

**Hydrodynamic Assessment of Estuarine Restoration of Pilgrim Lake, Moon Pond,
and Salt Meadow, Truro, Massachusetts**

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Table of Contents

Executive Summary

1. Background and Study Objectives
2. Hydrodynamic and salinity model for tidal inlet systems
3. Data collection programs in support of model application
4. Analysis of data from collection programs
5. Hydrodynamic and salinity model application, calibration, and sensitivity analysis
6. Application of hydrodynamic and salinity model to proposed restoration options
7. Summary and conclusions
8. References

Appendices

- Appendix A* NPS time series data of sea surface elevation collected at Provincetown Dock, Moon Pond, and Pilgrim Lake
- Appendix B1* Spreadsheets containing data collected during the intensive tidal cycle survey programs performed on May 19-20, 2004
- Appendix B2* Spreadsheets containing data collected during the intensive tidal cycle survey programs performed on July 15, 2004
- Appendix B3* Spreadsheets containing data collected during the intensive tidal cycle survey programs performed on August 5, 2004
- Appendix C* NPS salinity and temperature measurements from December 26, 2002 to November 3, 2003 in Moon Pond and Pilgrim Lake.
- Appendix D* Slade Associates Inc blueprints for the Pilgrim Lake, Moon Pond, and Salt Meadow Study area.
- Appendix E* Slade Associates Inc, location of benchmarks in the study area.
- Appendix F* NPS surface area versus elevation data for Pilgrim Lake, Moon Pond, Salt Meadow, and entire study area
- Appendix G* Water level time series for each of the restoration options analyzed
- Appendix H* Plan view plots of water surface for select restoration options

Executive Summary

The National Park Service (NPS) is interested in restoration of the natural tidal exchange between Cape Cod Bay and East Harbor to eliminate eutrophication, chronic oxygen depletions and fish kills in Pilgrim Lake and the peat drainage and acid sulfate soil formation in upstream wetlands. Within the context of this overall effort the goals of the present study, focusing on the physical processes in the system, are to:

1. Characterize the topography, bathymetry, and geomorphology of the system
2. Determine the existing hydrology and tidal hydrodynamics and hydrography (salinity and temperature) of the system.
3. Apply, calibrate, and verify hydrodynamic and salinity models for the system
4. Apply the hydrodynamic and salinity models to assess the impact of potential tidal restoration scenarios (control of tidal gates, installation of additional culverts, construction of tidal inlet) proposed by NPS.

As part of this study a variety of field collection efforts were performed to characterize the existing system. Intensive tidal cycle survey data were collected on May 19-20, 2004; July 15, 2004; and August 5, 2004, to characterize the currents/flows, sea surface elevations, salinity, and temperature field in the Pilgrim Lake system and adjacent Cape Cod Bay over a lunar, semi-diurnal (M_2) tidal cycle (period-12.42 hrs). Measurements were made at the Rte 6 and High Head Road culverts, with an accompanying hydrographic survey of Pilgrim Lake. In addition time series data on the water levels at Provincetown, Moon Pond, and Pilgrim Lake were collected simultaneously for period of about 7 months.

Analysis of the data resulted in the following insight into the lake dynamics.

- For the dominant M_2 tides, the amplitude decreases from 1.34 m at Provincetown to 0.153 m in Moon Pond (11% of the Provincetown amplitude). The M_2 phase in Moon Pond (126.7 degrees GMT) lags that at Provincetown (115.95 degrees GMT) by 10.75 degrees or 0.370 hrs (22.2 min). The other major tidal constituents (N_2 , S_2 , K_1 , and O_1) are seen to show amplitude reductions, on the order of a factor of 10, between Provincetown and Moon Pond. For comparison the intensive tidal cycle surveys showed a reduction in tidal range from the ocean (2.8 m) to Moon Pond (0.2 m) of about a factor of 14. The tidal range at Provincetown is approximately 96% of the Boston with high tide lagged by about 16 minutes.
- Water level fluctuations in Pilgrim Lake are dominated by low frequency non-tidal forcing. No water level variations at tidal time scales were observed in the lake. This is a direct result of the very limited tidally induced flux of water into the lake and the very large volume of the lake.
- Tidal current speeds are 40 % to 70 % stronger at flood than at ebb tide at the Rte 6 culvert. The flood tide however is of shorter duration (5.1 hrs) than the ebb

(7.3 hrs). The flood tide currents display a sine like shape, whereas ebb tides are almost constant throughout the ebb tide. Tidal currents at High Head Road culvert show a similar shape to those at Rte 6 but are about 2 to 3 times weaker. The shape of the tidal current curve is a direct result of strong ocean forcing on flood tide followed by draining of the system on the ebb.

- Hydrographic surveys show that lake waters are vertically and horizontally well mixed throughout the system. The exception is that in the northwestern end of the lake the water is stratified due to a local source of ground water entering the system. Since there were no observed tidal currents in the lake the lack of vertical or horizontal stratification seems likely due to wind mixing.

An inlet basin hydrodynamic model was applied to the Pilgrim Lake system. Two basins, Moon Pond and Pilgrim Lake, connected to each other by High Head Road culvert, and to the ocean via Moon Pond by the Rte 6 culvert, were used to represent the system. Input data on the culvert system geometry and elevations were based on a survey of the infrastructure and the *as built* drawings. The storage capacity of the basin was determined by NPS personnel based on an analysis of existing data, supplemented by a topographic survey of selected sections of the system, and in particular Salt Meadow, performed by Slade Associates Inc. as part of this study. The model was forced by the ocean water level. The model was calibrated by comparison of model predictions to data collected during the intensive tidal cycle surveys and the time series measurement program. A Manning coefficient was used to characterize losses in the culvert under High Head Road and a relative roughness coefficient was used for the same purpose for the culvert system from the ocean to Moon Pond.

