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memorandum

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from Louis White, PE (CA)

subject Hydraulic Modeling and Fish Passage Analysis for Swan Lake - REVISED

1. Introduction

ESA PWA is assisting Coastal Geologic Services Inc. (CGS) with the preparation of an engineering feasibility assessment of the creation of a tidal connection to Swan Lake as part of the Swan Lake Restoration Project for the Skagit Fisheries Enhancement Group (SFEG). This memorandum presents the results of hydraulic modeling efforts undertaken to evaluate the feasibility of providing a fish-passable tidal connection to the site through culverts or an open channel. Specifically, several culvert and channel designs were modeled to estimate the resulting velocities and water depths and to compare the conformance to fish passage criteria developed by the Washington Department of Fish and Wildlife (WDFW). The work described in this memorandum was completed by Louis White, Eddie Divita, and Doug George, with oversight by Bob Battalio, PE. Site measurements and other data, along with review and comments on this memo were provided by CGS.

1.1. Project Goals and Objectives

Tidal rearing habitat, including pocket estuaries or embayments, back-barrier lagoons, and salt marsh habitats, has been identified as a limiting factor in Chinook recovery in Puget Sound (SRSC & WDFW 2005). The amount of this type of habitat has significantly decreased from anthropomorphic pressure, and has been particularly vulnerable to development and historical land use. Swan Lake represents a potential site for reestablishing tidal rearing habitat due to the significant amount of shallow water area that can be converted from a predominantly static reservoir-drainage to a more dynamic tidal embayment. Restoration of tidal rearing habitat, such as Swan Lake, has been identified as a strategic need by the Puget Sound Nearshore Ecosystem Restoration Project (Schlenger et al. 2010).

The purpose of this study is to evaluate the feasibility of establishing a sustainable tidal connection to Swan Lake. The evaluation requires an understanding of the nearshore wave hydrology, sediment transport dynamics, and the sustainability and stability of a natural inlet or culverts. Results of wave modeling, sediment transport estimates, and an inlet stability analysis found that creation of a tidal inlet or installation of culverts could provide a tidal connection from the Strait of Juan de Fuca, as summarized in the preceding memo for this contract (ESA PWA 2012). The main findings of the inlet analysis suggest that although an open channel would be expected to remain open for a sand beach, it would likely close due to a buildup of cobbles in the mouth of the inlet during large wave events. The buildup of cobble in the mouth would reduce flows and velocities through the inlet, and would not likely re-open naturally, and would require periodic excavation of sediments. The analyses described below extend the previous studies to include hydrodynamic modeling of the system to evaluate whether an open channel or culvert structure could provide a connection that is fish-passable, which is a major driver of the overall project. Therefore, the specific objectives of this memorandum are:

- To evaluate the performance of different tidal connection alternatives (e.g. culverts or an open channel) between the Strait of Juan de Fuca and Swan Lake, including the impact of water levels in the lagoon under different scenarios;
- To select a tidal connection alternative that is "fish-passable" and meets specific fish passage criteria for tidal environments;
- To provide a conceptual framework for possible alternatives to develop further, including natural open channel and culvert alternatives with or without self-regulating tide (SRT) gates.

1.2. Background and Previous Work

Swan Lake is a back-barrier, closed lagoonal marsh located on the western edge of Whidbey Island, Washington, on the Strait of Juan de Fuca (Figure 1). The site is exposed to locally generated wind waves and longer period swell from the Pacific Ocean that penetrates through the Strait of Juan de Fuca. The tide range at the site is approximately 7.5 feet between mean lower low water (MLLW) and mean higher high water (MHHW). Tidal datums at Swan Lake were estimated by CGS using the program VDatum (Table 1). The relationship between MLLW and NAVD was verified to within 0.5 ft using water level data collected on site. The elevations in this memorandum are presented in feet relative to MLLW.

Table 1. Tidal datums used for the Swan Lake wave and inlet analyses.

Tide	Elevation (ft MLLW)
Mean Higher High Water (MHHW)	7.5
Mean High Water (MHW)	6.8
Mean Tide Level (MTL)	4.6
Mean Sea Level (MSL)	4.6
Mean Low Water (MLW)	2.4
North American Vertical Datum of 1988 (NAVD)	0.3
Mean Lower Low Water (MLLW)	0.0

Source: CGS, data from VDatum

Swan Lake is currently connected to the Strait of Juan de Fuca by two culverts that drain the approximately 100 acre lake through flap gates. These culverts are located where the shoreline angle jogs from a bearing of approximately 15° to 45°, which is also a relatively short distance from the lake to deep water offshore (Figure 2). The culverts consist of two 30-inch inside diameter pipes, one of which was slip-lined with a 24-inch high density polyethylene (HDPE) inside, based on construction documents (Island County 2008) and discussions with Island County staff. The culverts run from the tide gate box on the seaward side of the road and out into the lower intertidal zone. The culverts run through an Island County easement, located between two residential properties. Local operators indicated that cobble sometimes deposits in the aluminum pipe, and sand often deposits in both pipes during the summer. Debris comprising small pieces of wood often clogs the flap gates which require approximately weekly maintenance.

Locations for the new culvert and new open channel inlet were selected to provide the best conditions for each alternative rather than at the same locations. The reasons are developed later in this memorandum, but are summarized here to describe the alternatives.

Culvert: The existing culvert location appears to be the most favorable location for a new culvert because:

- Shortest distance to deeper Sound waters,
- Inflection point in shore minimizes sand intrusion, and
- Existing culvert location (e.g. access, space).

Open Channel Inlet / Outlet: The existing culvert location is not considered favorable for an open inlet because:

- Space is too narrow for anticipated width and possible migration, and
- The jog in the shore is an unstable place for a channel and channel armoring would be required.

An area of relatively low elevation with marsh vegetation located north of the existing culverts and residences was identified as a possible historic tidal connection to the sound (CGS 2010). Analyses of sediment diatoms indicate that this was primarily a freshwater and brackish area (EHH Consulting 2012). This location is a likely candidate for restoring an open channel connection between the sound and the lake, for the following reasons:

- The wave exposure is reduced relative to the culvert location;
- The sand transport pathway diverges slightly offshore from the cobble berm; and,
- The direction of mouth migration is more predictable, and there is little damage risk.

1.3. Fish Passage Criteria

Hydraulic features, such as culverts and engineered channels, can act as barriers to fish passage due to the presence of high flow velocities and low flow depths. A growing body of research has emerged which attempts to identify the maximum allowable velocity and minimum depths that various species of fish can successfully navigate past a hydraulic structure. The criteria used to evaluate fish passage through the proposed Swan Lake are based on data and guidelines presented in the Washington Administrative Code (WAC) 220-110-070, established by the Washington State Legislature for regulation of water crossing structures by WDFW, and a draft report on culvert design for fish passage (WDFW 2011).

Both of the above documents focus mainly on passage of fish through culverts in fluvial settings. In such situations the flow is in one direction (i.e. downstream), and relatively constant over time except during floods. In contrast, tidal connections exhibit daily reverses in direction (ebb to flood) and velocity varies widely during each tidal cycle. The WAC provides some information on how to determine hydrology for culverts in the tidal zone. For tidal conditions, WAC 220-110-070 recommends that total outflow be calculated by routing all stored tidal prism (tide water and stream-flow contributions) out through the culvert as the tide ebbs. The high fish passage design flow (10% exceedance flow) should then be calculated using one-hour increments of tidal change, assuming a tidal fluctuation between MLLW and MHHW. However, Appendix D of the draft report (WDFW 2011) acknowledges that the earlier guidance is insufficient to guarantee 90% passage of fish over the tidal cycle and identifies research that adult salmon migration can occur at 2% exceedance flows. In addition, a general discussion about the sizing of the culvert with respect to the tidal range concludes that an open channel is the preferred alternative in most cases. A culvert placed in the upper or lower edges of the tide range tends to limit juvenile salmon access to a lagoon as the fish tend to swim in the upper layers of the water (WDFW 2011). An open channel could improve the likelihood of juvenile salmon identifying a favorable lagoon and rearing habitat, and could support additional ecological benefits that exist in natural estuaries (including a gradual salinity gradient, tidal inundation, and natural channel morphology).

Tide gates are an additional component to consider with respect to fish passage. Specific operational criteria for SRT gates were developed for the Fisher Slough project, located in the Skagit River delta, to limit flooding and maintain fish passage of juvenile Chinook salmon (Beamer and Henderson 2012). The target velocity for the project was a maximum velocity of 8 feet per second at all times during spring juvenile Chinook migration from March 1 to May 31 (Table 2). Results of monitoring of the criteria variables indicate that water depths, gate operations, and velocities were met. However, the appropriateness of a maximum velocity of 8 feet per second was questioned, as the authors indicate a breadth of research that shows that juvenile salmon do not exhibit upstream migration in velocities greater than approximately 2 feet per second. It should also be noted that the Fisher Slough is located in a site that is very protected from wave and swell energy in comparison to the Swan Lake site and is located further upstream in the estuary, which may require more strict criteria for passage of outmigrating fry salmon.

Table 2. Fish passage and floodgate operation criteria for Fisher Slough floodgates (presented as analog case).

Period	Fish Passage Criteria and/or Floodgate Setting
Fall/Winter Flood Control (Oct. 1-Feb. 28/29)	Gate opening: gates shall have a minimum closure setting below MHHW
Spring Juvenile Chinook Migration (March 1-May 31)	Gate opening: gates shall remain open 90% of the time and have a minimum closure setting equal to the MHHW elevation for the site Water Velocity: discharge velocity through the floodgates shall not be greater than 8 fps Water Depth: depth associated with low tide conditions shall not be less than 0.5 ft (0.15 meters)for more than 10% of the time across the sill or openings of floodgate structures
Summer Irrigation (Jun. 1-Sept. 30)	Gate opening: gates shall remain open

Source: after Table 1 of Beamer and Henderson (2012)

Determining Culvert Fish Passage Criteria

Juvenile salmonids were identified as a target species for this project and in the guidance documents. The fish species of interest for this study are juvenile salmonids. According to WDFW guidelines, the passage requirements for juvenile salmonids are identical to those for adult trout. Table 3 lists the maximum allowable flow velocity criteria recommended for passage of various fish species based on WAC 220-110-070.

Table 3. Sizing requirements for fish and culverts (WAC 220-110-070).

	Adult Trout >6 in. or Juvenile Salmon
Culvert Length	**Maximum velocity (fps)**
10 - 60 feet	4.0
60 - 100 feet	4.0
100 - 200 feet	3.0
Greater than 200 feet	2.0
	Minimum water depth (ft)
	0.8
	Maximum hydraulic drop in fishway (ft)
	0.8

Source: WAC 220-110-070

The 2011 draft report from the WDFW presents additional findings from an experiment on testing fish passage through culverts with baffles. The baffles interrupt the flow to create areas of slower velocities that allow fish to rest during upstream swimming. The flow velocities and resulting fish passage efficiency indicate that approximately 70% of fish pass at an average velocity of 1.7 feet per second, but only 45% of fish pass through the culvert with average flow velocity of 2.4 feet per second.

On the opposite side of Whidbey Island from Swan Lake, the Dugualla Heights site near Dugualla Bay has been studied for restoration feasibility with culverts and an open channel. A design goal in that study was to achieve ebb tidal current velocities rapid enough to transport gravel out of the intertidal channel. Maximum velocities of approximately 7 feet per second were estimated in the hydraulic modeling for a culvert option (Moffatt and Nichol 2011). Although no fish passage criteria were specifically identified, the conclusions of the study imply that the project is fish-passable.

For this project, we assumed that the Swan Lake tidal connection described below will be comparable to a culvert with a length of at least 200 feet. However, additional conceptual alternatives are presented below that could reduce the culvert length. Based on the guidance from the State of Washington and other projects in various stages of design and monitoring, the fish passage criteria for juvenile salmon through a relatively long culvert have been interpreted to require maximum flow velocity less than 2 feet per second for approximately 90% of the time. In addition, we interpreted the flow depth criteria in a culvert to require a minimum water depth of 0.85 feet for approximately 90% of the time. However, we think that this guidance is geared toward fluvial flows in streams and creeks, and it is unlikely that tidal flows through culverts will meet these criteria for velocity based on the nature of tidal flows. Therefore, we think that fish passage criteria through culverts in tidal environments are somewhat ambiguous and quite restrictive, and suggest that a natural open channel is preferred over culverts.

Velocities observed in natural tidal systems known to support Salmonid use have been observed to exceed 2 feet per second. ESA PWA conducted a literature review of observed velocities in natural tidal channels to compare the hydraulic modeling results to criteria presented above. Velocity information for tidal channels was compiled to estimate a range of natural systems (Table 4). However, it should be noted that the data presented in the table does not include any coastal lagoon creek-type drainage outlets, as would be expected to occur in the open channel alternative for Swan Lake. The fundamental lack of data for this type of system suggests how little is known about fish use of coastal drainage outlets. Creek-type drainage outlets would likely have higher velocities due to the shallow flow depth and high hydraulic head gradient that would frequently occur due to the tides.

Table 4. Observed velocities in natural tidal channel systems.

Inlet	Velocity (fps)	Reference
Bolinas Lagoon, CA	4.0	PWA 2000
Crissy Field, CA	4.2	PWA 2001
Charley Creek, WA	1.3	NOAA 2012*
Fisher Reference, WA	8.2	NOAA 2012*
Lewis and Clark, WA	1.9	NOAA 2012*
North Indian Slough, WA	3.6	NOAA 2012*
Old Bridge, WA	4.4	NOAA 2012*

* Personal Communication, C. Greene and J. Hall

Hydraulic modeling of an open channel alternative for the Dugualla Bay project found a maximum tidal velocity of approximately 5 feet per second during peak flows through the inlet (Moffatt and Nichol 2011). Fish passage criteria were not explicitly described as part of the report, but the conclusions of the study imply that the project provides fish passage.

To summarize, we understand the criteria for fish passage to apply only to culverts, and not necessarily to open channels, creek mouths, inlets, or rivers. Typical velocities in natural tidal channel can often be greater than 2 feet per second, and therefore this is not an appropriate threshold velocity to assume that juvenile salmon do not utilize coastal lagoons. In addition, questions on whether fish swim with or against the flow direction in natural channels should be addressed in future refinement and development of fish passage criteria.

In addition, there are qualitative fish passage criteria that have been used in this analysis. These include:

- Preference for a free surface rather than a submerged culvert;
- Low intertidal to shallow subtidal thalweg elevation.

2. Hydraulic Modeling

Tidal dynamics of the Swan Lake system were analyzed using the hydrodynamic model Delft3D-FLOW (Deltares 2011) in two dimensions. The 2-dimensional (2-D) model was selected to more accurately simulate flow convergence and divergence in the vicinity of the culverts and channel. Velocity, flow and water surface elevation was used to identify the frequency with which the fish passage criteria will be met. A variety of potential tidal connections have been evaluated, including culverts and open channels of various geometries.

2.1 Model Development

Grid and Bathymetry

The region of study was defined using a regular curvilinear grid over the 2-D model domain. For this study, a single grid covering the Swan Lake area was used for all model simulations, as shown in Figure 3. The grid contains 163 cells in the M-direction and 163 cells in the N-direction. The average grid cell size is 18 ft by 35 ft, with higher resolution grid cells concentrated near the location of the proposed culverts and channels. The site bathymetry in Swan Lake and the nearshore environment (out to an elevation of approximately -30 ft MLLW) was measured by CGS using total station surveys and hydrographic survey with acoustic instruments, respectively. A bathymetric surface was developed by CGS using AutoCAD Civil 3D, and included both data sets. The bathymetric surface was supplemented with additional topographic and bathymetric data developed by Lim et al. (2011). The bathymetry and topography were projected onto the grid using triangular interpolation (Figure 3). Minor localized adjustments were made to the land surface elevations to simplify complex surface geometry and improve the model stability. Additional bathymetric changes specific to the tidal connection geometries are discussed in the “Model Setup” section below.

Boundary and Initial Conditions

The tidal boundary condition for the 2-D model was based on water level measurements from the Port Townsend tide gage (NOS #9444900) and adjusted to the project site based on published conversions to the Sunset Beach subordinate tide station (NOS #9447951) for the period May 13, 2012 to June 12, 2012. This time period for boundary conditions is consistent with juvenile salmonid outmigration along West Whidbey Island, and coincides with waver level data collected by CGS offshore of the project site on May 14-15, 2012. The selected tidal boundary condition time series includes a full spring-neap cycle, and is in close agreement (within 0.5 feet) with observed water level measurements offshore of the site by CGS on May 14-15, 2012. The maximum tide range in the boundary condition time series that was modeled was approximately 11.6 ft on June 5, 2012, from a lower low tide elevation of approximately -3.2 ft MLLW to a higher high tide elevation of 8.4 ft MLLW. The boundary condition time series water level data were used to force the model from the northwest side of the grid. Initial water levels were set to 4.9 ft, which was selected as a representative water surface elevation for normal conditions in Swan Lake. This water level was frequently observed and was based on water level measurements by CGS within the lake.

Bed Conditions

The model simulations were designed to investigate tidal velocities and circulation under different scenarios to open Swan Lake to the Strait of Juan de Fuca. As a result, the bed of the model was assumed to be non-mobile, with sediment dynamics and morphological change not simulated. Additionally, no sediment was included on the boundaries to enter the model. This approach assumes that suspended sediment in the water column does not affect flow velocities. Given the goal of this modeling exercise, changes to the velocities from sediment are assumed to be negligible.

2.2 Model Setup

Several model runs were conducted to simulate different possible alternatives for creating a tidal connection to the Swan Lake system:

- “Existing” simulation was conducted to estimate the creek inflow into the lake, and to represent the existing culverts with flap gates (Table 5);

- "Culvert" simulations represented more than a dozen culvert combinations (all without gates), including relatively "small" submerged culverts, "medium" sized box culverts in the intertidal range, and "large" box culverts in the intertidal range (Table 6);

- "Channel" simulations for a trapezoidal channel heading north-northwest from Swan Lake to the Strait of Juan de Fuca with three different sill elevations (Table 7);

- "Refined" culvert and channel simulations to represent final runs for the final scenarios to focus the evaluation of fish passage feasibility for the project. Parameters for the refined culvert and channel runs are presented in Tables 6 and 7, respectively.

Table 5. Model setup for "Existing" Conditions.

Pipe Size (inches)	Pipe invert elevation (ft MLLW)	Loss Coefficient	Initial WSE (ft MLLW)	Timestep (s)
24	1	0.15	4.9	12
30	1	0.15	4.9	12

Table 6. Model setup for "Culvert" simulations

Model Run Description	Number of culverts	Culvert size (ft) (height x width)	Invert Elevation (ft MLLW)	Creek Inflow (cfs)	Timestep (s)
Small Culverts (Submerged)	1	4 x 6	-10	15	15
	2	4 x 6	-10	15	15
	4	4 x 6	-10	15	15
	6	4 x 6	-10	15	15
	8	4 x 6	-10	15	15
Medium Culverts (intertidal)	4	8 x 12	0	15	6
	4	10 x 16	0	15	3
Large Culverts (intertidal)	1	10 x 20	0	15	3
	2	10 x 20	0	15	3
	4	10 x 20	0	15	3
	6	10 x 20	0	15	3
	8	10 x 20	0	15	3
Refined Culvert Run	3	8 x 10	2	2.4	3

Table 7. Model setup for "Channel" simulations.

