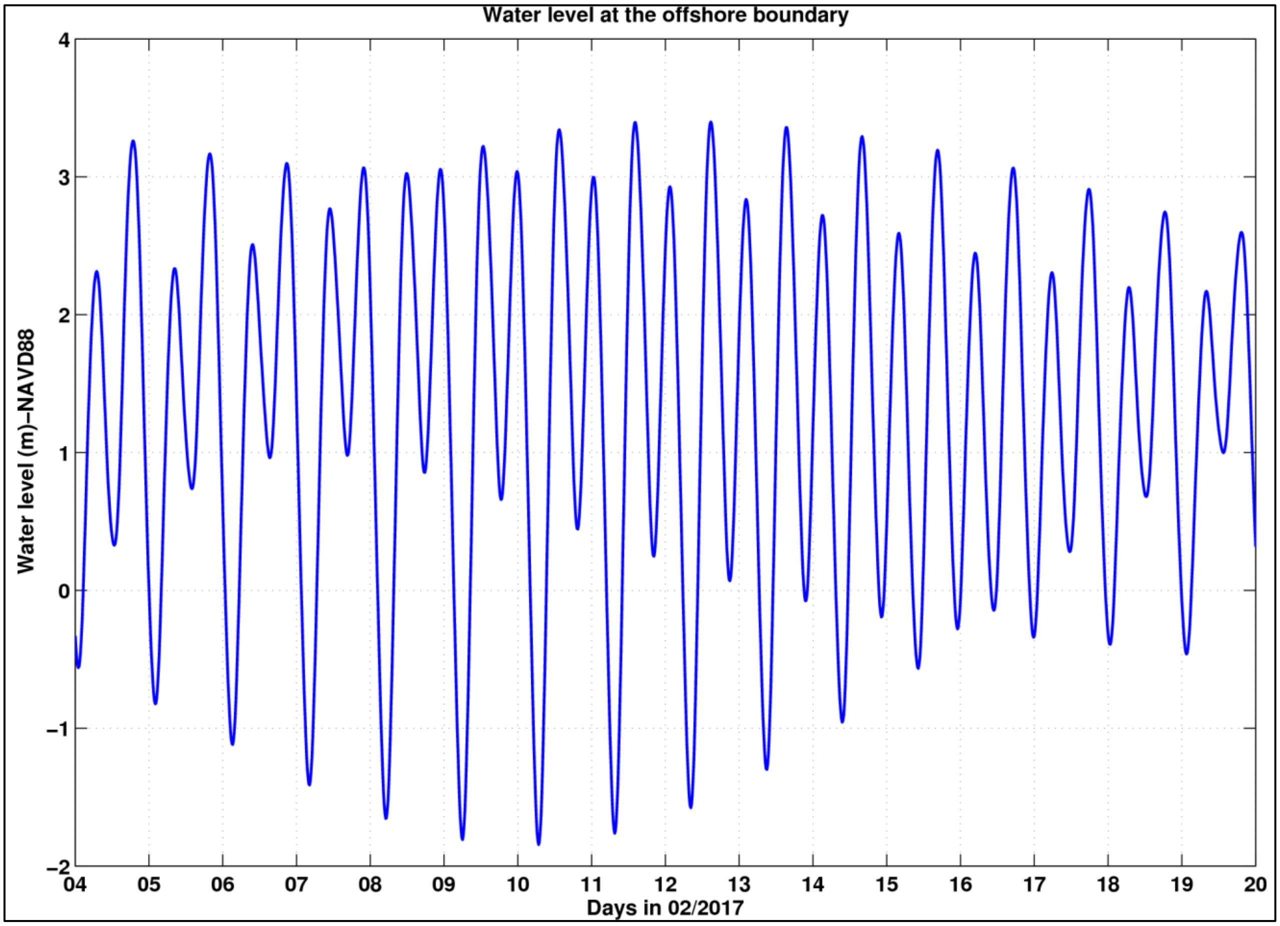
For the calibration process, water level time series during the proposed calibration period are plotted in Figure 4-11. Residual water level, besides the astronomical components, was not incorporated for model calibration/validation because hydrodynamics inside the Capitol Lake Basin are mainly governed by dam operation and river inflow. The effect of meteorological components (wind) on currents outside the Capitol Lake (in Budd Inlet) were evaluated during the calibration/validation process, see Section 4.4.4.

Table 4-1 Main Tidal Constituents at the Offshore Boundary (NOAA Station 9446807)

Constituents	Amplitude (m)	Phase (degree)
M2	1.46	30.30
K1	0.88	289.60
O1	0.47	266.40
S2	0.34	62.00
N2	0.28	4.50
P1	0.27	285.30
K2	0.10	58.80
Q1	0.07	264.70
L2	0.07	64.40
J1	0.05	331.40
M4	0.05	294.40
M6	0.03	143.80

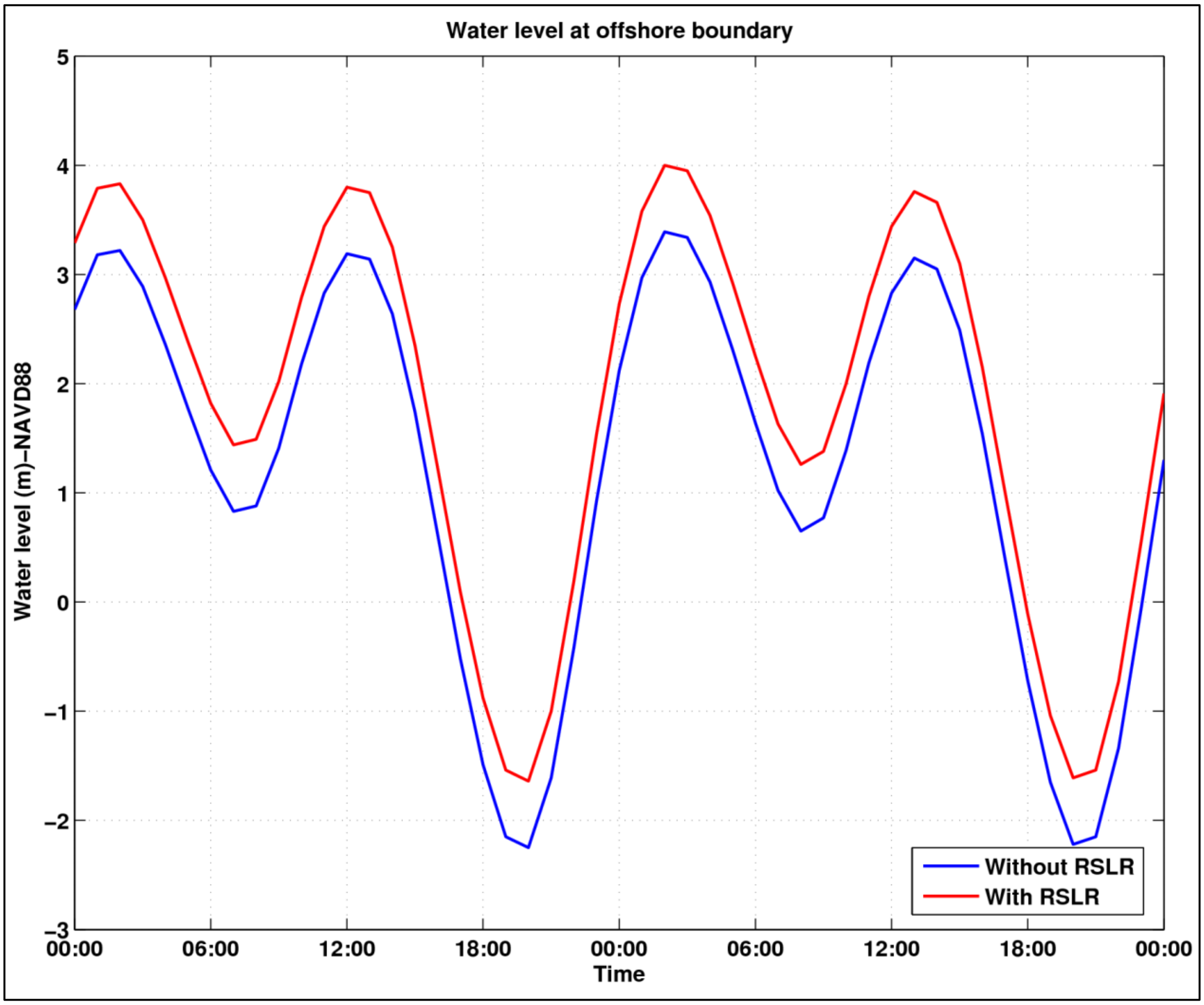
[2] Tidal constituent is one of the harmonic elements in a mathematical expression for the tide-producing force and in corresponding formulas for the tide or tidal current. Each constituent represents a periodic change or variation in the relative positions of the Earth, Moon, and Sun.

Figure 4-11 Water Level at the Offshore Boundary for Calibration/Validation Period



For the production runs, a typical spring tide was used for the offshore boundary condition without and with 0.61 m (2 ft) of RSLR added to the tidal water level. Potential increase in RSLR was simulated by applying a 0.61 m future increase in RSLR applied as a relative, i.e. local, upward shift in offshore water level boundary condition defined as “With RSLR Conditions”, see Figure 4-12.

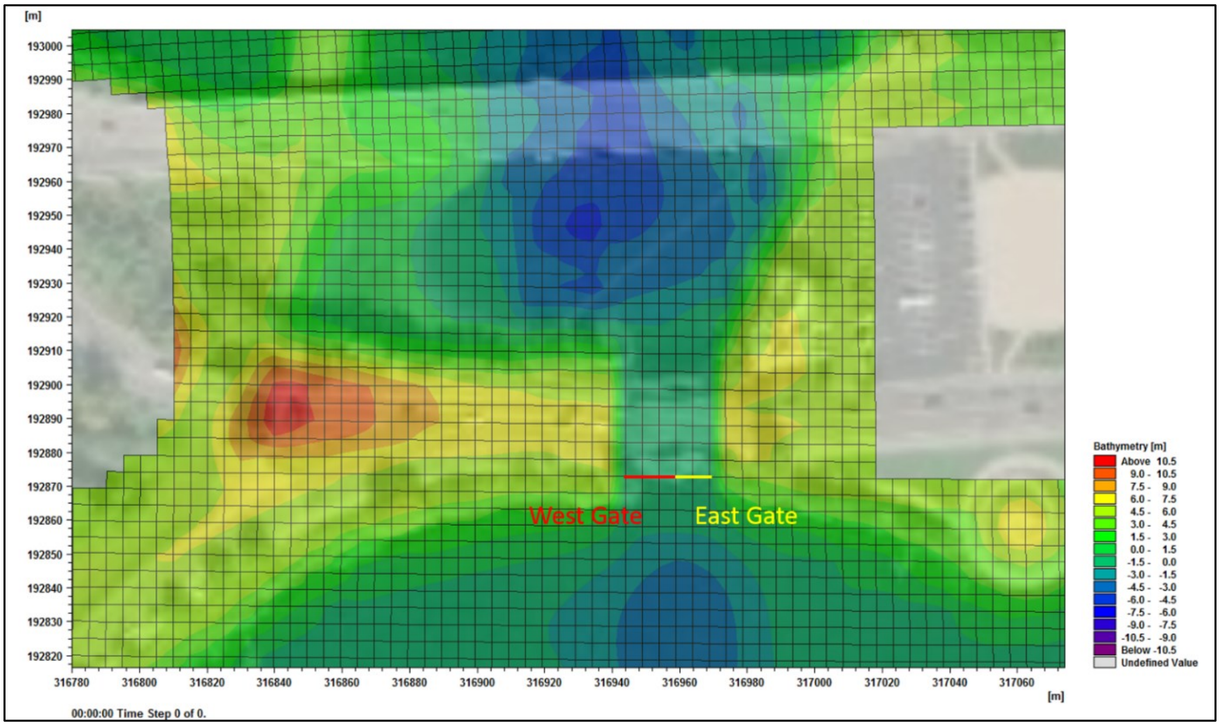
Figure 4-12 Typical Spring Tide Offshore Water Level Boundary Condition for Production Runs



4.3.3 5th Avenue Dam Operation Representation

To represent the 5th Avenue Dam operation, barrier structures were added to the model to control water infill and release using the Real-Time Control (RTC) Tools Package. The RTC Tools Package provides the capability to simulate hydraulic structures such as weirs and intakes with time-dependent controls in Delft3D model. Two barrier structures were used to represent the West and East Gates, as shown in Figure 4-13. The West Gate spans three grid cells and the East Gate spans two grid cells.

Figure 4-13 Location of Barrier Structures Representing the West and East Gates



Time series of gate opening height (bottom level) were developed based on two parameters: the estimated discharge at the gate and the relationship between discharge and gate height. The derivation of these parameters is described in the following two sections.

4.3.3.1 Discharge at the Gate

The net discharge to/from the Capitol Lake Basin can be approximated using the change in lake water levels over a period. For example, during a single gate operation, the net discharge can be calculated using equation:

$$Q_{net}(t) = \frac{\Delta h(t) \cdot A}{t_{open}} \qquad (1)$$

where t is the time, t_{open} is the duration of gate operation (open or closed), Q_{net} is the net discharge into the lake, Δh is the water level change at the dam during gate operation, and A is the average surface area of the lake.

Upstream of the dam, the net discharge can be calculated based on the conservation of water mass inside the lake using equation:

$$Q_{net}(t) = -Q_{gate}(t) + Q_{river}(t - t_{delay}) \tag{2}$$

where Q_{gate} is the total discharge at the dam; Q_{river} is the discharge from upstream rivers, and t_{delay} is the time delay. The time delay between Q_{net} computed from equation (1) and Q_{river} occurs due to the lag between river discharge and the change in water level at the dam. The delay was estimated to be 4 hours, assuming the distance between the upstream boundary and the dam is approximately 4.5 km and mean current velocity is approximately 0.3 m/s.

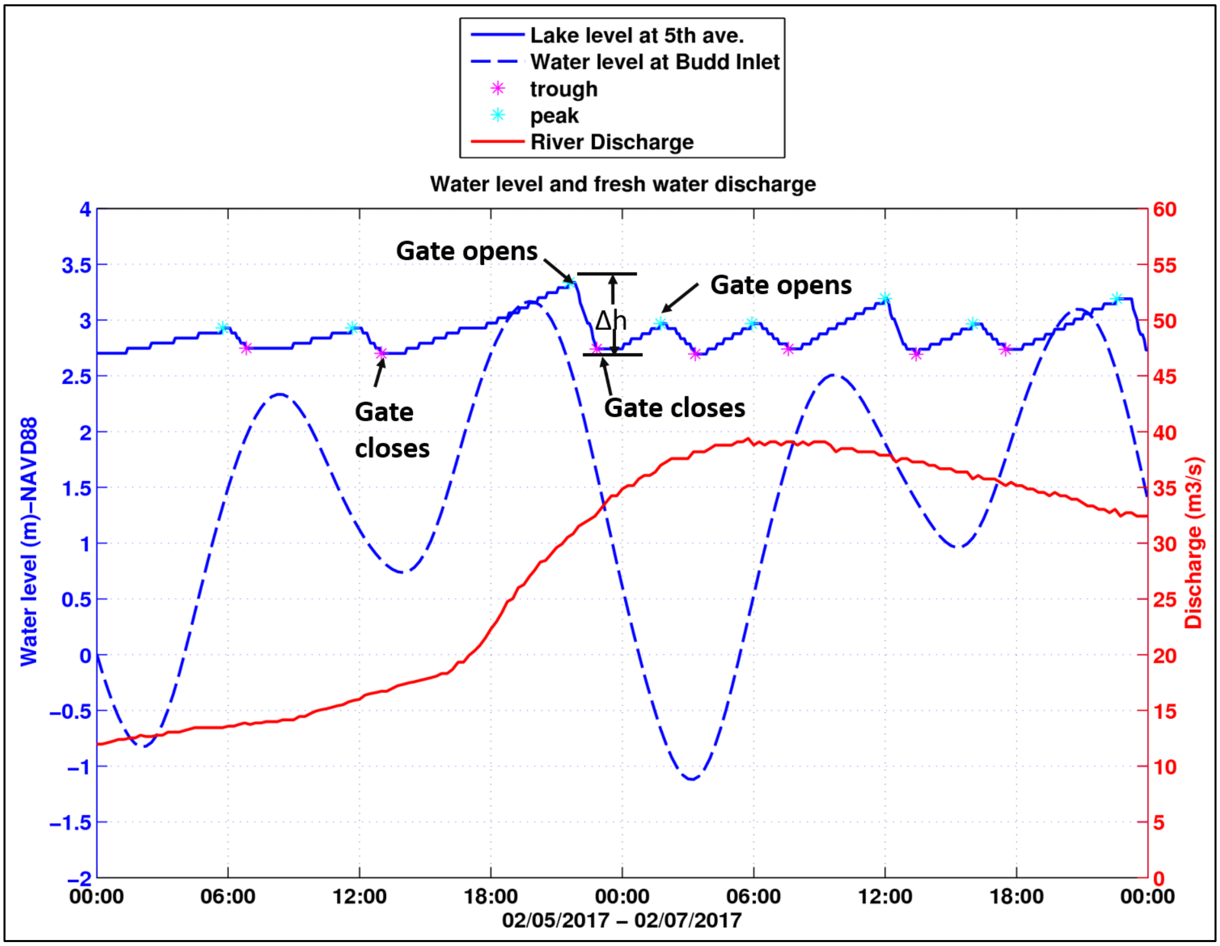
To further explain details of the computation procedure, an example shown in Figure 4-14 is used. From the lake level shown in Figure 4-14, there are two stages—water infill during dam gate closure and water release during dam gate opening. When the gate is closed and the lake is infilling, Q_{gate} equals zero, and Q_{net} is the same as Q_{river}. When the gate is open, Q_{net} and Q_{river} are calculated first and Q_{gate} equals the difference between them. Q_{river} is the summation of river discharge from Deschutes River and Percival Creek with a 4-hour shift (red line shown in Figure 4-14). Q_{net} is calculated using the following equation.

$$Q_{net}(t) = \Delta h \times Area(t) \tag{3}$$

This equation is the modified version of equation (1), where Δh is the difference between the peak and the trough (shown in Figure 4-14, and equals $\Delta h(t)/t_{open}$ in equation (1)), and Area is the total wetted area in the model domain ranging from 247 acre (1 million m^2) to 371 acre (1.5 million m^2) based on bathymetry survey and land-water boundary from Google Earth. To simplify, the averaged value of 309 acre (1.25 million m^2) was used for the calculation.

At the time of approximately 02/05/2017 22:00, Δh was approximately 0.6 m, and t_{open} was approximately 1.25 hours. As a result, Q_{net} = 0.6*1,250,000/1.25/3600 = 167 m^3/s. Q_{river} was approximately 33 m^3/s from the red line in Figure 4-14. With these values, Q_{gate} results in approximately 200 m^3/s.

Figure 4-14 Measured Water Level at the 5th Avenue Dam with Deschutes River Discharge



4.3.3.2 *Relationship between Discharge and Gate Opening Height*

The discharge through a hydraulic structure such as a barrier can be calculated using the following quadratic friction formula (Deltares 2018):

$$Q = \mu A \sqrt{2g\left|\zeta_u - \zeta_d\right|} \qquad (4)$$

Where Q is the discharge; μ is the contraction coefficient ($0 < \mu \leq 1$); A is the flow-through area; ζ_u and ζ_d are the upstream and downstream water levels, respectively. The contraction coefficient is used to determine the energy loss coefficient, and for a depth-averaged model, the energy loss coefficient, c_{loss}, is related to the barrier contraction coefficient as:

$$c_{loss} = \frac{1}{2\mu^2} \tag{5}$$

The energy loss coefficient, c_{loss}, can control the friction loss, which can compensate the differences between the modeled gate geometry and the actual gate geometry, as shown by Equations (4) and (5). In this study, c_{loss} was used as a calibration parameter.

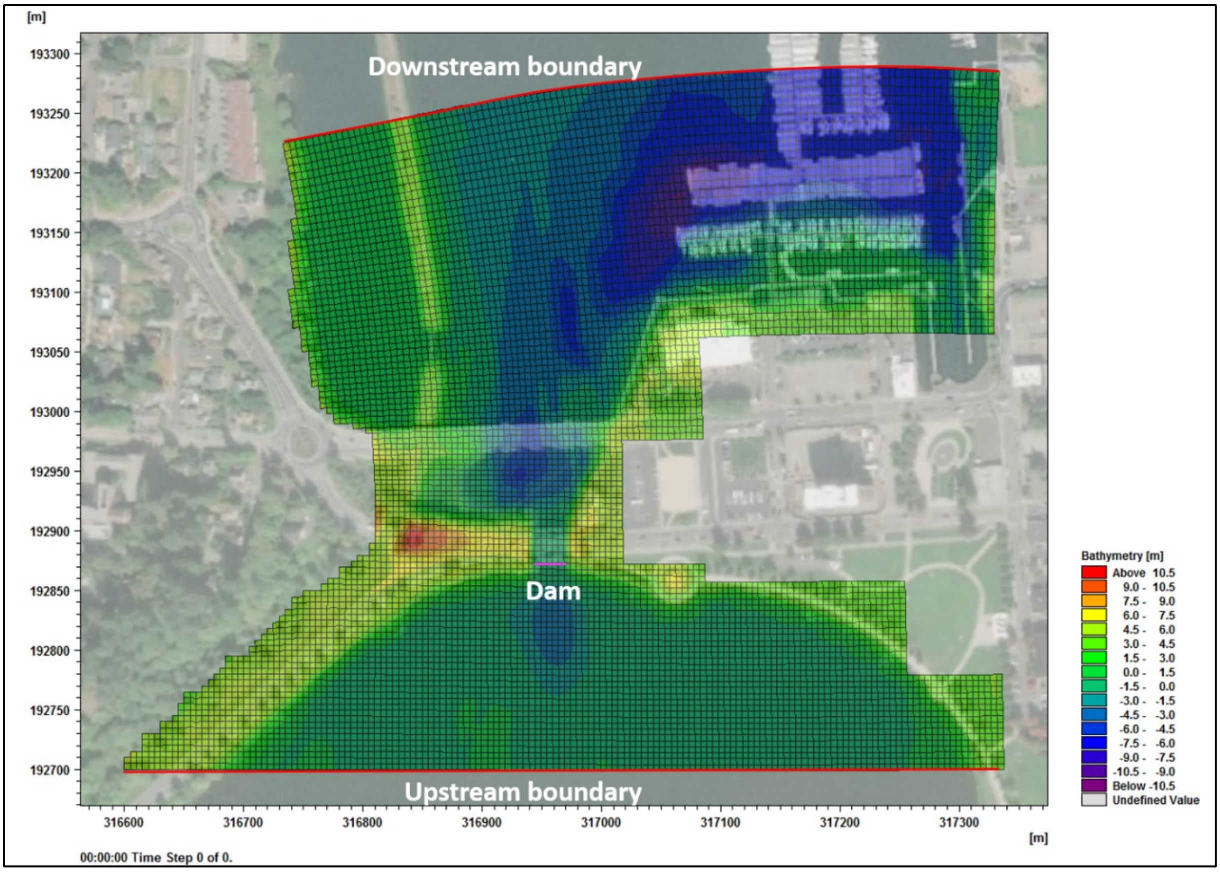
To obtain the relationship between discharge at the gate and the gate opening height efficiently, several steady state runs were developed using a smaller model domain extracted from the original model (Figure 4-15). In those runs, two water level boundaries were used with constant water levels in the Capitol Lake (upstream boundary) and in Budd Inlet (downstream boundary) to control the water flow through the gate. At the downstream boundary, water level of −1 m, NAVD88 were used. At the upstream boundary, water level was varied from 2 to 4 m, NAVD88 with a 0.2 m interval for 11 steady state cases to get a full range of the water level differences between the lake and the inlet. The bottom elevation of both gates is at −0.85 m, NAVD88 and the maximum opening elevation is approximately 2.77 m, NAVD88, as listed in Table 2-14.

For each steady state case, two gate opening configurations were investigated:

- First configuration included operation of the East Gate only with its opening height changing from −0.75 to 2.75 m using RTC. The West Gate was closed.
- Second configuration included operation of both gates with the West Gate height changing from −0.75 to 2.75 m using RTC. The East Gate was fully open.

The gate opening configurations were analyzed to represent the gate operations in reality, consistent with current water level management, where the East Gate was always first to open and the West Gate was open only during extreme events.

Figure 4-15 Local Model Setup for Obtaining Relationship between Discharge and Gate Opening Height



Results for the steady state cases are summarized in Figure 4-16 and Figure 4-17. Generally, an increased water level inside the Capitol Lake Basin results in a larger discharge at the gate due to the larger water level differences on two sides of the dam and the discharge changes non-linearly with the water level, which is expected based on the quadratic equation (4) for the Q-H relationship. Abrupt changes (spikes) in discharge occur when the Capitol Lake water level is close to the gate opening height and the gate no longer affects the discharge. For example, in Figure 4-16 for water level of 2 m, NAVD88 there is a jump between gate opening height of 1.5 m and 1.75 m and then stays constant above 80 m^3/s, which means it reaches the maximum discharge capacity with a gate opening height of 1.75 m.

In summary, first, the associated discharge can be calculated for any given water level change during water release using equations in Section 4.3.3.1. Then, based on the water level and discharge for that event, the gate height can be calculated based on Figure 4-16 and Figure 4-17 using piecewise interpolation to replicate the gate opening logic. This dam operation was used for both calibration and production runs presented in Sections 4.4 and 4.6, respectively.

Figure 4-16 Relationship between Discharge (Q) and East Gate (Bottom) Elevation

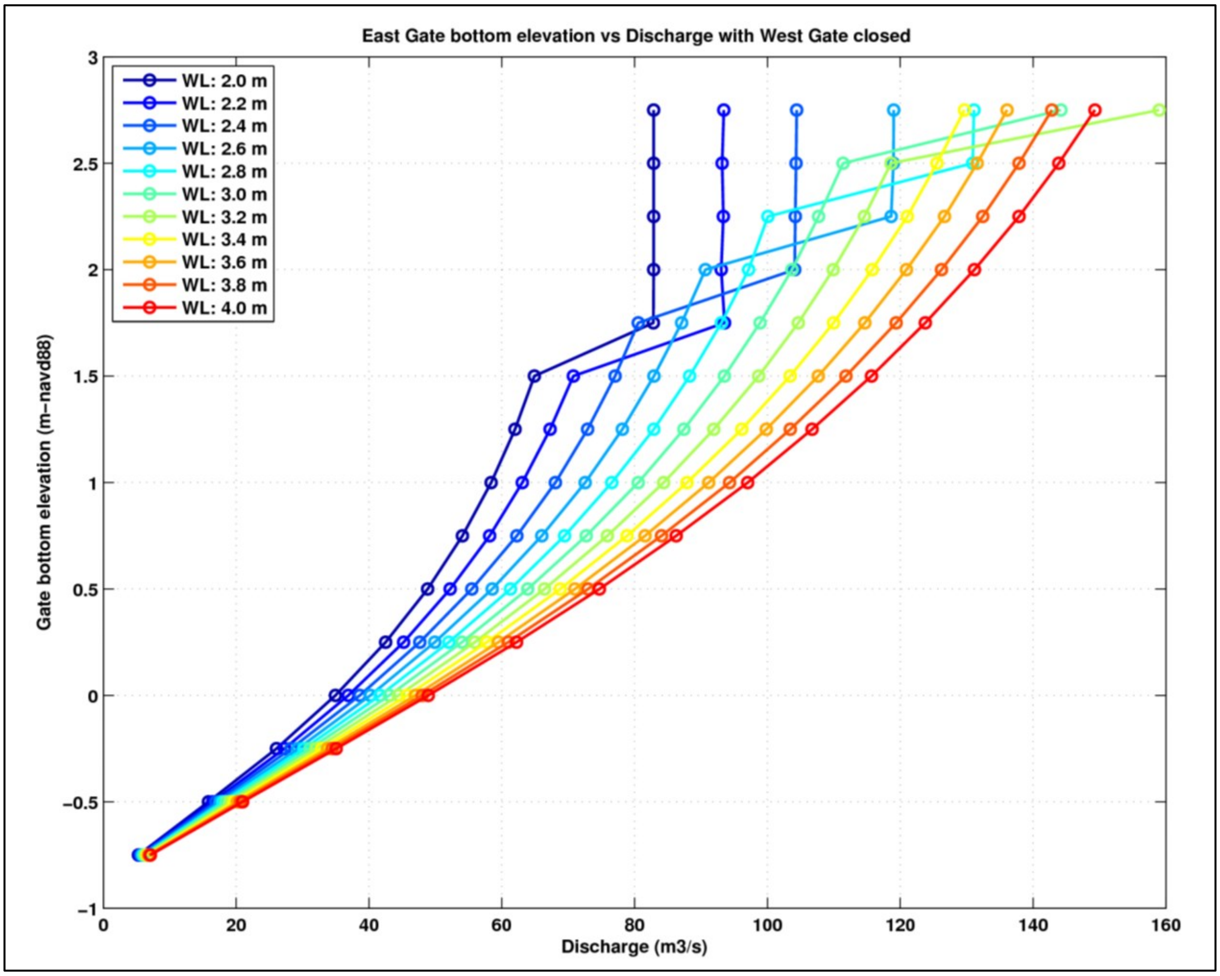
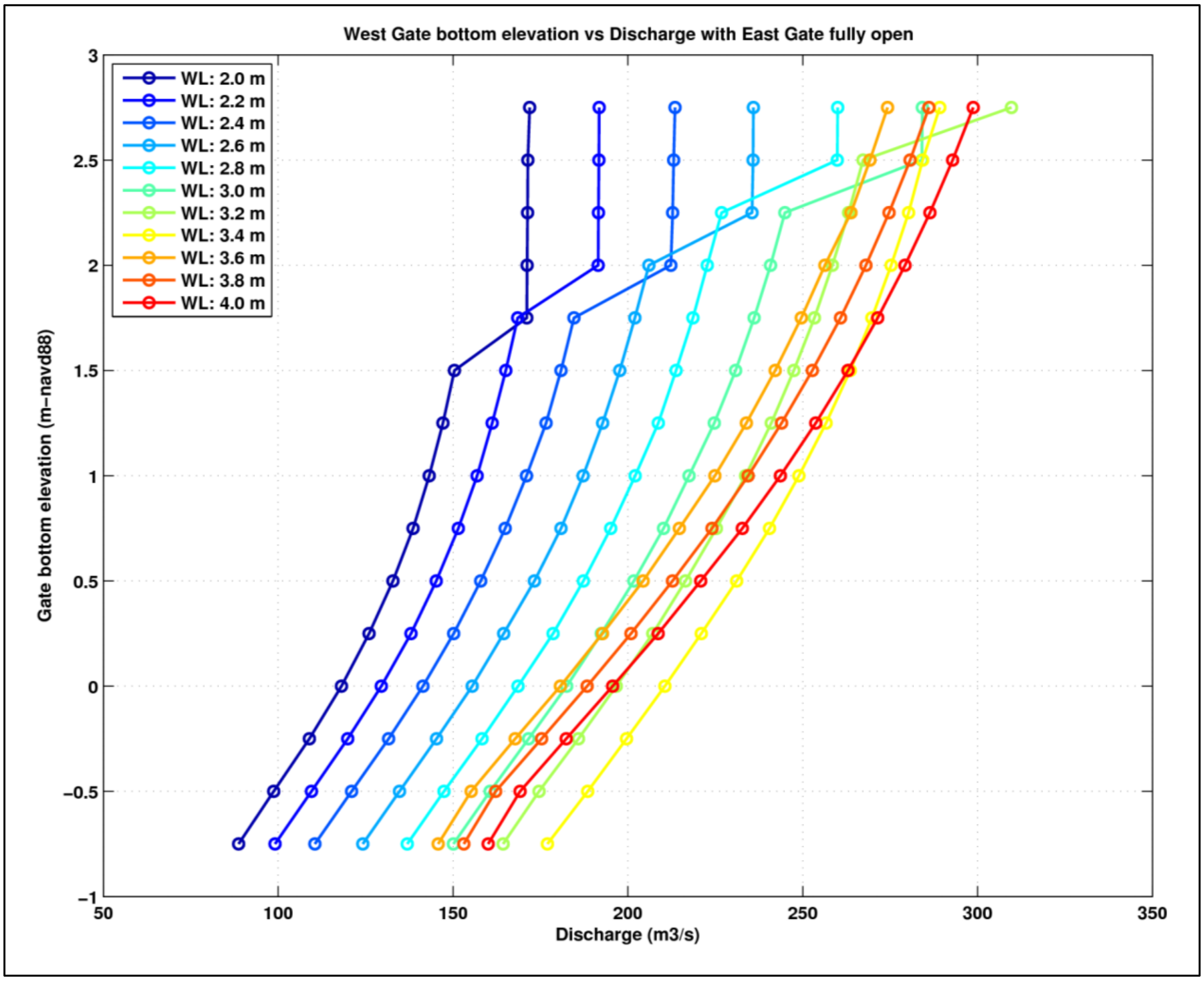


Figure 4-17 Relationship between Discharge And West Gate (Bottom) Elevation



4.4 MODEL CALIBRATION/VALIDATION

This section presents the model calibration/validation to evaluate model performance against measured data. It is important to note that the model is being used to predict behavior of a system that does not exist (for the Estuary and Hybrid Alternatives). Therefore, the model's performance in capturing existing conditions does not directly extend to the model's performance in capturing conditions that do not exist under the Estuary and Hybrid Alternatives. For project context, it is worth noting that the previous USGS numerical modeling studies (George et al. 2006 and Stevens et al. 2008) did not perform calibration/ validation, based on the rationale that the objective of their study was to predict conditions for an environment setting that did not exist and, therefore, no model calibration data is available to test or adjust model parameters.

The environment setting for the Estuary and Hybrid Alternatives does not exist and, therefore, the numerical model presented herein could not be calibrated/validated for these two alternatives. However, model calibration/validation was conducted to evaluate model performance in simulating the No Action Alternative to add confidence in the model's capability in predicting the system behavior for the Managed Lake Alternative. In addition, the model calibration/validation conducted herein informed the model's sensitivity to input parameters and assumptions.

4.4.1 Calibration/Validation Metrics

Several statistical metrics were used to assess model performance. These metrics include the mean error (*ME*), root mean square (*RMS*) error, normalized *RMS* error, mean absolute error (*MAE*), correlation coefficient (*R*), index of agreement (*d*), and time delay or lag (ΔT). These parameters are briefly described here.

If *x* and *y* are the measured and calculated (modeled) parameters respectively, the following statistics can be calculated:

Mean error (*ME*):

$$ME = \bar{y} - \bar{x} \qquad (6)$$

Where "bar" denotes the sample mean.

Root mean square (*RMS*) error:

$$\varepsilon_{RMS} = \sqrt{\overline{(x-y)^2}} \qquad (7)$$

To reduce the effect of measurement error and possible outliers, a 1-hour low-pass filter was applied to the measured data to compute trend x_f. Then the normalized error is calculated as:

$$\varepsilon_{norm} = \frac{\varepsilon_{RMS}}{x_{f,\max} - x_{f,\min}} \cdot 100\% \qquad (8)$$

Where $x_{f,\max}$ and $x_{f,\min}$ are the maximum and minimum values of the trend x_f. The residual in the denominator defines the range of measured data.

Mean absolute error (*MAE*):

$$MAE = \overline{|x-y|} \qquad (9)$$

The correlation coefficient *R* was calculated using standard method and represents a non-squared value.

The model prediction capability was estimated with an index of agreement between measured and calculated data (after Willmott 1982 and Willmott et al. 1985):

$$d = 1 - \frac{\overline{(x-y)^2}}{\overline{\left(|x-\bar{x}| - |y-\bar{x}|\right)^2}}, 0 \le d \le 1 \qquad (10)$$

The time delay, ΔT, shows expected time difference between corresponding events in measured and calculated data. To estimate the delay, the cross-correlation function between measured and calculated data is computed and the smallest time lag at which a maximum occurs is found. Because the cross-correlation function is calculated from discrete data, resulting time resolution may not be sufficient to accurately define the maximum. Therefore, computed values of the cross-correlation function were interpolated with a piecewise polynomial of 5th order, which was then used to determine the maximum.

Among these calibration metrics, *d* and *R* are the strongest indicators to evaluate the model's performance. In addition, the normalized *RMS* error is useful to quantify the differences between model results and measurements. However, visual comparison of model results against measurements itself is still the most comprehensive approach to evaluate the model performance.

4.4.2 Calibration/Validation Period

The hydrodynamic model was calibrated for three time periods using water levels at the 5th Avenue Dam station inside the lake, and one time period against velocity measurements from station M3 and M5 listed in Table 2-7. The four calibration periods listed in Table 4-2 were proposed based on availability of water level data, velocity data, and discharge values at USGS Station 12080010. It should be noted that there are some measurement data gaps in those three water level calibration periods, especially during medium and high flow conditions.

Table 4-2 Calibration/Validation Period

Period	Type	River Inflow	Start Time	End Time
1	Water Level	Low	02/04/2017 00:00	02/09/2017 00:00
2	Water Level	Medium	02/15/2017 20:00	02/19/2017 20:00
3	Water Level	High	02/09/2017 14:00	02/12/2017 20:00
4	Current Velocity	NA†	10/30/1996 00:00	11/07/1996 00:00

† River inflow is Not Applied (NA) for current velocity calibration and the 5th Avenue Dam was closed during the simulation since the calibration stations are both in Budd Inlet offshore.

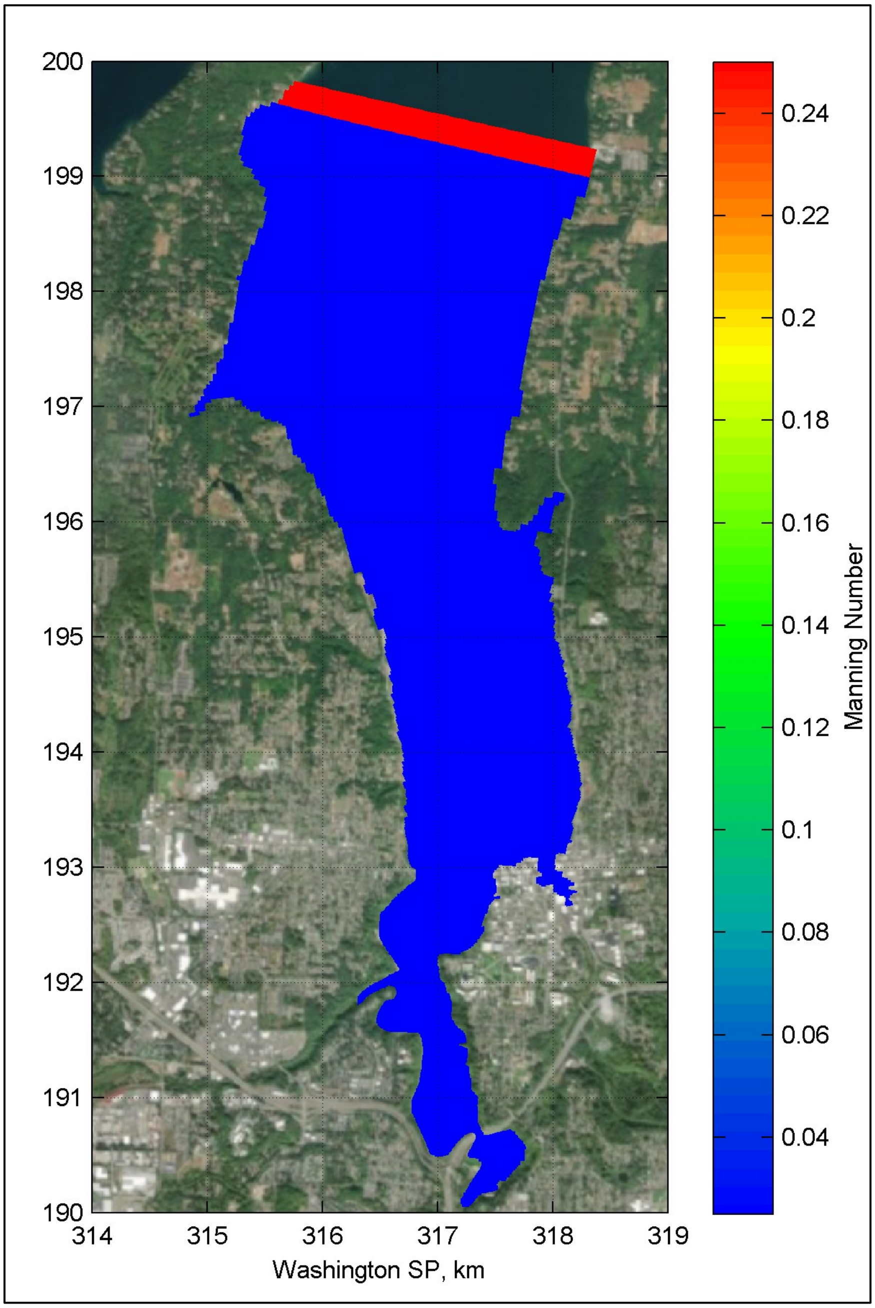
4.4.3 Calibration Parameters

In the water level calibration process, the height of gate opening and timing, as well as the gate energy loss coefficient, were used as the calibration parameters. Calibration was conducted by setting up the initial time series of gate opening height, discussed in Section 4.3.3, and then adjusting the timing and gate opening height as well as the energy loss coefficient to match the measured water level at the lake. For the current velocity calibration process, the bottom roughness was used as the calibration parameter.

The calibration process included an iterative process of selecting gate operation time (open or closed) and changing gate opening height to match modeled with measured water levels at the 5th Avenue Dam.

Modeled current velocities in Budd Inlet were calibrated against measured currents collected in 1997. A Manning number of 0.025 was applied uniformly in the model domain, except at the offshore boundary where 0.25 was used to prevent current rotation in the surrounding gird cells and improve model stability (see Figure 4-18 for details). The effect of wind speed on current velocities was investigated during the calibration/validation process, see Section 4.4.4.

Figure 4-18 Manning Number (-) Distribution in the Model



4.4.4 Calibration/Validation Results

Water levels obtained from the model results were compared against measurements at the 5th Avenue station inside the Capitol Lake. Comparison of time series of modeled vs measured water levels during low flow, medium flow, and high flow, are shown in Figure 4-19, Figure 4-20, and Figure 4-21, respectively, and the calibration metrics are listed in Table 4-3. Calibration results demonstrate that the model results are in agreement with the water level measurements in terms of magnitude and phase of water level fluctuations. Therefore, the model results have reasonably represented the non-linear changes in water level during both the infill and release phases.

The non-linear change in water level during infill periods with gates closed is related to the change in lake surface area between high and low water levels and its reasonable representation by model results indicates realistic bathymetry variations. The non-linear change in water levels during release periods with gates open indicates reasonable representation of gates in the model (gate opening height, timing, and loss coefficient) for all three flow conditions.

Table 4-3 Model Performance Metrics for Water Level Calibration/Validation at the 5th Avenue Dam

Case	Low Flow	Medium Flow	High Flow
ε_{RMS} (RMS Error) (m)	0.066	0.110	0.113
ε_{norm} (Normalized Error) (-)	10.6%	8.5%	4.8%
MAE (Mean Absolute error) (m)	0.05	0.08	0.10
R (Correlation Coefficient) (-)	0.93	0.86	0.98
ΔT (Time Delay) (min)	480	-11	13
d (Index of Agreement) (-)	0.95	0.87	0.98

Figure 4-19 Water Level Calibration/Validation Results – Low Flow Event

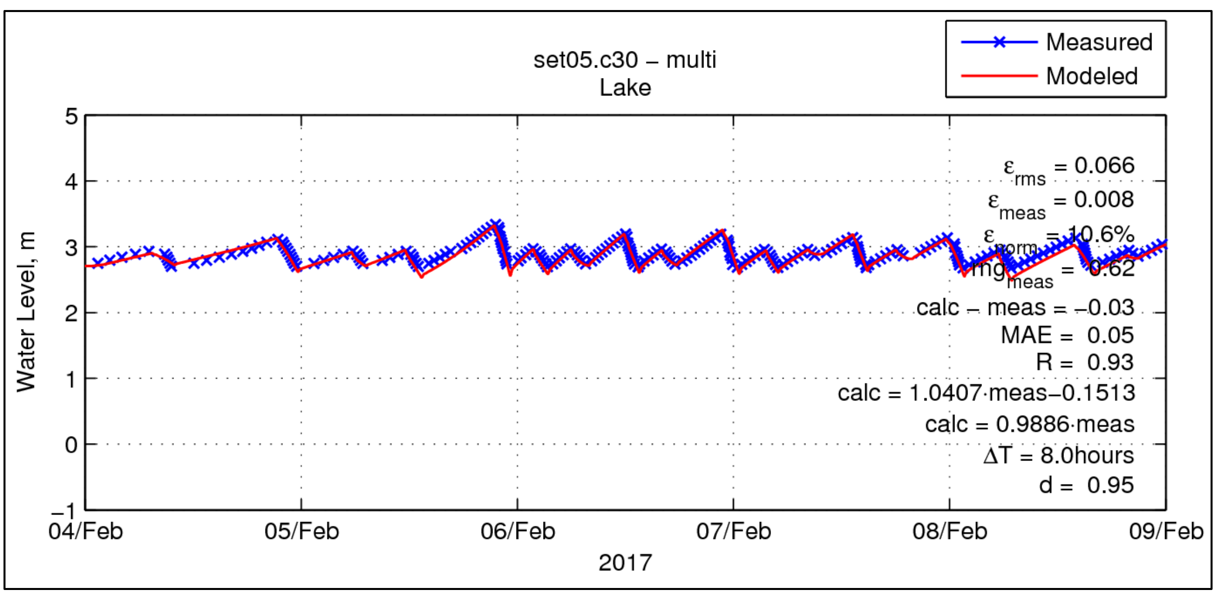


Figure 4-20 Water Level Calibration/Validation Results – Medium Flow Event

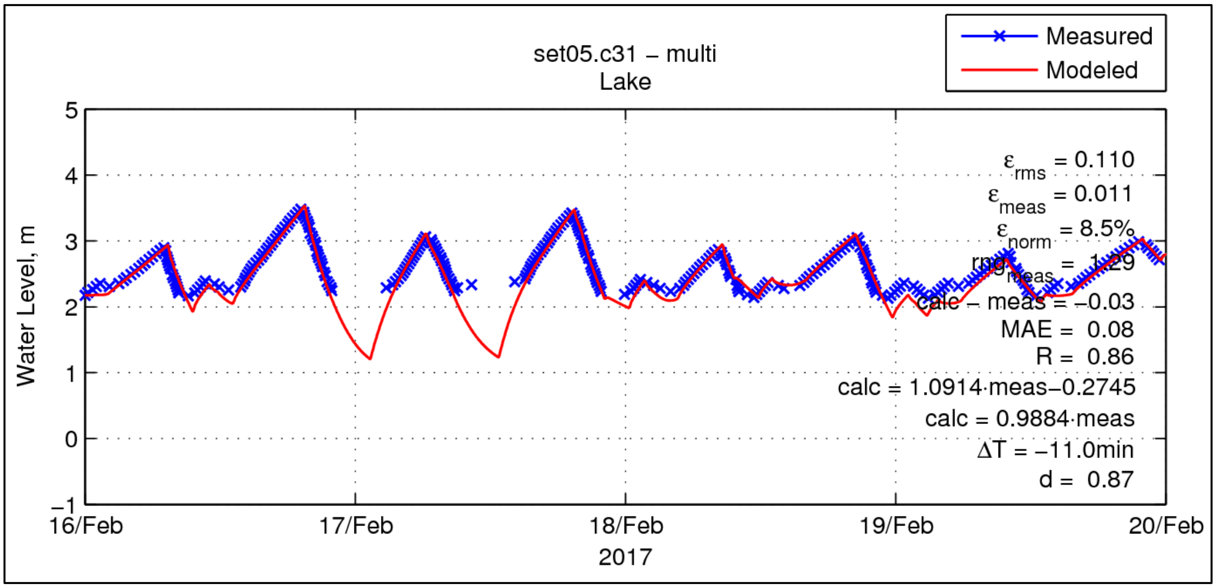


Figure 4-21 Water Level Calibration/Validation Results – High Flow Event

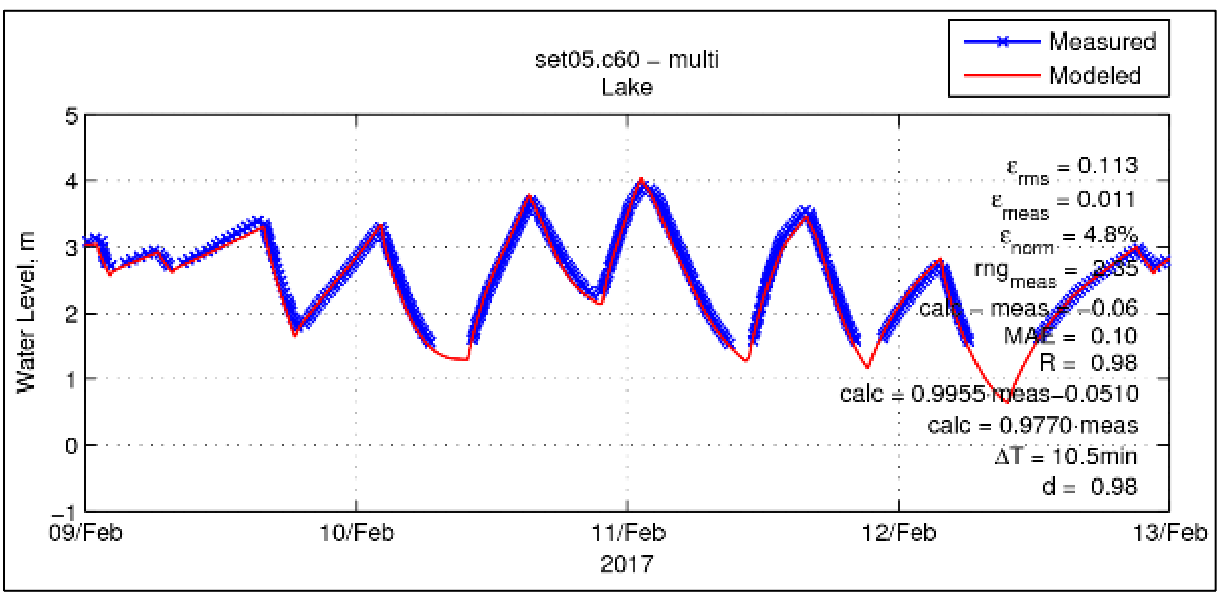


Figure 4-22 and Figure 4-23 show the comparison of depth-averaged currents at Stations M3 and M5, and the calibration metrics of those current velocity calibration runs are listed in Table 4-4. The current velocity in the area is very small, with a maximum velocity of approximately 0.15 m/s at M3 and 0.05 m/s at M5.

Table 4-4 Model Performance Metrics for Current Velocity Calibration/Validation at M3 and M5 Stations

Station	No Wind –M3 - (Speed)	No Wind –M3 - (Direction)	No Wind –M5 – (Speed)	No Wind –M5 – (Direction)
ε_{RMS} (RMS Error) (m/s)	0.036	68.666	0.013	66.248
ε_{norm} (Normalized Error) (-)	25.4%	6.5%	31.5%	2.4%
MAE (Mean Absolute Error) (m/s)	0.03	40.87	0.01	42.34
R (Correlation Coefficient) (-)	0.55	0.97	0.46	1.00
ΔT (Time Delay) (min)	33	-6	309	7.5
d (Index of Agreement) (-)	0.69	0.99	0.57	1.00

Sensitivity testing was conducted by applying spatially uniform wind field using wind speeds measured at the KOLM station (shown in Figure 2-26).

Calibration results with and without wind (Figure 4-24 and Figure 4-25) that modeled and measured currents are generally in agreement. Measured current velocities at Station M5 are so small that small absolute differences result in large relative differences that are not truly representative of the model accuracy. In addition, the current directions associated with flood and ebb tidal currents from the model results are in agreement with the measurements at station M3 and Station M5, with agreement indexes of 0.99 and 1, respectively.

Astronomical tidal components of measured velocities were compared with modeled results at Stations M3 and M5, see Figure 4-26 and Figure 4-27, respectively. The comparison is done using computation of tidal ellipses (based on tidal constituents of velocity components). By comparing major axes of tidal ellipses (minor axes are too small, in the order of 10^{-3} m/s), modeled and measurements match within 1.3% and 8.1% for the major tidal constituent M2 at Stations M3 and M5, respectively (Figure 4-26 and Figure 4-27).