The simulations show a dramatic reduction of tidal variations between Provincetown and Moon Pond and essentially no tidal signal in Pilgrim Lake; both consistent with the observations. Predicted water levels in Moon Pond were within several centimeters of the observed values. The model predicts a slightly earlier rise in water level in Moon Pond than observed but accurately reproduces the decrease in water level with time. The large differentials in water levels between Moon Pond and the ocean are a direct result of the frictional losses in the Rte 6 culvert system and the large differential in storage capacities of the two basins. At elevations typical of those currently observed in the field measurement program, Moon Pond comprises 2 % and Pilgrim Lake and Salt Meadow the remaining 98% of the surface area of the combined system. The amount of water entering/exiting Moon Pond on the flood/ebb tide is sufficient to raise/lower the water level in Moon Pond because of its relatively limited storage capacity. The amount of water that enters/exits Pilgrim Lake over a tidal cycle however is extremely small compared to the storage capacity of the basin and hence doesn't measurably affect the water level in the lake.

A tidal prism based model was applied to Pilgrim Lake System to predict the mean salinity in the system. The model used output from the hydrodynamic model to specify the volume exchanges between the lake and the ocean. A mean freshwater input rate of $0.073 \text{ m}^3/\text{sec}$ was assumed based on a groundwater and runoff model developed by

Masterson (2004). The ocean salinity was set at 31 ppt. Model predictions were compared with data collected by NPS at four monitoring stations that they occupied in the lake following the opening of the tidal gates. At approximate steady state conditions the model predicted a salinity of 24.5 ppt, compared to a mean of the observations of about 23.5 ppt.

A sensitivity study was performed varying the freshwater input to the lake by ± 10 and 20 %. As expected the predicted salinity decreases/increases as the freshwater input rate increases/decreases. Variations are on the order of 0.5 ppt. If the freshwater input is increased by 100 % then the salinity decreases by 5 ppt.

Next a series of simulations were performed where the freshwater input rate was held fixed at the mean value and the return parameter, b , varied between 0 and 1. The return parameter specifies the amount of water exiting on the ebb tide that re-enters on the next flood. The model shows that the higher the amount returned the lower the salinity in the lake. For $b = 0.8$ the salinity is about 17 ppt at the end of the simulation compared to a value of 25 ppt for $b = 0$. Model predictions with $b = 0.4$ result in a salinity of 23.5 ppt in good agreement with the average of all the station data.

Based on input from NPS, the State of Massachusetts, and the US Army Corp of Engineers a total of 26 restoration options were investigated. The options were divided into two major classes. Option 1 (12 cases) assumed that the current culvert system at the southwestern end of the lake continues to exist, connecting the ocean to Moon Pond, and that a new inlet is constructed at the location of the historic inlet on the northwestern end of the lake. Option 2 (14 cases) assumes that a new inlet replaces the current culvert system, with Sub-option 1 (2-1) assuming that the Salt Meadow Dikes are removed and Sub-option 2 (2-2) that they continue to exist. Within each option the impact of inlet width and bottom depth were investigated. For the new inlet on the northwestern end of the lake widths of 50, 100, 200, and 300 m were investigated. For the replacement inlet on the southwestern end of the system widths of 5, 10, 25, and 50 m were studied. The maximum width of the southwestern inlet was constrained by the existing Town of Truro Park. Inlet depths of 0.0, -0.5 and -1.0 m (NAVD88) were explored. For reference the mean depth of Pilgrim Lake is about -1 m. Simulations were performed for each case using the hydrodynamic model and results summarized in terms of the high and low water levels and tidal range in Pilgrim Lake compared to equivalent values in the ocean. In broad overview, model predictions show that

- Low tide levels decrease (lower levels) with increasing inlet width and depth and reach their lowest values for a width of 200 m or greater and depths of -1.0 m.
- High tide levels increase (higher levels) with increasing inlet width and reach their highest value for a width of 200 m or greater. The depth of the inlet has little impact on high tide levels. For inlet widths greater than 200 m high tides in the lake are the same as in the ocean.

- Tidal range increases with inlet width and reaches a maximum for a width of 200 m or greater. The lower the depth of the inlet the larger the tidal range. The depth of the inlet restricts the tidal range for the case with the largest width (300 m) and depth (-1.0 m).
- Removal of the Salt Meadow dike and culvert system decreases the tidal range slightly (about 15 %) compared to existing conditions. This difference is a direct result of the differential storage capacity for the lake with and without Salt Meadow dike restrictions.

To achieve the maximum tidal exchange with the ocean and hence the largest tidal range (approximately 80 % of the ocean range) in the lake requires an inlet with a width of 200 m or larger and an inlet depth of -1 m. The tidal range in this case is restricted by low tide levels and in turn the depth of the lake. At ebb tide much of the lake bottom would be exposed.

For the maximum width of the southern inlet of 50 m and an inlet depth of -1.0 m the tidal range in the lake is approximately 46% of that in the ocean. Restrictions in this case are imposed both by the high and low tide levels.

For three of the most probable remedial option cases (R21-1C (5 m width), R21-4C (50 m width), and R22-4C (50 m width), all with inlet depths of -1 m, predictions were made for the salinity and water level in the lake from 100 yr storm forcing. These simulations show that as the inlet width increases the lake salinity is predicted to increase and asymptotically approach the oceanic value. The maximum water level in the lake also increases as the width of the inlet increases. For the 50 m case maximum storm levels are about 75 % of those in the ocean. For reference, if an optimal inlet is constructed with a width of 300 m and a depth of -1.0 m, the salinity, high water and the maximum 100 yr water level will be the same as in the ocean. The tidal range in the lake will be about 82.5 % of the oceanic value and restricted by the depth of the lake. Plan view plots of the high and low tide water surface area were prepared for existing conditions and the most probable and optimum remedial options. High tide surface areas are shown to increase as the inlet widths increase (for widths of 50 and 300 m). The differential high tide surface area between the 50 m and 300 m width cases is quite modest and is a direct result of the change in slope of the storage capacity vs elevation curve, reflecting a more vertical sided basin. The low tide surface areas are predicted to decrease as the inlet width increases (for widths of 50 and 300 m). The bowl shaped geometry of the lake limits the change between the two cases.