Model Run Description	Bottom Channel Width (ft)	Top Channel Width (ft)	Sill Elevation (ft MLLW)	Creek Inflow (cfs)	Timestep (s)
Low Sill	40	123	2.5	15	1.5
Medium Sill	40	123	3.3	15	1.5
High Sill	40	123	4.9	15	1.5
Refined Channel Run	40	123	3.3	2.4	1.5

Existing Conditions Run and Estimation of Creek Inflow

Existing conditions were simulated with a focus on estimation of the creek inflow into Swan Lake from the local watershed (see below). The existing conditions comprise two existing culverts with flap gates: one 24" pipe and one 30” pipe drain the lake through flap gates that are located in a vault on the seaward side of West Beach Road next to a residential home. The modeled invert elevations of the pipes were 1 ft MLLW (the model limitations do not allow a slope of the culvert invert, and therefore horizontally flat culverts were simulated). The total pipe lengths are approximately 250 to 300 feet.

The tributary creek flows affect lagoon water levels. The creek flow rates are not known and are subject to management activities upstream. The modeling and field data were used to estimate flow during the model period. Water levels in the lake are influenced by the spring-neap cycle of the tides, such that the higher tides inhibit drainage of the lake and raise the lake water levels while the lower neap tides allow the lake to drain and lower the lake levels.

The creek inflow rate into Swan Lake was estimated based on observations made during a period in May 2012 when the tide gates on the existing culverts were known to have been in good working order where the flap gates were functioning properly. The stream flow was assumed to be constant for the duration of this period. The creek inflow rate was estimated using a conservation of mass equation with Swan Lake as the control volume:

$$\Delta \text{ (Storage in Lake)} / \Delta t = \text{Inflow Rate} - \text{Outflow Rate}$$

The rate of change in lake storage was calculated using the lake hypsometry and the observed change in water level over the period from May 13 to May 21, 2012. We found that storage within the lake decreased at an average rate of 11.5 acre-ft per day during this time. Outflows through the culverts were estimated using the “Existing” model configured with the existing culvert and tide-gate configurations. The model was first run with zero stream inflow in order to estimate the approximate rate of outflow through the culverts for this time period independent of the inflow rate. The head loss coefficients for the culvert and tide gate assemblies were calibrated by selecting values which best recreated the observed rate of decline in the lake’s water surface elevation during the ebb tides. Based on these model results we estimate the average flow rate through the culverts at 16.2 acre-ft/day. By applying the conservation of mass equation we are then able to estimate the average creek inflow rate to be:

$$\text{Inflow Rate} = \Delta \text{ (Storage in Lake)} / \Delta t + \text{Outflow Rate}$$

$$= -11.5 \text{ acre-ft/day} + 16.2 \text{ acre-ft/day} = 4.7 \text{ acre-ft/day} = 2.4 \text{ cfs}$$

This calculated inflow rate is consistent with flow measurements by SFEG, which range from 0.1 to 3.2 cfs with a mean measured flow of 1.2 cfs (SFEG 2012). We then ran the existing conditions model using the calculated creek inflow rate. The observed and modeled water surface elevations are compared in Figure 4. We note that the modeled water surface elevations for the scenario with no creek inflow quickly drop below the observed values, while the model results for the “With Creek” case closely matches the observed change in water surface elevation for the period of study. We note that the “With Creek” case overestimates the water surface elevation during the middle portion of the period modeled. This an artifact of the time-averaging implicit in our analysis likely due to variability in creek inflows over the period of study as well as the uncertainty in the hydraulic characteristics of the existing tide gates. We think that these uncertainties are acceptable for this feasibility level analysis.

Culvert Simulations

The “Culvert” simulations include different configurations of culvert numbers, sizes, and invert elevations. In particular, we modeled small submerged culverts, medium-sized intertidal culverts, and large intertidal culverts.

These runs represent a broad range of possibilities and are useful to establish an understanding of the relative responses of the lake to different culvert scenarios. The creek inflow included in these runs was 15 cfs – much larger than what was found for typical flows from the creek into the lake. The larger flow rate was part of a "first guess" at understanding the hydraulics of the system before further refinements were made.

Although model runs were completed for the "Submerged" culverts, the results are not presented in this memorandum. These runs were completed in an effort to understand the lake response to varying amount of tidal connection to the sound, and to check that the flows, velocities, and water level responses were realistic. These results were useful in evaluating the relative responses of the system to the more complicated culvert flows that include a free surface.

After the initial culvert runs were completed, a refined culvert model configuration was selected that most represents the type of structure that is physically relevant and constructible at the site. The refinements included:

- Decreasing the size and number of culverts that fit into the available space within the Island County easement – 3 culverts at 8 feet high by 10 feet wide (However, to improve model stability issues we modeled the three 10 foot wide culverts as six 5 foot wide culverts. We assumed that the additional friction and losses associated with the increased number of culverts is negligible.)

- Raising the invert elevation of the culverts to 2 ft MLLW to account for issues related to sediment transport and cobble berm buildup on the beach

- Investigating the effect of variable hydraulic losses (entrance and exit losses) that would be associated with gates, roughness, and other sources of friction (see below)

All culvert scenarios were modeled with hydraulic characteristics and loss coefficients representative of concrete box culverts with tide gates partially restricting flow. Tide gates and other hydraulic structures placed within or at either end of the culverts can significantly alter the depth and velocities of flows through culverts, and the extent to which these culverts meet the fish passage criteria will depend on the design and operations of such structures. At the time of this feasibility level analysis there is uncertainty as to whether gates or other hydraulic structures will be present in the final design. For purposes of informing future design work for this memorandum we have considered two scenarios as part of the "Refined" culvert runs: a scenario with high hydraulic losses representative of tide gates or other structures impeding flow and a scenario with low hydraulic losses representing a scenario with no gates or other structures resisting flow.

Calculation of Flow Velocity and Depth in Culverts

The Delft-FLOW model provides discharge through culvert in the model output, but not velocity. Therefore, the velocities resulting from simulated culvert flows were calculated based on the relative water surface elevations at either end of the culvert, and approximating the water surface slope as uniform from one end of the culvert to the other. Based on this assumption we apply the following rules to estimate the water surface elevation within each culvert:

1. If the water surface elevations at both the upstream and downstream culvert entrances are greater than the culvert invert elevation, set the water surface elevation within the culvert to the average of the upstream and downstream water surface elevations.

2. If the water surface elevation at either the upstream or downstream culvert entrance is less than the culvert invert elevation, set the water surface elevation within the culvert to the average of the culvert invert elevation and the higher of the two water surface elevations at the entrances.

3. If the water surface elevations at both of the culvert entrances are less than the culvert invert elevation, set the culvert water surface elevation equal to the culvert invert elevation (i.e. set the flowrate to zero).

The depth of flow within the culvert is then found by subtracting the culvert bed elevation from the culvert water surface elevation, for conditions 1 and 2.

Channel Simulations

Three "Channel" simulations were performed to assess the feasibility of a natural open channel connection between the sound and the lake. In general, the simulated channel comprises an approximately 2,000 foot long channel to the north of Swan Lake that would require dredging of an existing marsh area, and then flow over a sill located at the beach berm. The new channel is comprises a trapezoidal cross section with a bottom width of 35 ft, side slopes of approximately 4:1, a uniform bed elevation of 2.5 ft MLLW, and a sill at the beach berm of varying height. The channel dimensions were based on the results of the inlet stability analysis (ESA PWA, 2012). This study considers the influence of an elevated sill near the mouth of the new channel, modeling flow conditions with sill elevations at 2.5 ft, 3.3 ft and 4.9 ft MLLW. Here we assume that the beach berm, composed of a mix of cobble and sand, will likely build up into a sill somewhere in the intertidal range, although we expect that cobble will build up to around MHHW or higher during storm events. Three initial runs were completed that investigated the hydraulic effects of different sill elevations of 2.5, 3.3, and 4.9 ft MLLW. For the initial three runs we used a creek inflow of 15 cfs, similar to what is described above for the culvert simulations.

A refined channel run was developed to account for likely sill geometry and reduced creek inflow representative of average daily conditions. The refined channel run included the medium sill elevation of 3.3 ft MLLW, and a creek inflow rate of 2.4 cfs.

A major assumption in the channel model runs is that the sill elevation does not change over the simulated time period. In reality, the geometry of the channel mouth would likely change seasonally, as well as daily over the course of a tidal period (see DeTemple et al. 1999).

2.3 Model Results

The tidal dynamics of the openings from Swan Lake were analyzed using several methods: water levels inside the lake, percent exceedance for depth and percent exceedance for velocity. These different analyses can inform the probability of property flooding, the frequency of inundation of the outlets and the feasibility of fish passage for juvenile salmonids.

Culvert Simulations Results

This study considers several different culvert configurations. Here we present the results of different configurations as "Medium Culverts", "Large Culverts" and "Refined Culvert" runs.

Medium Culverts

The medium culverts scenarios consider the construction of four culverts of intermediate size (box culverts, 8 ft tall and 12 ft wide and 10 ft tall by 16 ft wide) with beds located at 0 ft MLLW. The results for the medium culverts scenarios show very little variation between the two designs with respect to water depth within the culverts. Time series of velocity, flow discharge, and water levels associated with the four 10 ft x 16 ft culvert run are presented in Figure 5. The modeled velocities through the culverts are relatively low with maximum flood and ebb velocities on the order of 3.5 to 4 fps. The water levels show that the high tides in the lake closely match the high tides in the sound, although the lake remains perched at approximately 2.5 ft MLLW during periods of low tide.

Figure 6 presents the velocities and depths in the culvert on a percent exceedance basis. Both of the medium sized culvert runs indicate that water depths within the culverts will exceed 5 feet approximately 50% of the time with a maximum depth of almost 8 feet. The minimum depth calculated for both medium culvert sizes was about 1.75 feet, meeting the depth requirements for fish passage 100% of the time. The model results for both medium culvert runs show maximum current speeds in either direction (incoming or outgoing tide) are approximately 3.5 to 4 fps. Furthermore, it was found that the modeled creek flow does not significantly change the predicted velocity for either culvert size. Absolute velocities less than 2 fps were observed about 50% and 25% of the time for the 10 ft x16 ft culverts and the 8 ft x 12 ft culverts, respectively (Table 8).

Figure 7 presents the predicted water levels in the lake compared to those in the sound for the two medium culvert scenarios. The high tides in the lake almost match those in the sound, but the lake remains perched above the sound through low tide periods. The figure also shows that the predicted tide range in the lake is slightly larger for the 10 ft x 16 ft culverts compared to the 8 ft x 12 ft culverts, on the order of 0.5 feet.

Large Culverts

Similar to the medium culvert runs, the large culvert scenarios consider tidal connections consisting of 1, 2, 4, 6, and 8 identical 10 ft x 20 ft culverts. Time series of velocity, flow discharge, and water levels associated with the four 10 ft x 20 ft culvert run are presented in Figure 8. As shown in the figure, velocities remain relatively low (less than 5 fps) for the duration of the simulated time period. The water levels in the lake match high tides in the sound, but remain perched during low tide periods.

Figure 9 presents the velocities and depths in the culverts on a percent exceedance basis. The velocity of the currents predicted within the culverts was found to be sensitive to the number of culverts in the design. The occurrence of fish passable low-velocity flow conditions (less than 2 fps) was found to increase for designs with a larger number of culverts (Table 8). The range of water depths was found to vary considerably based on the number of culverts in the design, although water depths are consistently greater than the critical threshold depth for fish passage. Increasing the number of culverts increases the range of water depths predicted within the culverts, and increases the tidal range observed in the lake (Figure 10). For example, with one culvert, depths range from 2.4 to 7.6 ft while with 8 culverts, the depths range from almost 0 to 8.5 ft. With the exception of the 8 culvert design, all the designs maintain at least 1 ft of water at all times. The 8 culvert designs maintained water depths above 1 ft 95% of the time, and water depths above fish passage criteria of 0.85 ft about 97% of the time.

Table 8. Percent exceedance of velocities and depths for the culvert simulations.

Model Run Description	Number of culverts	Culvert size (ft) (height x width)	Depth range inside culvert (ft)	Frequency of depth >0.85 ft (%)	Frequency of flow <|2 fps| (%)	Maximum absolute velocity (fps)	Tidal range in lake (ft MLLW)*
Medium Culverts (intertidal)	4	8 x 12	1.9-8.1	100	25	5.5	2.6-8.9
	4	10 x 16	1.6-8.0	100	50	3.4	2.3-7.9
Large Culverts (intertidal)	1	10 x 20	2.4-7.6	100	28	4.9	3.6-7.5
	2	10 x 20	2.0-7.9	100	43	3.9	3.0-7.9
	4	10 x 20	1.4-8.2	100	43	3.3	1.9-8.5
	6	10 x 20	1.0-8.3	100	60	3.3	1.1-8.5
	8	10 x 20	0.2-8.4	97	68	3.2	0.2-8.5

*Tide range in sound: -3.18 to 8.44 ft MLLW

Channel Simulation Results

The channel scenarios evaluate the flow conditions created by the construction of a new tidal channel connecting Swan Lake to the Strait of Juan de Fuca (Figure 11). The elevation of the sill was found to have a considerable impact on water depths and velocities in the channel. Water depths over the sill were measured during each simulation to be at least 0.5 ft and velocities ranging between 6 to 8 fps during ebb tides and about 9 to 10 fps during flood tides.

Figure 12 presents the predicted velocities and depths over the sill alternatives on a percent exceedance basis. The water depth above the sill decreases as the sill height increases, which causes the occurrence of fish passable flow depths to decrease (Table 9). Velocities less than 2 fps were found to be relatively infrequent for all three channel designs, with such flows occurring most frequently for the 2.5 ft MLLW sill design (13% of the time), and least frequently for the 4.9 ft sill design (9% of the time). Maximum flow velocities were much higher for the channel scenarios compared to the culvert scenarios, and occur during flood tides. The highest flow velocities, greater than 10 fps, were predicted for the 3.3 ft MLLW sill design. The highest flow velocities occurred during the peak of the flood tides (Figure 13), with more moderate velocities occurring during the peak of the ebb tides (Figure 14). Increasing the sill elevation was found to decrease the tidal range inside the lake by maintaining a higher stand of water at low tides and muting the water surface elevation during high tides (Figure 15).

Table 9. Percent exccedance of velocities and depths for the channel simulations

Model Run Description	Sill elevation (ft MLLW)	Depth range over sill (ft)	Frequency of depth over sill >0.85 ft (%)	Frequency of flow <|2 fps| (%)	Maximum absolute velocity (fps)	Tidal range in lake (ft MLLW)*
Low Sill	2.5	0.9-5.7	100	13	9.7	3.6-8.2
Medium Sill	3.3	0.4-4.8	95	12	10.9	4.2-8.1
High SIll	4.9	0.4-2.9	70	9	9.4	5.4-7.9

* Tide range on ocean boundary: -3.18 – 8.44 ft MLLW

The change in the results with variation of the channel sill elevation is an important point in understanding how the system would function over time. In reality, the sill elevation and channel geometry would change seasonally and even over the course of a tidal cycle. Although velocities at the site could maintain an open connection between the lake and the sound, wave-driven buildup of cobble in the channel mouth would likely occur during storm events. The behavior of the channel hydrology would shift to lower ebb velocities as the elevation of the sill increases, which means that there would be even less potential to scour an open channel or re-open a closed channel. Eventually the channel would likely close and require mechanical breaching and excavation to re-open the lake to the tides. Prediction of the frequency of closure is difficult, but large storm events would likely cause the berm to build up to elevations around MHHW (ESA PWA 2012).

Refined Model Runs

The refined model runs for the culvert and channel scenarios were performed to evaluate potential alternatives that are more likely to be constructed. These refined scenarios were selected and designed after careful consideration of the initial model results presented above, consultation with CGS, and through employing a more realistic approach to developing alternative that makes physical sense from a constructability and cost perspective. Results of the refined culvert scenario are presented, followed by results of the refined channel alternative.

Refined Culvert Run

The configuration of the refined culvert run includes three box culverts with dimensions of 8 ft high by 10 ft wide. However, the model considered six 8 ft high by 5 ft wide culverts to improve model stability, as discussed above. In addition the effect that the hydraulic roughness value has on the system was investigated as a means to understand the impact of complicated gates, and other features associated with the culvert design.

Figure 16 presents the predicted velocity, total flow discharge, and water levels associated with the low hydraulic loss scenario (i.e. no tidegates). Maximum velocities are observed on ebb tides at about 8 fps (compared to about 3 fps for the high hydraulic loss scenario). The velocities predicted during flood tides are somewhat lower than the ebb tides: about 5 to 7 fps and 2 to 3 fps for the low and high hydraulic loss (i.e. with tidegates) scenarios, respectively. This result contrasts the previous culvert runs in that the ebb velocities are greater than the flood velocities, and can likely be attributed to the fact that the velocities out of the culvert toward the sound are much greater due to the increased thalweg elevation of the culvert, and the high hydraulic head difference during low tides.

Figure 17 presents the velocities and depths in the culverts on a percent exceedance basis. Evident in the figure is the difference in velocities due to the high and low hydraulic loss assumptions. The high hydraulic loss scenario is likely representative of a culvert configuration with tide gate structures and other roughness elements. We think that in reality a designed culvert to be implemented will fall within this range of values, and can be designed to perform closer to the scenario with high hydraulic losses. The depths predicted in the culvert are greater than 1 foot 100% of the time. The results for the two “refined” culvert runs are summarized in Table 10.

A complication of this culvert alternative is that the culverts would be very tall running across the beach and would impact recreation, wave refraction, and natural sediment transport processes. The effects of the culverts on the beach would require sediment bypassing over or around the culvert structure. Some amount of downdrift erosion (north of the culverts) would likely occur under this scenario.

Table 10. Percent exceedance of velocities and depths for the “refined” culvert simulations.

Model Run Description	Number of culverts	Culvert size (ft) (height x width)	Depth range inside culvert (ft)	Frequency of depth >0.85 ft (%)	Frequency of flow <|2 fps| (%)	Maximum absolute velocity (fps)	Tidal range in lake (ft MLLW)*
Low Hydraulic Losses	3	8 x 10	0.9-5.9	100	10	8.8	1.5-5.9
High Hydraulic Losses	3	8 x 10	1.2-5.7	100	62	3.2	2.2-5.5

Refined Channel Run

The configuration of the refined channel run includes the sill elevation of 3.3 ft MLLW and a creek inflow reduced to 2.4 cfs.