Figure 4-22 Current Velocity Calibration Results – Station M3

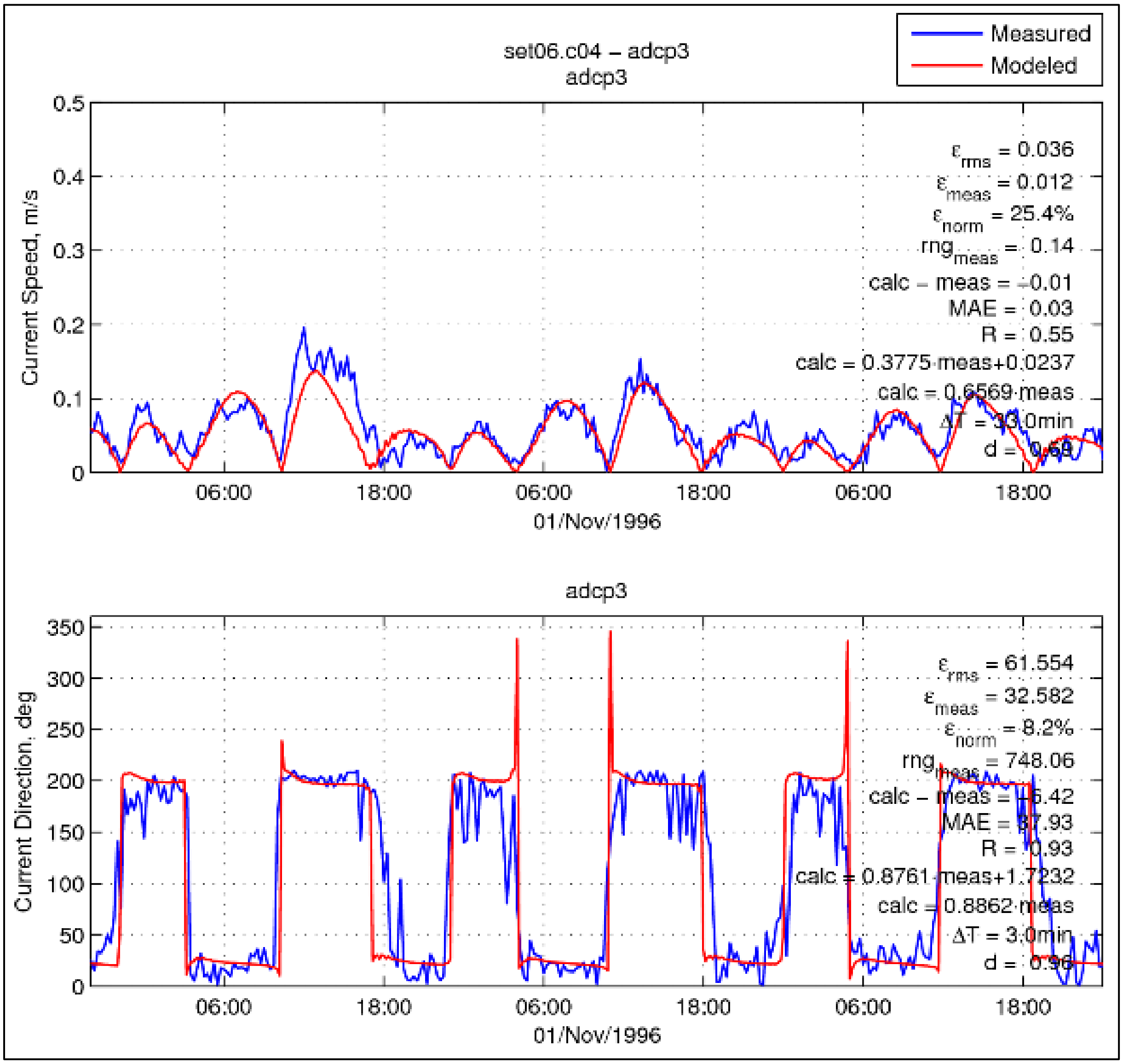


Figure 4-23 Current Velocity Calibration Results – Station M5

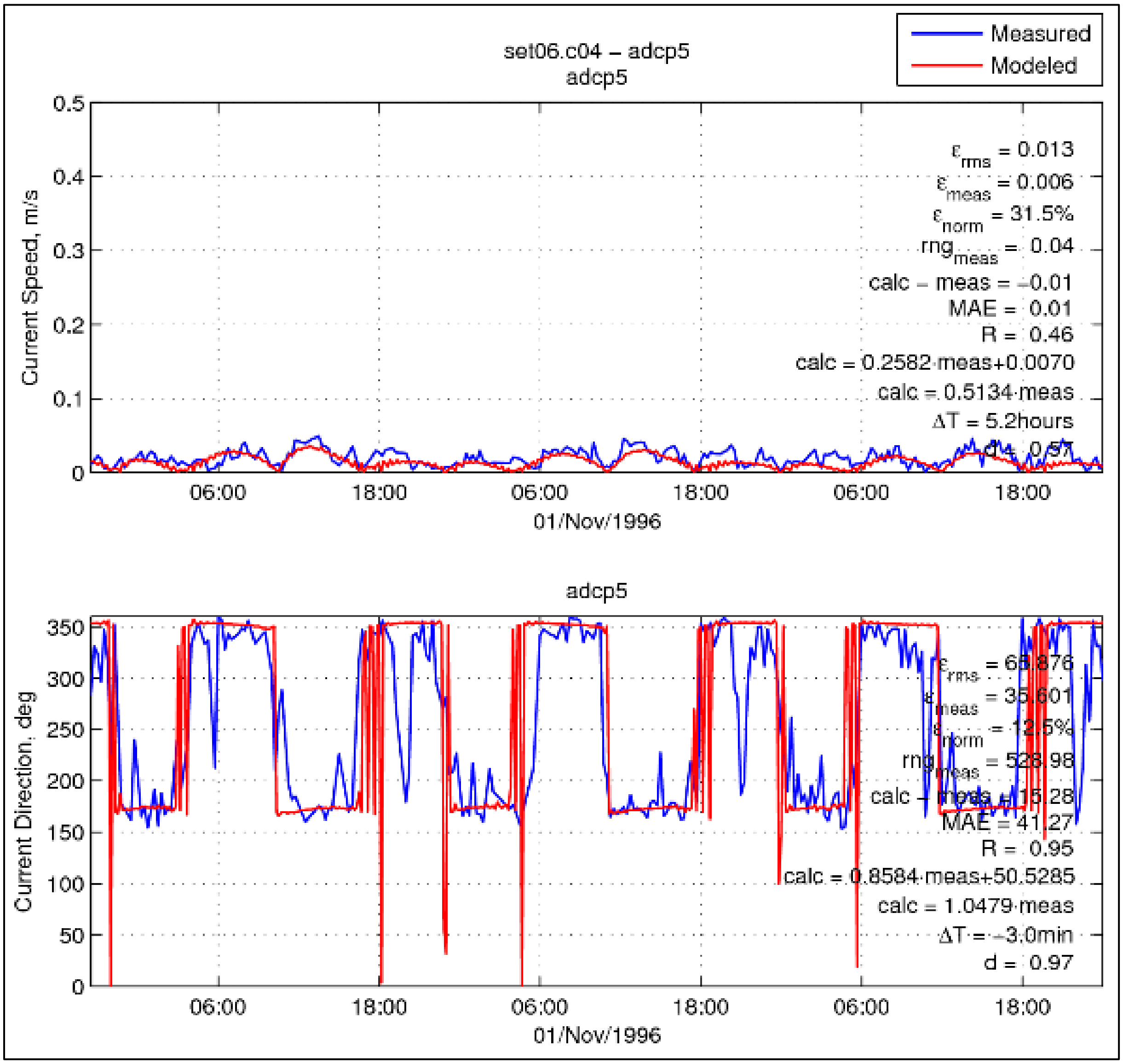


Figure 4-24 Current Velocity Sensitivity Test by Adding Wind – Station M3

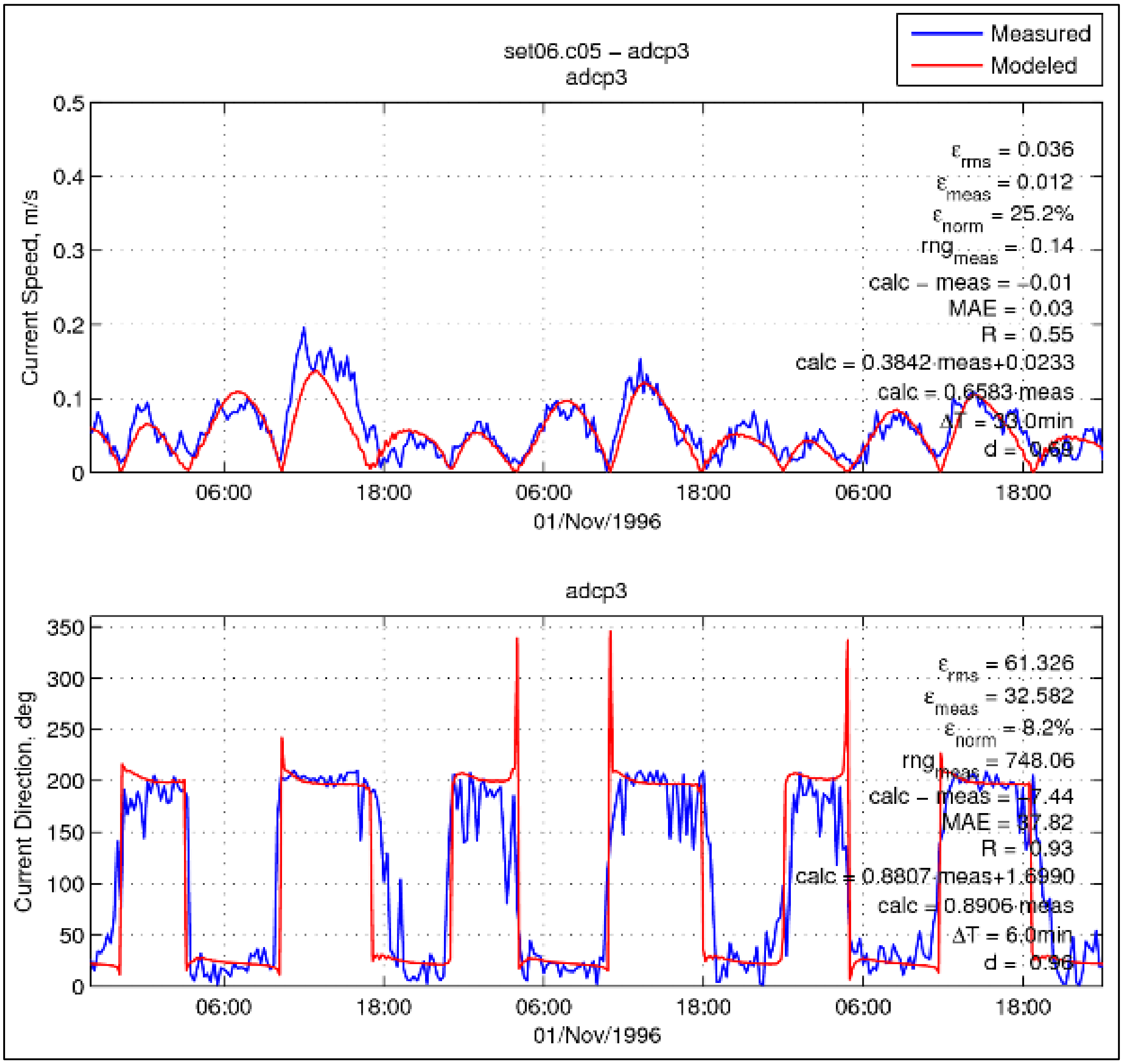


Figure 4-25 Current Velocity Sensitivity Test By Adding Wind – Station M5

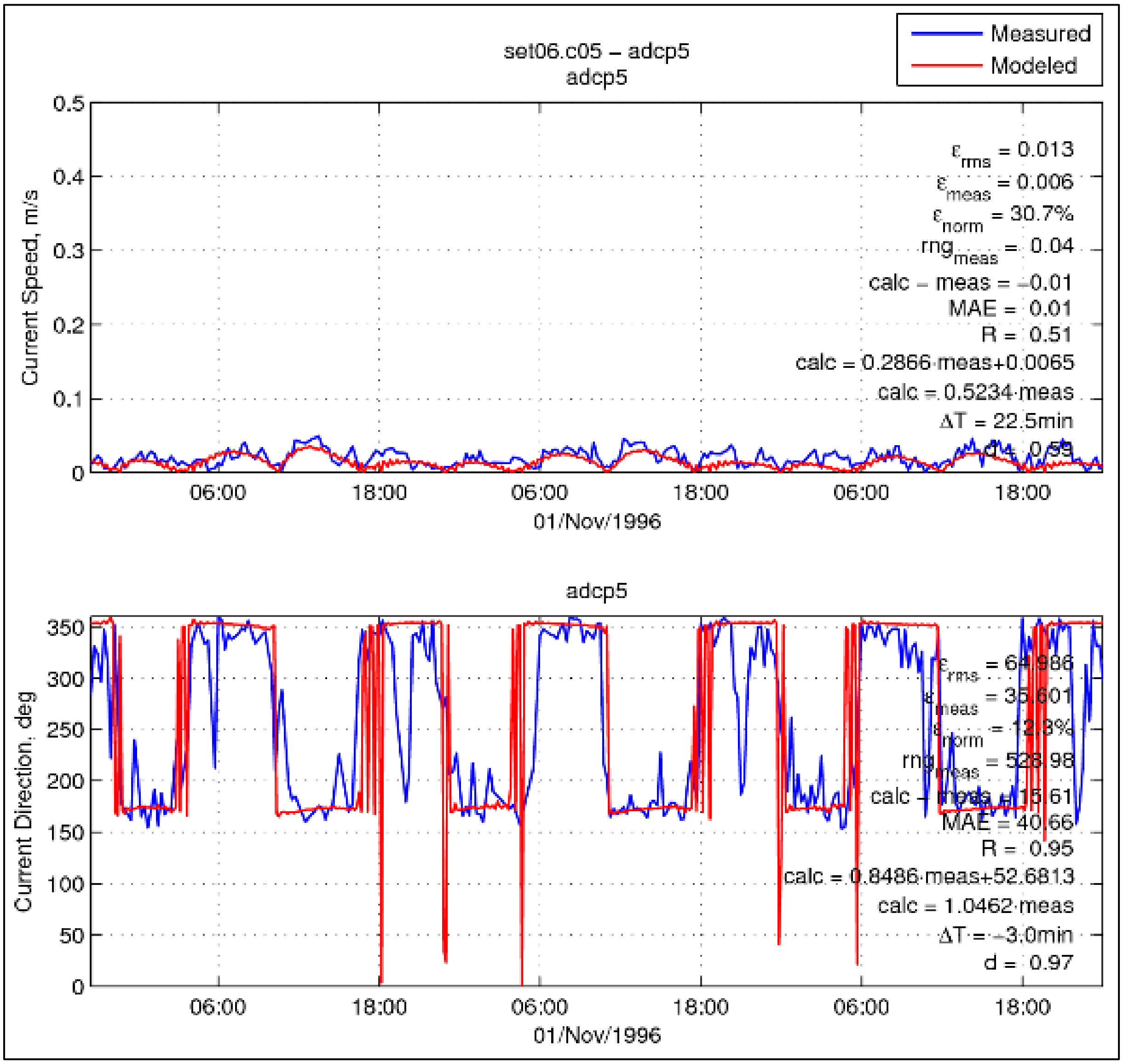


Figure 4-26 Current Velocity Calibration Results – Tidal Ellipse at Station M3

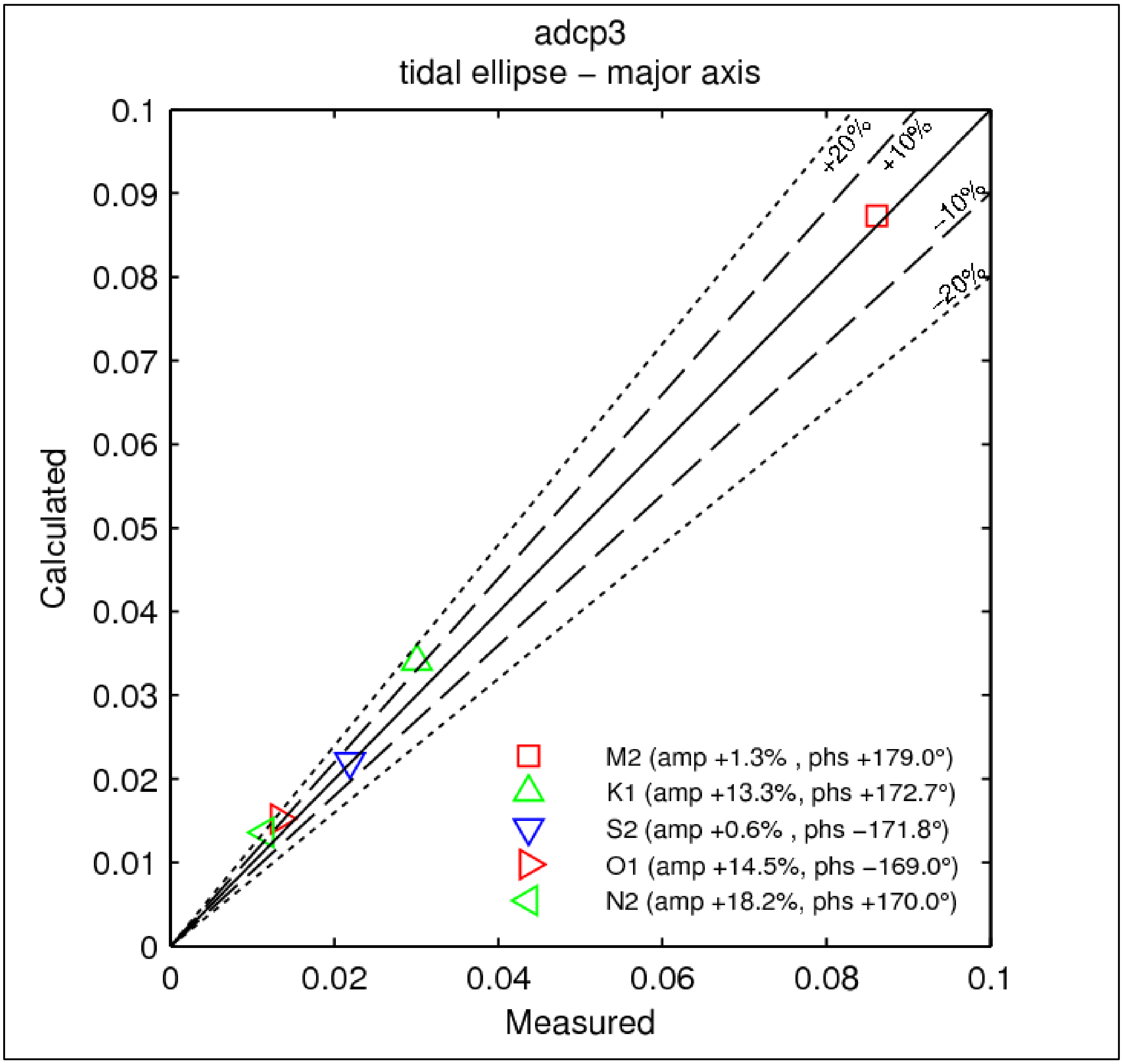
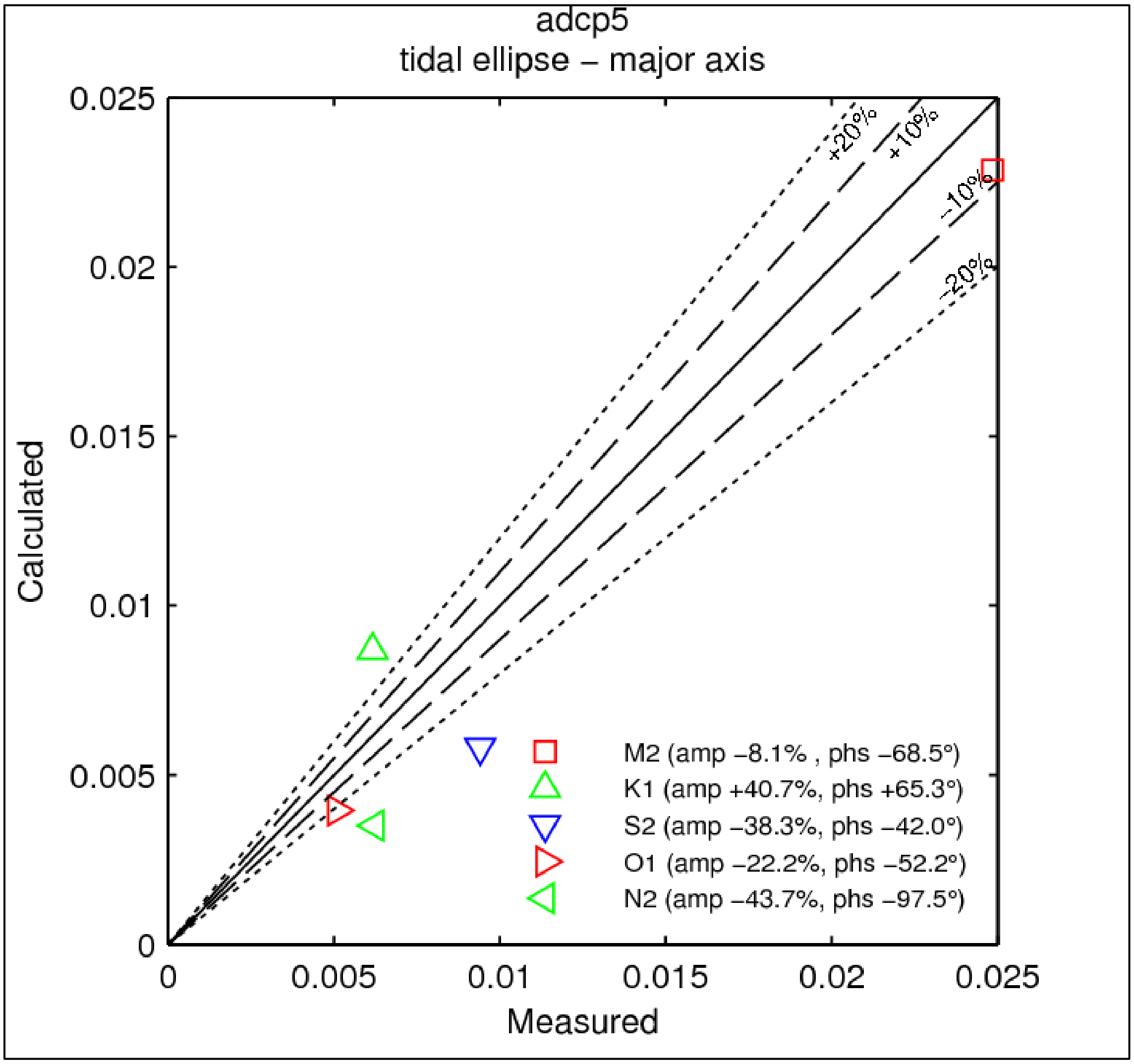


Figure 4-27 Current Velocity Calibration Results – Tidal Ellipse at Station M5



4.4.5 Model Performance

There are no specific codes or standards for assessing performance of numerical models in terms of simulation of observations. To assess the performance of this modeling study in representing the No Action Alternative and prediction of proposed alternatives, similar and recent studies conducted by U.S. Army Engineer Research and Development Center (ERDC) or approved by USACE were compiled and reviewed. A list of these studies and metrics used to report and quantify goodness of fit for water levels and currents is provided in Table 4-5 and Table 4-6, respectively. The model's performance metrics are listed in the last row of these two tables. This assessment identified that this study is consistent with recent and similar modeling studies conducted by ERDC or approved by USACE in terms of model performance.

Table 4-5 Descriptors and Metrics for Reporting Goodness of Fit for Hydrodynamic Model Results in terms of Water Levels

Project (Source)	Visual Inspection	Max. Diff	RMSE	IOA	Phase Shift	Sensitivity Analysis	Author's Description of Own's Model Performance
Channel Deepening in Thimble Shoals (Zhang et al. 2017)	✓	1.3 ft*	×**	0.92 – 0.95	6°	×	"Sufficient skill"
Seattle Harbor Deepening EIS (USACE 2016)	✓	< 0.1 ft*	×	×	×	×	"Excellent comparison"
Redwood City Harbor Navigation Improvement EIS (HydroPlan 2015)	✓	0.2 ft*	×	0.99	×	×	"Very accurate"
Houston-Galveston Navigation Channel (ERDC 2014)	✓	0.3 ft*–3 - 4%	×	0.99	×	×	"Good agreement"
Matagorda Ship Channel Study (ERDC 2013)	✓	0.7 ft*	×	×	×	×	×
Savannah Harbor Expansion Project (Tetra Tech 2011)	✓	0.3 ft*	×	×	×	×	×
Grays Harbor Navigation Improvement EIS (ERDC 2010)	✓	3.0 ft*	×	×	×	×	"Very good"
This Study	✓	0.4 ft	0–2 - 0.5 ft	0.87 – 0.98	×	×	"In agreement"

RMSE=Root Mean Square Error; IOA=Index of Agreement

* indicates that the value was not listed in the report and is based on interpretation of results

** symbol '×' indicates that this parameter was not estimated/reported to quantify model performance

Table 4-6 Descriptors and Metrics for Reporting Goodness of Fit for Hydrodynamic Model Results in terms of Currents

Project (Source)	Visual Inspection	Max. Diff	RMSE	Index of Agreement	Phase Shift	Sensitivity Analysis	Description of Model Performance
Channel Deepening in Thimble Shoals (Zhang et al. 2017)	✓	1 ft/s*	0.3 ft/s	> 0.7	✗**	✗	"Sufficient skill"
Seattle Harbor Deepening EIS (USACE 2016)	✗	✗	✗	✗	✗	✗	✗
Redwood City Harbor Navigation Improvement EIS (HydroPlan 2015)	✗	✗	✗	✗	✗	✗	✗
Houston-Galveston Navigation Channel (ERDC 2014)	✓	1.5 ft/s*	0–7 - 39%	✗	✗	✗	"Good agreement"
Matagorda Ship Channel Study (ERDC 2013)	✗	✗	✗	✗	✗	✗	✗
Savannah Harbor Expansion Project (Tetra Tech 2011)	✓	0.01 ft/s*	✗	✗	✗	✗	✗
Grays Harbor Navigation Improvement EIS (ERDC 2010)	✓	3.0 ft/s*	✗	✗	✗	✗	"Reasonable"
This Study	✓	0.3 ft/s	0.04 -0.1ft/s	0.–7 - 0.69	✗	✓	"In agreement"

RMSE=Root Mean Square Error; IOA=Index of Agreement

* indicates that the value was not listed in the report and is based on interpretation of results

** symbol '✗' indicates that this parameter was not estimated/reported to quantify model performance

4.5 SENSITIVITY ANALYSIS

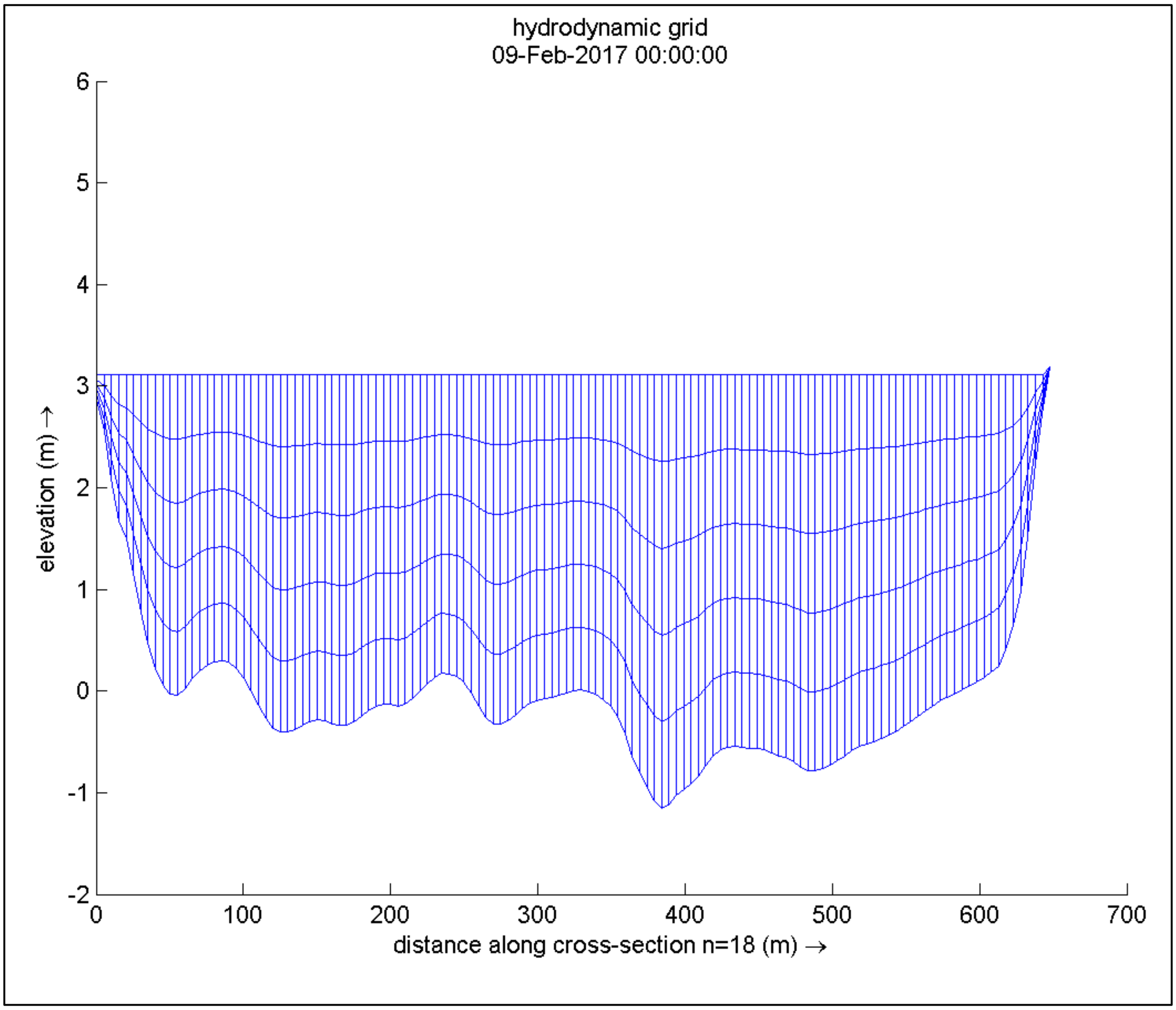
4.5.1 Three-Dimensional Model

Delft3D includes 3D or 2D mode. The 3D configuration of the model requires significantly more computational time than a 2D model.

The 2D configuration cannot capture the vertical structure of the flow and vertical density stratification driven by salinity differences in the water column. Since salinity can impact sedimentation processes, particularly due to enhanced flocculation for the Estuary and Hybrid Alternatives, for the sediment transport model for the Estuary and Hybrid Alternatives, modeling was conducted implementing the 3D configuration of the model incorporating salinity, see Section 5.0.

A sensitivity analysis was performed and simulations with a 3D setup were tested to compare the results with 2D simulations for both the No Action and Estuary Alternatives. For the 3D setup, five uniform sigma layers were tested, and a cross-section view for the vertical layers in the North Basin is shown in Figure 4-28. The sensitivity model results showed small differences between 2D and 3D configurations. Therefore, to keep the computational run times practical, the 2D model configuration was selected to perform the hydrodynamics modeling.

Figure 4-28 Cross-Section View of Sigma Layers in the North Basin



4.5.1.1 No Action Alternative

Modeled depth-averaged current velocities at Stations M3 and M5 (locations shown in Figure 2-1) are shown in Figure 4-29 and Figure 4-30, respectively, using the 2D and 3D model configurations. The comparison metrics computed for the 3D model against the 2D model are listed in Table 4-7. Modeled velocities are almost identical between the 2D and 3D model configurations shown in Figure 4-29 and Figure 4-30. The normalized RMS error at Station M3 is 2.0% for current speed, and 1.4% for current direction, and normalized RMS error at Station M5 is 1.4% for current speed, and 0.4% for current direction. The indexes of agreement, d, are all equal to 1.

Table 4-7 Currents (Speed and Direction) Comparison Metrics under No Action Alternative for 3D Model against 2D Model at Stations M3 and M5

Station	Station M3 Speed	Station M3 Direction	Station M5 Speed	Station M5 Direction
εRMS (RMS Error) (m/s)	0.003	13.039	0.000	7.671
εnorm (Normalized Error) (-)	2.0%	1.4%	1.4%	0.4%
MAE (Mean Absolute Error) (m/s)	0.00	5.99	0.00	0.88
R (Correlation Coefficient) (-)	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	480.00	1.00	4.00	-1.00
d (Index of Agreement) (-)	1.00	1.00	1.00	1.00

Figure 4-29 Modeled Currents at Station M3 using 2D and 3D Model Configurations

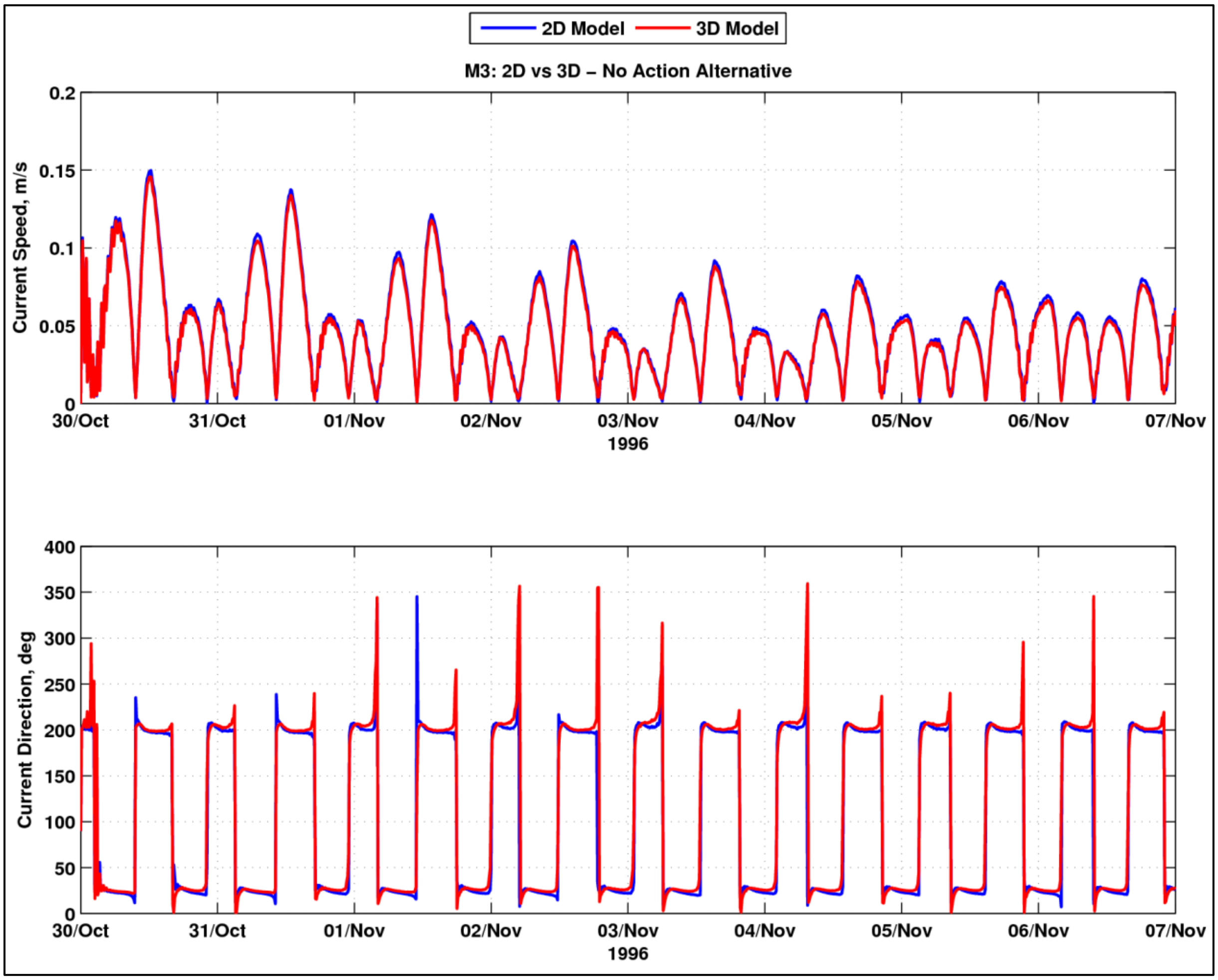
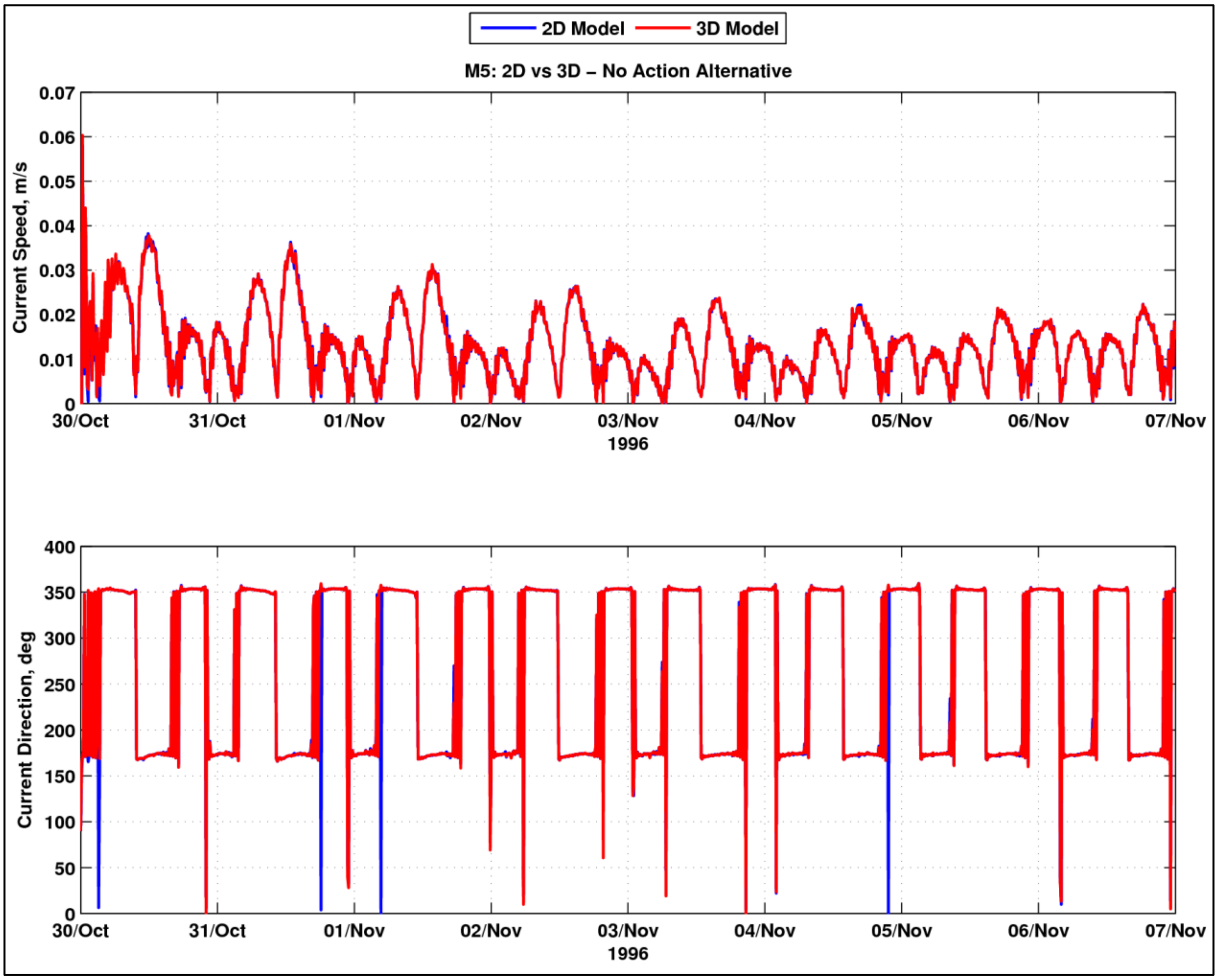


Figure 4-30 Modeled Currents at Station M5 using 2D and 3D Model Configurations



4.5.1.2 Estuary Alternative

To investigate the model performance after removing the dam, both the 2D and 3D models were simulated for the same period as the current velocity calibration period without the dam. The depth-averaged current velocity results are shown in Figure 4-31 and Figure 4-32. Without the dam blocking flows between Capitol Lake and Budd Inlet, the current velocity increased at Station M5 at the Port compared to the existing condition, while the current velocity at Station M3 further downstream in Budd Inlet did not experience significant changes. As shown in Figure 4-31 through Figure 4-32, velocity results between the 2D model and 3D model are almost identical. The normalized RMS error at Station M3 is 2.0% for current speed, and 1.9% for current direction, and the normalized RMS error at Station M5 is 0.7% for current speed, and 0.2% for current direction. The indexes of agreement, d, are all equal to 1.

Table 4-8 Currents (Speed and Direction) Comparison Metrics under Estuary Alternative for 3D Model against 2D Model at Stations M3 and M5

Station	Station M3 Speed	Station M3 Direction	Station M5 Speed	Station M5 Direction
ε_{RMS} (RMS Error) (m/s)	0.003	16.942	0.000	5.290
ε_{norm} (Normalized Error) (-)	2.0%	1.9%	0.7%	0.2%
MAE (Mean Absolute Error) (m/s)	0.00	6.47	0.00	0.31
R (Correlation Coefficient) (-)	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	480.00	0.00	-480.00	0.00
d (Index of Agreement) (-)	1.00	1.00	1.00	1.00

Figure 4-31 Modeled Currents at Station M3 using 2D and 3D Model Configurations

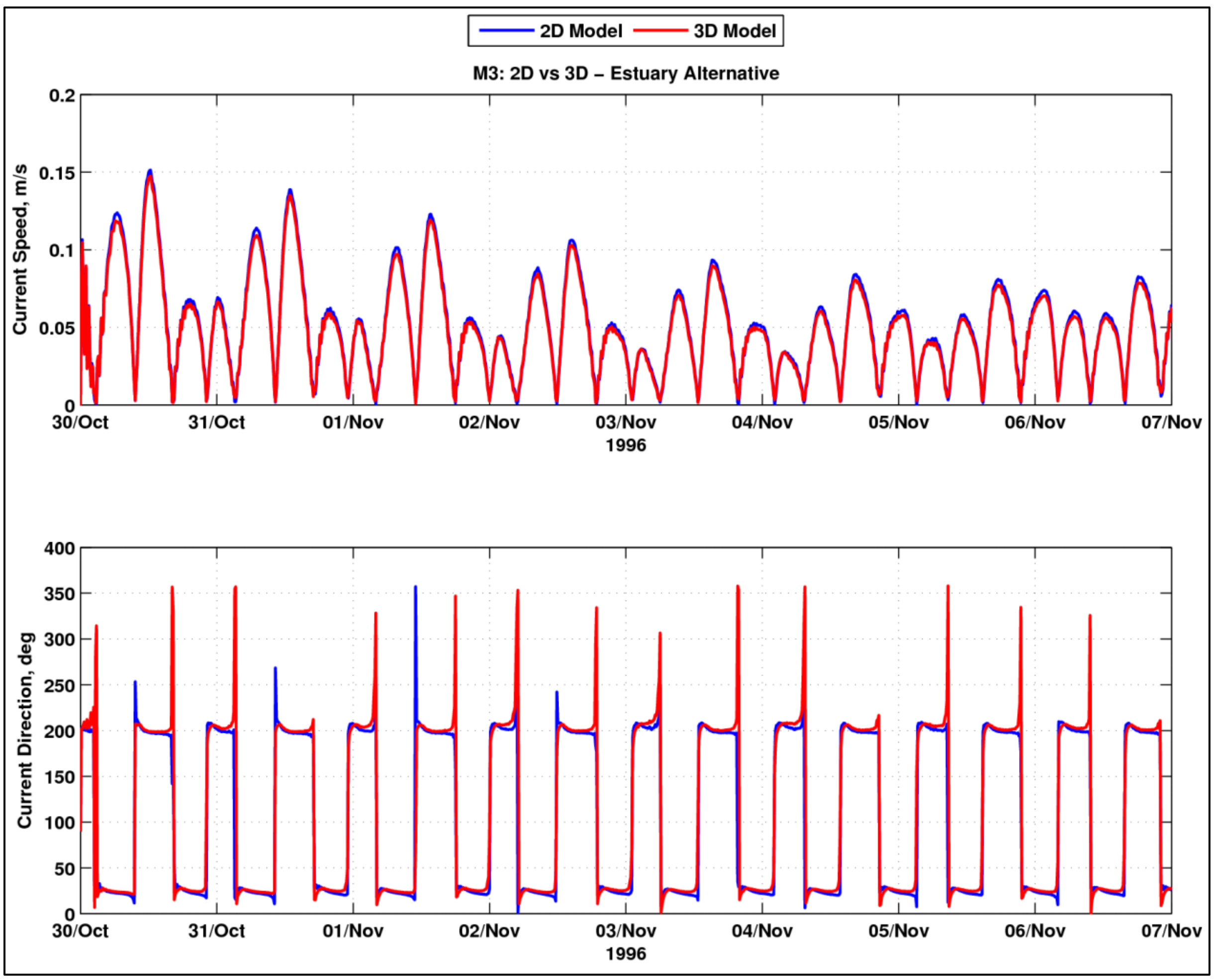
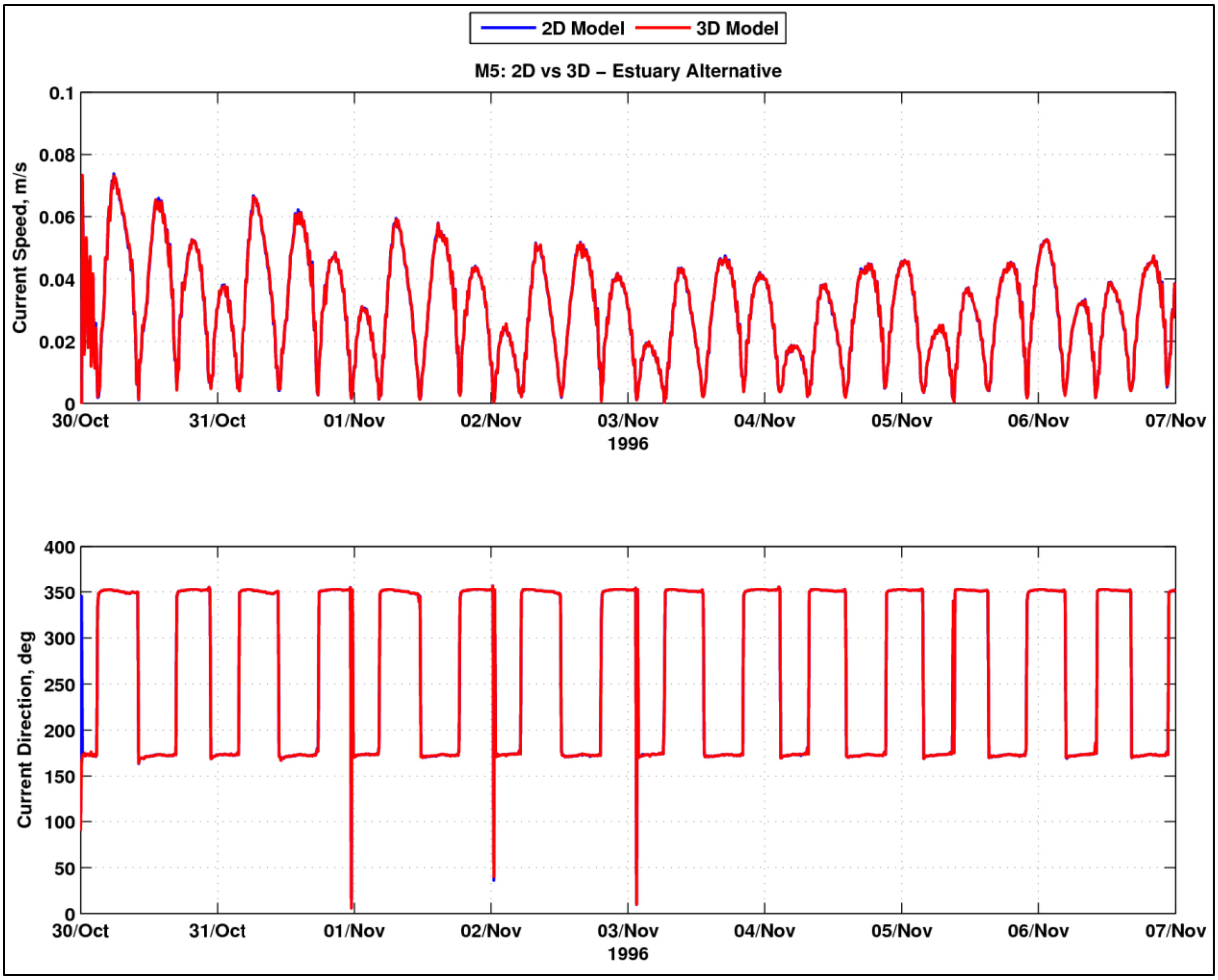


Figure 4-32 Modeled Currents at Station M5 using 2D Model and 3D Model Configurations



4.5.2 Roughness

The calibration/validation in this study was focused on the gate operation to match the water level in the lake. To supplement this calibration process and check the potential alternatives with the dam removal, bottom roughness was tested as part of the sensitivity analyses, described in Sections 4.5.2.1 and 4.5.3.

4.5.2.1 No Action Alternative

For the No Action Alternative, roughness sensitivity analyses for the water level at the 5th Avenue Dam station inside the North Basin were conducted. Three constant Manning numbers including 0.015, 0.025, and 0.035 were used in the sensitivity analyses, and water level calibration results for each

Manning number are shown in Figure 4-33 through Figure 4-35. The comparison metrics computed between Manning numbers of 0.015 and 0.025 (final value) and Manning numbers of 0.035 and 0.025 (final value) are listed in Table 4-9 for low flow, medium flow and high flow. Generally, the water level results are similar for the three Manning numbers (0.015, 0.025, and 0.035) tested with the normalized RMS error ranging from 1.8% to 4.2% and the indexes of agreement, d, all close to 1.

Table 4-9 Comparison Metrics for Modeled Water Level at the 5th Avenue Dam for Manning n 0.015 and 0.035 against 0.025

	Low Flow	Low Flow	Medium Flow	Medium Flow	High Flow	High Flow
Manning n (-)	0.015	0.035	0.015	0.035	0.015	0.035
εRMS (RMS Error) (m)	0.027	0.034	0.052	0.069	0.061	0.076
εnorm (Normalized Error) (-)	3.3%	4.2%	2.3%	3.0%	1.8%	2.2%
MAE (Mean Absolute Error) (m)	0.02	0.03	0.05	0.06	0.06	0.07
R (Correlation Coefficient) (-)	0.99	0.99	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	0.80	-1.10	-0.10	-0.30	0.10	-0.40
D (Index of Agreement) (-)	0.99	0.99	1.00	0.99	1.00	1.00

Figure 4-33 Modeled Water Level at 5th Avenue Dam During Low Flow Condition With Varying Manning's n

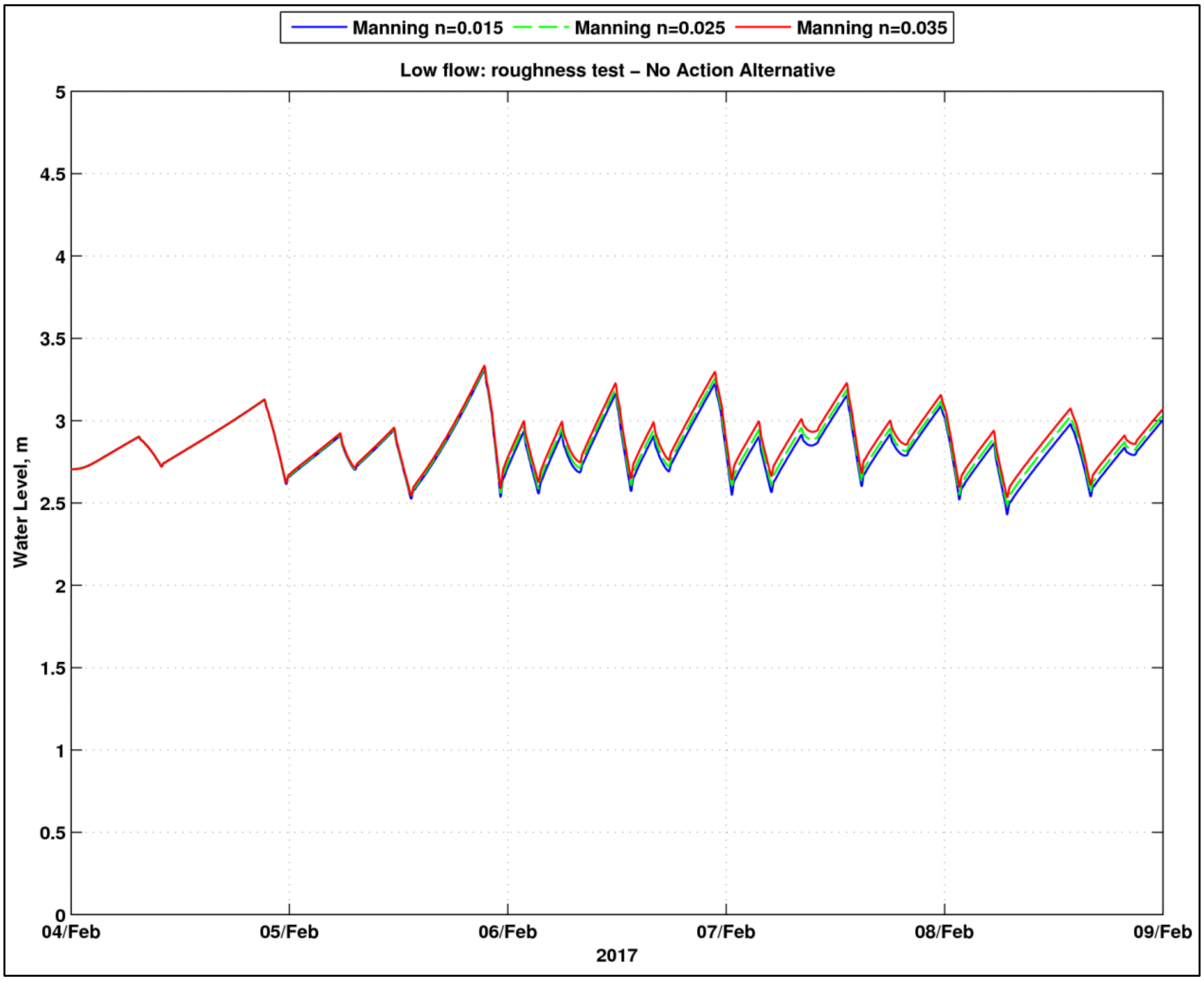


Figure 4-34 Modeled Water Level at 5th Avenue Dam During Medium Flow Condition With Varying Manning's n

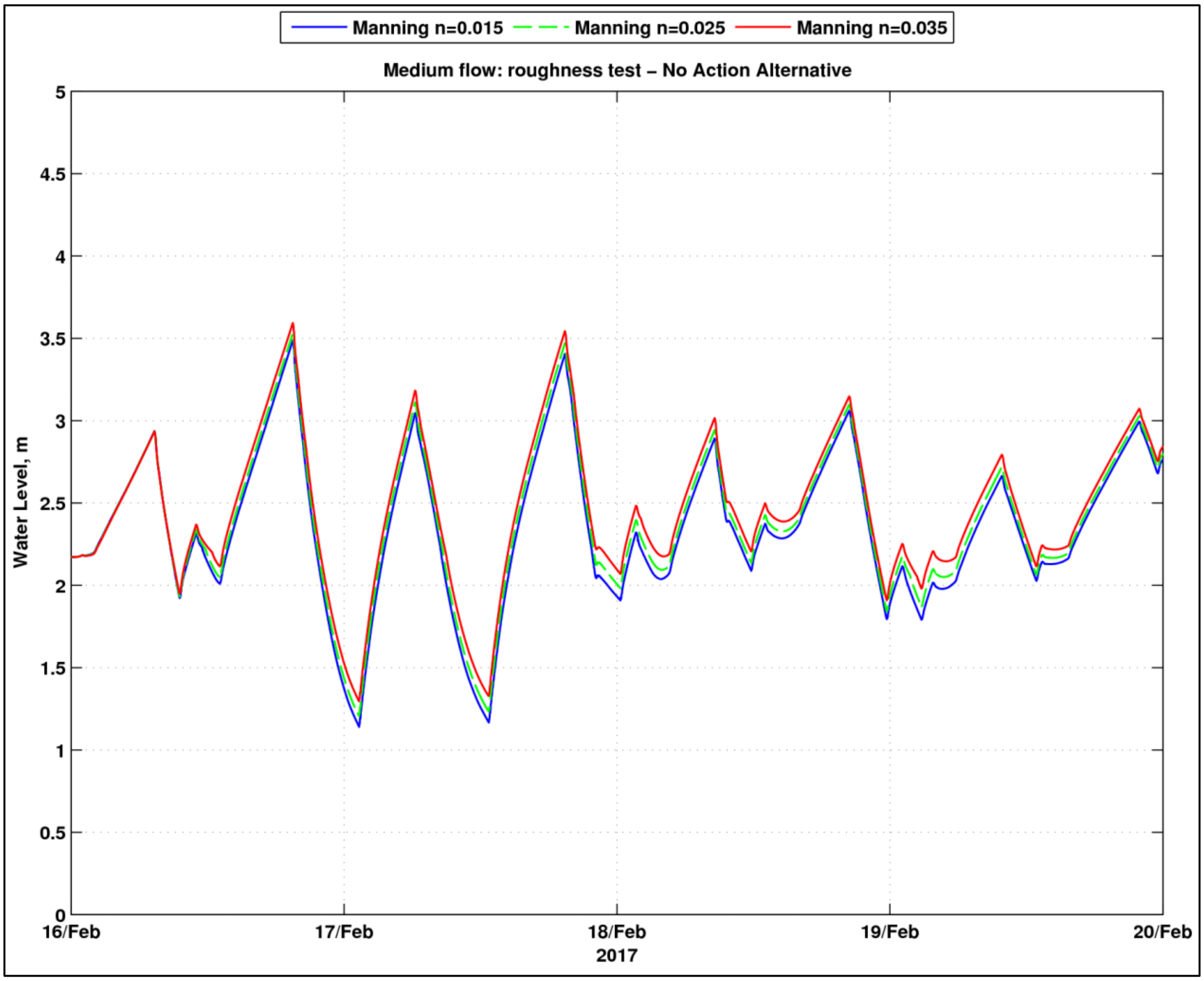
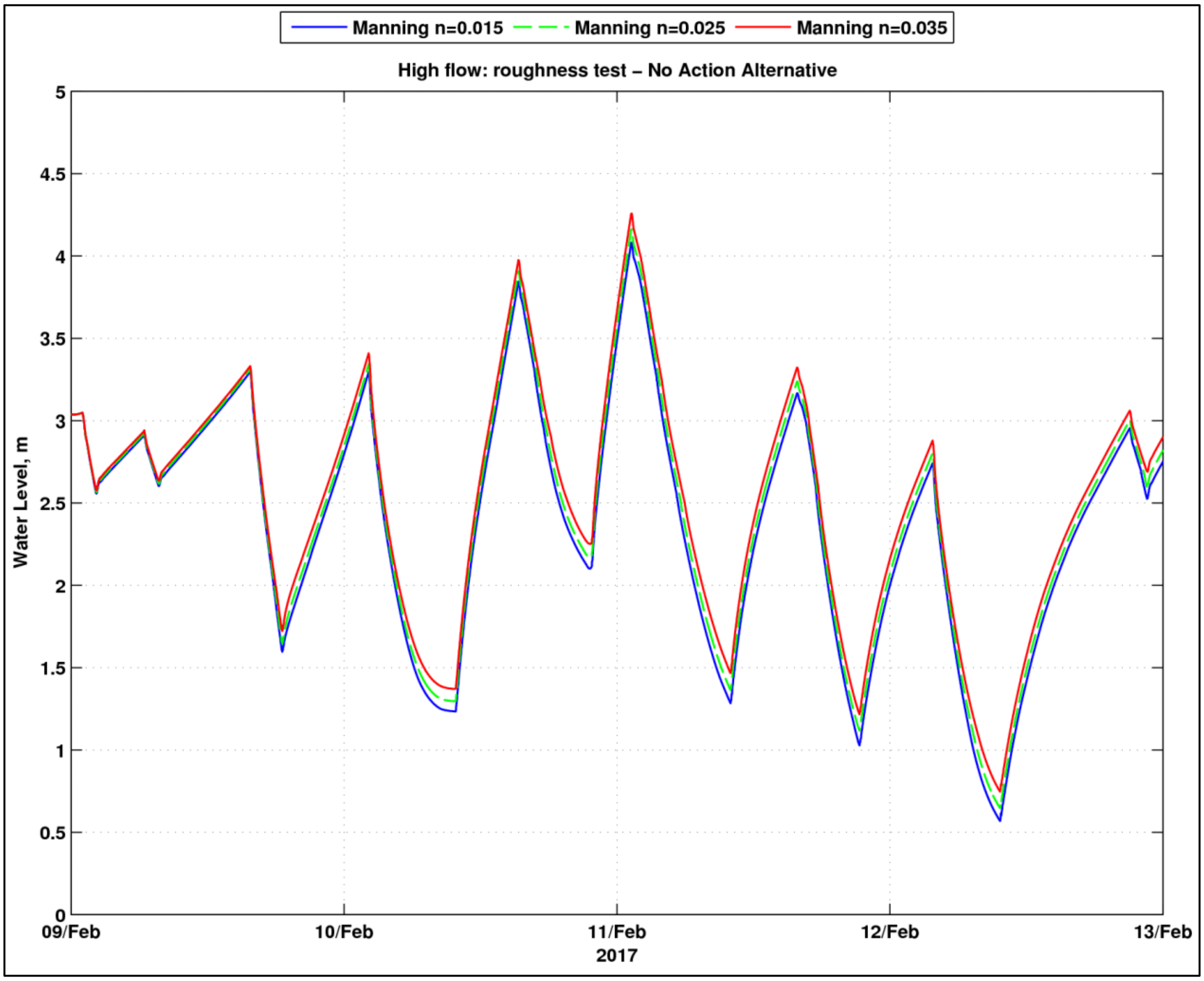


Figure 4-35 Modeled Water Level at 5th Avenue Dam During High Flow Condition With Varying Manning's n



4.5.2.2 Estuary Alternative

For the Estuary Alternative, roughness sensitivity analyses for the current velocity in Budd Inlet at Stations M3 and M5 were conducted. The calibration results are shown in Figure 4-37 and Figure 4-38 for Manning numbers of 0.015, 0.025, 0.035, and a spatially varying roughness based on bed elevation. For the spatially varying roughness, a Manning number of 0.025 was used for elevations shallower than 0.0 m NAVD88 (1.3 m below MSL), and 0.015 for elevations deeper than 10.0 m NAVD88, (11.3 m below MSL) with interpolated values for elevations between those two limits, see Figure 4-36.

