APPENDIX B: HYDRODYNAMIC MODELING REPORT

EXECUTIVE SUMMARY

ES.1 - INTRODUCTION

The Herring River is a 1000+ acre estuary system located on Outer Cape Cod. A majority of the system is located in Wellfleet, Massachusetts and is physically separated from Wellfleet Harbor by a compound dike system at the Chequessett Neck Road crossing. The system is hydraulically connected to Wellfleet Harbor through the dike by three 6-foot wide box culverts, each with a flow control structure. One culvert has an adjustable sluice gate, which is currently set to be partially open two (2) feet and allows bi-directional tidal flow. The remaining two culverts have tidal flap gates, which are designed to permit flow only during an ebbing (outgoing) tide. Tidal exchange between the tidal marsh and harbor is severely restricted by the dike and culvert system. Herring River has been tidally restricted for over a century, which has resulted in significant degradation of the ecological functions and values of the marsh.

Prior to the dike construction in 1909, Herring River was connected to Wellfleet Harbor through a natural inlet at Chequessett Neck. The marsh system consisted of nearly 1,100 acres of thriving coastal wetlands, including a productive herring run, shellfishery, and salt marsh habitats. The dike construction, intended to control mosquitoes and create additional developable land area, significantly degraded the natural marsh ecosystem. Today, after 100 years of influence, as well as numerous other anthropogenic impacts (e.g., upstream culverts, railroad crossings, ditch creation, etc.), hundreds of acres of intertidal salt marsh have been degraded. This transition has eliminated habitat for estuarine flora and fauna. On-site monitoring has documented reduced tidal amplitudes, minimal salinity levels, loss of marsh vegetation, degraded fish and wildlife habitat, decomposition and subsidence of soils/sediments, and colonization by invasive species.

The Herring River Restoration Committee (HRRC), a multi-agency group appointed by the Cape Cod National Seashore and the Towns of Wellfleet and Truro, has recognized the environmental and socioeconomic benefits of restoring this tidally restricted and degraded wetland system, and is currently developing a comprehensive restoration project/plan that is geared towards identification of restoration actions and adaptive management strategies that will improve the system through a monitored and adjustable approach. As part of the restoration effort, the HRRC requested the development of a comprehensive hydrodynamic model that could be used to assess existing conditions within the estuarine system, as well as evaluate a range of alternatives and their potential impacts. The model was required to be sufficiently flexible to integrate with the adaptive management approach, capable of simulating the complexities of the Herring River system (e.g., marsh surface wetting and drying, salinity levels, a range of flow control structures, etc.). Working with the Towns of Wellfleet and Truro, the HRRC, contracted with the Woods Hole Group (WHG) to identify and develop the hydrodynamic model for the Herring River system.

The hydrodynamic modeling effort is a major component of the restoration plan that will address numerous concerns associated with re-establishing increased tidal exchange, as well as provide the necessary information to design an appropriate system of dikes, culverts, and road crossings. The purpose of this report is to provide details on the development and implementation of the hydrodynamic model for the Herring River System. It is expected that as the restoration plan continues to progress, the model could also be used to assess final design alternatives, refine the adaptive management approach, address additional physical mechanisms as needed, provide visualizations of the proposed alternatives, and provide an adaptive tool for integration of monitoring results.

ES.2 – MODEL SCOPING AND SELECTION

The overall goal of the Herring River Restoration Project is to create a productive, natural environment that will sustain itself with improved water quality and a strengthened ecosystem by restoring tidal flow to the estuary. While it would be desirable to allow the Herring River estuary to simply resume its previous natural state of unimpeded tidal flow, human and environmental constraints pose limitations on the extent to which the natural tidal flow can be restored. The success of the project will largely depend on the successful implementation of a comprehensive restoration plan, which addresses all the important issues related to those limitations. Hydrodynamic modeling is a central piece in developing this plan as it allows for the evaluation of specific questions about potential changes to surface water flow, velocities, water surface elevation, and salinity levels within the estuary.

Following an eel kill in the fall of 1980, which drew attention to the poor and declining water quality in the Herring River upstream of the dike, a significant amount of literature was generated documenting studies conducted within the area. These studies indicated the detrimental impact caused by the diking of the system and called for tidal restoration in order to revitalize the ecosystem. This led to the development of some hydrodynamic model efforts to assess the Herring River System. Overall and not surprisingly, the previous modeling efforts demonstrated that larger openings in the dike would cause increases to the mean tidal elevation and the tidal range. Increasing the opening would also increase the saltwater penetration distance. These modeling efforts provided a good initial evaluation of potential restoration options for Herring River.

The model developed by the WHG as part of this scope of work further advances the hydrodynamic understanding throughout the entire Herring River estuarine system. The model more precisely represents the geometry of the estuary (including its plan form); it considers variable frictional effects throughout the estuary; it allows for flooding, drying, and ponding of water; it produces accurate current velocities and water surface elevations throughout the estuary; and it properly represents the physics of mixing for a wide range of forcing conditions.

The Herring River restoration project requires a model that incorporates the physics necessary to analyze water surface elevation, current velocities, salinity, sediment transport, and water quality. The model has to be dynamic, capable of handling bi-directional flow, high resolution to identify important processes, and flexible enough to link with other potential modeling tools (e.g., biological models) in an adaptive management setting. After evaluation of over 10 of the most capable hydrodynamic models in conjunction with the goals of the restoration project, the Environmental Fluid Dynamics Code (EFDC) model was selected to simulate the Herring River estuarine system. The model has been applied to studies of circulation, discharge dilution, water quality, Total Maximum Daily Load (TMDL), and sediment transport. EFDC is capable of predicting hydrodynamics and water quality in multiple dimensions and is a widely accepted Environmental Protection Agency (EPA) approved model.

ES.3 – MODEL APPROACH

The overall model approach that was applied to develop the hydrodynamic model for the Herring River system consisted of a phased approach that allowed for key stopping points to evaluate model performance and progress. This allowed for a flexible approach that included the incorporation of new data, and/or a re-direction of the effort based on the results of the current modeling phase. The primary steps in the modeling approach include:

1. Model Calibration - Model calibration is the process by which adjustments are made to the model parameters to ensure the model appropriately simulates measured water surface elevation, salinity, and other observed parameters.