Figure 18 presents the predicted velocity, discharge, and water levels over the period of simulation. Evident in the figure is the high flood velocities toward the lake with a magnitude about 10 to 11 fps. Ebb velocities are significantly lower at about 7 to 8 fps. These velocities are comparably greater than modeled velocities as part of the Dugualla Heights project located on the opposite side of Whidbey Island (Moffatt and Nichol 2011). However, the Dugualla Heights project site is significantly smaller in area and has a much smaller tidal prism than Swan Lake. Therefore, we would expect greater flows and velocities through the channel at Swan Lake. The water levels in the lake match the high tides observed in the sound, but remain perched during periods of low tide.

Figure 19 presents the velocities and depths predicted over the 3.3 ft MLLW sill in the channel on a percent exceedance basis. Flow depths are greater than 1 foot 100% of the time. Flood velocities occur for approximately 30% of the time, and reach maximum velocities close to 11 fps, while the flows ebb for about 70% of the time with maximum velocities of 8 fps. Absolute velocities are less than 4 fps for approximately 40% of the time.

3. Discussion of Results

3.1 Tidal connections

Based on the modeling and previous analysis on nearshore processes, intertidal culverts or an open channel can allow tidal processes to return to Swan Lake. Tidal ranges in the lake differ considerably depending on the scenario (Figure 20). Of most interest in the figure are the three scenarios on the far right: the 3.3 ft MLLW sill (revised), three 8 ft x 10 ft low losses, and the three 8 ft x 10 ft high losses. The tidal ranges predicted for these three scenarios are all comparable in magnitude and elevations. The medium culverts and the larger number of large culverts show the largest ranges when compared to the channel designs and the smaller number of large culverts. We expect a similar result for runs that would have fewer medium culverts. In addition, the maximum tidal elevations are lowest when there are fewer large culverts. The smaller medium culvert design differs from all other scenarios by allowing a perched lake to develop at high tide (a maximum water depth higher than the ocean high tide), due to the low tides not matching and inhibited drainage through the limited amount of total culvert area (a more exaggerated version of this scenario occurs under existing conditions). For the channels scenarios, the sill height limits the tidal range to higher tides, but maintains a lake surface of at least 3.5 ft MLLW, which may be a positive result for natural lagoon habitat with a combination of subtidal areas and fringe marsh.

All of the scenarios increase the inundation area of the lake as compared to the existing conditions for a normal hydrologic condition (Figure 21). The area submerged at the highest tide during each simulation was added to an estimate of the existing lake (approximately 75 acres used as a basis). The least amount of additional area is gained from the fewest number of large culverts but overall, approximately 20-30 acres becomes intertidal for all scenarios.

3.2 Fish Passage

The ten design scenarios for the intertidal culverts and open channels connect Swan Lake to the marine environment with varying hydrodynamics in the waterway. As described above, the waterway in all of the scenarios contains water 100% of the time but the minimum water depth in the culvert or channel differs (Figure 22). Water depths in the inlet channel all drop to less than 1 ft MLLW in the channel scenarios, while depths stay above 1.5 ft MLLW for the medium culvert scenarios. The large culvert scenarios show the widest range of minimum water depths, spanning from above 2 ft to less than 0.5 ft MLLW. Refined channel and culvert scenarios are comparable to the other runs.

The ten modeling scenarios discussed above suggest that care will be required in refining the designs further to best facilitate fish passage, as well as review by biologists and regulators. In general, the larger culverts created more favorable conditions for fish passage, while the medium sized culverts and the channel designs showed conditions favorable for fish passage less frequently. Refined culvert alternatives provided a range of potential velocities, and assumptions of the amount of hydraulic losses are important and greatly affect the frequency of low, fish-passable flows in a culvert. The channel designs all have a relatively low frequency of low velocities, and also generate the fastest maximum velocities. However, fish passage guidelines for an open channel are not evident at this time, and should be further researched and evaluated. Here we have assumed that the simulated channel alternatives will allow fish passage, especially considering the possibility that outmigrating juvenile fish likely travel with flow direction, rather than against it (Beamer and Henderson 2012).

3.3. Open Channel Uncertainties

As documented in previous analyses on nearshore processes at the project site, including wave climate, sediment transport, and inlet dynamics, inlet stability and buildup of a cobble berm in the open channel poses a potential problem with providing a sustainable and fish-passable, tidal connection to Swan Lake (ESA PWA 2012). Current modeling presented above confirms that velocities in the open channel may provide sufficient velocities that can induce scour of small to medium sized cobble, as discussed in previous analysis. However, the maximum ebb velocities are highly dependent on sill elevation, with the main relationship of a decrease in velocity with an increase in sill elevation. Although this study presented sill elevations lower than MHHW, a buildup of the cobble berm in front of the open channel could be greater than MHHW according to analog reference elevations of the cobble berm located to the north of the proposed inlet location. Specific site geomorphology may work in favor of an open and sustainable inlet, although we expect a cobble berm to build during storm events with relatively larger waves. Therefore, the open channel alternative might require periodic maintenance to excavate materials depositing in the channel. Once the material is excavated we do not expect the channel to fill in very fast, as has been observed at similar lagoon sites throughout Puget Sound. The frequency of required maintenance is difficult to estimate, but large storm events are expected to build up the cobble berm and block the channel.

3.4. Flooding Considerations

Opening Swan Lake to tidal action has the potential to change water levels on the perimeter of the site, with the possibility of flooding properties that are not normally inundated. Figure 23 presents possible inundation elevations at the site if open to the tides – the colored lines represent elevation contours for high lake level (green), MHHW (blue), and the highest observed water level (HOWL; red). A zoomed-in view of the water levels along the berm is presented in Figure 24. Cross-sections across the berm illustrate how low and vulnerable homes and infrastructure located on the spit are to storm events and coastal flooding (Figure 25). The HOWL of 10.2 ft MLLW was estimated by CGS for Swan Lake based on the NOAA Sunset Beach subordinate station (NOS #9447951). Note that water levels at high tide are not as high locally as at the Port Townsend station. It should be noted that the water levels presented in the figures represent the still water level (SWL), and do not account for the effects of waves and flood phenomena associated with wave dynamics, and therefore under-represent the flood risk for a particular SWL. High water levels in the Sound could flood the spit under any scenario, but one important consideration is that septic tanks or drainfields located at lower elevations landward of the houses could be negatively impacted.

Although this preliminary assessment does not explicitly evaluate the existing and changed flood risks due to the alternatives described, we have generated possible approaches to be refined for managing flood risks. Flooding scenarios were not modeled as part of this study. Residential homes are located along the spit and on the landward edge of Swan Lake, and are likely susceptible to flooding under the existing conditions. Extreme coastal flood events that overtop West Beach Road have been documented, although we are not aware that these events cause a significant rise in the elevation of Swan Lake greater than normal lake levels. Opening the lake to tidal action could potentially have the effect that lake water levels will increase to the elevated sound water levels during storm events. Additional effects of locally generated waves would cause flood limits to be even higher.

Two strategies for managing flood risk as part of this project include construction of a berm around the perimeter of the lake to protect properties and the use of SRT gates. Construction of the berm is a low-tech approach that can be constructed using onsite borrow material, and be built up as a linear embankment with relatively flat slopes to keep lake waters from impacting properties. Details of berm feasibility, geometry, subgrade investigations, drainage issues, and impacts to existing wetland habitats would also need to be evaluated if a perimeter berm is pursued.

Including SRT gates on the culvert structure has the potential to limit extreme or high tides from inundating the site. SRT gates have the ability to close and block flow when the water level exceeds a set elevation, as well as allowing fish passage during periods of when the gate is open. Several projects in the area have been constructed or are in design and review currently, including Fisher Slough on the Lower Skagit River delta (Beamer and Henderson 2012) and at Dugualla Heights project at Dugualla Bay (Moffatt and Nichol 2011). The benefit of SRT gates is that lake water levels can be controlled to an agreed-upon elevation, except for during coastal storm events that overtop the road, which could continue to occur and which would probably cause flooding. Larger culverts and SRT gates would allow the lake to drain faster than it currently does during flood events, which would clearly be seen as a benefit in terms of flood damage reduction. For typical conditions, a muted tide range can be achieved to limit the high and low tides in the lake from being too extreme, and will open during periods of low hydraulic gradient to provide flow with velocities that allow successful fish passage.

3.5. Additional Design Considerations for Refined Alternatives

We developed additional design considerations that could be included in the “refined” culvert and channel alternatives described above, especially if one or more of these alternatives are progressed into the next stage of design and review. These consideration were not modeled, but are thought to improve the refined alternatives presented above. Additional refinements to the culvert and channel alternatives are described below.

Figure 26 shows a plan and section drawing of a modified culvert alternative. This conceptual configuration reduces the length of culvert by including an open basin or channel in the Island County easement. The benefits of the open basin include:

- Shorter culvert lengths, and therefore higher threshold velocity criteria for fish passage;
- Ideal location for SRT gates away from the active intertidal beach;
- Opportunity for juvenile fish to rest on their way to and from the lake.

The open basin alternative would require excavation of an open channel or basin that could serve as a location for juvenile fish to rest, as well as providing easy access to operating and maintaining SRT gates. Further considerations for “naturalizing” the open basin would likely be required, possibly including strategically placed large woody debris to deter predation on juvenile fish. The major benefits of this alternative are that the velocities would likely be reduced due to the complexities of gates, debris, and the several entrances and exits, and that use of SRT gates can be included. Regardless of inclusion of the open basin, it is likely that SRT gates would require placement in vaults similar to the existing culverts. To minimize the impacts to beach recreation and sediment transport, we would recommend placing the culverts as low as practical and to allow the beach to cross over the tops of the culverts without significantly more impact on wave refraction than under existing conditions. However, this alternative would require review and input from regulators and biologists, as well as more detailed design and impact assessments.

Figure 27 presents plan and section views of modifications to the refined open channel alternative presented above. Here we have included a minor groin-sluiceway that would act to minimize cobble and sand transport into the channel, and train the channel to exit along the pile supported “L” wall. Pre-filling the updrift area with cobble would minimize temporary accelerated erosion to the north of the site. Designing a low-profile structure that is not overly intrusive could allow alongshore process to continue with minor impacts, as well as helping to maintain an open channel. However, we still think that periodic excavation of sediments would be required to re-open the channel after buildup of cobbles in the opening, but likely less frequent. Further design considerations and evaluations, including regulatory and biological input, would be required for developing this alternative.

3.6. Evaluation of Alternatives

The alternatives described in this memorandum were developed to evaluate the feasibility of creating a fish-passable connection between Swan Lake and the Strait of Juan de Fuca. Our general approach evaluated culvert and open channel alternatives to provide tidal flows to the site and provide fish-passable velocities acceptable to juvenile salmonids. Table 11 presents a matrix of benefits, disadvantages and risks associated with channel and culvert alternatives. Selection of an alternative for implementation will have to balance these elements as well as stakeholders’ short-term and long-term goals, objectives, risk management strategies, and financial resources.

Apparent in the table are the main differences between the channel and culvert alternatives:

- Habitat value of natural channel versus hydraulic structure
- Greater disruption to alongshore sediment transport from culvert structure on beach compared to a natural tidal inlet
- Damage risk to residential properties associated with culvert structure, but little to no risk of inlet migration toward homes
- Little to no control of managing extreme water levels in channel versus more control using culverts
- Unknown usage of long culverts by fish, whereas channel alternative is closer to natural habitat
- Channel alternative requires a new bridge/road crossing while culvert can pass underneath West Beach Road in the existing easement
- Unknown maintenance requirements for culvert (possibly mechanical), while channel will require periodic but infrequent excavation of sediments

From this information it is not clear whether one alternative is superior to another. However, the Open Channel Beyond Easement and Extensive Culverts Beyond Easement are not likely to be good candidates for continued study because of the unnecessary risks to residential homes from constrained channel through Island County easement, and because the large number of culverts does not provide a justifiable tradeoff of habitat benefit to risk and cost of implementation. The Open Channel to the North alternative was not favored by the client because the expected maintenance to maintain an opening and concerns of increased flood risks due to conveyance of Sound waters through the open channel. The Culverts Within Easement alternative appears to be a viable alternative that would improve conditions over existing conditions, and is worth evaluating further. It should be noted that the discussion above does not constitute a complete and rigorous alternatives analysis, but can be used as a start for consideration of possible alternative considerations.

In regards to fish passage improvement, there is no fish passage under existing conditions. Installation of SRT gates with the Culverts Within Easement alternative would provide fish access for considerable time periods. The lack of appropriate fish passage criteria makes quantitative assessments very difficult, but details presented in this report suggest substantial improvements would be achieved. Periods of operation do not meet the requirements for (fluvial) juvenile salmonids for velocity over considerable amounts of time. However, minimum channel depth is almost always achieved and juvenile salmonids are known to travel with the tides. It remains for these results to be further evaluated from a biological perspective to assess the potential passage and usage of these alternatives by juvenile salmonids. If the culvert and channel alternatives are deemed fish-passable, we would further investigate and progress design of the Culverts Within Easement alternative, with or without the additional design considerations for refined alternatives described above in this memorandum.

Table 11. Summary of benefits, disadvantages, and risks of different alternatives.

Alternative	Benefits	Disadvantages	Risk
Refined Open Channel to North	Resembles natural conditions	Likely require groin and sluiceway	May close during large swell events
	Moderate velocities	Requires road crossing/bridge	Could require mechanical opening
	Best habitat option	High cost	Potential impact to septic tanks and drainfields from elevated water levels
	Avoids impacting houses on spit	Requires easement – BCTel Private, State Parks	Increased flooding in lake due to conveyance of water through open channel
		Increased flooding of east side of spit	
		May require recurring maintenance excavation	
Refined Culverts Within Easement	Feasible with easement	Higher velocities than larger culvert system	Down-drift erosion, damage
	Location favorable with change in shore orientation	Limited habitat benefits during periods of closed SRT gates	Possible sediment blockage at west end of culverts
	Ability to manage water levels in the lake	Large and very expensive	Potential short-term flooding due to malfunctioning SRT gates
	Most direct route	Likely ongoing maintenance requirements of SRT gates	Flow through open basin may create noise
	Lower velocities than open channel alternative		

4. Conclusions and Recommendations

Hydraulic modeling of culvert and channel alternatives for creation of a tidal connection to Swan Lake was used to evaluate the feasibility of establishing a fish-passable connection for juvenile salmonids. Several scenarios were developed to investigate different configurations of culvert structures to provide a broad understanding of the hydraulic response of the lake to tidal action.

For the culvert scenarios, we found:

- Low velocity flows are achievable that meet magnitude requirements, but not duration requirements of existing and incomplete fish passage criteria
- Increasing the size and number of culverts increases the matching of high tides in the lake to high tides in the sound, but has less of an effect on velocities
- Lake water levels are perched during periods of low tide
- Increasing the invert elevation of the culvert above MLLW causes the maximum velocities through the culvert to change from flood-dominated to ebb-dominated
- Incorporation of SRT gates provides some flexibility in managing water levels and to some extent, velocities
- Increasing the roughness and losses through the culvert significantly decreases the velocities through the culvert
- Large culverts on the beach will likely create an impact to alongshore sediment transport and wave refraction, and could require mitigation of downdrift erosion impacts

For the channel scenarios, we found:

- Low to moderately high velocities were predicted from the model for all of the open channel runs
- Velocities less than 2 feet per second are observed about 10% of the time for all channel runs
- Increasing the elevation of the sill at the channel mouth decreases the tidal range in the lake, and decreases the ebb velocities
- Maximum velocities were predicted for flood tides
- The channel will likely close after large swell or storm events that push cobble into the mouth and build up a cobble berm
- Flows are unlikely to re-open the channel, requiring periodic but infrequent mechanical opening and excavation of sediments
- Water levels in the lake could exceed current conditions and could cause flood damage to the lower portions of yards or septic tanks and drainfields

- An open channel is not favored by the client because the expected maintenance to maintain an opening and concerns of increased flood risks due to conveyance of Sound waters through the open channel

Our recommendations for the next steps of this project and the feasibility of alternatives are as follows:

- A culvert alternative is feasible with additional consideration of interactions of the structure with the local wave climate and sediment transport issues

- Biologists and regulators should provide feedback and guidance as to whether the results of this memorandum indicate that the alternatives are actually fish passable

- If conceptual design moves forward, alternatives should consider the additional design considerations described above in Section 3.5

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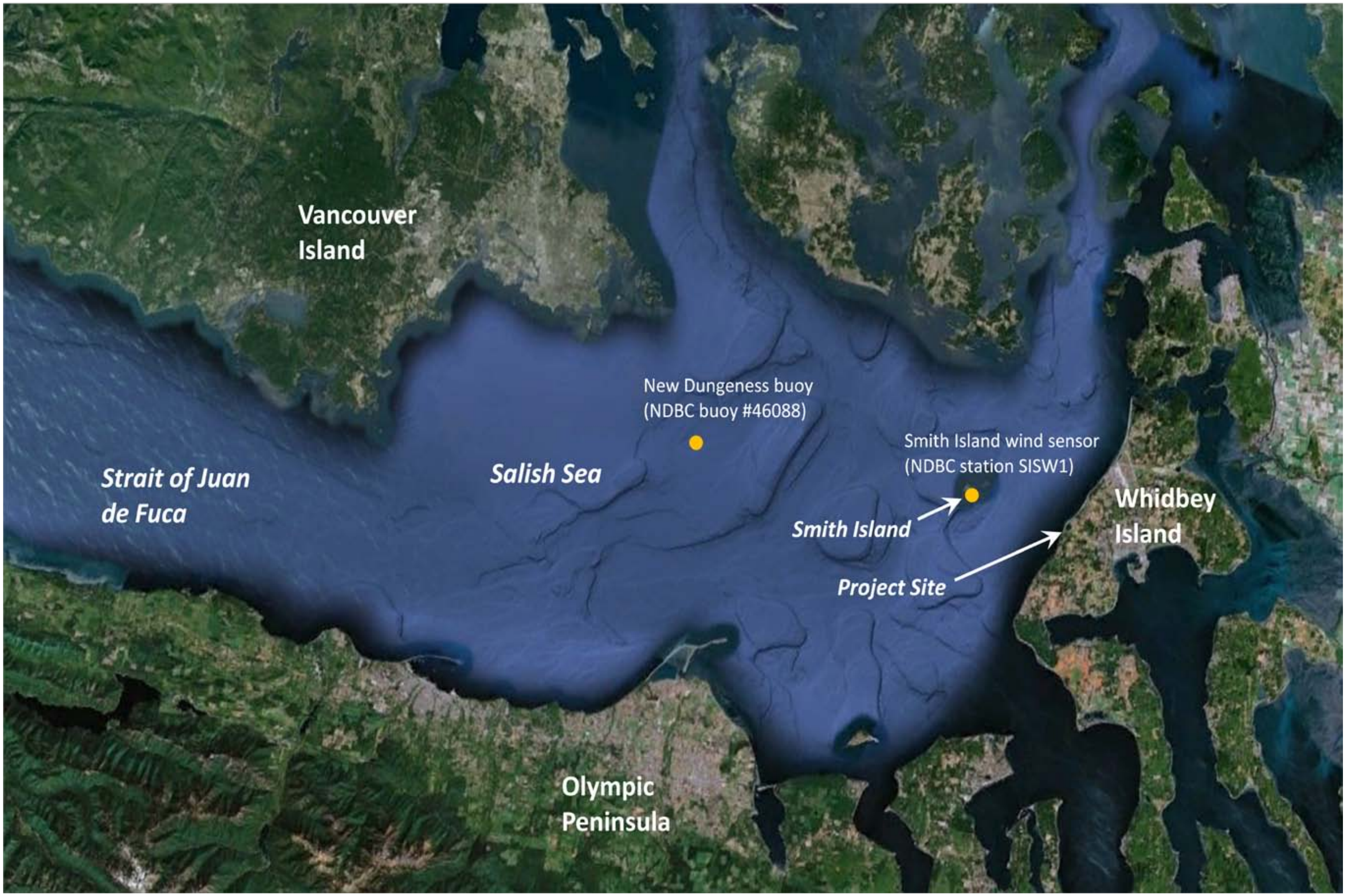
Figures