The comparison metrics computed between Manning numbers of 0.015, and 0.025 (final value), Manning numbers of 0.035 and 0.025 (final value) and spatially varying Manning numbers and 0.025 (final value) are listed in Table 4-10 for Station M3 and Table 4-11 for Station M5. Velocity results are almost identical among those runs with different Manning numbers. The normalized RMS error at

Station M3 ranges from 0.1% to 0.2% for current speed, and from 0.2% to 0.3% for current direction. The normalized RMS error at Station M5 ranges from 0.2% to 1.5% for current speed, and from 0.2% to 0.3% for current direction. The indexes of agreement, d, are all equal to 1 for all tested Manning numbers at Stations M3 and M5.

Figure 4-36 Spatially Varying Manning's n

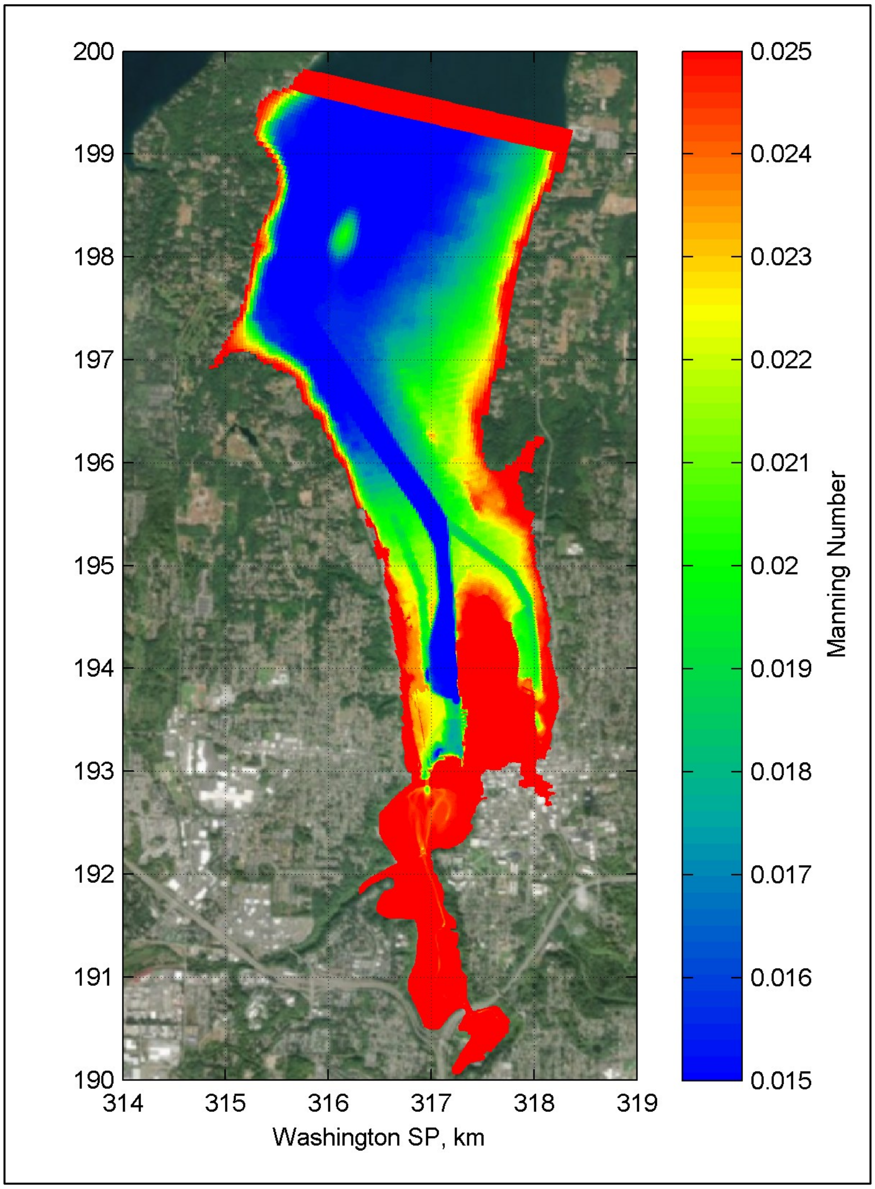


Table 4-10 Currents (Speed and Direction) Comparison Metrics for Manning n 0.015, 0.035, and Spatial Varying Distribution against 0.025 at Station M3

Manning n	0.015 Speed	0.015 Direction	0.035 Speed	0.035 Direction	Spatially Varying Speed	Spatially Varying Direction
ε_{RMS} (RMS Error) (m/s)	0.000	2.721	0.000	2.477	0.000	2.041
ε_{norm} (Normalized Error) (-)	0.2%	0.3%	0.2%	0.3%	0.1%	0.2%
MAE (Mean Absolute Error) (m/s)	0.00	0.69	0.00	0.88	0.00	0.59
R (Correlation Coefficient) (-)	1.00	1.00	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	480.00	1.00	-480.00	-1.00	480.00	0.00
d (Index of Agreement) (-)	1.00	1.00	1.00	1.00	1.00	1.00

Table 4-11 Currents (Speed and Direction) Comparison Metrics for Manning n 0.015, 0.035, and Spatial Varying Distribution against 0.025 at Station M5

Manning n	0.015 Speed	0.015 Direction	0.035 Speed	0.035 Direction	Spatially Varying Speed	Spatially Varying Direction
ε_{RMS} (RMS Error) (m/s)	0.001	6.554	0.001	8.421	0.000	5.266
ε_{norm} (Normalized Error) (-)	1.4%	0.2%	1.5%	0.3%	0.2%	0.2%
MAE (Mean Absolute Error) (m/s)	0.00	0.68	0.00	0.89	0.00	0.25
R (Correlation Coefficient) (-)	1.00	1.00	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	480.00	0.00	-480.00	-1.00	480.00	0.00
d (Index of Agreement) (-)	1.00	1.00	1.00	1.00	1.00	1.00

Figure 4-37 Modeled Current Velocity at Station M3 with Varying Manning for Estuary Alternative

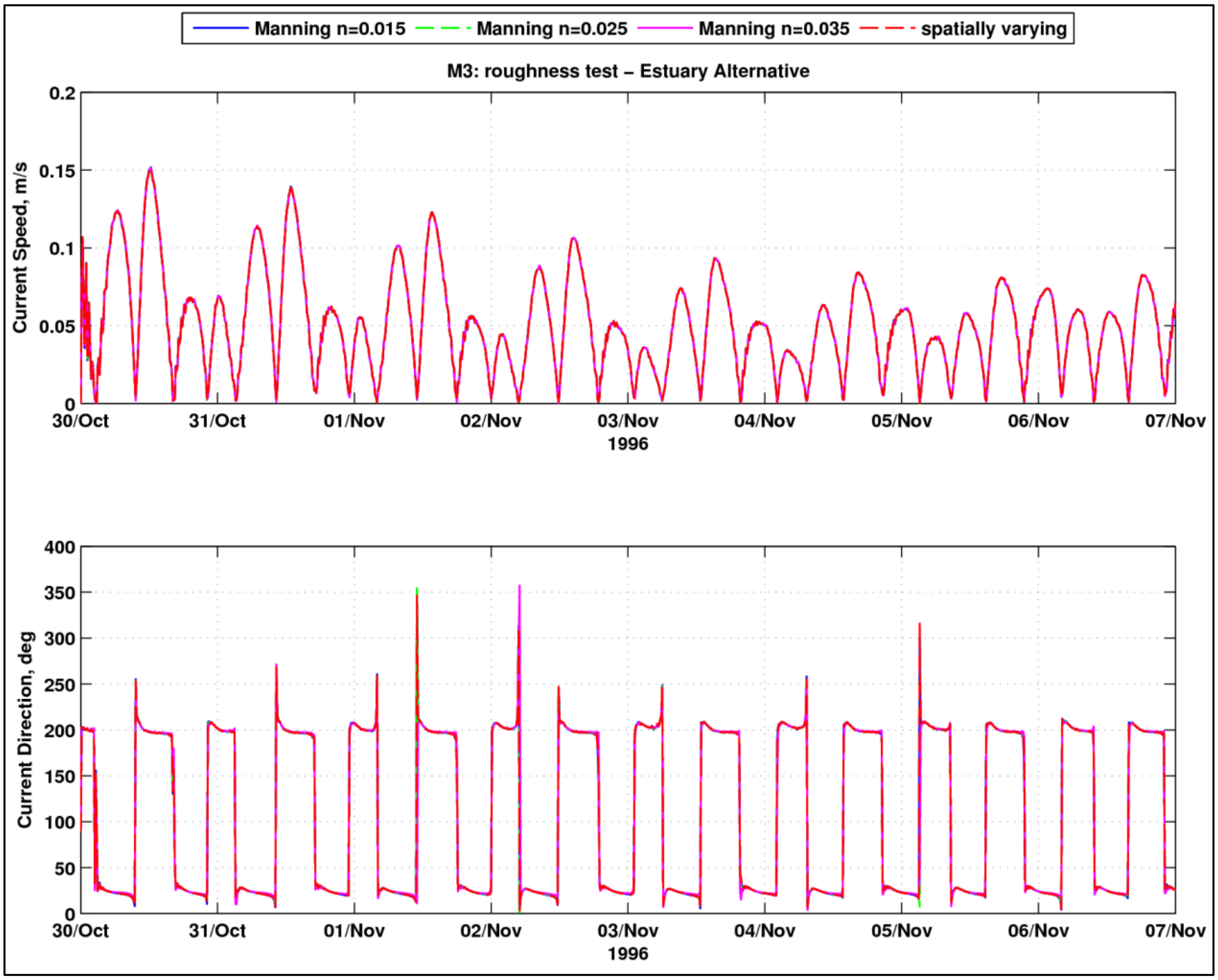
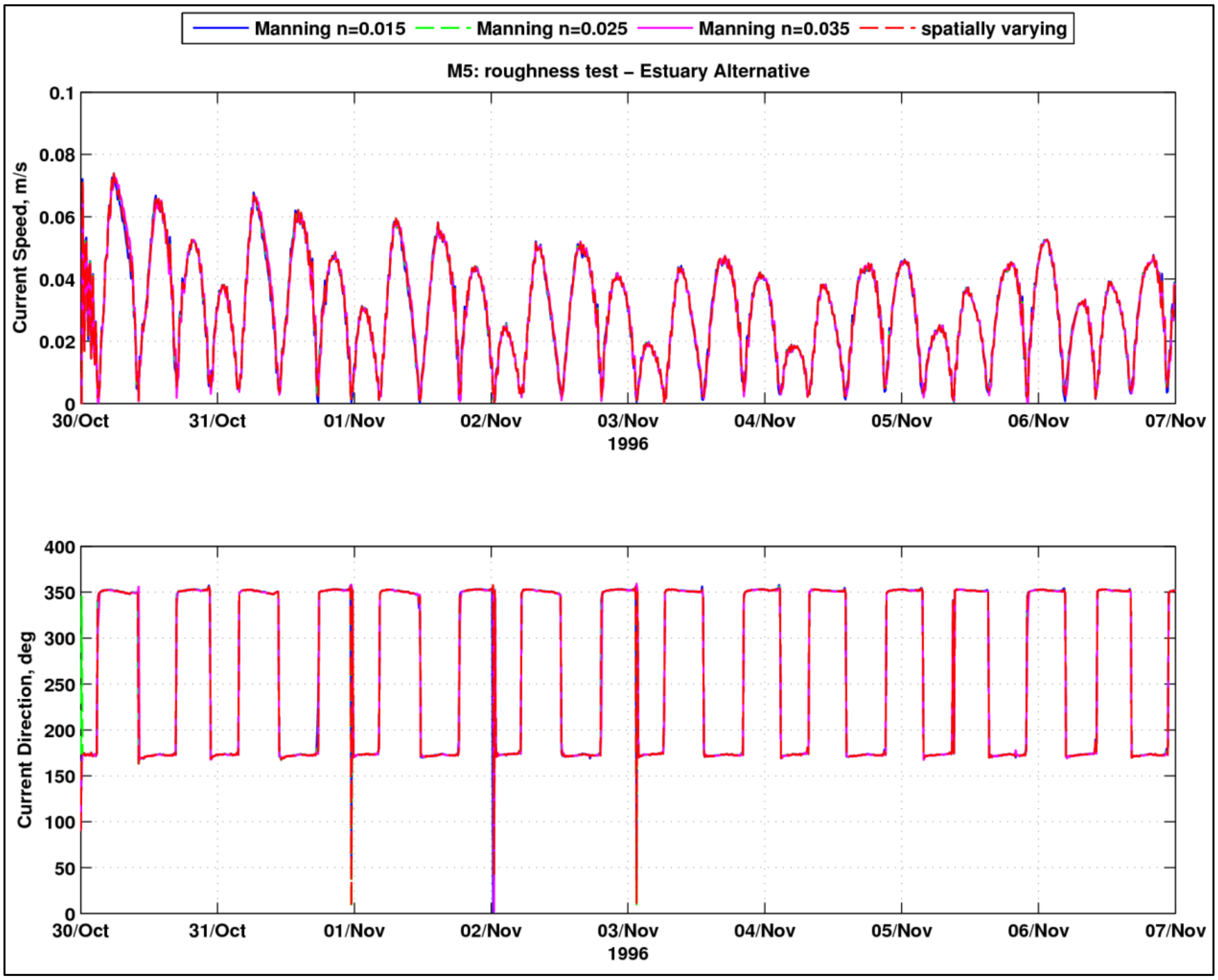


Figure 4-38 Modeled Current Velocity at Station M5 with Varying Manning for Estuary Alternative



In addition to the sensitivity test at Stations M3 and M5, velocities at contraction points including under the I-5 Bridge, under the BNSF Railroad Trestle, and at the Capitol Lake river mouth (where the existing dam is located) for Manning numbers of 0.015, 0.025, 0.035, and a spatial varying roughness were tested to demonstrate the maximum differences during high flow conditions. The simulation period is from 02/09/2017 to 02/13/2017, which included the high flow with peak discharge of 158 m^3/s (Figure 4-10). The comparison metrics computed between Manning numbers of 0.015 and 0.025 (final value), Manning numbers of 0.035 and 0.025 (final value), and spatial varying Manning numbers and 0.025 (final value) are listed from Table 4-12 to Table 4-14. The time series plots are shown from Figure 4-39 to Figure 4-41.

Velocity differences are small among those runs with different Manning numbers except at peaks where higher current speed occurs with a smaller Manning number. The normalized RMS error at the I-5 Bridge ranges from 0.2% to 3.5% for current speed, and from 4.0% to 24.7% for current direction. The normalized RMS error at the BNSF Railroad Trestle ranges from 0.6% to 4.6% for current speed, and from 0.0% to 0.5% for current direction. The normalized RMS error at the river mouth of Capitol Lake ranges from 0.6% to 4.6% for current speed, and from 0.0% to 0.5% for current direction.

The indexes of agreement, d, are all equal to 1 for all tested manning numbers except for a Manning number of 0.015 at the BNSF Railroad Trestle (0.99) and at the Capitol Lake river mouth (0.94). The Manning number of 0.015 seems to be an outlier based on the comparison metrics and the time series at the velocity peak, especially at the Capitol Lake river mouth (Figure 4-41). A Manning number around 0.015 is usually only applied in clean, recently completed navigation channels (Chow 1959), and thus is not appropriate for use in Capitol Lake. The normalized RMS error for current speed is 3.6% between Manning number of 0.035 and 0.025 at the BNSF Railroad Trestle (Table 4-13). The normalized RMS error of current speed is 4.6% between Manning number of 0.015 and 0.025 at the BNSF Railroad Trestle (Table 4-13). The normalized RMS error of current speed is only 0.6% between spatial varying Manning number and Manning number of 0.025 at the BNSF Railroad Trestle (Table 4-13). Therefore, the originally selected Manning number of 0.025 was kept for future runs.

Table 4-12 Currents (Speed and Direction) Comparison Metrics for Manning n 0.015, 0.035, and Spatial Varying Distribution against 0.025 at the I-5 Bridge

Manning n	N = 0.015 Speed	N = 0.015 Direction	0.035 Speed	0.035 Direction	Spatial Varying Speed	Spatial Varying Direction
ε_{RMS} (RMS Error) (m/s)	0.050	0.481	0.033	0.384	0.003	0.078
ε_{norm} (Normalized Error) (-)	3.5%	24.7%	2.3%	19.7%	0.2%	4.0%
MAE (Mean Absolute Error) (m/s)	0.04	0.31	0.03	0.23	0.00	0.03
R (Correlation Coefficient) (-)	1.00	0.62	1.00	0.76	1.00	0.99
ΔT (Time Delay) (min)	2.00	-6.00	-6.00	480.00	1.00	5.00
d (Index of Agreement) (-)	1.00	0.79	1.00	0.87	1.00	0.99

Table 4-13 Currents (Speed and Direction) Comparison Metrics for Manning n 0.015, 0.035, and Spatial Varying Distribution against 0.025 at the BNSF Railroad Trestle

Manning n	0.015 Speed	0.015 Direction	0.035 Speed	0.035 Direction	Spatially Varying Speed	Spatially Varying Direction
ε_{RMS} (RMS Error) (m/s)	0.049	8.848	0.039	12.683	0.007	0.464
ε_{norm} (Normalized Error) (-)	4.6%	0.5%	3.6%	0.7%	0.6%	0.0%
MAE (Mean Absolute Error) (m/s)	0.03	2.32	0.02	1.95	0.00	0.26
R (Correlation Coefficient) (-)	0.99	1.00	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	0.00	-3.00	3.00	-1.00	0.00	0.00
d (Index of Agreement) (-)	0.99	1.00	1.00	1.00	1.00	1.00

Table 4-14 Goodness of Fit for Currents at 5th Avenue Dam Location for Variable Manning n

Manning n	0.015 Speed	0.015 Direction	0.035 Speed	0.035 Direction	Spatially Varying Speed	Spatially Varying Direction
ε_{RMS} (RMS Error) (m/s)	0.144	7.853	0.028	8.294	0.007	1.630
ε_{norm} (Normalized Error) (-)	16.0%	0.4%	3.1%	0.5%	0.8%	0.1%
MAE (Mean Absolute Error) (m/s)	0.07	1.97	0.01	3.51	0.00	0.46
R (Correlation Coefficient) (-)	0.98	1.00	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	-21.00	1.00	3.00	0.00	-1.00	0.00
d (Index of Agreement) (-)	0.94	1.00	1.00	1.00	1.00	1.00

Figure 4-39 Modeled Current Velocity at the I-5 Bridge with Varying Manning for Estuary Alternative

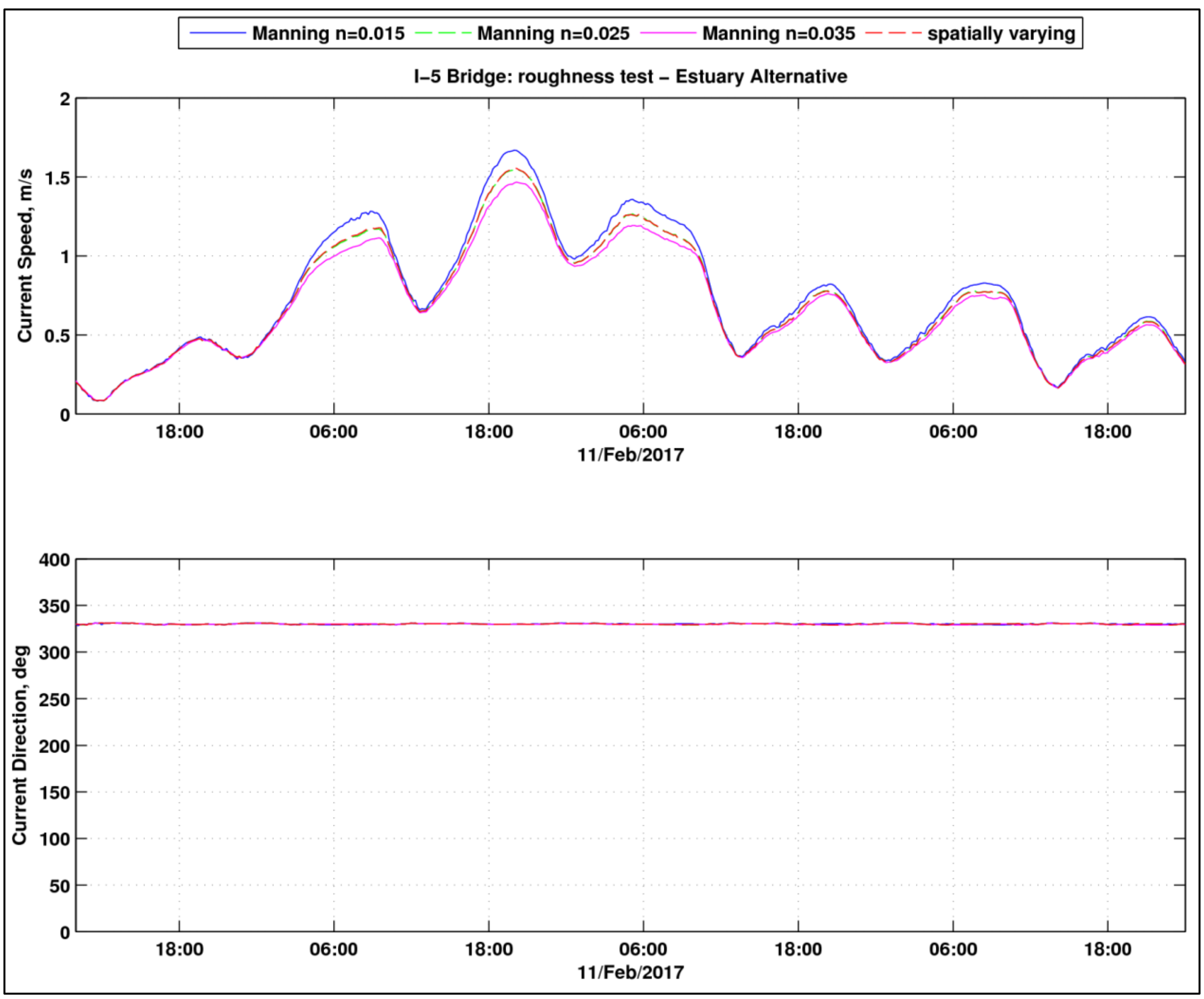


Figure 4-40 Modeled Current Velocity at the BNSF Railroad Trestle for Variable Manning for Estuary Alternative

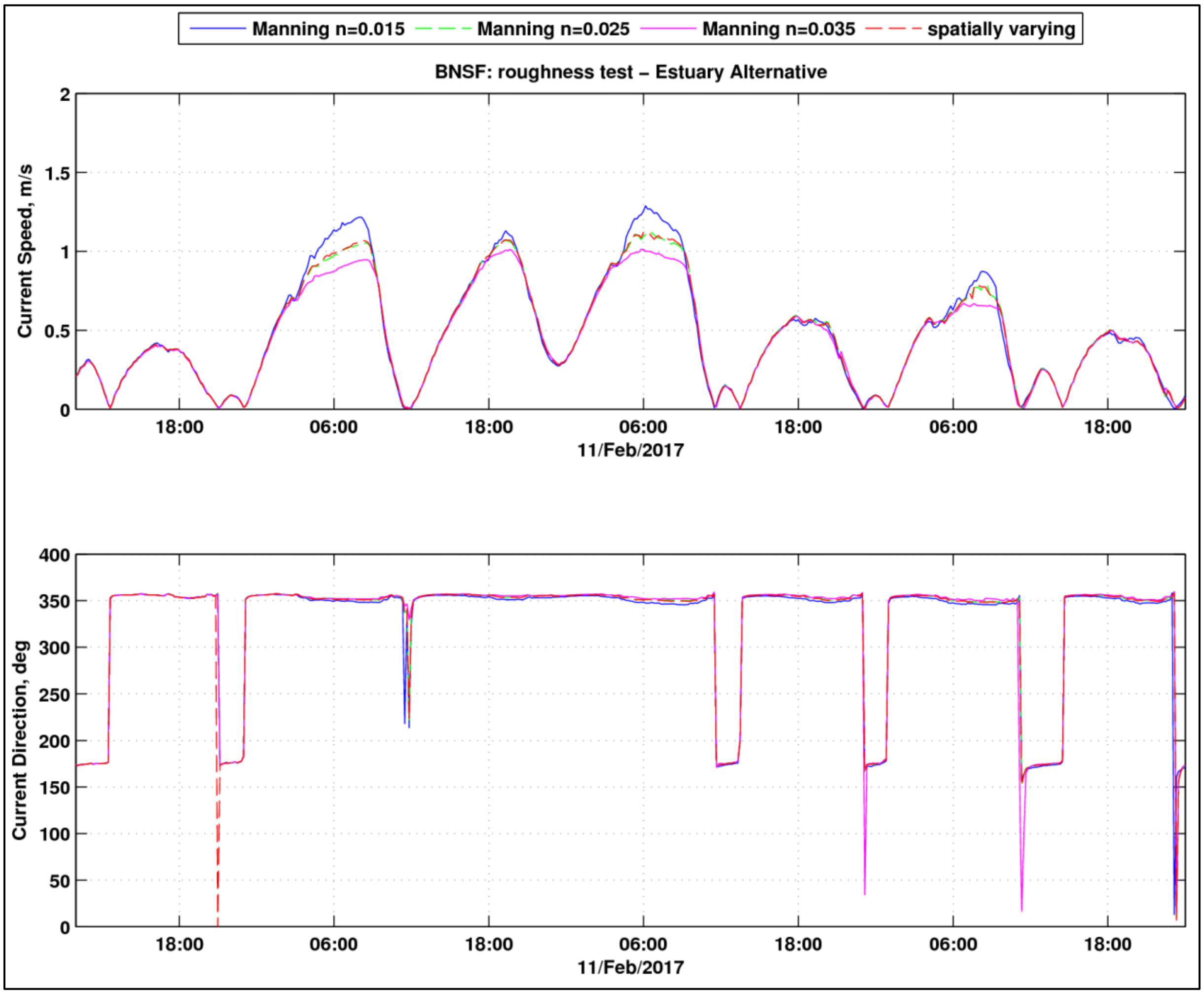
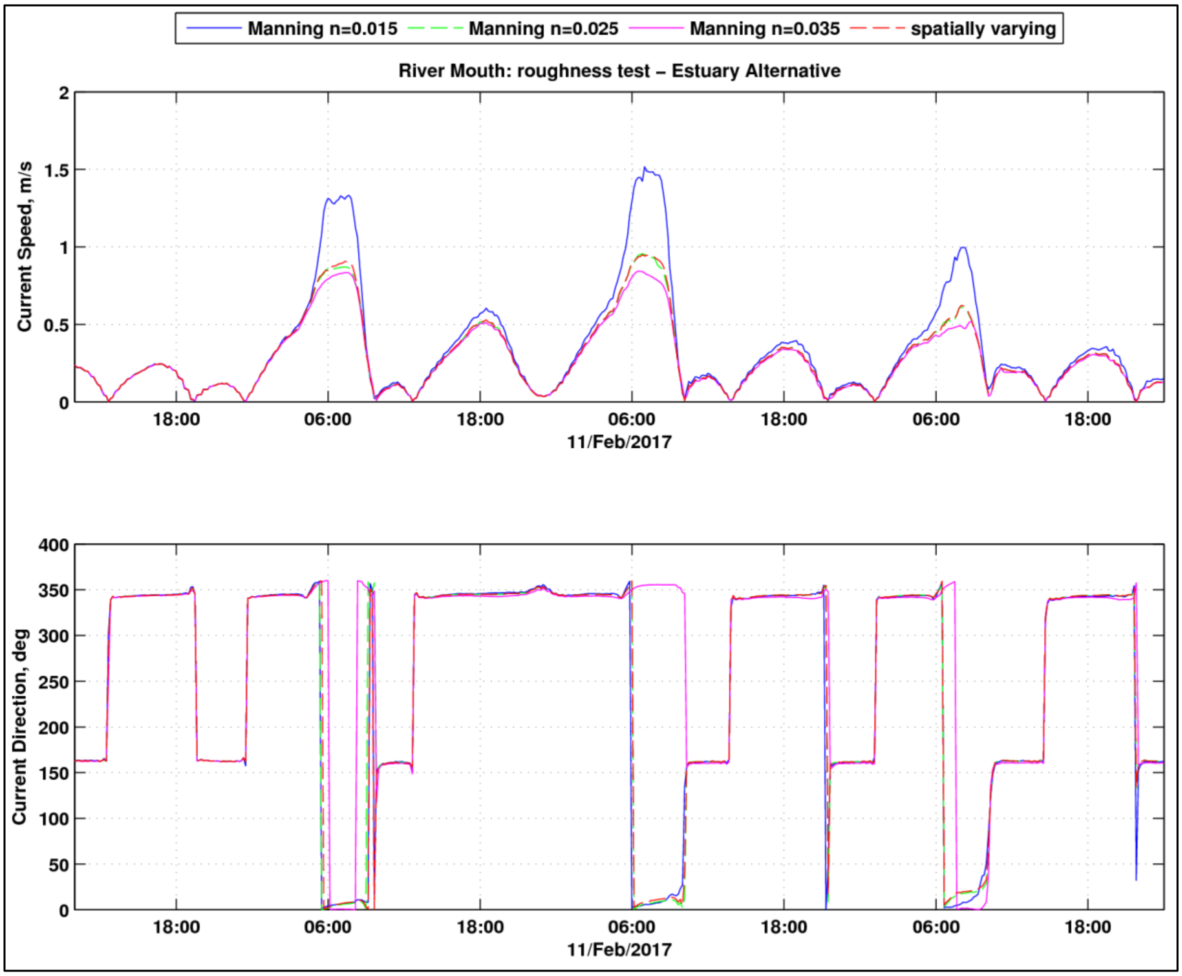


Figure 4-41 Modeled Current Velocity at Capitol Lake River Mouth for Variable Manning for Estuary Alternative



4.5.3 Bathymetry

Bathymetry used for the navigation channel in Budd Inlet was from 2019 USACE survey data, while the calibration period for offshore currents was from 1996 with no survey data available. As a result, sensitivity analyses were developed with bathymetry in the navigation channel increased and decreased 0.3 m to test the bathymetry effect on the current velocities in Budd Inlet. Because Station M3 is outside of the navigation channel, only results for Station M5 are shown here. As shown in Figure 4-42 and Figure 4-43, velocity results between increased depth and original depth or between decreased depth and original depth are almost identical. The normalized RMS error for the No Action Alternative is 1.0% for current speed, and 0.2% - 0.3% for current direction, and the normalized RMS error for the Estuary Alternative is 0.9% for current speed, and 0.2% for current direction. The indexes of agreement, d, are all equal to 1.

Table 4-15 Sensitivity of Goodness of Fit to Bathymetry for Currents at Station M5 for No Action Alternative

Depth	0.3 m Shallower Speed	0.3 m Shallower Direction	0.3 m Deeper Speed	0.3 m Deeper Direction
ε_{RMS} (RMS Error) (m/s)	0.000	4.818	0.000	5.499
ε_{norm} (Normalized Error) (-)	1.0%	0.2%	1.0%	0.3%
MAE (Mean Absolute Error) (m/s)	0.00	0.53	0.00	0.65
R (Correlation Coefficient) (-)	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	1.00	0.00	-1.00	0.00
d (Index of Agreement) (-)	1.00	1.00	1.00	1.00

Table 4-16 Sensitivity of Goodness of Fit to Bathymetry for Currents at Station M5 for Estuary Alternative

Depth	0.3 m Shallower Speed	0.3 m Shallower Direction	0.3 m Deeper Speed	0.3 m Deeper Direction
ε_{RMS} (RMS Error) (m/s)	0.001	5.262	0.001	4.787
ε_{norm} (Normalized Error) (-)	0.9%	0.2%	0.9%	0.2%
MAE (Mean Absolute Error) (m/s)	0.00	0.32	0.00	0.32
R (Correlation Coefficient) (-)	1.00	1.00	1.00	1.00
ΔT (Time Delay) (min)	480.00	0.00	-480.00	0.00
d (Index of Agreement) (-)	1.00	1.00	1.00	1.00

Figure 4-42 Modeled Currents at Station M5 with Varying Water Bathymetry for No Action Alternative

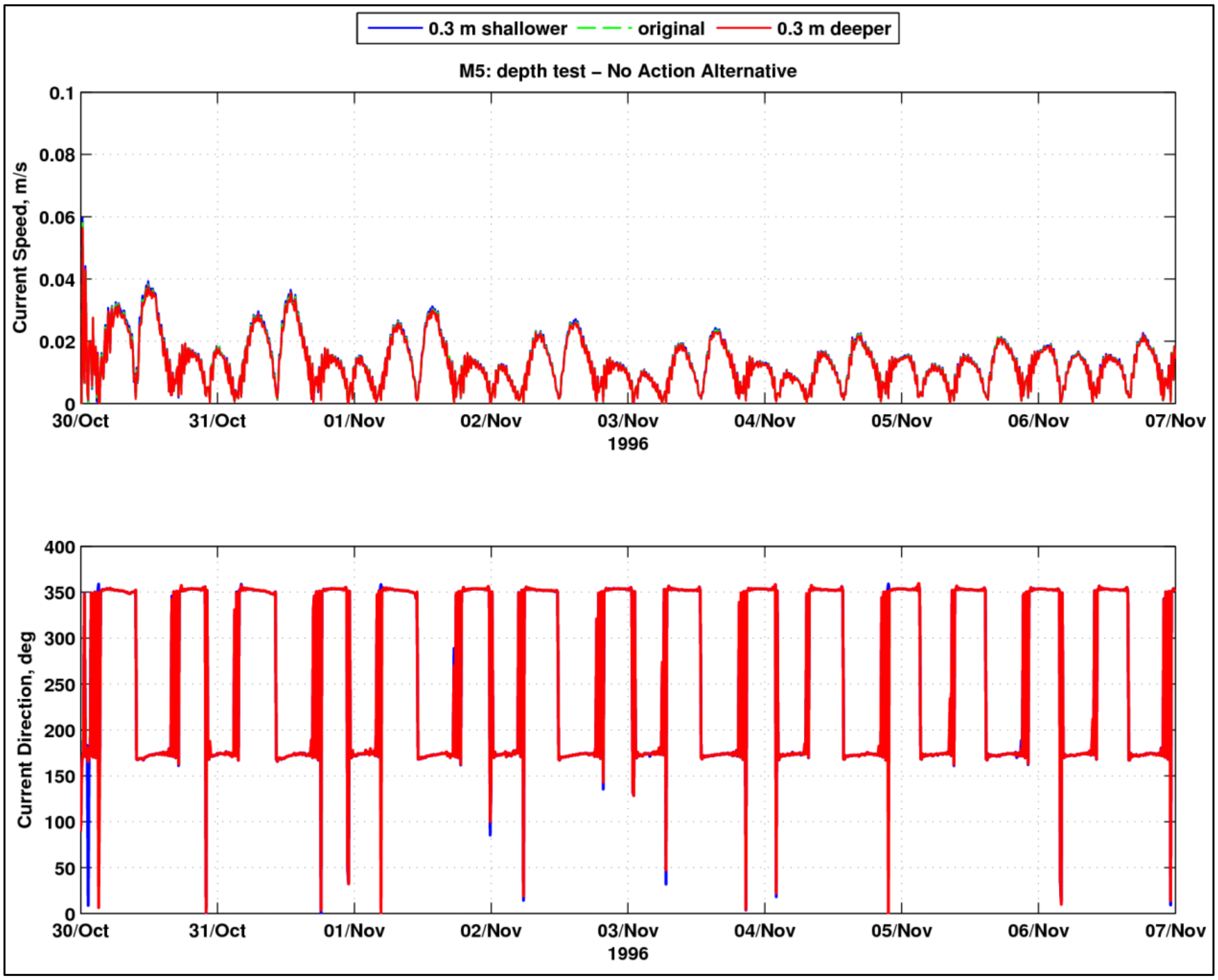
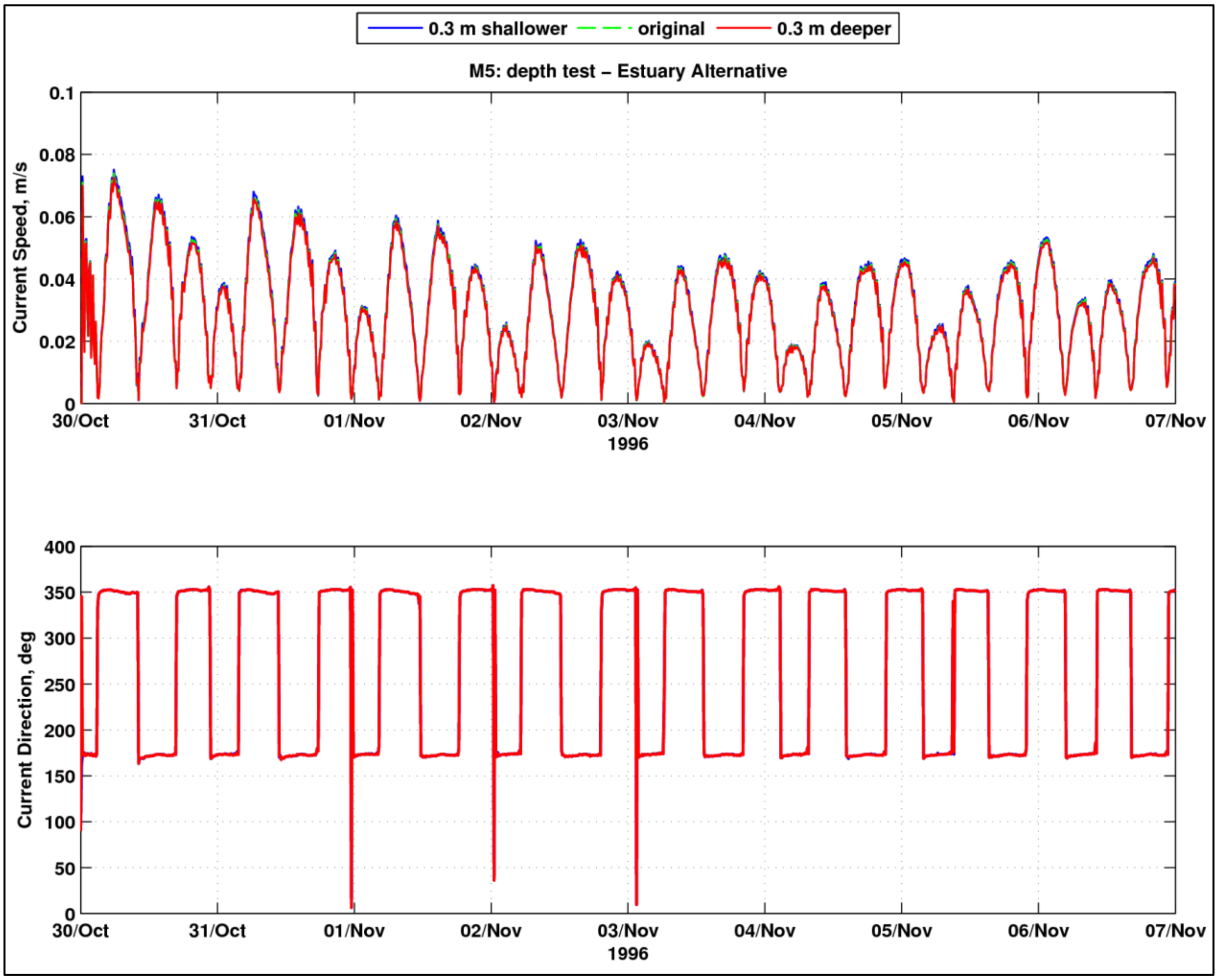


Figure 4-43 Modeled Currents at Station M5 with Varying Bathymetry for Estuary Alternative



4.6 HYDRODYNAMIC MODEL RESULTS

Hydrodynamics were assessed for the four alternatives described in Section 3.0 in terms of water levels and depth-averaged velocities. The hydrodynamics were assessed for the following two extreme flow events using the 2D version of Delft3D:

- Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide, and
- Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide.

The two selected modeled events represent extreme tidal flooding conditions from Budd Inlet (Event 1) and riverine flooding from the Deschutes River (Event 2). Both riverine and tidal flooding are known to impact the Capitol Lake Basin under existing conditions, resulting in downtown flooding and stormwater backups during king tides and high river stages. A 100-year event, which has a 1% annual chance of occurrence, is often considered as part of engineering risk assessments, and is the standard floodplain level analyzed for FEMA Flood Insurance Studies.

The hydrodynamic numerical simulations included time history of an extreme flow event developed based on scaling real events to evaluate the hydrodynamic conditions in the model domain (see Section 4.3 for boundary conditions). The hydrodynamic model results in terms of maximum water levels and maximum flow velocities were characterized for the four alternatives without and with RSLR and are presented in the following sections. The simulations with RSLR included a 0.61 m (2.0 ft) increase in water level at the offshore boundary condition to represent future RSLR.

The value of RSLR equal to 0.61 m (2.0 ft) was selected because the recent City of Olympia SLR Response Plan acknowledges that by the time 0.61 m (2.0 ft) of RSLR occurs, significant physical adaptation measures (e.g. raising the seawall, building a berm) would have been adapted to protect City of Olympia's infrastructure and properties along the shoreline. The Plan acknowledges that SLR projections range higher than 2.0 feet, and that adaptation measures will continue beyond 2.0 feet of rise. Two feet of RSLR is roughly equivalent to a 5% probability of exceedance at 2060 or a 10% probability of exceedance at 2070, according to the high greenhouse gas estimates from the Projected Sea-Level Rise for Washington State report for Olympia (Miller et al 2018).

4.6.1 Maximum Water Levels

Hydrodynamic model results in terms of maximum water levels for the two extreme hydrologic events (Events #1 and #2) without and with RSLR were extracted and are presented in Sections 4.6.1.1 and 4.6.1.2, respectively. All water levels presented herein are referenced to NAVD88 in meters unless noted otherwise.

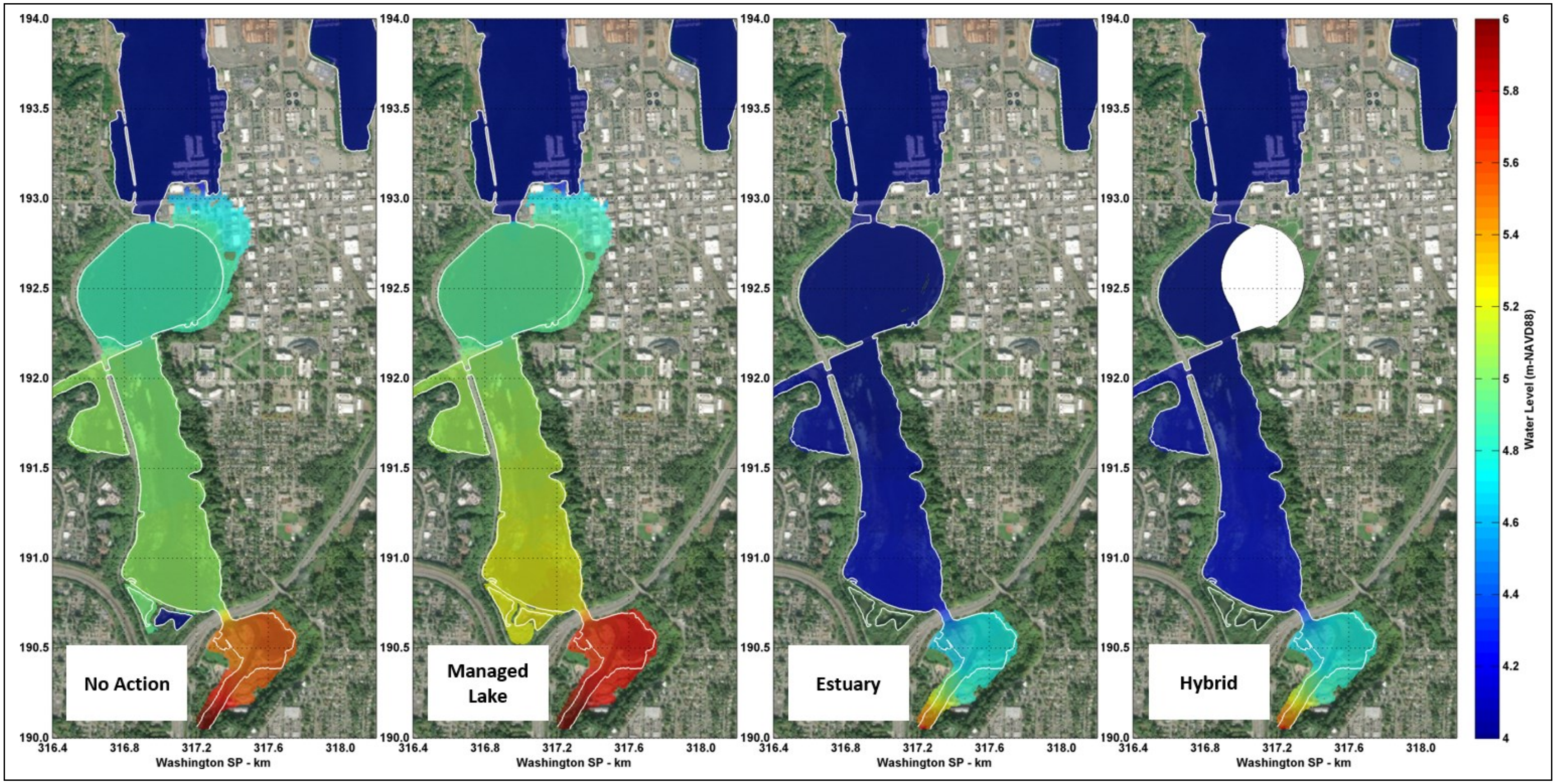
In general, for the Estuary and Hybrid Alternatives, the tidal connection with Budd Inlet is immediately restored after removal of the 5th Avenue Dam and the water level within the Capitol Lake Basin is mostly driven by water level fluctuations in Budd Inlet. However, for the No Action and Managed Lake Alternatives, water levels within the Capitol Lake Basin are controlled by the gate operation.

4.6.1.1 Without RSLR

Model results in terms of maximum water levels over the entire modeling domain for the four alternatives without RSLR for Events #1 and #2 are presented in Figure 4-44 and Figure 4-45, respectively.

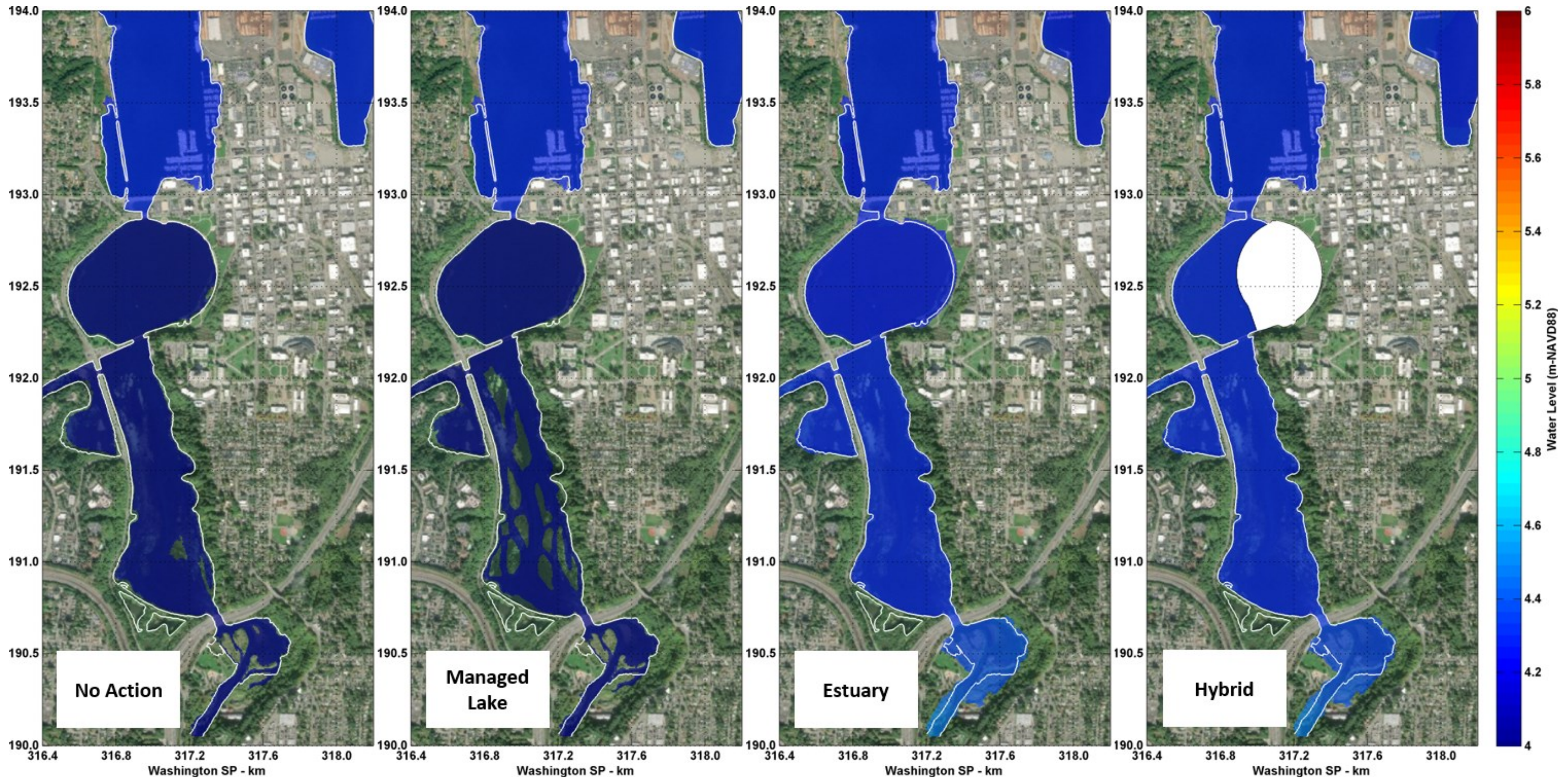
Model results in terms of maximum water level for Events#1 and #2 were extracted at observation points. The locations of these observation points are shown in Figure 4-46 and their maximum water levels for Events #1 and #2 without RSLR are listed in Table 4-17, Table 4-18, and Table 4-19.

Figure 4-44 Maximum Water Level (m, NAVD88) for Event #1 Without RSLR



Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Figure 4-45: Maximum Water Level (m, NAVD88) for Event #2 Without RSLR



Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Figure 4-46 Location of Observation Points Within the Model Domain

Table 4-17 Coordinates of Observation Points (Washington State Plane South NAD83 in meters) and Elevation (m, NAVD88) under Each Alternative

Observation Point	X	Y	No Action	Managed Lake	Estuary	Hybrid
SB01	317252	190103	+2.0	+2.0	+2.0	+2.0
SB02	317645	190600	+0.8	+0.8	+0.8	+0.8
SB03 (I-5 Bridge)	317345	190710	-0.1	-0.1	-1.8	-1.8
MB01	317070	190774	+1.5	+1.5	+2.6	+2.6
MB02	316916	190863	+1.9	+1.9	+3.2	+3.2
MB03	316905	191250	+3.3	+3.3	+3.3	+3.3
MB04	317240	191275	+3.3	+3.3	+3.3	+3.3
MB05	317125	191565	-0.2	-0.2	-0.4	-0.4
PC01	316315	191855	+1.5	+1.5	+1.5	+1.5
PC02	316685	192040	+1.5	+1.5	+1.5	+1.5
NB01 (RR Bridge)	316945	192214	-0.9	-0.4	-0.5	-0.5
NB02	316875	192365	-0.8	-0.9	-0.7	-0.7
NB03	317324	192620	+1.0	+2.0	+1.9	N/A
NB04	316570	192530	+1.0	+0.4	+2.8	+2.8
NB05	317059	192699	-0.8	-0.9	-1.2	N/A
NB06 (gate)	316950	192895	-0.9	-3.5	-4.9	-4.9
BI01	316938	193114	-3.6	-3.6	-3.6	-3.6
BI02	317222	193553	-6.2	-6.2	-6.2	-6.2
BI03	317167	194206	-11.8	-11.8	-11.8	-11.8
BI04	317083	195459	-10.8	-10.8	-10.8	-10.8
BI05	315672	197497	-11.1	-11.1	-11.1	-11.1

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

Table 4-18 Maximum Water Level (m, NAVD88) for Event #1 without RSLR

Observation Point	Model Results: No Action	Model Results: Managed Lake	Model Results: Estuary	Model Results: Hybrid	Change w.r.t No Action: Managed Lake	Change w.r.t No Action: Estuary	Change w.r.t No Action: Hybrid
SB01	+6.1	+6.3	+5.7	+5.7	3%	-7%	-7%
SB02	+5.6	+5.8	+4.8	+4.9	4%	-14%	-13%
SB03 (I-5 Bridge)	+5.1	+5.4	+4.4	+4.4	6%	-14%	-14%
MB01	+5.0	+5.3	+4.3	+4.3	6%	-14%	-14%
MB02	+5.1	+5.3	+4.3	+4.3	4%	-16%	-16%
MB03	+5.1	+5.2	+4.3	+4.3	2%	-16%	-16%
MB04	+5.1	+5.2	+4.3	+4.3	2%	-16%	-16%
MB05	+5.1	+5.2	+4.3	+4.3	2%	-16%	-16%
PC01	+5.1	+5.2	+4.3	+4.4	2%	-16%	-14%
PC02	+5.1	+5.1	+4.2	+4.2	0%	-18%	-18%
NB01 (RR Bridge)	+5.0	+5.0	+4.1	+4.1	0%	-18%	-18%
NB02	+4.9	+4.9	+4.0	+4.1	0%	-18%	-16%
NB03	+4.9	+4.9	+4.0	N/A	0%	-18%	N/A
NB04	+4.9	+4.9	+4.0	+4.1	0%	-18%	-16%
NB05	+4.9	+4.9	+4.0	N/A	0%	-18%	N/A
NB06 (gate)	+4.0	+4.0	+4.0	+4.0	0%	0%	0%
BI01	+4.0	+4.0	+4.0	+4.0	0%	0%	0%
BI02	+4.0	+4.0	+4.0	+4.0	0%	0%	0%
BI03	+4.0	+4.0	+4.0	+4.0	0%	0%	0%
BI04	+4.0	+4.0	+3.9	+4.0	0%	-3%	0%
BI05	+3.9	+3.9	+3.9	+3.9	0%	0%	0%

Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

Table 4-19 Maximum Water Level (m, NAVD88) for Event #2 without RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	+3.8	+3.8	+4.5	+4.6	0%	18%	21%
SB02	+3.3	+3.4	+4.4	+4.4	3%	33%	33%
SB03 (I-5 Bridge)	+3.1	+3.3	+4.4	+4.4	6%	42%	42%
MB01	+3.5	+3.6	+4.4	+4.4	3%	26%	26%
MB02	+2.7	+2.9	+4.4	+4.4	7%	63%	63%
MB03	+3.4	+3.4	+4.4	+4.4	0%	29%	29%
MB04	+3.7	+3.6	+4.4	+4.4	-3%	19%	19%
MB05	+3.0	+3.2	+4.3	+4.4	7%	43%	47%
PC01	+3.0	+3.2	+4.4	+4.4	7%	47%	47%
PC02	+3.0	+3.1	+4.3	+4.3	3%	43%	43%
NB01 (RR Bridge)	+3.0	+3.1	+4.3	+4.3	3%	43%	43%
NB02	+3.0	+3.1	+4.3	+4.4	3%	43%	47%
NB03	+3.0	+3.1	+4.3	N/A	3%	43%	N/A
NB04	+3.0	+3.1	+4.3	+4.4	3%	43%	47%
NB05	+3.0	+3.1	+4.3	N/A	3%	43%	N/A
NB06 (gate)	+4.4	+4.4	+4.3	+4.3	0%	-2%	-2%
BI01	+4.4	+4.4	+4.3	+4.3	0%	-2%	-2%
BI02	+4.4	+4.4	+4.3	+4.3	0%	-2%	-2%
BI03	+4.4	+4.4	+4.3	+4.3	0%	-2%	-2%
BI04	+4.3	+4.3	+4.3	+4.3	0%	0%	0%
BI05	+4.3	+4.3	+4.3	+4.3	0%	0%	0%

Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

For Event #1, the model results demonstrate that maximum water levels within the Capitol Lake Basin are generally higher for the No Action and Managed Lake Alternatives than the Estuary and Hybrid Alternatives (see Figure 4-44). Model results for the No Action and Managed Lake Alternatives have a similar pattern with maximum water levels within the Capitol Lake Basin, approximately 0.9 m higher than maximum water levels in Budd Inlet.