2. Model Validation - Model validation is achieved by applying the calibrated model, with its fixed parameters, to one or more sets of observed data that are independent from the calibration data. Typically, sets of data for validation are collected at a different time and under conditions that differ from the calibration period.

3. Existing Conditions Simulations - Once the model has been calibrated and validated, additional simulations are conducted to provide a better understanding of the behavior of the system over a broader range of forcing conditions. These existing conditions simulations also provide a baseline for comparison to proposed restoration alternatives in order to gauge the potential benefits and/or risks associated with different restoration alternatives. Various conditions simulated include the spring/neap tidal conditions, storm scenarios, and sea level rise cases.

4. Chequessett Neck Road Dike Alternative Simulations – Several alternatives were simulated to evaluate the response to the Herring River system to modifications of the Chequessett Neck Road dike. These simulations included, but were not limited to, the removal of all anthropogenic structures (to provide an estimate of maximum restoration potential and assess historic conditions), optimization of a new dike opening width, and various opening heights with flow control structures to provide potential adaptive management openings.

5. Upstream Feature Evaluations and Alternative Simulations - Alternative simulations focused on the culverts located in the upstream portions of the system. Specifically, this included evaluation of the crossing at High Toss Road, removal of the large flood tidal shoal existing just upstream of the dike, and assessment of the various road/culverts upstream throughout the system.

6. Mill Creek Sub-Basin Alternative Simulations - Alternative simulations were focused on evaluation of the Mill Creek sub-basin, including the potential implementation of a new dike restricting tidal exchange into this portion of the system. Evaluation of these simulations included construction of a Mill Creek Dike, optimization of a Mill Creek dike

culvert (height and width), a re-graded Chequessett Yacht & Country Club (CYCC) golf course, and a preliminary assessment of potential groundwater impacts.

ES.4 – MODEL DEVELOPMENT

The development of the Herring River hydrodynamic model required configuration so the model would represent the form and function of the real system (i.e., the Herring River Estuary). Model configuration involves compiling observed data from the actual estuarine system into the format required for the execution of the model. The Herring River estuary model was developed using various data observed throughout the Herring River system. Data provided were assumed to be correct and appropriate for model development of the Herring River system and the accuracy of the observations was not a component of this modeling study.

ES.4.1 Existing Data

The data required for the development of a more robust and detailed hydrodynamic model, are of two distinct types, topographic and hydrographic data. The topographic data are required to construct the model geometry, while the hydrologic data are required for model forcing and proper calibration and verification to ensure the model will provide accurate predictions. Additional data types are also required to further utilize the model to assess other physical processes. For example, sediment information is required for sediment transport modeling, salinity observations to assess salt levels in the system, etc.

High-resolution photogrammetry data (approximately 200,000 points within the estuary above the mean low water elevation) were used to accurately model the flooding and drying of the marsh surface. The photogrammetry provided the necessary high resolution and precision required to accurately develop the model elevations in the marsh system. Bathymetric data (below the lower limit of the photogrammetry data) were used to provide the depths within the creeks and streams of the Herring River estuary system, as well as for the area just downstream of the dike.

Water surface elevation data were collected by the National Park Service at various locations throughout the estuary. Data were collected in 2007 and 2010. Salinity and temperature data were also collected at two (2) locations. Subsets of these data were used for both model calibration and verification. Other hydrologic data that was also used in model verification includes the data collected for the earlier modeling studies from 1999-2000. Water surface elevation, salinity, temperature, and other data records continue to be collected throughout the Herring River estuary system by National Park Service.

Various types of sediment data were also used to analyze and model sediment mobilization and transport. These data included sediment samples and associated grain size analysis, sediment cores, synoptic measurements of total suspended solids, and continuous measurements of turbidity.

ES.4.2 Model Grid Generation

The development of a model grid defines the spatial domain on which the model performs its calculations. The model grid is a digital abstraction of the real life geometry of the Herring

River system. The grid building process involves using geo-referenced digital maps or aerial photos to define the model domain, generating a grid within this domain providing the desired degree of spatial resolution, and assigning elevation values to the grid using the topographic and bathymetric data sets. The accuracy of the model is highly dependent on accurate representation of the form of the real system expressed through the model grid. For this system, a curvilinear orthogonal grid was developed because of its increased flexibility, allowing grid boundaries to better follow natural irregular boundaries. The curvilinear orthogonal grid also allows gradual variation in horizontal resolutions, such that higher resolution areas can be defined in areas where greater detail is required. The resulting Herring River grid has over 85,000 cells with resolution in critical areas of less than 10 feet. The grid has satisfactory orthogonality and aspect ratio, as well as smooth boundary point distribution and smooth resolution change. A portion of the model grid is depicted in Figure ES-1.

ES.4.3 Boundary Conditions and Model Parameters

In order for the Herring River model to compute a hydrodynamic solution it is necessary to specify the model variables on the domain boundaries. The Herring River model consisted of the following:

- Most of the model's boundary is considered to be a "land" boundary, which for the Herring River model was specified at an elevation of 12 feet NAVD88. This elevation provides the upper limit of expected water surface elevation during extreme storm events (100-year return period). At these land boundaries, water is constrained to flow only parallel to the boundary.

- The primary forcing for the model is provided by an open boundary at the southern end of the model domain in Wellfleet Harbor. At this location, time dependent water surface elevation and salt concentration is specified, as observed by gauge data from Wellfleet Harbor.

- Freshwater inflow volumetric flux is also specified in the model at three separate locations (Bound Brook, upper Herring River, and Pole Dike Creek) to simulate freshwater inflow into the estuary.

- Bihourly precipitation data collected at the National Atmospheric Deposition Program (NADP) station MA01 was used to provide rainfall input to the model.

- Bottom friction (or roughness length) throughout the model domain was assigned to individual cells to represent the characteristics of the flow through the system. Physically, bottom drag forces depend on a number of phenomena that are difficult to characterize. These include bottom material type, growth of biota, and the amount of channel meander, which all contribute to the overall energy loss that are accounted for by the bottom friction. Bottom friction parameters are typically used for "tuning" hydrodynamic model to reproduce the data observations. For the Herring River model, local adjustments were made to the roughness length values in order to improve the model results to match observed data. For example, observed data at the Pole Dike Creek gauge locations show the complete dampening of the tidal signal at this point in the estuary. This is likely due to the dense submerged aquatic vegetation (SAV) that exists in this creek and other vegetative influences in this relatively narrow channel. Observations conducted in 2008 indicated the creek to be almost impenetrable by canoe. Therefore, there are significant frictional and/or constriction influences in this portion of the estuarine system and a higher frictional parameter was assigned to replicate the real world conditions. All final assigned values are considered within the range of normal bottom friction values determined through empirical laboratory testing.

