# RESTORATION ALTERNATIVES FEASIBILITY EVALUATION
# DEER LAGOON RESTORATION

**Prepared for**

Wild Fish Conservancy


**Prepared by**

Anchor QEA, LLC

1423 Third Avenue

Suite 300

Seattle, WA  98101



**October 2010**

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 1-D | one-dimensional |
| 2-D | two-dimensional |
| Anchor QEA | Anchor QEA, LLC |
| cfs | cubic feet per second |
| DEM | digital elevation model |
| Ecology | Washington State Department of Ecology |
| ft/s | feet per second |
| LiDAR | Light Detection and Ranging |
| MHHW | mean higher high water |
| MHW | mean high water |
| MTL | mean tide level |
| MLW | mean low water |
| MLLW | mean lower low water |
| NAVD88 | North American Vertical Datum of 1988 |
| NOAA | National Oceanic and Atmospheric Administration |
| USACE | U.S. Army Corps of Engineers |
| USDA | U.S. Department of Agriculture |
| WFC | Wild Fish Conservancy |
| WWHM | Western Washington Hydrology Model |

# 1 INTRODUCTION

Anchor QEA, LLC (Anchor QEA) was contracted by Wild Fish Conservancy (WFC) to evaluate proposed restoration alternatives for Deer Lagoon. The project area is located on the southern portion of Whidbey Island at Useless Bay in Island County, Washington. Deer Lagoon comprises three areas—the western lobe, the central lobe, and the eastern lobe. A project site map is provided in Figure 1. The purpose of the study is to assess the feasibility of increasing tidal inundation to the western lobe through modifications to the current levee system. This report includes an assessment of post-restoration conditions for each of several alternatives using a hydrodynamic model to evaluate changes to tidal flushing (water surface elevation and velocity) in the western and central lobes, potential flooding risk for surrounding properties, and scour/sediment transport potential.

The restoration alternatives evaluated in this study consist of partial and total removal of the existing north-south levee system, which separates the western lobe from the central lobe of Deer Lagoon, and replacement of the existing tide gate system within the levees with a fish-friendly tide gate option. Evaluations included a site characterization, hydrologic (runoff) modeling, one-dimensional (1-D) hydrodynamic modeling to evaluate existing water elevation conditions, and two-dimensional (2-D) hydrodynamic modeling of Deer Lagoon and vicinity to evaluate habitat benefits, flooding concerns, and sediment transport issues related to implementation of proposed alternatives. Site-specific topographic and bathymetric survey data collected by WFC as part of this study were used to develop the hydrologic and hydrodynamic models. This report outlines the data used, methods employed, and results of the modeling effort to evaluate four levee modification alternatives.

# 2 DATA COMPILATION AND COLLECTION

Data compiled and used for the alternatives evaluation are listed in Table 1. These data, and how they were utilized in this study, are discussed in greater detail in the following sections of this report.

Data collected specifically for use in this study included a topographic and bathymetric survey completed by WFC during May and June of 2010, and a vertical control survey completed by Thatcher and Morrison, Inc. in August 2010. These survey data were combined with Light Detection and Ranging (LiDAR) data to create a seamless map of topography and bathymetry within Deer Lagoon and the western lobe, which is shown in Figure 2. This topographic surface was used to develop the hydrologic and hydrodynamic models utilized for this study.

**Table 1**
**Summary of Data Used for Evaluation**

| Data Type | Data Source (date, author) | Purpose of Data | Notes |
|---|---|---|---|
| Elevation (DEM[1]) | 2002, PSLC[2] | Elevation data for hydrologic and hydrodynamic modeling | 6-foot x 6-foot cell size; 1-foot elevation resolution. NAVD88 datum. |
| MLLW[3] Datum | 2010, VDatum[4] | Converted NAVD88 (feet) datum data to MLLW[3] (feet) datum | MLLW[3] = NAVD88 + 1.74 feet |
| Wind | 2010, NOAA[5] | Wind data to determine wave set-up, potential for flooding | Wind speed and directional data 1984 to 2009 from NOAA[5] Station WPOW1 in West Point, Washington. |
| Tides | 2010, NOAA[5] | Tidal data to determine wave set-up, potential for flooding | Monthly high water levels January 1972 to June 2010 from NOAA[5] Station 9444900 in Port Townsend, Washington. |
| Bathymetric Survey | 2010, WFC[6] | Elevation data for hydraulic and hydrodynamic modeling | Supplemental survey data of lagoon, below water surface. Lagoon bottom probe survey, cross-sections in central lobe. Data obtained in project coordinates, converted to MLLW[3]. |
| Bathymetric Survey | 2010, NOAA[5] | Elevation data for hydrodynamic modeling | Supplemental survey data of Useless Bay, below water surface. |
| Survey (upland) | 2010, T&M[7] | Supplemental survey of tide gate system | Gained vertical control and invert elevations of tide gate system. |

| Data Type | Data Source (date, author) | Purpose of Data | Notes |
| --- | --- | --- | --- |
| Soil Data | 2010, USDA[8] | Soil types for input to Western Washington Hydrology Model analysis | Data obtained from USDA[8] Natural Resources Conservation Service Web Soil Survey website. |

Notes: [1] digital elevation model, [2] Puget Sound LiDAR Consortium, [3] mean lower low water, [4] Vertical Datums Transformation Tool 2.2.7 (NOAA[5]), [5] National Oceanic and Atmospheric Administration, [6] Wild Fish Conservancy, [7] Thatcher and Morrison, Inc., [8] U.S. Department of Agriculture.

# 3 SITE DESCRIPTION

The Deer Lagoon estuary is located on southern Whidbey Island along the northern shoreline of Useless Bay. Historically, the estuary was much larger than at present and extended inland to the west and east/northeast of its current extent. Figure 3 shows the T-sheet (USCGS 1872) for the area with the current vector shoreline. While the extent of the estuary has been changed dramatically due to the construction of multiple levee systems and subsequent residential/agricultural development, the size, shape, and orientation of the tidal inlet and sand spits have changed very little since the late 1800s. Littoral drift, as defined by the Washington State Department of Ecology (Ecology; 2002), is from west to east in the area west of the lagoon and from east to west, in the area east of the lagoon (see Figure 3). The lagoon inlet itself is designated as a convergence zone for littoral drift and, therefore, is net depositional. Feeder bluffs to both the east (Indian Point) and west (Double Bluff) of the site provide sediment for the shoreline and nearshore zone within Useless Bay, and through littoral drift, to Deer Lagoon itself. Freshwater input to the estuary, both historically and at present, is primarily from upland drainage/seeps. At present, stormwater runoff from surrounding roads and residential communities likely provides additional freshwater input to the estuary, although the quantity of this drainage is unknown. The estuary is characterized by coarse to medium sand substrate and is connected to Useless Bay through a series of intertidal channels. The estuary is generally quite shallow, with most of the estuary elevation above mean lower low water (MLLW). The tidal inlet is also perched above MLLW and is unconfined. Sand spits extend into the inlet from the west and east. A wide, shallow sandy shelf extends out at low tide from the mouth of the inlet into Useless Bay.

The western lobe of Deer Lagoon is separated from the tidal estuary by a system of parallel earthen levees, and is hydraulically connected to the estuary through a tide gate system located at the northern extent of the levees (see Figure 1). The eastern levee was constructed to convert the estuary to farmland in the early 1900s, while the western levee was constructed between 1944 and 1957 (from examination of historical aerial photographs); likely to house a private water line that runs the length of that levee. The western lobe is currently owned by Island County and has no current land use activity. Residential development is present along the perimeter of the western lobe. The eastern lobe (see

Figure 1) was similarly converted for agricultural purposes through levee construction and remains in private ownership. The central lobe is tidally-influenced and is the only portion of the historical estuary that has a direct, unconfined hydraulic connection to Useless Bay.

# 4 HYDRAULICS AND HYDRODYNAMICS – EXISTING CONDITIONS

## 4.1 Water Surface Elevations in Deer Lagoon Estuary

Deer Lagoon is a tidal lagoon connected through an unconfined tidal inlet to Useless Bay. A tide gate in the northeastern corner of the western lobe provides a hydraulic connection between the central and western lobes. The tide gate provides flow into the central lobe during lower phases of the tide, which flows out a meandering tidal channel through the lagoon and out into Useless Bay.

Tidal elevations at Useless Bay were evaluated using VDatum, developed by the National Oceanic and Atmospheric Administration (NOAA; 2009). VDatum provides tidal datum conversions for select U.S. coastal regions, including coverage of southern and northern Puget Sound and the Straits of Juan de Fuca. Tidal datums for Useless Bay used in this study are provided in Table 2.

**Table 2**
**Tidal Datums Referenced to Mean Lower Low Water for Useless Bay**
**(NOAA VDatum, Puget Sound Dataset)**

| Datum | Elevation (feet, relative to MLLW) |
|---|---|
| Mean higher high water (MHHW) | 10.4 |
| Mean high water (MHW) | 9.5 |
| Mean tide level (MTL) | 6.1 |
| Mean low water (MLW) | 2.7 |
| North American Vertical Datum of 1988 (NAVD88) | 1.7 |
| Mean lower low water (MLLW) | 0 |

The tidal range within the lagoon is equivalent to the range within Useless Bay, but is constrained on the low range of the tide by the elevation of the inlet channel thalweg and water input from the tide gate system. Topographic data collected by WFC for this study (Figure 2) found the thalweg elevation of the tidal channel in the central lobe of the lagoon ranges from 2.5 feet MLLW at the inlet mouth to a maximum elevation of 5.5 feet MLLW inland from the mouth. Outside of the tidal channel, elevations within the central lobe of the lagoon range from 4.0 to 10.0 feet MLLW. At low tide, there are several pools of standing water in the central lobe that are disconnected from the tidal channel. The tidal channel continues to flow out towards Useless Bay during low tide due to discharge from the western lobe through the tide gate system.

## 4.2 Water Surface Elevations in the Western Lobe

Water surface elevation within the western lobe is currently controlled by a tide gate system (located at the northern shoreline connection of the levee system), which connects the western lobe to the estuary. The tide gate system consists of two circular culverts placed side by side with hinged control gates on the western side of the levees (in the western lobe). As-built drawings for the tide gate system were not available during the course of this study; therefore, a local surveyor was retained by WFC to obtain invert elevations for the culverts. Invert elevations for the tide gate culverts are 3.6 feet North American Vertical Datum of 1988 (NAVD88) on the western side, and 2.9 feet NAVD88 on the eastern side.

Island County measures western lobe water levels and keeps tide gate maintenance records on a semi-regular basis. Data are available from January 2003 through July 2010. Water level data are referenced to the top of the concrete weir box; these data are not referenced to any survey datum. WFC collected water surface elevations within the western lobe using differential GPS survey equipment. Anchor QEA cross-referenced the water surface elevation data collected by Island County and those collected by WFC to convert the Island County data to feet MLLW. Figure 4 shows these water surface elevations from January 2003 through July 2010, referenced to MLLW.

As shown in Figure 4, water surface elevations in the western lobe tend to increase over the winter months, sometimes reaching elevations greater than 8.5 feet MLLW (approximate). This increase in water surface elevation is likely due to increased runoff into the western lobe during winter months, coupled with coastal storms that push woody debris and other material into the tide gate system. Elevated water surface elevations within the western lobe during winter months are a flooding concern to private property owners to the south along East Shore Avenue. Once water surface elevations reach 8.0 feet MLLW (or higher), Island County generally performs maintenance activities on the tide gate that results in a slow drop in water surface elevation through the spring. The lowest water surface elevations within the western lobe occur during the summer months.

## 4.3 Freshwater Input to the Western Lobe (Hydrologic Model)

The potential for flooding in the western lobe is influenced by the performance of the tide gate and freshwater input to the western lobe due to runoff from upland drainage areas during rainfall events. Stormwater runoff from adjacent residential communities and roadways, as well as groundwater seepage, may also be sources of fresh and saline water to the western lobe. Stormwater and groundwater data are not available for the project site. Additional data collection and modeling could further quantify input to the western lobe from these sources.

Hydrology data associated with the drainage basin for the western lobe is not currently available. In order to determine the potential runoff discharge into the western lobe, a hydrologic evaluation was conducted using the Western Washington Hydrology Model (WWHM). The model was used to determine a range of return-period flows, based on surface water runoff from a drainage basin upstream of the western lobe. No information was available on specific streams or stormwater outfalls that may be presently discharging into the western lobe.

The WWHM, developed by Ecology, is widely used and recognized as a tool to "size stormwater control facilities to mitigate the effects of increased runoff (peak discharge, duration, and volume) from proposed land use changes that impact natural streams, wetlands, and other water courses" (WWHM Version 3.0 User Manual; Clear Creek Solutions, Inc. 2006). The model employs continuous simulation hydrology (HSPF), using actual long-term recorded precipitation data, measured pan evaporation data, and regional HSPF parameters, among other factors. The model is developed for use in 19 counties of western Washington; the Island County dataset was used for this analysis without any modification. The model was used to develop the range of return-period flows.

Input required by the model consists of entering a project location and entering the amount of area for each land-use type that comprises the drainage basin of interest. The drainage basin used for the analysis was provided by WFC and was developed with the use of ArcGIS hydrology tools. The dataset used for calculation of the drainage basin included a digital elevation model (DEM; see Table 1). The resulting drainage basin is 1,385 acres and is roughly bounded on the east by the levees in Deer Lagoon and local high topography, on the north by State Route 525, on the west by local high topography, and on the south by East Shore Avenue (Figure 5). Specific land use, soil type, and slope of the drainage basin for use in the WWHM were approximated using soil data obtained from the U.S. Department of Agriculture (USDA; see Table 1), and by visual observation using aerial photography (Figure 5). The model input for the drainage basin is summarized in Table 3. Approximately 36% of the basin is assumed to be impervious, which includes ponded areas.