For Event #1, the maximum water level for the No Action Alternative varies from +4.9 m, NAVD88 in the North Basin to +5.0 m at the Railroad Bridge in the Middle Basin to +6.1 m at the Deschutes River boundary in the South Basin. Similarly, for the Managed Lake Alternative, maximum water level varies from +4.9 m, NAVD88 in the North Basin to +5.3 m at the Railroad Bridge in the Middle Basin to +6.3 m at the Deschutes River boundary in the South Basin. The model results show that high water levels for both the No Action and Managed Lake Alternatives will result in upland flooding in Heritage Park, Interpretive Park, and along stretches of the Deschutes Parkway, see Figure 4-44. These model results are consistent with past flooding along the Capitol Lake Basin based on anecdotal observations provided by DES staff in charge of the 5th Avenue Dam operation. Model results for No Action Alternative are consistent with past upland flooding at the Tumwater Historical Park along the South Basin based on anecdotal observations provided by the Tumwater Parks and Recreation staff.

For Event #1, maximum water levels for the Managed Lake Alternative are slightly (≤0.3m) higher than that of the No Action Alternative in the Middle and South Basins. Consequently, the extent of upland flooding for the Managed Lake Alternative is larger at Interpretive Park. This is most likely due to a net reduction in flood storage capacity for the Managed Lake Alternative due to the creation of habitat areas in the Middle Basin and despite the North Basin dredging.

For Event #1, for the Estuary and Hybrid Alternatives, maximum water level in the North Basin and Budd Inlet is approximately equal to +4.0 m. Maximum water levels for these alternatives gradually increase to +4.1 m at the Railroad Bridge in the Middle Basin to +5.7 m at the Deschutes River boundary in the South Basin. No upland flooding is observed for the Estuary and Hybrid Alternatives.

For Event #2, model results demonstrate that maximum water levels within the Capitol Lake Basin are generally lower for the No Action and Managed Lake Alternatives than the Estuary and Hybrid Alternatives, see Figure 4-45. This is consistent with present dam operation, which keeps the 5th Avenue Dam kept closed during high tide events to control the Capitol Lake water level within the summer and winter limits. Upon removal of the dam, during a high tide event, water levels within Capitol Lake will be driven by tides and will be as high as water levels within Budd Inlet.

In addition, it can be observed that Event #2 does not result in upland flooding for any of the four alternatives. For Event #2, maximum water levels for the No Action and Managed Lake Alternatives are equal or smaller than +3.1 m and generally lower than maximum water levels of +4.4 m in Budd Inlet. Maximum water levels for the No Action Alternative increase from +3.0 m in the North Basin to +3.8 m at the Deschutes River boundary in the South Basin.

For Event #2, for the Estuary and Hybrid Alternatives, maximum water levels within the North Basin are approximately equal to that of Budd Inlet (+4.3 m). Maximum water levels gradually increase to +4.6 m at the Deschutes River boundary in the South Basin.

4.6.1.2 With RSLR (Includes 0.61 m of RSLR)

Model results in terms of maximum water levels over the entire modeling domain for the four alternatives with 0.61 m of RSLR for Events #1 and #2 are presented in Figure 4-47 and Figure 4-48, respectively. Model results were extracted at the aforementioned observation points and are listed in Table 4-20 and Table 4-21 for Events #1 and #2, respectively.

For Event #1, comparison of maximum water levels with and without 0.61 m of RSLR (see Figure 4-47 and Figure 4-44, respectively) shows that application of the 0.61 m of RSLR at the offshore boundary has resulted in an increase (up to 0.6 m) in water levels within the Capitol Lake Basin for all four alternatives. Consequently, the extent of upland flooding for future conditions is greater than that of the 'without RSLR' for all four alternatives. Most visibly, upland flooding in downtown Olympia with 0.61 m of RSLR has extended further north and east compared to the conditions without RSLR.

For Event #1, maximum water levels for the No Action Alternative increase from +5.3 m, NAVD88 in the North Basin to +5.4 m at the Railroad Bridge in the Middle Basin to +6.4 m at the Deschutes River boundary in the South Basin. Similarly, for the Managed Lake Alternative, maximum water levels increase from +5.3 m, NAVD88 in the North Basin to +5.4 m at the Railroad Bridge in the Middle Basin to +6.5 m at the Deschutes River boundary in the South Basin.

For Event #1, maximum water levels for the Managed Lake Alternative are slightly (≤0.2 m) higher than that of the No Action Alternative within the Capitol Lake Basin. This difference is most visible in the Middle and South Basins. This is most likely due to a net reduction in flood storage capacity for the Managed Lake Alternative due to the creation of habitat areas in the Middle Basin and despite the North Basin dredging.

For Event #1, the maximum water level in the North Basin is equal to the maximum water level in Budd Inlet (approximately equal to +4.6 m) for the Estuary and Hybrid Alternatives. The maximum water level for these alternatives gradually increases to +4.7 m at the Railroad Bridge in the Middle Basin to +5.9 m and +6.0 m at the Deschutes River boundary in the South Basin for Estuary and Hybrid Alternatives, respectively.

For Event #2, comparison of maximum water levels with and without 0.61 m of RSLR (see Figure 4-48 and Figure 4-45, respectively) shows that application of the 0.61 m of RSLR at the offshore boundary has resulted in a relatively uniform increase of approximately 0.61 m in maximum water levels within the Capitol Lake Basin for the Hybrid and Estuary Alternatives. This is because for these two alternatives, Capitol Lake Basin is tidally connected to Budd Inlet and water levels within the Capitol Lake Basin are primarily controlled by water level fluctuations in Budd Inlet.

For Event #2, contrary to the Estuary and Hybrid Alternatives, application of RSLR at the offshore boundary has not changed maximum water levels within the Capitol Lake Basin for the No Action and Managed Lake Alternatives. This is expected because the 5th Avenue Dam isolates the Capitol Lake Basin from water level fluctuations in Budd Inlet. Upland flooding in downtown Olympia for the No

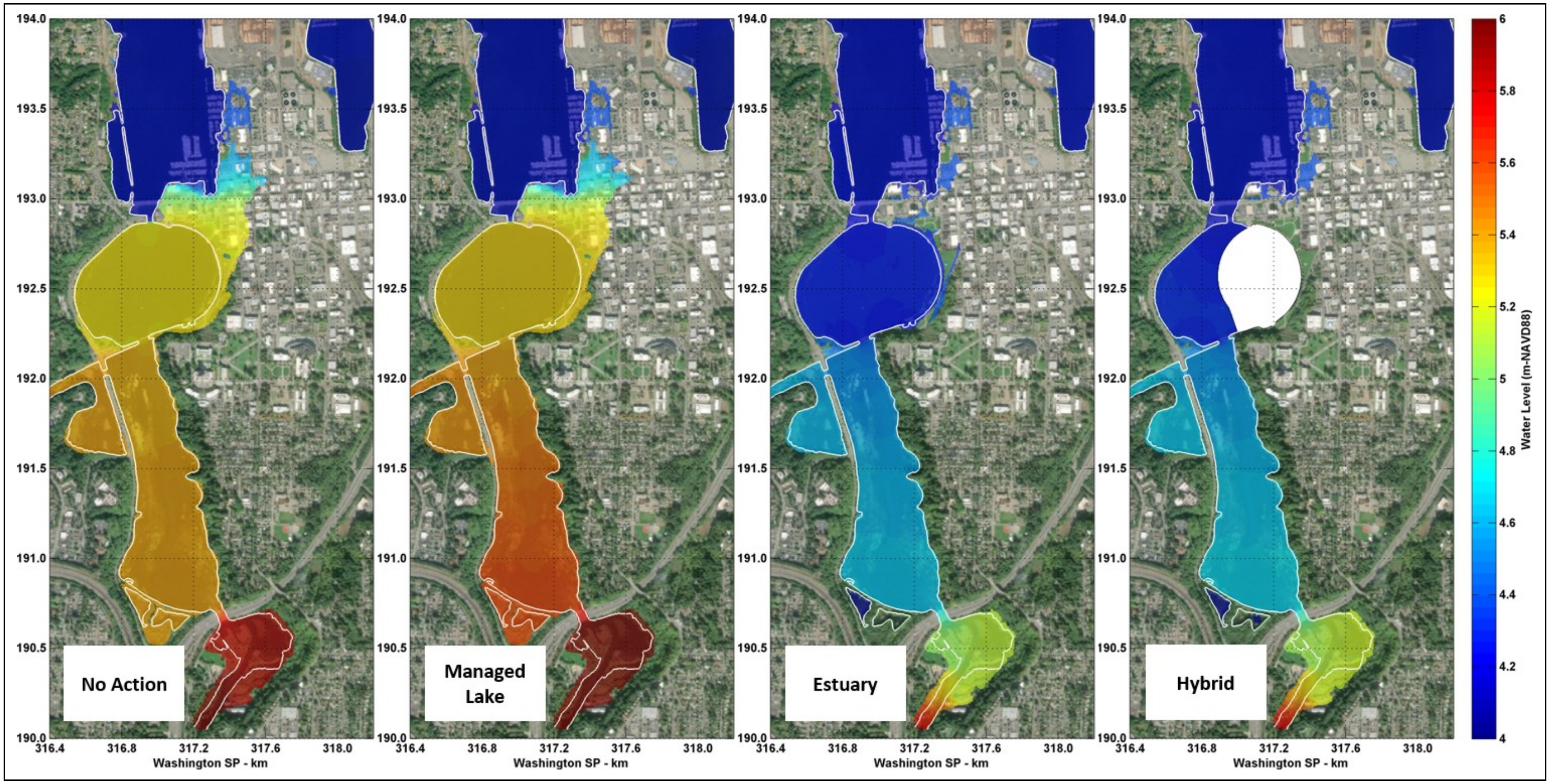
Action and Managed Lake Alternatives with 0.61 m of RSLR is limited to bathtub inundation of low-lying upland areas surrounding Budd Inlet, including areas in Heritage Park, Percival Landing, and the Port.

For Event #2, maximum water levels for the No Action and Managed Lake Alternatives are equal or smaller than +3.8 m and generally lower than the maximum water levels of +4.9 m in Budd Inlet. Maximum water levels for the No Action Alternative increase from +3.0 m in the North Basin to +3.8 m at the Deschutes River boundary in the South Basin.

For Event #2, for the Estuary and Hybrid Alternatives, maximum water levels within the North Basin are approximately equal to that of Budd Inlet (+4.9 m). Maximum water levels gradually increase to +5.1 m at the Deschutes River boundary in the South Basin.

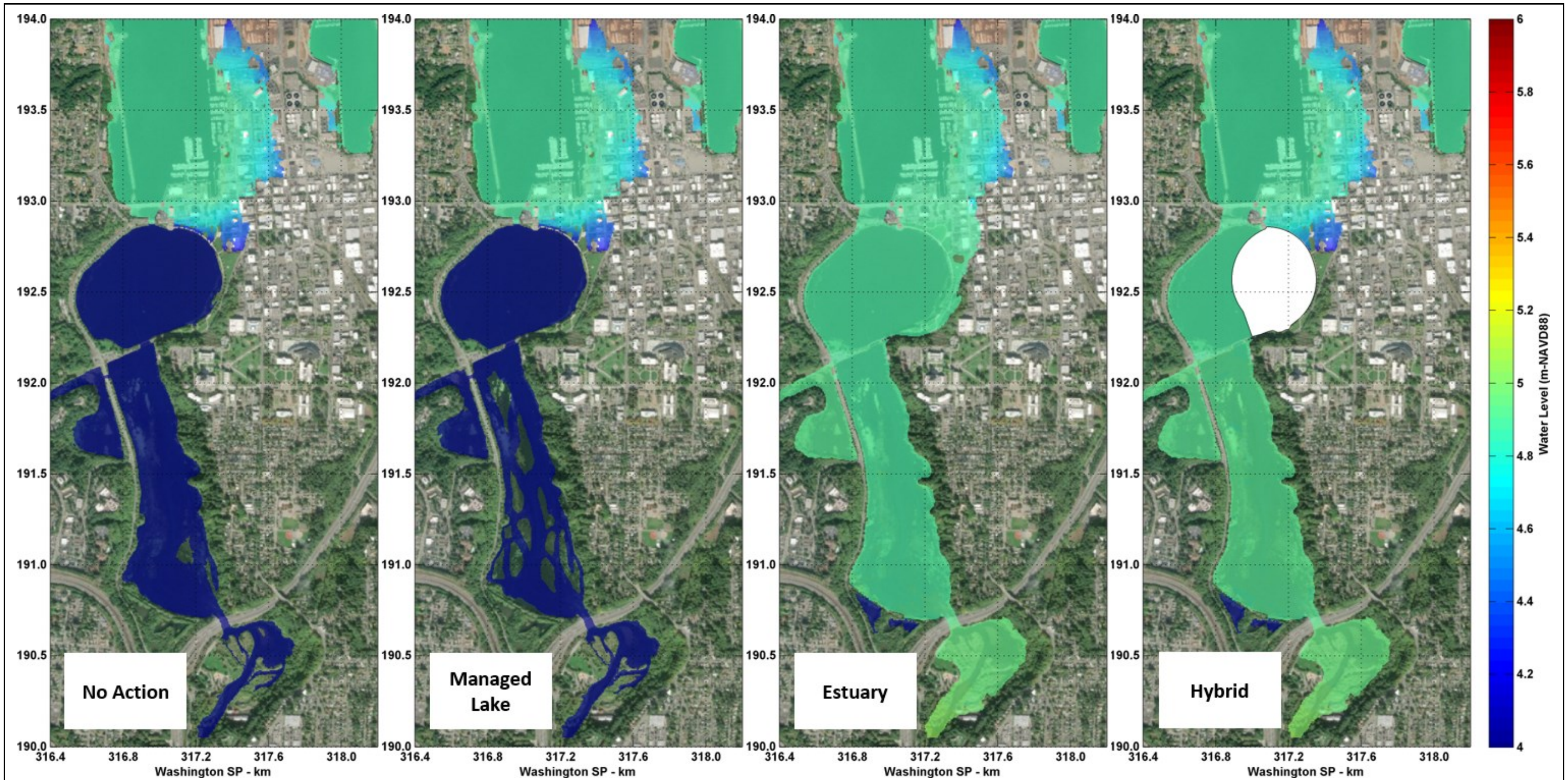
Comparison of model results for Event #1 (see Figure 4-47) and Event #2 (see Figure 4-48) shows that with 0.61 m of RSLR, (a) for the No Action and Managed Lake Alternatives, maximum water levels within the Capitol Lake Basin are controlled by Event #1; and (b) for the Estuary and Hybrid Alternatives, maximum water levels in the North and Middle Basins are controlled by Event #2, while maximum water levels in the South Basin are controlled by Event #1.

Figure 4-47 Maximum Water Level (m, NAVD88) for Event #1 under with 0.61 m of RSLR



Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Figure 4-48 Maximum Water Level (m, NAVD88) for Event #2 with 0.61 m of RSLR



Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Table 4-20 Maximum Water Level (m, NAVD88) for Event #1 with 0.61 m of RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	+6.4	+6.5	+5.9	+6.0	2%	-8%	-6%
SB02	+5.9	+6.1	+5.3	+5.3	3%	-10%	-10%
SB03 (I-5 Bridge)	+5.5	+5.7	+4.9	+5.0	4%	-11%	-9%
MB01	+5.4	+5.6	+4.8	+4.8	4%	-11%	-11%
MB02	+5.5	+5.6	+4.8	+4.8	2%	-13%	-13%
MB03	+5.4	+5.6	+4.8	+4.9	4%	-11%	-9%
MB04	+5.4	+5.6	+4.8	+4.9	4%	-11%	-9%
MB05	+5.4	+5.5	+4.8	+4.8	2%	-11%	-11%
PC01	+5.5	+5.5	+4.9	+4.9	0%	-11%	-11%
PC02	+5.4	+5.5	+4.8	+4.8	2%	-11%	-11%
NB01 (RR Bridge)	+5.4	+5.4	+4.7	+4.7	0%	-13%	-13%
NB02	+5.3	+5.4	+4.6	+4.7	2%	-13%	-11%
NB03	+5.3	+5.4	+4.6	N/A	2%	-13%	N/A
NB04	+5.3	+5.4	+4.6	+4.7	2%	-13%	-11%
NB05	+5.3	+5.4	+4.6	N/A	2%	-13%	N/A
NB06 (gate)	+4.6	+4.6	+4.6	+4.6	0%	0%	0%
BI01	+4.6	+4.6	+4.6	+4.6	0%	0%	0%
BI02	+4.6	+4.6	+4.6	+4.6	0%	0%	0%
BI03	+4.6	+4.6	+4.6	+4.6	0%	0%	0%
BI04	+4.6	+4.6	+4.6	+4.6	0%	0%	0%
BI05	+4.5	+4.5	+4.5	+4.5	0%	0%	0%

Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

Table 4-21 Maximum Water level (m, NAVD88) for Event #2 with 0.61 m of RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	+3.8	+3.8	+5.1	+5.1	0%	34%	34%
SB02	+3.3	+3.5	+5.0	+5.0	6%	52%	52%
SB03 (I-5 Bridge)	+3.1	+3.3	+5.0	+5.0	6%	61%	61%
MB01	+3.5	+3.6	+5.0	+5.0	3%	43%	43%
MB02	+2.7	+2.9	+5.0	+5.0	7%	85%	85%
MB03	+3.4	+3.4	+5.0	+5.0	0%	47%	47%
MB04	+3.7	+3.6	+5.0	+5.0	-3%	35%	35%
MB05	+3.1	+3.2	+4.9	+5.0	3%	58%	61%
PC01	+3.1	+3.2	+5.0	+5.0	3%	61%	61%
PC02	+3.1	+3.2	+4.9	+4.9	3%	58%	58%
NB01 (RR Bridge)	+3.0	+3.2	+4.9	+4.9	7%	63%	63%
NB02	+3.0	+3.1	+4.9	+4.9	3%	63%	63%
NB03	+3.0	+3.1	+4.9	N/A	3%	63%	N/A
NB04	+3.0	+3.1	+4.9	+4.9	3%	63%	63%
NB05	+3.0	+3.1	+4.9	N/A	3%	63%	N/A
NB06 (gate)	+5.0	+5.0	+4.9	+4.9	0%	-2%	-2%
BI01	+5.0	+5.0	+4.9	+4.9	0%	-2%	-2%
BI02	+5.0	+5.0	+4.9	+4.9	0%	-2%	-2%
BI03	+5.0	+5.0	+4.9	+4.9	0%	-2%	-2%
BI04	+4.9	+4.9	+4.9	+4.9	0%	0%	0%
BI05	+4.9	+4.9	+4.9	+4.9	0%	0%	0%

Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

4.6.2 Maximum Flow Velocities

Hydrodynamic model results in terms of maximum depth-averaged flow velocities for the two extreme hydrologic events (Events #1 and #2) for without and with RSLR were extracted and are presented in Sections 4.6.2.1 and 0, respectively. All flow velocities presented herein are in meters per second (m/s) unless noted otherwise. It should be noted that plots of maximum current presented in this section do not correspond to the same time stamp as that captured by the plots of maximum water level presented in Section 4.6.1. The former represents ebb tide and the latter represents slack tide.

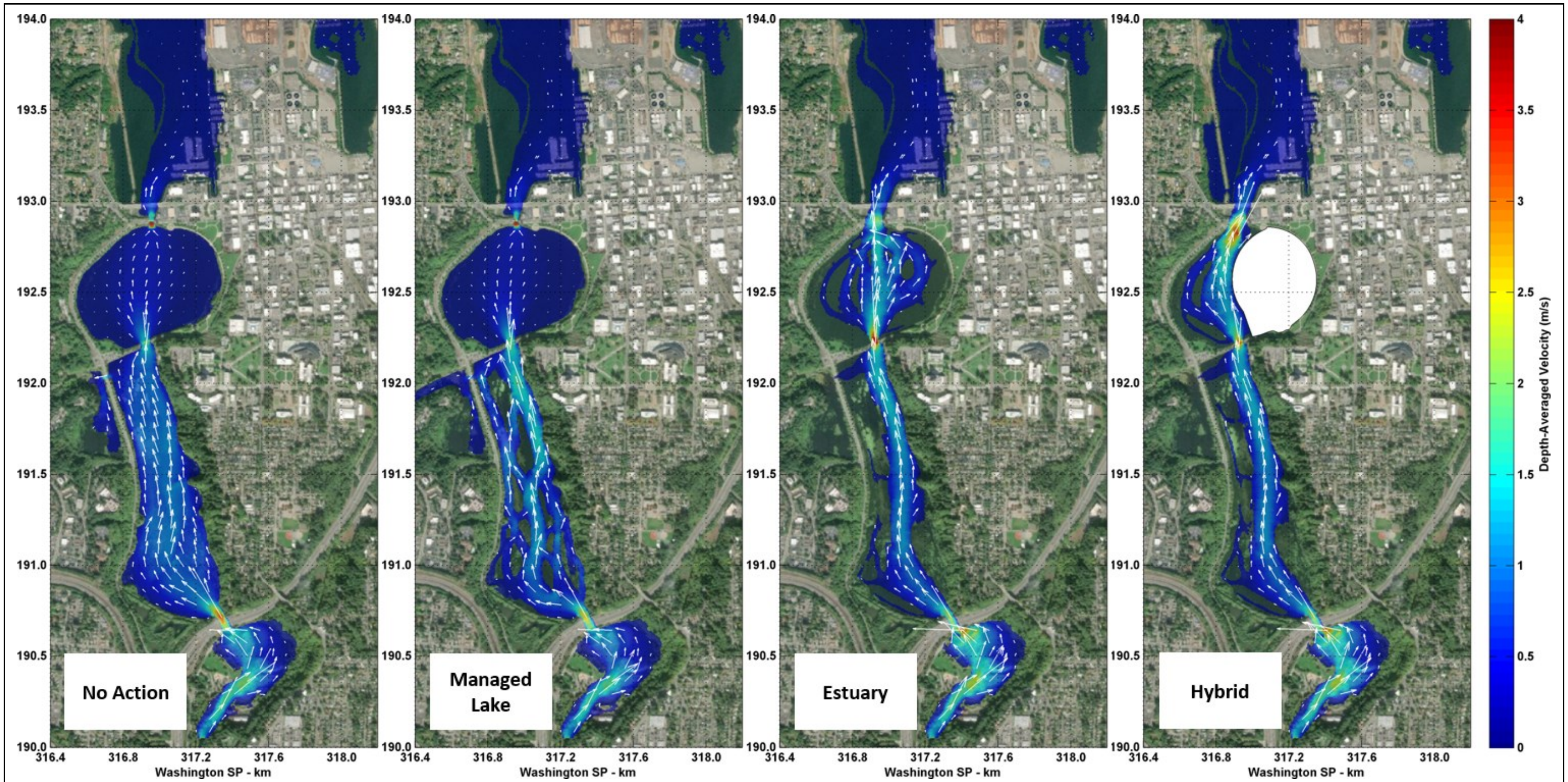
In general, for the Estuary and Hybrid Alternatives, the tidal connection with Budd Inlet would be immediately restored after removal of the 5th Avenue Dam. For these two alternatives, flood and ebb currents flow into and out of the Capitol Lake Basin without presence of an obstructing structure. However, for the No Action and Managed Lake Alternatives, current speeds within the Capitol Lake Basin are constrained by the gate operation and size of the gate opening.

4.6.2.1 Without RSLR

For Event #1, the maximum flow velocity occurs during ebb tide for all four alternatives, see Figure 4-49. For the No Action Alternative, current velocities are smaller than 0.5 m/s in most parts of the lake except at constrictions, including at the I-5 Bridge, BNSF Railroad Trestle Bridge, 5th Avenue Dam, and Deschutes River boundary. At the Deschutes River boundary, the maximum velocity is 1.5 m/s. Under the I-5 Bridge, Railroad Bridge, and 5th Avenue Dam, the maximum velocity reaches 2.5 m/s, 1.5 m/s, and >4m/s, respectively. Velocity under the Managed Lake Alternative is similar to the No Action Alternative except for some island interference in the Middle Basin.

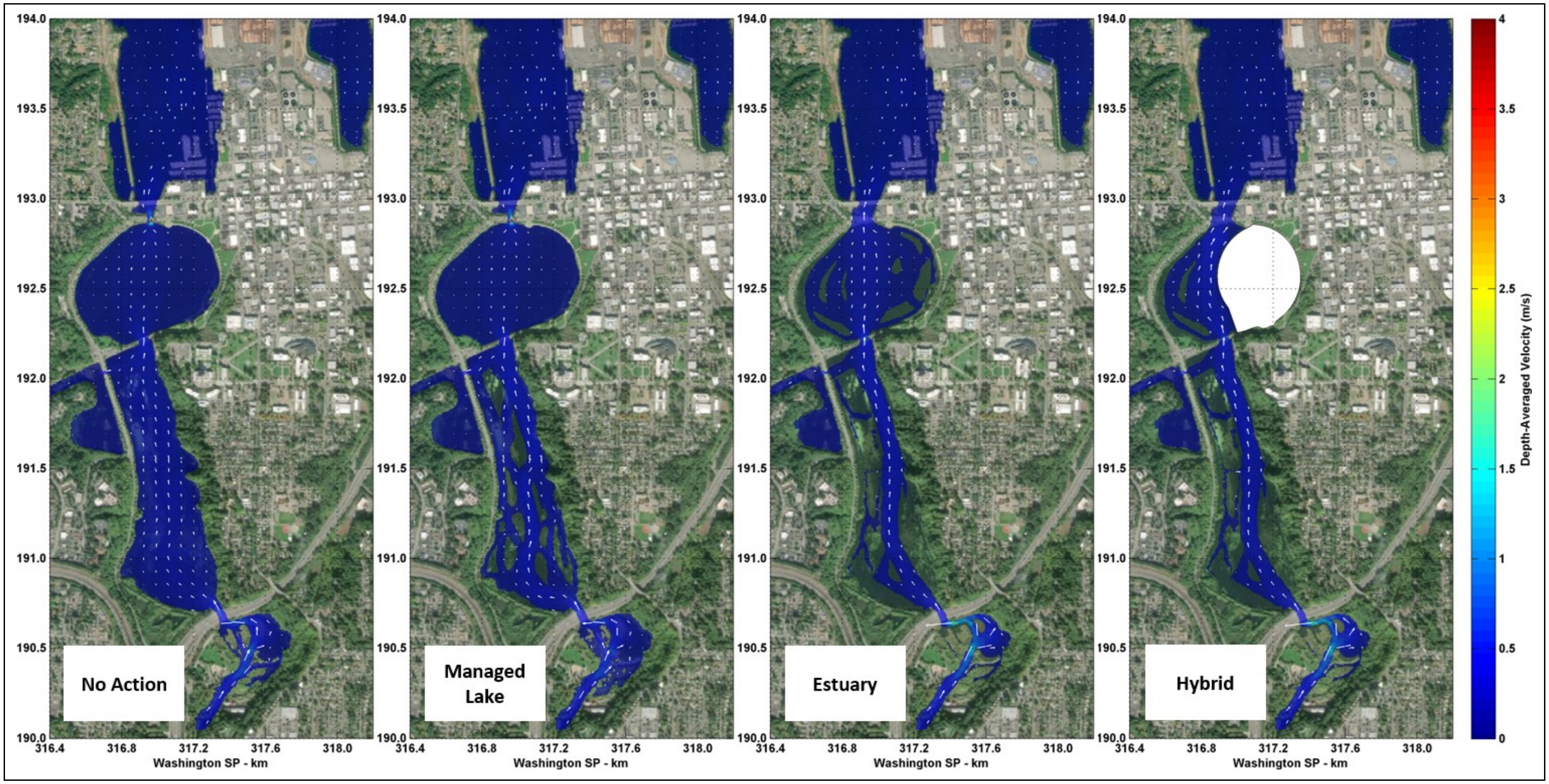
For Event #1, maximum flow velocities under the Estuary Alternative are higher than the No Action Alternative with high velocities at the dredged channel in the Middle and North Basins. The highest velocities occur at the I-5 Bridge, BNSF Railroad Trestle Bridge, 5th Avenue Dam, and Deschutes River boundary, but the high velocity areas are larger than the No Action Alternative. At the I-5 Bridge, BNSF Railroad Trestle Bridge, and 5th Avenue Dam, the maximum velocity reaches 2.3 m/s, 3.2 m/s, and >4m/s, respectively. Velocities under the Hybrid Alternative are similar to the Estuary Alternative; however, due to the new reflecting pool, flow is following the shape of the new reflecting pool in the North Basin and has a larger area at the Capitol Lake river mouth with high current speed.

Figure 4-49 Maximum Depth-Averaged Current Speed (m/s) for Event #1 Without RSLR



Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Figure 4-50 Maximum Depth-Averaged Current Speed (m/s) for Event #2 Without RSLR



Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Model results in terms of maximum flow velocities were extracted at the aforementioned observations points and are listed in Table 4-22 and Table 4-23 for Events #1 and #2, respectively.

For Event #1, for the No Action and Managed Lake Alternatives, the maximum current velocity in the domain can reach 3.15 m/s under the I-5 Bridge and 2.76 m/s at the 5th Avenue Dam, respectively. For the Estuary and Hybrid Alternatives, the maximum current velocity in the domain can reach 3.03 m/s and 2.88 m/s, respectively, under the BNSF Railroad Trestle. For all four alternatives, the smallest current velocity values occur on the banks of the Middle Basin.

For Event #2, flow velocities are generally smaller than current velocities for Event #1 for all four alternatives. Peak velocities occur under the BNSF Railroad Trestle and reach 0.51 m/s, 0.50 m/s, 1.63 m/s, and 1.48 m/s for the No Action, Managed Lake, Estuary, and Hybrid Alternatives, respectively.

Table 4-22 Maximum Depth-Averaged Velocity (m/s) for Event #1 without RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	1.63	1.59	1.67	1.67	-2%	2%	2%
SB02	0.68	0.68	0.69	0.66	0%	1%	-3%
SB03 (I-5 Bridge)	3.15	2.59	2.21	2.19	-18%	-30%	-30%
MB01	0.15	0.28	0.12	0.12	87%	-20%	-20%
MB02	0.43	0.17	0.12	0.12	-60%	-72%	-72%
MB03	0.39	0.60	0.16	0.16	54%	-59%	-59%
MB04	0.02	0.06	0.01	0.01	200%	-50%	-50%
MB05	0.74	1.11	0.75	0.73	50%	1%	-1%
PC01	0.86	0.80	0.75	0.70	-7%	-13%	-19%
PC02	1.03	0.75	0.98	0.89	-27%	-5%	-14%
NB01 (RR Bridge)	2.06	2.06	3.03	2.88	0%	47%	40%
NB02	0.88	0.72	1.10	1.35	-18%	25%	53%
NB03	0.08	0.02	0.04	N/A	-75%	-50%	N/A
NB04	0.29	0.02	0.02	0.07	-93%	-93%	-76%
NB05	0.19	0.17	1.06	N/A	-11%	458%	N/A
NB06 (gate)	2.39	2.76	1.36	0.22	15%	-43%	-91%
BI01	0.59	0.61	0.74	0.78	3%	25%	32%
BI02	0.62	0.64	0.89	1.22	3%	44%	97%
BI03	0.36	0.36	0.37	0.64	0%	3%	78%
BI04	0.76	0.76	0.77	0.94	0%	1%	24%
BI05	0.34	0.34	0.34	0.41	0%	0%	21%

Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

Table 4-23 Maximum Depth-Averaged Velocity (m/s) for Event #2 without RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	0.40	0.40	0.40	0.40	0%	0%	0%
SB02	0.42	0.42	0.54	0.53	0%	29%	26%
SB03 (I-5 Bridge)	0.82	0.78	0.66	0.64	-5%	-20%	-22%
MB01	0.00	0.00	0.00	0.00	0%	0%	0%
MB02	0.00	0.00	0.00	0.00	0%	0%	0%
MB03	0.00	0.00	0.06	0.08	0%	0%	0%
MB04	0.00	0.00	0.00	0.00	0%	0%	0%
MB05	0.31	0.51	0.35	0.32	65%	13%	3%
PC01	0.29	0.27	0.27	0.37	-7%	-7%	28%
PC02	0.44	0.56	1.15	1.08	27%	161%	145%
NB01 (RR Bridge)	0.51	0.50	1.63	1.48	-2%	220%	190%
NB02	0.16	0.13	0.40	0.60	-19%	150%	275%
NB03	0.03	0.09	0.13	N/A	200%	333%	N/A
NB04	0.02	0.01	0.08	0.07	-50%	300%	250%
NB05	0.09	0.08	0.42	N/A	-11%	367%	N/A
NB06 (gate)	0.57	0.65	0.79	0.24	14%	39%	-58%
BI01	0.18	0.20	0.68	0.47	11%	278%	161%
BI02	0.60	0.60	0.46	0.37	0%	-23%	-38%
BI03	0.41	0.41	0.26	0.26	0%	-37%	-37%
BI04	0.77	0.77	0.37	0.37	0%	-52%	-52%
BI05	0.35	0.35	0.17	0.17	0%	-51%	-51%

Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

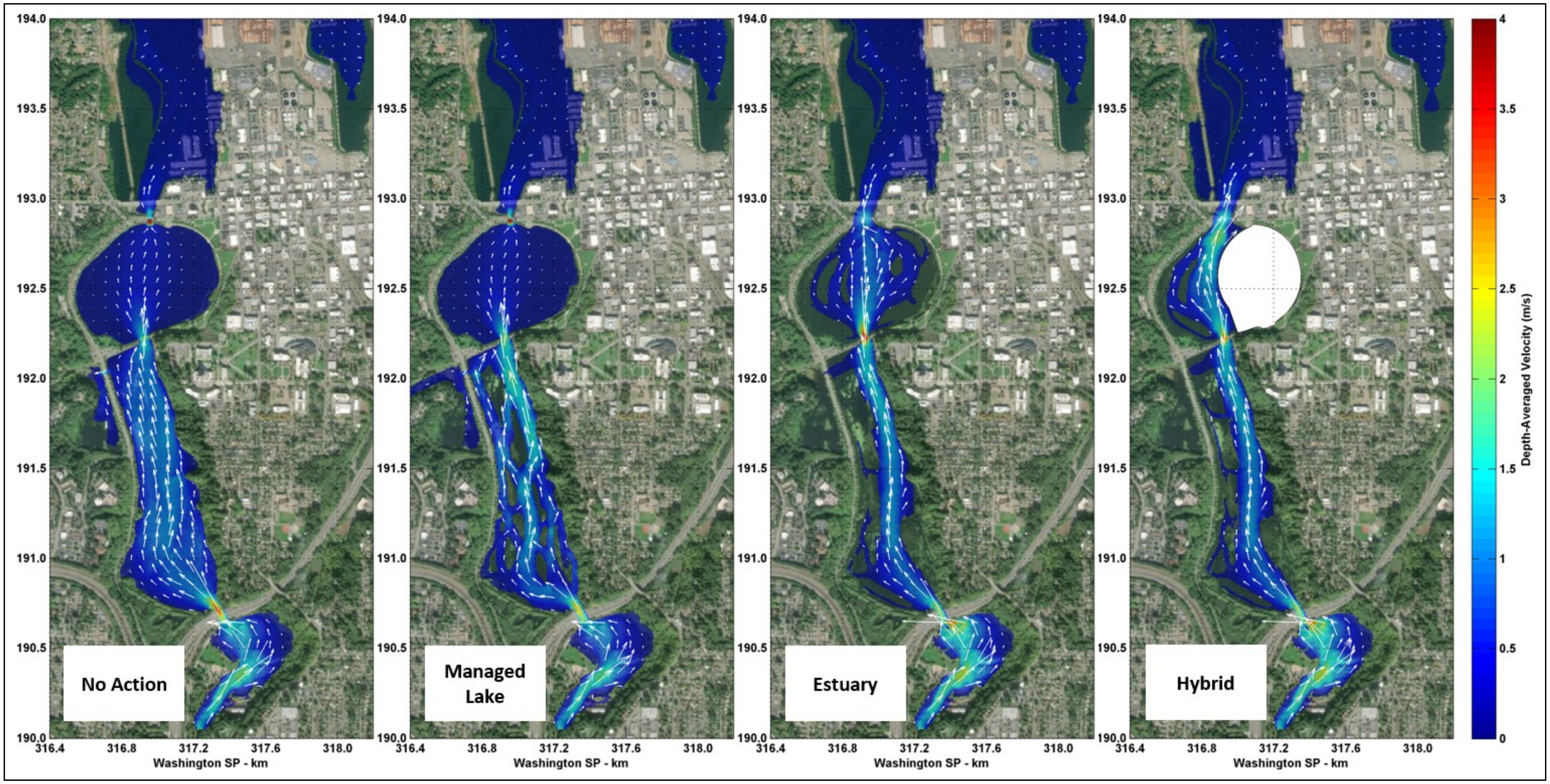
4.6.2.2 With RSLR (Includes 0.61 m of RSLR)

In Figure 4-51 with 0.61 m of RSLR, the maximum velocity distribution for the four alternatives are similar to the results without RSLR. Model results in terms of maximum current velocity at the observation points were extracted for Events #1 and #2 and are listed in Table 4-24 and Table 4-25, respectively.

For Event #1, for the No Action Alternative, the maximum current velocity in the domain can reach 3.16 m/s under the I-5 Bridge. For the Managed Lake Alternative, the maximum current velocity in the domain can reach 2.62 m/s at the 5th Avenue Dam. For the Estuary Alternative, the maximum current velocity in the domain can reach 2.82 m/s under the BNSF Railroad Trestle. For the Hybrid Alternative, the maximum current velocity in the domain can reach 2.63 m/s. For all four alternatives, the smallest values occur on the banks of the Middle Basin channel.

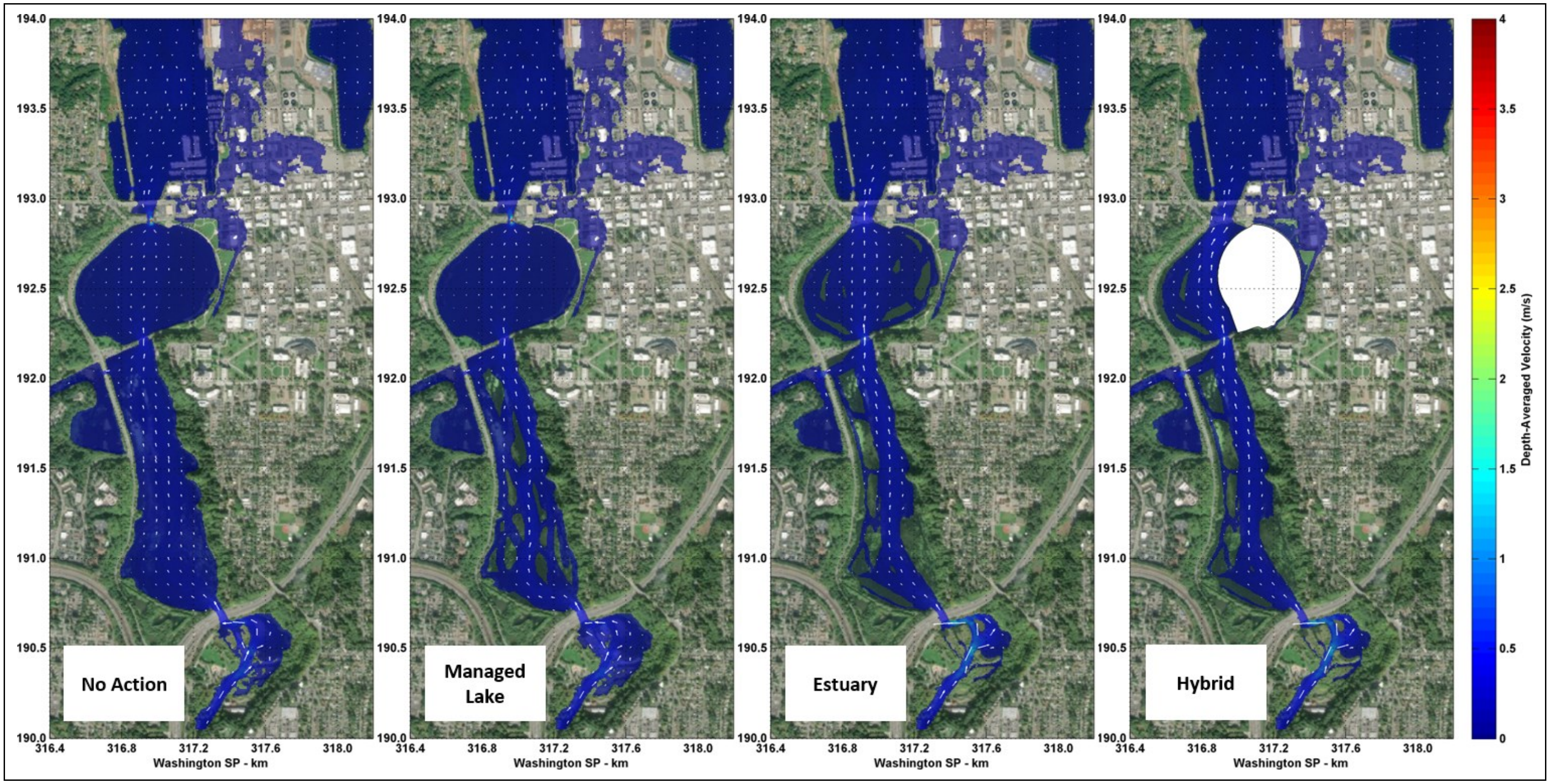
For Event #2, current velocities are generally smaller than current velocities for Event #1 for all four alternatives. For the No Action and Managed Lake Alternatives, peak velocities in the domain occur under the I-5 Bridge and reach 0.82 m/s and 0.79 m/s, respectively. For the Estuary and Hybrid Alternatives, peak velocities occur under the BNSF Railroad Trestle and reach 2.33 m/s and 2.16 m/s, respectively.

Figure 4-51 Maximum Depth-Averaged Current Speed (m/s) for Event #1 With 0.61 m of RSLR



Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Figure 4-52 Maximum Depth-Averaged Current Speed (m/s) for Event #2 With 0.61 m of RSLR



Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Table 4-24 Maximum Depth-Averaged Current Speed (m/s) for Event #1 with 0.61 m of RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	1.62	1.59	1.66	1.66	-2%	2%	2%
SB02	0.68	0.68	0.69	0.66	0%	1%	-3%
SB03 (I-5 Bridge)	3.16	2.57	2.19	2.17	-19%	-31%	-31%
MB01	0.17	0.17	0.17	0.17	0%	0%	0%
MB02	0.18	0.18	0.17	0.17	0%	-6%	-6%
MB03	0.36	0.57	0.17	0.17	58%	-53%	-53%
MB04	0.01	0.06	0.06	0.01	500%	500%	0%
MB05	0.74	1.12	0.73	0.72	51%	-1%	-3%
PC01	0.67	0.87	0.76	0.82	30%	13%	22%
PC02	1.01	0.73	0.99	0.87	-28%	-2%	-14%
NB01 (RR Bridge)	2.11	2.14	2.82	2.63	1%	34%	25%
NB02	0.92	0.76	0.97	1.25	-17%	5%	36%
NB03	0.07	0.04	0.10	N/A	-43%	43%	N/A
NB04	0.26	0.03	0.10	0.10	-88%	-62%	-62%
NB05	0.19	0.17	1.04	N/A	-11%	447%	N/A
NB06 (gate)	2.29	2.62	1.34	0.21	14%	-41%	-91%
BI01	0.60	0.60	0.66	0.75	0%	10%	25%
BI02	0.50	0.51	0.73	1.15	2%	46%	130%
BI03	0.31	0.31	0.31	0.61	0%	0%	97%
BI04	0.62	0.62	0.62	0.84	0%	0%	35%
BI05	0.27	0.27	0.27	0.35	0%	0%	30%

Event #1: A +100-yr Deschutes River flow combined with a 1-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

Table 4-25 Maximum Depth-Averaged Current Speed (m/s) for Event #2 with 0.61 m of RSLR

Observation Point	Model Results No Action	Model Results Managed Lake	Model Results Estuary	Model Results Hybrid	Change w.r.t No Action Managed Lake	Change w.r.t No Action Estuary	Change w.r.t No Action Hybrid
SB01	0.40	0.40	0.39	0.39	0%	-3%	-3%
SB02	0.42	0.41	0.52	0.52	-2%	24%	24%
SB03 (I-5 Bridge)	0.82	0.79	0.65	0.63	-4%	-21%	-23%
MB01	0.00	0.00	0.00	0.00	0%	0%	0%
MB02	0.00	0.00	0.00	0.00	0%	0%	0%
MB03	0.00	0.00	0.07	0.07	0%	0%	0%
MB04	0.00	0.00	0.01	0.01	0%	0%	0%
MB05	0.32	0.51	0.50	0.48	59%	56%	50%
PC01	0.25	0.43	0.44	0.26	72%	76%	4%
PC02	0.44	0.56	1.49	1.44	27%	239%	227%
NB01 (RR Bridge)	0.46	0.46	2.33	2.16	0%	407%	370%
NB02	0.14	0.12	0.53	0.69	-14%	279%	393%
NB03	0.03	0.09	0.13	N/A	200%	333%	N/A
NB04	0.02	0.03	0.04	0.11	50%	100%	450%
NB05	0.08	0.07	0.40	N/A	-13%	400%	N/A
NB06 (gate)	0.47	0.55	1.11	0.33	17%	136%	-30%
BI01	0.16	0.18	0.91	0.65	13%	469%	306%
BI02	0.49	0.49	0.62	0.52	0%	27%	6%
BI03	0.35	0.35	0.37	0.37	0%	6%	6%
BI04	0.63	0.63	0.53	0.53	0%	-16%	-16%
BI05	0.28	0.28	0.24	0.24	0%	-14%	-14%

Event #2: A 1-yr Deschutes River flow combined with a 100-yr tide

Observation Points: see Figure 4-46 for location of observation points

N/A: within reflecting pool

4.7 DISCUSSION

The hydrodynamic characteristics of the four alternatives were assessed for two extreme hydrologic events (Events #1 and #2) using the Delft3D software package.

In general, for the Estuary and Hybrid Alternatives, the tidal connection with Budd Inlet is immediately restored after removal of the 5th Avenue Dam and water levels within the basin are mostly controlled by tidal fluctuations in Budd Inlet. However, for the No Action and Managed Lake Alternatives, water levels within the Capitol Lake Basin are controlled by the gate operation. Main observations of this section can be summarized as follows:

- Dredging the North Basin has a small (<0.2 m) effect on maximum water levels elevations. Construction of habitat areas in the Middle Basin is likely reducing flood storage capacity and resulting in a small (<0.1 m) increase in peak water levels within the Middle and South Basins.
- For the Estuary and Hybrid Alternatives, the maximum water levels are dominated by tide levels and are approximately 0.6 m lower in Capitol Lake than those for the No Action and Managed Lake Alternatives for Event #1. However, for the extreme tides in Event #2, the maximum water levels are 1.4 m higher in the Capitol Lake Basin for the Estuary and Hybrid Alternatives than those for the No Action and Managed Lake Alternatives. A previous hydraulic study (M&N 2008) observed similar patterns for the system behavior but since their modeling event were different, the reached slightly different conclusions.

  M&N (2008) study concluded that the maximum water levels for the Estuary Alternative were approximately 0.5 feet higher than the No Action Alternative during a 100-yr event, but the 100-yr event was defined by a maximum tide level of 4.2 m, NAVD88 (13.9 ft, NAVD88), and a peak river inflow of 212 m^3/s. This 100-yr event has a similar tidal elevation to Event #2, while the inflow is between Event #1 (341 m^3/s) and Event #2 (50 m^3/s). This means that whether removal of the dam and construction of the Estuary or Hybrid Alternatives will result in increased or decreased maximum water levels (peak flood elevations) depends on which extreme event occurs in the future. With a more extreme tidal level event, the maximum water levels will be higher for the Estuary and Hybrid Alternatives than the No Action and Managed Lake Alternatives. With a more extreme river inflow, the results will be reversed.
- The Estuary and Hybrid Alternatives can result in maximum flow velocities exceeding 3.0 and 2.8 m/s at the Railroad Bridge, respectively. These estimated velocities correspond to 48% and 40% increases in maximum velocity for the Estuary and Hybrid Alternatives, compared to the No Action Alternative. The stability of the shoreline and bridge foundations against scour at the Railroad Bridge should be evaluated if either alternative is further advanced to the design phase.

4.8 CONCLUSIONS

Main conclusions of the hydrodynamic simulations are as follows. Model results in terms of peak water level and maximum velocities are summarized in Table 4-26.

- Model results for the Managed Lake Alternative differ from the No Action Alternative in terms of small (<0.2 m) changes in maximum water levels, and a < 0.6 m/s change in maximum depth-averaged velocity, but they show an approximately equal extent of upland flooding.

- Under the No Action and Managed Lake Alternatives, maximum flow velocities at the 5th Avenue Dam/Gate are higher than that for the Estuary and Hybrid Alternatives. The higher velocity at the gate is because of the small opening to Budd Inlet. Under the Estuary and Hybrid Alternatives, the opening to Budd Inlet is widened/deepened resulting in reduced flow velocities at the 5th Avenue Dam.
- The Estuary Alternative, compared to the No Action and Managed Lake Alternatives, increases flow velocities within the Capitol Lake Basin because under this alternative, with removal of the 5th Avenue Dam, the fast-moving river flow will not be controlled (slowed down) by the 5th Avenue Dam. This is shown in the extracted maximum flow velocities at the RR Bridge listed in Table 4-26.
- The Hybrid Alternative is slightly different from the Estuary Alternative in terms of maximum water level and depth-averaged velocities.
- Numerical simulations of the four alternatives were conducted with 0.61 m (2 ft) of RSLR. Model results showed that the general observations and findings are similar with and without 0.61 m of RSLR. However, the erosion/deposition rates are lower with RSLR compared to without. This is likely due to the higher water levels associated with RSLR resulting in reduced current velocities and reduced erosion of sediments in the Middle Basin. Reduced erosion of sediments in the Middle Basin will consequently result in reduced deposition within Budd Inlet.

Table 4-26: Summary of Hydrodynamic Model Results for Four Alternatives Without and With 0.61 m of RSLR

		No Action: Without RSLR	No Action: With RSLR	Managed Lake: Without RSLR	Managed Lake: With RSLR	Estuary: Without RSLR	Estuary: With RSLR	Hybrid: Without RSLR	Hybrid: With RSLR
Maximum Water Level (m, NAVD88)	Event 1	+6.1	+6.4	+6.3	+6.5	+5.7	+5.9	+5.7	+6.0
	Event 2	+4.4	+5.0	+4.4	+5.0	+4.5	+5.1	+4.6	+5.1
Maximum Depth-Averaged Velocity (m/s)	Event 1								
	I-5 Bridge	3.2	3.2	2.6	2.6	3.5	3.4	3.4	3.4
	RR Bridge	2.1	2.1	2.1	2.1	3.0	2.8	2.9	2.6
	5th Avenue Dam/Opening	2.4	2.3	2.8	2.6	2.2	1.7	3.3	2.1
	Event 2								
	I-5 Bridge	0.8	0.8	0.8	0.8	1.8	1.3	1.8	1.3
	RR Bridge	0.5	0.5	0.5	0.5	1.6	2.3	1.5	2.2
	5th Avenue Dam/Opening	0.6	0.5	0.7	0.6	05	0.5	0.5	0.4

Event #1 (high flow): A +100-yr Deschutes River flow combined with a 1-yr tide

Event #2 (high tide): A 1-yr Deschutes River flow combined with a 100-yr tide

4.8.1 Modeling Assumptions and Limitations

There are inherent limitations to any numerical simulation of physical processes. These limitations should be kept in mind when interpreting model results. Some of the limitations and assumptions for this study are as follows:

- For No Action and Managed Lake Alternatives, water levels and upland flooding is controlled by the gate operation at the 5th Avenue Dam. Currently, gate openings and water levels are manually managed during storm events, as described in Section 2.14. Model results for No Action and Managed Lake Alternatives assume that there are no mechanical failures (such as the gates being jammed open or shut), human errors, or similar adverse events during storms.
- The model results for Estuary and Hybrid Alternatives predict conditions in an environmental setting (without presence of the 5th Avenue Dam) that does not currently exist. There are no measurements of water level and current velocity to represent these alternatives and to be used for model calibration/validation. Model calibration/validation for this study used sensitivity testing to quantify uncertainties in model prediction.
- Hydrodynamic simulations presented herein did no capture subgrid elements (e.g. storm drains and other smaller scale infrastructure), which may affect the extent and depth of localized upland flooding.
- Hydrodynamic evaluation of the four alternatives was conducted for an extreme hydrologic event (100-yr flow event). For the hydrodynamic simulations, as a conservative measure, a constant discharge during the simulation period was used and not an actual hydrograph.
- Estuary bed levels are expected to change immediately after removal of the dam. For Estuary and Hybrid Alternatives, hydrodynamic simulations were conducted using the initially designed bed levels, which may be different from actual bed levels after the system reaches a dynamic equilibrium.
- Simulations with a 0.61 m (2.0-foot) increase in RSLR were conducted to represent a future rise in sea level. Extent of upland flooding with RSLR were evaluated assuming no modifications would be made to the infrastructure around Capitol Lake, including seawall structures and armored slopes. Through a separate initiative, the City, LOTT and Port of Olympia have developed a SLR Response Plan (and have identified physical and operational adaptation strategies to implement; some of which are within the project area (AECOM 2019).

5.0 Sediment Transport Modeling

This section describes the development, calibration/validation, and results of the sediment transport numerical modeling for the Capitol Lake – Lower Deschutes Estuary.

5.1 MODEL DESCRIPTION

The sediment transport model was developed based on the calibrated Delft3D hydrodynamic model described in Section 3.0. Delft3D is a process-based model that is widely used worldwide for simulation of sediment transport and morphological change in estuarine systems. This modeling effort builds on the previous studies by USGS (George et al. 2006; Stevens et al. 2008) using Delft3D based on a similar approach.