- Various types of flow control structures were also modeled throughout the systems. This included developing hydraulic routines embedded in the model to simulate culverts, slide (sluice) gates, and flap gates.

ES.4.4 Model Calibration and Validation

Model calibration is the process in which model parameters are systematically adjusted through a range of acceptable values and results are examined using standard measures of error. The Herring River model was calibrated to water surface elevation observations collected between September 5, 2007 and October 3, 2007 at seven locations throughout the estuary and salinity at a station in the Lower Herring River. The model performance is evaluated by comparing time series output from the model at specific observation points to the observed time series of both water surface elevation and salinity. The results are presented visually as time series plots and scatter plots, and absolute error of the model is quantified by calculating the bias and Root Mean Square Error (RMSE). Additionally, the most dominant tidal constituents (both amplitude and phase) as determined from tidal constituent analysis are compared.

The magnitudes of the water surface elevation errors were well within bounds of standard calibration limits for hydrodynamic models. The model bias was less than 0.1 feet for all locations meaning that the calibration simulation reproduced average water levels that were within an inch or two of observed levels. The root mean square error was less than 0.4 feet for all locations indicating that on average the modeled water level is within a few inches of the observed level at any given time. Relative errors were approximately 1-2% at all locations. Representative plots portraying modeling calibration are provided in Figures ES-2 and ES-3.

Salt penetration in the Herring River in its current restricted state is not normally observed above High Toss Road. As such, verifying that the model could accurately simulate salinity throughout the entire system was not feasible since currently salt only penetrates into the lower portion of the Herring River system. In the Lower Herring River where salinity data are available, the model is well calibrated with a relative error of 11%, which is well below the EPA recommended value.

Following calibration, the model was also validated to two additional data sets collected in 1999 and 2010. Validation involves applying the calibrated model to set of observed data that are independent from the calibration data set without changing the model configuration or parameterization. The water surface elevation relative errors were 1.7% and 2.8% for the 1999 and 2010 data sets, respectively.

ES.5 – Existing Conditions

The calibrated and validated model was further applied to simulate a number of scenarios to aid in understanding the behavior of the Herring River estuary in its current restricted state. In addition to providing better understanding of the current system, these simulations also provided a baseline for comparison to alternative simulations. For example, the impact of opening the Chequessett Neck Road dike on the potential storm surge signal throughout the estuary system can be evaluated compared to existing conditions.

The existing conditions simulations consisted of normal tidal conditions, storm scenarios, and sea level rise cases. Normal tidal conditions were simulated by using the same water surface elevation data used during calibration and validation without the inclusion of temporally specific atmospheric forcing (wind, rainfall, etc.). Storm events and forecasted sea level rise (SLR) scenarios were simulated by modifying the water surface elevation boundary conditions to represent storm surge and/or long-term sea level rise increases.

The return-period tidal flood simulations demonstrate the effectiveness of the existing Chequessett Neck Dike in reducing storm surge. For example, during the 100-year flood event, the greatest increase in peak elevation is only 0.7 feet above the normal high water conditions in Lower Herring River, a 63% reduction in storm surge height between Wellfleet Harbor and High Toss Road. Sea level rise simulations were also conducted to provide an estimate of future predicted water levels in the Herring River over the next half century. Three (3) predicted rates of sea level rise (high, intermediate, and low) were used based on federal guidelines for incorporating sea level change considerations in civil works programs.

ES.6 – Alternative Evaluation and Screening

A series of alternatives were simulated that were geared towards gaining a better understanding of system response to potential modifications, while determining potential adaptive management steps and restoration endpoints. The results of alternative evaluation and screening were used to assist in defining specific restoration alternatives that were further analyzed, detailed, and selected for design consideration.

First a simulation of the “natural” Herring River system through the removal of all anthropogenic features (e.g., culverts, dikes, railroad beds, etc.) was conducted. In this scenario, the system was allowed to be fully open to tidal flow and allow relatively uninhibited exchange throughout the entire estuarine system. This simulation could be considered a reasonable representation of the greatest restoration level that may be expected for a natural system (excluding natural and/or anthropogenic changes to the bathymetry/topography) and a reasonable facsimile of the historic (a century ago) conditions of the system. Although the fully open alternative is not likely a reasonable final solution given the upland infrastructure that has been developed over the last century, this alternative does provide a reasonable estimate of the maximum restoration potential for the Herring River system and is used for comparison purposes.

Next, a range of potential opening widths at Chequessett Neck Road was simulated to determine the water surface elevations, tidal ranges, and salinity levels throughout the Herring River system. The results indicated that a 100 foot opening would optimize the water surface elevations and tidal range within the Herring River system, while a 165 foot opening would optimize the salinity penetration into the system. Although wider openings (greater than 165 feet) continued to let more tidal water and salt into the system, the changes were minimal and therefore produced diminishing restoration value. A 165 foot opening at Chequessett Neck Road was determined to be the largest width required to optimize restoration. A comparison of model results for a range of Chequessett Neck Road dike openings in provided in Figure ES-4. Predicted salinity penetration for 100- and 165-foot wide dike openings are shown in Figures ES-5 and ES-6.

Following the selection of the optimal Chequessett Neck Road dike opening width, simulations for various opening heights (assumed to be controlled by slide/sluice gate structures in the new dike opening) were conducted. These simulations evaluated targeted endpoints for restoration (based on limiting water surface elevations that could be accepted during storm conditions throughout the system) and provided opening sizes that could be used as initial set points in the adaptive management process. Results indicated that:

- A uniform 3' slide (sluice) gate opening across the entire 165' dike opening would limit the 100-year storm event water surface elevation to less than 6.0 feet NAVD88 throughout the system.

- A uniform 10' slide (sluice) gate opening, which is fully vertically open, limits the 100-year storm event water surface elevation to less than 7.5 feet NAVD88 throughout the system.