Figure 24. Tidal and flood water levels projected onto LiDAR topography around Swan Lake in vicinity of the berm/spit (see cross-sections in Figure 25)

Figure 25. Berm cross-sections showing the tidal and flood-level still water levels at the site relative to homes and infrastructure

Figure 26. Culvert alternative

Figure 27. Channel alternative



SOURCE: Google Earth

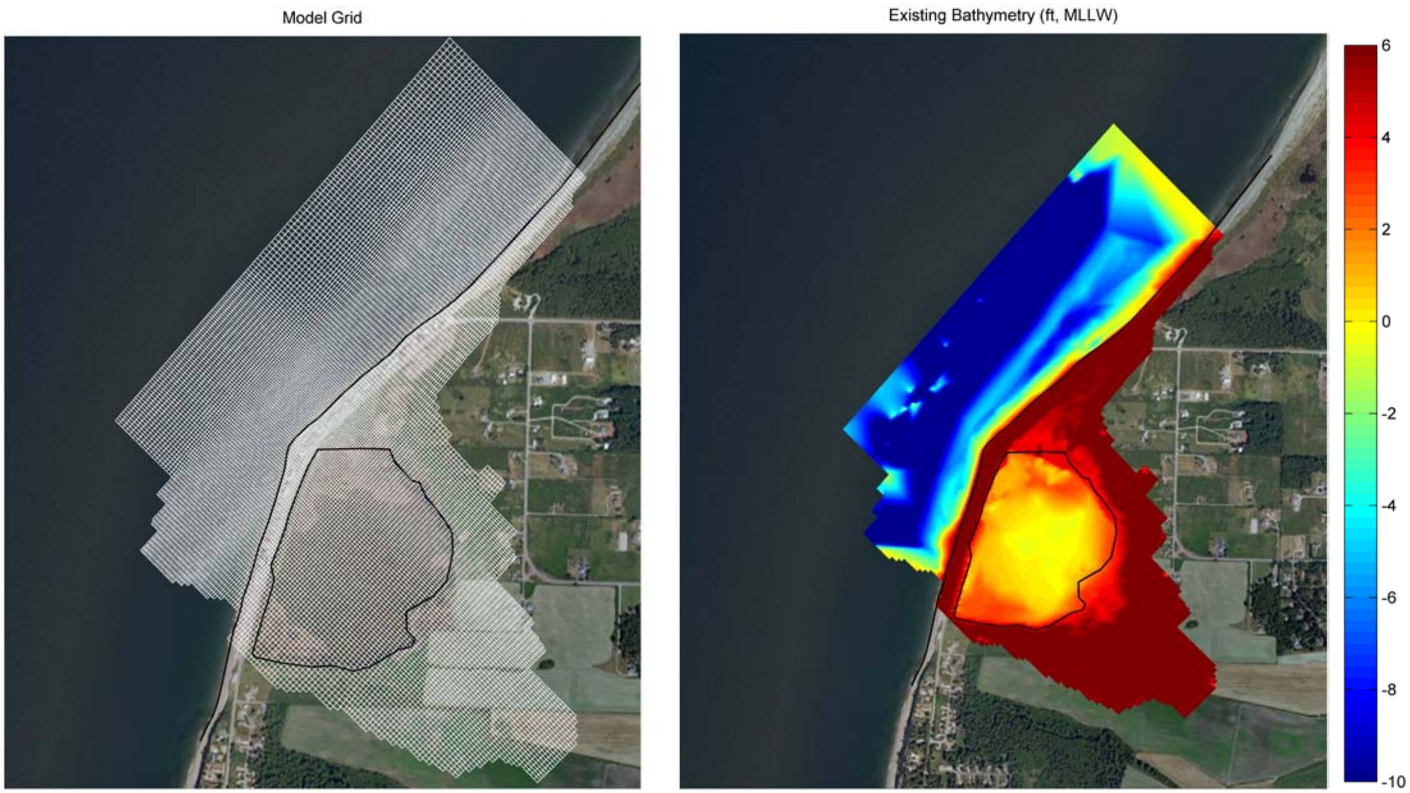
Swan Lake Engineering Feasibility . 120062.00

Figure 1

Location Map and geographic setting of the project site

SOURCE: Image from Google Earth

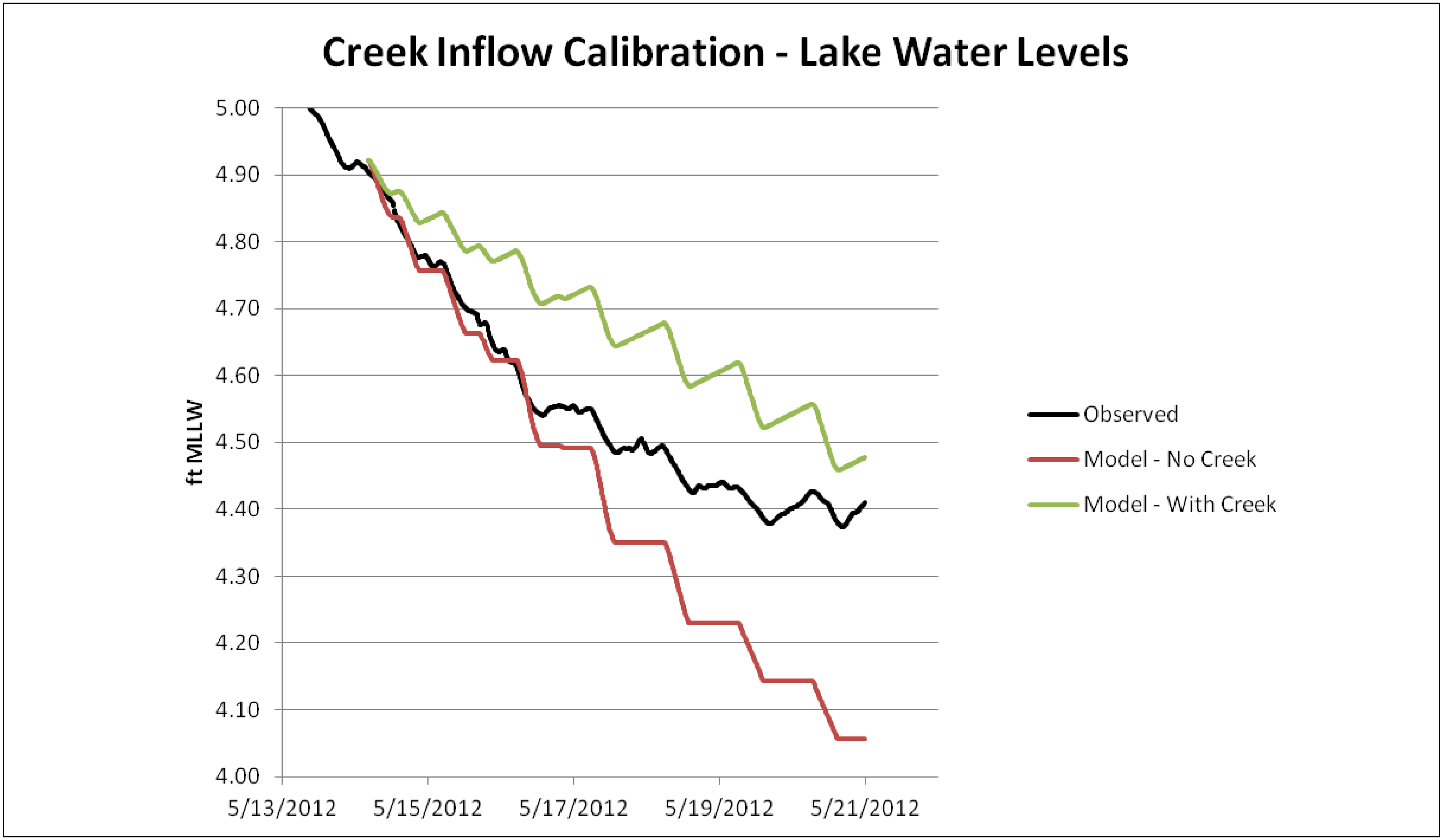
Figure 2
Site Map of Swan Lake showing the location of the existing culvert and proposed Northern Inlet site



SOURCE: Processed Delft hydraulic model output

Swan Lake Engineering Feasibility . D120062.00

Figure 3
Grid and Bathymetry

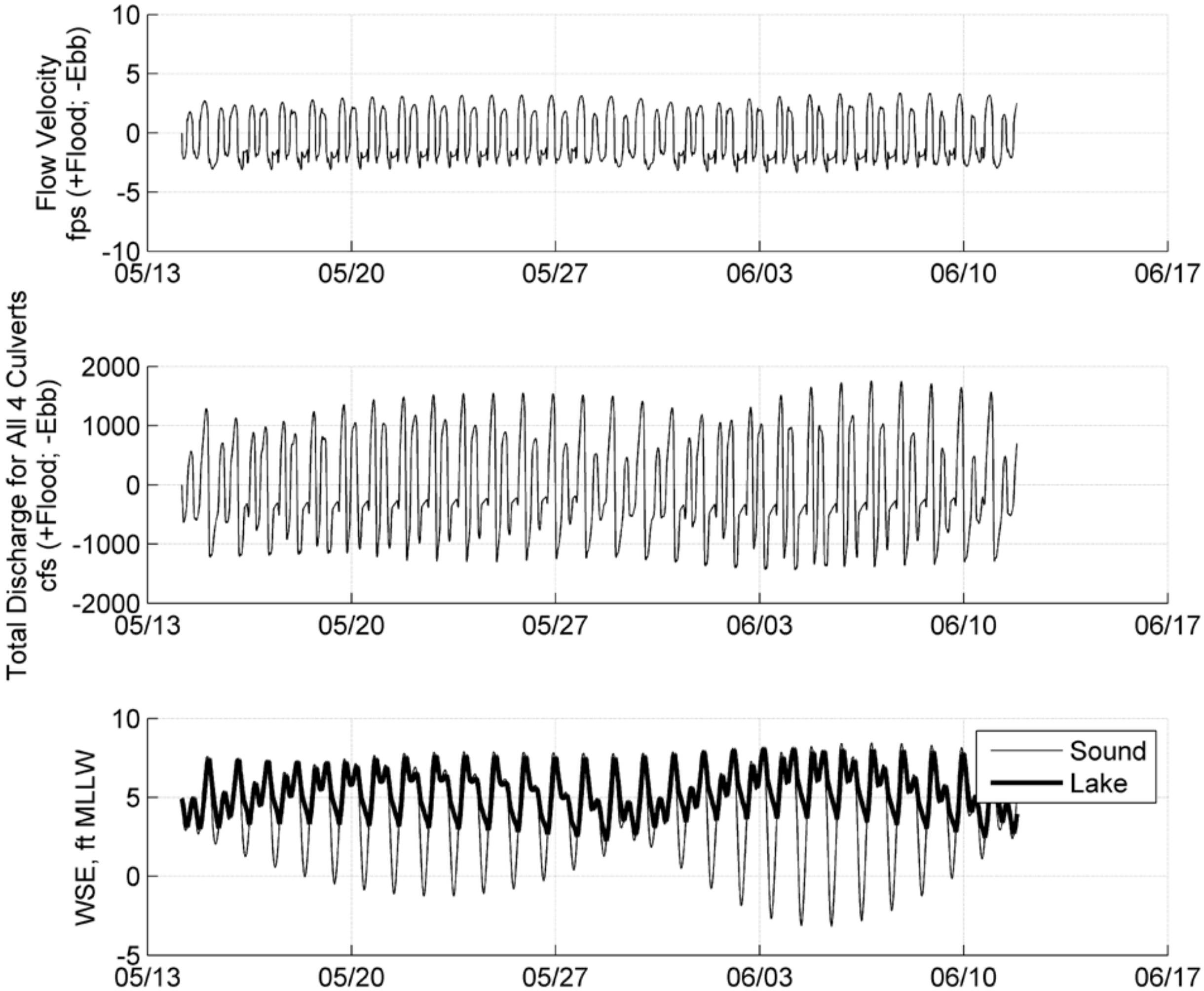


SOURCE: Processed Delft hydraulic model output

Swan Lake Engineering Feasibility . D120062.00

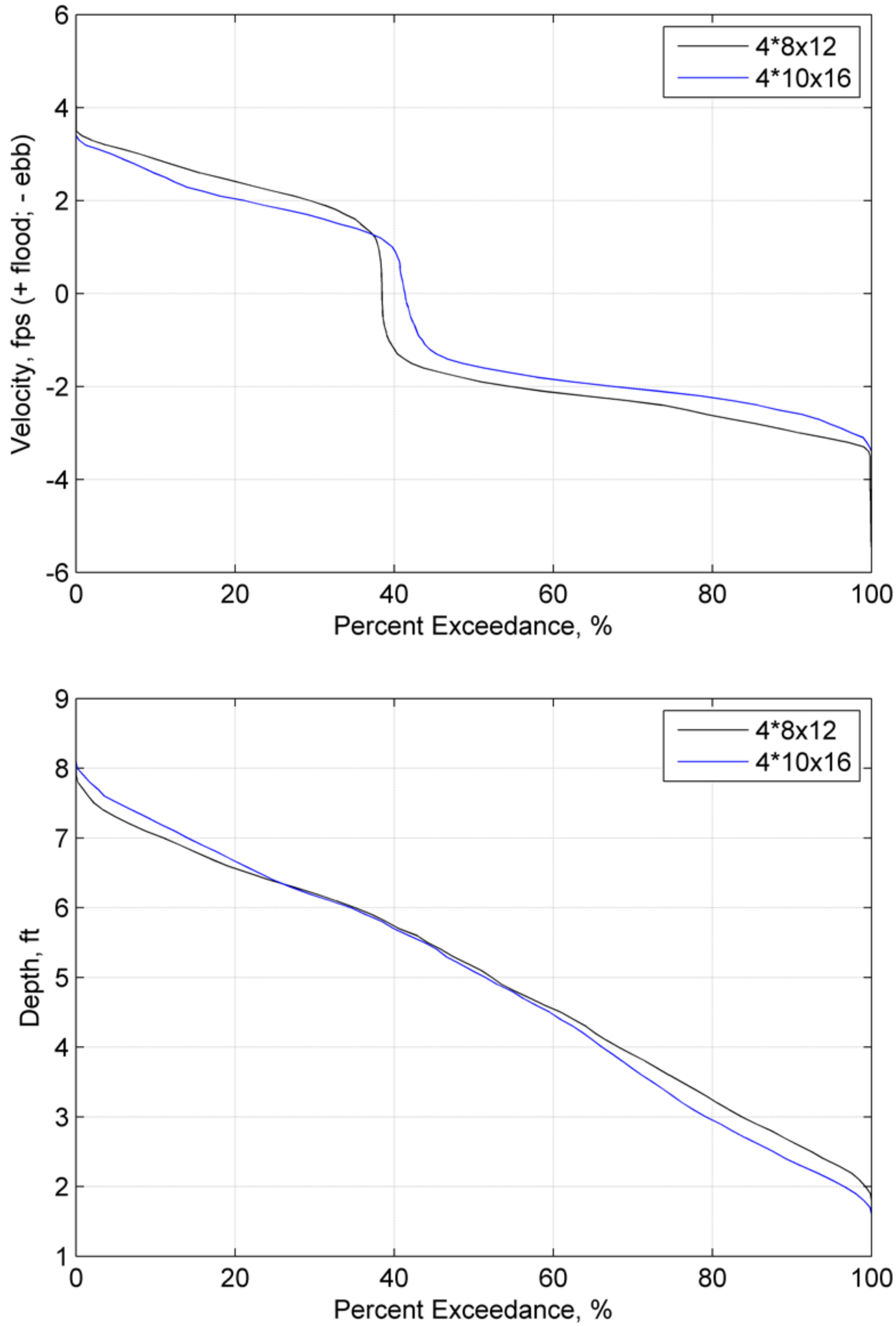
Figure 4

Existing Conditions – Creek Inflows



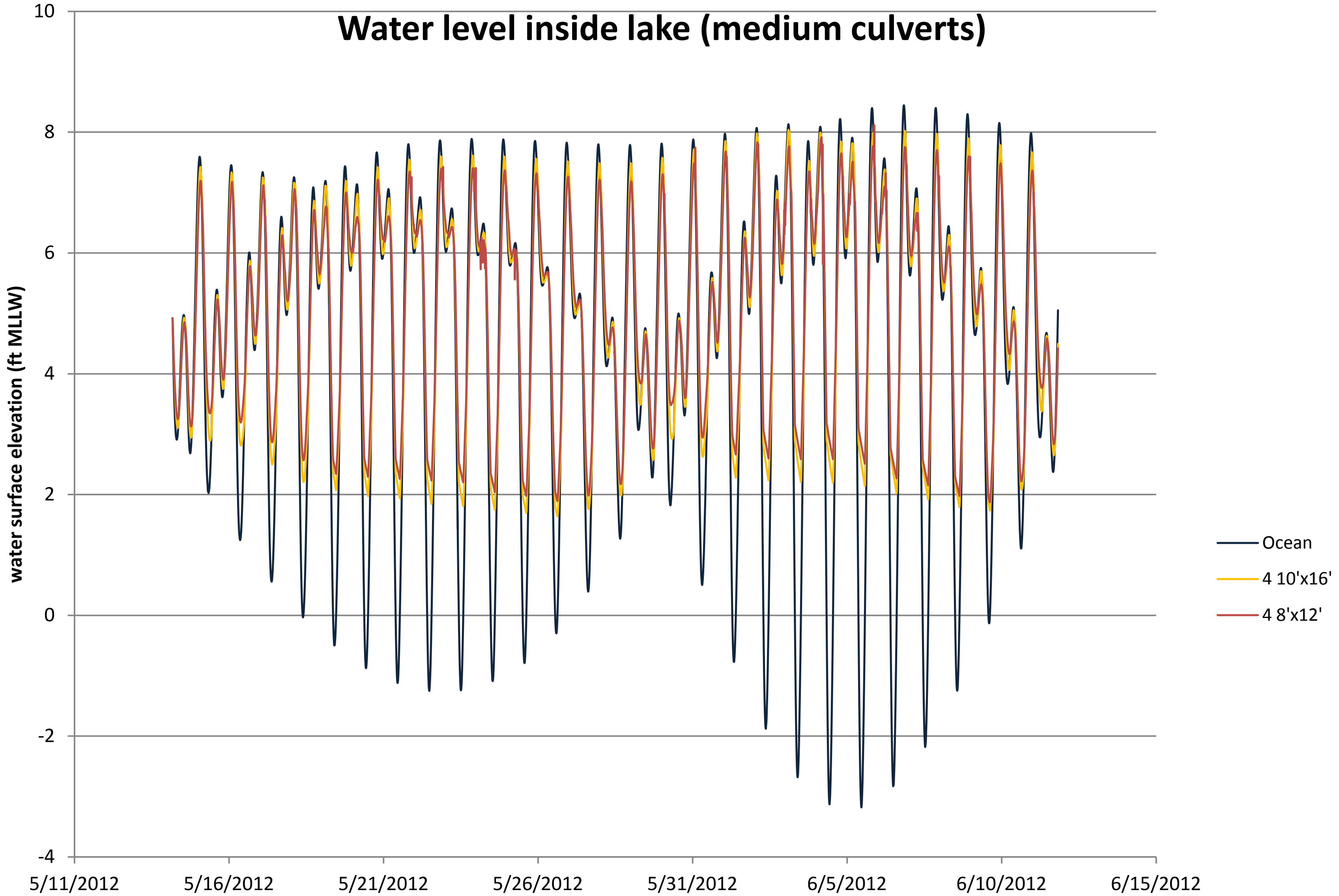
SOURCE: Processed Delft hydraulic model output