To capture density-driven estuarine circulation and enhanced flocculation associated with salinity gradients, the 3D configuration of the model was used, and freshwater/saltwater mixing was incorporated. Operating the model in 3D configuration with salinity significantly increases the computational run times for each simulation compared to the 2D (depth-averaged) configuration. To have practical computational run times for multi-year sediment transport simulations with multiple sediment classes, sensitivity testing was conducted using 2D vs 3D configurations to characterize the potential influence of stratification caused by the interaction of freshwater and saltwater on sediment erosion/deposition.

5.2 MODEL DEVELOPMENT

5.2.1 Model Grid

The model grid used in the sediment transport model is the same as the grid used for the hydrodynamic model described in Section 4.2.2.

5.2.2 Sediment Data and Model Parameters

A summary of available Capitol Lake sediment data and characteristics was provided in Section 2.8. In general, the Capitol Lake Basin is characterized by silt-sized sediments with coarser sediments (mostly sand and limited gravel) in areas that frequently experience higher velocities (in the main channel as well as areas under the I-5 Bridge and the BNSF Railroad Trestle).

In this study, two sediment classes of mud[3] and sand were used for simulations. Clay and silt were merged as one fraction of mud to represent the cohesive sediment. Gravel was excluded because previous USGS modeling studies showed that gravel was not as mobile as mud and sand (George et al. 2006 and Stevens et al. 2008). Sensitivity testing was conducted to evaluate the potential influence of using three classes (clay, silt, and sand) on erosion/deposition results. Model parameters for sediment properties were selected based on previous USGS studies (George et al. 2006 and Stevens et al. 2008) as a starting point and then were modified during the calibration process.

For non-cohesive-sediment (sand) transport, the Van Rijn (1993) formulation implemented in Delft3D was used. This formulation separates the calculation of bed load and suspended load transports and can include the effect of waves. Suspended sediment transport is computed by the advection-diffusion solver, while bed load is calculated by using a nonlinear empirical relationship, see Van Rijn (1993) for transport formulations. Dry sediment density and median grain size are the most influential parameters on sediment erosion/deposition for this sediment class. The values for these parameters were selected based on previous USGS studies as a starting point and then were modified during the calibration/validation process. Model parameter values used herein as well as values recommended in the Delft3D manual and those used by previous USGS studies are listed in Table 5-1.

For cohesive sediments (mud class), the Partheniades-Krone formulation (Partheniades 1965) implemented in Delft3D was used. Model parameter values used herein as well as values recommended in the Delft3D manual and those used by previous USGS studies are listed in Table 5-2. Critical shear stresses for erosion and sediment settling velocity are the most influential parameters on sediment erosion and deposition, respectively, for this sediment class. These parameters were selected based on previous USGS studies as a starting point and then were modified during the calibration/validation process. Dry density for mud was the same as that used for previous USGS studies. A sensitivity analysis for other parameters was performed to select the rest of model parameters.

[3] 'Mud' is a mixture of water and some combination of soil, silt, and clay. However, 'mud' is used herein as a general term to refer to river-borne silt and clay-sized sediments.

Table 5-1 Model Parameters for Van Rijn (1993) Formulation for Non-Cohesive Sediment Transport

Parameter	Default Value in Delft3D	USGS Studies	This Study
Dry sediment density (kg/m³)	500 - 3000	1600	1600
Median grain size (µm)	64 - 2000	200	100
Van Rijn's reference height factor (-)	1	1	1
Current related roughness height (m)	0.01	0.01	0.01
Wave related roughness height (m)	0.02	0.02	0.02
Wave related roughness factor (-)	2	2	2
Streamwise bed gradient factor for bed load transport (-)	1	1	1
Transverse bed gradient factor for bed load transport (-)	1.5	1.5	1.5
Wave-related suspended sed. transport factor (-)	1	1	1
Wave-related bed load sed. transport factor (-)	1	1	1

Table 5-2 Model Parameters for Partheniades (1965)-Krone Formulation for Cohesive Sediment Transport

Parameter	Default Value In Delft3D	USGS Studies	This Study
Dry sediment density (kg/m³)	500	316 - 594	455
Erosion parameter (kg/m²/s)	0.0001	0.001 – 0.0147	0.004
Critical shear stress for sedimentation (N/m²)	1000	1000	1000
Critical shear stress for erosion (N/m²)	0.5	0.18 – 0.78	0.7
Settling velocity (mm/s)	0.25	0.032 (clay) - 0.76 (silt)	0.2

5.2.3 Initial Bed Thickness

Available data regarding the spatial and vertical composition of sediments within the Capitol Lake Basin indicates significant variability and lack of a general pattern, see Section 2.10. The previous USGS studies assumed that bottom sediments in Capitol Lake Basin were composed of approximately 60%-70% mud, and 30%-40% sand (George et al. 2006). The initial bed thickness for calibration/ validation runs was developed consistent with previous USGS studies, as shown in Figure 5-1. In Budd Inlet, the initial total sediment thickness was 0.0 m, to serve as a baseline to easily identify sediment deposition (a conservative approach that would not capture erosion in Budd Inlet). In the Capitol Lake Basin the initial total sediment thickness was 2.0 m with 1.3 m of mud and 0.7 m of sand in most areas except in some portions of the channel where the mud thickness was 0.2 m and the sand thickness was 1.8 m.

For the production runs (presented in Section 5.9), the initial total sediment thickness and the ratio between mud and sand fractions were similar to the calibration/validation runs with an increased magnitude to provide adequate sediment on the bottom after removal of the 5th Avenue Dam. In Budd Inlet, the initial total sediment thickness was 0.0 m, to serve as a baseline to easily identify sediment deposition (a conservative approach that would not capture erosion in Budd Inlet). In Capitol Lake Basin, the initial total sediment thickness was 10 m with 6.5 m of mud and 3.5 m of sand in most areas except in some portions of the channel where the mud thickness was 1.0 m and the sand thickness was 9.0 m, as shown in Figure 5-2. Additionally, a transition zone for the sediment thickness was incorporated between the South Basin and Middle Basin, and between the North Basin and Budd Inlet to avoid abrupt changes in sediment thickness and potential numerical instabilities.

Figure 5-1 Initial Bed Thickness (m) for (a) Mud and (b) Sand for Calibration/Validation Run

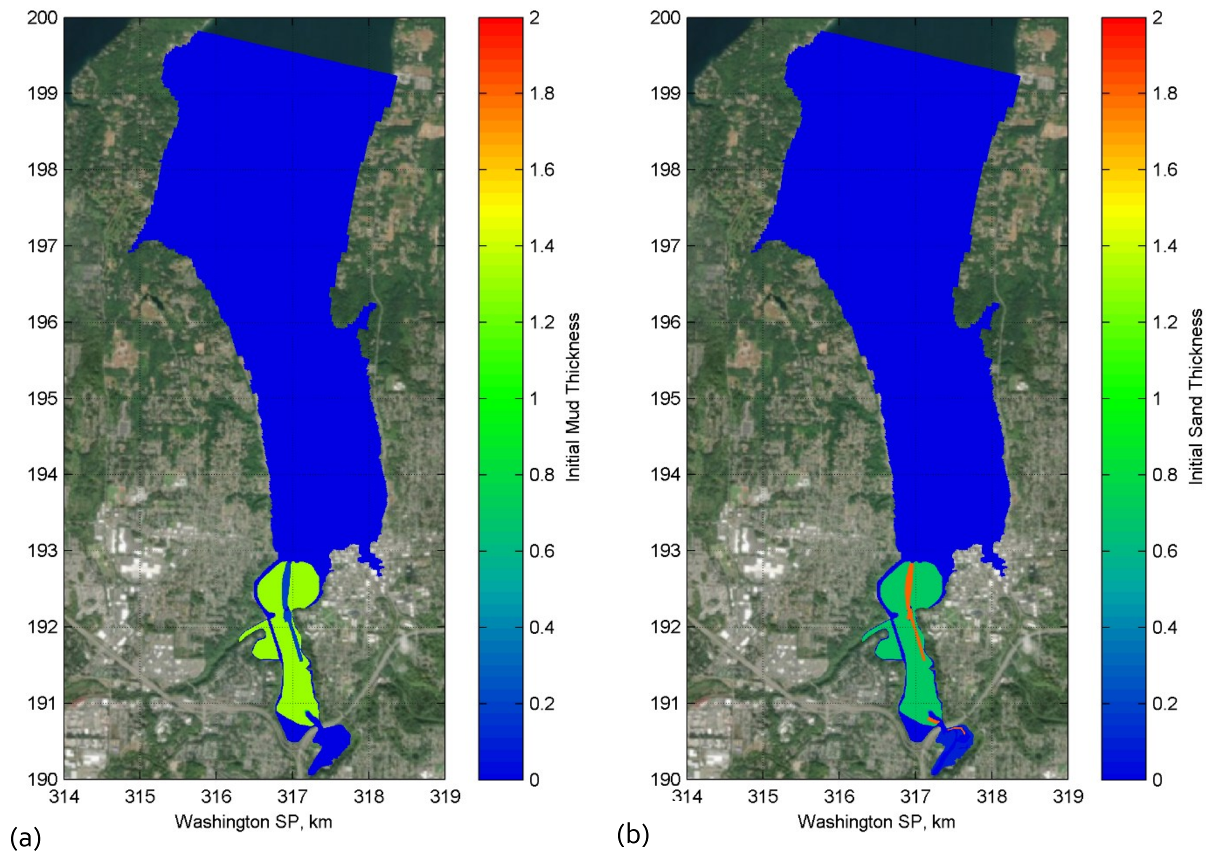
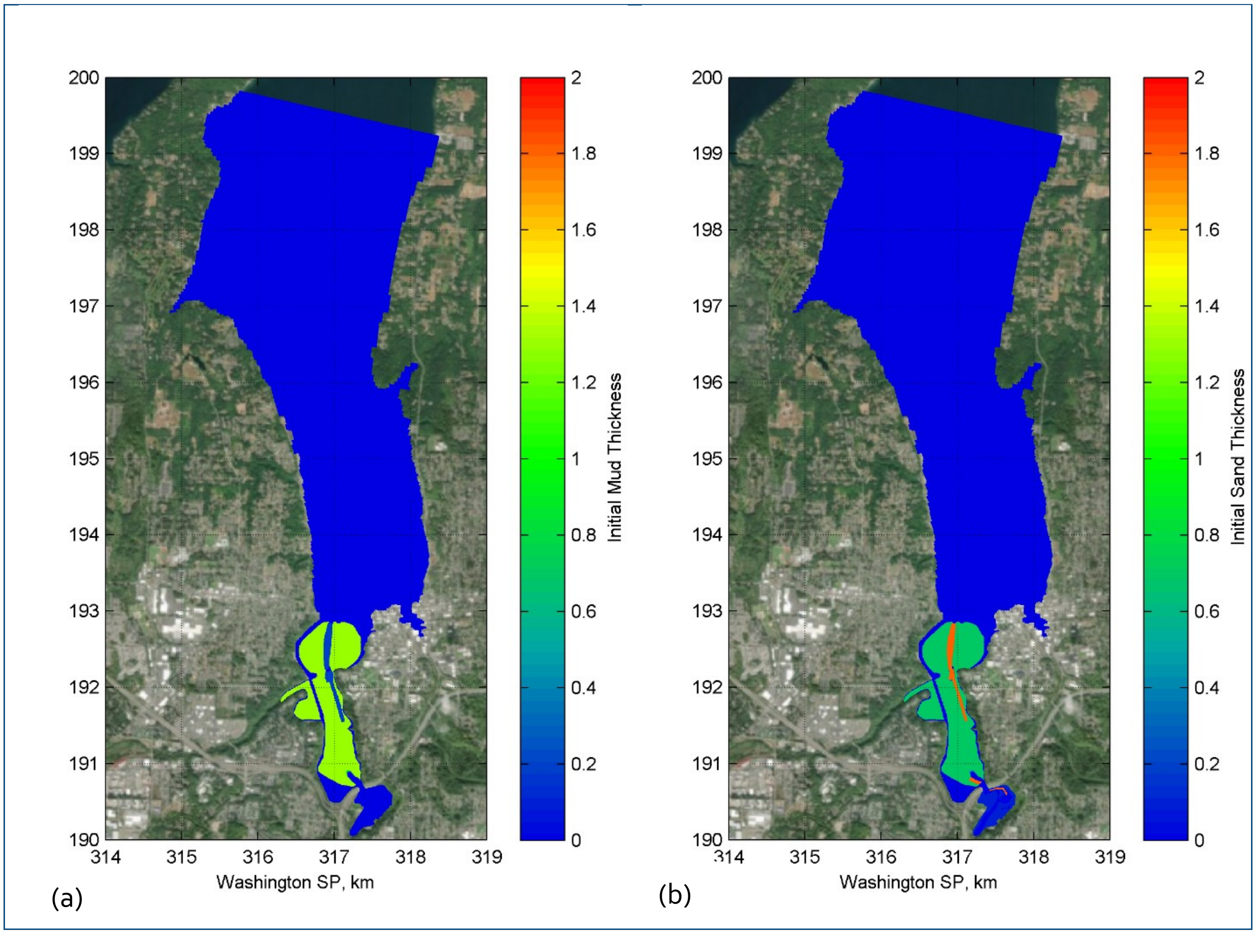


Figure 5-2 Initial Bed Thickness (m) for (a) Mud and (b) Sand for Productions Run



5.3 MODELING APPROACH

Long-term (multi-year) simulations of sediment transport and morphological changes within estuaries require significant computational effort. These simulations commonly rely on parallel computation and use of a morphological acceleration factor (MORFAC) for keeping the computational run times reasonable. Use of MORFAC assumes a linear relationship between hydrodynamics and sediment erosion/deposition within the estuary.

Hydrodynamic and morphologic behavior of the No Action and Managed Lake Alternatives is heavily influenced by the non-linear gate operation and inhibits use of MORFAC. Additionally, the complex gate operation can best be represented in the Delft3D model using the RTC feature, which could not be implemented for parallel computations at the time that this study started.

Because of the constraints associated with simulation of the gate operation (inability to use MORFAC because of non-linear gate operation and inability to use RTC within parallel computations), two different approaches were selected to simulate alternatives with and without the 5th Avenue Dam. For the calibration/validation run, as well as the No Action and Managed Lake Alternatives, a lookup table approach was used. For the Estuary and Hybrid Alternatives where the 5th Avenue Dam would be removed, a MORFAC approach was used. These two approaches are described in the following sections.

5.3.1 MORFAC Approach

The most common approach for long-term morphologic modeling is application of a MORFAC. Use of MORFAC involves acceleration of morphological changes during hydrodynamic simulations. The MORFAC applies a scalar multiplier to the sediment continuity equation and is often applied in morphodynamic simulations to reduce computational time.

The MORFAC approach allows speeding up the morphological simulation when hydrodynamic conditions do not change significantly over an extended period of time. Therefore, instead of running the same hydrodynamic conditions for that extended period of time, the hydrodynamic conditions are simulated for a shorter duration, but morphological changes are accelerated to represent the entire duration of that extended period.

5.3.2 Lookup Table Approach

For the model calibration/validation process and simulation of the No Action and the Managed Lake Alternatives where the 5th Avenue Dam was modeled, a modeling methodology based on the application of lookup tables of river discharges versus erosion/deposition rates was implemented to simulate the long-term morphological changes with a real-time hydrograph (daily discharge). This approach was previously used in a similar study for the Mississippi River morphological evolution near a borrow site (M&N 2011). The lookup approach and the morphological modeling study were reviewed and approved by USACE representatives before the (M&N 2011) study report was issued. The lookup tables were constructed based on a group of quasi steady state simulations for progressive bathymetry conditions, from which expected erosion/deposition rates for various inflow conditions were derived. The lookup tables were recalculated when morphological changes were deemed significant compared to the previous bathymetry state.

To build the initial lookup table, Delft3D simulations of the quasi steady state runs were carried out using the initial bathymetry. From the model results, a lookup table of erosion/deposition rates was created. The lookup table then was used to estimate the erosion/deposition in each cell of the model domain for any given river discharge by interpolation.

After constructing the initial lookup table, it was used to estimate the erosion/deposition in each cell of the model domain for any given river discharge by interpolation. The vertical changes in bed elevation were computed offline by integrating the computed erosion/deposition rates over time. The offline computation was performed in the MATLAB software package. The total changes in bed elevation were checked for every grid cell after each incremental change, and if they were significant (for example, if they exceeded preset thresholds), then a new lookup table of erosion/deposition rates was constructed at that time step.

In this study, a percent of the total water depth was applied as the threshold. A threshold value of 10% was used, meaning that if changes to the bathymetry exceeded 10% of the water depth, a new lookup table would be initiated. For shallow areas, the 10% difference in water depth can be a small value and to prevent frequent lookup table rebuilds, a minimum 0.5 m threshold was used. Below this value, the lookup table update was not triggered. Similarly, in deep areas when changes to bathymetry exceed 3.0 m, the lookup table was rebuilt regardless of the percentage. The 3.0 m value is relatively large and, therefore, was never triggered.

Based on these settings, the model would re-run under two conditions: (a) when the bathymetry change exceeded 10% of total water depth provided the absolute value of bathymetry change was larger than 0.5 m, or (b) when the absolute value of bathymetry change was larger than 3.0 m regardless of the percentage change. The final threshold values were selected by trying different combinations of threshold values after model parameters were calibrated. Comparisons of erosion/deposition results using those threshold values are discussed in Section 5.6.3.

Morphological updates also track the amount of available sediments on the bottom and would not erode the non-erodible layer where no sediments are available on the bottom. Similarly, to prevent unrealistic deposition (e.g., deposition above the channel bank level), the maximum deposition level can be imposed. However, these two limiting conditions affect the balance between deposited and eroded sediment quantities because there is no feedback between cells with erosion and cells with deposition to limit the cells' deposition even if the erosion cells already reached the non-erodible layer or vice versa. Therefore, updating the lookup table after significant morphological changes is required to correct the sediment availability at the bottom as well as the bathymetry changes.

The lookup table approach uses interpolation to approximate sediment erosion/deposition rates for the intermediate discharge conditions, while the MORFAC approach would be limited to the preselected discharge states for which probabilities of occurrence are computed. Therefore, the lookup table approach is suitable for simulation of real hydrographs. The estimated erosion/deposition rates are then integrated over time. This was done under the assumption that the erosion/deposition rates do not change significantly with small morphological changes. If morphological changes are significant, the lookup tables are updated for the new bathymetric conditions.

The lookup table approach for the No Action and Managed Lake Alternatives is advantageous over the MORFAC approach because it supports having a more realistic representation of the gate operation's effects during morphological computations as both hydrodynamic and morphological simulations are performed at the same time scale. However, the disadvantage of the lookup table over MORFAC approach is that the lookup table approach does not preserve mass conservation.

5.4 BOUNDARY CONDITIONS

The three open boundaries in the model (two upstream boundaries at the Deschutes River and Percival Creek, and the offshore boundary in Budd Inlet) were the same as the hydrodynamic model. However, the sediment transport model simulated a significantly longer time period than the hydrodynamic model (years compared to weeks) and focused on the long-term effects. Therefore, the boundary conditions in the sediment transport model were different from the hydrodynamic model and were based on the modeling approaches described in Section 5.3.

5.4.1 Upstream Boundary

5.4.1.1 River Inflow

The time series of daily discharge in the Deschutes River at the E Street Bridge in Tumwater, WA (USGS Stream Gage 12080010) is shown in Figure 5-3 for 1990 to 2020. Peak annual daily discharge varies from 50 m3/s to 250 m3/s.

For the calibration process, 12 steady state (constant discharge) runs from 2.5 m^3/s to 250 m^3/s at the Deschutes River boundary were developed to represent the range of discharges. These representative discharge values are listed in Table 5-3. Inflow at the Percival Creek boundary was calculated by multiplying the discharge from the Deschutes River using the scaling factors discussed in Section 2.5 and listed in Table 5-3 as well.

Figure 5-3 Daily River Discharge at USGS Stream Gage 12080010) with Extreme Discharges

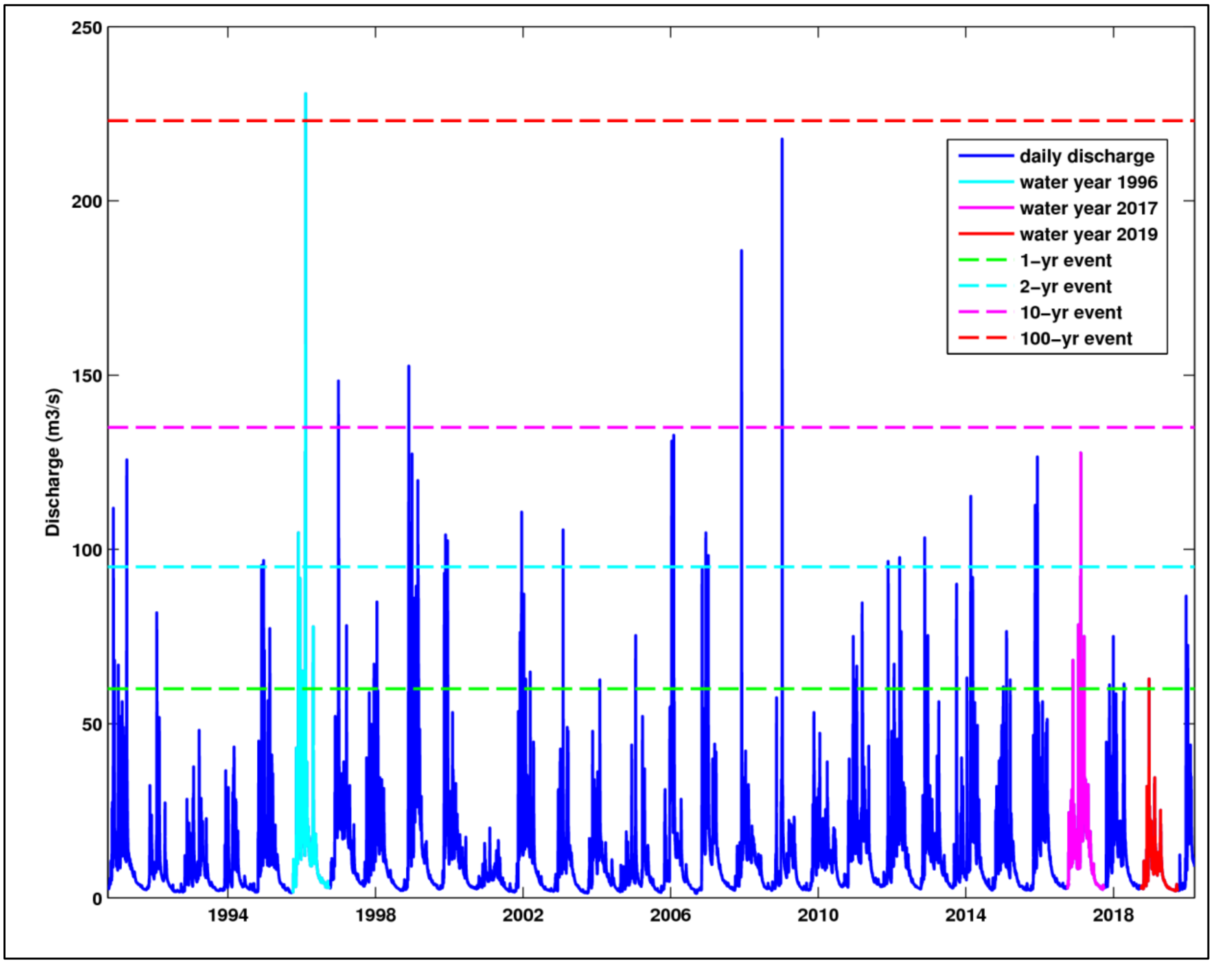


Table 5-3 Representative Steady State Daily Discharges

Run No.	Daily Discharge at Deschutes River (m³/s)	Daily Discharge at Percival Creek (m³/s)
1	2.5	0.2
2	7.5	0.8
3	15	1.8
4	25	2.6
5	50	4.3
6	75	5.6
7	100	7.1
8	125	8.6
9	150	9.9

Run No.	Daily Discharge at Deschutes River (m³/s)	Daily Discharge at Percival Creek (m³/s)
10	175	11.0
11	200	12.0
12	250	13.6

For the No Action and the Managed Lake Alternatives, the same approach was implemented as the calibration process with 12 steady state (constant discharge) runs from 2.5 m3/s to 250 m3/s at the Deschutes River boundary and scaled constant discharge at the Percival Creek boundary (Table 5-3).

For the Estuary and Hybrid Alternatives, the discretized daily discharge time series with MORFAC was used (see Section 5.8).

5.4.1.2 Sediment Load

There are inherent uncertainties associated with any sediment rating curve because rating curves are developed based on limited field measurements. The model calibration/validation attempted to refine the sediment input based on available survey data.

Sediment concentrations at the Deschutes River and Percival Creek boundaries were first calculated based on the lower bound of the rating curve and were adjusted to match the sedimentation volume in the Capitol Lake during the calibration process.

Table 5-4 and Table 5-5 list the final sediment concentration applied at the upstream boundaries for each steady state flow condition. The annual sediment loads were computed using the real hydrograph and multiplied by the concentration. Sensitivity testing showed that inclusion of sand at the Percival Creek boundary resulted in high deposition rates within Percival Cove that did not agree with rates obtained from the survey comparison. This is most likely due to the low flow velocity of Percival Creek.

Table 5-4 Sediment Concentrations at Deschutes River Boundary

Case	Discharge at Deschutes River (m³/s)	Mud C (mg/L)	Sand C (mg/L)
1	2.5	0.2	0.1
2	7.5	1.6	0.8
3	15	6.2	3.1
4	25	16.7	8.4
5	50	63.6	32.1
6	75	139.2	70.2
7	100	242.5	122.2
8	125	373	188.1
9	150	530.3	267.4

Case	Discharge at Deschutes River (m^3/s)	Mud C (mg/L)	Sand C (mg/L)
10	175	714	360.0
11	200	923.9	465.8
12	250	1421.2	716.6

Table 5-5 Sediment Concentrations at Percival Creek Boundary

Case	Discharge at Percival Creek (m^3/s)	Mud C (mg/L)	Sand C (mg/L)
1	0.2	0.0	0
2	0.8	0.4	0
3	1.8	2.1	0
4	2.6	4.6	0
5	4.3	13.1	0
6	5.6	22.2	0
7	7.1	37.4	0
8	8.6	54.8	0
9	9.9	73.5	0
10	11.0	92.5	0
11	12.0	111.1	0
12	13.6	143.8	0

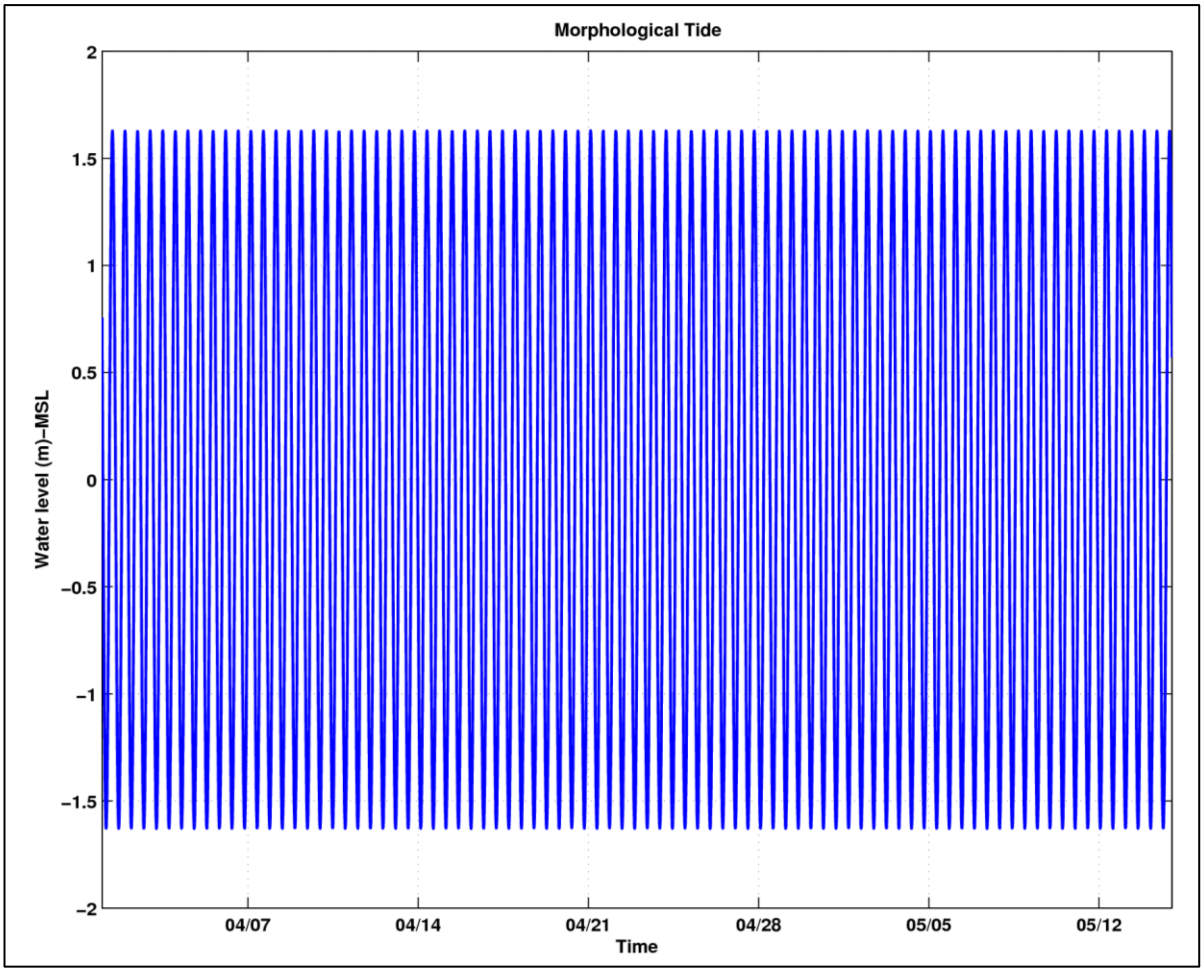
5.4.1.3 Salinity

Salinity at the Deschutes River boundary and Percival Cove boundary was set to zero based on the previous USGS study (George et al. 2006).

5.4.2 Offshore Boundary

Since each quasi steady state condition was modeled for a period of 12 hours and model results are representative of a longer period, appropriate tidal conditions in Budd Inlet were needed. Therefore, instead of forcing the model with the real tide, a harmonic "morphological tide" was applied at the offshore boundary for tidal forcing, which represents a simple sinusoidal variation. M2, the amplitude of the largest component, multiplied by 1.1, generated the morphological tide boundary condition, and this morphological tide boundary condition was applied to both the calibration runs and production runs. This offshore boundary condition was the same as that used by the previous USGS studies (George et al. 2006; Stevens et al. 2008). An example of the morphological tide is shown in Figure 5-4. Sediment concentrations at the offshore boundary were set to zero, and salinity was set to 28 ppt (George et al. 2006).

Figure 5-4 Morphological Tide for Long-Term Sedimentation Transport Model

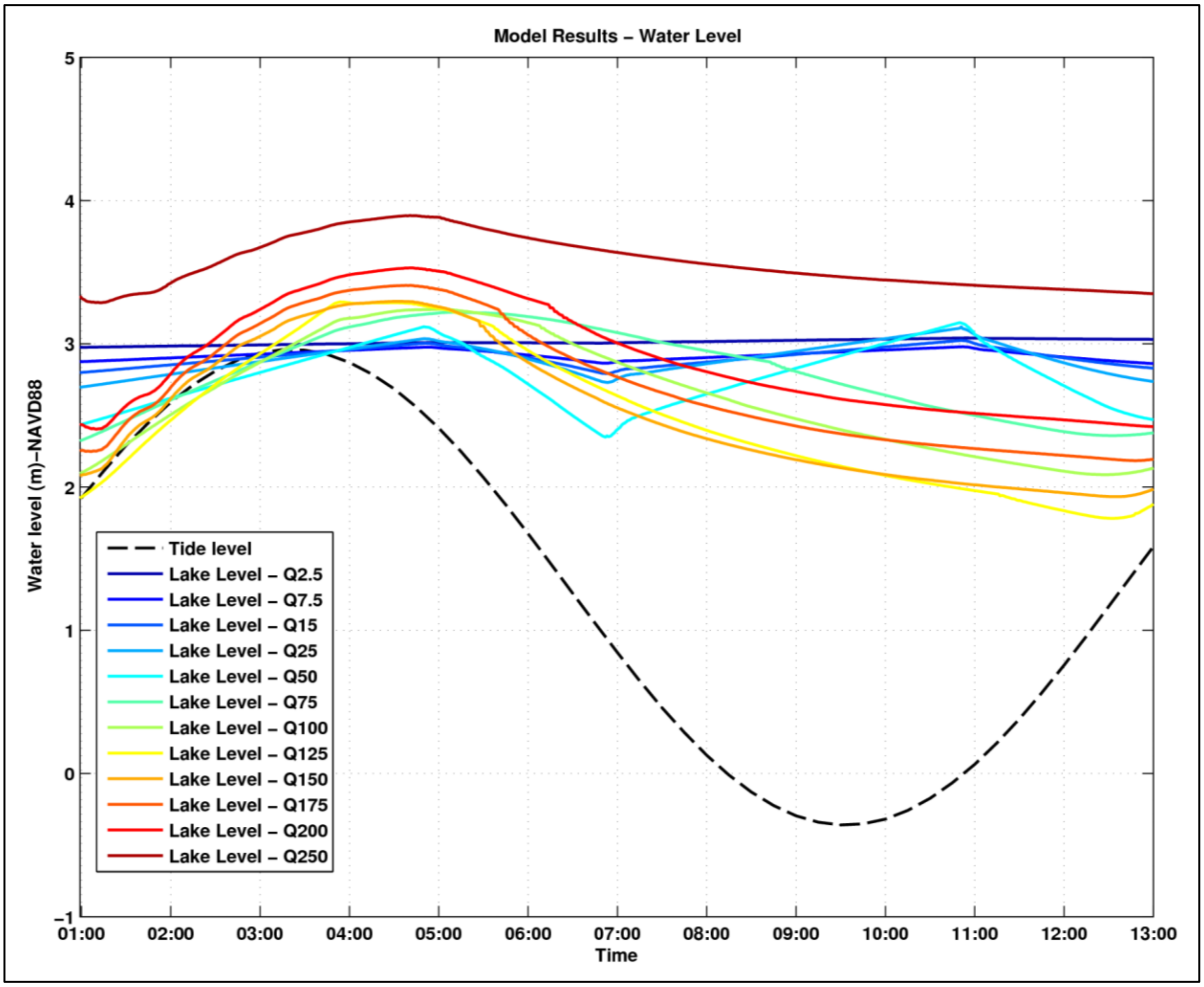


5.4.3 Dam Operation

To incorporate the dam operation in the quasi steady state runs, such as the gate open/close timing and gate opening height, the water level calibration results for low, medium, and high flow conditions in the hydrodynamic model (Section 4.4.4) were used to construct the dam operation logic for each quasi steady state case.

For each steady state run, the model ran 12 hours to cover one tidal cycle with an additional one-hour spin-up time. Time series of water level in the lake (lake level) and water in Budd Inlet (tide level) during all runs are presented in Figure 5-5. For river flow under 50 m3/s, the gate opened and closed twice during one tidal cycle. For river flow between 50 m3/s and 200 m3/s, the gate opened and closed once during one tidal cycle. For the largest flow condition of 250 m3/s, the gate was left open all the time. The gate operation logic followed the calibration results where the gate opened more frequently during low flow and less frequently during high flow. More importantly, the gate operation logic was utilized to meet two goals. First, the tide never entered the lake when the gate was open. Second, the lake level stayed the same at the start and end of the tidal cycle to make this process repeatable. Therefore, no significant transitions between water levels should occur between the different quasi steady state runs.

Figure 5-5 Time Series of Water Level at North Basin and Budd Inlet for Quasi Steady State Runs



5.5 MODEL CALIBRATION/VALIDATION

This section presents the sediment transport model calibration/validation to evaluate model performance. The goal of the sediment calibration/validation process was to reproduce the erosion/deposition within the Capitol Lake Basin captured by comparison of 2013 and 2020 survey data sets in terms of rates and distribution of erosion/deposition.

5.5.1 Calibration/Validation Criteria and Metrics

There are no specific standard criteria for performance evaluation of hydrodynamics or sediment transport models. Consequently, there are no specific criteria for acceptance of model calibration/validation. Performance of hydrodynamic models can be evaluated using various "goodness of fit" metrics for matching modeled against measured time histories of water level or currents. Unlike hydrodynamic model calibration/validation, sediment transport models are often calibrated/validated against measured data in terms of erosion/deposition patterns and/or rates or volumes.

For this study, the sediment transport model calibration/validation was based on matching modeled results with measured data in terms of the spatial pattern and average annual erosion/deposition volumes in each basin (South Basin, Middle Basin, and North Basin) during the calibration period.

5.5.2 Calibration/Validation Period

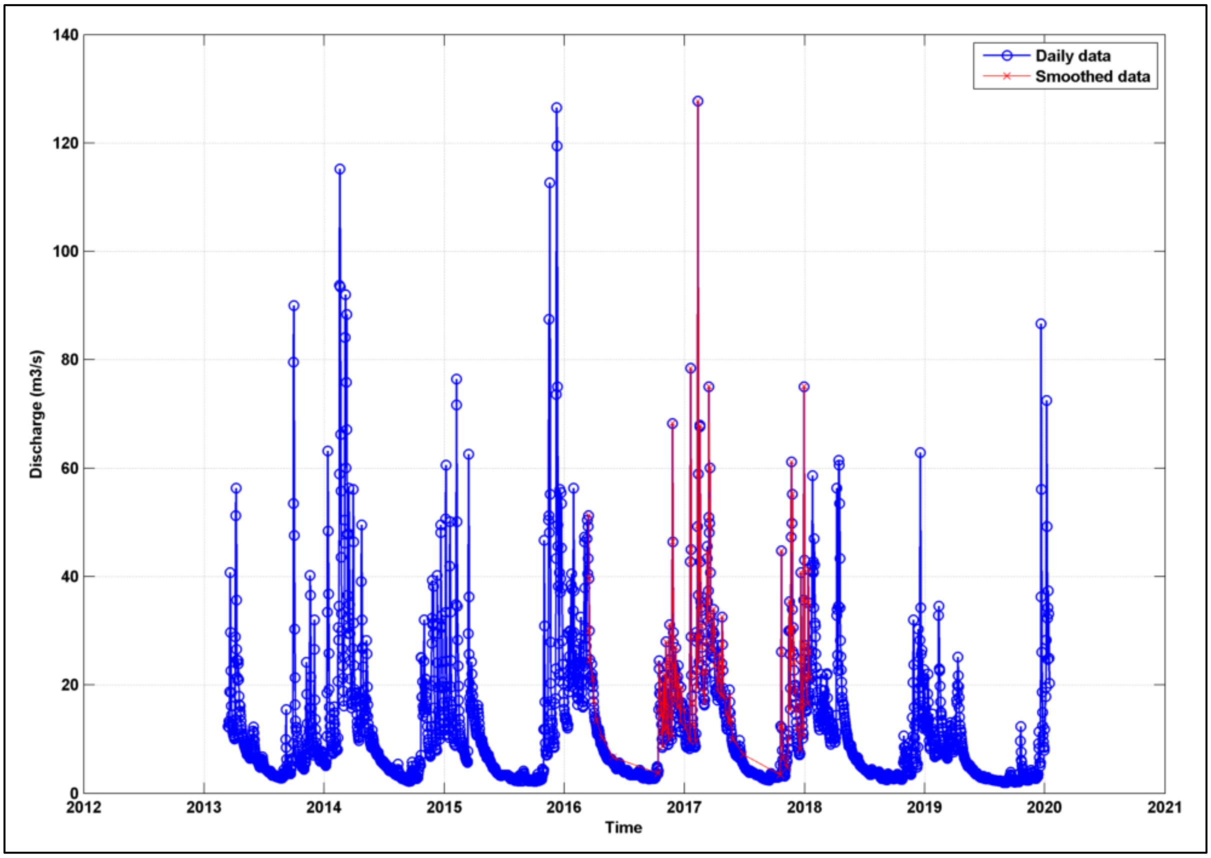
The calibration/validation period was selected as the period between the 03/2013 (TerraSond 2013) and 01/2020 (eTrac 2020) surveys of the Capitol Lake Basin; see Section 2.10 for further details about these surveys and erosion/deposition patterns during this period. The daily discharge at Deschutes River during this time period is shown in Figure 5-6. The time history of daily discharge shows a repetitive annual pattern with a few high extreme discharge events in winter and generally lower discharge in summer than the rest of the year.

Given the size and resolution of the model grid, the MATLAB computation for each daily morphological update took approximately 5 minutes. For all daily discharges (approximately 2,500 time steps), the total computation time, not including lookup table recalculation, would require eight to nine days. To keep run times practical to allow multiple sensitivity tests, a representative time period was selected instead. The river discharge for this period is shown in Figure 5-6 using a red line. The time period from 03/2016 to 01/2018 was selected to represent the whole time series. For the erosion/deposition results discussed in Section 5.5.4, a uniform scale factor of 3.72 computed from the ratio of the calibration/ validation period and the simulation time period was used to scale the morphological changes up to represent the full calibration/validation period between 03/2013 and 01/2020.

The time history of daily discharge was then smoothed to reduce the number of discharge inputs. The summer discharge was low for a long period of time and a low sedimentation process could be expected. The approach for smoothing the time series data was to remove similar discharge data points based on a selected tolerance value of 3 m^3/s. The removed data points were replaced with a single data point with a value equal to the average of the removed values.

After smoothing the data, the selected calibration time period was from 03/19/2016 to 01/15/2018 with 152 discharge inputs. The total simulation time was reduced to approximately one day.

Figure 5-6 Daily Discharge Time Series at Deschutes River Mouth from 03/2013 to 01/2020



5.5.3 Calibration Parameters

During the calibration process, several parameters were adjusted to obtain a better match between model results and measured data. These calibration parameters and the final values selected in the calibration process for sand and mud are listed in Table 5-6.

Table 5-6 Range of Model Parameters Tested through the Calibration Process, and Final Values Selected

Sediment Property	Tested Value Mud	Tested Value Sand	Final Value Mud	Final Value Sand
Dry density (kg/m^3)	455	1,600	455	1,600
Settling velocity (mm/s)	0.1 - 0.5	N/A[4]	0.2	N/A
Critical shear stress for erosion (N/m^2)	0.48 - 1	N/A	0.7	N/A

[4] N/A means that a sediment property was not a model parameter in the sediment transport formulation used herein.

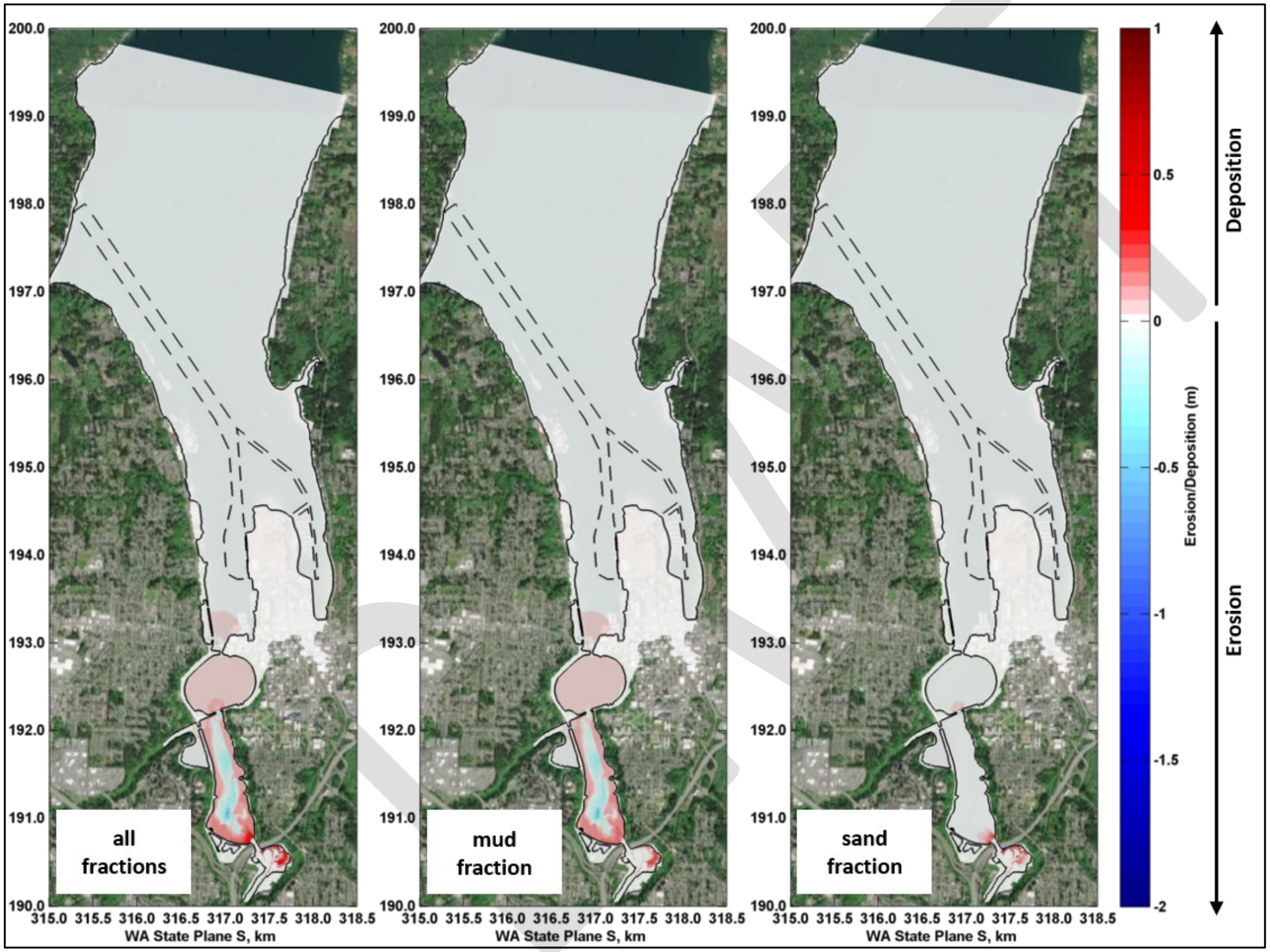
Sediment Property	Tested Value Mud	Tested Value Sand	Final Value Mud	Final Value Sand
Erosion parameter (kg/m²/s)	0.004	N/A	0.004	N/A
D50 (µm)	N/A	100-200	N/A	100

5.5.4 Calibration/Validation Results

To obtain the cumulative erosion/deposition in the model domain, the sediment thickness changes between the start and end of the simulation were computed for all sediment fractions, mud fraction only, and sand fraction only. A cumulative erosion/deposition map between 03/2013 and 01/2020 scaled from the simulation period from 03/2016 to 01/2018 for all fractions, mud fraction only, and sand fraction only is shown in Figure 5-7. Most morphological changes in the model domain are contributed by the mud fraction, and sand related morphological changes are limited to mostly in the South Basin, downstream of the I-5 Bridge, the river channel in the Middle Basin, and at the BNSF Railroad Trestle.

Model results show that mobilized mud that did not deposit within the Capitol Lake Basin was transported downstream of the 5th Avenue Dam and ended up at Budd Inlet. The thickness of sediment deposits decreased from a maximum of 0.08 m with increasing distance from the 5th Avenue Dam.

Figure 5-7 Cumulative Erosion/Deposition (m) in the Model Domain



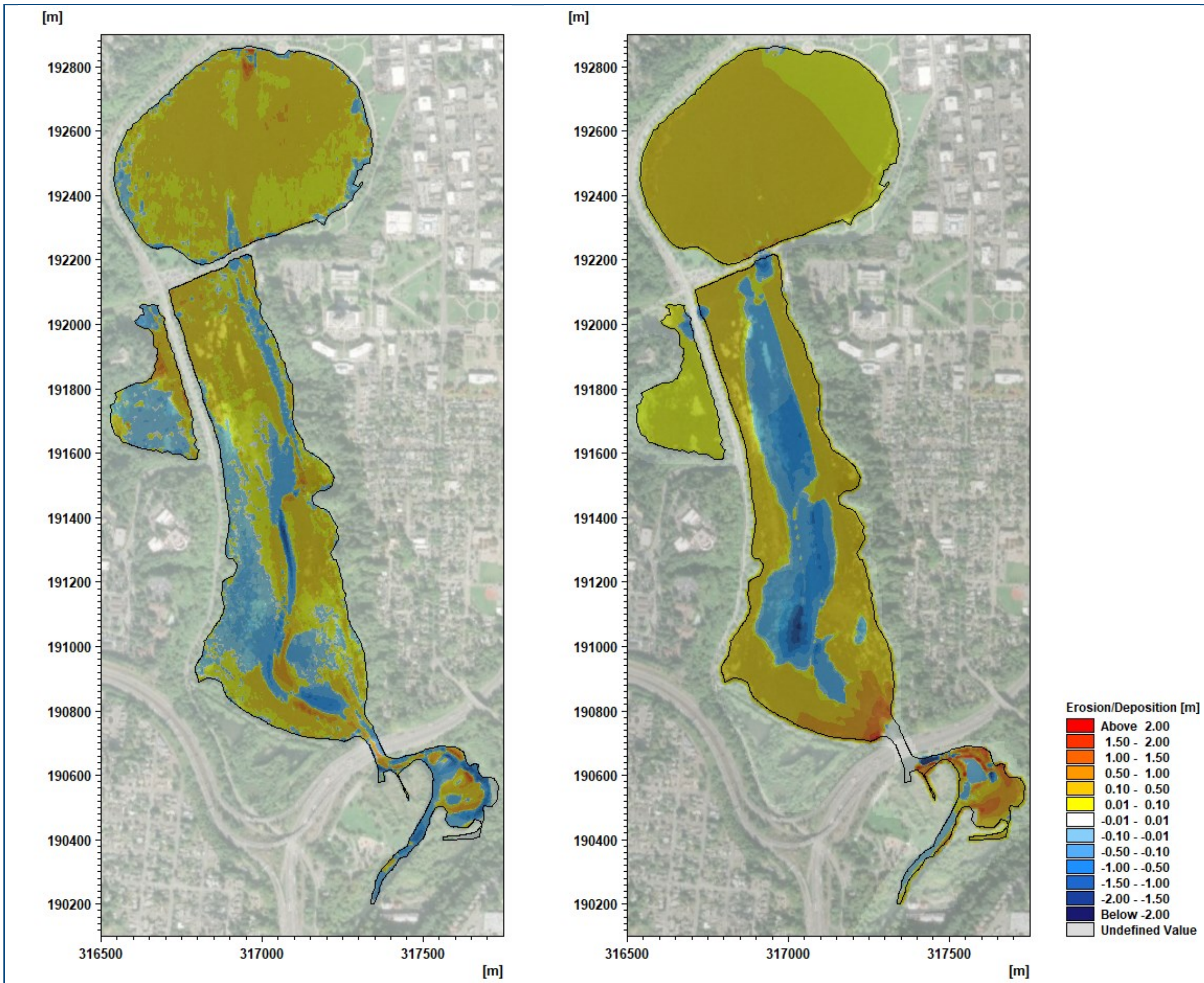
** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Model results zoomed into the Capitol Lake Basin are presented in Figure 5-8 to compare with the survey data. In the North Basin, the elevation changes show an overall depositional pattern. The survey data show more deposition in the central part of the North Basin, while the model results show most deposition in the west and central part of the North Basin. The sedimentation thickness for survey data in most of the North Basin is 0.01 m - 0.5 m except near the gate where the deposition around the scour hole in front of the gates is 1.5 m. The sedimentation thickness associated with model results in the North Basin is 0.01 m - 0.3 m.

In the Middle Basin, the survey data demonstrate erosion in the river channel and deposition over the shallow banks, and the same overall pattern can be seen in the model results. However, the distributions of those morphological changes between the survey data and model results are different. Erosion in the survey data occurs at the river channel and some riverbanks around the channel where the channel has a large curvature. In the model results, most erosion occurs in the middle part of the Middle Basin with a larger erosional area than the survey data.

In the South Basin, there are areas with erosion along the river channel from the survey data (Figure 5-8 (a)). There are two possible reasons that this erosion occurs. First, the 2013 survey did not capture several sections of the South Basin with the same sample density as the 2020 survey conducted as part of the EIS. Some of the erosion shown here is due to data interpolation mismatch between the two surveys. Another reason is the river channel in the southeast part of the South Basin has migrated to the southeast direction. The model results do not capture the channel migration pattern and show most of the South Basin with deposition.

Figure 5-8 Cumulative Erosion and Deposition in the Capitol Lake during Calibration Period

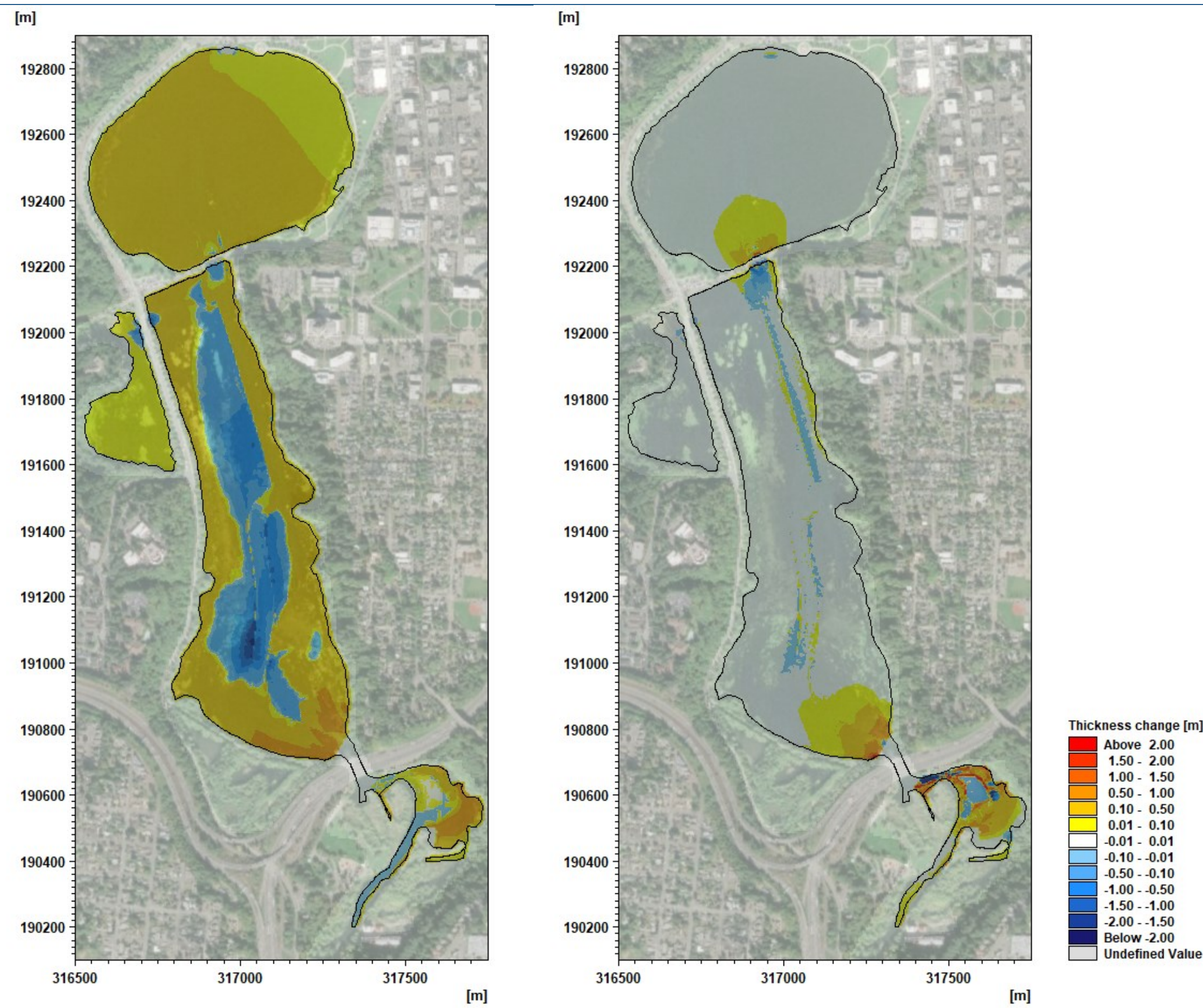


(a) Survey Comparison **(b) Model Results**

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88)

Model results for the mud and sand fractions zoomed to Capitol Lake are presented in Figure 5-9. The mud distribution is similar to the cumulative erosion and sedimentation for all fractions. Morphological changes of sand fraction occurred in regions with high current velocity, such as downstream of the I-5 Bridge, the river channel in the Middle Basin, and at the BNSF Railroad Trestle, as well as the South Basin where it received the sand from the upstream boundary.