The simulations show that the tide range, surface area at high tide, and mean salinity can all be substantially increased, compared to existing conditions, by construction of a 50 m wide, -1.0 m deep inlet, within the existing right of way, at southwestern end of the Pilgrim Lake system. With Salt Meadow dikes removed this case results in flooding of the majority of the Salt Meadow system. The optimum inlet, as defined by the largest tidal range, largest high and smallest low tide surface areas, and highest salinity is achieved for inlet widths greater than 200 m with a depth of -1.0 m.

1. Background and Study Objectives

Historically East Harbor (Figure 1), comprised of Moon Pond, Pilgrim Lake, and Salt Meadow located in Truro, Massachusetts, developed as a 286 hectare (700 acre) back barrier salt marsh and coastal lagoon behind a barrier beach (presently called Beach Point). East Harbor was connected to Cape Cod Bay by a 300 m (about 1000 ft) wide tidal inlet, located at the west end of the system. The inlet was filled in 1868, eliminating the tidal exchange between the harbor and adjacent Cape Cod Bay. A railroad line was installed along the barrier beach in 1874. In 1894 a culvert system was installed in the southeastern end of the system (Moon Pond) to drain freshwater entering the harbor to the bay. Apparently at the same time a tidal gate(s) (flapper type) was installed in the culvert system near the beach and a weir placed at High Head Road. These hydraulic structures allowed control of the water levels in East Harbor and penetration of salt water into the system from the bay. In 1920 Route 6A was built just south of and parallel to the railway along the barrier beach. The culvert system was reconstructed in 1935 and in 1952-53 Highway 6 was constructed, running parallel to Route 6A. The Massachusetts Division of Highways reconstructed the present drainage system in 1956-58. The drainage system currently consists of a 213 m (700 ft) long concrete culvert extending from Cape Cod Bay under Rtes 6A and 6 to Moon Pond. The portion of the culvert from the ocean to a transition chamber (Rte 6) on the western side of Rte 6 is oval in shape with a height of 1.22 m (4 ft) and a width of 1.83 m (6 ft). This culvert was outfitted with a chamber containing two (in series) tidal gates. These are accessible through two manholes located just landward of Rte 6A and seaward of Rte 6. From the Rte 6 transition chamber, proceeding under Rte 6 to Moon Pond, the concrete culvert is circular, with a diameter of 1.22 m (4 ft). A concrete box culvert (3.2 m wide by 1.2 m high), located under High Head Road, allows water to flow from Moon Pond to Pilgrim Lake. On the Pilgrim Lake side of the culvert is a weir gate that allows penetration of salt water and the water level in Pilgrim Lake to be controlled by adding or removing boards from the weir. Salt Meadow, a 3.2 km (2 mile) long extension in the southeastern corner of Pilgrim Lake, is partially free to exchange water with the lake. Salt meadow is restricted by two earthen dikes, the first has a two-foot (60 cm) diameter culvert and the second (farther upstream), has a one-foot (30 cm) diameter culvert; neither has clapper valves. Salt Meadow has several drainage ditches that facilitates water entering and exiting the meadow.

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1. Characterize the topography, bathymetry, and geomorphology of the system
2. Determine the existing hydrology and tidal hydrodynamics and hydrography (salinity and temperature) of the system.

3. Apply, calibrate, and verify hydrodynamic and salinity models for the system
4. Apply the hydrodynamic and salinity models to assess the impact of potential tidal restoration scenarios (control of tidal gates, installation of additional culverts, construction of tidal inlet) proposed by NPS.

2. Hydrodynamic and salinity modeling

An overview of the inlet-basin hydrodynamic and salinity model used in the present study is presented here.

Hydrodynamics Model

The spatially integrated numerical model is based on the equations derived from the complete equations of motion by Harris and Bodine (1977). The presentation of the basic model follows that given by Seelig et al (1977).

Assumptions made in the process of model derivation were:

- Sea level is a specified function of time.
- The bay water level remains horizontal. This means that the bay water level rises and falls at the same rate throughout the entire bay at each point in time. This occurs when the length of the long wave (tidal wave) forcing the system is much longer in the bay than the longest axis of the bay. (Bay here refers to Pilgrim Lake, Moon Pond and Salt Meadow basins)
- The bay is connected to the sea by one or more inlets. (Sea here refers to Cape Cod Bay)
- At least one inlet must continuously connect the bay to the sea. Some areas of inlets may go dry during the water level cycle, and one or more inlets may go dry as long as one inlet contains water.
- Bay water surface area is a function of bay water level (or a function of time).
- Inlet cross-sectional area is a function of local depth (or a function of time).
- The local, water level slope in the inlet is assumed to be linearly related to the local friction loss along the inlet, between the sea and bay levels.
- There is a water level drop along the inlet that is proportional to the un-recovered velocity head lost through turbulent eddy diffusion in the bay (flood flow) or sea (ebb flow).
- Storage of water in the inlet is negligible. This means that the flow into

the inlet is equal to the flow exiting the inlet at any time. In addition, the volume of water stored in the inlet between high and low water should be small compared to the tidal prism. This is generally the case if the surface area of the bay is much larger than the surface area of the inlet.