Based on the width and height variants simulated, recommended alternatives were selected for the new dike opening at Chequessett Neck Road that represented specific restoration endpoints. These restoration endpoints were intended to be eventually achieved through an adaptive management approach that would allow for controlled advancement towards the endpoints. Specifically, the following three alternatives were defined for the Chequessett Neck Road dike:

1. A new Chequessett Neck Road dike with a 165' wide opening and a future targeted maximum 100-year storm water surface elevation of 6.0 feet NAVD88 in the Lower Herring River (achieved with an approximate 3' slide [sluice] gate opening). Golf course re-grading and other flood proofing would be required in the Mill Creek sub-basin for this alternative. Several segments of low-lying roads would also require elevation increases and re-grading. Restoration would be significant through most of the system, but would not be maximized since the lower infrastructure elevations in the Mill Creek sub-basin would limit the maximum water surface elevation allowed in the system as a whole.

2. A new Chequessett Neck Road dike with a 165' wide opening and a future targeted maximum 100-year storm water surface elevation of 7.5 feet NAVD88 in the Lower Herring River (achieved with an approximate 10' slide [sluice] gate opening) with a new dike at Mill Creek to ***eliminate*** tidal exchange. A new proposed dike at the entrance to

Mill Creek with a one-way flap gate flow control structure would be installed to eliminate the tidal exchange into Mill Creek. This would allow freshwater flow out of the Mill Creek basin, but would not allow tidal water into the Mill Creek basin. As such, this alternative would maximize restoration throughout the Herring River system, but the Mill Creek sub-basin would remain a non-tidal system. No re-grading or flood proofing in the Mill Creek sub-basin would be proposed, but flood mitigation would be required in other sub-basins, including elevating and re-grading low lying roads.

3. A new Chequessett Neck Road dike with a 165' wide opening and a future targeted maximum 100-year storm water surface elevation of 7.5 feet NAVD88 in the Lower Herring River (achieved with an approximate 10' slide [sluice] gate opening) with a new dike at Mill Creek to ***limit*** tidal exchange. This alternative would maximize restoration throughout the entire system; however, the new dike at the entrance to Mill Creek with appropriate flow control structure(s) would limit the tidal exchange into Mill Creek. This new Mill Creek dike would produce similar water levels as the 3' slide/sluice opening alternative within the Mill Creek sub-basin. Flood proofing and mitigation would be needed in selected locations within the Herring River flood plain.

Since the Mill Creek sub-basin was a critical element of each of these defined alternatives, these three (3) final alternatives were further detailed through detailed assessment of the Mill Creek sub-basin. Therefore, simulation of potential tidal control at the entrance to the Mill Creek sub-basin, which followed a similar approach to the modeling and assessment of an opening at the Chequessett Neck Road dike, were conducted. This includes (1) optimization of an opening width at a new Mill Creek dike; (2) potential opening heights of a flow control structure to allow limited water into Mill Creek sub-basin; (3) simulations of a re-graded golf course region; (4) evaluation of the Mill Creek sub-basin completely blocked from tidal exchange and the effect on freshwater outflow, and (5) a preliminary assessment of potential groundwater impacts in the Mill Creek sub-basin relative to both sea level rise and the restoration effort. These results indicated that:

- A 25 foot opening in a new dike at the entrance to Mill Creek would optimize restoration in the Mill Creek sub-basin with the optimized opening at the Chequessett Neck Road dike.

- Alternatives that could be considered for managing water levels within Mill Creek include a maximum 3 foot sluice opening at CNR with no dike at Mill Creek, or a dike at Mill Creek that would allow for managed water levels when the sluice opening at the CNR dike is increased to opening sizes greater than 3 feet. The Mill Creek sluice/slide gate could also be closed completely and only allow flow out of the system.

- A re-graded golf course would remove some flood storage capacity from the Mill Creek sub-basin. For example, under the alternative with a 10 foot sluice opening at CNR and a 3 foot sluice opening at Mill Creek, a peak water surface elevation of approximately 6.4 feet would occur during a 100-year storm surge event in the re-graded Mill Creek sub-basin, while a peak water surface elevation of 6.0 feet would occur with the existing topography. Therefore, for a re-graded golf course area, an adaptive management approach would need to be implemented that would be able to adequately anticipate and manage water surface elevations in the Mill Creek sub-basin.

- Simulations of freshwater storm events (heavy rainfall) in the Mill Creek sub-basin, indicated that proposed alternatives would decrease the ability of the additional water to drain from the system, but would not increase the water surface elevation level above the normal mean high water level within Mill Creek. For the alternative that would completely eliminate tides from the Mill Creek sub-basin, the water surface elevation would not exceed 2 feet NAVD88 during any of the storm cases considered.

- Using the results of a preliminary evaluation, the impacts of sea level rise on the groundwater levels in the Mill Creek sub-basin indicate that under all three sea level rise scenarios (low, intermediate, high), the greatest increase in water table elevation would be 1.12 feet in 50 years in areas closest to Wellfleet Harbor. In general, a larger increase in water table elevation is expected at locations closer to Wellfleet Harbor, while a smaller increase is expected at locations near Mill Creek.

Additional findings and recommendations, corresponding to the overall restoration effort, include:

- Lowering the culvert inverts at the Chequessett Neck Road dike does allow a greater volume of flow (slightly higher tides); however, without a significant adjustment to the local bathymetry upstream and downstream of the dike, the low water level does not decrease. It may be feasible that a lower culvert invert, combined with the increased volumetric flow, would cause scour and an eventual lowering of the river bed and thereby a more significant change to the mean low water elevation. However, this lowering would have to occur over a significant distance both upstream and downstream of the dike and it is more likely that the actual scour would occur in a localized area at the dike only.

- Assessment of High Toss Road indicates that under restored conditions (Chequessett Neck Road dike openings of 65 feet or greater), the roadway will be overtopped. As such, the road would require mitigation to remain useable, or be abandoned. The existing High Toss Road and culvert also negatively impact restoration potential in the upper portions of the Herring River estuary. Specifically, the restrictive culvert and causeway impede the draining of the upper system during an ebbing tide, resulting in a reduced tidal range, excessive ponding, and higher MLW. The removal of the High Toss Road culvert and creation of an open channel at this location is recommended.