Figure 5-9 Modeled Cumulative Erosion and Deposition in Capitol Lake for Mud and Sand Fractions



(a) Mud Fraction **(b) Sand Fraction**

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88)

Annual sedimentation volume for the survey data and the model results are listed in Table 5-7. In the Middle Basin, the modeled erosion/deposition matches the estimated annual volume based on survey data within 10%. In the North Basin, the modeled erosion/deposition matches the estimated annual volume based on survey data within 12%. In Budd Inlet, the modeled erosion/deposition matches the annual volume based on empirical estimates within 2%. In the South Basin, survey coverage of the TerraSond (2013) survey was not adequate to allow a comparison and estimation of erosion/deposition volumes. In general, the model captured the overall erosion/deposition patterns and modeled volumes were in agreement with volumes estimated based on survey comparisons.

Table 5-7 Annual Erosion/Deposition Volume within Capitol Lake Basin and Budd Inlet for 2013 to 2020

	South Basin m^3/yr (cy/yr)	Middle Basin m^3/yr (cy/yr)	North Basin m^3/yr (cy/yr)	Budd Inlet m^3/yr (cy/yr)
Survey Comparison	N/A	2,742 (3,586)	8,414 (11,005)	3,057 (3,998)
Model Results	N/A	3,004 (3,929)	7,343 (9,604)	2,991 (3,912)
Difference	N/A	10%	-13%	-2%

5.6 SENSITIVITY ANALYSIS

Several tests were conducted to evaluate sensitivity of model results to model parameters and assumptions for both cohesive (mud) and non-cohesive (sand) sediments. The influence of model parameters, threshold values for lookup table approach, and incorporating salinity on erosion/ deposition results were investigated and are presented in the following sections.

5.6.1 Cohesive Sediment (Mud)

The tested and selected values for model parameters used in the sensitivity analyses for mud are listed in Table 5-8. The following sections describe the findings of the sensitivity analyses for each parameter.

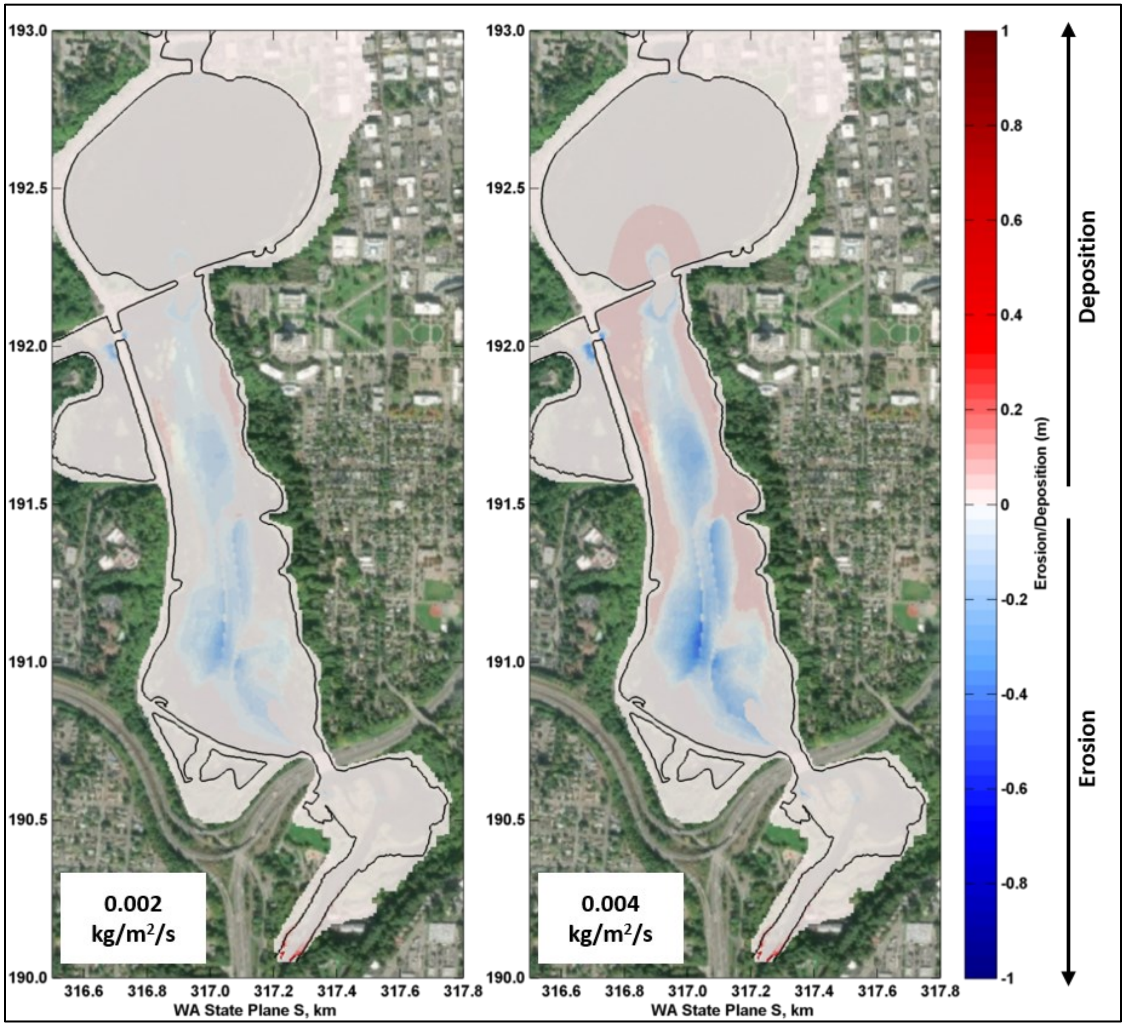
Table 5-8 Parameters Tested in Sensitivity Analysis for Cohesive Sediment (Mud)

Parameter	Tested Value(s)	Selected Value
Erosion Parameter (kg/m2/s)	0.002, 0.004	0.004
Settling Velocity (mm/s)	0.1, 0.2, 0.5	0.2
Critical Shear Stress for Erosion (N/m2)	0.48, 0.7, 1.00	0.70

5.6.1.1 Erosion Parameter

Model results in terms of cumulative erosion/deposition for erosion parameters of 0.002 and 0.004 kg/m²/s are shown in Figure 5-10. Model results show that increasing the erosion parameter results in more erosion in the Middle Basin along the main channel and more deposition on the channel banks in the Middle and North Basins. The results demonstrate that in the Middle Basin, maximum erosion increases from 0.4 m to 0.8 m while increasing the erosion parameter, and in the North Basin, deposition downstream of the BNSF Railroad Trestle increases from 0.05 m to 0.1 m while increasing the erosion parameter from 0.002 kg/m²/s to 0.004 kg/m²/s. This could be expected because the sediment flux (erosion/deposition between water column and riverbed) is proportional to the erosion parameter. In the South Basin, the morphological changes were small (< 0.05 m) for both values of erosion parameter and the difference in erosion/deposition resulting from increasing the erosion parameter was small (<0.01m).

Figure 5-10 Cumulative Erosion/Deposition (m) with Varying Erosion Parameter (kg/m²/s)

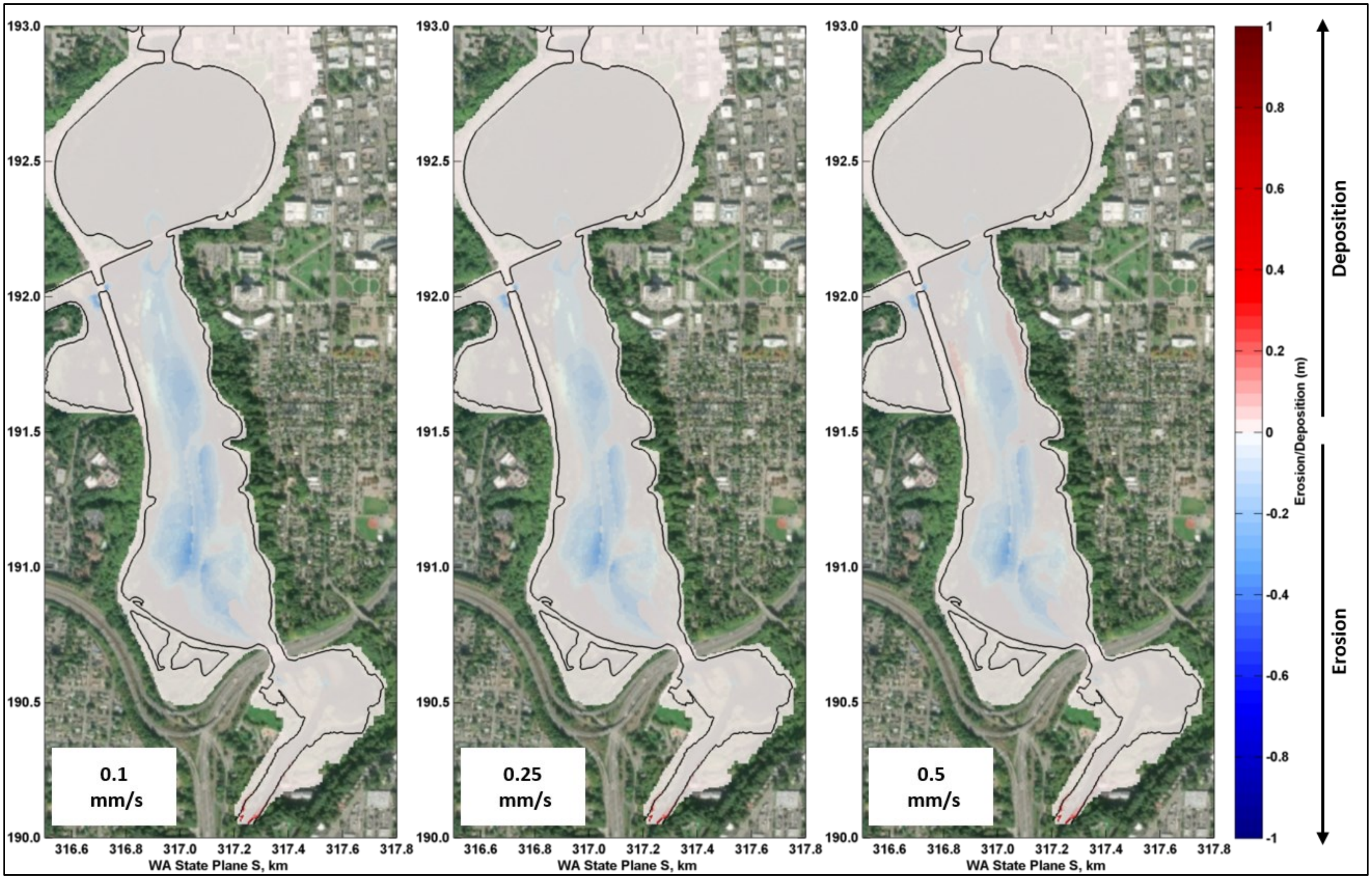


** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88)

5.6.1.2 Settling Velocity

Model results in terms of cumulative erosion/deposition for cohesive sediment settling velocities of 0.1, 0.25, and 0.5 mm/s are shown in Figure 5-11. Model results show that increasing settling velocity from 0.1 to 0.5 mm/s results in reduced erosion in the Middle Basin, with maximum erosion reducing from 0.6 m to 0.4 m. Additionally, it is shown that increased settling velocity results in deposition on the channel banks within the Middle Basin. Since a larger settling velocity represents a coarser cohesive sediment size, it is anticipated that erosion would decrease, and deposition would increase with a larger settling velocity. Model results show that changing the settling velocity results in small changes (<0.05 m) in erosion/deposition in the North and South Basins.

Figure 5-11 Cumulative Erosion/Deposition (m) with Varying Settling Velocity (mm/s)



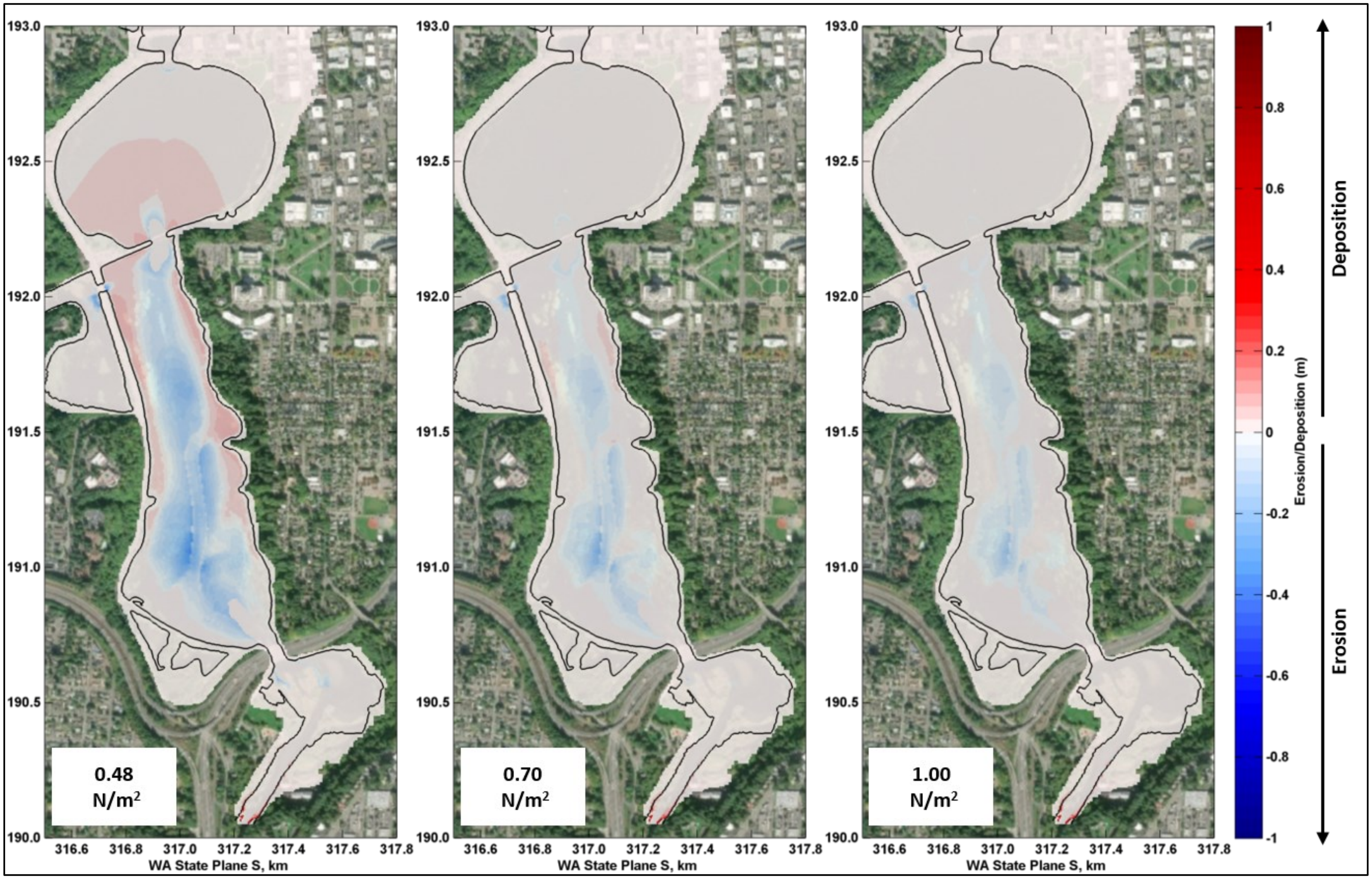
** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88)

5.6.1.3 Critical Shear Stress for Erosion

Model results in terms of cumulative erosion/deposition results for critical shear stresses for erosion of 0.48, 0.70, and 1.00 N/m^2 are shown in Figure 5-12. It is anticipated that erosion would be inversely proportional to critical shear stress for erosion. Model results show reduced erosion in the Middle Basin with increased critical shear stress for erosion, with the maximum erosion decreasing from 0.6 m to 0.2 m in the Middle Basin when the critical shear stress for erosion increased from 0.48 to 1.00 N/m^2.

In the North Basin, deposition downstream of the BNSF Railroad Trestle decreased from 0.2 m to less than 0.05 m when the critical shear stress for erosion increased from 0.48 to 1.00 N/m^2. In the South Basin, the morphological changes were small (< 0.05). The decreased erosion in the Middle Basin and decreased deposition in the North Basin with increasing critical shear stress for erosion is due to the higher probability that the shear stress is smaller than the critical shear stress. Therefore, this caused less erosion in the Middle Basin and consequently transported less sediment downstream to the North Basin.

Figure 5-12 Cumulative Erosion/Deposition (m) with Varying Critical Shear Stress for Erosion (N/m²)



** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88)

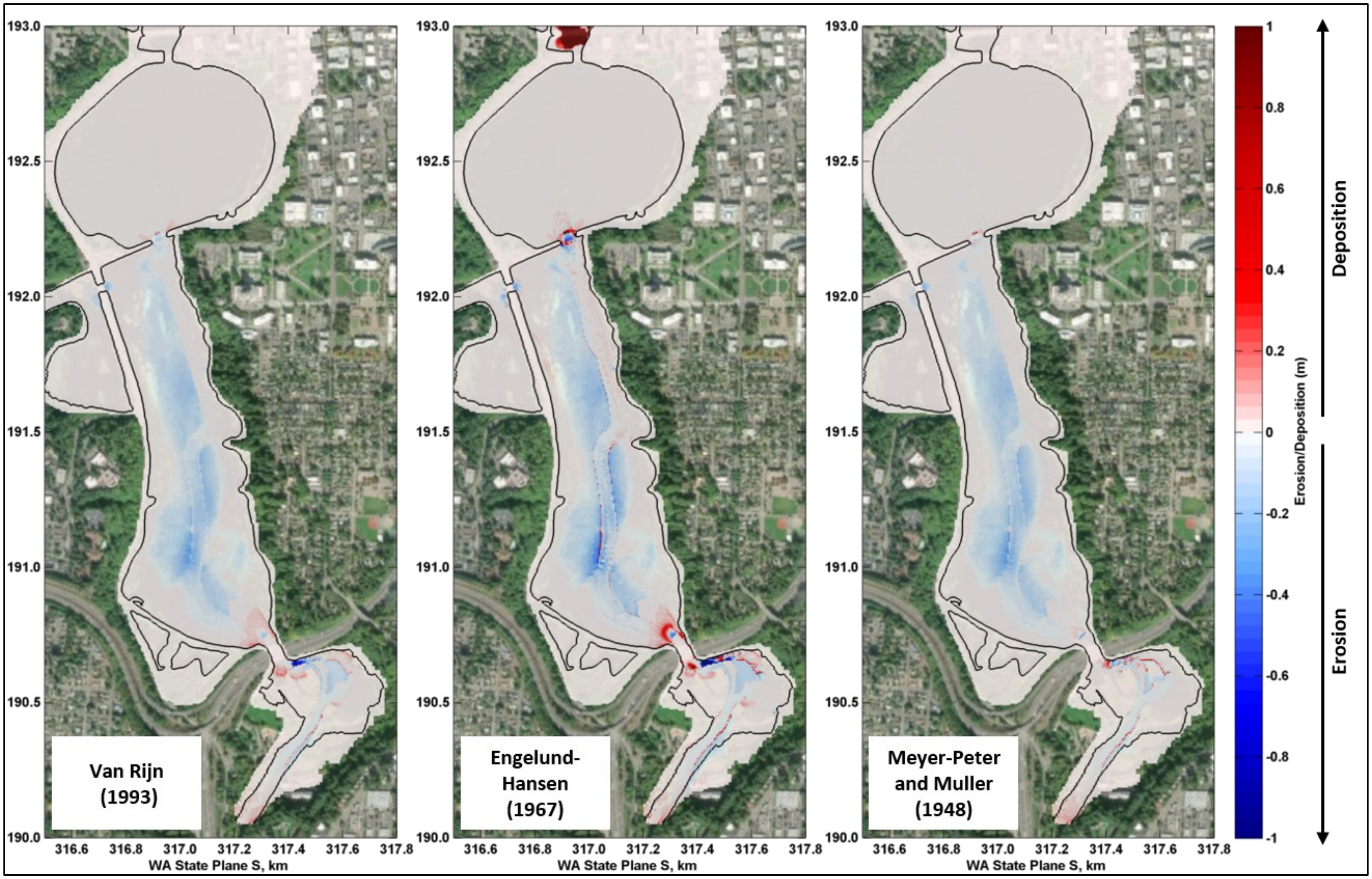
5.6.2 Non-Cohesive Sediment (Sand)

Sensitivity of erosion/deposition patterns to sediment transport formulations for sand was tested. These tested formulations are listed in Table 5-9. Cumulative erosion/deposition results using these formulations are shown in Figure 5-13. The erosion/deposition patterns are generally similar except for unrealistic deposition in areas that experience high current velocities such as downstream of the dam, and adjacent to the BNSF Railroad Trestle and I-5 Bridge using the Engelund-Hansen (1967) formulation.

Table 5-9 Parameters Tested in Sensitivity Analysis for Non-Cohesive Sediment (Sand)

Parameter	Tested Formulations	Selected Formulation
Sediment transport formula	Van Rijn (1993), Engelund-Hansen (1967), and Meyer-Peter and Muller (1948)	Van Rijn (1993)

Figure 5-13 Cumulative Erosion/Deposition (m) with Varying Sediment Transport Formulations



** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88)

5.6.3 Threshold Values

Sensitivity of model results in terms of erosion/deposition to threshold values used for the lookup table approach (see 5.3.2) were tested. Three groups of threshold values were tested in the model with threshold values increasing from low to high from Group 1 to Group 3, and the simulation period was the same as the calibration run from 03/19/2016 to 01/15/2018 (see Table 5-10).

Table 5-10 Lookup Table Approach Threshold Values Tested in the Model

	Percentage of the Total Depth	Minimum Absolute Bed Level Change	Maximum Bed Level Change
Group1	5%	0.25 m	1.5 m
Group2	10%	0.5 m	3.0 m
Group3	20%	1.0 m	6.0 m

The average annual net erosion/deposition volumes for these three threshold groups, as well as erosion/deposition volumes estimated using bathymetric survey comparison, are listed in Table 5-11. Comparison of modeled volumes with estimated volumes indicates that Group 2 has values in the South and Middle Basins closest to the survey measurements, while deposition values are similar among all three groups in the North Basin and Budd Inlet. As a result, the threshold values with 10% of the total depth and absolute values between 0.5 m and 3.0 m were selected for the final model setup.

Table 5-11 Annual Erosion/Deposition Volume within the Capitol Lake Basin and Budd Inlet with Varying Threshold Values

	South Basin m^3/yr (cy/yr)	Middle Basin m^3/yr (cy/yr)	North Basin m^3/yr (cy/yr)	Budd Inlet m^3/yr (cy/yr)
Group1	3,027 (3,959)	1,988 (2,600)	7,240 (9,470)	2,838 (3,712)
Group2	2,910 (3,806)	3,004 (3,929)	7,343 (9,604)	2,991 (3,912)
Group3	3,697 (4,835)	5,361 (7,011)	7,707 (10,080)	2,999 (3,923)
Survey Comparison	-967 (-1,265)	2,742 (3,586)	8,414 (11,005)	3,057 (3,998)

5.6.4 Salinity

Cohesive sediment tends to flocculate in saltwater and these sediment flocs have a much larger size than the individual particles, thereby settling at a faster rate (referred to as enhanced flocculation) that can affect the pattern and rates of sediment deposition. To incorporate the salinity impact on morphological changes in Capitol Lake and Budd Inlet after the dam is removed tests on four model configurations listed in Table 5-12 were developed for the Estuary Alternative and the Hybrid Alternative. The No Action and Managed Lake Alternatives were not modeled with salinity because the 5th Avenue Dam isolates tidal exchange between Budd Inlet and Capitol Lake Basin.

Boundary conditions for hydrodynamics-salinity simulations included a constant salinity value of 28 ppt applied at Budd Inlet offshore boundary, and a constant salinity of 0 ppt applied at the upstream river boundaries, similar to the previous USGS study (George et al. 2006).

The flocculation effect was simulated by setting the settling velocity to 1 mm/s when the salinity value was equal or larger than 10 ppt (Hill 1998). When salinity values were less than 10 ppt, the settling velocity was set to 0.2 mm/s, the same as configurations without salinity. For 3D configurations, seven sigma layers were used.

Table 5-12 Model Configurations Tested for Salinity's Impact on Sediment Transport Model

Configuration	Dimension	Salinity
1	2D	No
2	2D	Yes
3	3D	No
4	3D	Yes

In lieu of in-situ salinity measurements to represent the Estuary Alternative (because this environment setting does not exist), the modeled salinity (using the 3D configuration) was qualitatively compared with results of the previous USGS study (George et al. 2006) and limited measured salinity data in Budd Inlet. The comparison was conducted along two transects (see location of Transects A and B shown in Figure 5-14). Salinity results from the 3D model qualitatively agree with the field measurements and the USGS model results along Transect A (Figure 5-15). The modeled salinity matches the measurements with a range from 23 to 27 ppt, as well as the salinity distribution where there is a fresh water layer on top of the water column on the east side of Budd Inlet.

Figure 5-14 Transects A and B used to Compare Salinity Results

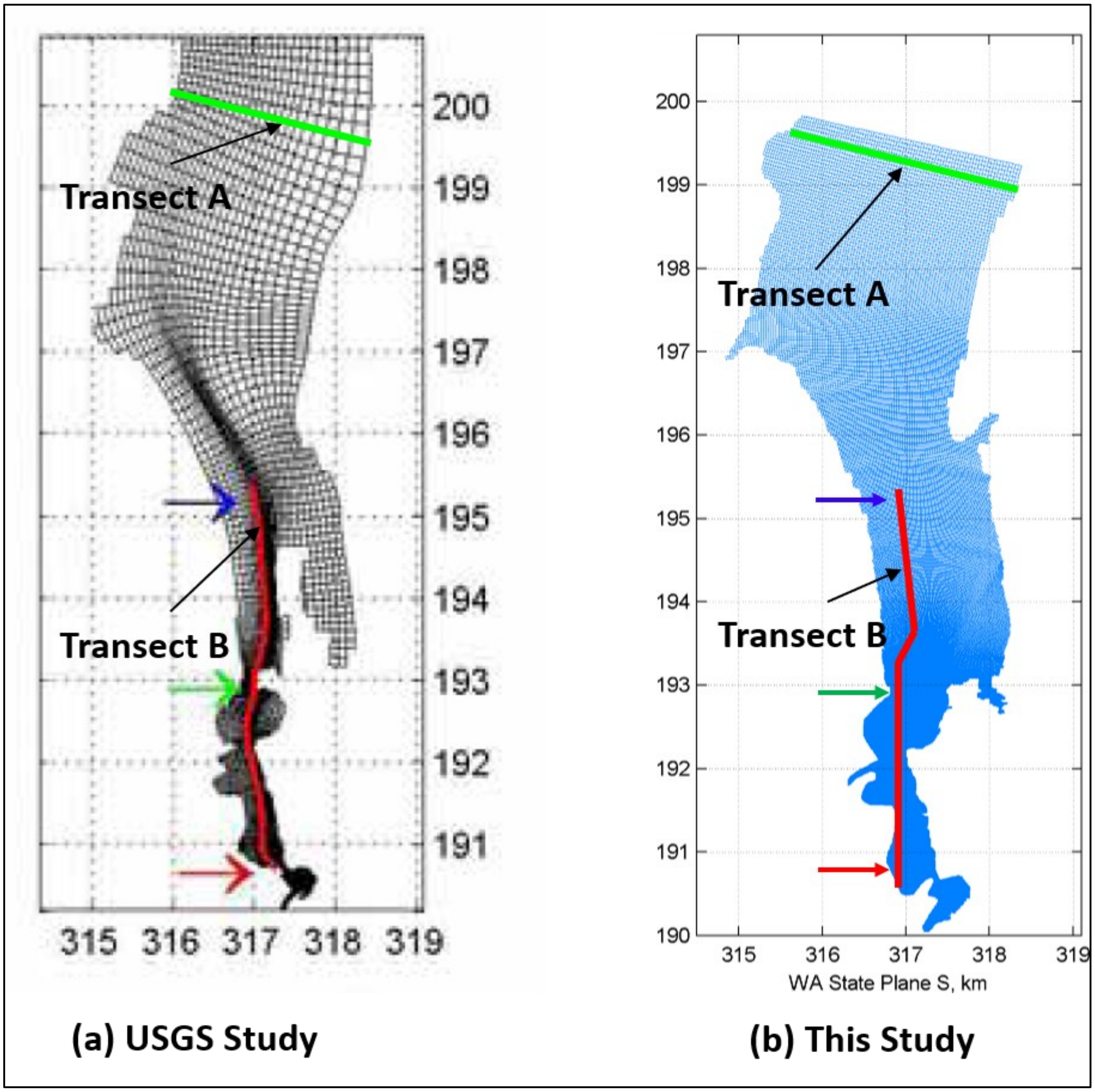
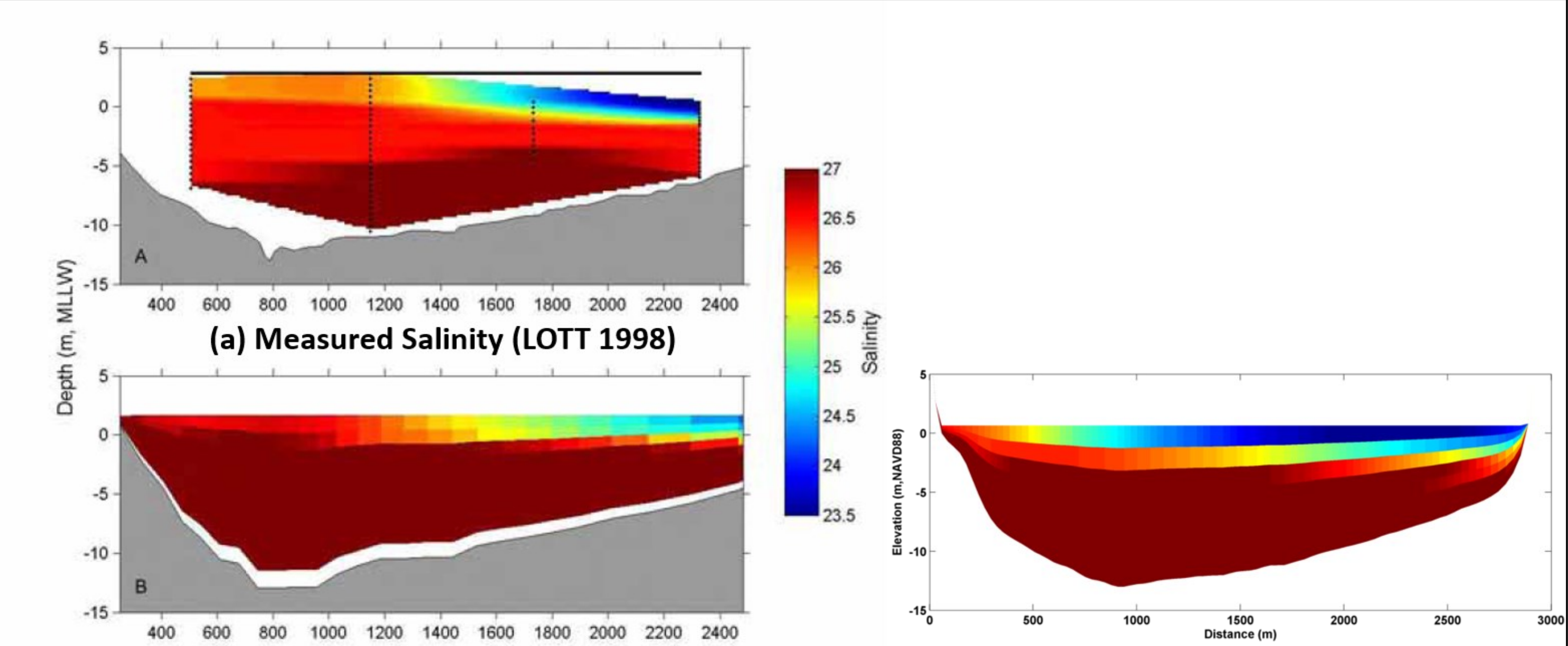


Figure 5-15 Comparison of Modeled vs. Measured Salinity Along Transect A



(a) Measured Salinity (LOTT 1998)

(b) Modeled Salinity, USGS Study (George et al. 2006)

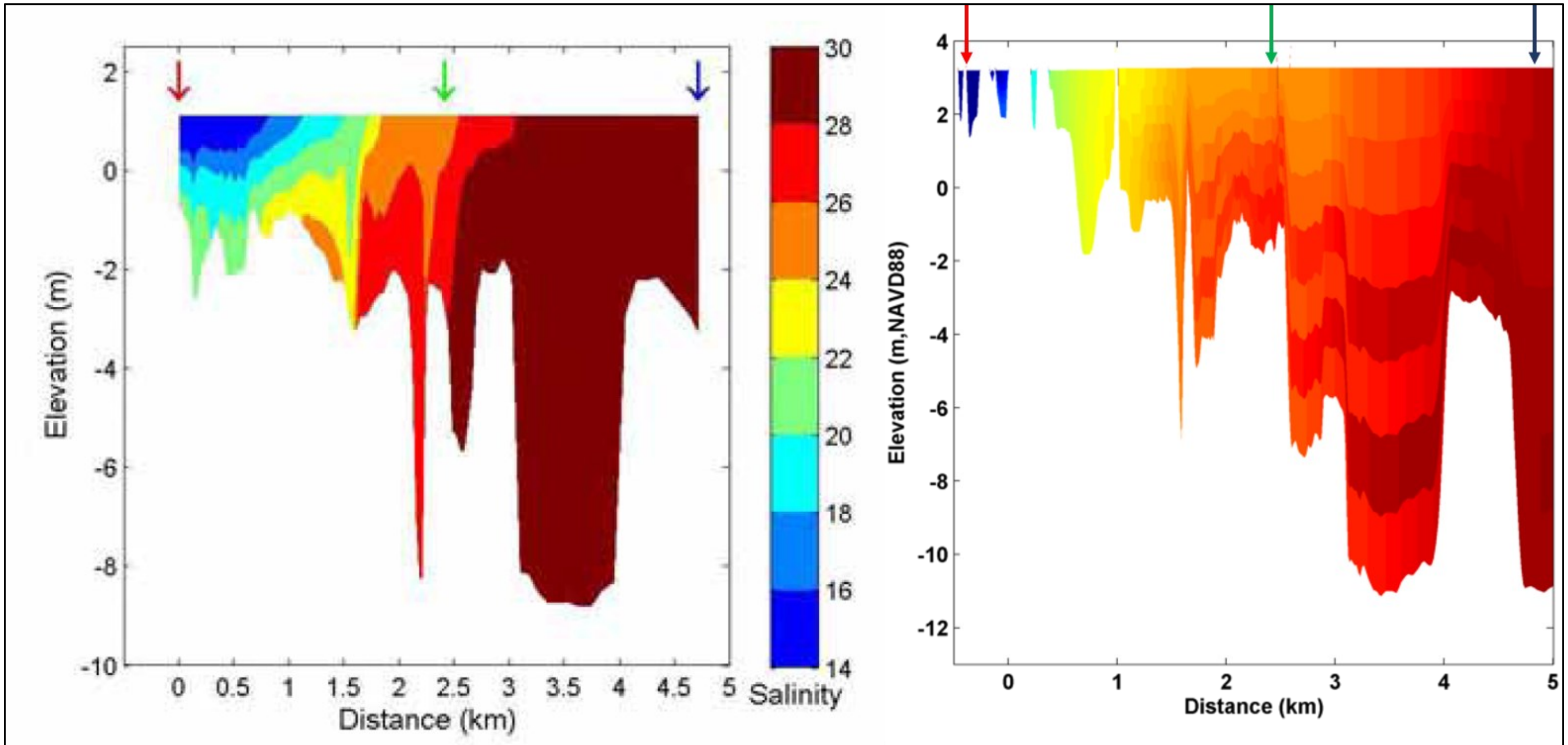
(c) Modeled Salinity, This Study

The second comparison is along Transect B extending from the Port of Olympia to 5th Avenue, and from the North Basin to the Middle Basin (location shown in Figure 5-14(a). USGS model results along Transect B are shown in Figure 5-16, with the blue, green, and red benchmarks matching the locations in the model domain, see Figure 5-14. Along this transect, within Budd Inlet between the Port of Olympia and 5th Avenue, USGS model shows that the estuary is well mixed with salinity ranging from 26 to 28 ppt. Salinity in the North Basin is well-mixed with salinity ranging from 22 to 26 ppt, while salinity in the Middle Basin is partially mixed with a larger range from 14 to 22 ppt.

The Transect B used to extract results of this modeling study was developed to match the transect shown in the USGS model as much as possible (see Figure 5-14). Salinity results along Transect B are shown in Figure 5-16, with the blue, green, and red benchmarks representing the location in the domain.

The model results from this study along Transect B qualitatively agree with the USGS model results (George et al. 2006) but highlight some differences as well (USGS model results predict higher stratification in Middle Basin and higher salinity in Budd Inlet). The differences in model results are most likely due to differences in location/alignment of the section as well as differences in modeling event (the modeling event for USGS was not clearly specified in the report and could not be confirmed in correspondence with the authors).

Figure 5-16 Comparison of Modeled vs. Measured Salinity Along Transect B



(a) Modeled Salinity, USGS Study (George et al. 2006)

(b) Modeled Salinity, This Study

After comparing the salinity results to the model results developed by USGS (George et al. 2006), cumulative erosion/deposition results were compared in the model focusing on Budd Inlet, which would be impacted the most by enhanced flocculation due to salinity. Four configurations listed in Table 5-12 were simulated for four days between 02/09/2017 and 02/13/2017 covering the high flow event on 02/10/2017 (Figure 4-10). Model results in terms of cumulative erosion/deposition are shown in Figure 5-17 and Figure 5-18 for the Estuary and Hybrid Alternatives, respectively.

Model results indicate that incorporating salinity will increase deposition in Budd Inlet. Additionally, it is shown that using the 3D configuration of the model results in increased sediment deposition in Budd Inlet.

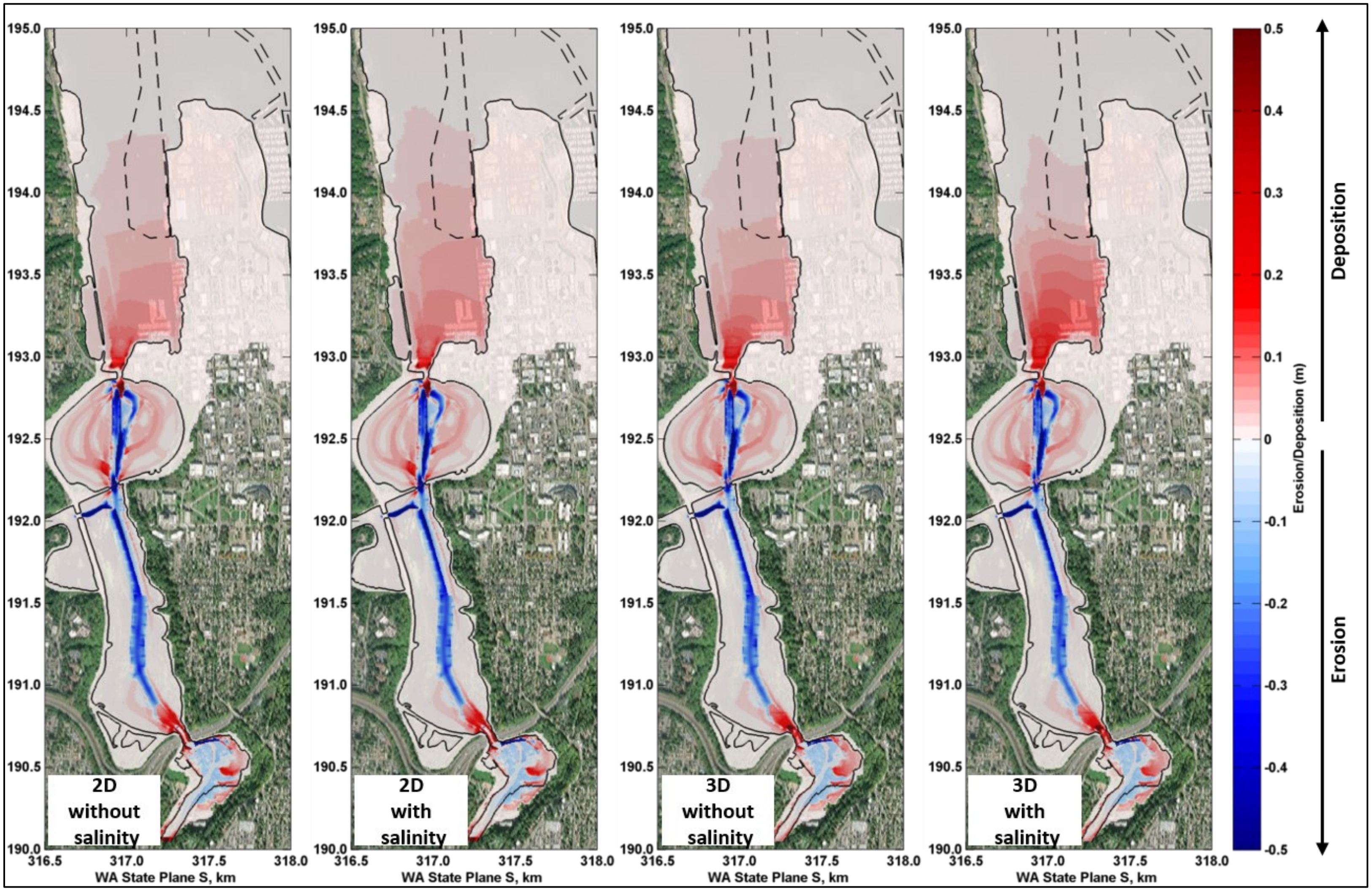
Erosion/deposition within the Capitol Lake Basin looks similar among the four model configurations. To further quantify the differences, erosion/deposition values were calculated inside each polygon in the basins and in Budd Inlet along with the percent changes from 2D model without salinity to other three configurations. Those results are listed in Table 5-13 and Table 5-14 for Estuary and Hybrid Alternatives, respectively.

For the Estuary Alternative, the South Basin, Middle Basin, and North Basin, all have a net erosion while Port and marina have a net deposition. Adding salinity into 2D model will provide results that reduce the erosion in the basin (< 8%) and increase the deposition at the Port and marina to 15%. Changing model from 2D to 3D reduces the erosion in the South Basin (76%-77%) and Middle Basin (6%-7%), and percent changes are larger in the South Basin due to the relatively smaller erosion values in this region comparing to other basins. More erosion (8%-23%) is seen in the North Basin from 2D to 3D because less sediment was eroded from the South Basin and the Middle Basin. Finally, in Budd Inlet, 3D model with salinity has the largest deposition increase of 30%, following by 15% from 2D model with salinity, and 5% from 3D model without salinity.

Similar results can be seen in Table 5-14 under the Hybrid Alternative, except larger erosion values in the North Basin with less percent changes among configurations, and larger deposition in the Port and marina. The larger erosion in the North Basin is due to existence of the new reflecting pool, which confines the flow in the middle part of the North Basin causing more erosion there. The larger deposition results from the larger erosion in the North Basin. The percent changes in the Port and marina is similar to the Estuary Alternative with largest deposition increase of 31% from 3D model with salinity, following by 18% from 2D model with salinity, and 4% from 3D model without salinity.

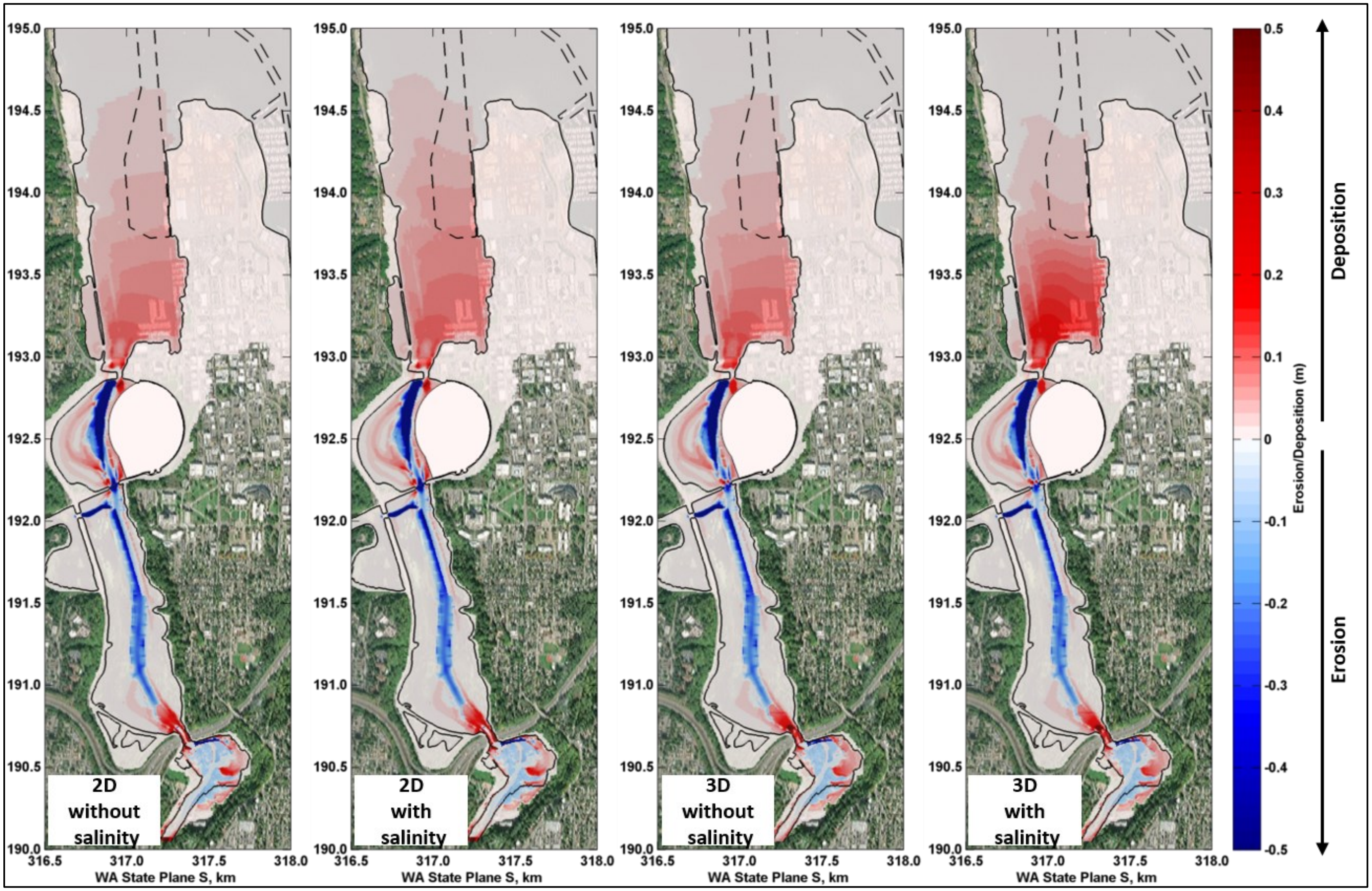
In summary, the 3D model with salinity configuration provides the highest rates of deposition within Budd Inlet at the Port and marina after dam removal. This configuration was used to produce model results for the Estuary and Hybrid Alternatives.

Figure 5-17 Cumulative Erosion/Deposition (m) – Sensitivity Testing of Estuary Alternative to Incorporating Salinity



** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Figure 5-18 Cumulative Erosion/Deposition (m) – Sensitivity Testing of Hybrid Alternative to Incorporating Salinity



** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Table 5-13 Erosion/Deposition for Estuary Alternative for 2D and 3D Models With and Without Salinity

	South Basin (m^3)	% change	Middle Basin (m^3)	% change	North Basin (m^3)	% change	Budd Inlet (m^3)	% change
2D	-1622	-	-18974	-	-2869	-	27662	-
2D + salinity	-1569	-3%	-18269	-4%	-2634	-8%	31847	15%
3D	-391	-76%	-17867	-6%	-3099	8%	29108	5%
3D + salinity	-372	-77%	-17592	-7%	-3532	23%	35824	30%

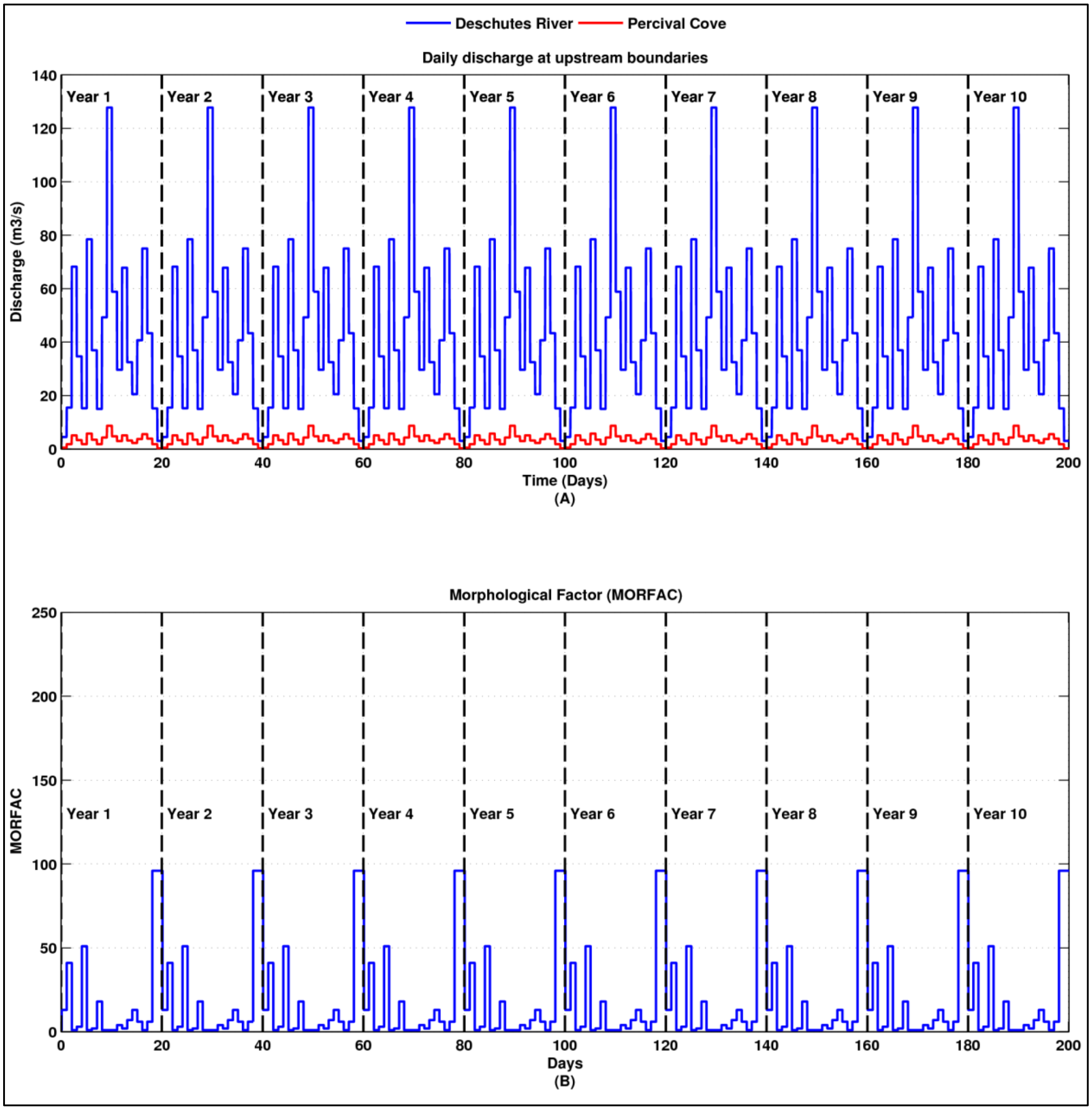
Table 5-14 Erosion/Deposition for Hybrid Alternative for 2D and 3D Models With and Without Salinity

	South Basin (m^3)	% change	Middle Basin (m^3)	% change	North Basin (m^3)	% change	Budd Inlet (m^3)	% change
2D	-1558	-	-16390	-	-18148	-	35836	-
2D + salinity	-1485	-5%	-15745	-4%	-17760	-2%	42118	18%
3D	-332	-79%	-15206	-7%	-18803	4%	37440	4%
3D + salinity	-310	-80%	-15062	-8%	-18795	4%	46836	31%

5.7 EQUILIBRIUM STATE AFTER DAM REMOVAL

A 10-year simulation with discretized flow from water year 2017 (10/01/2016 – 09/30/2017, see Figure 5-3) repeating 10 times was assessed to investigate when the dynamic equilibrium state of the sediment transport would be achieved after removal of the 5th Avenue Dam in the Estuary and Hybrid Alternatives described in Section 3.0. The reason to select water year 2017 was that the largest daily discharge for 2017 was 128 m^3/s, which was a medium case over the recorded period (close to 2-year event) and the largest annual daily discharge in the most recent 10 years (Figure 5-3). To eliminate the impacts from varying flow between years on the annual morphological changes, the discretized flow from water year 2017 was repeated 10 times to evaluate when the system would reach equilibrium state. The 10-year discretized flow with the time varying MORFAC is shown in Figure 5-19.

Figure 5-19 10-year Medium Flow Condition used in the Estuary and Hybrid Alternatives



(A) Discretized Discharges; (B) MORFAC

Time series of the deposition volumes in Budd Inlet are shown in Figure 5-20 and Figure 5-21 for the Estuary and Hybrid Alternatives, respectively. For the Estuary Alternative in Figure 5-20, the largest deposition is in the first year with an estimated 73,400 m^3 of deposition. The deposition trend decreases with time and becomes almost linear after five years with an estimated annual deposition volume of 26,800 - 29,800 m^3. For the Hybrid Alternative in Figure 5-21, the largest deposition is also in the first year with an estimated 110,100 m^3 of deposition, and the deposition trend decreases with time becoming almost linear after five years with an annual deposition volume of 32,100 – 37,500 m^3.

The modeled cumulative depositions in Budd Inlet demonstrate that the system is more dynamic with more erosion in the basin and more sediment being transported into Budd Inlet during the first three years, especially for the first year. The more drastic changes in the first three years are due to the initial response of the basin to removal of the 5th Avenue Dam as well as the proposed constructed bathymetry in the Estuary and Hybrid Alternatives. After five years, the system reaches an equilibrium state with a steady sediment flux from the basin to Budd Inlet for both the Estuary and Hybrid Alternatives.