- Wind stress on the inlet and bay surfaces is negligible. This means that the model is most useful for cases when the wind is light, has a short duration, or has a short fetch over the bay.
- Water has constant properties throughout the inlet and bay. No attempt has been made to model saltwater intrusion or other density gradient effects.
- Radiation stress (the interaction with wind waves) is neglected.
- Coriolis effects are neglected.

The derivation of the model begins with the one-dimensional equation of motion as derived by Harris and Bodine (1977),

$$\frac{\partial \bar{u}}{\partial t} + \frac{1}{2} \frac{\partial \bar{u}^2}{\partial x} + g \frac{\partial h}{\partial x} + \frac{1}{A_c} \int_{y_1}^{y_2} (\tau_{zx})_z dy = R \quad (1)$$

where

- $\bar{u}$ = cross-sectional mean water velocity in the inlet (positive on flood flow)
- t = time
- x = distance along the main axis of the inlet
- y = cross stream distance, from one side of the inlet, y_1 , to the other, y_2 .
- h = water level above some datum
- g = acceleration due to gravity
- A_c = inlet cross-sectional flow area at x
- $(\tau_{zx})_z$ = component of the stress tensor at the bottom of the inlet in the direction of the main axis of the inlet
- R = remainder terms, which are neglected in this model ($R=0$). This means that the water level is taken as constant at each inlet cross section. See Harris and Bodine (1977) for a discussion of these neglected terms.

The first term on the left hand side of Equation 1 is the temporal acceleration, the second term is the convective or advective acceleration, the third term is the slope of the water surface along the inlet, and the fourth term is the bottom stress.

To obtain a simplified equation, the expressions in Equation 1 are integrated over the length of the inlet between the sea and the bay, where x_s and x_b are the respective limits,

$$\begin{aligned} & \int_{x_s}^{x_b} \frac{\partial \bar{u}}{\partial t} dx + \int_{x_s}^{x_b} \frac{1}{2} \frac{\partial \bar{u}^2}{\partial x} dx + \int_{x_s}^{x_b} g \frac{\partial h}{\partial x} dx \\ & + \int_{x_s}^{x_b} \frac{1}{A_c} \int_{y_1}^{y_2} (\tau_{xz})_z dy dx = 0. \end{aligned} \quad (2)$$

Carrying out selected integrations and rearranging, Equation 2 becomes,

$$\begin{aligned} & \frac{\partial}{\partial t} \int_{x_s}^{x_b} \bar{u} dx + \frac{1}{2} \left[(\bar{u}_b)^2 - (\bar{u}_s)^2 \right] \\ & + g [h_b - h_s] + \int_{x_s}^{x_b} \frac{1}{A_c} \int_{y_1}^{y_2} (\tau_{xz})_z dy dx = 0. \end{aligned} \quad (3)$$

In Equation 3, terms involving $\partial x_b / \partial t$ and $\partial x_s / \partial t$ have been set to zero since x_b and x_s are assumed to be independent of time.

From continuity the cross-section mean inlet water velocity is equal to the inlet discharge, Q , divided by the inlet cross-sectional area, A_c ,

$$\bar{u} = Q / A_c \quad (4)$$

Substituting Equation 4 and using the product rule for integration, the first term on the left of Equation 3 can be integrated to yield,

$$\int_{x_s}^{x_b} \partial \left(\frac{Q}{A_c} \right) dx = \frac{\partial Q}{\partial t} \int_{x_s}^{x_b} \frac{dx}{A_c} + Q \frac{\partial}{\partial t} \left(\int_{x_s}^{x_b} \frac{dx}{A_c} \right), \quad (5)$$

where the second part of the equation,

$$\frac{\partial}{\partial t} \left(\int_{x_s}^{x_b} \frac{dx}{A_c} \right),$$

is taken as zero because channel storage terms are neglected.

After substitution of Equation 4, the second and third terms on the left hand side of Equation 3 are,

$$\frac{1}{2} \left(\frac{1}{A_b^2} - \frac{1}{A_s^2} \right) Q^2 + g(h_b - h_s) \quad (6)$$

where A_b and A_s are the cross-sectional areas of the inlet at the bay and sea ends of the inlet, and h_b and h_s are the water levels in the bay and sea referenced to a common datum. The convective acceleration, the left term of Equation 6, may also be expressed in terms of empirical loss coefficients.

The bottom stress is evaluated by using Manning's equation,

$$(\tau_{zx})_z = \frac{gn^2}{kD^{1/3}} |u| u \quad (7)$$

where u is the water velocity in the inlet, D is the water depth at that point, and k is a conversion factor to adapt Manning's equation to the system of units used. The value of k is [1.0 meter (3.2808 feet) per second cubed]^{2/3}. The absolute value function of u accounts for the alternating direction of bottom stress with flood and ebb tide. The bottom stress is approximated by determining the water velocity, u , at a number of grid points throughout the inlet.

For flows in culvert systems (concrete pipes) the frictional losses are represented by Colebrook's formula (White, 1999), which is applicable for both transitional and turbulent flows. This formula is parameterized in terms of the pipe Reynolds number, Re ,

and the relative pipe roughness (ϵ/D), where ϵ is the height of the roughness element and D is the diameter of the culvert. The larger the value of ϵ/D the larger the frictional loss.

The value of u is obtained from a plan view flow net system of channels and cross sections which are representative of flow throughout the tidal cycle. The main axis of each channel is drawn approximately parallel to the direction of flow and the cross sections are drawn approximately perpendicular to the flow. The subscript, i , then denotes the cross-section number and the subscript, j , indicates the channel number. Section $i=1$ is the seaward cross section and section $i=IS$ is the inlet cross section at the entrance to the bay. Channel $j=1$ and channel $j=IC$ are the two channels adjacent to land. A typical cell, denoted as cell (i,j) , consists of that part of channel j situated between cross-sections i and $i+1$. The water velocity in cell (i,j) , u_{ij} , is assumed to be at the centroid of cell (i,j) and to act parallel to the axis of channel j .