**Table 3**
**Western Washington Hydrology Model Drainage Basin Delineation**

| Land-Use Type | Soil Type | Surface | Slope | Area (acres) |
|---|---|---|---|---|
| Forest | A/B | Pervious | Flat | 60 |
| Forest | A/B | Pervious | Moderate | 170 |
| Forest | A/B | Pervious | Steep | 50 |
| Pasture | A/B | Pervious | Flat | 142 |
| Pasture | A/B | Pervious | Moderate | 229 |
| Pasture | A/B | Pervious | Steep | 60 |
| Lawn | A/B | Pervious | Flat | 54 |
| Lawn | A/B | Pervious | Moderate | 60 |
| Pasture | C | Pervious | Moderate | 58 |
| | | | *Total Pervious Area* | *883* |
| Roads | N/A | Impervious | Flat | 10 |
| Roads | N/A | Impervious | Moderate | 20 |
| Roads | N/A | Impervious | Steep | 15 |
| Roof Tops | N/A | Impervious | Flat | 10 |
| Pond | N/A | Impervious | N/A | 447 |
| | | | *Total Impervious Area* | *502* |
| | | | **Total Basin Area** | **1,385** |

Notes: Land-Use Types in the model are Forest (second growth Douglas fir), Pasture (non-forested natural areas), and Lawn (sod lawn, grass, landscaped urban vegetation). Soil types in the model are A/B (outwash soils) and C (till). Slope types in the model are flat (0 to 5%), moderate (5 to 15%), and steep (greater than 15%).

Results from the hydrologic model include flows at varying frequency, as summarized in Table 4. The 100-year flow is a relatively small value considering the spatial extent of the western lobe. For example, a 100-year rainfall event would raise the water level in the western lobe only 0.20 feet per hour of storm duration (assuming the wetted surface of the western lobe is approximately 125 acres on average). The reasonable storm duration for a 100-year rainfall event is between 4 and 6 hours; therefore, the increase in water surface elevation in the western lobe associated with the 100-year event lies between 0.8 and 1.2 feet.

**Table 4**
**Western Washington Hydrology Model Runoff Flow Frequency**

| Frequency | Flow (cfs) |
|---|---|
| 2-Year | 113 |
| 5-Year | 153 |
| 10-Year | 181 |
| 25-Year | 220 |
| 50-Year | 251 |
| 100-Year | 283 |

A review of water level data collected by the county in the western lobe (see Figure 4) shows an increase in water surface elevation of approximately 2 feet from summer to winter months each year since 2006. This increase is higher than would be expected due to runoff from upland drainage alone. Although the presence of streams and/or stormwater outfalls discharging into the western lobe could result in a higher than estimated range of return-period flows, it is likely that there are other sources of fresh or saline water input to the western lobe during winter months that have not been considered in the runoff evaluation. These sources may include:

- Seepage of saline water from the lagoon into the western lobe through the tide gate (at high tide) due to malfunction or fouling of the tide gate mechanism.
- Stormwater input from adjacent residential communities and roadways.
- Groundwater input from upland seeps or groundwater infiltration from the uplands north of the western lobe, through the coastal spit to the south of the western lobe, or

through the levees themselves.

These data gaps will need to be addressed before moving forward with design of a preferred restoration alternative for the site. However, for the purposes of this feasibility evaluation, the runoff model coupled with water surface elevation data in the western lobe (provided by Island County) is sufficient to evaluate existing flood risk associated with the proposed restoration alternatives.

## 4.4 Existing Tide Gate Hydraulics (1-D Hydrodynamic Model)

The topographic surface developed from site-specific topography and bathymetry data and existing LiDAR data for the site was used to develop a 1-D hydrodynamic model of the tidal channel in Deer Lagoon. The HEC-RAS model, developed by the U.S. Army Corps of Engineers (USACE), was used for this effort. The purpose of the modeling was to evaluate velocities within the tidal channel at low tide when discharge from the tide gate system is at a maximum. This evaluation is in addition to tidal circulation modeling (2-D) completed for this study to evaluate dynamic tidal currents within Deer Lagoon and the tidal channel.

The HEC-RAS model begins in the western lobe, east of the levee system, and extends downstream through the central lobe and into Useless Bay. Figure 6 shows a schematic of the HEC-RAS model developed for this evaluation. Input to the HEC-RAS model includes topography of the site, flow out of the tide gates at MLLW, and the tidal elevation at the mouth of the inlet, which was set to MLLW for the model runs. These conditions provided the maximum flow velocity within the tidal channel due to flow from the tide gate.

A culvert hydraulics model, HY-8, was used to estimate the potential discharge from the existing tide gate system based on surveyed invert elevations and anticipated water levels within the western lobe. HY-8 is recognized by the Washington State Department of Transportation for use as a culvert design tool. The tide gates were simulated, in HY-8, as two 2-foot diameter culverts with the physical characteristics (e.g., length, slope, invert elevations, etc.) as reported in the survey conducted by Thatcher and Morrison, Inc. (see Table 1). The model provides estimates of flow rates and velocities through the culverts based on a range of upstream (in the western lobe) and downstream (in the estuary) water surface elevations.

Water level data measurements taken by Island County staff between October 2005 and July 2010 indicate that the water level elevation within the western lobe roughly varies between 7 and 9 feet MLLW. This range of water level elevation corresponds to approximate tide gate flow between 45 and 65 cubic feet per second (cfs), respectively. The estimate of flow through the tide gate system reported by the HY-8 model is conservatively high since the model assumes fully unobstructed flow, which does not occur within the existing tide gates due to bio-fouling of the interior of the pipes and partial flow obstruction due to the presence of woody debris or sediment in the culverts.

The HEC-RAS model provided estimates of maximum velocities in the tidal channel in Deer Lagoon at MLLW for a range of flows from the tide gate between 50 and 100 cfs. The maximum velocity in the channel predicted by the HEC-RAS Model was 2.5 feet per second (ft/s). This result will be used to compare maximum in-channel velocities for existing conditions (with tide gate) with predicted velocities based on proposed restoration alternatives.

## 4.5 Tidal Hydrodynamics (2-D Hydrodynamic Model)

A 2-D tidal circulation model of Deer Lagoon was developed for this study and used to evaluate existing flow velocities within the lagoon due to tidal fluctuations. The RMA2 hydrodynamic model was used for this evaluation. The RMA2 model is a 2-D, depth-averaged (i.e., the model computes lateral variations in flows, not vertical variations), finite element, hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for free-surface flows. It is currently part of the USACE TABS-MD modeling package, which is supported by the USACE Engineering Research and Development Center. RMA2 has been used in studying multi-dimensional hydrodynamics in rivers, reservoirs, bays, and estuaries (Donnell et al. 2006).

The topographic surface created from site-specific survey and LiDAR data (see Figure 2) was used to develop a model mesh for the 2-D model. The model extent included the interior of

Deer Lagoon, the mouth of the lagoon, and portions of Useless Bay. Figure 7 shows the 2-D model mesh used to evaluate existing tidal hydrodynamics at the site.

A limitation of the 2-D tidal circulation model requires that all depressions where standing water could collect at low tide be filled in to match the surrounding grade. Therefore, the original topographic surface developed for the project was altered to remove areas where ponding would occur at low tide. This limitation does not have any significant effect on model results for water surface elevations or tidal velocities. This limitation can have an effect on the reported water depths within the model areas where the topography was altered. Therefore, evaluation of water depths was done in ArcGIS using water surface elevation output from the model and the original topographic (unaltered) surface.

Tidal elevations were applied at the boundary of the model within Useless Bay. Tidal elevations were developed from verified water level measurements taken January 15-29, 2010, at Port Townsend, Washington. These tidal elevations were adjusted by 0.7 feet to convert tidal heights from MLLW at Port Townsend to MLLW at Useless Bay. This conversion was done using VDatum, developed by NOAA, to provide tidal datums for Port Townsend and Useless Bay (Table 2). The tidal signal for this time period varies in elevation from nearly -2.0 to nearly 12.0 feet MLLW, and represents both semi-diurnal and diurnal oscillations. The tidal signal was input into the model in 6-minute intervals. Figure 8 shows a time-series of the tidal elevations used in the 2-D model.

Velocities within the tidal channel of the lagoon were extracted from the model results at several discrete locations in the domain. Figure 9 shows the locations within the lagoon where velocity and water surface data were extracted for further evaluation. (Figures 16 through 20 show velocities at these locations for existing conditions and proposed alternatives). Water surface elevations in the lagoon are the same magnitude and phase as the tidal elevations in Useless Bay, except for lower low tides where the elevation of the lagoon is higher than the tidal elevation in the Bay. At these lower tides, most of the area in the western and central lobes of the lagoon is dry. The maximum current velocity due to tidal oscillation within the channel is approximately 1.5 ft/s. In addition to static plots, animations of tidal inundation and velocities over the entire simulation were also created as AVI files and are provided on a DVD in Appendix B.

# 5 ALTERNATIVES EVALUATION

Three restoration alternatives were identified by WFC for consideration in this study. The RMA2 model, which was used to evaluate existing tidal hydrodynamics, was used to develop a hydrodynamic model for each proposed alternative (except Alternative 4). Results from the modeling were used to evaluate the increase in tidal inundation into the western lobe, potential for flooding to adjacent properties, increase in tidal velocities in the tidal channels and inlet to Deer Lagoon, velocities at levee breach locations, and scour potential within the Deer Lagoon tidal channels and inlet compared to existing conditions.

## 5.1 Description of Proposed Alternatives

The alternatives are listed in order of increasing complexity and/or increasing magnitude of proposed modifications to the existing condition. Figure 10 provides a site plan for all proposed action alternatives.

### *5.1.1 Alternative 1: Single Breach of Levee System*

This alternative includes breaching both levees at the location of the existing tide gate. The proposed opening is approximately 100 feet wide with a centerline elevation of 5.5 feet MLLW and breaches the levees at their northern connection.

### *5.1.2 Alternative 2: Double Breach of Levee System*

This alternative includes breaching both levees at two discrete locations. The first breach would be located at the existing tide gate location (the same location as the Alternative 1 breach), and the second location is in the approximate middle of the levee system. Both proposed openings are approximately 100 feet in width with a centerline elevation of 5.5 feet MLLW.

### *5.1.3 Alternative 3: Removal of Levee System*

This alternative includes removing both levees by lowering their elevation to match the existing estuary elevations adjacent to the levees. The levees would be lowered to an approximate elevation of 5.5 feet MLLW at their northern connection and would be lowered to an elevation of 8.0 feet MLLW at the southern extent of proposed removal.

### 5.1.4 Alternative 4: Replacement/Retrofit Existing Tide Gate System

This alternative requires the least amount of modification to the existing levees (except for the no-action alternative), and includes the replacement or retrofit of the tide gate system with a better functioning fish-passable tide gate system. The new tide gate system would be constructed in the same location as the existing system. Although no specific design of this tide gate system was developed, this alternative focused on identifying a range of water levels required to restore maximum ecosystem function and limit flooding to adjacent properties. These water levels will act as design criteria for any future tide gate design for the site.

## 5.2 Hydrodynamic Model Development

The topographic surface created from site-specific survey and LiDAR data (see Figure 2) was modified to represent the geometry of the lagoon and western lobe for Alternatives 1 through 3. The model extent for proposed alternatives included the western lobe (ponded water and wetlands), adjacent uplands (including the coastal spit) up to an elevation of 16 feet MLLW, the levees, the Deer Lagoon estuary, and an adequate distance out into Useless Bay. Figures 11, 12, and 13 show model geometries used to develop a model mesh for the 2-D model. The model extent included the interior of Deer Lagoon, the mouth of the lagoon, and portions of Useless Bay. Figure 6 shows the 2-D model mesh used to evaluate existing tidal hydrodynamics at the site.

As with the existing conditions RMA2 model, the original topographic surface developed for the project was altered to remove areas where ponding would occur at low tide. This limitation of the RMA2 model was discussed in Section 4.5. This limitation does not have any significant effect on model results for water surface elevations or tidal velocities, but it can have an effect on the reported water depths within the model in areas where the topography was altered. Therefore, as with the existing conditions model, the evaluation of water depths was done in ArcGIS using water surface elevation output from the model and the original topographic (unaltered) surface.

The same tidal boundary conditions as the existing conditions model were used for the hydrodynamic modeling of proposed alternatives. The simulation was run with a 14-day tidal signal representing winter higher high tides in Useless Bay. Figure 8 shows the tidal time series that was used to drive the hydrodynamic model for all runs.

## 5.3 Hydrodynamic Model Results

### *5.3.1 Predicted Inundation in the Western Lobe*

Water surface elevation and flooded extent within the western lobe were examined using the RMA2 model results for Alternatives 1 through 3. All alternatives (single and double breach, and complete levee removal) resulted in full tidal inundation within the western lobe (e.g., water surface elevations within the western lobe reached the same elevation as in the eastern lobe). The maximum water surface elevation over the simulation period predicted by the model was 11.4 feet MLLW. Figure 14 illustrates the tidal inundation extent and water depths within the western lobe at this maximum tidal elevation. As seen in Figure 14, the increase in water surface elevation in the western lobe due to tidal inundation has the potential to flood several properties located to the south of the western lobe along East Shore Avenue. Therefore, a set-back levee built to the north of and parallel to East Shore Avenue would be required to manage flood risk for property owners post-restoration.

In addition to tidal inundation, on-shore winds (wind set-up) and wind waves (wave set-up) from storm events can temporarily increase the water surface elevation along the coast above mean higher high water (MHHW). These periodic local increases in water surface elevation can increase flooding and wave energy along the coast, and need to be taken into account when evaluating flood risk along the coast or designing levee or tide gate design elevations. The design of set-back levees or other flood protection structures associated with restoration alternatives is outside the scope for this study. However, Appendix A includes results of a coastal evaluation to estimate potential wind and wave set-up for Useless Bay and Deer Lagoon, which could be used for design. The increase in local water surface elevation due to a combination of wind and wave set-up ranges from 1.9 feet for a 2-year return period event to 3.1 feet for a 100-year return period event (Appendix A).