- As the restoration process advances, several upstream culverts, specifically the culverts at Pole Dike Road and Old County Road, may need to be replaced with larger culverts. However, since the effect on water surface elevation is relatively small, especially in the early stages of the restoration, these culverts do not need to be replaced during the initial restoration effort. Monitoring of water surface elevations and salinities during the adaptive management process should be conducted to determine the potential influence of these anthropogenic structures.

ES.7 – FINAL ALTERNATIVE ASSESSMENT AND MODEL OUTPUT

Modeling results of the recommended alternatives were summarized to analyze potential changes to the Herring River system and to provide more easily digestible modeling output. The detailed results of the hydrodynamic model were also used to complete a preliminary sediment transport assessment. This assessment does not determine actual sediment movement but rather areas where there is potential for erosion or deposition. However, the analysis does provide reasonable results that can be utilized to help guide the adaptive management restoration approach.

ES.7.1 Tidal Benchmarks and Salinity

Water surface elevations and salinity throughout the Herring River system were evaluated using the results of the hydrodynamic model. Water surface elevation results from the alternative simulations were presented in three specific ways:

1. Tables that present relevant tidal benchmarks (Mean Low Water, Mean High Water, Mean High Water Spring, Annual High Water), the 100-year storm water level, and potential future sea level rise scenarios for restoration endpoint alternatives. These water surface elevation values were provided for each sub-basin.

2. Graphical aerial overviews and geo-rectified bounds of the water surface elevation level for each specific tidal benchmark.

3. Interactive Google© Earth files that provide both tabular and spatial data files for each of the simulated water levels.

Results are provided within each sub-basin and include data for existing conditions, fully open, and a range of sluice/slide gate openings associated with the proposed opening sizes both at Chequessett Neck Road and Mill Creek. Water surface elevation results show the limited tidal range under existing conditions, as a vast majority of the system is non-tidal, and the overall intertidal area is minimal, even just upstream of the dike. From a salinity perspective, under existing conditions, the salt water does not propagate beyond High Toss Road, while for the proposed 3 foot sluice opening and greater, salt water advances into a significant portion of the upper sub-basins. Modeling results for all the various adaptive management cases can be used to determine changes to intertidal areas, expected high water locations, and assess potential marsh vegetation areas.

ES.7.2 Tidal Flushing

The proposed opening at Chequessett Neck Road would result in substantially improved flushing within the system. The improved opening size is particularly effective at flushing the extents of the system beyond High Toss Road. Under existing conditions, the sub-basins of the system do not exchange water efficiently with Wellfleet Harbor. For example, the Herring River System above High Toss Road takes approximately 200 days to fully flush with Wellfleet Harbor under existing conditions, while under the alternative opening scenarios the flushing time is reduced to 6-8 days.

ES.7.3 Sensitive Receptors

Sensitive receptors include specific low-lying infrastructure (e.g., roadways, etc.), as well as other critical locations (e.g., golf course areas) that may potentially be influenced by the restoration and changes to the water surface elevations. Model results were evaluated to determine the water surface elevation at critical locations. Water surface elevation results from the alternative simulations were presented at the sensitive receptor locations as:

1. Tables that present relevant tidal benchmarks (Mean Low Water, Mean High Water, Mean High Water Spring, Annual High Water), the 100-year storm water level, and potential future sea level rise scenarios for restoration endpoint alternatives. These water surface elevation values are provided for each sensitive receptor (e.g., roadway).

2. Interactive Google© Earth files that provide the tables at each sensitive receptor location.

ES.7.4 Marsh Receptors

Similar to the sensitive receptors, water surface elevations and salinity values were evaluated at specific locations throughout the marsh plain. Additional metrics, hydroperiod, percent of tides wetting, and a classification values were also determined at each marsh receptor location. These locations can be used to assess the relative changes, and potential ecological changes that may occur throughout the Herring River system. The model results for the marsh receptor locations are presented as:

1. Tables that present relevant tidal benchmarks (Mean High Water and Mean High Water Spring) critical for marsh vegetation delineation, mean and maximum salinity levels, hydroperiod (the length of time [in hours] a point stays wet once it has gotten wet), and percent wetting (the percentage of high tides that wet that point). The tables also provide a classification of values.

2. Interactive Google© Earth files that provide the tables at each marsh receptor location.

ES.7.5 Ponding

Simulations of the adaptive management steps and restoration endpoints revealed there were certain areas within the system that were prone to ponding of water with the introduction of the increased tidal exchange. These areas are generally due to subsidence that has occurred over the century of marsh degradation, or caused due to poor drainage pathways. Although these potential ponding areas appear in the hydrodynamic model for restoration endpoint simulations (3 foot and 10 foot height openings), this does not indicate that these will occur during the restoration process. The hydrodynamic model is using the existing bathymetry to simulate future restoration endpoints. However, due to the adaptive management approach that is intended to be applied to the system (smaller incremental openings over time), it is likely that this topography will change as the system responds to increased tidal exchange. For example, it is expected that additional sediment will be transported into the system and be deposited in the lower velocity zones of the subsided areas. Additionally, existing channels leading to limited drainage areas will be naturally widened and deepened due to the increased tidal flux during the restoration process. Therefore, widespread ponding during the restoration effort is not expected as long as monitoring is conducted and the appropriate adaptive management actions are applied.

ES.7.6 Sediment Mobilization and Transport

In order to assess the potential impact of the proposed dike openings, a preliminary sediment transport assessment was conducted using the results of the hydrodynamic model. The analytical sediment transport model employed was based on the established concept that sediments begin to move when sufficient stress is applied to the grains on the estuary seabed. The sediment transport potential was determined for normal tidal conditions and for a 100 year extreme storm surge event. Each scenario was simulated for existing conditions, and for the restoration alternative with a 165 feet wide span at Chequessett Neck Road with sluice openings of 3 feet.

- Under existing conditions with normal tides, increased tidal asymmetry imposed by Chequessett Neck Road dike reduces the total volume of water and suspended sediment that can physically be transported into the lower Herring River. Any suspended sediment that does pass through the sluice gate quickly settles out because flood tide currents in the lower Herring River are severely reduced by the dike (this is supported by existence of the flood tide shoal in that is present in the existing system). The dike also causes a significant reduction in the flood tide current velocity in the area downstream of the dike. This reduction in current velocity likely deposits a portion of suspended sediment in the upper region of the area downstream of the dike during slack flood tide.