A weighting function, W_{ij} , is then used to determine what fraction of the total inlet flow, Q , passes through a grid cell (i,j) at an instant in time.

$$Q_{ij} = W_{ij} Q \quad (8)$$

where Q_{ij} is the discharge in cell (i,j) . Various weighting functions are discussed later in this section.

The mean water velocity in cell (i,j) , u_{ij} , is taken equal to the discharge in the cell divided by the mean cross-sectional area of the cell perpendicular to the flow, A_{ij} ; i.e.,

$$u_{ij} = W_{ij} Q / A_{ij} \quad (9)$$

Substituting Equations 7 and 9 into the fourth term of Equation 3 and integrating over x and y give the total bottom friction, F ,

$$F = \sum_{i=1}^{IS-1} \frac{1}{\sum_{j=1}^{IC} (A_{ij})} \sum_{j=1}^{IC} \frac{g(n_{ij})^2 |W_{ij} Q| W_{ij} Q B_{ij} L_{ij}}{k (D_{ij})^{1/3} A_{ij}^2} \quad (10)$$

where n_{ij} is the Manning's coefficient of friction for each grid cell, D_{ij} is the mean instantaneous water depth in a cell, and B_{ij} and L_{ij} are the mean cell width and length, respectively. All of the cell parameters are taken to apply to the centroid of the cell.

Let I_g be a geometry integral defined for convenience as,

$$I_g = \frac{1}{\int_{x_s}^{x_b} \frac{dx}{A_c}} = \frac{1}{\sum_{i=1}^{IS-1} \left[\frac{IC}{\sum_{j=1}^{IS-1} L_{ij} / IC} \right]} \quad (11)$$

which has units of length.

Substituting Equations 5, 6, and 10 into Equation 3, multiplying by I_g , and setting dQ/dt equal to the other terms gives,

$$\frac{dQ}{dt} = \frac{-I_g}{2} \left(\frac{1}{A_b^2} - \frac{1}{A_s^2} \right) Q^2 - g I_g (h_b - h_s) - I_g F \quad (12)$$

where F is defined by Equation 10.

If M inlets connect the bay to the sea, there will be one equation (Equation 12) for each inlet. Let Q_m be the discharge of the m th inlet, then the total discharge for all inlets, Q_T , is the sum of inlet discharges,

$$Q_T = \sum_{m=1}^M Q_m. \quad (13)$$

The rate of change of water level in the bay, dh_b/dt , is related to inlet discharge, Q_T , plus discharge into the bay from other sources, Q_{inflow} , by the continuity equation,

$$\frac{dh_b}{dt} = \frac{Q_T}{A_{bay}} + \frac{Q_{inflow}}{A_{bay}} \quad (14)$$

where A_{bay} is the instantaneous surface area of the bay.

There are several methods available for solving the simultaneous differential equations (Eq. 12 for M inlets, and Eq. 14 for a total of $M+1$ equations). The method selected for this model is a fourth-order Runge-Kutta-Gill technique. Advantages of this method are that it is self-starting, extremely stable, may use a longtime step, has wide application, and converges quickly. The main disadvantage of this technique is that it may cost approximately twice as much as other methods because of the technique that the Runge-

Kutta-Gill method uses to calculate each time step, to check error bounds, and to establish the next time step.

The weighting function, W_{ij} (the fraction of the total flow that passes through a grid cell at a time step), provides a systematic method of distributing flow throughout an inlet for use in evaluating the bottom stress. There are three weighting functions that can be used.

First, a weighting function to distribute flow between channels at each cross section so that total friction in the section is minimized. This function may allow some water to move perpendicular to the main axis of the flow net at each cross section, but the flow should be small for a well-drawn net.

Second, a weighting function is developed by assuming that all flow is parallel to the streamlines of the flow net and distributes the discharge in each channel of the inlet to minimize overall friction. This method is consistent with the equations of motion used in the model derivation and assumes that the grid system permits an accurate representation of the inlet streamline patterns.

In practice both of the minimum friction weighting functions produce similar results for many inlets. Comparisons with prototype measurements show that either minimum friction weighting function adequately predicts the flow distribution across inlet cross sections tested.

Jet formation in flow exiting the inlet throat, not accounted for in these weighting functions, may also cause differences between observed and predicted flow patterns. However, an empirical coefficient may be used to account for these losses.

The third weighting function is the same as that used in lumped parameter models. It assumes that discharge is the same in all grid cells throughout the inlet at any instant in time. This means that the flow in each grid (channel) is equal to the total flow for the inlet divided by the number of channels, IC .

Salinity Model

A review of the salinity data collected during the intensive tidal cycle surveys and data collected by NPS (described in Section 3) to monitor the change in salinity in the pond with time after the closing of the tidal gates shows that the salinity in the pond is almost uniform over the entire pond with only a very limited vertical stratification. The one exception is the northwestern end of the system reflecting a local source of freshwater to the lake (J. Masterson, USGS, personal communication; Masterson, 2004). Since tidal currents in the lake are almost nonexistent the well-mixed conditions observed are likely a result of wind induced mixing. The shallow depth of the lake (about 0.8 to 1.3 m) and the predominantly westerly winds, along the central axis of the lake, further support this assumption.

A simplified model, developed by Barber and Wearing (2004, 2004) and Barber (2003) based on tidal prism theory, was selected to model the salinity field in the lake. The model requires the following assumptions:

- Complete internal mixing within the system after each tidal cycle.
- No vertical stratification of the water column due to either thermal or salinity effects.
- Freshwater input is constant over the simulation period.
- A fixed amount of the water that exits the embayment on ebb tide is returned on the following flood tide.