Figure 5-20 Cumulative Deposition Volumes (10^3 m^3) in Budd Inlet for the Estuary Alternative

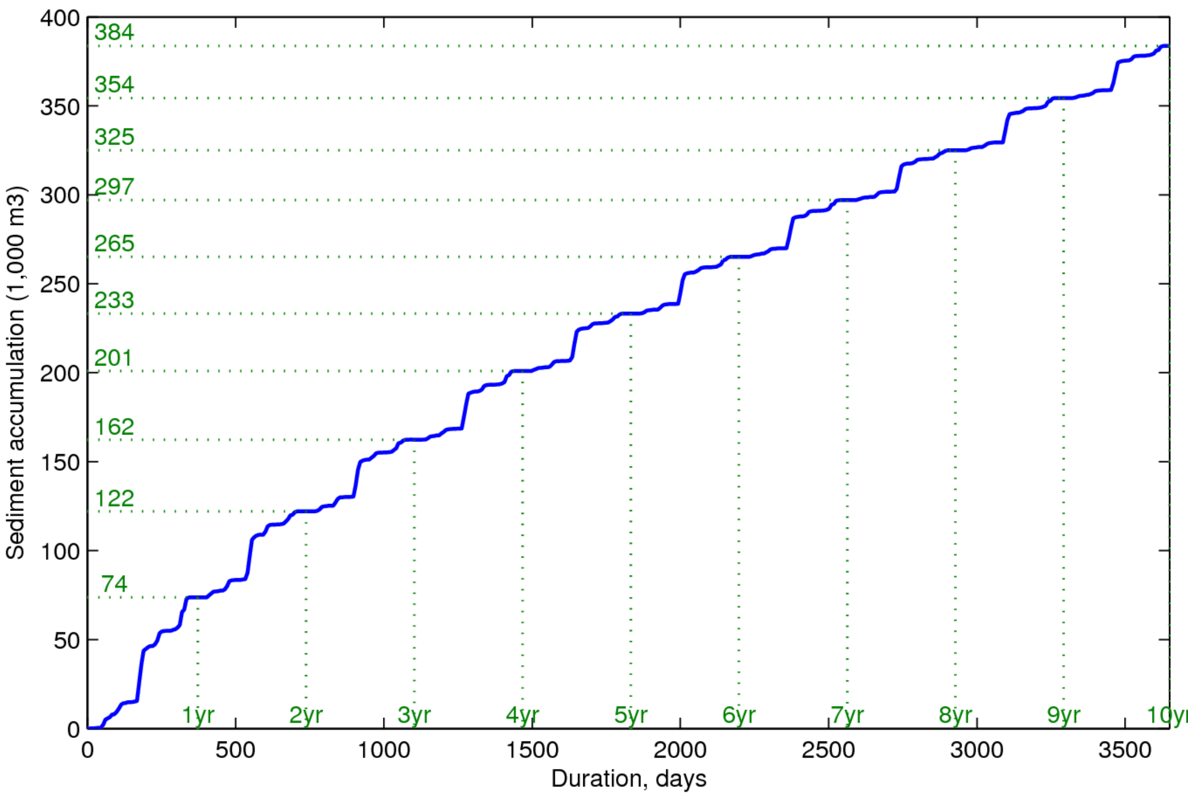
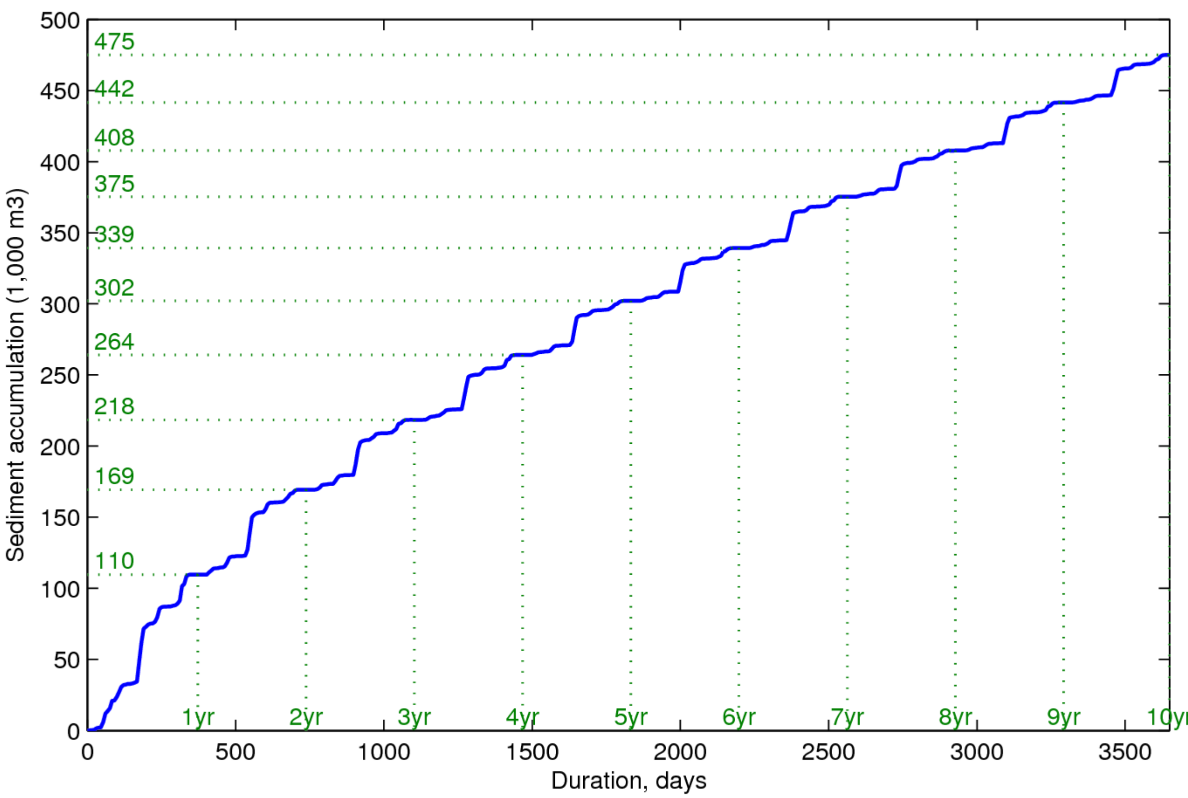


Figure 5-21 Cumulative Deposition Volumes in Budd Inlet for the Hybrid Alternative



5.8 SEDIMENT TRANSPORT MODELING EVENTS

Two production run periods were selected from water year 2019 and water year 1996 to represent the low flow year and high flow year, respectively. The daily discharge time series demonstrate that water year 1996 has the largest peak flow on record and water year 2019 has the lowest peak flow in the most recent 10 years. Additionally, the peak flow values of 63 m^3/s and 231 m^3/s cover a large range of the maximum annual flow. Therefore, those two time periods can predict the reasonable range of morphological changes in the future.

The long-term flow conditions were constructed by repeating the water year for three times for the low and high flow conditions. To save the simulation time, the same smoothing/discretization method used in the calibration process in Section 5.5.2 was applied to the No Action and the Managed Lake Alternatives where the same lookup table approach was implemented. The three-year river discharges with the smoothed data for the low and high flow period are shown in Figure 5-22 and Figure 5-23, respectively.

Table 5-15 Production Run Time Period

Flow	Real Time Period	Simulation Time Period	Peak Daily Discharge (m^3/s)
Low	10/01/2018 – 09/30/2019	three years	63
High	10/01/1995 – 09/30/1996	three years	231

Figure 5-22 Daily Discharge and Smoothed Data of Low Flow Condition used in the No Action and Managed Lake Alternatives

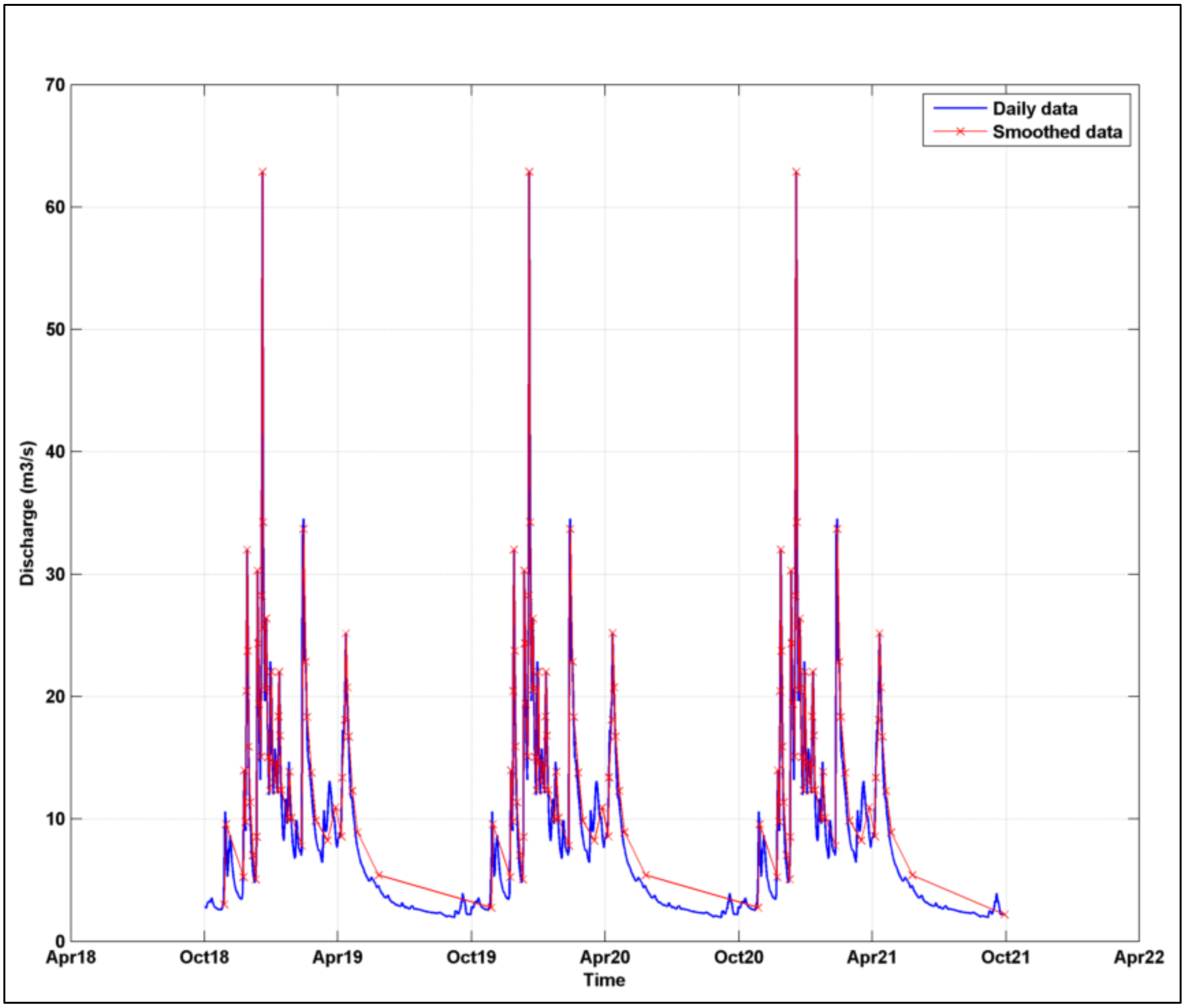
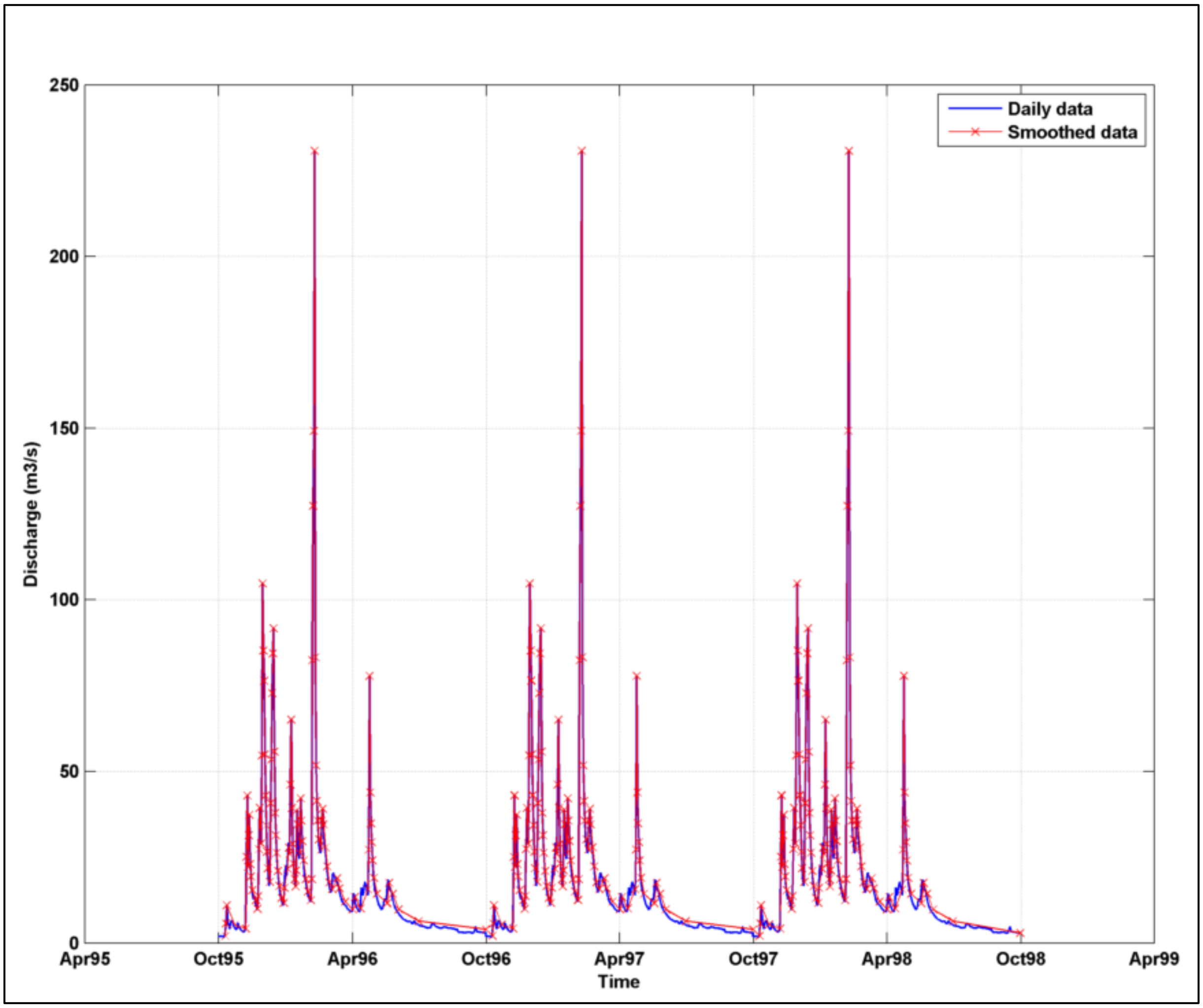


Figure 5-23 Daily Discharge and Smoothed Data of High Flow Condition used in the No Action and Managed Lake Alternatives



For the MORFAC approach applied in the Estuary and the Hybrid Alternatives, the smoothing/ discretization method was modified to accommodate the usage of a MORFAC and further reduce the simulation time. The smoothed data and final flow input for the upstream boundaries with MORFAC are shown in Figure 5-22 through Figure 5-27 .

Figure 5-24 Daily Discharge and Discretized Data of Low Flow Condition

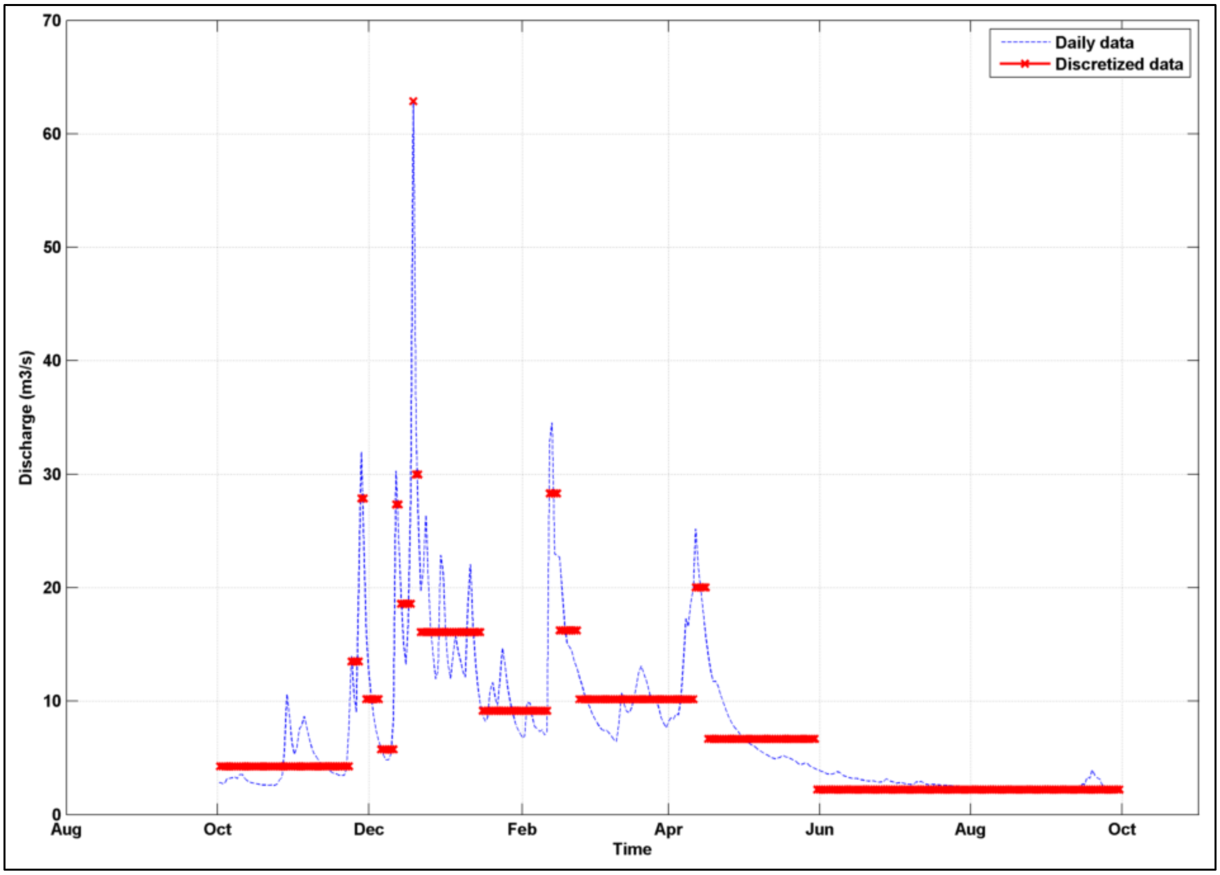
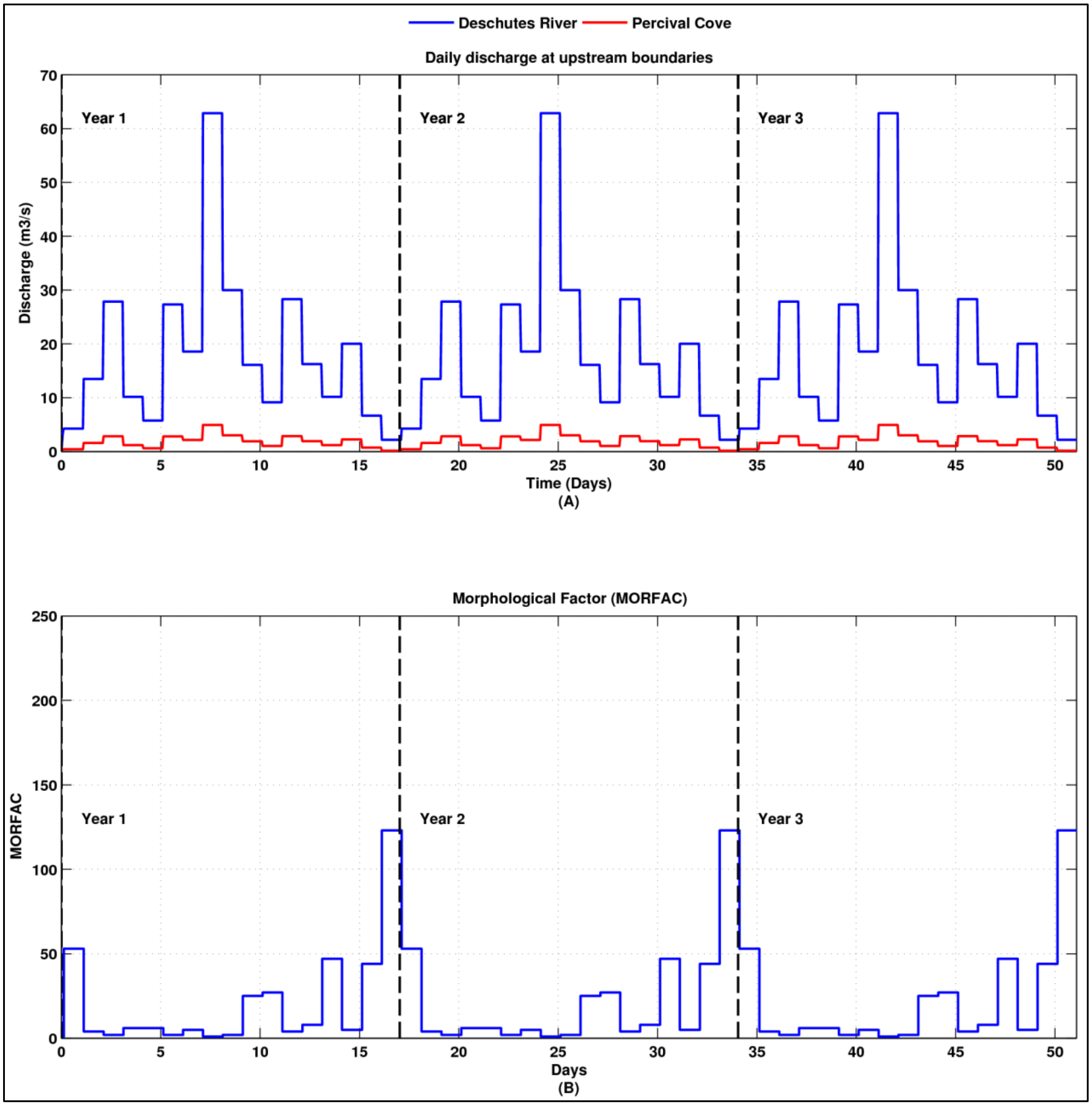


Figure 5-25 3-year Low Flow Condition used in the Estuary and Hybrid Alternatives



(A) Discretized Discharges; (B) MORFAC

Figure 5-26 Daily Discharge and Discretized Data of High Flow Condition

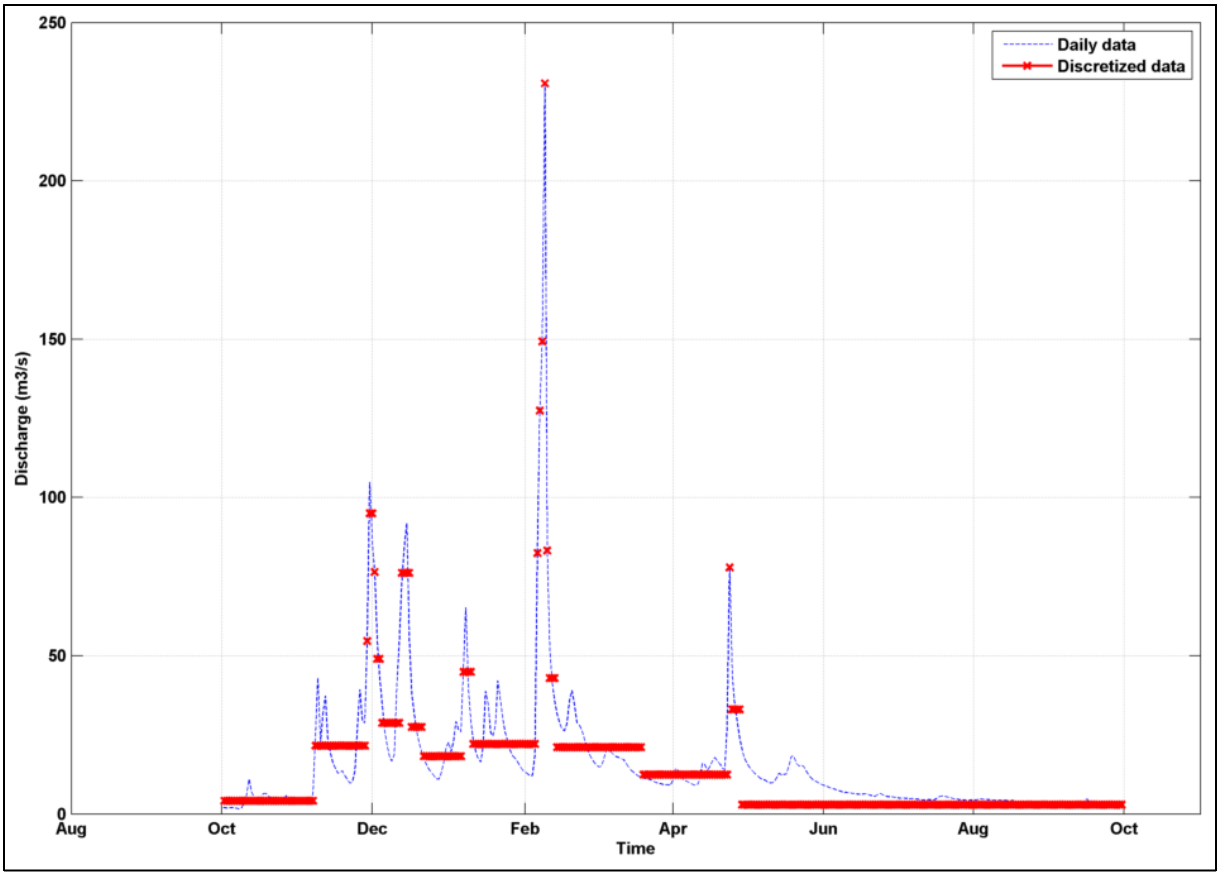
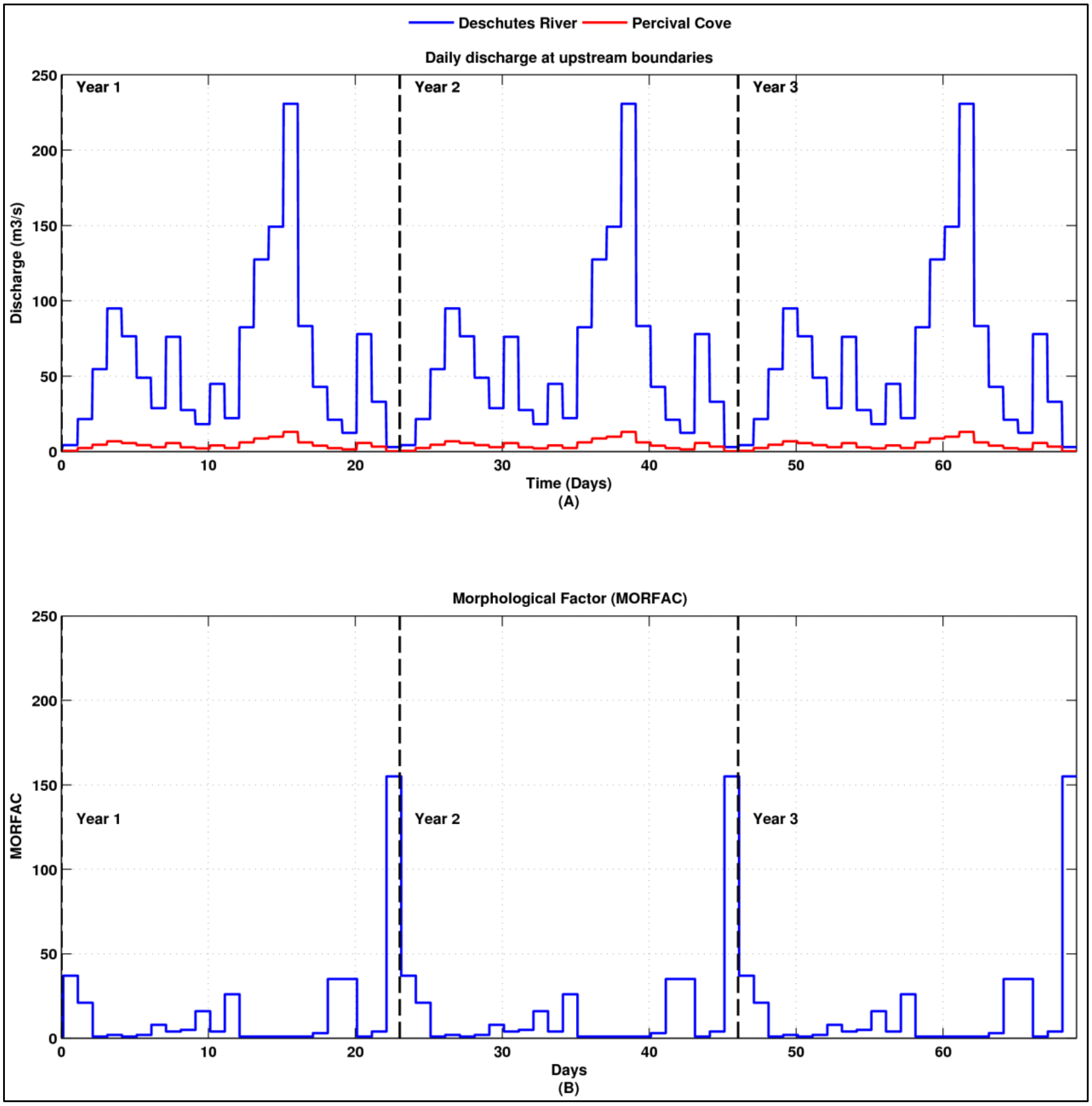


Figure 5-27 Three-year High Flow Condition used in the Estuary and Hybrid Alternatives



(A) Discretized Discharges; (B) MORFAC

5.9 SEDIMENT TRANSPORT MODEL RESULTS

Sediment erosion/deposition within the Capitol Lake Basin as well as Budd Inlet for the four alternatives described in Section 3.0 were assessed using the calibrated long-term morphological model. The model simulates the erosion/deposition over a three-year cycle by simulating sequential storm events which carry sediment load through high freshwater inflows and resuspend sediments within the Capitol Lake Basin. Sediment erosion/deposition patterns were assessed for the following two flow events. For the No Action and Managed Lake Alternatives, the two-dimensional version of Delft3D incorporating salinity and mixing of freshwater and saltwater was used; whereas for the Estuary and Hybrid Alternatives, the three-dimensional version of Delft3D incorporating salinity and mixing of freshwater and saltwater was used:

- Event A: a three-year simulation based on the water year 2019 (10/01/2018 – 09/30/2019) repeating three times in a row (see Figure 5-25), corresponding to a 1-yr flow event occurring three times in a row
- Event B: a three-year simulation based on the water year 1996 (10/01/1995 – 09/30/1996) repeating three times in a row (see Figure 5-27), corresponding to a 115-yr flow event occurring three times in a row

The peak daily discharge for Event A is 63 m^3/s with a return period of approximately 1 year. This peak annual discharge is the lowest measured daily discharge for an annual peak in the last 10 years (2010 to 2020). Modeling Event A represents a low flow scenario and consequently, a lower bound for sediment erosion/deposition.

On the other hand, the peak daily discharge for Event B is the highest daily discharge on record (1945 to 2020). The highest measured daily discharge is 231 m^3/s with a return period of approximately 115 years. Modeling Event B represents a high flow event and, consequently, an upper bound for sediment erosion/deposition. These two events were defined to bracket the possible range of erosion/deposition within Budd Inlet upon removal of the 5th Avenue Dam. A detailed description of these two events and their implementation for the modeling is presented in Section 5.8.

Sediment transport model results in terms of deposition/erosion patterns for both events for the without and with 0.61 m (2.0 ft) of RSLR - were extracted and are presented in Sections 5.9.1 and 5.9.2, respectively.

The value of RSLR equal to 0.61 m (2.0 ft) was selected because the recent City of Olympia SLR Response Plan acknowledges that by the time 0.61 m (2.0 ft) of RSLR occurs, significant physical adaptation measures (e.g. raising the seawall, building a berm) would have been adapted to protect City of Olympia's infrastructure and properties along the shoreline. The Plan acknowledges that SLR projections range higher than 2.0 feet, and that adaptation measures will continue beyond 2.0 feet of rise. Two feet of RSLR is roughly equivalent to a 5% probability of exceedance at 2060 or a 10%

probability of exceedance at 2070, according to the high greenhouse gas estimates from the Projected Sea-Level Rise for Washington State report for Olympia (Miller et al 2018).

The total and annual rates of erosion/deposition are presented herein in meters (m) and centimeters per year (cm/yr), respectively, unless noted otherwise.

Sediment transport model results presented in this section were all developed incorporating salinity. This was because it is likely that capturing the vertical density stratification of the flow could affect the results.

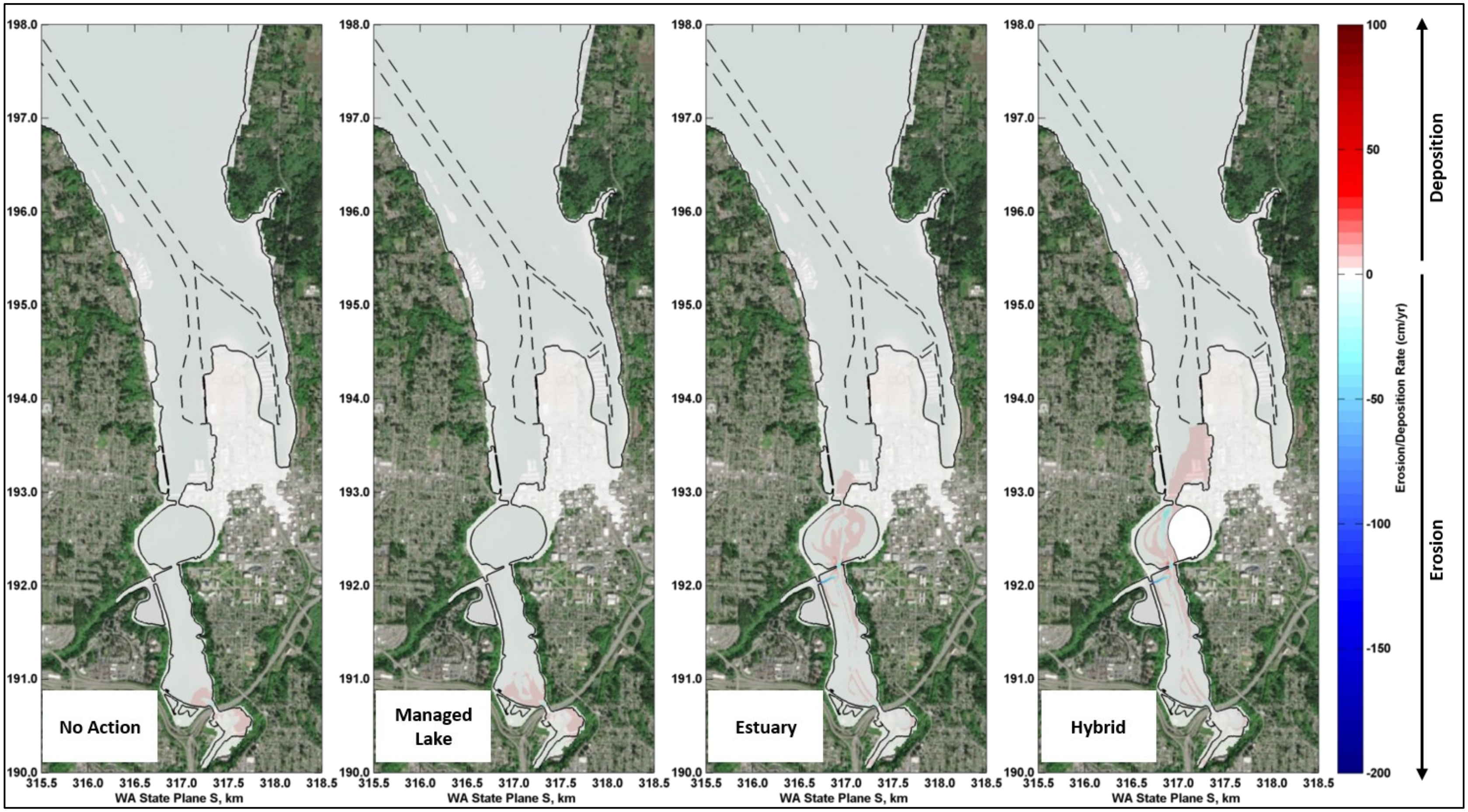
For the No Action and Managed Lake Alternatives, since model calibration/validation demonstrated agreement with measured data (based on survey comparisons) using the 2D with salinity model configuration, this model configuration was used to produce results for these two alternatives. For the Estuary and Hybrid Alternatives, sediment transport model results presented in this section were developed using the 3D model configuration incorporating salinity (3D with salinity).

5.9.1 Without RSLR

Model results in terms of annual deposition/erosion patterns over the entire modeling domain for the four alternatives without RSLR for Events A and B are presented in Figure 5-34 and Figure 5-35, respectively. Model results are presented in terms of annual rate of sediment erosion/deposition averaged over the three-year simulation period.

Additionally, to capture the vertical density stratification of the flow and its potential impact on rates and spatial pattern of sediment deposition model results with (2D + salinity) and (3D with salinity) for the Estuary and Hybrid Alternatives are presented in Figure 5-30 and Figure 5-31, respectively.

Figure 5-28 Erosion/Deposition Pattern (cm/yr) for Event A without RSLR

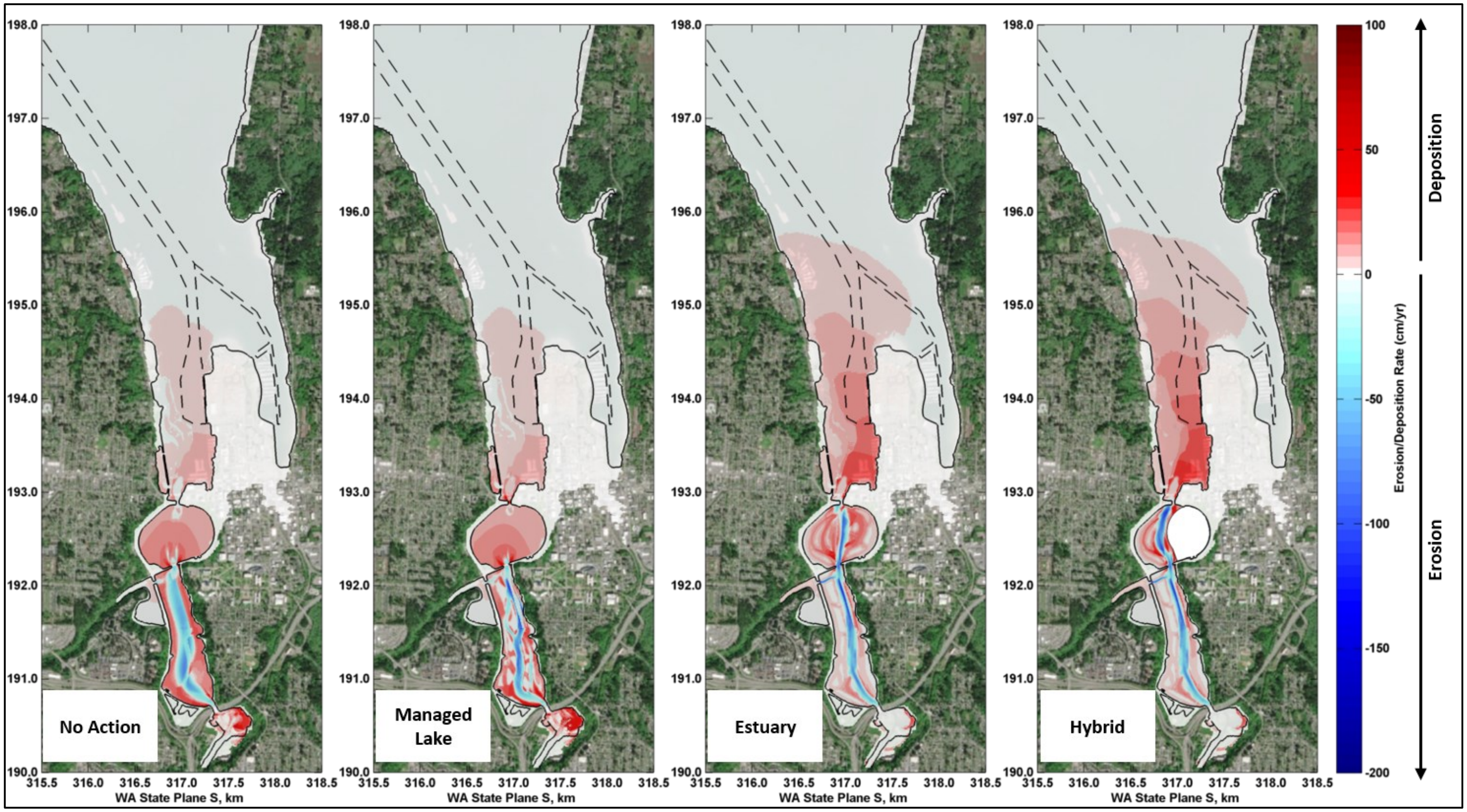


*Event A: a three-year simulation based on the water year 2019 (10/01/2018 – 09/30/2019) repeating three times in a row (see Figure 5-25)

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Figure 5-29 Erosion/Deposition Pattern (cm/yr) for Event B without RSLR

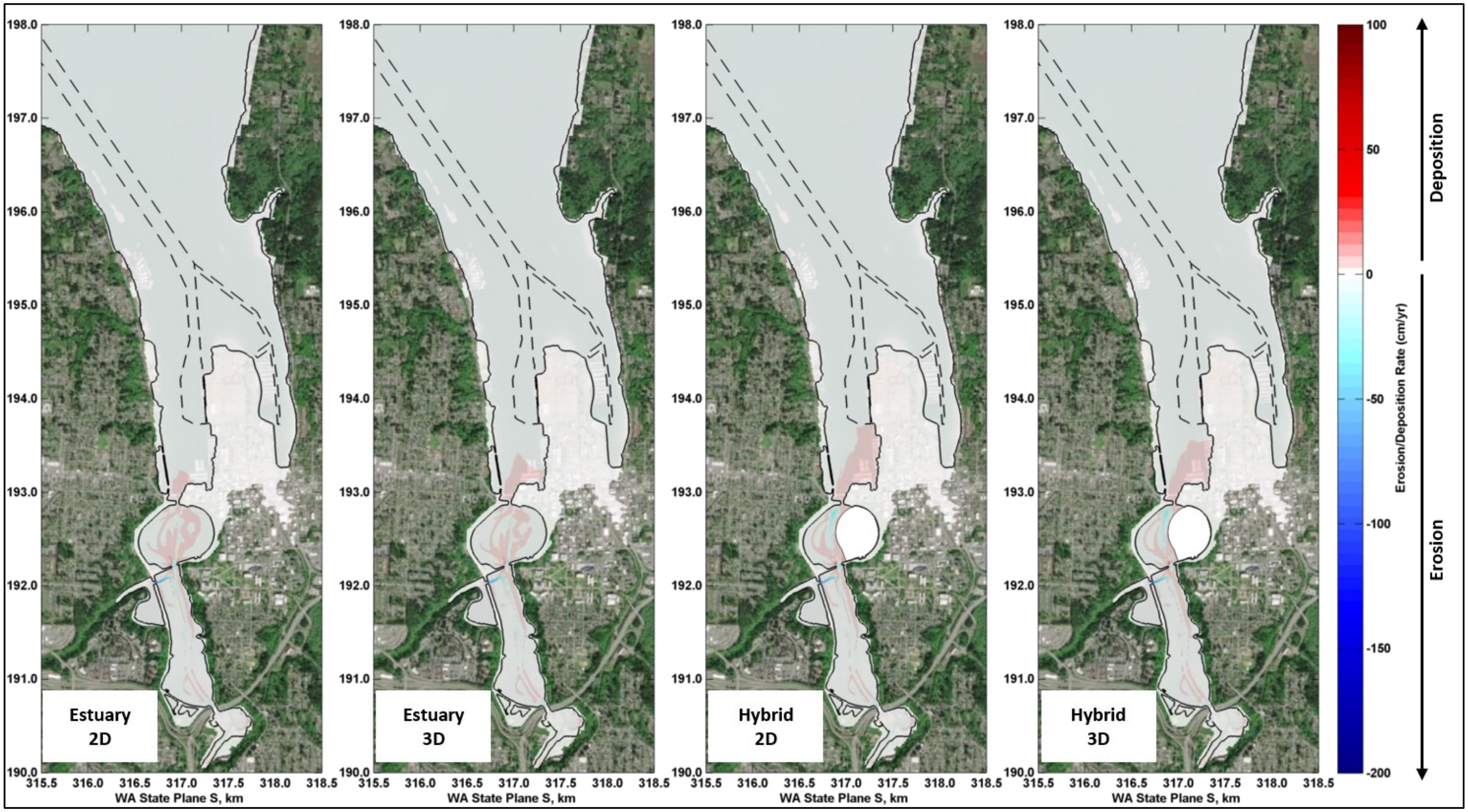


* Event B: a three-year simulation based on the water year 1996 (10/01/1995 – 09/30/1996) repeating three times in a row (see Figure 6.29)

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Figure 5-30: Erosion/Deposition (cm/yr) for Event A with 2D and 3D Models for Estuary and Hybrid Alternatives

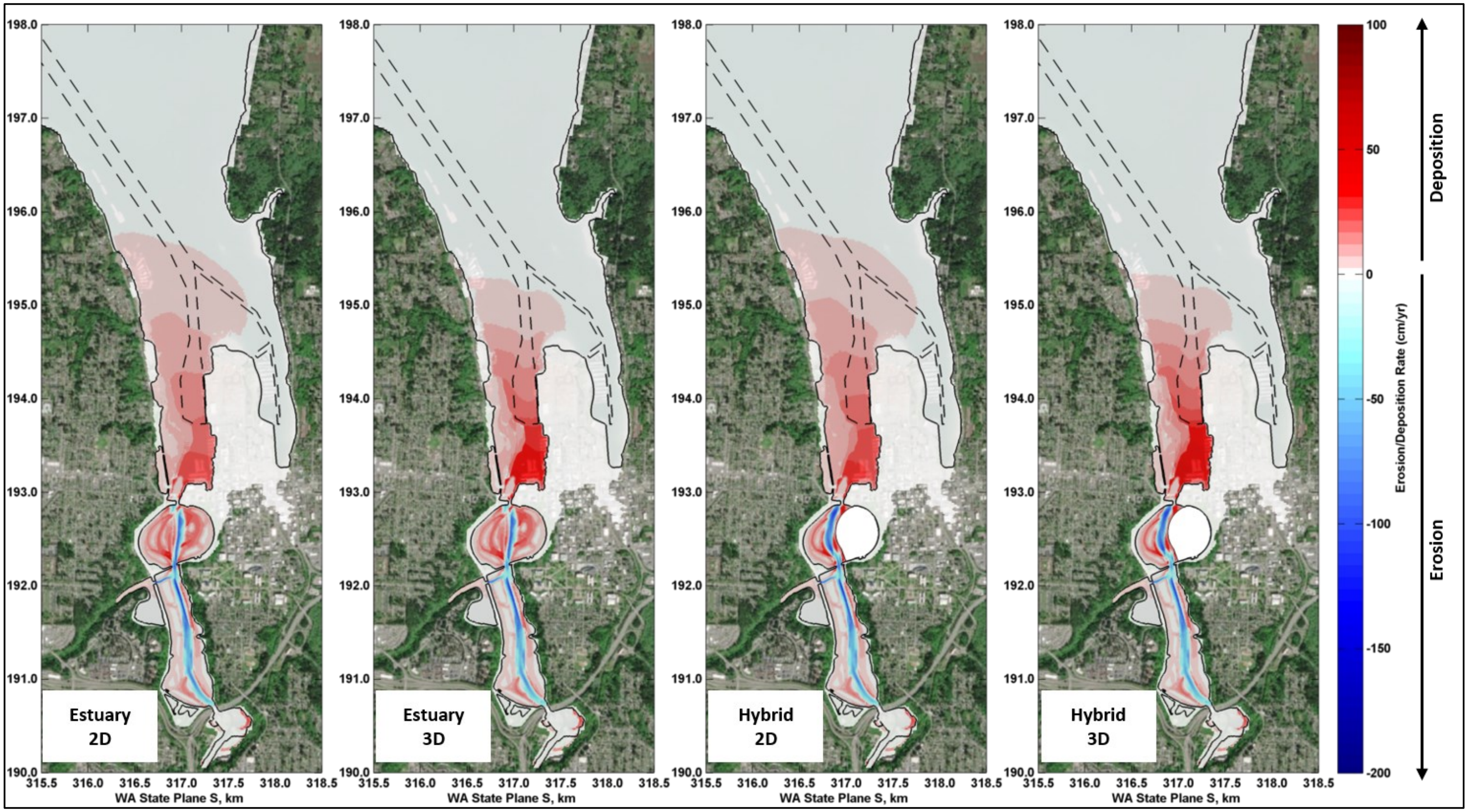


*Event A: a three-year simulation based on the water year 2019 (10/01/2018 – 09/30/2019) repeating three times in a row (see Figure 5-25)

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Figure 5-31: Erosion/Deposition (cm/yr) for Event B with 2D and 3D Models for Estuary and Hybrid Alternatives



* Event B: a three-year simulation based on the water year 1996 (10/01/1995 – 09/30/1996) repeating three times in a row (see Figure 6.29)

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)
Modeled area includes the Capitol Lake Basin, West Bay, East Bay and Budd Inlet south of Gull Harbor

The model results demonstrate that annual erosion/deposition rates in the model domain for Event B are generally higher than that for Event A. This is anticipated because stronger flows associated with Event B will result in higher erosion/deposition rates and more drastic morphological changes compared to Event A.

The model results for both events indicate that removal of the 5th Avenue Dam results in increased sediment deposition within Budd Inlet as sediments get transported farther downstream into the Capitol Lake Basin and Budd Inlet for the Estuary and Hybrid Alternatives. For both modeling events, sediment deposition within Budd Inlet for the Estuary and Hybrid Alternatives is higher than that for the No Action and Managed Lake Alternatives.

The model results for both events indicate that the Hybrid Alternative results in higher rates of deposition within Budd Inlet compared to the Estuary Alternative. This is most likely due to acceleration of the flow within the North Basin as flow is forced to bend around the reflecting pool for the Hybrid Alternative. This acceleration of the flow results in increased erosion within the North Basin and increased deposition within Budd Inlet compared to the Estuary Alternative.

For Event A, for the No Action and Managed Lake Alternatives, sediment deposition is mostly limited to the South and Middle Basins with sediment deposition rates within the rest of the domain (North Basin, Percival Cove, and Budd Inlet) less than 0.2 cm/yr. For the Estuary and Hybrid Alternatives, the sediments are carried farther downstream, increasing deposition at Budd Inlet. For example, sediment deposition at the Olympia Yacht Club increases from 0.1 cm/yr (No Action Alternative) to 1.3 cm/yr for the Estuary Alternative and 2.5 cm/yr for the Hybrid Alternative, see Table 5-16.

For Event B, the model results indicate that removal of the 5th Avenue Dam results in creation of a distinct channel within the North Basin and the transport of sediments farther downstream within Budd Inlet for the Estuary and Hybrid Alternatives. Comparison of model results for the Estuary and No Action Alternatives indicate that removal of the 5th Avenue Dam can result in increased deposition rates within Budd Inlet. For example, sediment deposition at the Olympia Yacht Club increases from 8.3 cm/yr (No Action Alternative) to 20.3 cm/yr for the Estuary Alternative and to 23.4 cm/yr for the Hybrid Alternative, see Table 5-16.

For Event B, the increased deposition at Budd Inlet with removal of the 5th Avenue Dam is associated with a reduction in deposition within the Capitol Lake Basin. For example, sediment deposition at the South Basin reduces from 7.1 cm/yr (No Action Alternative) to 1.6 cm/yr for the Estuary and the Hybrid Alternatives, see Table 5-16.

For Event B, the model results for the No Action and Managed Lake Alternatives demonstrate a similar pattern. However, sediment deposition within Budd Inlet is higher (< 5%) for the No Action Alternative than the Managed Lake Alternative. This is likely due to deepening of the North Basin, which would create a more effective settling basin for the sediments before entering Budd Inlet.

For Event B, the model results indicate that for all alternatives, sediment deposition with the West Bay of Budd Inlet is skewed with higher deposition rates on the east side of West Bay of Budd Inlet. This is due to the presence of an area of shallow intertidal habitat along the remnants of the old trestle on the west side of West Bay within Budd Inlet, see Figure 5-32. This pattern of stronger deposition on the east side of West Bay within Budd Inlet is consistent with findings of previous USGS studies (George et al. 2006 and Stevens et al. 2008).

Figure 5-32: Google Earth Aerial Images during Low Tide for (a) 7/2006 and (b) 8/2011

Model results for the Estuary and Hybrid Alternatives using the (2D with salinity) and (3D with salinity) model configurations for Events A (Figure 5-36) and Event B (Figure 5-37), indicate that use of the 3D with salinity configuration increases rates of sediment deposition within Budd Inlet closer to the 5th Avenue Dam while reducing the footprint of deposition.

Model results indicate that sedimentation will occur throughout West Bay of Budd Inlet under all alternatives for Event B, and at a greater rate under the Estuary and Hybrid Alternatives. Not all areas of sedimentation would result in an impact. For example, sedimentation along the undeveloped western shoreline of West Bay may provide an improvement to existing habitat conditions. However, sedimentation along the developed eastern shoreline of West Bay would result in impacts to existing land uses that depend on sufficient water depth for safe navigation and access. Sedimentation is evaluated at those locations specifically to identify potential impacts.

This study looks at potential impacts to areas of interest including the Olympia Yacht Club, Marinas (Fiddlehead and Martin Marinas), Port of Olympia, Federal Navigation Channel, and the rest of Budd Inlet in addition to Capitol Lake Basins and Percival Cove as areas of interest. Mitigation measures to offset potential project impacts is also evaluated, see Section 5.12. Model results were extracted at select polygons to represent erosion/deposition patterns at these areas of interest and are listed in Table 5-16. The location and boundary of these polygons are shown in Figure 5-33.

Figure 5-33 Polygons for Extracting Sediment Transport Results

Table 5-16 Average Annual Sediment Erosion/Deposition in cm/yr for Modeling Events A and B without RSLR

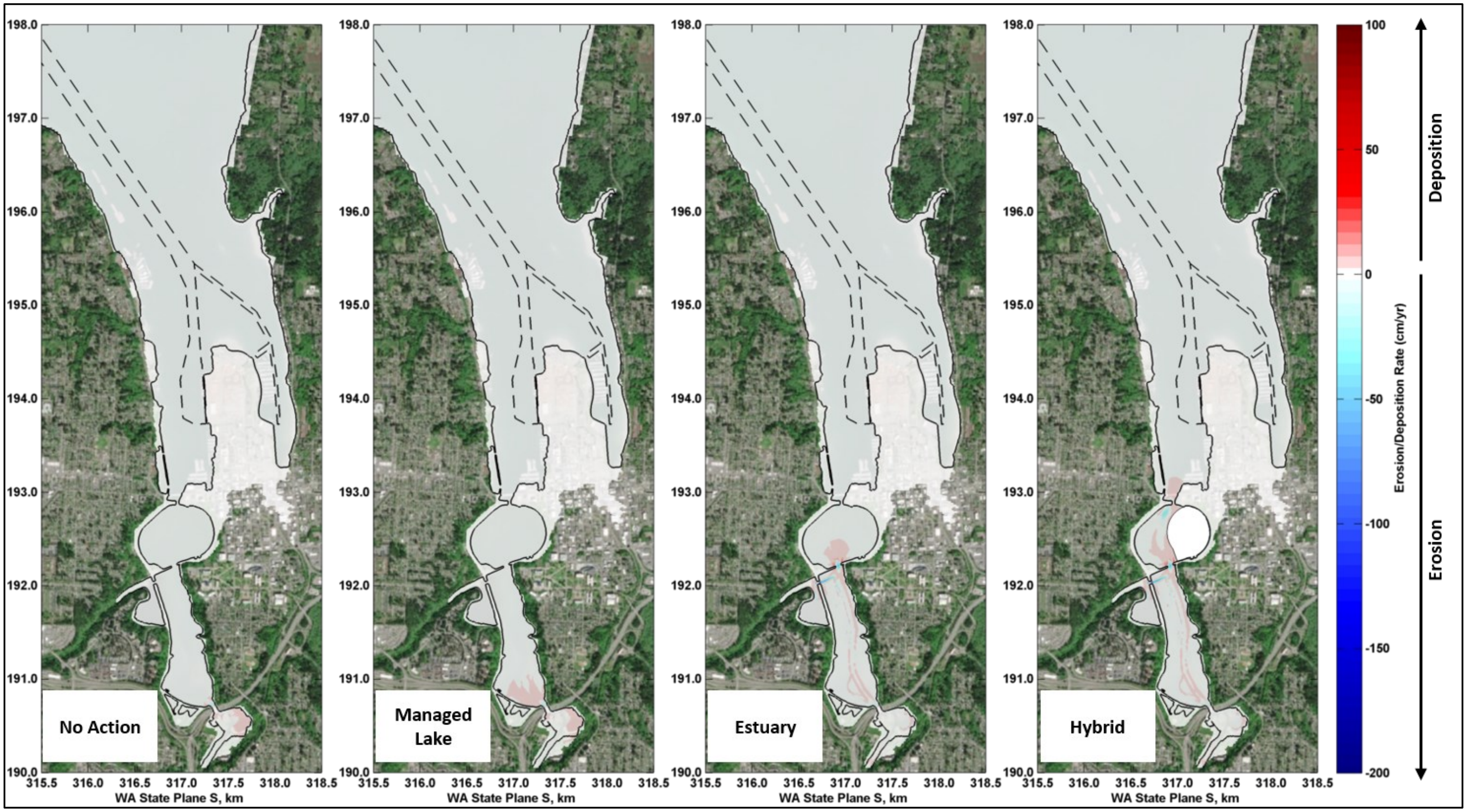
	No Action A	No Action B	Managed Lake A	Managed Lake B	Estuary 2D A	Estuary 2D B	Hybrid 2D A	Hybrid 2D B	Estuary 3D A	Estuary 3D B	Hybrid 3D A	Hybrid 3D B
South Basin	0.6	7.1	0.7	10.0	0.4	1.6	0.4	1.6	0.4	1.6	0.4	1.6
Middle Basin	0.5	-5.2	0.4	-3.9	-0.3	-7.1	-0.1	-6.7	-0.3	-7.1	-0.1	-6.7
Percival Cove	0.1	0.8	0.1	0.7	0.2	1.0	0.2	1.0	0.2	1.0	0.2	1.0
North Basin	0.1	8.7	0.2	8.7	0.8	2.6	-0.1	-3.0	0.7	2.5	-0.3	-3.1
Olympia Yacht Club	0.1	8.4	0.1	8.4	1.3	20.3	2.5	23.4	1.6	29.8	3.2	35.5
Marinas	0.0	4.2	0.0	4.2	0.5	11.0	1.2	12.9	0.5	15.8	1.1	18.8
Port of Olympia & Turning Basin	0.0	4.2	0.0	4.1	0.3	12.6	0.8	15.0	0.2	15.4	0.4	17.9
Navigation Channel (excluding Turning Basin)	0.0	0.2	0.0	0.2	0.0	1.2	0.0	1.4	0.0	0.6	0.0	0.7
Rest of Budd Inlet	0.0	0.2	0.0	0.3	0.0	0.8	0.0	0.9	0.0	0.7	0.0	0.9

5.9.2 With 0.61 m of RSLR

Model results in terms of annual deposition/erosion patterns over the entire modeling domain for the four alternatives with RSLR for low flow and high flow are presented in Figure 5-34 and Figure 5-35, respectively.