At low tide, portions of the western lobe would continue to be inundated. Based on the current maximum tidal channel thalweg elevation in the central lobe (5.5 feet MLLW), it is expected that inundation would be present at low tide for each restoration scenario in areas of the western lobe with mudline elevations lower than 5.5 feet MLLW. Figure 15 shows the extent of inundation at low tide within the western lobe. However, the velocities associated with each restoration scenario in the central lobe tidal channel could result in scour below existing tidal channel elevations, which could result in less widespread inundation at low tide.

### 5.3.2 Water Surface Elevations and Water Velocities

Water surface elevations within the western lobe and water velocities within the western lobe, levee breaches, and central lobe (Deer Lagoon tidal channel) were extracted from the model over the entire simulation period. This information was used to evaluate scour potential within the levee breaches and the Deer Lagoon tidal channel. Locations where these data were extracted are shown in Figure 9. Figures showing comparisons of water surface elevation and water velocity for existing conditions and for Alternatives 1 through 3 at several locations within the restored areas are shown in Figures 16 through 20 and described below:

- Figure 16: Water surface elevation and velocity within the western lobe (Point WL on Figure 9)
- Figure 17: Water surface elevation and velocity at the northern levee breach location (Point LB on Figure 9)
- Figure 18: Water surface elevation and velocity in the northern portion of the Deer Lagoon Tidal Channel (Point DL1 on Figure 9)
- Figure 19: Water surface elevation and velocity near the inlet of Deer Lagoon (Point DL2 on Figure 9)
- Figure 20: Water surface elevation and velocity at the mouth of Deer Lagoon (Point DL3 on Figure 9)

Water surface elevations within the western lobe (Figure 16) are not attenuated and reach as high as those in Deer Lagoon estuary and Useless Bay. The water surface elevation in the western lobe drops more slowly on ebb tide for the single levee breach (Alternative 1) than for the double breach (Alternative 2). Water surface elevations within the western lobe are in line with those in the estuary when the entire levee system is removed (Alternative 3), and shows little delay in water surface elevation change.

Water surface elevations in the northern levee breach (Figure 17) show a similar pattern as those in the western lobe between the three proposed alternatives. Water surface elevations within the central lobe of Deer Lagoon (Figures 18, 19, and 20) are unaffected by all proposed modifications to the levees.

Water velocities within the western lobe, levee breach locations, and the central lobe show more variation between alternatives than the water surface elevations. Figures 16 through 19 illustrate the following trends:

- Velocities within the western lobe tend to increase as additional portions of the levee system are removed.
- Velocities within the levee breach locations decrease significantly as additional portions of the levee system are removed.
- Velocities within the western lobe and central lobe tidal channel tend to increase as additional portions of the levee system are removed. Velocities in these locations for Alternatives 1 through 3 are higher compared to existing conditions.
- Velocities in the inlet mouth are not as affected by levee modifications as velocities in the central lobe tidal channel closer to the levee breach/removal locations.

Table 5 compares maximum predicted velocities within the western lobe, in the northern levee breach, and in the Deer Lagoon tidal channel for existing conditions and Alternatives 1 through 3. There are two maximum velocities listed for existing conditions; one is based on the 2-D tidal circulation model, and one is based on the 1-D hydrodynamic model that evaluated velocity in the tidal channel due to flow from the tide gate at low tide. The locations of data points used to develop Table 5 are shown in Figure 9.

**Table 5**
**Comparison of Predicted Water Velocities**

| Location | Approximate Maximum Water Velocity (ft/s) | | | |
|---|---|---|---|---|
| | Existing Conditions | Alternative 1: Single Levee Breach | Alternative 2: Double Levee Breach | Alternative 3: Complete Levee Removal |
| Western Lobe (Point WL1[a]) | n/a | 0.6 | 0.9 | 1.1 |
| Northern Levee Breach (Point LB1[a]) | n/a | 10.1 | 8.0 | 2.2 |
| Deer Lagoon Tidal Channel – North (Point DL3[a]) | 2.5 (flow from tide gate)<br>0.5 (tidal circulation) | 0.5 | 0.4 | 0.8 |
| Deer Lagoon Tidal Channel – Middle (Point WL6[a]) | 2.5 (flow from tide gate)<br>2.0 (tidal circulation) | 2.5 | 3.1 | 4.2 |
| Deer Lagoon Tidal Channel – Inlet Mouth (Point WL8[a]) | 2.5 (flow from tide gate)<br>1.5 (tidal circulation) | 3.2 | 3.2 | 3.2 |

a. Locations of data points are shown in Figure 9.

### *5.3.3 Scour Potential*

The increase in tidal prism to the Deer Lagoon estuary by opening up the western lobe to tidal inundation increases the velocities in the tidal channel from 2.5 ft/s, based on existing conditions, to a maximum of 4.2 ft/s for the complete levee removal (Alternative 4). The increase in tidal prism and tidal velocity will cause an increase in scour of the tidal channel within Deer Lagoon. Sediment within Deer Lagoon is medium to coarse sands; no site-specific grain size information is available. Since the tidal inlet at the mouth of Deer Lagoon is not confined, and sediment gradation is not known, it is difficult to predict the shape (width and depth) of the tidal channel post-restoration. However, an estimate of the maximum expected scour depth in the tidal channel due to the increase in tidal prism can be estimated by using the steady state conservation of mass equation to develop an equation for the scour depth in the channel, shown in Equation 1:

$$V_1 A_1 = V_2 A_2 = Q_1 = Q_2 \qquad \text{Equation 1}$$

where:
$V_1$, $A_1$, and $Q_1$ are the velocity, cross-sectional flow area, and discharge in the tidal channel for existing conditions, respectively; and $V_2$, $A_2$, and $Q_2$ are the velocity, cross-sectional flow area, and discharge in the tidal channel for Alternatives 1, 2, or 3, respectively.

An equation for the scour depth within the channel due to an increase in tidal discharge (flow) can be developed from Equation 1 by making the following assumptions:

- The maximum velocity that is realized in the existing tidal channel is approximately 2.5 ft/s, which is the velocity in the channel at lower low tide due to discharge from the tide gate (as determined by this study).
- The existing tidal channel has reached an equilibrium depth and is not currently eroding. As a result, 2.5 ft/s is the equilibrium velocity for the channel (velocity at which the current channel sediments will not continue to erode). This is $V_1$ in Equation 1.
- There is no source of sediment to the tidal channel. Because this is likely not the case for the project site, this assumption will give a maximum potential scour depth.
- The width of the tidal channel is 50 feet (taken from the topographic survey data, LiDAR data, and measurements made in the field).
- The channel width does not change; all scour is realized as an increase in the depth of the channel. Use of this assumption will give a maximum potential scour depth.
- Average flow depths in the tidal channel range from 2 to 5 feet over the tidal cycle (taken from the topographic survey data, LiDAR data, measurements made in the field, and model predictions of water surface elevation).
- The cross-sectional area of flow is rectangular in shape.

Using the above assumptions and Equation 1, an equation can be derived to estimate scour depth, $d_s$, in the channel due to the increase in tidal discharge in the channel post-restoration. This was done by setting the velocity post-restoration equal to the equilibrium velocity assumed for the channel (2.5 ft/s), and solving for the new cross-sectional flow area as shown in Equations 2 through 4:

$$V_1 A_s = Q_2$$ Equation 2

where:
$A_s$ is the cross-sectional flow area after channel scour has occurred.

$$V_1 W(D + d_s) = Q_2$$ Equation 3

where:
W is the width of the channel, D is the original depth of flow in the channel, and $d_s$ is the scoured depth in the channel.

$$d_s = \frac{Q_2}{V_{1W}} - D$$ Equation 4

From Equation 4, the maximum scour depth within the Deer Lagoon tidal channel for Alternatives 1 through 3 is as follows:

- Alternative 1 (Single Breach of Levee System) – Maximum channel scour is expected to be between 0.5 and 1.0 feet.
- Alternative 2 (Double Breach of Levee System) – Maximum channel scour is expected to be between 0.5 and 1.5 feet.
- Alternative 3 (Removal of Levee System) – Maximum channel scour is expected to be between 1.5 and 2.5 feet.

It is important to note that since the increase in velocity within the tidal channel due to levee modifications was not uniform, the scour depth will also vary along the tidal channel.

# 6 CONCLUSIONS

Hydrodynamics within the Deer Lagoon estuary at present are dominated by tidal currents and discharge from the tide gate at lower low tides. The shoreline adjacent to Deer Lagoon is net depositional due to nearshore sediment sources (i.e., feeder bluffs) and the direction of littoral drift along the northern shoreline of Useless Bay. The maximum velocities within the Deer Lagoon estuary (approximately 2.5 ft/s) are found in the tidal channel at MLLW due to discharge from the tide gate. Velocities induced by tidal inundation are lower, reaching an approximate maximum of 2.0 ft/s. The elevation of the tidal channel thalweg is higher than MLLW. Elevations within the lagoon range from 3.0 feet MLLW within the tidal channel to above 10.0 feet MLLW.

The western lobe of Deer Lagoon is currently separated from the estuary by two levees. The water surface elevation within the western lobe is controlled by a tide gate located at the northern shoreline connection of the levee system. Water level data compiled by Island County show that the water surface elevations in the western lobe slowly increase over the winter months due to increased surface runoff and fouling of the tide gate by debris. Groundwater and stormwater input to the western lobe may also contribute to this increase; however, there is no data to support the quantity of this contribution. This increase in water elevation in the western lobe is a flooding concern to adjacent private properties to the south. Island County staff generally maintain the levee once the water surface elevation is higher than 8.0 to 8.5 feet MLLW (usually in winter months), after which the water surface elevation in the western lobe starts to fall slowly through the spring and summer.

Restoration of the western lobe through breaching or complete removal of the levee system will increase the water surface elevation within the western lobe to approximately 11 feet MLLW. This will increase the risk of flooding to private property owners that live along the north side of East Shore Avenue. Implementation of Alternatives 1, 2, or 3 would require construction of a set-back levee on Island County property to alleviate flood risk to adjacent properties. Design and construction of this levee system will need to take into account low-frequency coastal storm events, which could raise the water surface elevation from 2 to 3 feet above MHHW during a sustained onshore wind event. It is expected that a set-back levee would be approximately the same height as the current levees separating the central and western lobes of Deer Lagoon.

At low tide, portions of the western lobe would continue to be inundated. Based on the current maximum tidal channel thalweg elevation in the central lobe (5.5 feet MLLW), it is expected that inundation would be present at low tide for each restoration scenario in areas of the western lobe with mudline elevations lower than 5.5 feet MLLW. However, the velocities associated with each restoration scenario in the central lobe tidal channel could result in scour below existing tidal channel elevations, which could result in less widespread inundation at low tide.

A new tide gate could be designed to keep the water level within the western lobe at a specific elevation. This could also result in a larger area that would be inundated during low tide than would naturally occur with any of the levee breach alternatives. Similarly, a newer tide gate could be designed to keep water levels within the western lobe below a maximum elevation, which could provide some protection from flooding to homeowners. However, it would be important to understand the contributions of other hydrologic inputs into the western lobe if the new tide gate were to be designed to limit maximum water level in the western lobe.

Increased tidal prism and velocities within the tidal channels of Deer Lagoon would increase the potential for scour within those channels. Maximum anticipated scour depths associated with Alternatives 1, 2, and 3 are 1.0, 1.5, and 2.5 feet, respectively.

# 7 REFERENCES

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U.S. Coast and Geodetic Survey (USCGS), 1872. Topographic Sheet T-1388b, Useless Bay, Washington Territory. 1872.

Washington State Department of Ecology (Ecology), 2002. Net Shore-Drift in Washington State. September 1, 2002.