Figure 5
Model Output Time Series
4x10'x16' Culverts'



SOURCE: Processed Delft hydraulic model output

Figure 6
Exceedance velocities (top) and depths (bottom) for medium-sized intertidal culverts



SOURCE: Delft Model Output for culvert runs

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Figure 7

Water levels inside lake (medium culverts)

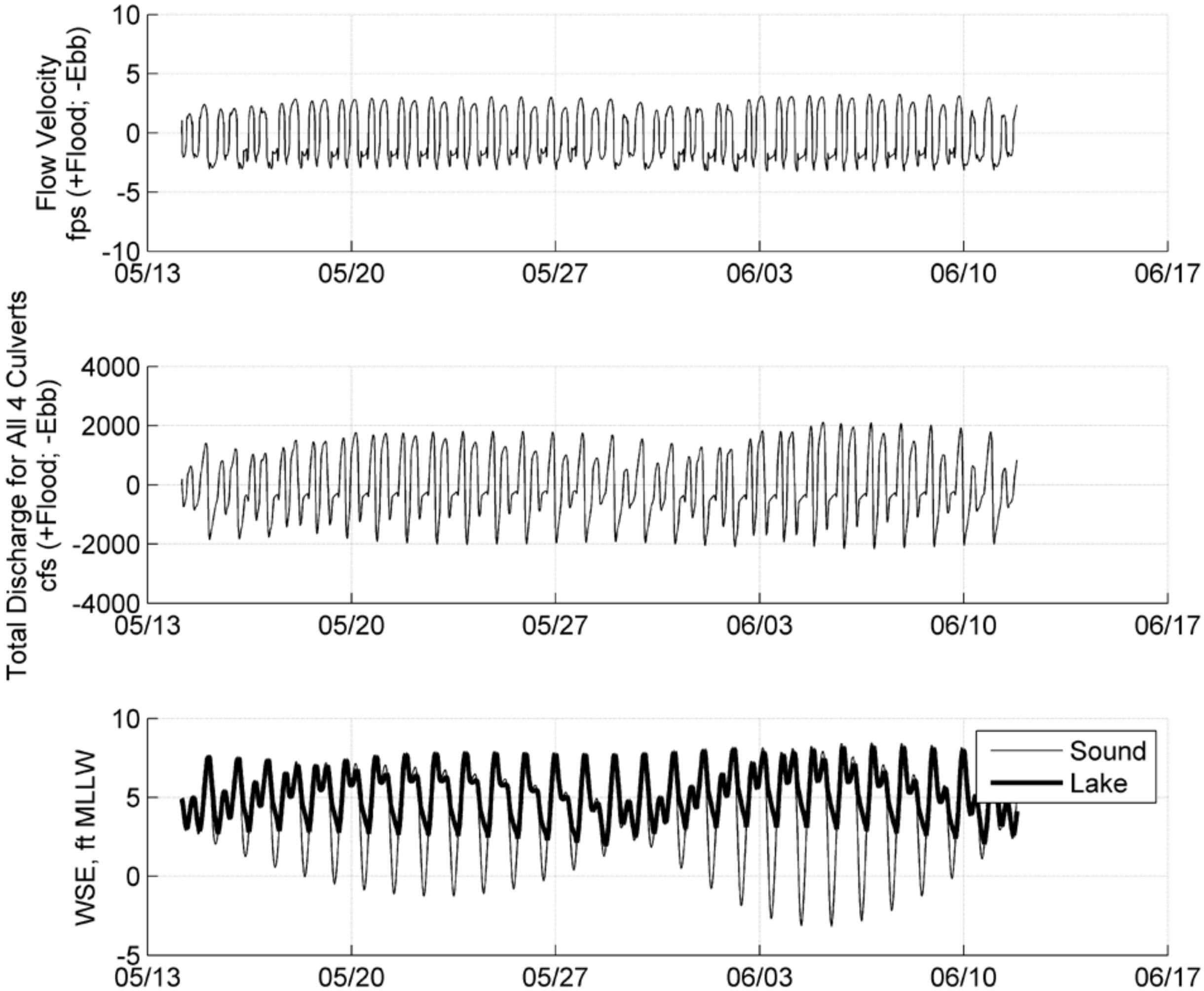
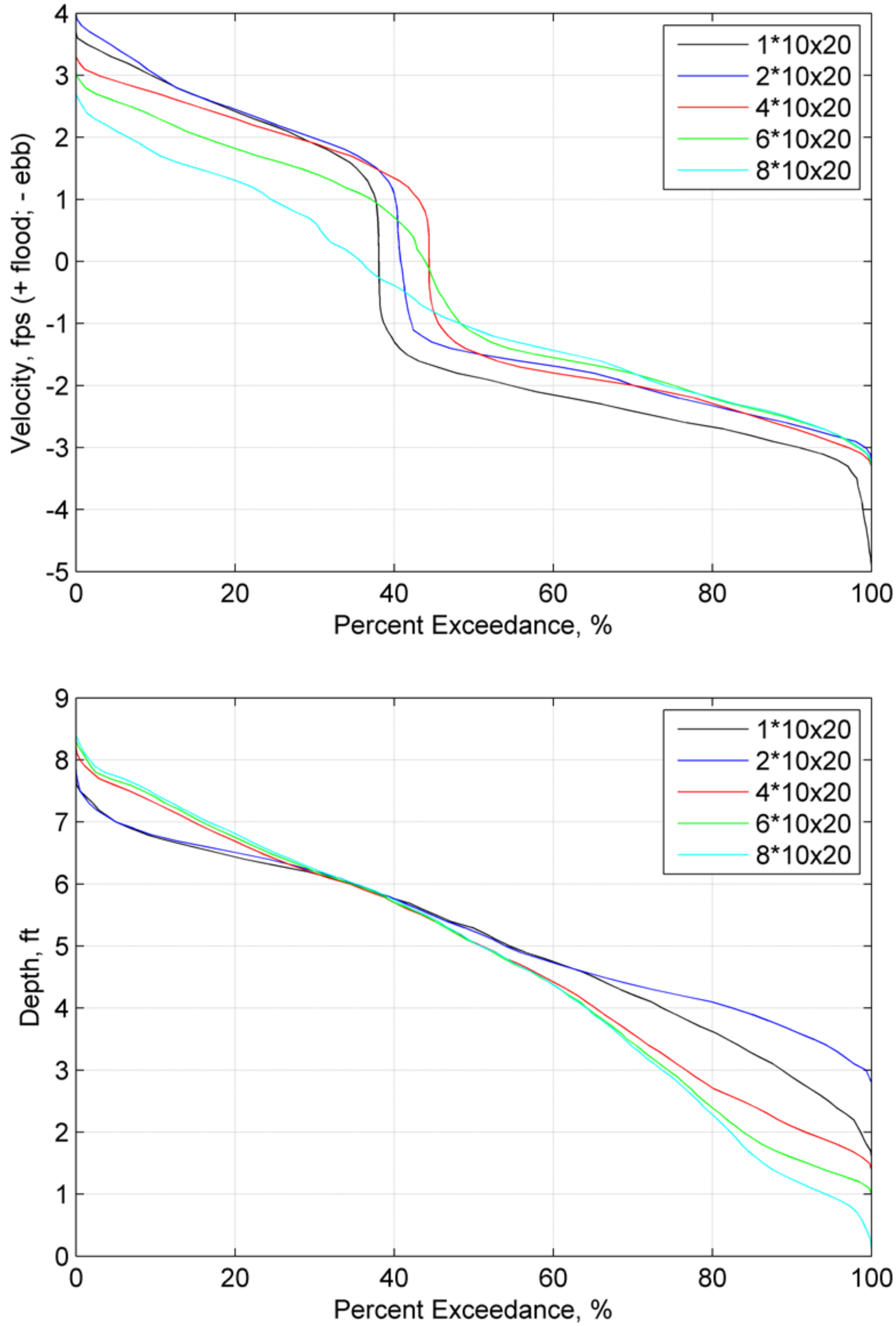
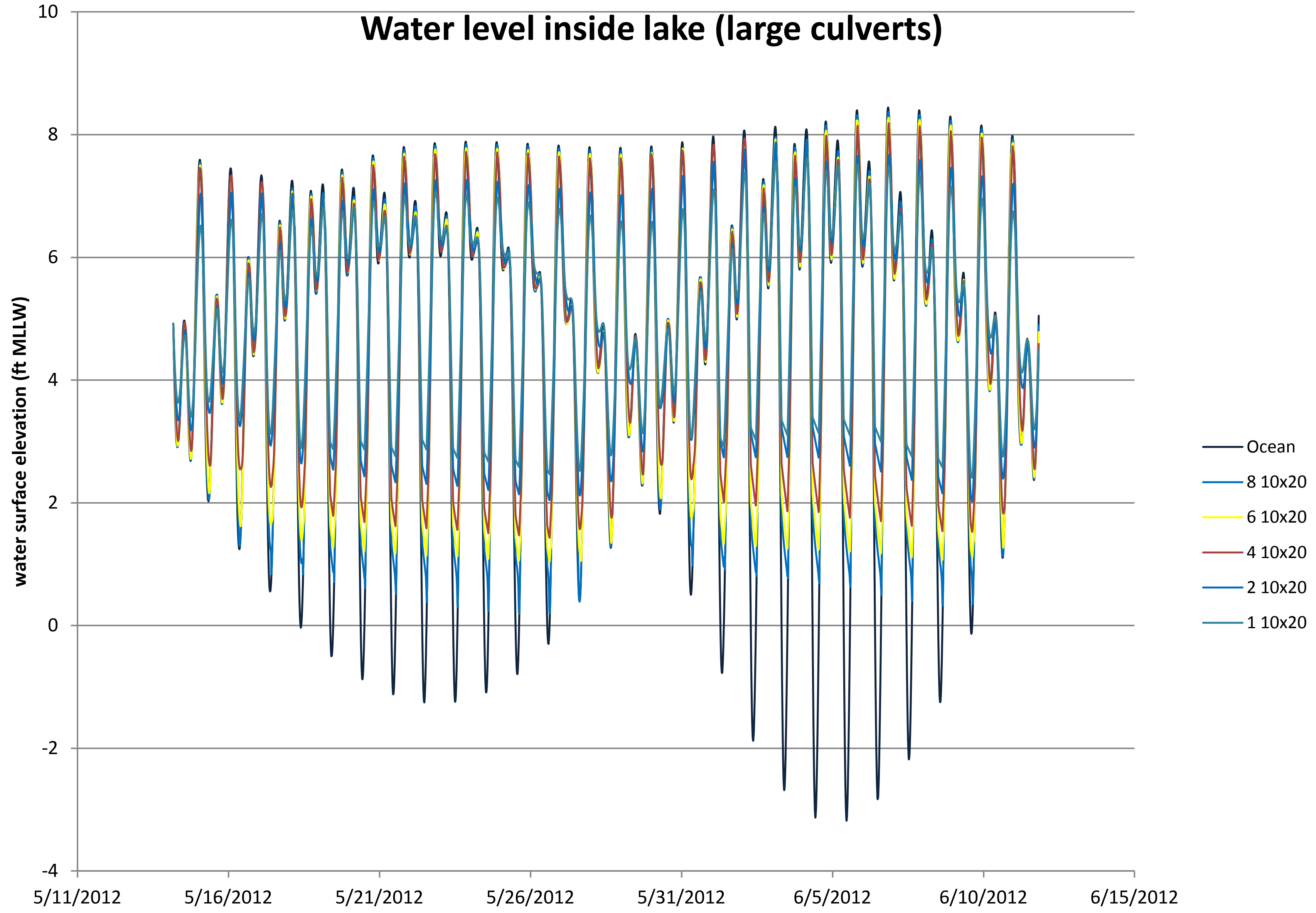


Figure 8
Model Output Time Series
4x10'x20' Culverts'



SOURCE: Processed Delft hydraulic model output

Figure 9
Exceedance velocities (top) and depths (bottom) for large-sized (10’ x 20’) intertidal culverts



SOURCE: Delft Model Output for culvert runs

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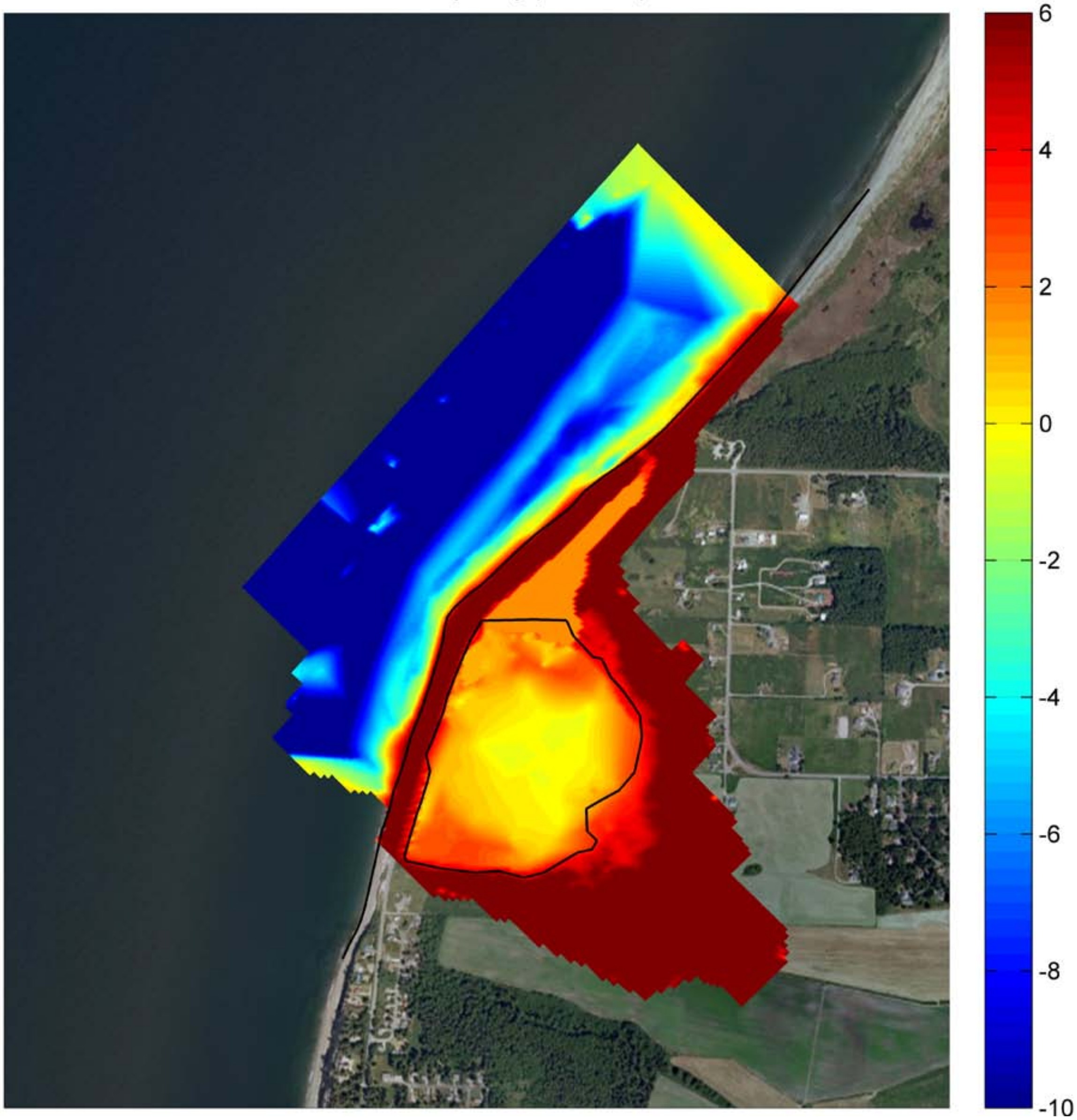
Figure 10