- When compared to existing conditions, the 3 foot opening shows similar pathways for sediment transport in the areas downstream of the dike. Generally, bed load is expected to move slightly seaward or remain in the same location, while a majority of the suspended sediment would ultimately be transported farther upstream into the estuary. For the 3 foot opening conditions, this general process is expected to increase, with potential bed load transport extending from the lower Herring River to the area downstream of the dike, while increased loads of suspended sediments would make their way upstream past Chequessett Neck Road during flood tides. Over time, these processes would likely lead to a coarsening of the sediment, particularly in the area downstream of the Chequessett Neck Road dike. With the new dike opening, potential sediment transport in the lower Herring River during both the flood and ebb tides would begin to occur. Initially, this is likely to lead to some transport of fine-grained material out of the lower Herring River that will not easily settle and would be transported into Cape Cod Bay and possibly dispersed within Wellfleet Harbor. In addition, a significant portion of this material would be transported into the subsided, upper portions of the estuary due to asymmetry in the tidal current and trapping by vegetation. The upper Herring River would remain primarily a depositional environment with the exception of the area near High Toss Road during the flooding tide. Considering the greater volume of sediment that is able to enter the upper Herring River, it is likely that 3 foot opening will lead to significant deposition of suspended sediment and fines in the upper estuary, specifically in lower lying areas that have historically subsided.

- During the 100-year storm under existing conditions, there is a large area of potential transport just downstream of the dike and sediment would be mobilized and transported upstream towards and potentially beyond Chequessett Neck Road (if the material can make it past the existing dike). Overall, the storm surge is not expected to cause significant mobilization of sediment in the lower or upper Herring River, although more suspended sediment would be carried above Chequessett Neck Road than during normal tidal conditions from outside the dike. The model results show a larger area of potential mobilization during the rising surge suggesting a net upstream transport bed load and coarser suspended sediment. Fines entrained during the surge would likely make their way out of the system and ultimately become dispersed in Cape Cod Bay.

- Qualitatively, sediment transport pathways in the area downstream of the dike are similar for both existing conditions and the restoration alternatives. However, because the Chequessett Neck Road dike severely restricts flow in the upstream reaches under existing conditions, a significantly smaller volume of water enters the estuary during the 100-year storm surge when comparing current conditions to proposed conditions. For existing conditions, there is practically no sediment mobilization above Chequessett Neck Road even during the 100-year storm surge. However, there will be a moderate increase of suspended sediment entering the lower Herring River and being deposited during a storm event when compared to normal tidal conditions. For the 3 foot opening, storm surge simulations indicate a significant mobilization of sediment in both the lower Herring River, as well as in the lower portion of the upper Herring River near High Toss Road. Significantly greater mobilization and erosion exists at the area near High Toss Road as the storm surge floods into the upper estuary and transports sediment upstream into depositional areas (primarily subsided regions). Downstream of High Toss Road, it is likely that bed load will be moved in both directions resulting in little net movement. Some sediment suspended during the flooding storm tide will likely deposit in areas of the estuary that are not typically flooded during normal conditions. As the surge recedes fines that are not deposited in the upper estuary will proceed toward the dike. Some of this sediment may make it into Wellfleet Harbor and become dispersed before the following tide brings it back into the estuary or it is carried into Cape Cod Bay.

Sediment transport processes are expected to change when the Herring River system is restored. Since the restoration project will use an adaptive management approach, it is expected that the changes to the sediment transport regime will occur over smaller incremental steps (via incremental opening of the sluice gates). As such, the sediment transport changes and amount of sediment transported will be less than is indicated in the modeling, which represents a significant opening size immediately after construction of a new dike.

Significant and valuable shellfish aquaculture exist in Wellfleet Harbor and there are concerns that the proposed restoration may result in smothering of these resources areas with sediment discharged from the Herring River system due to the increased tidal exchange. It is expected that when the system is initially opened, some fine grain material would be likely transported downstream into the Wellfleet Harbor area. Over the long-term however, sediment would be transported upstream into the Herring River system. In addition, the amount of sediment deposited in the Wellfleet Harbor area is not expected to be significant. The adaptive management approach will limit the total amount of material mobilized and a significant portion of the fine grained material will stay in suspension to areas seaward of Wellfleet Harbor. Additionally, the total volume of sediment mobilized from within the Herring River system is small compared to the area of Wellfleet Harbor. For example, if it is assumed that (1) all sluices are immediately opened to 3 feet (e.g., no adaptive management), (2) all sediment mobilized is transported downstream and deposited in Wellfleet Harbor, and (3) the depth of erosion for all mobilized areas is 1 foot, then the total thickness of sediment deposited in Wellfleet Harbor would be less than 1 cm (approximately 0.76 cm). As such, even using conservative assumptions, the potential sediment deposition thickness is minimal.