The model is based on conservation of salt and water mass (continuity) equations.

The basic equations are:

1. Salt conservation

$$d/dt (SV) = S_{\text{flood}}Q_{\text{flood}} - S_{\text{ebb}}Q_{\text{ebb}} \quad (15)$$

where V is the volume of water in the basin (m^3), Q_{flood} and Q_{ebb} are the flows of water entering (flood) or exiting (ebb) the basin (m^3/s), and S_{flood} and S_{ebb} (ppt) are the corresponding salt concentrations associated with those flows.

2. Water mass conservation

$$dV/dt = Q_{\text{flood}} - Q_{\text{ebb}} + Q_f \quad (16)$$

where Q_f , the flux of fresh water entering the basin

Substituting Equation 16 into 15 results in one equation to predict the time rate of change of salinity in the basin.

We have elected to represent Moon Pond and Pilgrim Lake as two separate basins. Moon Pond is connected to the ocean by the Rte 6 culvert system and to Pilgrim Lake by the box culvert under High Head Road. Pilgrim Lake is connected to Moon Pond via the High Head Road culvert. Separate freshwater inflows for Moon Pond and Pilgrim Lake are also included. Presented below are the equations for the time rate of change of salinity in Moon Pond and Pilgrim Lake for flood and ebb tide. The subscripts m, l, and o refer to Moon Pond, Pilgrim Lake, and the ocean, respectively. As an example, S_o is the concentration of salinity in the ocean, while Q_o is the flux of water from the ocean to Moon Pond

- In Moon Pond,

$$dS_m/dt = (1/V_m) [(S_oQ_o - S_mQ_m) - (Q_o - Q_m + Q_{fm}) S_m], \quad \text{at flood tide (17a)}$$

$$dS_m/dt = (1/V_m)[(S_m Q_o - S_l Q_m) - (Q_o - Q_m + Q_{fm}) S_m], \quad \text{at ebb tide} \quad (17b)$$

- In Pilgrim Lake,

$$dS_l/dt = (1/V_l)[(S_m Q_m) - (Q_m + Q_{fl}) S_l], \quad \text{at flood tide} \quad (18a)$$

$$dS_l/dt = (1/V_l)[(S_l Q_m) - (Q_m + Q_{fl}) S_l], \quad \text{at ebb tide} \quad (18b)$$

The boundary conditions for S_o , at the end of ebb and flood tides, are

$$S_o(t+1) = b S_m(t) + (1-b) S_{o0} \quad \text{at end ebb tide} \quad (19a)$$

$$dS_o/dt = 0 \quad \text{at flood tide} \quad (19b)$$

where, S_o , is the ocean salinity, assumed constant, and, b is a return parameter expressing the proportion of water exiting the system that is returned on the next tidal cycle.

The initial conditions for salinity, S_{o0} in the ocean, S_{m0} in Moon Pond and S_{l0} in Pilgrim Lake, are specified by the user.

In practice Equations 17 and 18 are integrated numerically to predict the time varying evolution of the salinity in Moon Pond and Pilgrim Lake. The hydrodynamic model provides the values for the flow rates.

3. Data collection programs in support of model application

The data collection program was divided into four separate activities: (1) time series data on the sea surface elevation at stations at MacMillian Wharf (hereafter referred to as Provincetown Dock), Moon Pond, and Pilgrim Lake; (2) three intensive tidal cycle surveys of the system during the summer of 2004 (May 19-20, July 15, and August 5), (3) time series salinity and temperature data collected at selected stations in the lake following opening of the tidal gates in December 2001, and (4) data on the topography of the study area and the geometry and vertical elevations of the culvert systems from the ocean to Moon Pond and from Moon Pond to Pilgrim Lake under High Head Road.

National Park Service (NPS) personnel, using equipment jointly provided by the NPS and the University of Rhode Island (URI), collected time series data (1). The three intensive tidal cycle surveys (2) were joint efforts of NPS and URI personnel. The post tidal gate opening salinity/temperature surveys (3) were conducted by NPS. Slade Associates, Inc performed the topographic and culvert systems survey (4), under contract to the URI. Each program is defined in detail below.

Time series data collected at Provincetown Dock, Moon Pond and Pilgrim Lake

Time series data were collected for surface elevation by the National Park Service using YSI/Endeco 6600 water quality sensing systems located at the dock in Provincetown, in Moon Pond, and in Pilgrim Lake. Figure 7 shows the location of the observation stations in the pond and lake. Data were recorded and stored in memory every 15 minutes over the typical 30 day deployment periods. In practice, for each deployment cycle, the instruments were retrieved, data downloaded and the instrument redeployed within the next day or two. The data sets therefore have a characteristic one to two day gap during consecutive deployments. Data were collected from February to October 2004 (Appendix A). The locations of the sensing systems were established, relative to a NAVD88 reference, by NPS using standard surveying techniques. NPS personnel subsequently corrected surface elevation records to an NAVD88 reference and provided them to us.

Overview of the Intensive Tidal Cycle Surveys for the Pilgrim Lake System

The overall goal of the three intensive tidal cycle experiments, performed on May 19-20, 2004; July 15, 2004; and August 5, 2004, (Appendix B1, B2, and B3) was to collect data to characterize the currents/flows, sea surface elevations, salinity, and temperature field in the Pilgrim Lake system and adjacent Cape Cod Bay over a lunar, semi-diurnal (M_2) tidal cycle (period-12.42 hrs). The three periods were selected to cover a range of tidal forcing conditions and within the constraints of the availability of field equipment. There was no rainfall during the first two experiments and a small amount (0.86 cm) during the last. Data were collected over a period of 13 hours, at 15 minute intervals, typically starting at 6:00 and proceeding to 19:00 local time. The data will be used to provide insight into the flow and salt transport dynamics and to calibrate and validate the hydrodynamic and salinity models of the system described in Section 2.