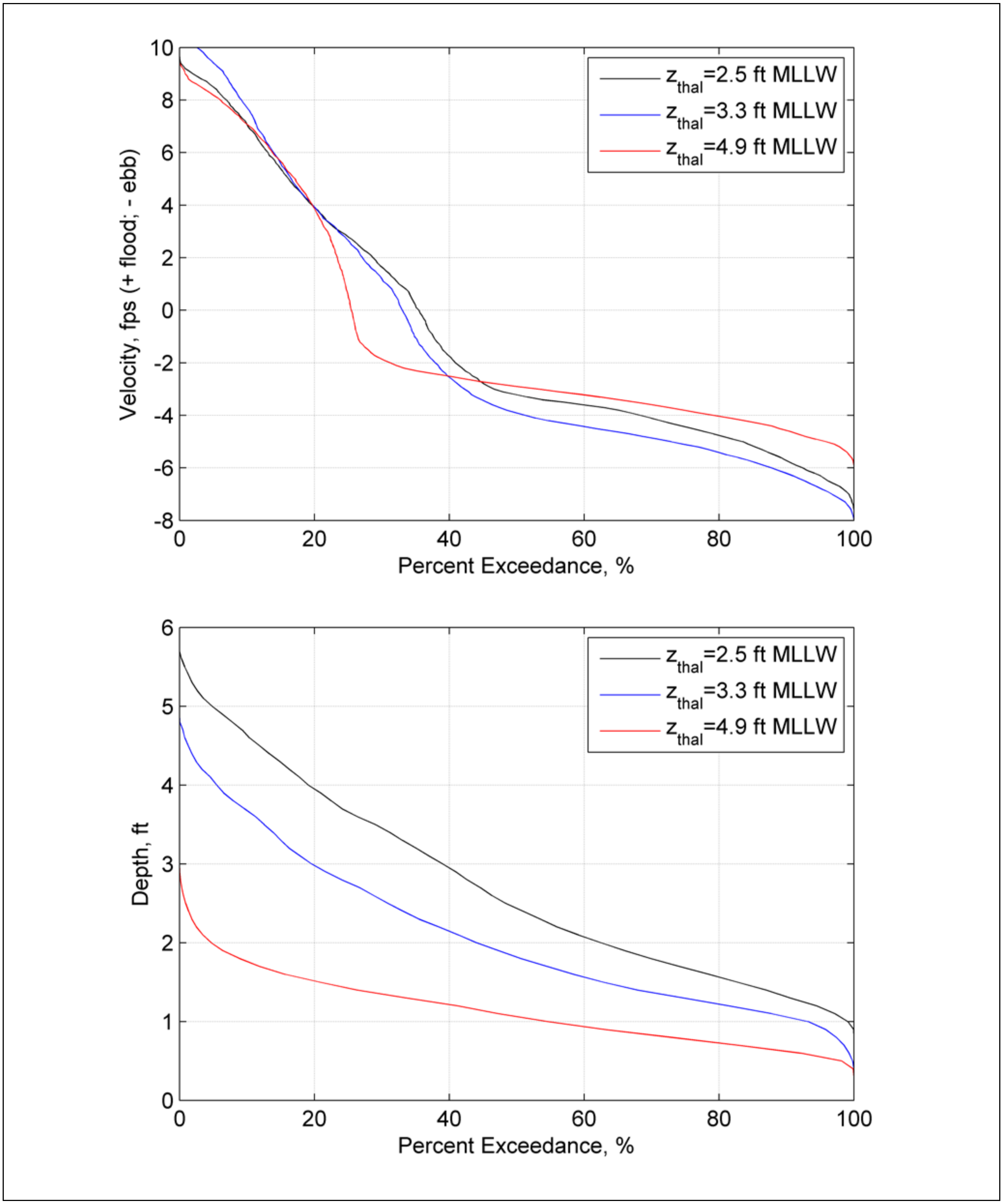
Water levels inside lake (large culverts)

Channel Bathymetry (ft, MLLW)



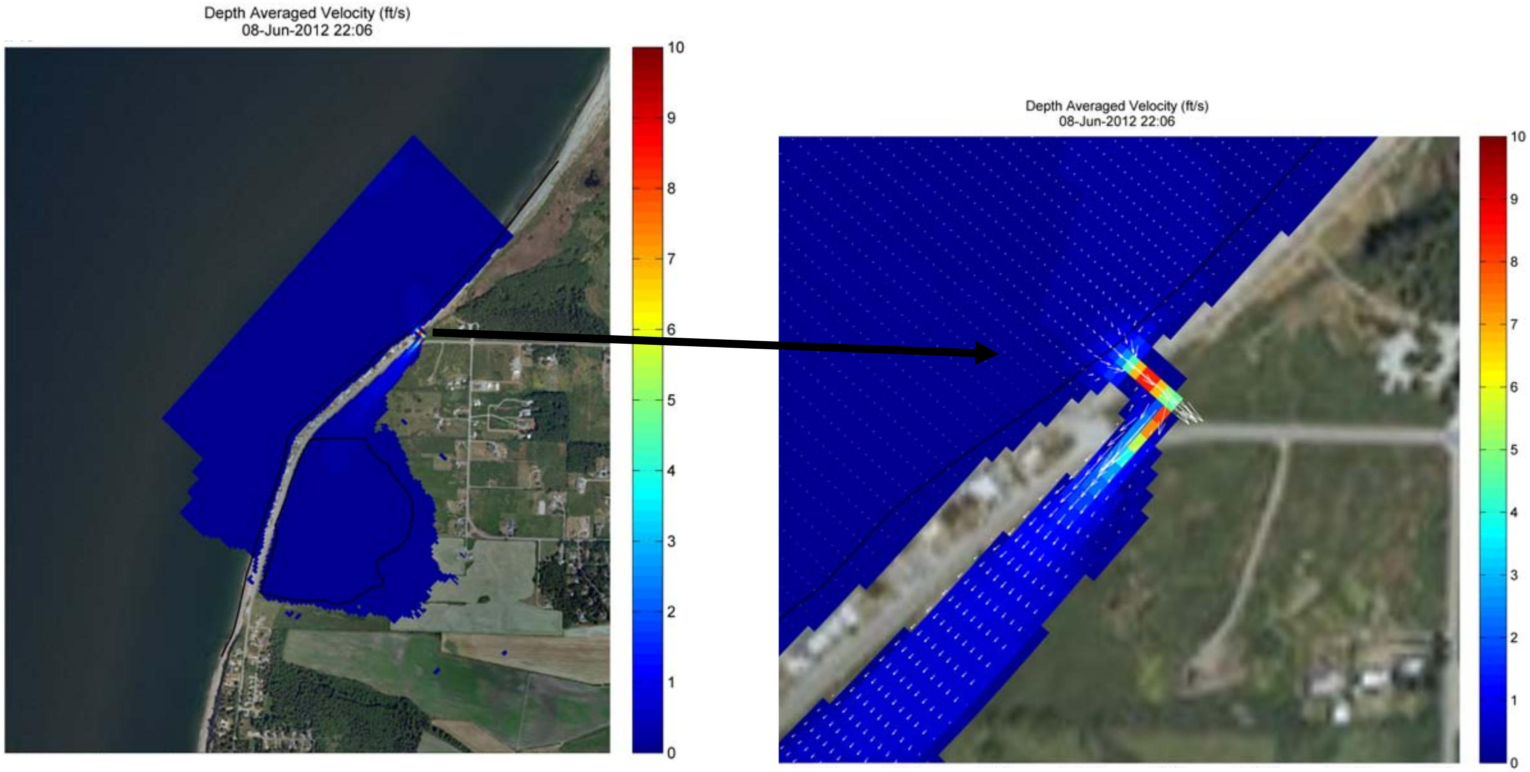
SOURCE: Processed Delft hydraulic model output

Figure 11
Bathymetry for simulations with channel



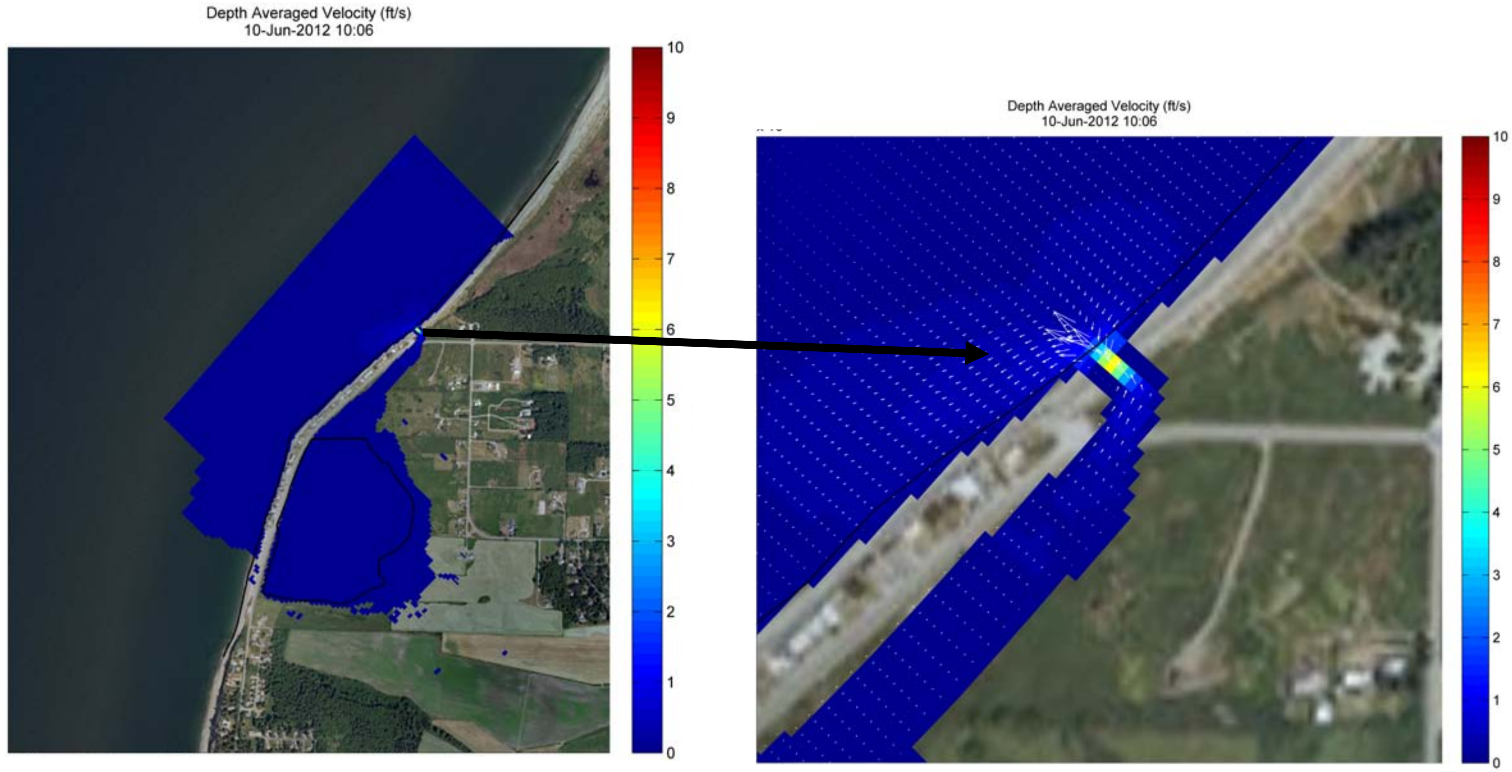
SOURCE: Processed Delft hydraulic model output

Figure 12
Exceedance velocities (top) and depths (bottom) for an open channel with varying sill elevations.



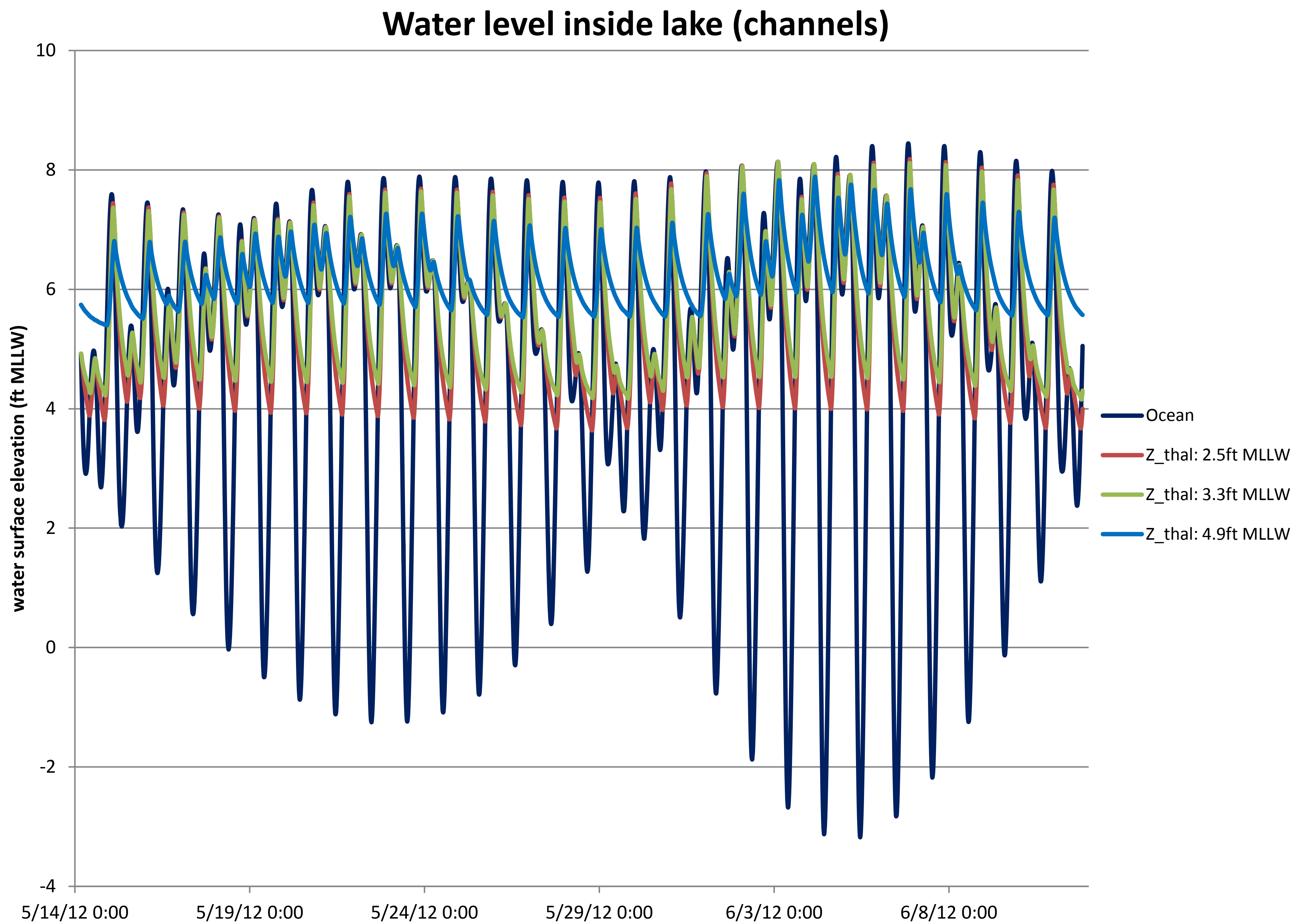
SOURCE: Processed Delft hydraulic model output

Figure 13
Velocities for flooding tide, high silled channel simulation (z_{thal}:4.9 ft MLLW).



SOURCE: Processed Delft hydraulic model output

Figure 14
Velocities for ebbing tide, high silled channel simulation (z_{thal}:4.9 ft MLLW).



SOURCE: Delft Model Output for channel runs

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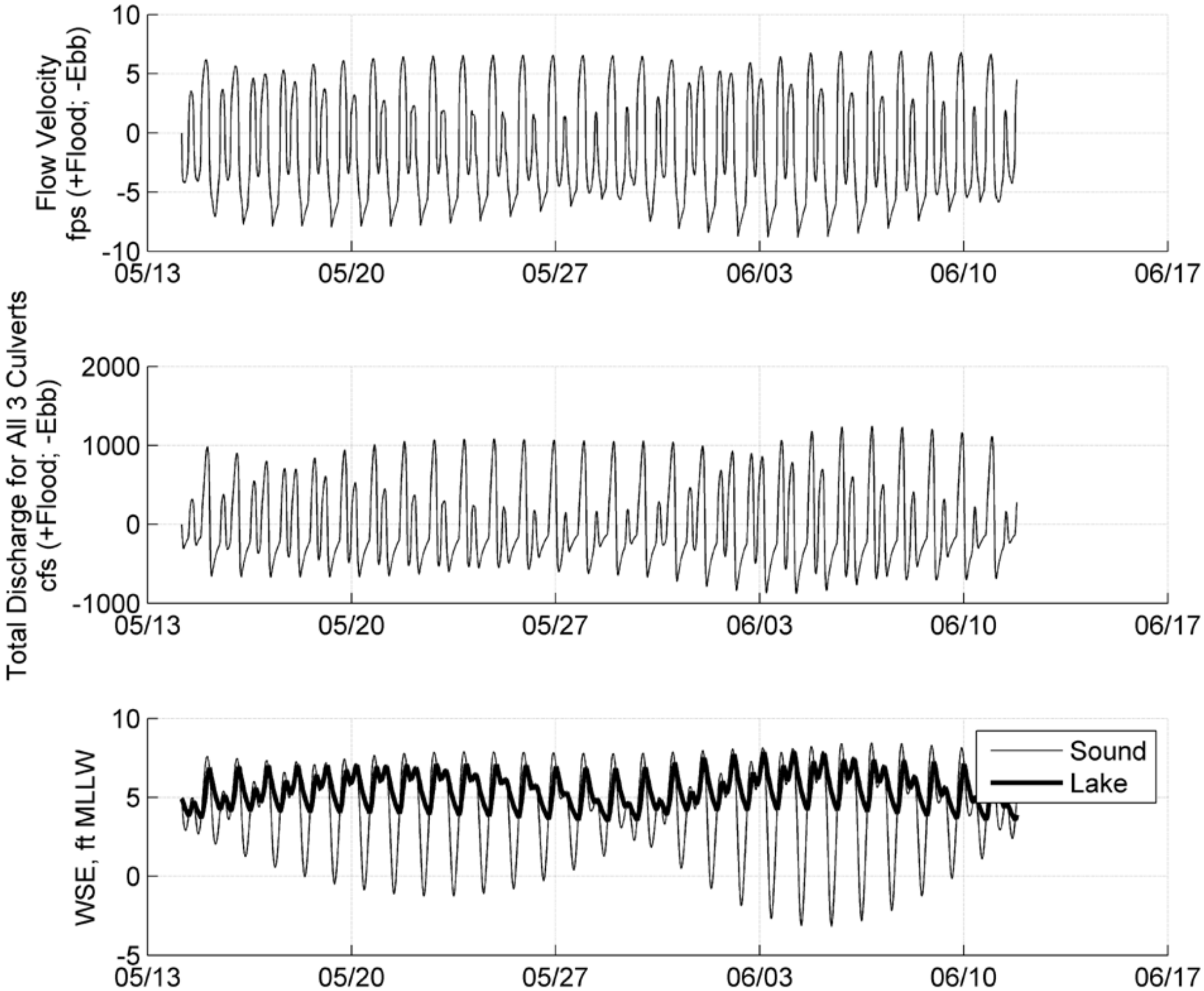
Figure 15

Water levels inside lake (channels)