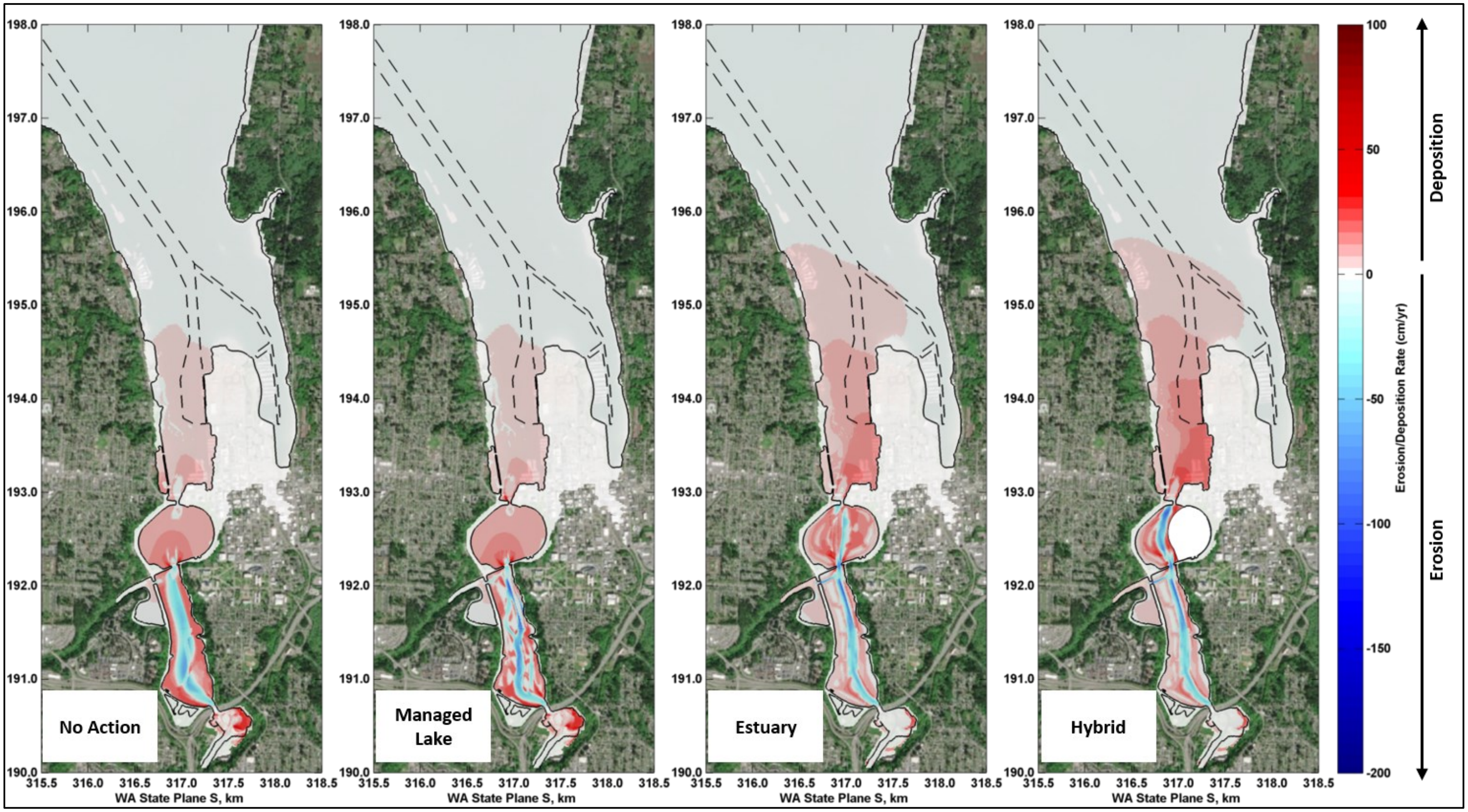
Model results in terms of annual rate of sediment thickness changes averaged over the three years for Event A and B were computed at select polygons (see Figure 5-33) and the results with RLSR are listed in Table 5-17.

Figure 5-34 Erosion/Deposition Pattern (cm/yr) for Event A with 0.61m of RSLR



*Event A: a three-year simulation based on the water year 2019 (10/01/2018 – 09/30/2019) repeating three times in a row (see Figure 5-25)
** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)
Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Figure 5-35 Erosion/Deposition (cm/yr) for Event B with 0.61m of RSLR

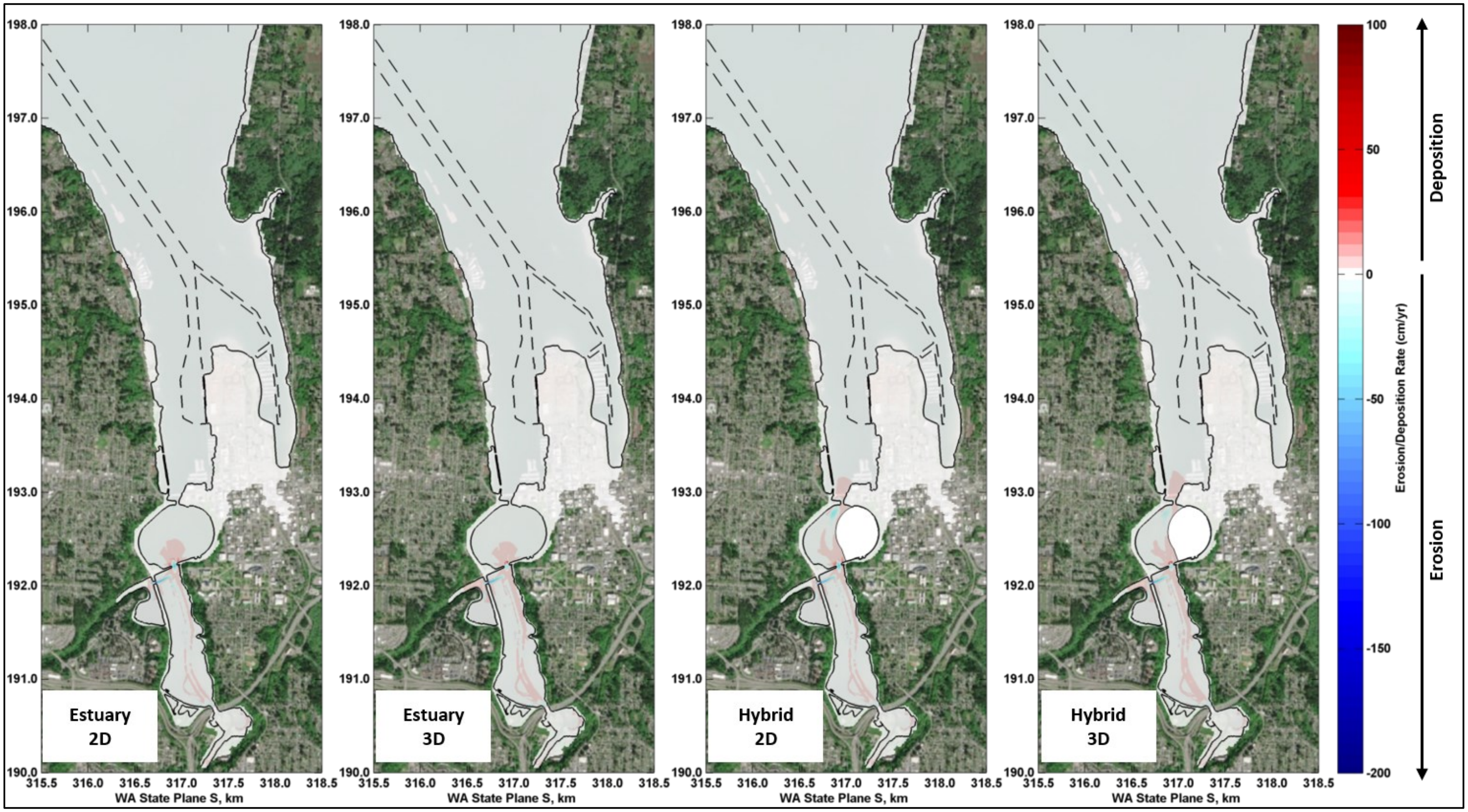


* Event B: a three-year simulation based on the water year 1996 (10/01/1995 – 09/30/1996) repeating three times in a row (see Figure 6.29)

** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

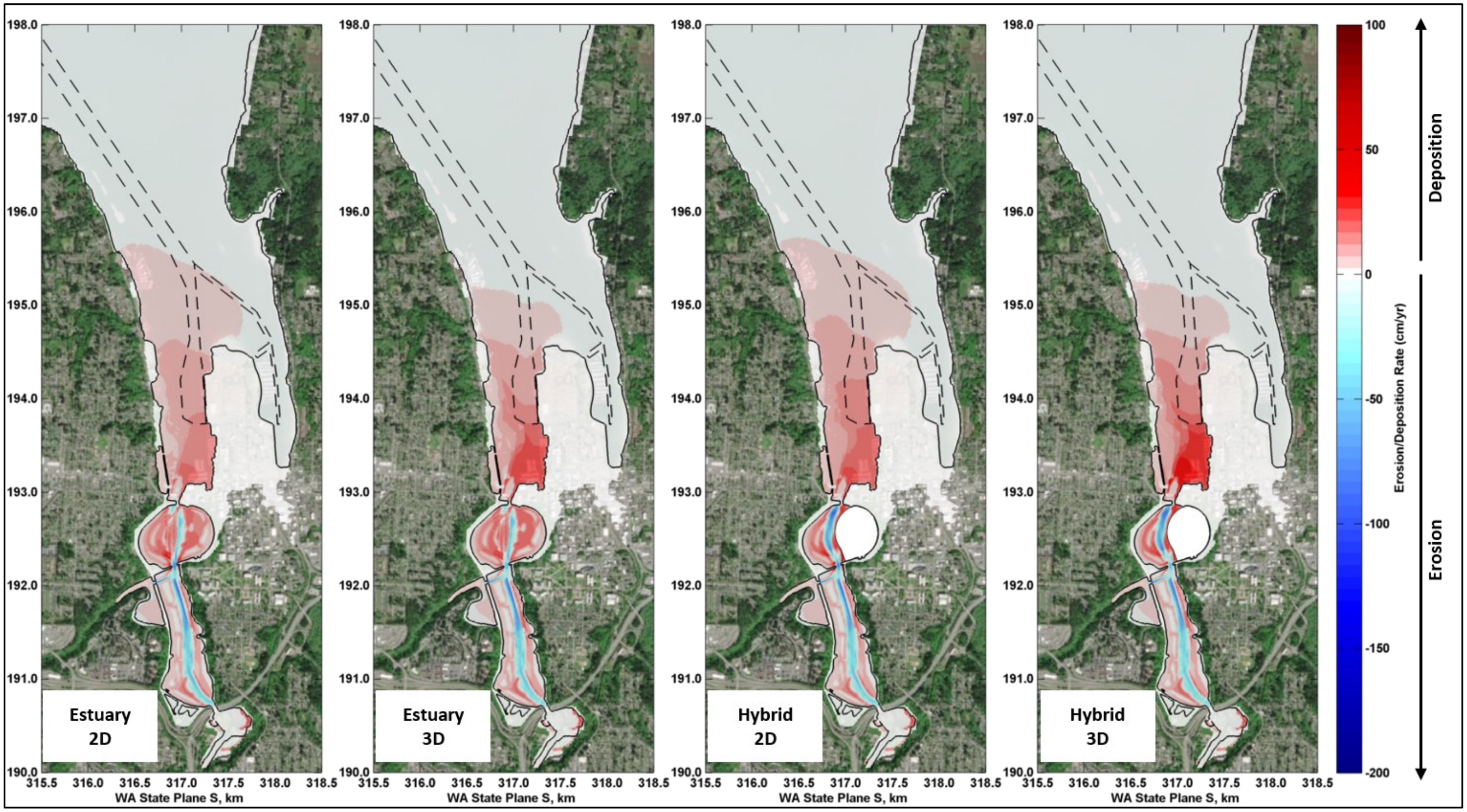
Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Figure 5-36: Erosion/Deposition (cm/yr) for Event A with 2D and 3D Models for Estuary and Hybrid Alternatives with 0.61 m of RSLR



*Event A: a three-year simulation based on the water year 2019 (10/01/2018 – 09/30/2019) repeating three times in a row (see Figure 5-25)
** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)
Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Figure 5-37: Erosion/Deposition (cm/yr) for Event B with 2D and 3D Models for Estuary and Hybrid Alternatives with 0.61 m of RSLR



* Event B: a three-year simulation based on the water year 1996 (10/01/1995 – 09/30/1996) repeating three times in a row (see Figure 6.29)
** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)
Modeled area includes the Capitol Lake Basin, West Bay, East Bay and Budd Inlet south of Gull Harbor

Table 5-17 Average Annual Sediment Erosion/Deposition in cm/yr for Modeling Events A and B with 0.61 m of RSLR

	No Action A	No Action B	Managed Lake A	Managed Lake B	Estuary 2D A	Estuary 2D B	Hybrid 2D A	Hybrid 2D B	Estuary 3D A	Estuary 3D B	Hybrid 3D A	Hybrid 3D B
South Basin	0.6	6.1	0.7	5.9	0.4	1.9	0.4	1.9	0.4	1.8	0.4	1.8
Middle Basin	0.4	-3.5	0.6	-3.5	-0.1	-4.7	0.0	-4.3	0.0	-4.6	0.0	-4.3
Percival Cove	0.1	0.8	0.1	0.8	0.2	1.3	0.3	1.3	0.3	1.1	0.3	1.2
North Basin	0.1	7.6	0.1	7.8	0.7	5.3	0.1	-1.2	0.6	5.4	0.2	-1.2
Olympia Yacht Club	0.0	6.7	0.1	6.4	0.5	15.1	1.2	19.0	0.3	21.7	1.1	28.6
Marinas	0.0	3.3	0.0	3.3	0.2	8.5	0.6	10.7	0.1	12.1	0.4	15.8
Port of Olympia & Turning Basin	0.0	3.1	0.0	3.1	0.1	9.2	0.3	11.8	0.0	10.5	0.1	13.1
Navigation Channel (excluding Turning Basin)	0.0	0.1	0.0	0.1	0.0	0.9	0.0	1.1	0.0	0.4	0.0	0.5
Rest of Budd Inlet	0.0	0.2	0.0	0.2	0.0	0.7	0.0	0.8	0.0	0.6	0.0	0.8

The model results for both events with 0.61 m of RSLR demonstrate a similar pattern to results under the without RSLR conditions. General observations and findings for the without RSLR listed in Section 5.9.1 remain valid for with RSLR as well.

For Event A, the model results indicate that deposition/erosion under the with RSLR conditions have a similar pattern and approximately the same rates as that of the without RSLR conditions, see Table 5-17 and Table 5-16, respectively.

For Event B, differences in deposition/erosion between the with and without RSLR conditions are more noticeable than Event A. In general, the deposition/erosion rates are reduced with implementing a 0.61 m of RSLR. This is likely due to the higher water levels associated with implementing RSLR resulting in reduced current velocities and reduced erosion of sediments in the Middle Basin. For example, for the Estuary Alternative, erosion in the Middle Basin reduces from -7.1 cm/yr (without RSLR) to -4.7 cm/yr (with RSLR). This reduction in erosion at the Middle Basin will result in a reduction in sediment supply for the system and a consequent reduction in deposition at Budd Inlet. It should be acknowledged that the 'with RSLR' scenario, did not account for any future sediment deposition within the Capitol Lake Basin that would result in reduced water depth within the basin.

Model results for the Estuary and Hybrid Alternatives using the (2D with salinity) and (3D with salinity) model configurations for Events A (Figure 5-36) and Event B (Figure 5-37), indicate that use of the 3D with salinity configuration increases rates of sediment deposition within Budd Inlet closer to the 5th Avenue Dam while reducing the footprint of deposition.

5.10 DISCUSSION

Historically, the Capitol Lake – Deschutes Estuary and the area that is now Capitol Lake was a part of Budd Inlet, consisting of intertidal mudflats that typically form at the mouths of estuaries. Construction of the 5th Avenue Dam has blocked the tidal exchange between the Deschutes River and Budd Inlet and has prevented tidal flow across the mudflats.

Capitol Lake now provides a settling basin for sediments transported by the Deschutes River. It is expected that removal of the 5th Avenue Dam would gradually transform the system back to its historical conditions prior to construction of the dam.

Historical and recent patterns and rates of erosion/deposition within the Capitol Lake Basin as well as Budd Inlet (including the Port, Marinas, and Federal Navigation Channel) can be directly estimated by comparing available bathymetric surveys (provided dredging did not occur between the surveys). For the No Action Alternative, these direct estimates provide a more realistic representation of the erosion/deposition pattern compared to estimates developed by the numerical modeling presented herein. These direct estimates of erosion/deposition can be used in lieu of modeling results for the No Action Alternative. However, these estimates are constrained by the number, coverage, and time period between available bathymetric surveys.

Main findings of the sediment transport modeling presented in this section can be summarized as follows:

- The model results demonstrate that annual erosion/deposition rates in the model domain for Event B (high flow) are generally higher than that for Event A (low flow). This is anticipated because stronger flows associated with Event B will result in higher deposition/erosion rates and more drastic morphological changes compared to Event A.
- The model results for both events indicate that removal of the 5th Avenue Dam results in increased sediment deposition within Budd Inlet as sediments get transported farther downstream into the Capitol Lake Basin and Budd Inlet for the Estuary and Hybrid Alternatives. For both modeling events, sediment deposition within Budd Inlet for the Estuary and Hybrid Alternatives is higher than that for the No Action and Managed Lake Alternatives.
- The model results for both events indicate that the Hybrid Alternative results in higher rates of deposition within Budd Inlet compared to the Estuary Alternative. This is most likely due to acceleration of the flow within the North Basin as flow is forced to bend around the reflecting pool for the Hybrid Alternative. This acceleration of the flow results in increased erosion within the North Basin and increased deposition within Budd Inlet compared to the Estuary Alternative.
- For Event B, the model results indicate that for all alternatives, sediment deposition with Budd Inlet is skewed with higher deposition rates on the east side of Budd Inlet. This is due to the presence of an area of shallow intertidal habitat along the remnants of the old trestle on the west side of Budd Inlet. This pattern of stronger deposition on the east side of Budd Inlet is consistent with findings of previous USGS studies (George et al. 2006 and Stevens et al. 2008).

5.11 CONCLUSIONS

Main conclusions of the sediment transport/morphology numerical simulations are as follows. Model results in terms of erosion/deposition rates are summarized in Table 5-18.

- In the No Action Alternative, the 5th Avenue Dam controls (slows down) the fast-moving river flow during extreme hydrologic events. As a result, the North Basin and flanks of Middle Basin function as a settling basin that captures most of the river-borne sediments before the flow enters Budd Inlet.
- The Managed Lake Alternative can result in increased (4%) sediment deposition within the North Basin and small changes (< 4%) in sediment deposition within Budd Inlet under high flow events, compared to the No Action Alternative. This is likely due to deepening of the North Basin which would create a more effective settling basin for the sediments before entering Budd Inlet.

- The Estuary Alternative, compared to the No Action Alternative, can result in up to 283% increase in sediment deposition within Budd Inlet and 64% decrease in deposition within the North Basin under high flow events. This change in deposition rates and patterns occurs because the river-borne sediments are transported into Budd Inlet instead of settling within the North Basin during extreme hydrologic events.

  In the Estuary Alternative, with removal of the 5th Avenue Dam, the fast-moving river flow will not be controlled (slowed down) by the dam and the Middle and North Basins can experience increased flow velocities. Consequently, the Estuary Alternative, compared to the No Action Alternative, can result in deepening/widening of the channel in the Middle and North Basins. In addition, the Estuary Alternative can result in transport and deposition of Deschutes River sediments that would have been captured by the North Basin in Budd Inlet. Therefore, the increase in sediment deposition within Budd Inlet will not be uniform and the areas immediately downstream of the 5th Avenue Dam will experience higher rates of sediment deposition with decreasing deposition farther away from the dam.

- The Hybrid Alternative, compared to the No Action Alternative, can result in transport and deposition of Deschutes River sediments, that would have been captured by the North Basin, into Budd Inlet. Therefore, up to 366% increase in sediment deposition within Budd Inlet and (<138%) decrease within North Basin can occur as sediments get transported into Budd Inlet instead of settling within the North Basin during extreme flow events. The Hybrid Alternative, compared to the Estuary Alternative, can result in higher (up to 23%) rates of deposition within Budd Inlet and an erosional pattern within North Basin instead of a depositional pattern.

- Numerical simulations of the four alternatives were conducted with 0.61 m (2 ft) of RSLR. Model results showed that all four alternatives perform similarly with and without 0.61 m of RSLR. However, the erosion/deposition rates are lower with RSLR than that without. This is likely due to the higher water levels associated with RSLR resulting in reduced flow velocities and reduced erosion of sediments in the Middle Basin. Reduced erosion of sediments in the Middle Basin will consequently result in reduced deposition within Budd Inlet.

Table 5-18: Average Annual Sediment Erosion/Deposition in (cm/yr) for Modeling with and without 0.61 m (2 ft) RSLR

	No Action w/o RSLR	No Action w RSLR	Managed Lake w/o RSLR	Managed Lake w RSLR	Estuary w/o RSLR	Estuary w RSLR	Hybrid w/o RSLR	Hybrid w RSLR
South Basin (% Change w.r.t. No Action)	3.9	3.4	5.4 (39%)	3.3 (-2%)	1.0 (-75%)	1.1 (-67%)	1.0 (-75%)	1.1 (-67%)
Middle Basin (% Change w.r.t. No Action)	-2.4	-1.6	-1.7 (-28%)	-1.5 (-7%)	-3.7 (54%)	-2.3 (46%)	-3.4 (44%)	-2.2 (37%)
Percival Cove (% Change w.r.t. No Action)	0.4	0.4	0.4 (-15%)	0.4 (-1%)	0.6 (43%)	0.7 (67%)	0.6 (44%)	0.7 (71%)
North Basin (% Change w.r.t. No Action)	4.4	3.8	4.5 (2%)	4.0 (4%)	1.6 (-64%)	3.0 (-21%)	-1.7 (-138%)	-0.5 (-113%)
Olympia Yacht Club (% Change w.r.t. No Action)	4.2	3.4	4.3 (1%)	3.2 (-4%)	15.7 (271%)	11.0 (228%)	19.4 (358%)	14.8 (341%)
Marinas (% Change w.r.t. No Action)	2.1	1.7	2.1 (-1%)	1.7 (0%)	8.2 (283%)	6.1 (268%)	9.9 (366%)	8.1 (387%)
Port of Olympia & Turning Basin (% Change w.r.t. No Action)	2.1	1.5	2.1 (-2%)	1.6 (2%)	7.8 (265%)	5.3 (239%)	9.1 (328%)	6.6 (328%)
Navigation Channel (excluding Turning Basin) (% Change w.r.t. No Action)	0.1	0.1	0.1 (-4%)	0.1 (0%)	0.3 (195%)	0.2 (236%)	0.3 (234%)	0.3 (304%)
Rest of Budd Inlet	0.1	0.1	0.1 (17%)	0.1 (1%)	0.4 (236%)	0.3 (200%)	0.4 (300%)	0.4 (285%)

Event A (low flow): a three-year simulation based on the water year 2019 (10/01/2018 – 09/30/2019) repeating three times in a row (see Figure 5 27). This is the lowest peak annual discharge in the last 10 years.

Event B (high flow): a three-year simulation based on the water year 1996 (10/01/1995 – 09/30/1996) repeating three times in a row (see Figure 5 29). This is the highest annual discharge on the record.

5.11.1 Modeling Assumptions and Limitations

There are inherent limitations to any numerical simulation of physical processes. These limitations should be kept in mind when interpreting model results. Some of the limitations and assumptions for this study are as follows:

- The physical processes deriving the sediment transport and morphologic changes within estuaries are quite complex. Presence of multiple sediment classes adds additional complexity to these morphological processes. Despite significant recent advances in numerical simulations of these processes, state of the art modeling capabilities for prediction of sediment transport within estuaries are associated with a level of uncertainty higher than that of hydrodynamics. These uncertainties are associated with model design, sediment transport theory, and field data.
- The model results for Estuary and Hybrid Alternatives, predict conditions in an environmental setting (without presence of the 5th Avenue Dam) that does not currently exist. To the best of our knowledge, there are no estimates of sediment deposition/erosion patterns within the Lower Deschutes Estuary prior to construction of the 5th Avenue Dam. Model calibration/validation for this study used sensitivity testing to characterize uncertainties in model prediction.
- Long-term simulations of sediment transport within estuaries rely on parallel computation and use of MORFAC for keeping the computational time for each simulation reasonable. Use of MORFAC assumes a linear relationship between hydrodynamics and sediment deposition/erosion within the estuary. Hydrodynamic and morphologic behavior of the No Action and Managed Lake Alternatives is heavily influenced by the non-linear gate operation and inhibited use of MORFAC. Additionally, the complex gate operation was simulated in the Delft3D model using the RTC feature, which could not be implemented for parallel computations at the time that this study started.
- The lookup table approach was used for the No Action and Managed Lake Alternatives because of these two constraints: inability to use MORFAC because of non-linear gate operation and inability to use RTC within parallel computations. To keep the computational times reasonable, the standard and significantly faster MORFAC approach was implemented for the Estuary and Hybrid Alternatives. The former approach (use of lookup table) can have higher levels of uncertainty compared to that of MORFAC approach. This modeling effort relied on available long-term estimates of sediment deposition within the Capitol Lake and Budd Inlet to refine uncertainties in estimates of sediment deposition/erosion within the estuary.
- Two different sediment transport modeling approaches were used herein depending on whether the 5th Avenue Dam was present, and the gate operation had to be simulated for each alternative. The MORFAC approach was used for the Estuary and Hybrid Alternatives

while the lookup table was used for the No Action and Managed Lake Alternatives. This limitation should be acknowledged when comparing results for the No Action Alternative with results for the Estuary or Hybrid Alternatives. Direct estimates of sediment erosion/deposition for the No Action Alternative (developed based on comparison of available surveys) can be used to support this comparison.

- Composition (type, distribution, and thickness) of lakebed sediments can influence the results of the sediment deposition/erosion. There is an inherent limitation in representing a realistic composition of present lakebed sediments given limited available field data. Model calibration/validation for this study used sensitivity testing to quantify uncertainties in model prediction associated with variability in lakebed sediment composition.
- Sediment input to the Capitol Lake –Deschutes estuary can influence the results of sediment deposition/erosion. The sediment input is typically represented by a sediment rating curve. There are inherent uncertainties associated with any sediment rating curve because rating curves are developed based on limited field measurements. The model calibration/validation treated the sediment input as a calibration parameter and refined the sediment input based on available survey data.

5.12 IMPACTS AND MITIGATION

Sediment transport/morphology simulations indicated that parts of Budd Inlet can experience higher rates of sediment deposition under the Estuary and Hybrid Alternatives, compared to the No Action Alternative. This increase in deposition rates over Budd Inlet will not be uniform and will reduce with distance from the 5th Avenue Dam. It is expected that areas closer to the 5th Avenue Dam (e.g. Olympia Yacht Club) will experience higher sedimentation rates compared to other marinas and the Port.

5.12.1 Included Measures to Avoid and Minimize Potential Impacts

To reduce higher sediment deposition rates within Budd Inlet associated with removal of the 5th Avenue Dam (under the Estuary and Hybrid Alternatives), pre-dredging the Capitol Lake Basin was included in design of the Estuary Alternative. Pre-dredging the Capitol Lake Basin, already implemented in design, includes widening/deepening the channel within the Middle Basin and dredging the North Basin before the existing 5th Avenue Dam is removed. This dredging will remove the sediment source that will be available to the fast-moving flows during extreme hydrologic events that can be eroded from the Middle and North Basins and deposited in Budd Inlet.

Model elevations of the basin with and without pre-dredging were developed and are shown in Figure 5-38. The model results with and without pre-dredging for Event B (high flow) are shown in Figure 5-39 and listed in Table 5-19. Model results demonstrate that pre-dredging Capitol Lake before removal of the 5th Avenue Dam reduces erosion within the Middle and North Basins and results in lower rates of deposition in Budd Inlet. This is anticipated because pre-dredging removes the sediment source that would have been available to be eroded from the Middle Basin. Additionally, pre-dredging the Middle

Basin results in a deeper river channel and smaller flow velocities and consequently, less erosion in the Middle Basin can be expected.

Comparison of model results for the Estuary alternative with and without pre-dredging shows that sediment erosion in the Middle Basin decreases from -20.4 cm/yr to -7.1 cm/yr (65% decrease), and sediment deposition at the Olympia Yacht Club decreases from 39.6 cm/yr to 20.3 cm/yr (48% decrease). Model results show that pre-dredging Capitol Lake Basin is effective in reducing sediment deposition in Budd Inlet. This understanding informed the design and development of the Estuary Alternative, described in Section 3.0.

Figure 5-38: Model Elevation for the Estuary Alternative with and without Pre-Dredging the Basin

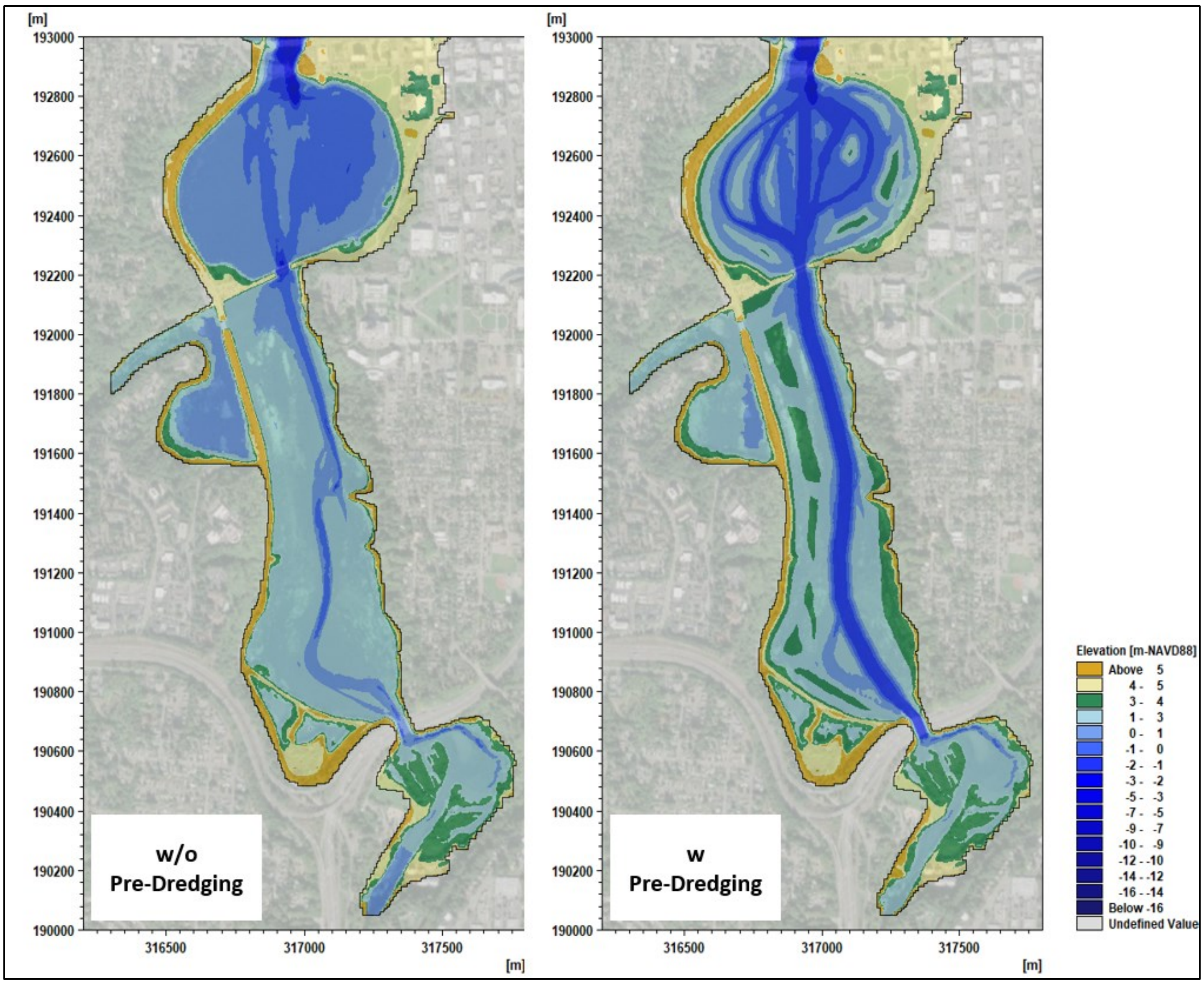
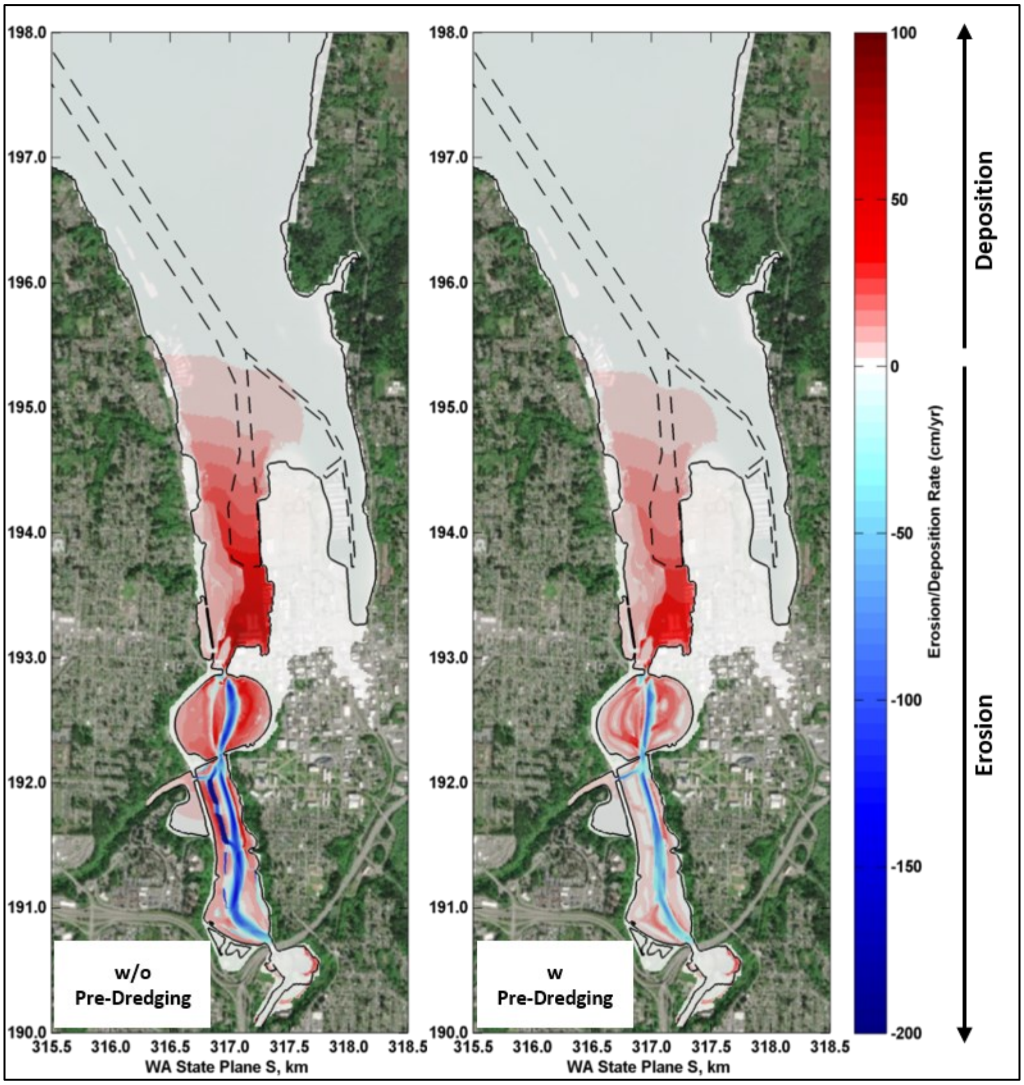


Figure 5-39: Erosion/Deposition (cm/yr) for the Estuary Alternative with and without Pre-Dredging



** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Table 5-19: Sediment Erosion/Deposition (cm/yr) for the Estuary Alternative with and without Pre-Dredging for Event B (High Flow)

	With Pre-Dredging	Without Pre-Dredging
South Basin	1.6	1.9
Middle Basin	-7.1	-20.4
Percival Cove	1.0	1.6
North Basin	2.6	3.4
Olympia Yacht Club	20.3	39.6
Marinas	11.0	19.6
Port	12.6	20.3
Federal Navigation Channel	1.2	1.6
Rest of Budd Inlet	0.8	1.2

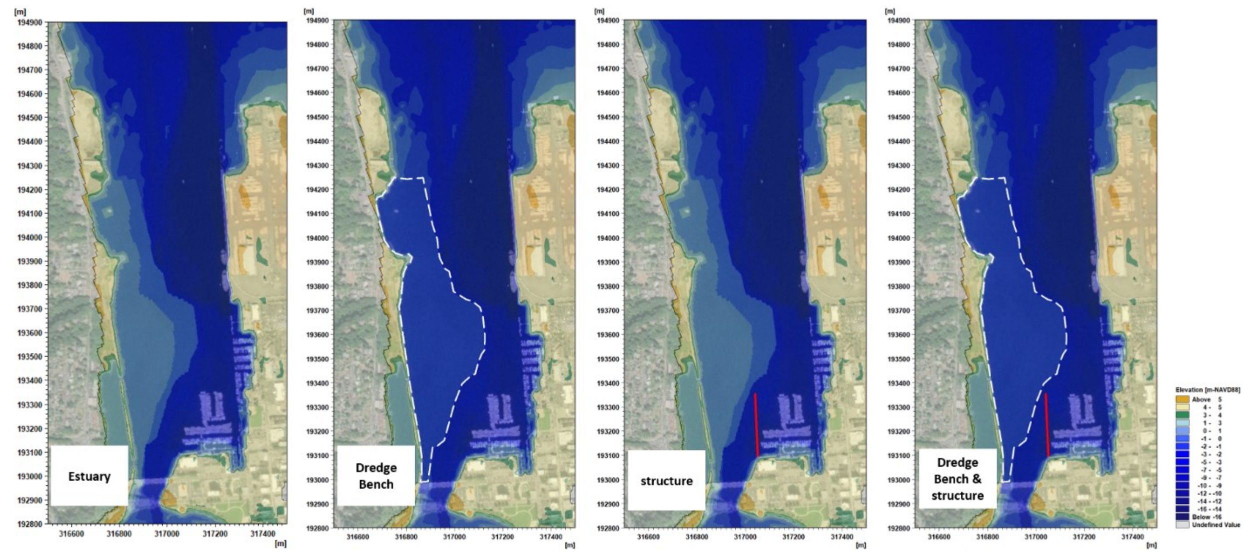
5.12.2 Mitigation Measures

Various mitigation measures and their influence on sediment deposition in Budd Inlet were evaluated. These measures, if effective at reducing sediment deposition in Budd Inlet, could be implemented to minimize sediment deposition under the Estuary and Hybrid Alternatives. The following measures were investigated:

- Measure #1, Dredging the Shallow Bench: includes dredging the intertidal and subtidal bench immediately downstream of the 5th Avenue Dam, see Figure 5-32. Model results showed that this bench forces the Deschutes River flow exiting the North Basin to bend towards the east side of West Bay within Budd Inlet, which moves sediment deposition toward he land uses on the east side of West Bay. Dredging this bench could potentially result in a uniform pattern of deposition across the width of West Bay of Budd Inlet and reduced deposition at the Olympia Yacht Club and Marinas.
- Measure #2, Sediment Control Structure: includes constructing a control structure (e.g. a vertical wall) to the west of Olympia Yacht Club to force the Deschutes River flow exiting the North Basin to stay on the west side of the Olympia Yacht Club and Marinas, minimizing potential sediment deposition at the Olympia Yacht Club and Marinas.
- Measure #3, Dredging the Shallow Bench and Sediment Control Structure: includes combining Measures #1 and #2.
- Measure #4, Sediment Trap: includes dredging a settling basin immediately downstream of the 5th Avenue Dam to create a sediment trap to capture some of the river-borne sediments before they are transported and deposited in the Budd Inlet, see Figure 5-42.
- Measure #5, Dredged Channel: includes dredging a channel connecting deep areas of the North Basin with the Federal Navigation Channel to direct the fast-moving flow and contain the deposition along this channel as much as possible, see Figure 5-42.

To investigate the potential effect of dredging the shallow bench downstream of the 5th Avenue Dam and constructing a sediment control structure (Measures #1 to #3) on sediment deposition in Budd Inlet, model elevations representing these measures were developed, see Figure 5-40. Model results for the Estuary Alternative and these three measures for Event B without RSLR are shown in Figure 5-41.

Figure 5-40: Model Elevations for the Estuary Alternative with Dredging the Bench and Control Structure

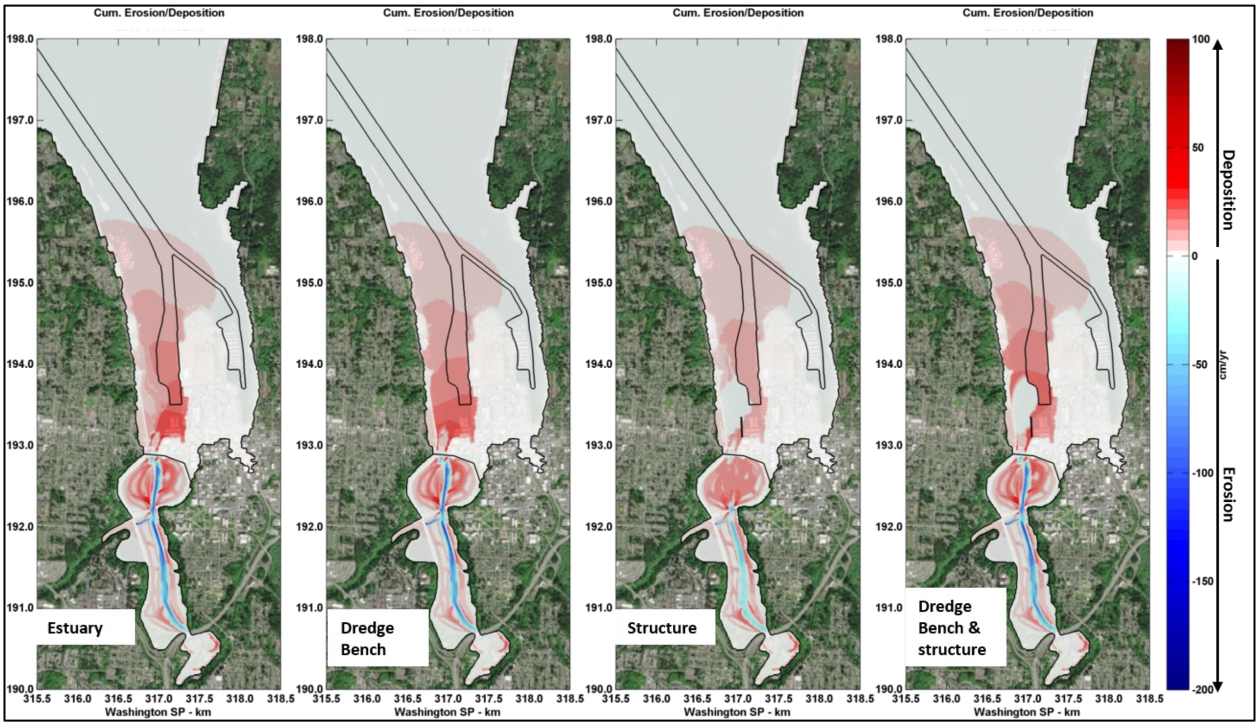


The model results for Measure #1 (dredging the shallow bench on the west side of the West Bay within Budd Inlet) can result in a more uniform sediment deposition across the width of the West Bay within Budd Inlet. This uniform sediment deposition means reduced deposition on the east side and increased deposition on the west side of the West Bay within Budd Inlet, compared to the Estuary and Hybrid Alternatives. This mitigation measure may have unintended adverse impacts to the aquatic environment and sensistive shoreline habitat and may not have regulatory feasbility.

The model results for Measure #2 (constructing a sediment control structure) demonstrtate that building the structure can result in reduced sediment deposition on the east side of West Bay within Budd Inlet. However, the structure would reduces the tidal connection between Budd Inlet and the North Basin during low tides and would defy the purpose of the Estuary Alternative, which is restoring the tidal connectivity. This mitigation measure may have unintended adverse impacts to water quality and visual quality.

The model results for Measure #3 (constructing a sediment control structure and dredging the bench to avoid blocking tidal connection) demonstrtate that this measure can be effective at reducing sediment deposition on the east side of West Bay within Budd Inlet. Unlike Measure #2, Measure #3 does not reduce the tidal connection because the dredging provides a full connection. However, dredging the shallow intertidal bench on the west side of West Bay within Budd Inlet may have adverse impacts on aquatic habitat and may not have regulatory feasiblity.

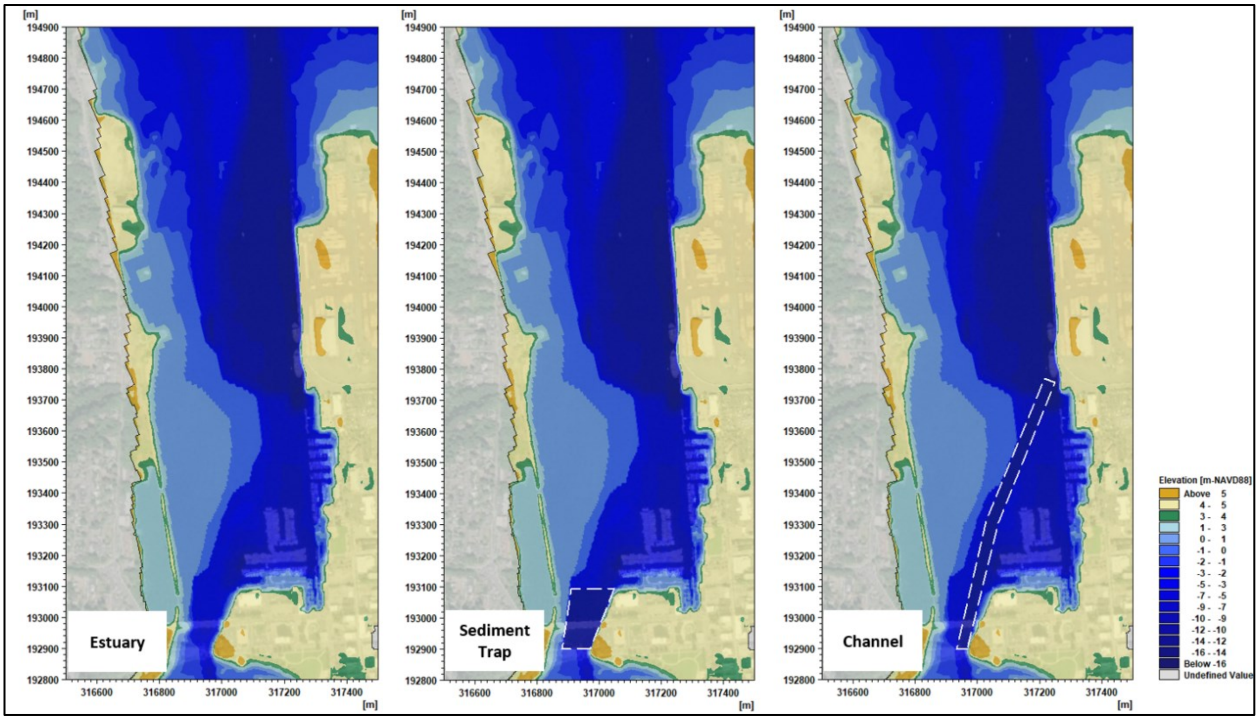
Figure 5-41: Erosion/Deposition (cm/yr) for the Estuary Alternative with Dredging the Bench and Control Structure



Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

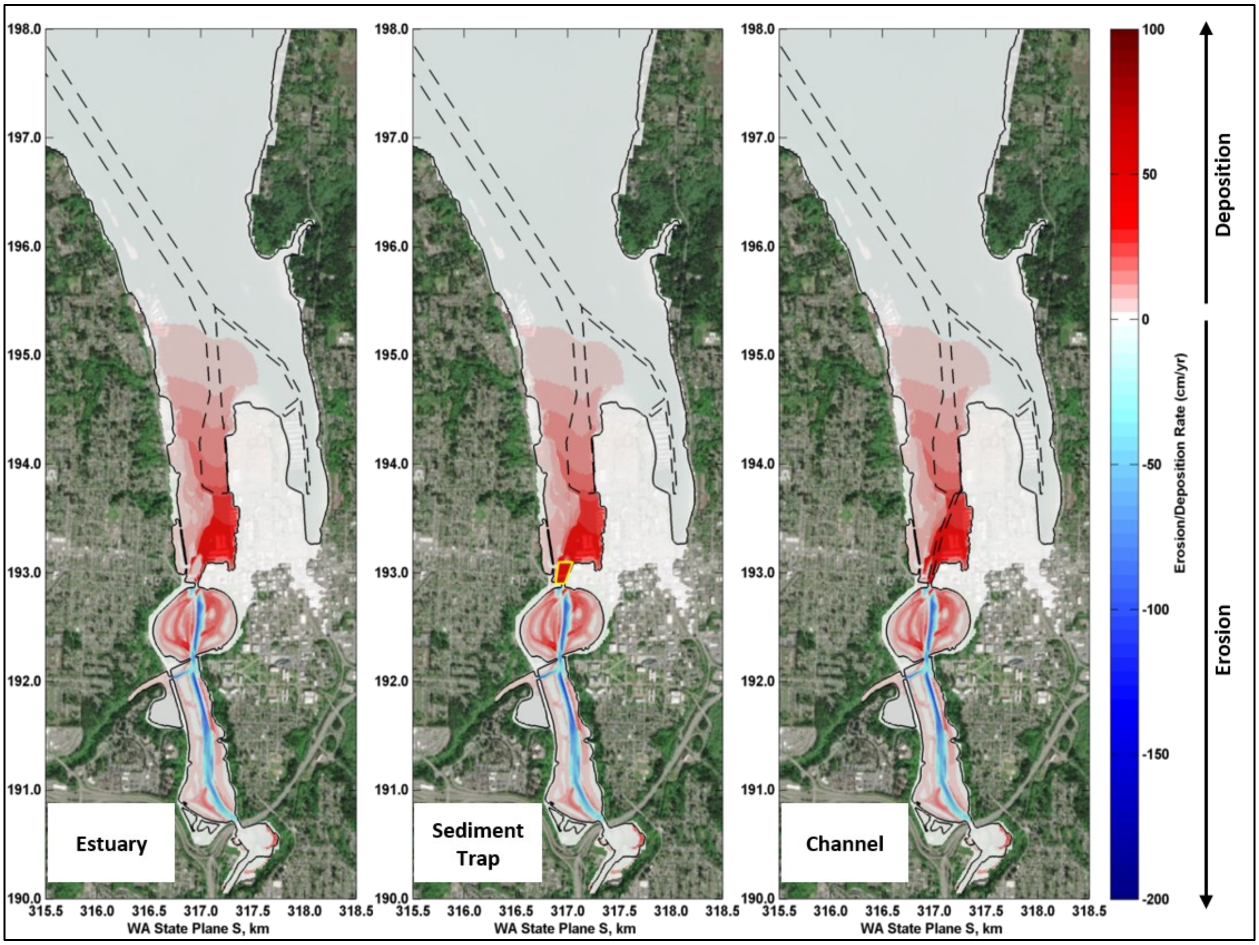
To investigate mitigation of impacts associated with increased sediment deposition in Budd Inlet after removal of the 5th Avenue Dam, a sediment trap immediately downstream of 5th Avenue (Measure #4) and dredging a connection channel between the North Basin and Federal Navigation Channel (Measure #5) were investigated. Model elevations for these two measures along with the Estuary Alternative are shown in Figure 5-42). Model results for these two measures for Event B under without RSLR are shown in Figure 5-43 and listed in Table 5-19.

Figure 5-42: Model Elevation for the Estuary Alternative, with Sediment Trap, and With a Channel



The model results demonstrate that dredging the sediment trap can capture some sediments before they get transported and deposited in Budd Inlet. It is shown that a small (<2%) reduction in deposition rates occrur in Budd Inlet. Dredging a channel to connect the North Basin with the Federal Navigation Channel is not effective at reducing sediment deposition in Budd Inlet and may even negligibly result in increased sediment deposition in Budd Inlet.

Figure 5-43: Erosion/deposition (cm/yr) for the Estuary Alternative with Sediment Trap, and with a Channel



** Shoreline boundary (solid line) identified with MHHW (elevation of +3.2m, NAVD88); Federal Navigation Channel (dashed line)

Modeled area includes the Capitol Lake Basin, West Bay, East Bay, and Budd Inlet south of Gull Harbor

Table 5-20: Erosion/Deposition (cm/yr) for the Estuary Alternative w a Sediment Trap and with a Channel

	Estuary	With Sediment Trap	With Channel
South Basin	1.6	1.6	1.6
Middle Basin	-7.1	-7.2	-7.1
Percival Cove	1.0	1.0	1.0
North Basin	2.5	2.5	2.4
Olympia Yacht Club	29.8	29.3	30.0
Marinas	15.8	15.3	15.6
Port	15.4	14.3	14.6
Federal Navigation Channel	0.6	0.6	0.6
Rest of Budd Inlet	0.7	0.8	0.8

In summary, to reduce sediment deposition on the east side of West Bay within Budd Inlet, various measures as alterations to the Estuary Alternative were evaluated. These measures vary in effectiveness at reducing sediment deposition in Budd Inlet but can be considered along with regulatory requirements and potential environmental impacts on aquatic habitat. This evaluation of mitigation measures, including the varied performance and regulatory feasibility issues, highlights the importance of long-term maintenance dredging, which is assumed as part of the project action. The location of long-term maintenance dredging must be considered relative to potentially impacted land uses, and occur at a frequency to avoid or minimize potential impacts to Olympia Yacht Club, Marinas, Port of Olympia and the Federal Navigation Channel in Budd Inlet.

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