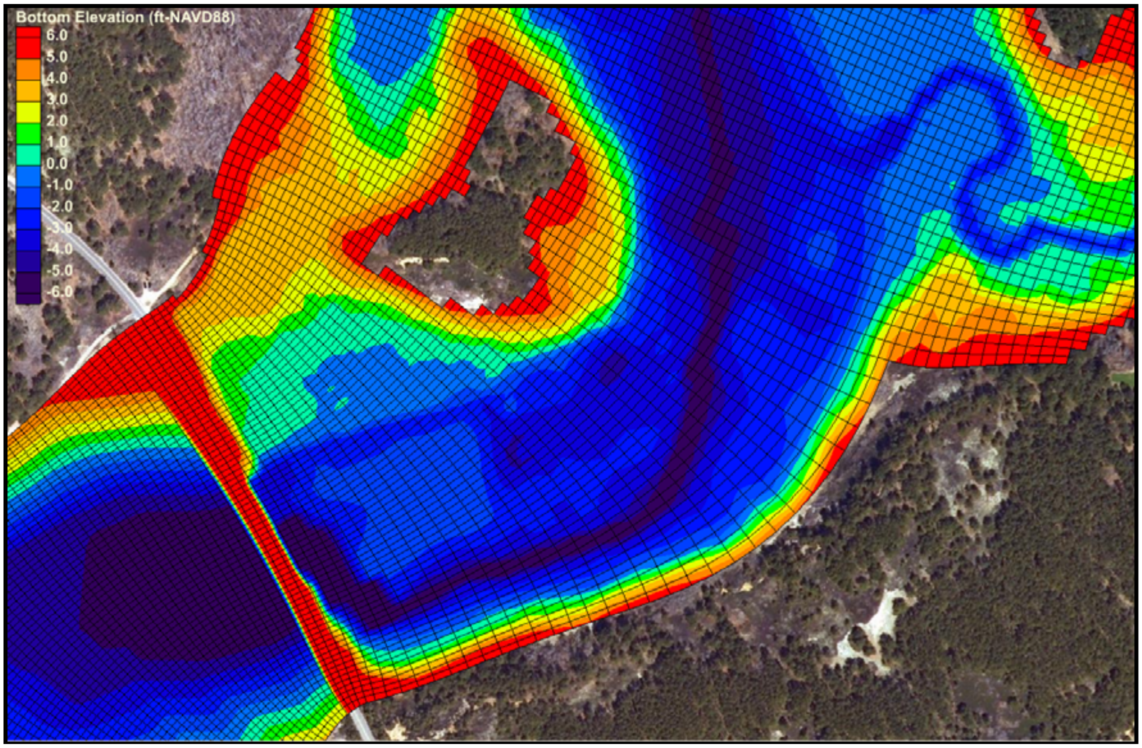

Figure ES-1. Detail of model grid showing bottom elevation contours and individual grid cells near the Chequessett Neck Road Dike.

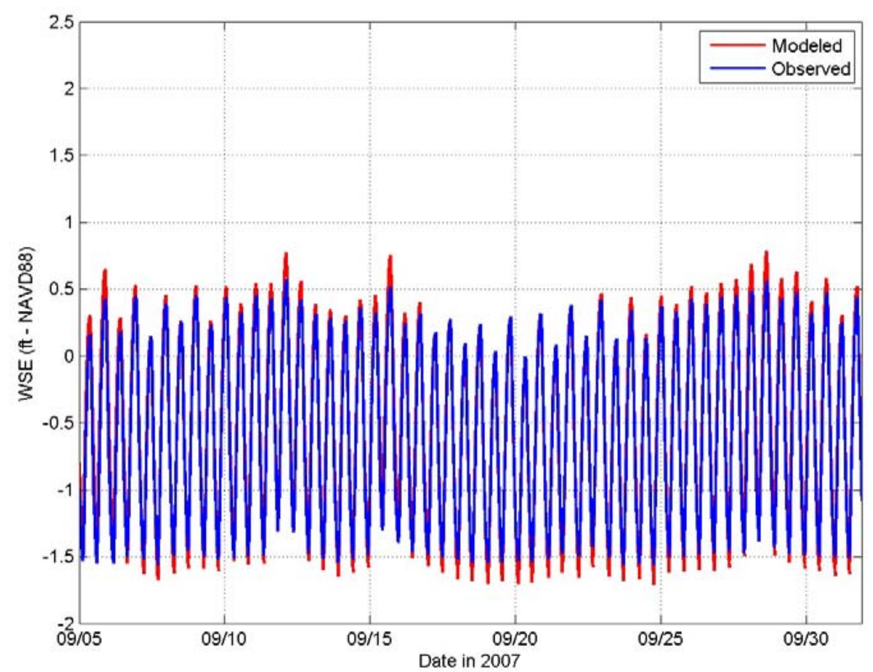

Figure ES-2. Upstream of High Toss Road (HT_up) water surface elevation comparison for modeled (red) and measured (blue) time series.

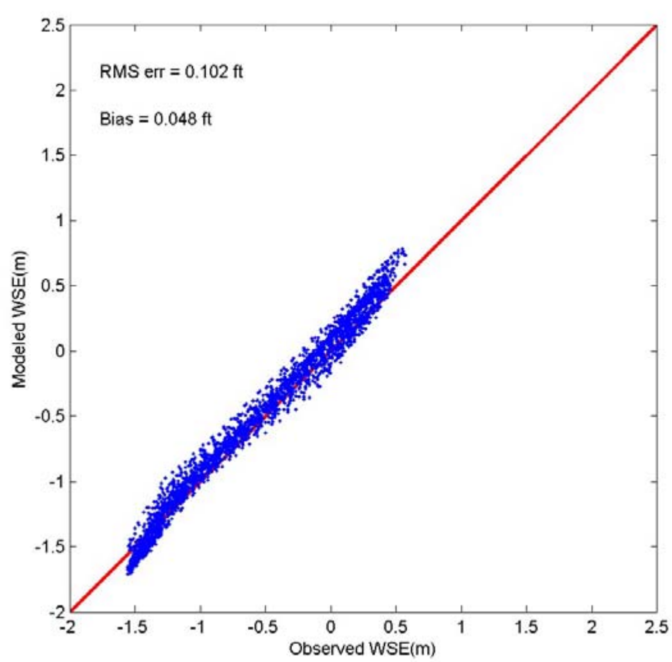

Figure ES-3. HT_up water surface elevation scatter plot comparing modeled and measured water surface elevations.