SOURCE: Processed Delft hydraulic model output

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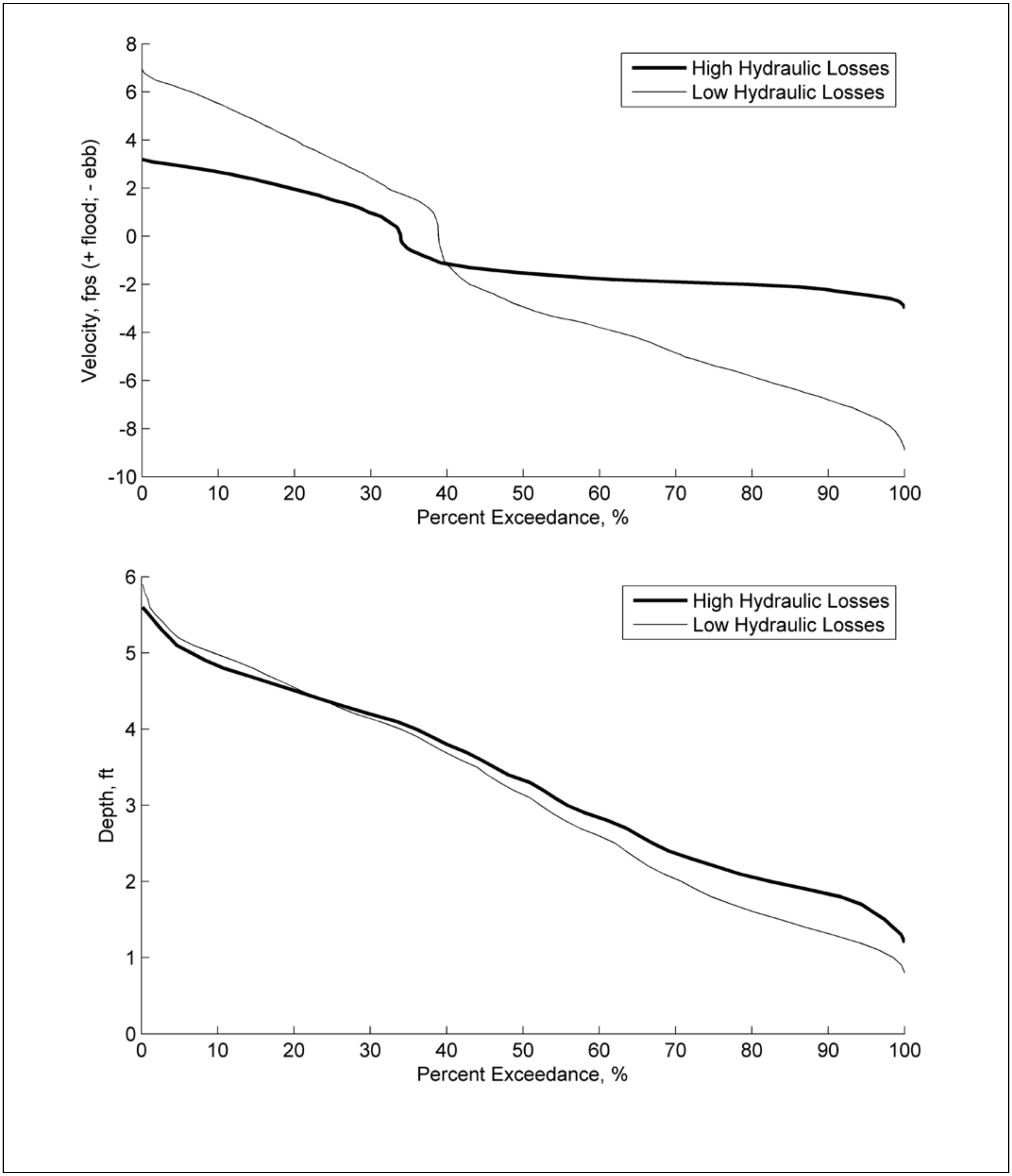
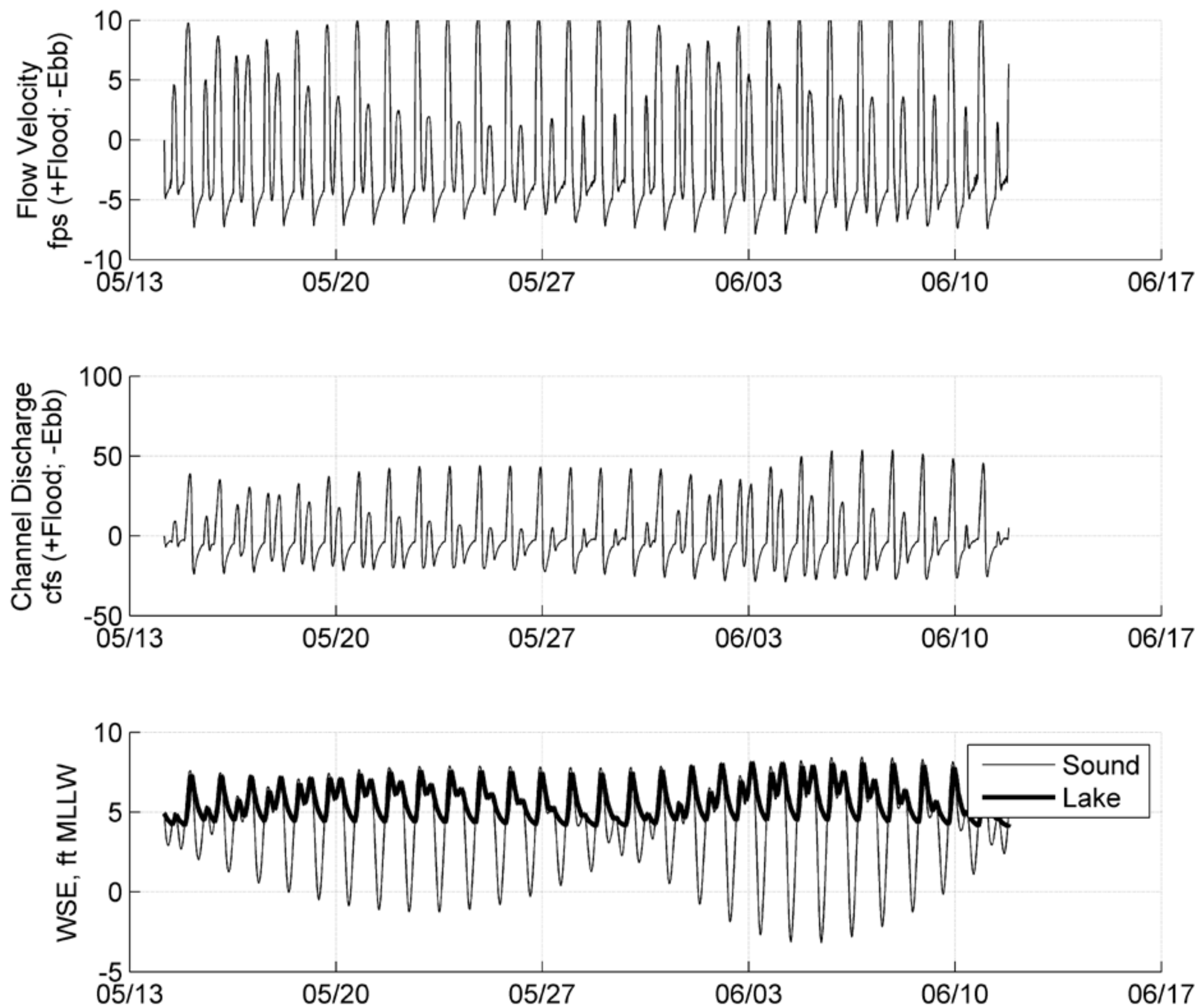
Figure 16
Model Output Time Series
3x 10’ x 8’ Culverts
Low Roughness



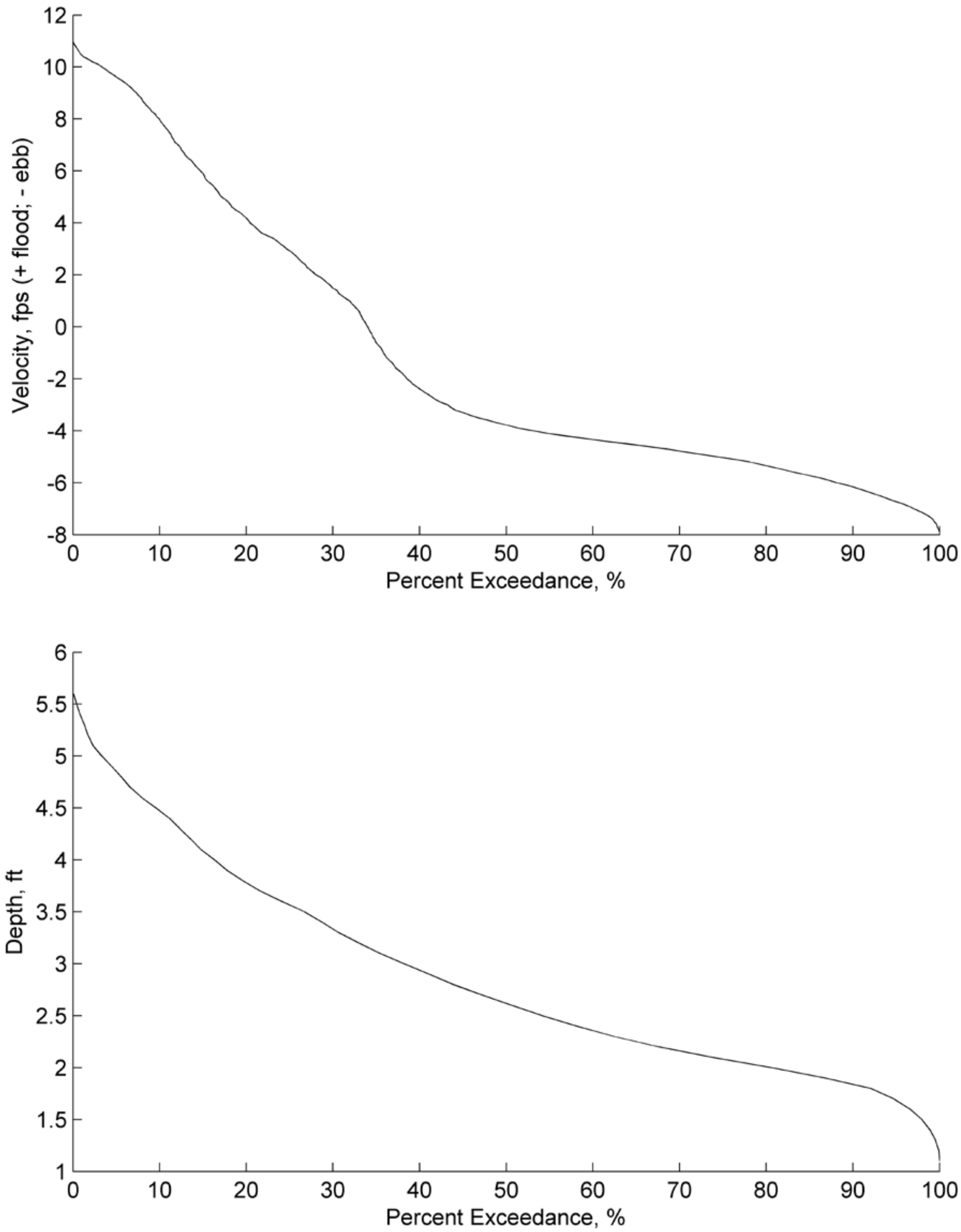
SOURCE: Processed Delft hydraulic model output

Figure 17
Exceedance velocities (top) and depths (bottom)
3x 10’ x 8’ Culverts
With Updated Creek Inflow Estimate



SOURCE: Processed Delft hydraulic model output

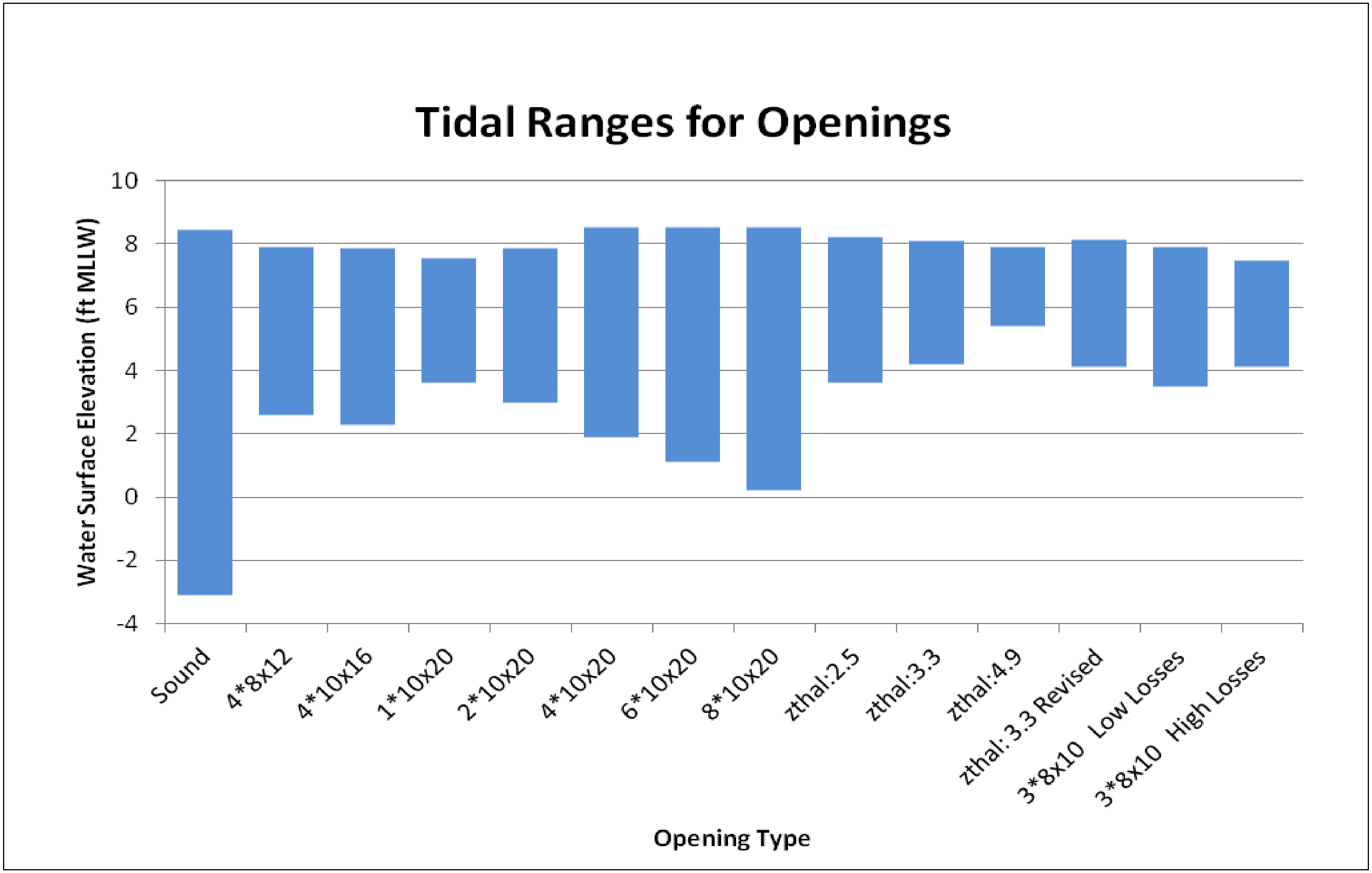
Figure 18
Model Output Time Series
Chanel @ Elevation 3.3ft MLLW



SOURCE: Processed Delft hydraulic model output

Figure 19

Exceedance velocities (top) and depths (bottom)
Channel @ Elevation 3.3 ft MLLW
With Updated Creek Inflow Estimate



SOURCE: Processed Delft hydraulic model output

ESA PWA

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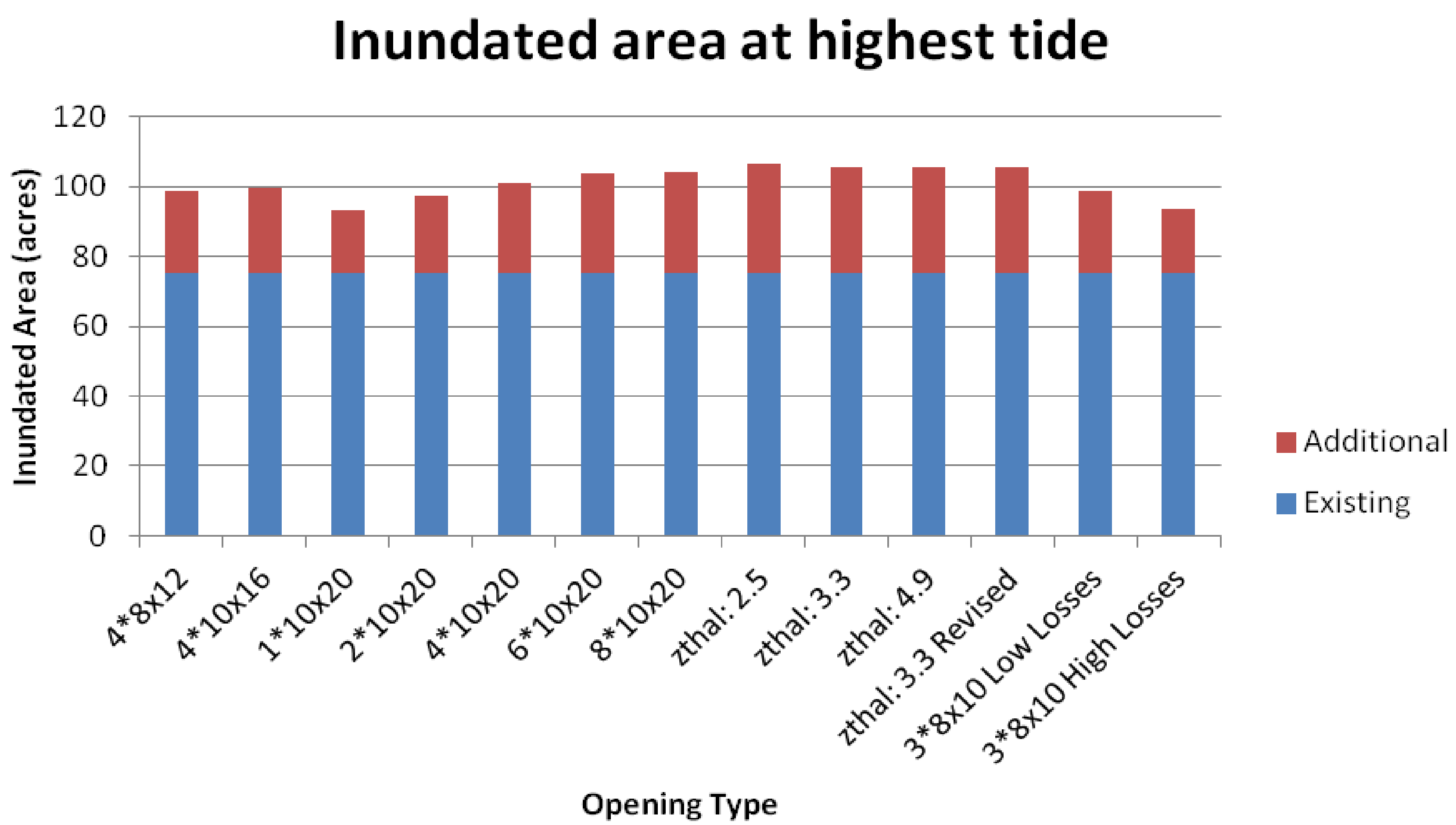
Figure 20

Tidal ranges inside lake for different opening alternatives to the Strait of Juan de Fuca from Swan Lake.