A brief summary of the experimental protocol is given below. The protocol was the same for all surveys, except as noted. The presentation is divided by type or location of the measurement.

Rte 6 Culvert- Moon Pond

Measurements were made of the water level, current speed and direction, and salinity and temperature at the outlet of the 4 ft (1.22 m diameter) concrete culvert, which passed under Rte 6, as it entered Moon Pond. Figure 2 shows a photograph of the culvert (in center of concrete bulkhead) as it discharges into Moon Pond. Water levels were measured using a wooden meter stick referenced to the top inside diameter (invert) of the culvert. The elevation was bench marked to NAVD88 using data collected by Slade Associates, Inc. During the experiments the water level in Moon Pond was higher than the culvert invert during much of the tidal cycle. For the first two experiments water level measurements were not made when the culvert was full and hence the water level higher than the culvert invert. During the final August 5 experiment, data were collected throughout the entire tidal cycle and water levels above the culvert invert reported as negative values.

Current speeds were measured by a single axis, electromagnetic (Marsh McBirney) current meter. Current direction was determined by observing whether the flow was entering (flooding) or exiting (ebbing) Moon Pond. A mount system was constructed to allow the current meter to be placed approximately 1 m inside the end of the culvert and suspended 40 cm from the top of the culvert. This was done to eliminate the possibility that entry or exit effects would impact the observed current speeds and to place the culvert sufficiently far from the top of the culvert so that it was in the water independent of tidal stage. The mount consisted of a 4 ft (1.33 m) long, 5 inch deep (12.7 cm) I beam that was held at the top (inside) of the culvert by "U" shaped mounting brackets, located on the culvert bulkhead. The lower flange of the I beam served as a guide rail which allowed the current meter mounting system to be positioned up to 1 m from the end of the culvert. The current meter was mounted on a stang with an orienting guide vane, allowing it to rotate as the current changed direction from flood to ebb. The stang was in turn mounted to a guide system that allowed the meter to slide along the lower flange of the I beam. Figure 3 shows a photograph of the current meter, guide vane and associated mounting system. Care was taken to ensure that the cable to the current meter sensing head allowed the current meter sensing head to rotate freely throughout the experiment. Installation of this mounting system was complicated by the presence of a reinforced steel bar grate placed on the end of the culvert. A portion of the grate was removed to allow installation of the current meter mounting system.

Salinity and temperature measurements were made using a YSI/Endeco hand held conductivity and temperature sensor. The measurements were made approximately 30 cm below the water surface, adjacent to the mouth of the culvert.

High Head Road Culvert

Measurements were made of the water level, current speed and direction, and salinity and temperature at the Pilgrim Lake end of the box culvert under High Read Road (Figure 4). The box culvert converts into a flume with a weir gate (Figure 5 and 6) at this location. The gate is located approximately 5 m from the end of the box culvert. The culvert, oriented approximately 130 - 310 degrees N, has a width of 3.2 m and a depth of 1.2 m from the culvert invert to the bottom. Depth measurements were made, referenced to the culvert invert at the location of the Pilgrim Lake end of the culvert and revealed that sedimentation had occurred primarily on the northeastern side of the culvert. The depth of the culvert was reduced to 0.8 m on the northeastern side increasing linearly to about 1.1 m on the southwestern side. Detailed depth measurements across the culvert are provided in Appendix B2. It was observed in the field that the effective flow width of the culvert was approximately 1 m less than the actual culvert width of 3.2 m, or 2.2 m (0.5 m on either side). This reduction was due to the presence of the mounting guides for the weir boards, which are located on the Pilgrim Lake end of the culvert -flume system (Figure 6). Estimates of the volumetric flow will assume this reduced width.

Measurements of the current speeds were made using a Marsh McBirney electromagnetic current mounted to an orienting guide vane. The current meter was deployed from a weighted (5 kg) line tied to the bridge rail on the Pilgrim Lake end of the culvert (Figure 5). The meter was located mid-way (1.6 m from either side) across the culvert width, 40 cm above the seabed. Data were collected over a period of 13 hours, at 15-minute intervals, typically starting at 6:00 and proceeding to 19:00 local time. Measurement times coincided with those at the Rte 6 culvert, summarized above. For the July 15, 2004 and August 5, 2004 surveys currents were also measured with a Swiffer propeller current and an Aanderaa Instruments acoustic current meter (Model DCS 3900). These meters were positioned at the same depth as the Marsh McBirney electromagnetic current meter, but 15 cm on either side of it. All three meters were hence within a span of 30 cm horizontally in the middle of the culvert and at the same depth relative to the bottom.

Water level measurements were made every 15 minutes using a wooden meter stick for the duration of the experiment, referenced to the culvert invert on the Moon Pond and Pilgrim Lake ends of the box culvert. The observations were converted to the NAVD88 vertical reference.

Salinity and temperature measurements were made, every 15 minutes for the duration of the experiment, using a YSI/Endeco hand-held conductivity (salinity) and temperature sensor. The measurements were made approximately 30 cm below the water surface, near the center of the culvert.