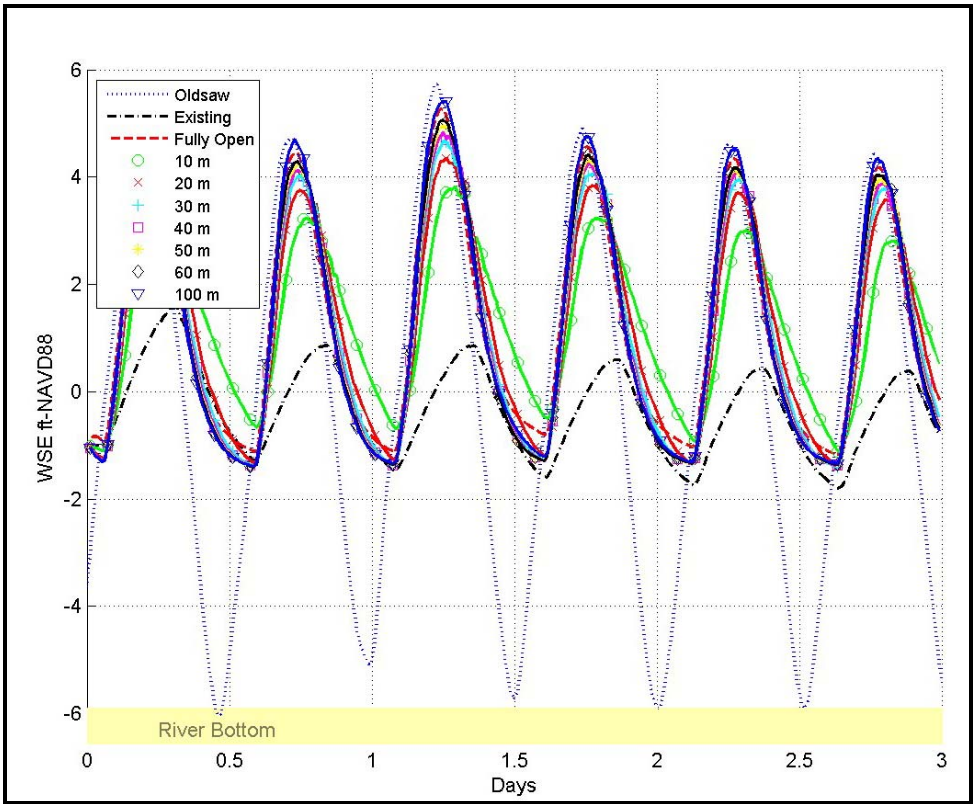

Figure ES-4. Water surface elevation (WSE) results in the Lower Herring River location for all alternative cases of dike opening width.

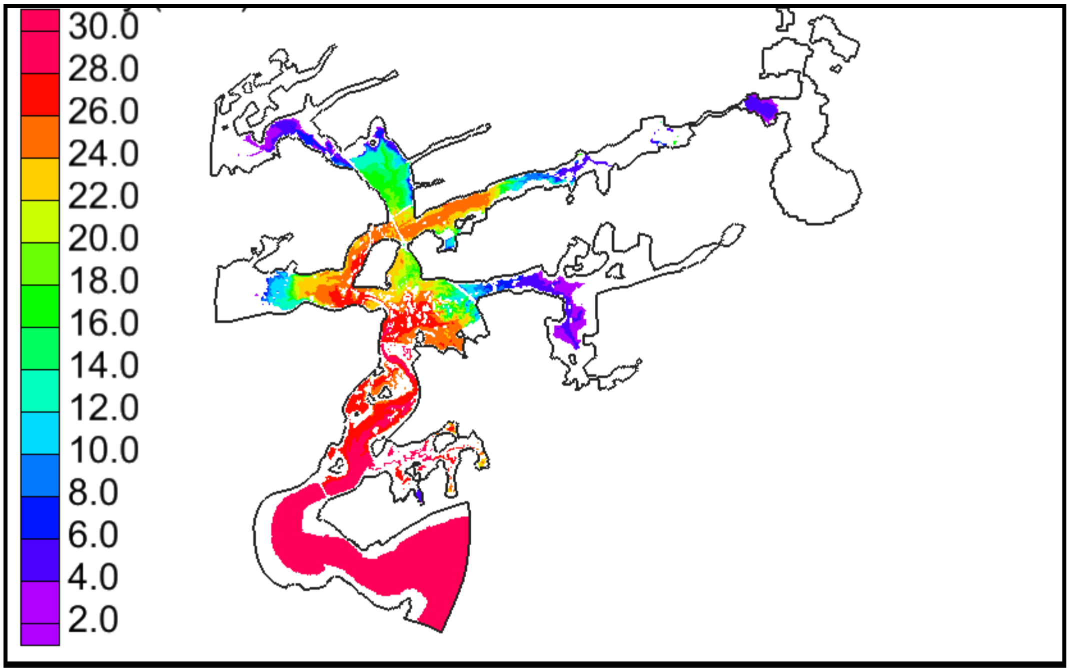

Figure ES-5. Salinity concentration throughout the Herring River system with an opening of 30 meters at the Chequessett Neck Road. Salinity contours are presented in ppt.

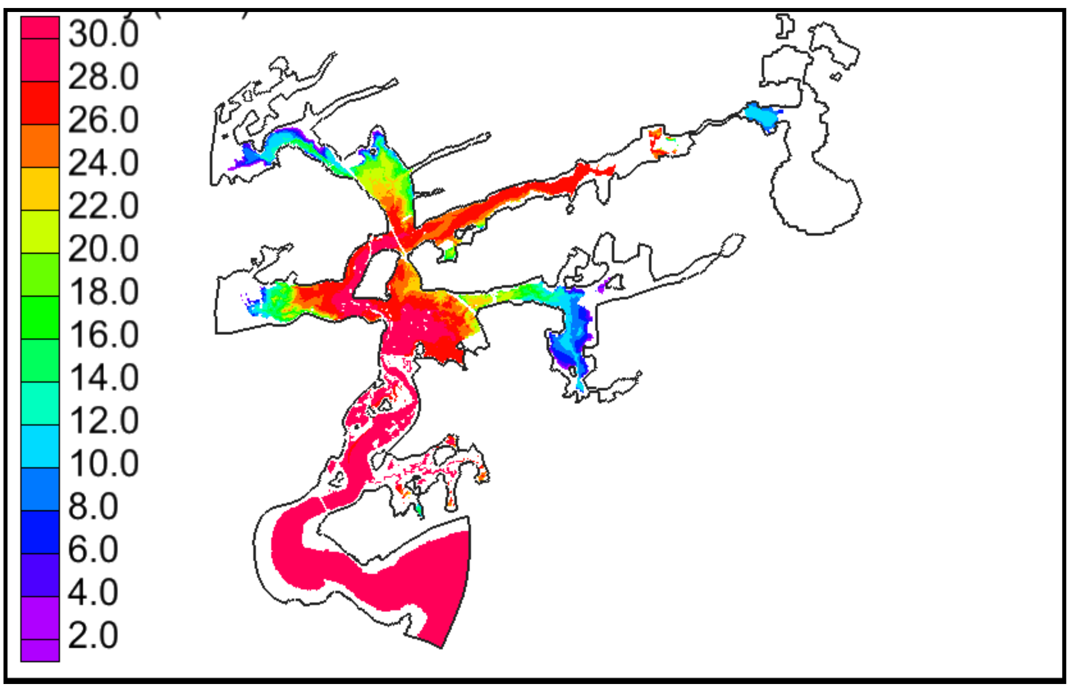

Figure ES-6. Salinity concentration throughout the Herring River system with an opening of 50 meters at the Chequessett Neck Road. Salinity contours are presented in ppt.