# FIGURES


**Figure 1**
Project Site Map
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

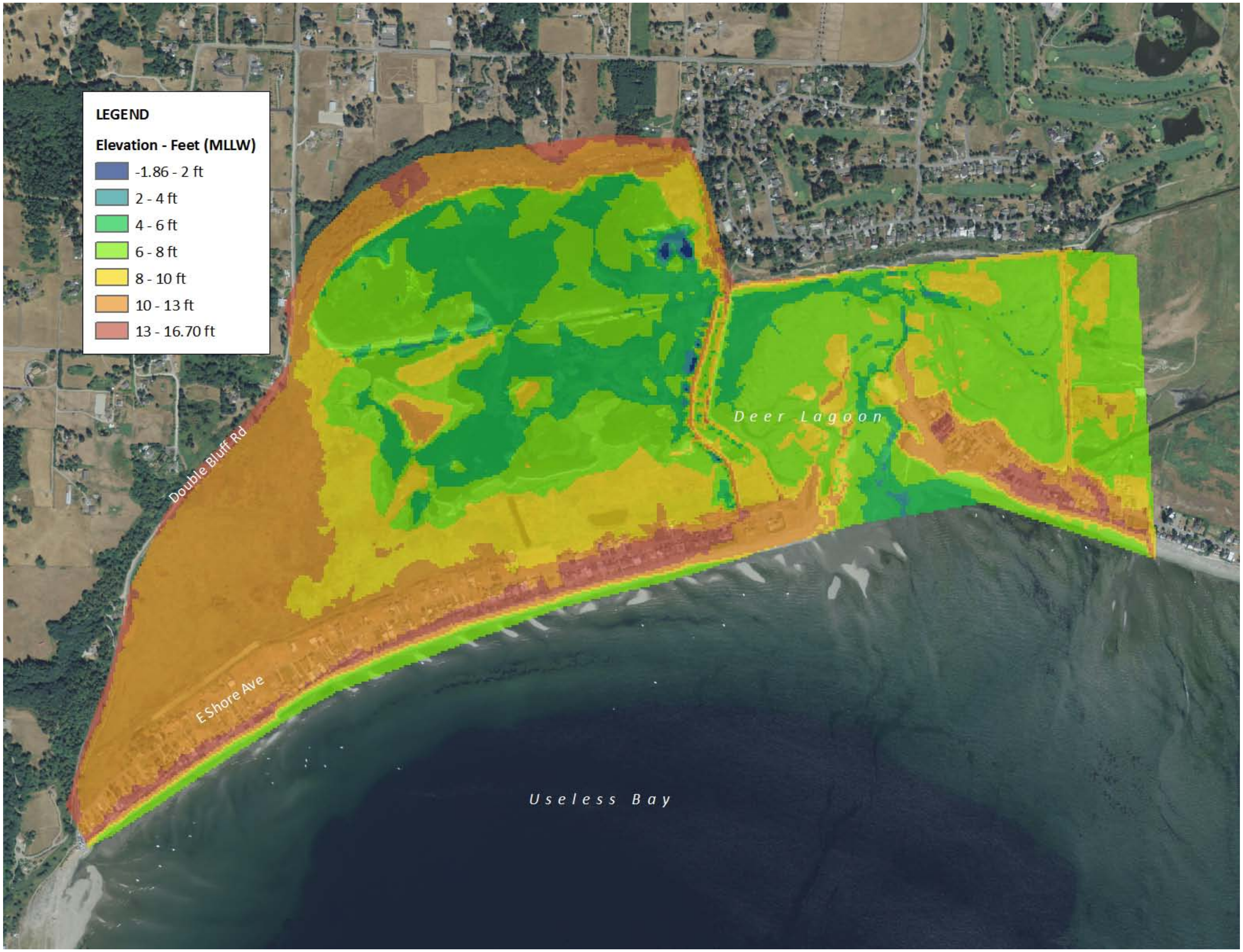
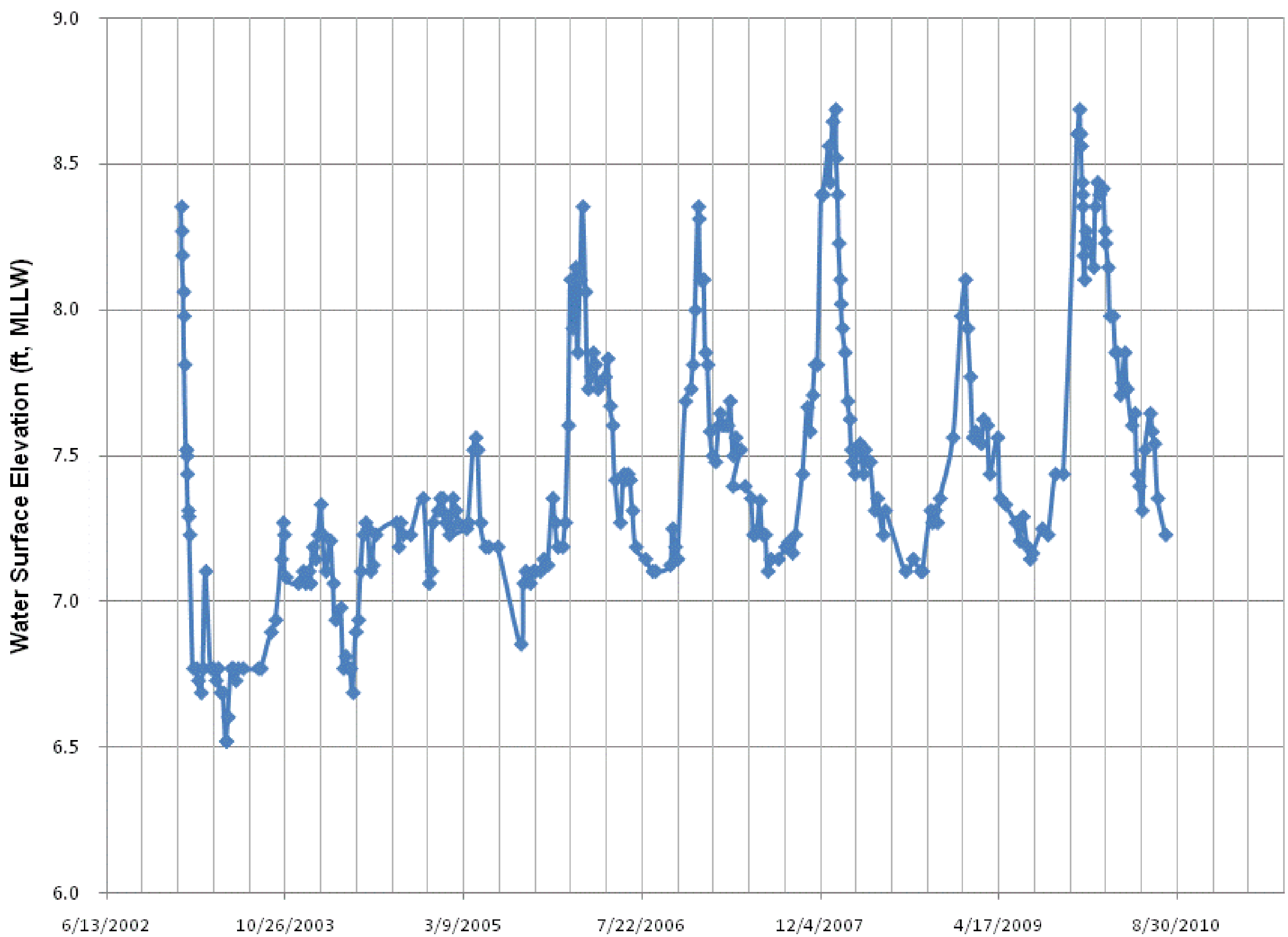



**Figure 2**
Topographic Map of Project Area
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration


**Figure 3**
T-Sheet, Useless Bay
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration




Notes:
Data provided by Island County

**Figure 4**
Water Surface Elevations in Western Lobe Referenced to Mean Lower Low Water
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

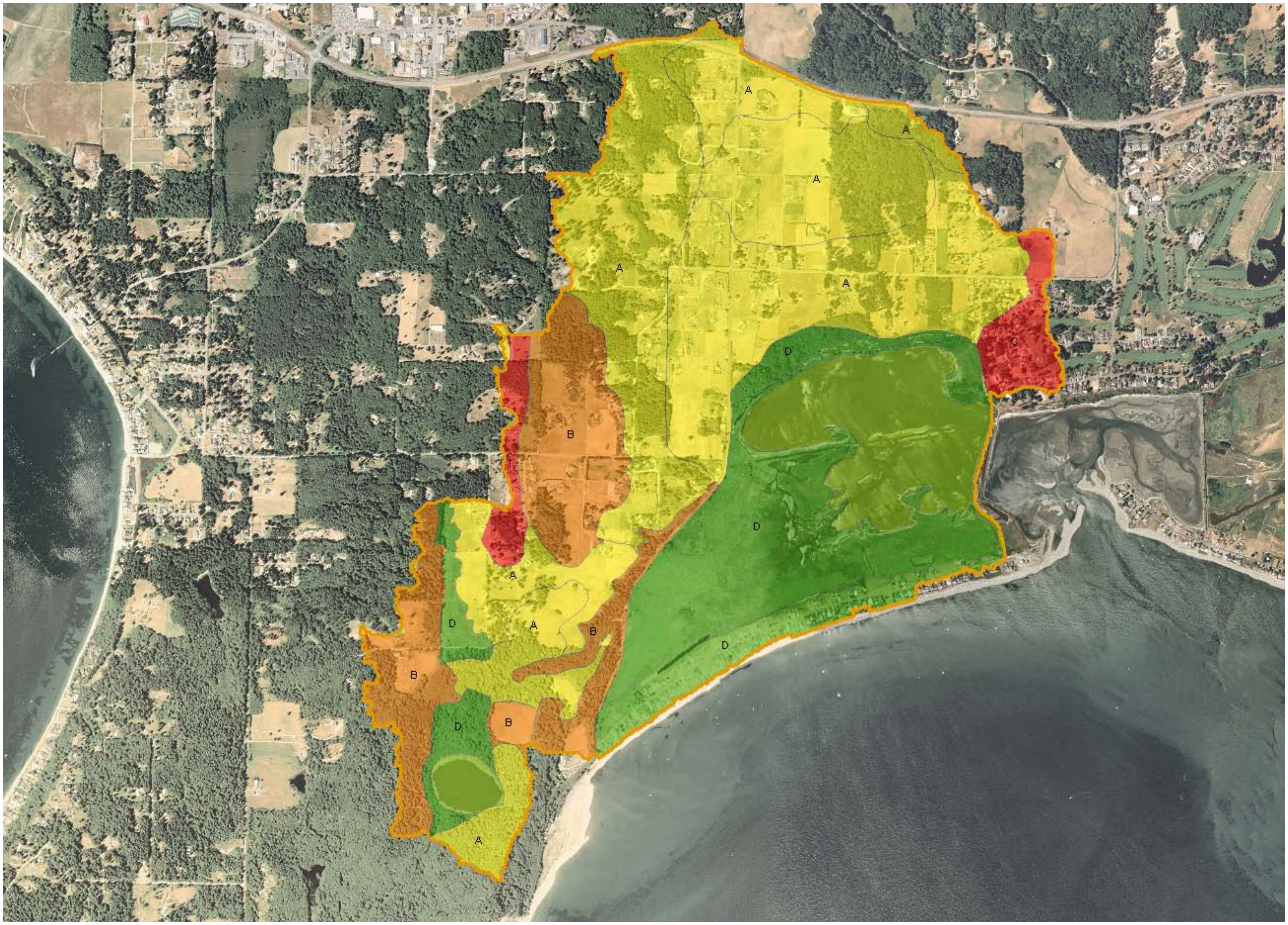



**Figure 5**
Drainage Basin for Western Lobe, Hydrologic Model Input
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