SOURCE: Processed Delft hydraulic model output

ESA PWA

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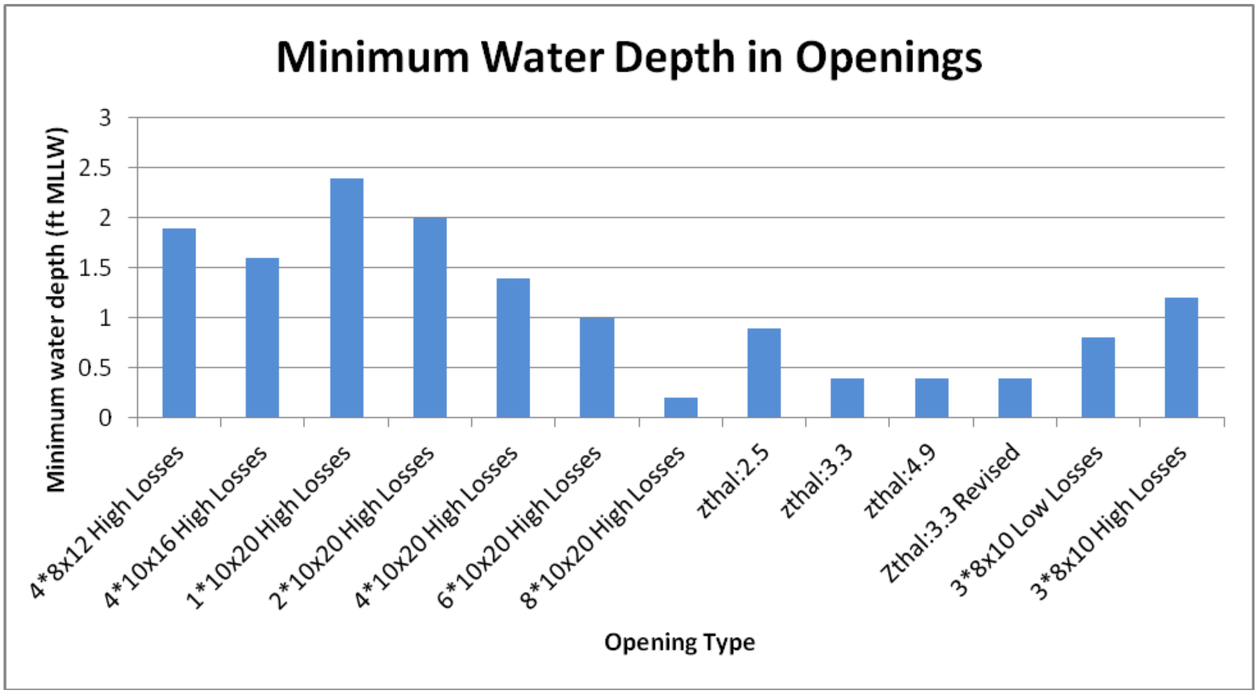
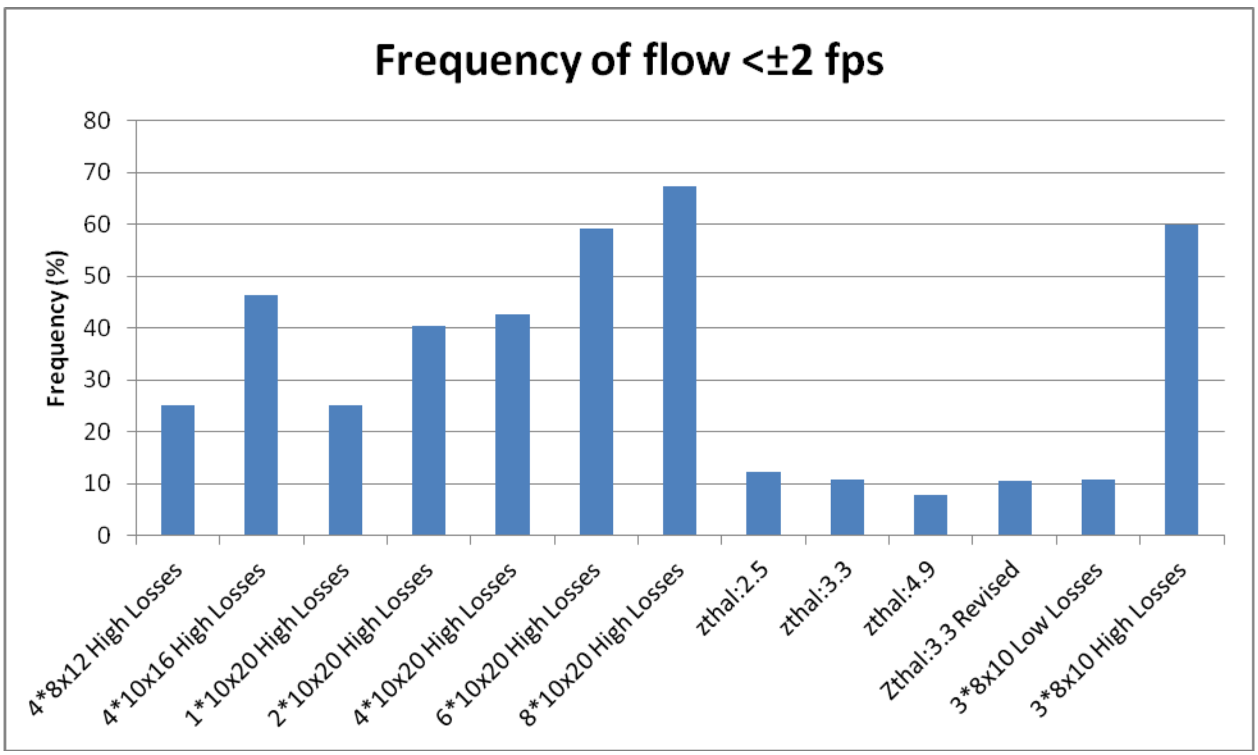
Figure 21

Inundated area at highest tide during a simulation.





SOURCE: Processed Delft hydraulic model output

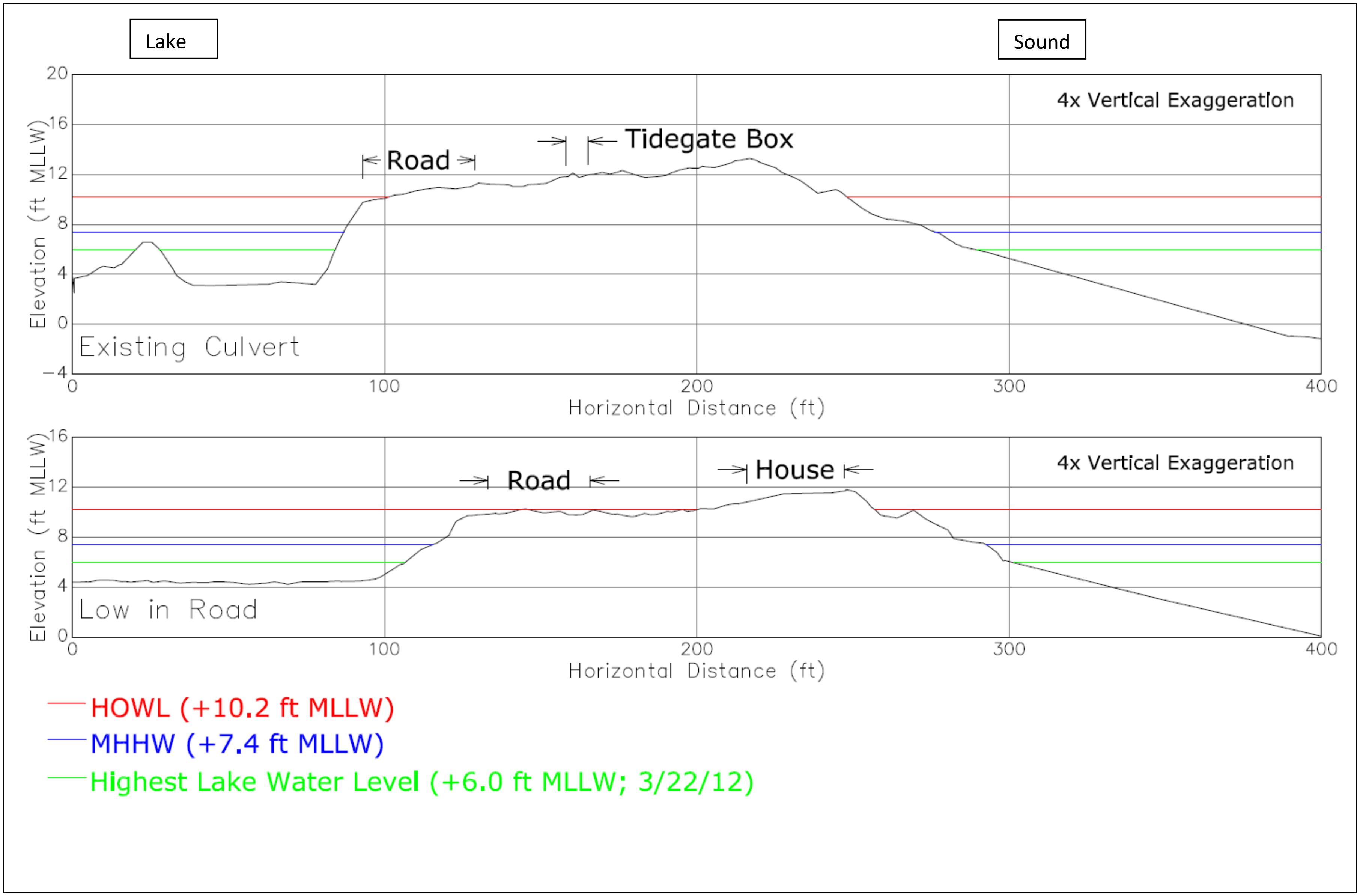
Figure 22
Minimum water depths in openings (top) and frequency of velocity <±2 fps (bottom) for all opening alternatives.

SOURCE: CGS
NOTES: Water levels indicated in the figure represent the still water level (SWL), and do not include waves and flood phenomena associated with wave dynamics

Figure 23
Tidal and flood water levels projected onto LiDAR topography around Swan Lake

SOURCE: CGS
NOTES: Water levels indicated in the figure represent the still water level (SWL), and do not include waves and flood phenomena associated with wave dynamics

Figure 24
Tidal and flood water levels projected onto LiDAR topography around Swan Lake in vicinity of the berm/spit (see cross-sections in Figure 25)

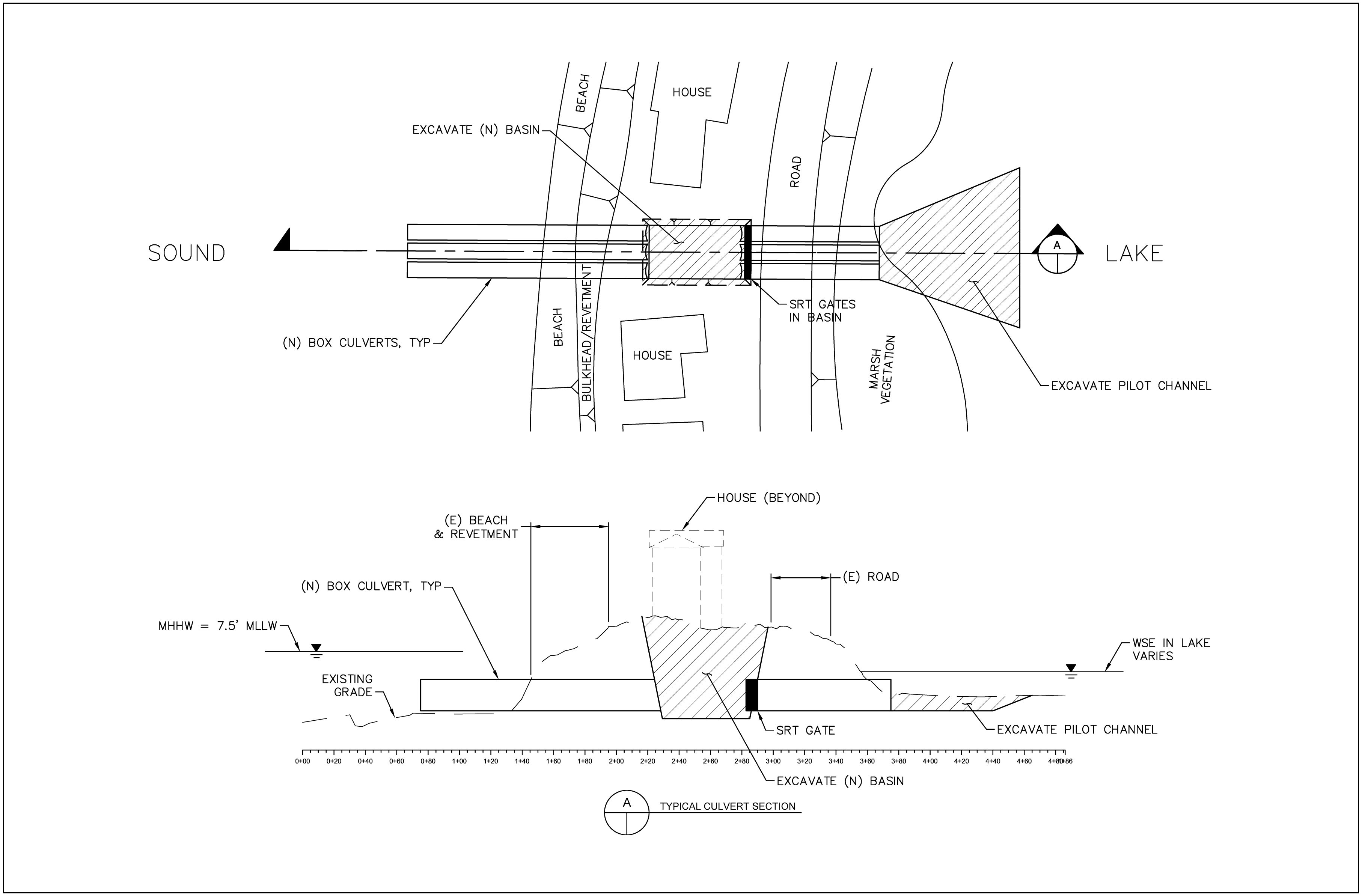


SOURCE: CGS

NOTES: Water levels indicated in the figure represent the still water level (SWL), and do not include waves and flood phenomena associated with wave dynamics

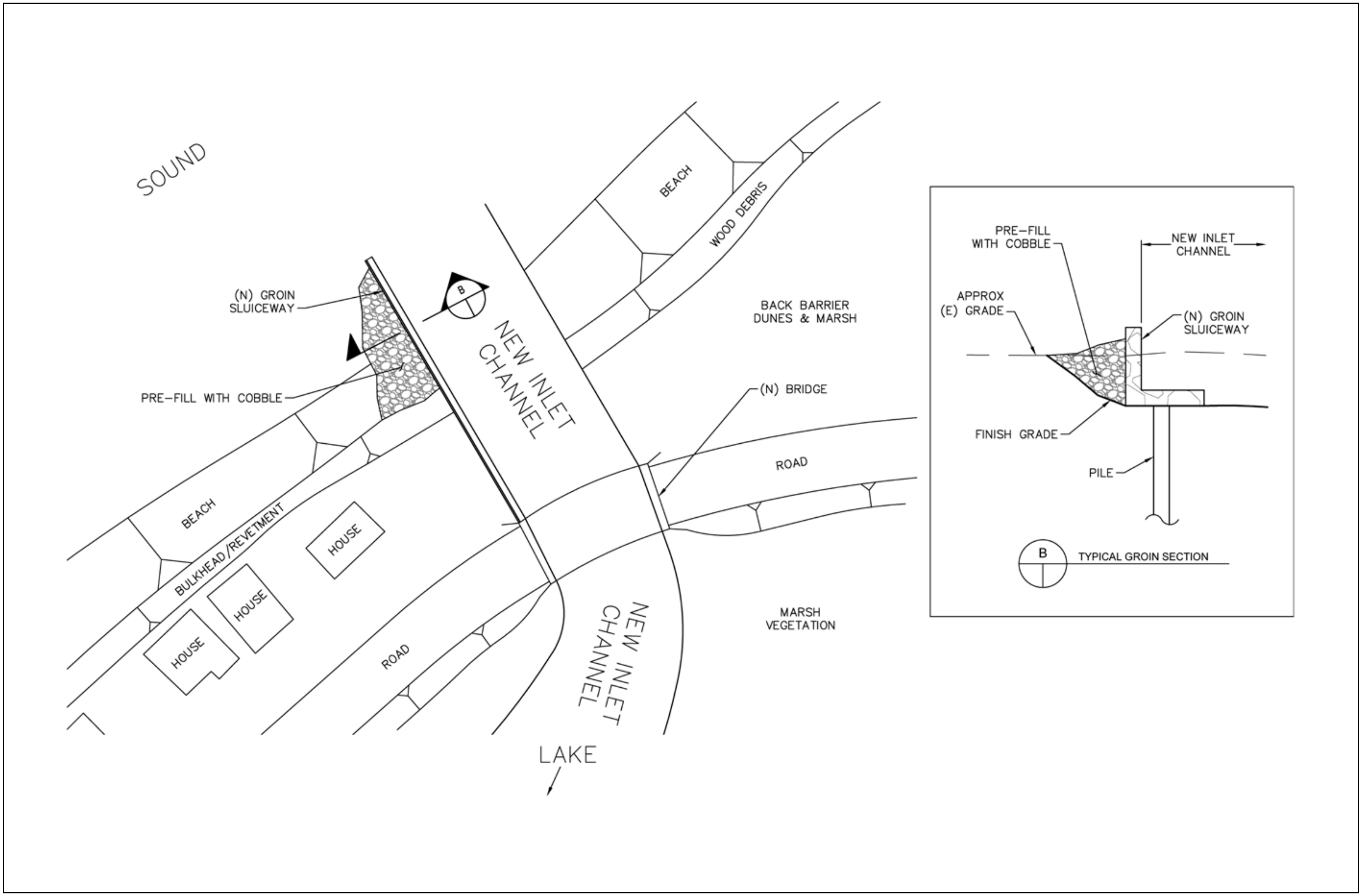
Figure 25

Berm cross-sections showing the tidal and flood-level still water levels at the site relative to homes and infrastructure



SOURCE: Processed Delft hydraulic model output

Figure 26
Culvert Alternative



SOURCE: Processed Delft hydraulic model output

Figure 27
Channel Alternative