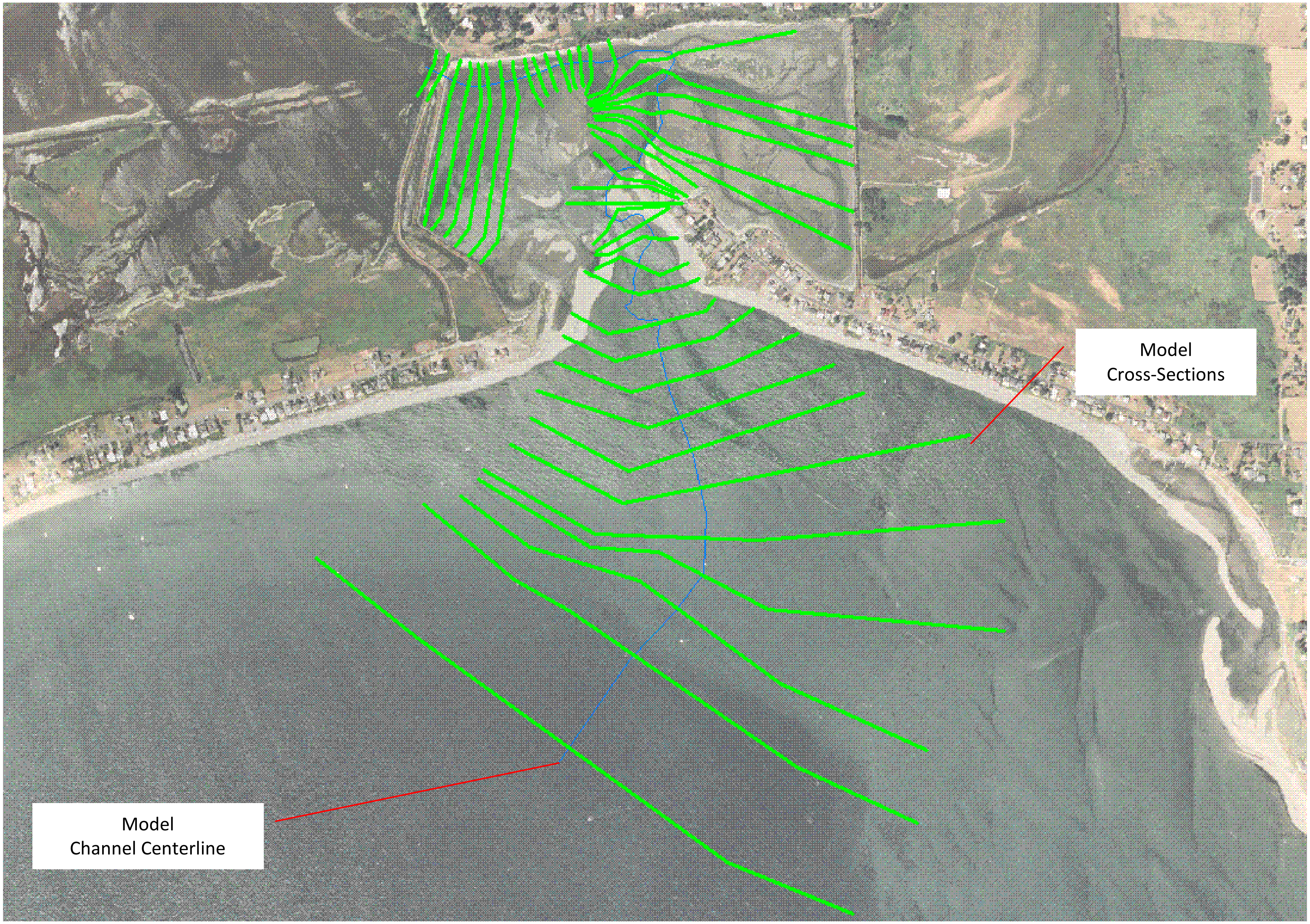



**Figure 6**
HEC-RAS Model of Deer Lagoon Tidal Channel
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

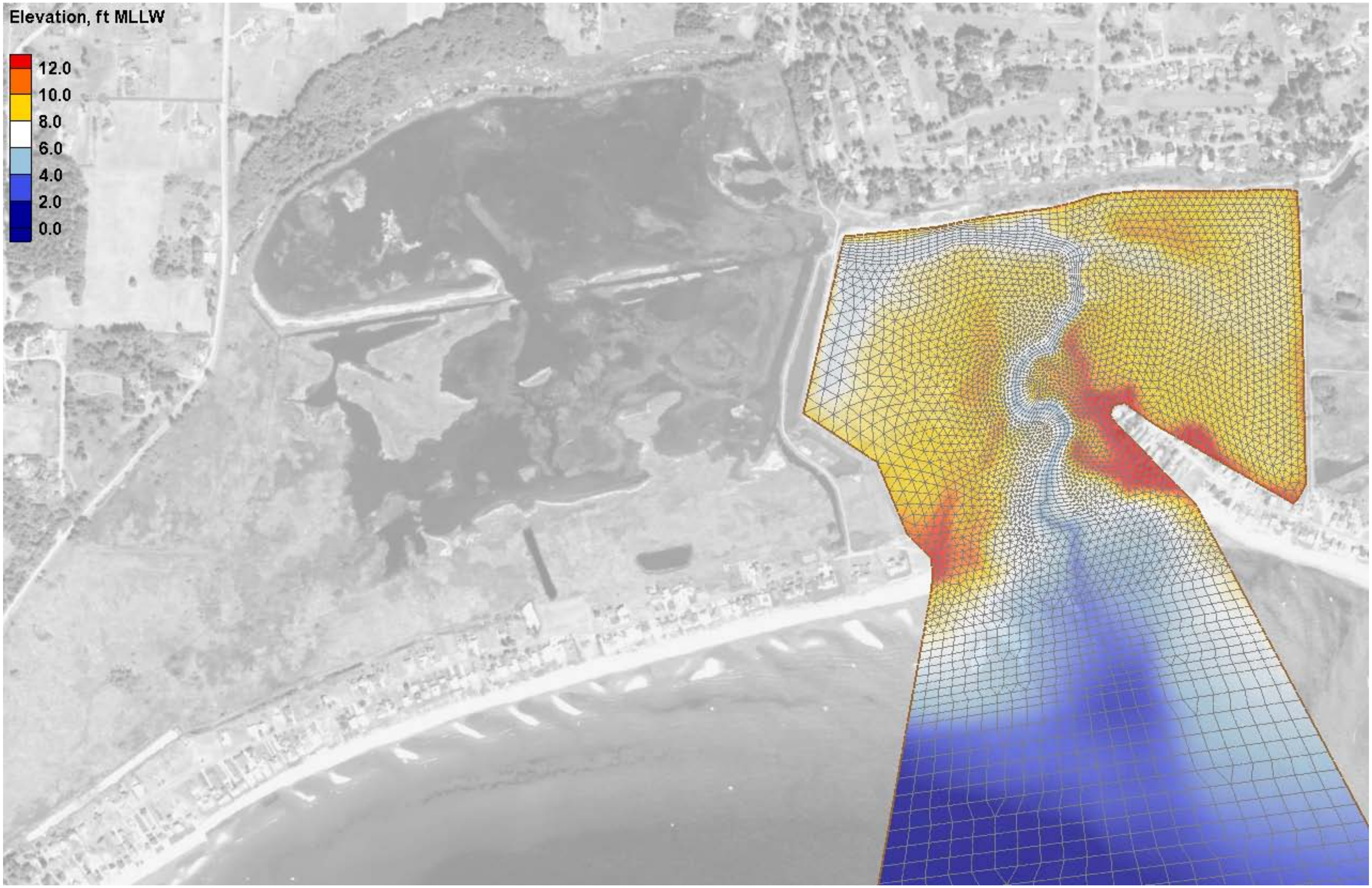
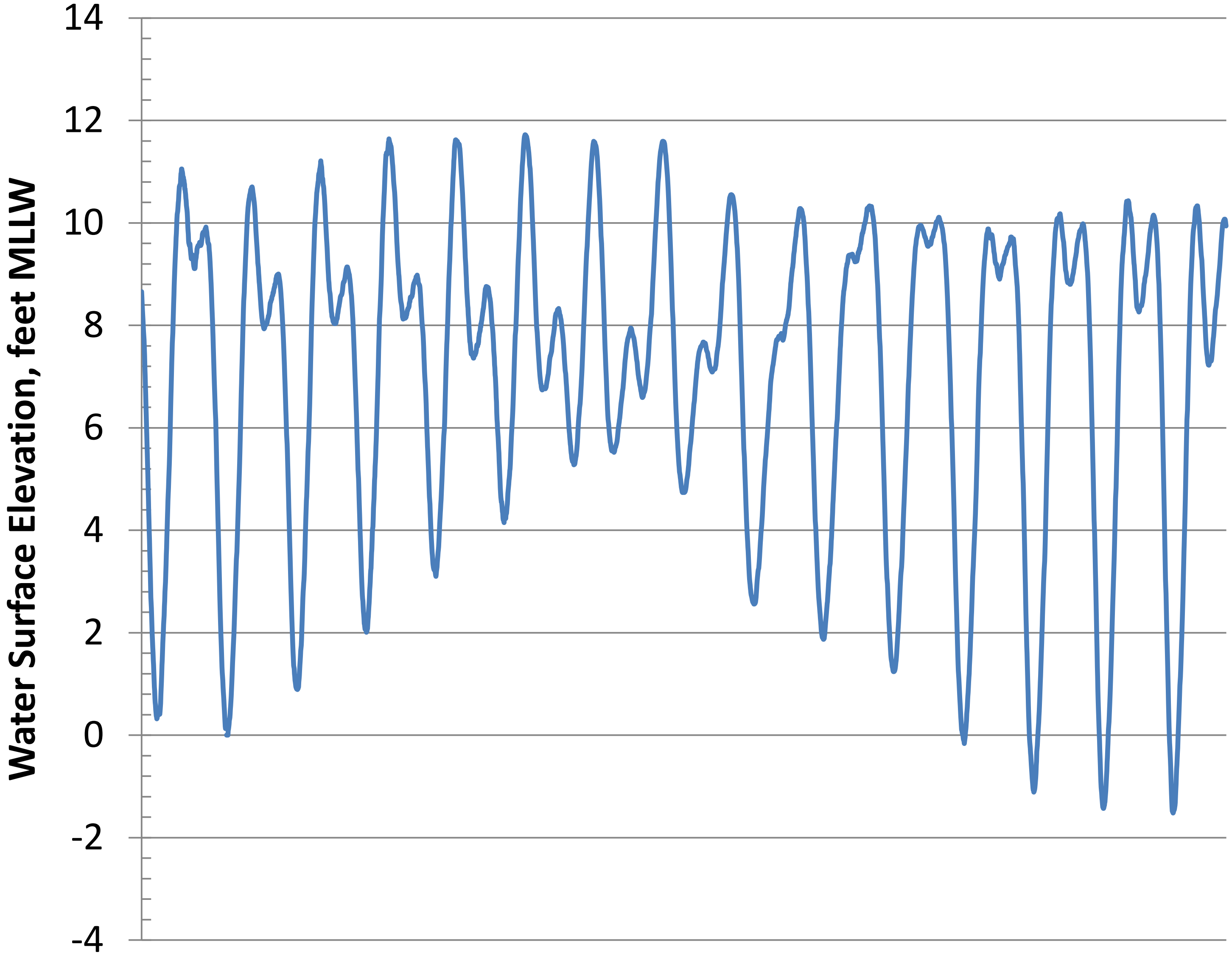



**Figure 7**
2-D Hydrodynamic Model (RMA2) Mesh, Existing Conditions
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration




Notes:

MLLW Mean Lower Low Water

**Figure 8**
Tidal Elevations used as Input to 2-D Hydrodynamic Model
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration


**Figure 9**
Data Extraction Points, 2-D Hydrodynamic Model
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

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**Figure 10**
Site Plan of Proposed Restoration Alternatives
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

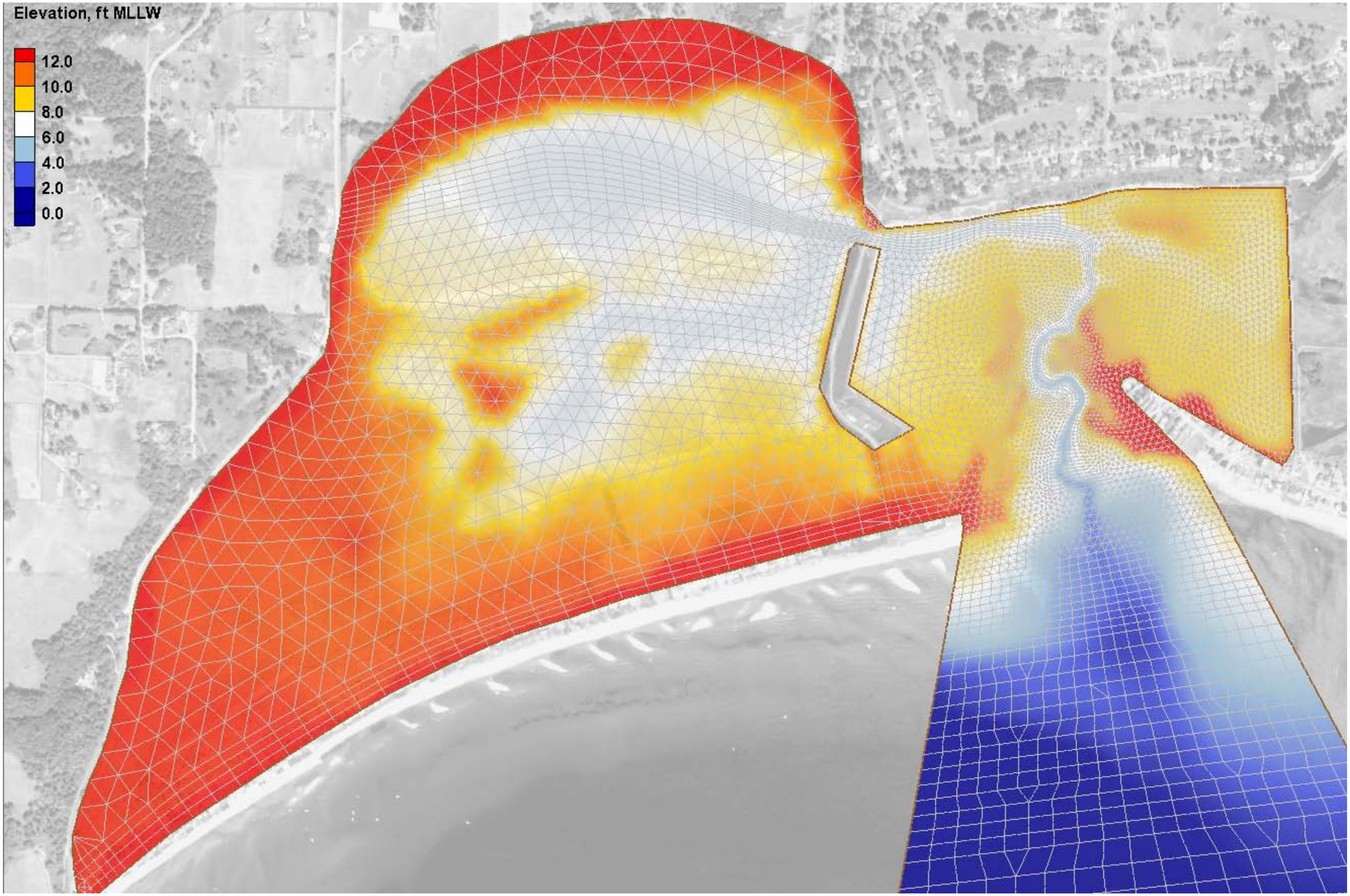


**Figure 11**
2-D Hydrodynamic Model (RMA2) Mesh, Alternative 1, Single Levee Breach
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

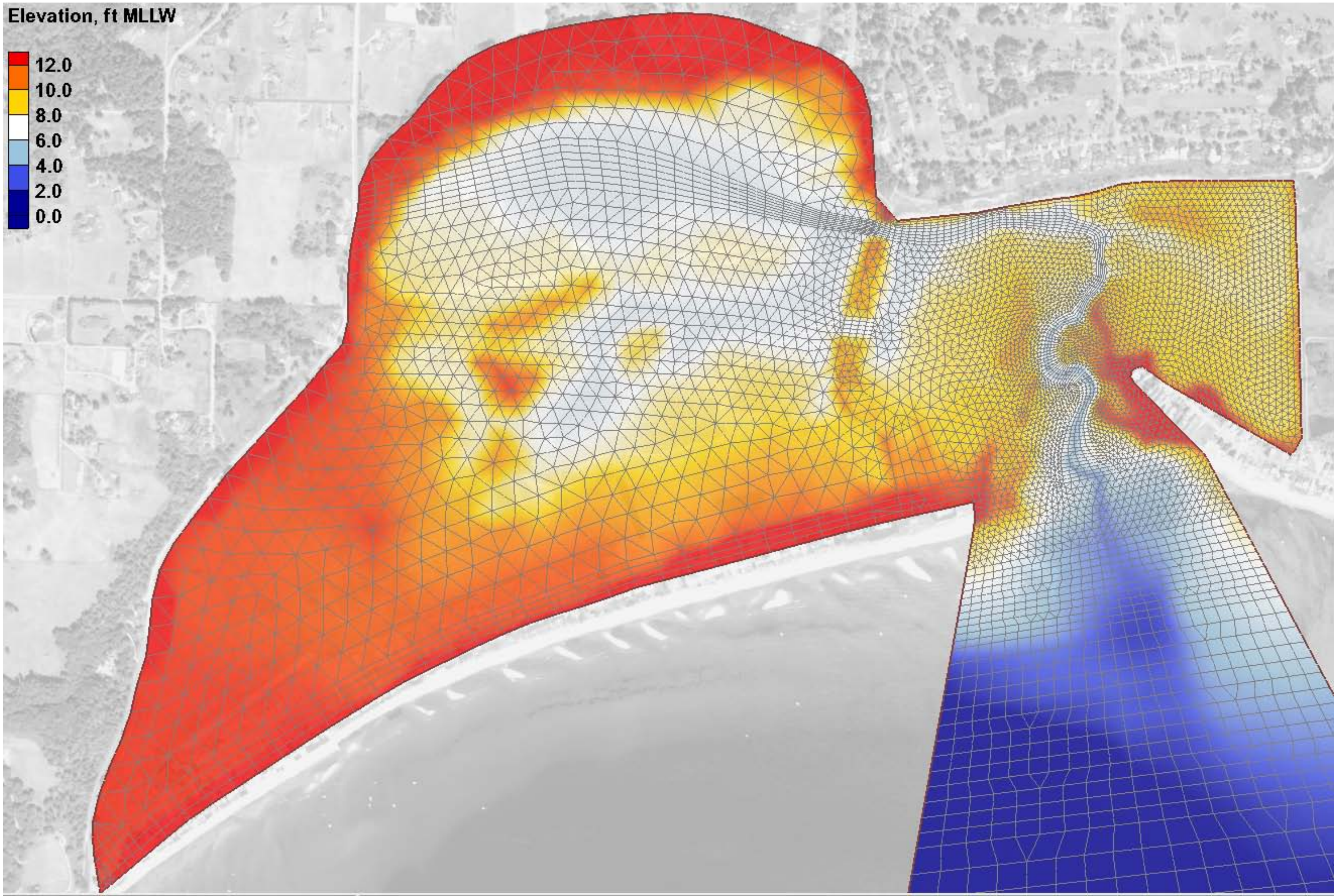


**Figure 12**
2-D Hydrodynamic Model (RMA2) Mesh, Alternative 2, Double Levee Breach
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

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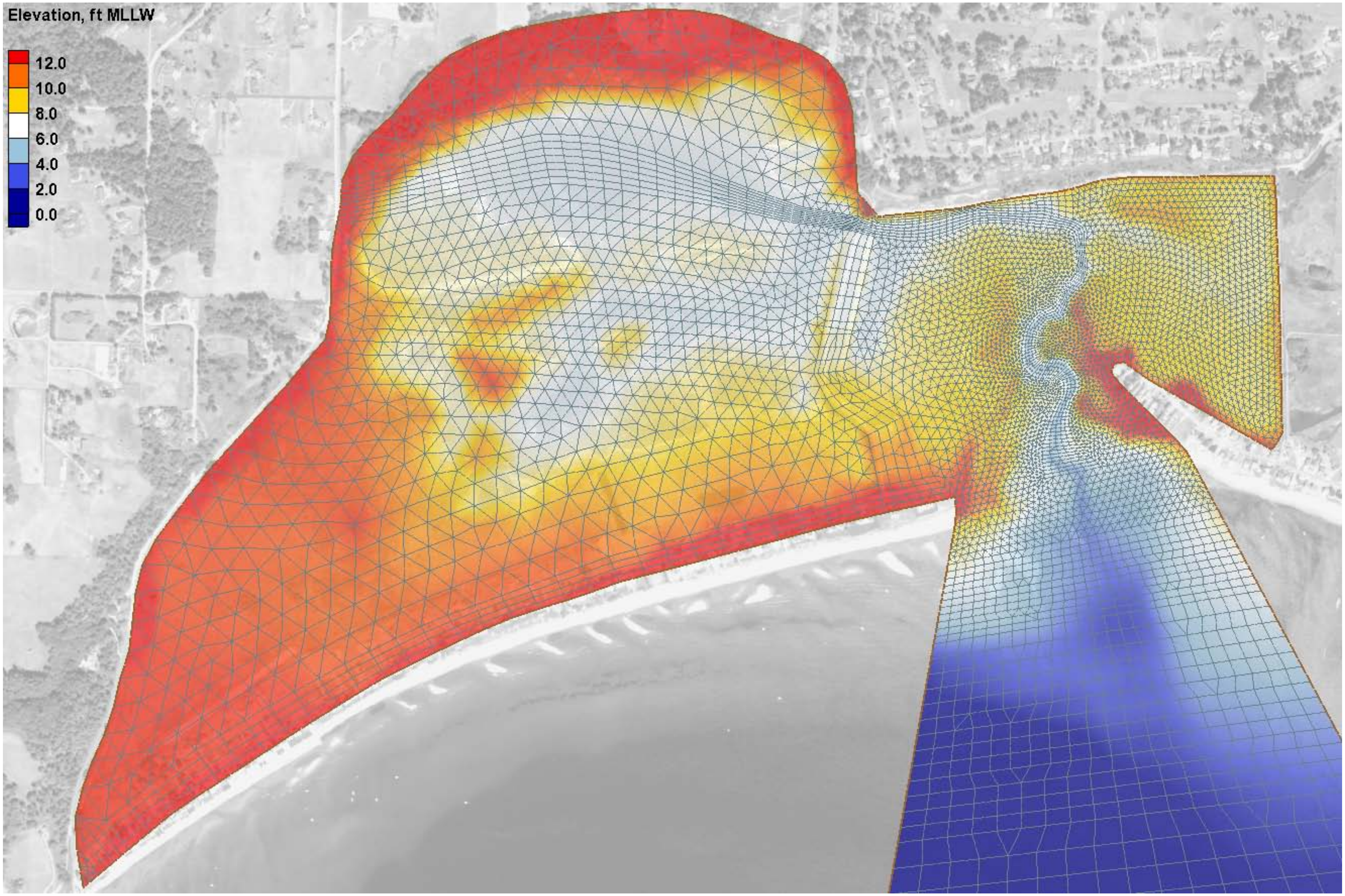


**Figure 13**
2-D Hydrodynamic Model (RMA2) Mesh, Alternative 3, Complete Levee Removal
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

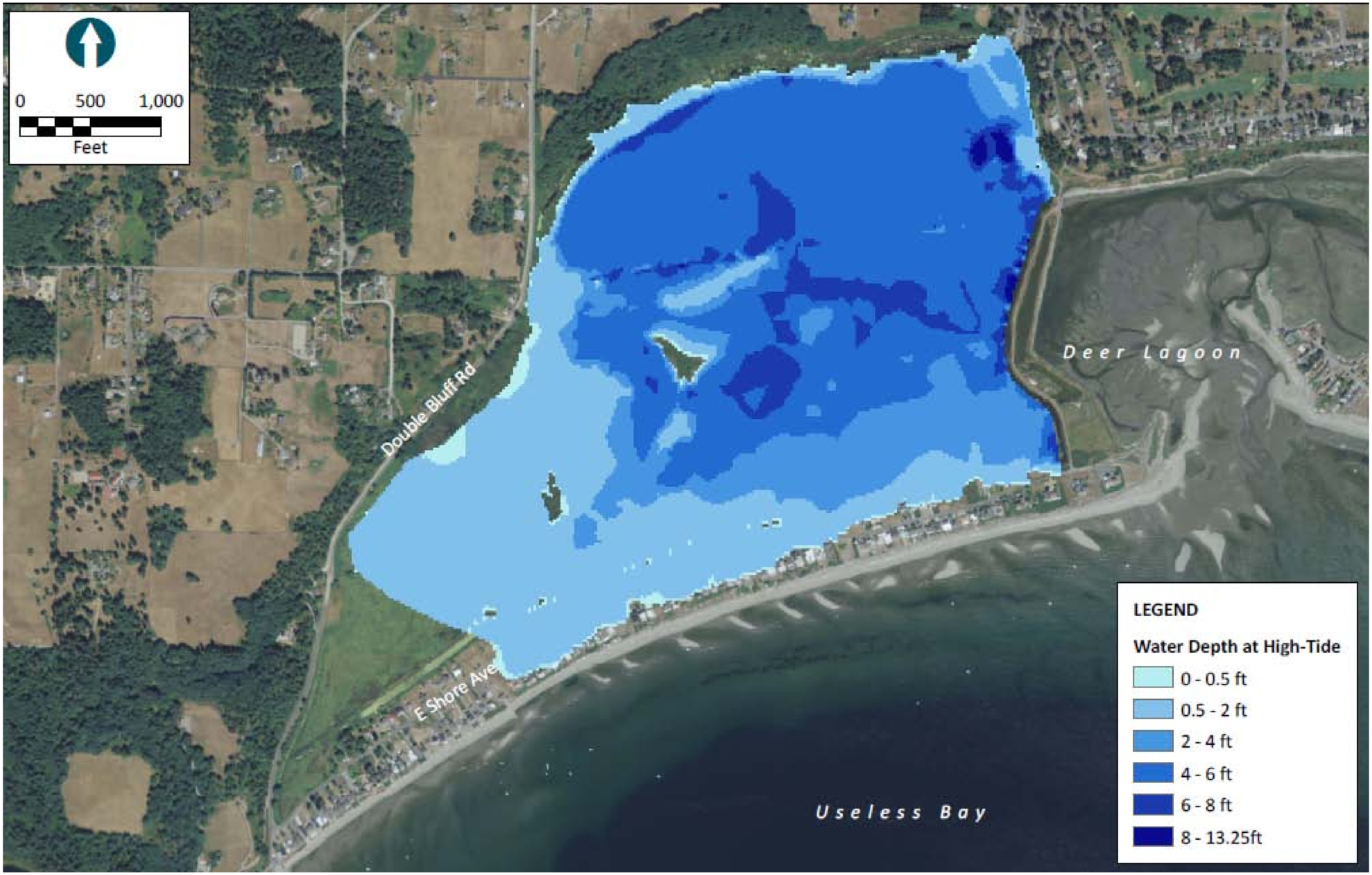


**Figure 14**
Tidal Inundation in Western Lobe at MHHW for All Alternatives
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration


**Figure 15**
Tidal Inundation in Western Lobe at MLLW for All Alternatives
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

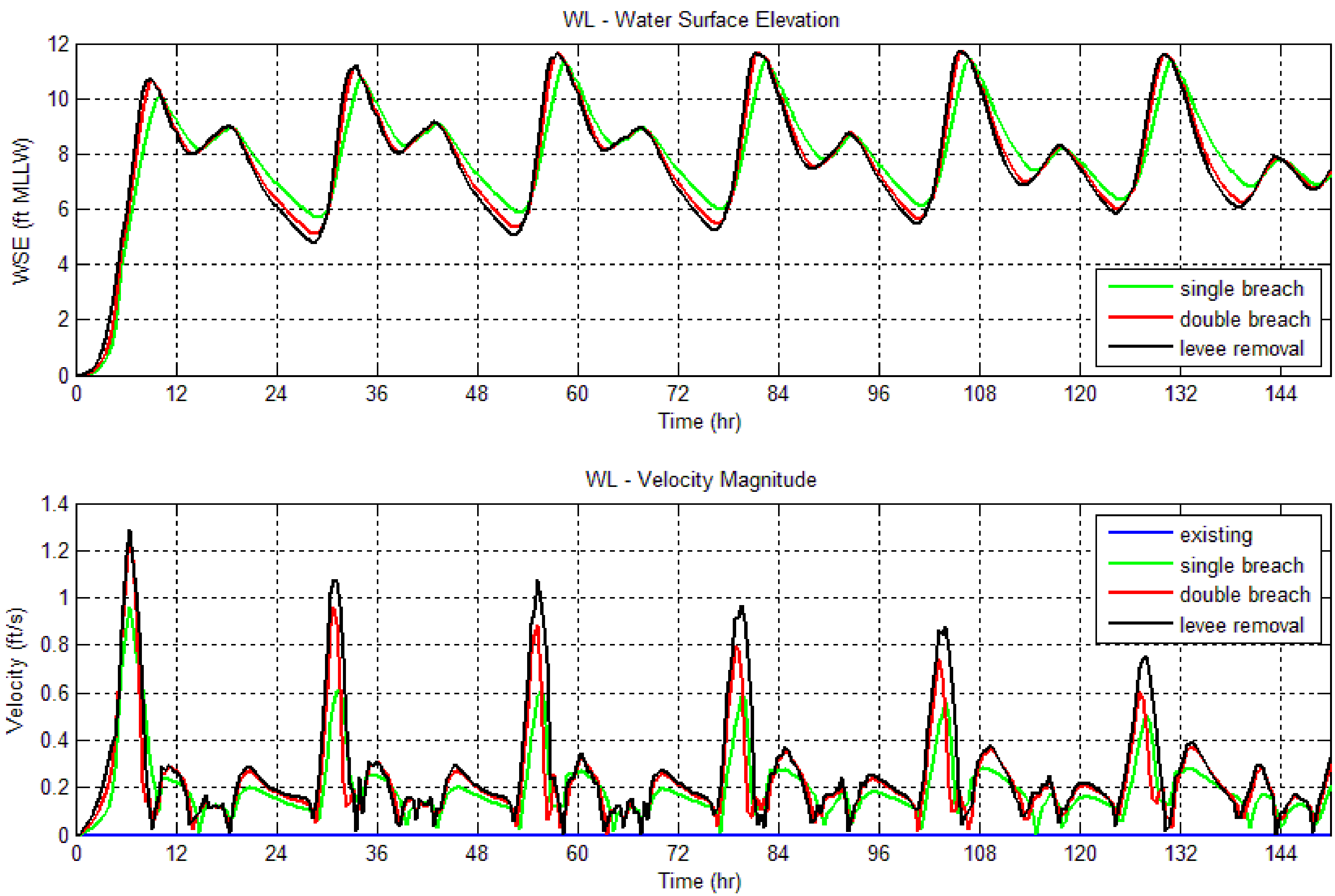


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**Figure 16**
Comparison of Water Surface Elevations and Velocities within the Western Lobe (Point WL in Figure 9)
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

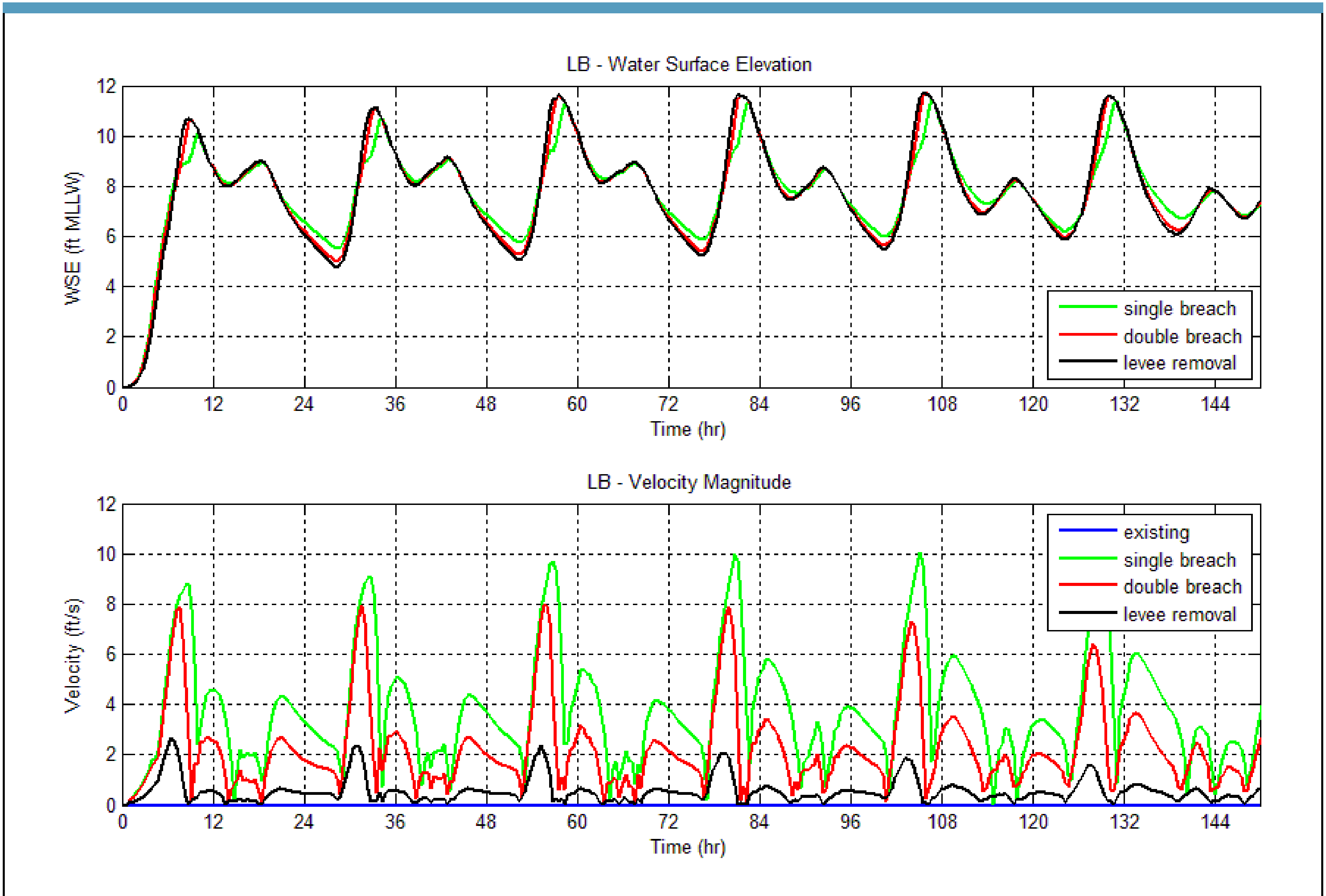


**Figure 17**

Comparison of Water Surface Elevations and Velocities in the First (Northern) Levee Breach (Point LB in Figure 9)

Restoration Alternatives Feasibility Evaluation

Deer Lagoon Restoration

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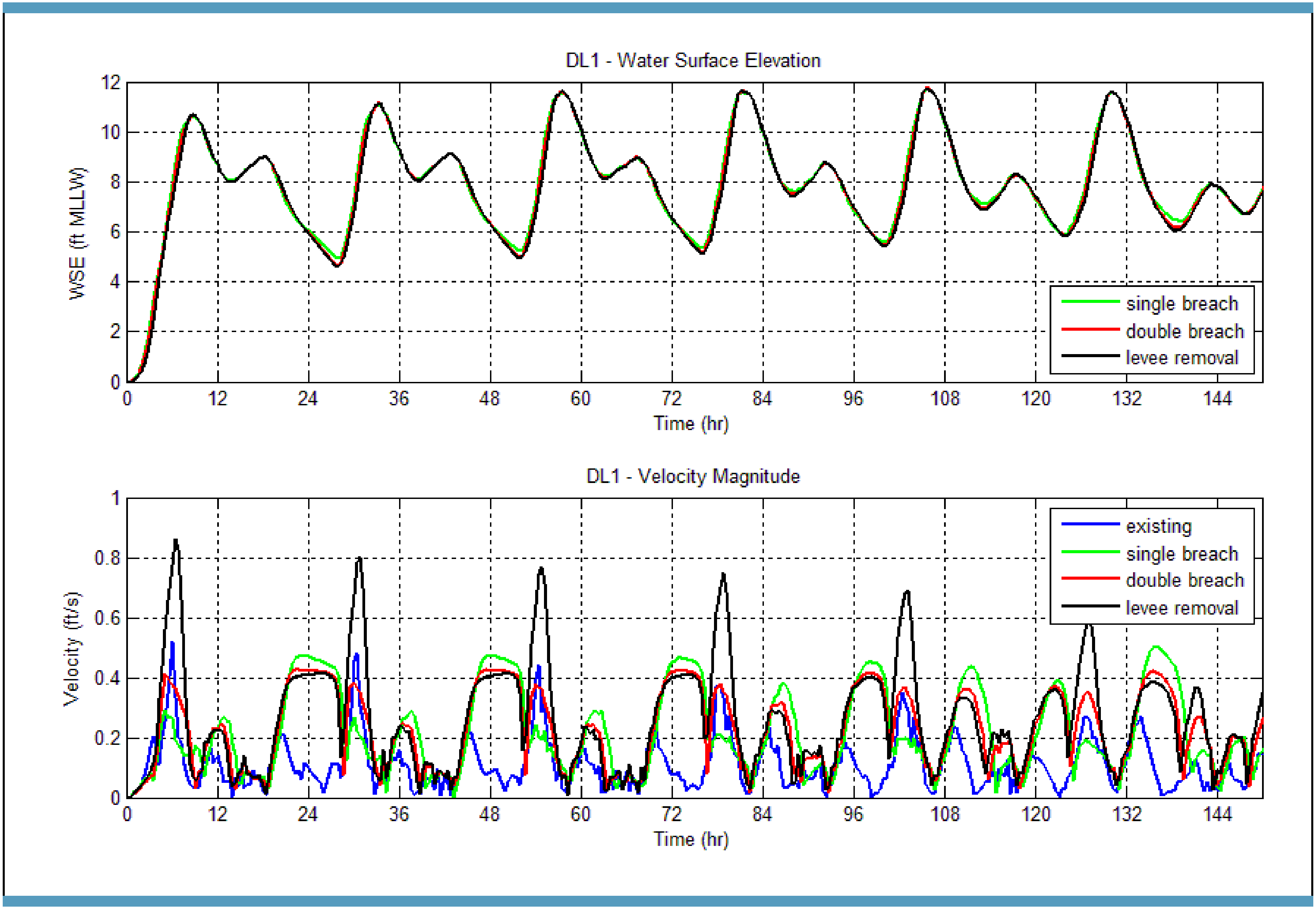


**Figure 18**
Comparison of Water Surface Elevations and Velocities in the Northern Tidal Channel in Deer Lagoon (Point DL1 in Figure 9)
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

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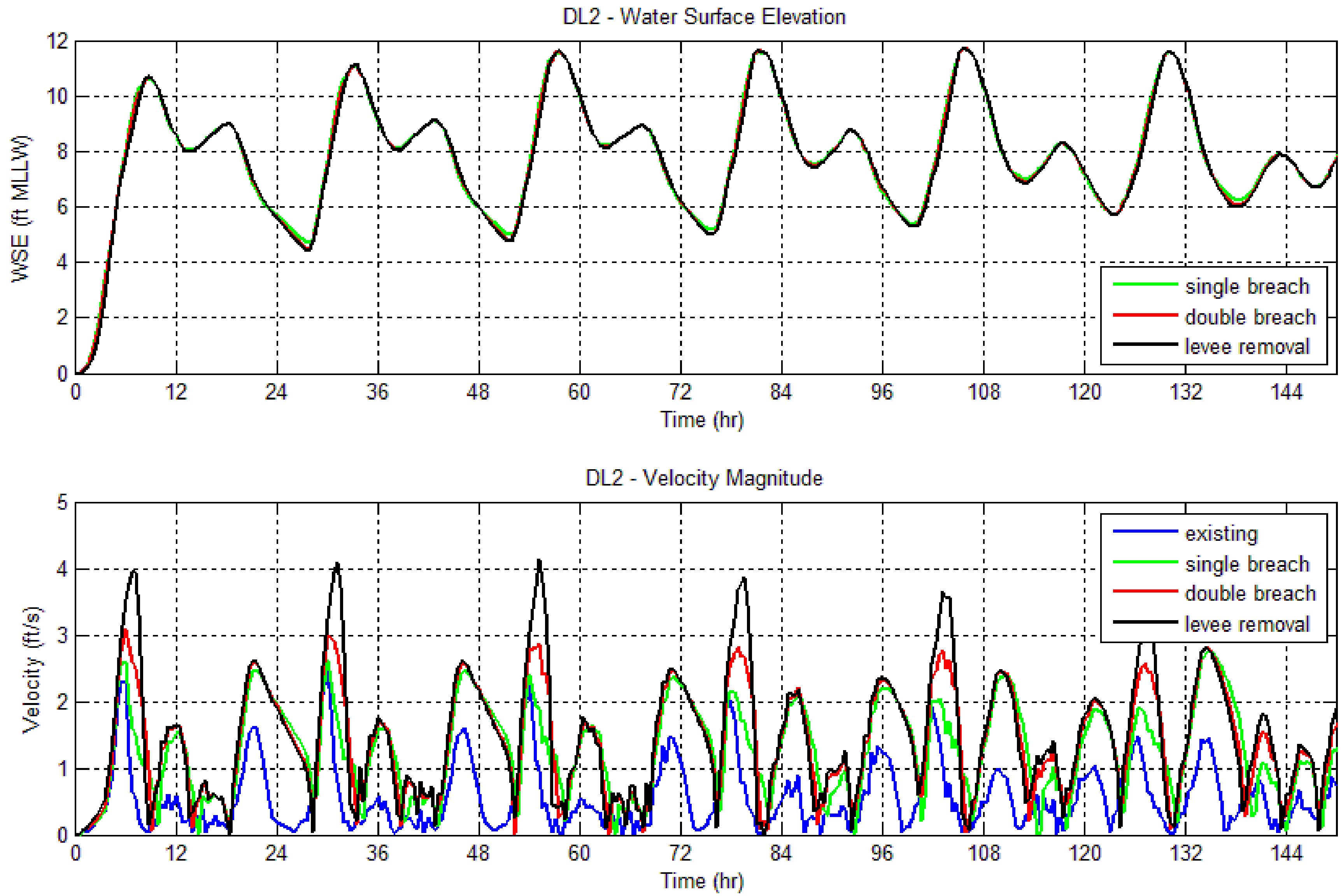


**Figure 19**
Comparison of Water Surface Elevations and Velocities Near the Tidal Inlet in Deer Lagoon (Point DL2 in Figure 9)
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

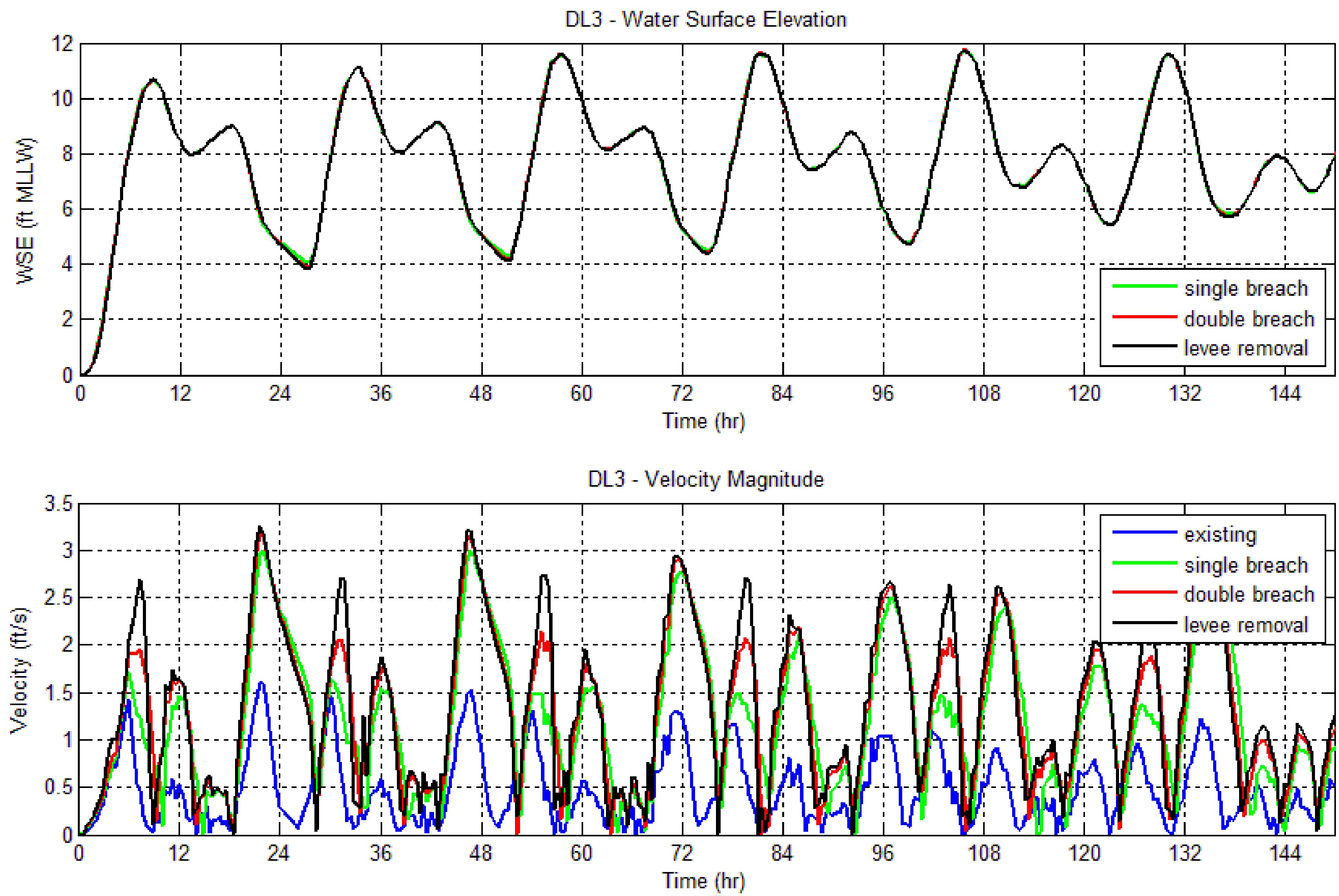


**Figure 20**
Comparison of Water Surface Elevations and Velocities at the Mouth of Deer Lagoon (Point DL3 in Figure 9)
Restoration Alternatives Feasibility Evaluation
Deer Lagoon Restoration

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# APPENDIX A:
# RESULTS OF COASTAL WIND AND WAVE SET-UP EVALUATION

## STORM SURGE

Extreme return period storm surge heights were estimated by analyzing historical water levels from a nearby tide gauge, National Oceanic and Atmospheric Administration (NOAA) Station 9444900 in Port Townsend, Washington. Monthly high water levels are archived for the period from February 1972 to June 2010. From this data, annual maximum water levels were extracted, sorted, and assigned a return period based on the length of the dataset. These annual maximums were then fitted to a Rayleigh distribution so that water levels for long-term return periods could be estimated. Figure A1 illustrates the annual maximum water levels fitted to the Rayleigh distribution; Table A1 outlines the water surface elevations for the 2-, 10-, 20-, 50-, and 100-year return period events. The mean lower low water (MLLW) to North American Vertical Datum of 1988 (NAVD88) conversion of -2.35 feet was taken from NOAA Station 9447130 in Seattle, Washington.

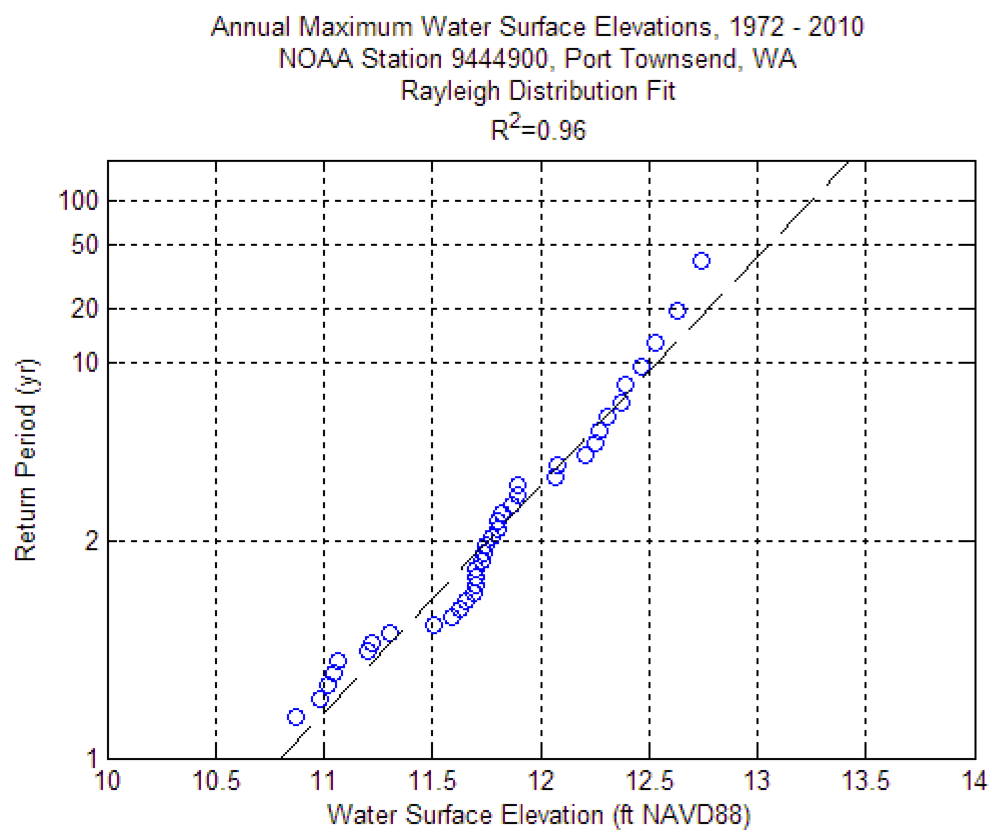


**Figure A1**

**Storm Surge Elevations and Return Periods, Port Townsend, Washington, 1972 to 2010**

**Table A1**
**Extreme Return Period Water Levels**

| Return Period (years) | Water Surface Elevation (feet NAVD88) | (feet MLLW) |
|---|---|---|
| 2 | 11.8 | 14.2 |
| 10 | 12.6 | 15.0 |
| 20 | 12.8 | 15.2 |
| 50 | 13.1 | 15.5 |
| 100 | 13.3 | 15.7 |

## EXTREME WIND SPEEDS

NOAA Station WPOW1 in West Point, Washington, has archived wind speed and directional data from 1984 through 2009. For Deer Lagoon, the wave-producing winds originate from the south-southeasterly direction, so the data were cropped to only include directions between 135° and 190°. Once cropped, the same procedure used to analyze storm surge was used to determine the extreme return period wind speeds. Figure A2 shows the annual maximum wind speeds along with the Rayleigh fit.

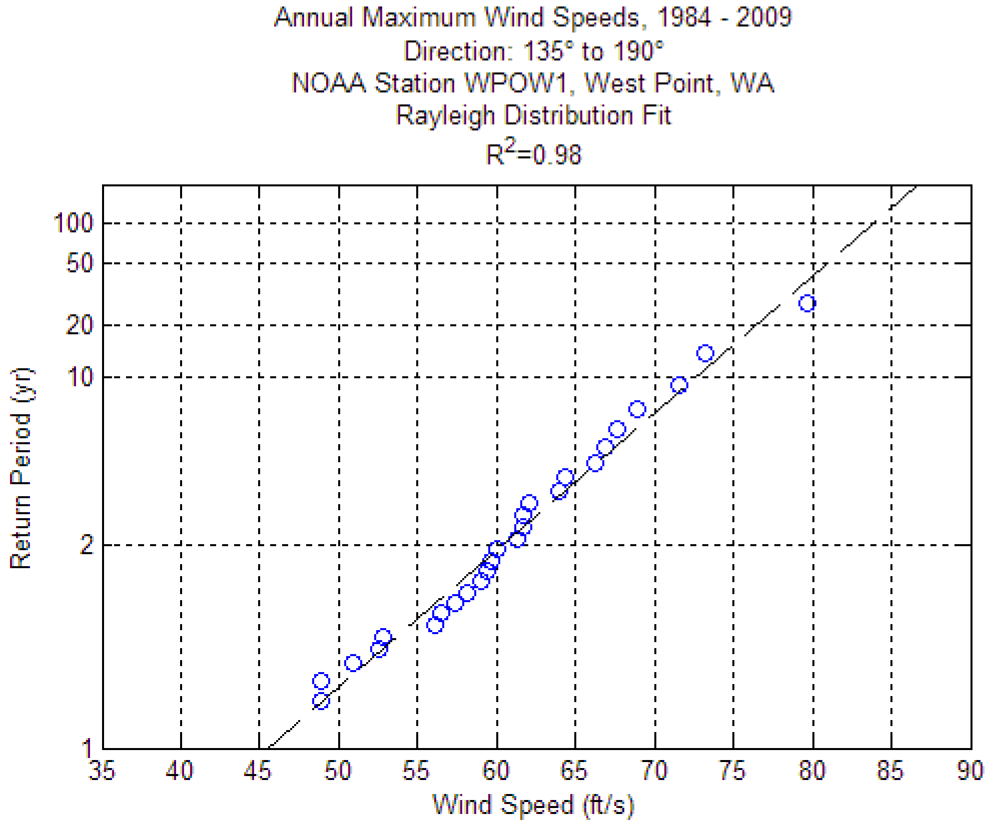


**Figure A2**

**Extreme Wind Speeds and Return Periods, West Point, Washington, 1984 to 2009**

## WIND WAVE GROWTH

Results from the wind analysis were used to determine the wave heights and periods associated with extreme return period wind events. From the 100-foot depth contour offshore of Deer Lagoon to the south-southeast, the longest straight-line fetch measures approximately 207,000 feet to Vashon Island, south of Seattle. Along this fetch, the average depth is approximately 400 feet. Using this fetch and depth along with the wind speeds in Table A2, shallow water, fetch-limited wave development equations adapted from the U.S. Army Corps of Engineers (USACE) Automated Coastal Engineering System (ACES) computer program were used to model wave growth (USACE 1992). The resulting wave conditions (significant wave height and period) are listed in Table A3.

**Table A2**
**Extreme Return Period Wind Speeds**

| Return Period (years) | Wind Speed | |
|---|---|---|
| | (ft/s) | (mph) |
| 2 | 60 | 41 |
| 10 | 73 | 50 |
| 20 | 76 | 52 |
| 50 | 81 | 55 |
| 100 | 84 | 57 |

**Table A3**
**Extreme Return Period Wave Heights and Periods**

| Return Period (years) | Wind Speed | | Wave Height (ft) | Wave Period (s) |
|---|---|---|---|---|
| | (ft/s) | (mph) | | |
| 2 | 60 | 41 | 7.1 | 5.3 |
| 10 | 73 | 50 | 8.6 | 5.8 |
| 20 | 76 | 52 | 9.0 | 5.9 |
| 50 | 81 | 55 | 9.6 | 6.1 |
| 100 | 84 | 57 | 9.9 | 6.2 |

## WIND SET-UP

Onshore winds of sufficient strength and fetch can cause elevated water levels along the shoreline; this effect must be accounted for to ensure that a structure is designed with sufficient elevation. The procedure outlined in *Estuary and Coastline Hydrodynamics* (Ippen 1966) is used here to estimate wind set-up over a sloping bottom, as shown in Equation 1, which must be solved iteratively:

(1) $$S = \frac{KU^2L}{g(h_0 - h - S)} \ln\left(\frac{h_0}{h + S}\right)$$

In Equation 1, $S$ is the wind set-up height, $K$ is a constant equal to $3.3 \times 10^{-6}$, $U$ is the wind speed, $L$ is the fetch length, $g$ is gravitational acceleration, $h_0$ is the offshore depth, and $h$ is the shallow water depth. The wind speeds were taken from Table A3. The fetch length is 213,000 feet from Vashon Island to the shoreline at Deer Lagoon. The offshore depth is 400 feet, and the shallow depth is 10 feet. Table A4 presents the results of the wind set-up analysis.

**Table A4**
**Water Level Set-up Due to Extreme Winds**

| Return Period (years) | Wind Speed (ft/s) | Wind Speed (mph) | Wind Setup (ft) |
|---|---|---|---|
| 2 | 60 | 41 | 0.7 |
| 10 | 73 | 50 | 1.1 |
| 20 | 76 | 52 | 1.2 |
| 50 | 81 | 55 | 1.3 |
| 100 | 84 | 57 | 1.4 |

## WAVE SET-UP

Recall that in the wave growth analysis, the 100-foot depth contour was used as the downwind boundary. To estimate wave setup, linear wave theory was used to estimate wave breaking characteristics as the waves propagate from the 100-foot contour to shore. Breaking characteristics were used to calculate set-up.

The distance from the 100-foot contour the shoreline is 7,300 feet, which results in a bottom slope of 0.0137. Assuming the waves approach perpendicular to shore, the wave breaking characteristics (breaking height and depth) can be found using Equations 2, 3, and 4, adapted from *Water Wave Mechanics for Engineers and Scientists* (Dean and Dalrymple 1991). In these equations, $H_b$ is the breaking wave height, $h_b$ is the breaking depth, $\kappa$ is the breaking index, $g$ is gravitational acceleration, $T$ is the wave period, $m$ is the bottom slope, $H_0$ is the deep water wave height, $c_0$ is the deep water wave celerity, and $\theta_0$ is the deep water angle of incidence:

(2) $$H_b = \kappa h_b$$

(3a) $$\kappa = b(m) - a(m)\frac{H_b}{gT^2}$$

(3b) $$a(m) = 43.8(1.0 - e^{-19m})$$

(3c) $$b(m) = 1.56(1.0 + e^{-19.5m})^{-1}$$

(4) $$H_b = \left(\frac{\kappa}{g}\right)^{1/5} \left(\frac{H_0^2 c_0 \cos\theta_0}{2}\right)^{2/5}$$

Offshore wave heights and periods were from Table A3. The deep water angle of incidence was assumed to be zero. Known parameters were substituted into Equation 3, giving the breaking index as a function of breaking wave height. Combining Equations 3 and 5 resulted in an equation for breaking wave height that was solved iteratively, then Equations 3 and 2 were used to find the breaking index and breaking depth, respectively. Because each breaking index was nearly equal to 0.80, equation II-4-24 in the *Coastal Engineering Manual* (USACE 2002) is simplified and the mean wave setup can be approximated as 15% of the breaking wave depth. Table A5 outlines the wave breaking characteristics and wave setup height for each return period event of interest.

**Table A5**
**Wave Set-up and Breaking Characteristics**

| Return Period (yr) | Breaking Wave Parameters | | | Wave Setup (ft) |
|---|---|---|---|---|
| | Height (ft) | Depth (ft) | Breaking Index | |
| 2 | 6.5 | 8.0 | 0.81 | 1.2 |
| 10 | 7.9 | 9.7 | 0.81 | 1.5 |
| 20 | 8.2 | 10.2 | 0.81 | 1.5 |
| 50 | 8.8 | 10.8 | 0.81 | 1.6 |
| 100 | 9.1 | 11.2 | 0.81 | 1.7 |

## REFERENCES

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# APPENDIX B:
# ANIMATIONS (DVD)