Pilgrim Lake hydrographic surveys

National Park Service personnel made measurements of salinity and temperature versus depth (in 0.5 m vertical increments) from the surface to just above the seabed at 10 stations (S1 to S10) located along the central axis of Pilgrim Lake (Figure 7) during the three intensive tidal cycle surveys. At stations 2, 3, 4, and 5 measurements were made at stations North and South of the center station to provide insight into lateral variations of

salinity and temperature in the lake. The measurements were made from a small motorboat with a hand held YSI/Endeco conductivity and temperature sensor. Multiple trials were performed in a round robin fashion so that each site was visited 7 to 10 times over the tidal cycle. Measurements of dissolved oxygen were made near the surface during the July 15 and the early portion of the August 5 surveys. Measurements were discontinued mid way through the August 5 survey due to instrument failure.

Hydrographic surveys following tidal gate opening

On December 6, 2001 the Town of Truro opened the tidal gates at NPS's request to allow seawater to enter Moon Pond and Pilgrim Lake. At that time NPS instituted a program to measure the salinity and temperature at the surface and bottom for six stations located in: Moon Pond (1), entrance to Salt Meadow (1) and Pilgrim Lake (4, south shore of lake from the eastern to western ends). Measurements were made about every week to monitor the impact of opening the gates on the lake and pond salinity and temperature (Appendix C). Measurements were made independent of the stage of the tide until November 3, 2003. The tidal gates were closed and reopened several times during this period (closed on February 27, 2002; opened on June 24, 2002; closed on July 4, 2002), until they were re-opened on November 4, 2002. They have remained open since that time and hence were open during the intensive tidal cycle surveys.

Topographic and infrastructure survey

In order to apply the hydrodynamic and salinity models to the study area, a complete description of the hydraulic structures (their horizontal and vertical locations) in the system and the surface area versus elevation relationships for Pilgrim Lake (and the two major basins (lower and upper) that make up Salt Meadow) and Moon Pond is required. While engineering blueprints (1956-57) for the culvert systems connecting the ocean and Moon Pond and Moon Pond and Pilgrim Lake were available, it was deemed appropriate to verify the accuracy of those drawings, particularly the vertical elevations of the culvert system. The model requires a detailed description of the storage capacity of Moon Pond and Pilgrim Lake. This is normally obtained from an analysis of topographic data. The areas of primary interest for the topography includes Pilgrim Lake and Moon Pond and Salt Meadow, located on the southern end of Pilgrim Lake (Figure 1). Topographic data in the current and potential (post restoration) inter-tidal area, and hence in the elevation range from - 0.5 to + 2.0 m, relative to NAVD88 is of primary interest.

The National Park Service collected elevation data using a real time, kinematic GPS system in 2004 for selected areas of the marsh. In addition, as part of this study, Slade Associates, Inc. was contracted to obtain:

1. Horizontal locations and vertical elevations of the key hydraulic control structures
2. Topography along the NPS proposed transect lines provided in Figure 8.

A more detailed description of the data collected is summarized below and provided in the form of blueprints in Appendix D.

Data on structures and roads/berms

Culvert- tide gate system connecting Cape Cod Bay to Moon Pond

- Elevations (invert) and geometric characterization of the inlet system from Cape Cod Bay to Moon Pond. This includes the entrance and exit elevations (invert) and geometry of the following major sections: (1) box /elliptical culvert from Cape Cod Bay, under Rte 6A, to the tidal gate chamber (located immediately north of Rt 6A), (2) tide gate chamber/manhole, (3) culvert from tide gate chamber to transition chamber/manhole (located immediately south of Rte 6), and (4) culvert from transition chamber/manhole to Moon Pond, under Rte 6. There is recent evidence that a partial collapse has occurred in the culvert between the tide gate and transition chambers.

Culvert-weir system connecting Moon Pond to Pilgrim Lake

- Elevations (invert) of the entrance (seaward) and exit (landward) of the culvert and culvert geometry under High Head Road. Geometry and elevations of the weir, located on the northern side of High Head Road.
- Elevations of High Head Road; approximately 10 measurements taken along the centerline of the Road, in the region where the road divides Moon Pond from adjacent Pilgrim Lake.

Culverts in earthen berms in Salt Meadow (upper and lower)

- Elevations (invert) of the entrance (seaward) and exit (landward) of culvert and culvert geometry and dimensions under the upper (landward) earthen berm.
- Elevations (invert) of the entrance (seaward) and exit (landward) of culvert and culvert geometry and dimensions under the lower earthen (adjacent to Pilgrim Lake) berm
- Approximately 10 measurements (each) were made along the central axis of the upper and lower earthen berms. The measurements were approximately equally spaced along each berm.

Topographic data

Topographic data were collected along the transect lines noted in Figure 8. Measurements were made approximately every 5 m along each transect line. Exact placement of transects varied slightly, but captured the top and bottom of each bank at the edge of the channel and shoreline edges.

Measurements of horizontal location were made within 0.5 m and vertical measurements within 10 cm. Horizontal position information was referenced to Massachusetts State

Plane and UTM coordinates. The vertical data were referenced to NAVD 88. Four benchmarks were placed in the study area for future reference: one near the Truro-Provincetown Town Line, one at the northerly parking lot at Head-of-the-Meadow beach, one near the Pilgrim Spring, and one near the location where High Head Road divides to go up the hill and to the parking lot. The exact locations are provided in Appendix E.

NPS (Mark Adams) assembled all topographic data (USGS data, Slade Associates Inc. August 2004 transect survey, total station GPS data collected in 2004) and through the use of ArcGIS developed a detailed topographic map of the study area, which is shown in Figure 9. NPS then prepared area versus elevation curves for Salt Meadow, Moon Pond, and Pilgrim Lake (Appendix F). Figure 10 shows the area versus elevation curves for Pilgrim Lake, Moon Pond, Salt Meadow, and Pilgrim Lake and Salt Meadow combined. The plot shows that there is a rapid increase in surface area with elevations, between elevations of 0 to 0.7 m. The rate of increase in area however declines rapidly at higher elevations. At low elevations (below 0.2 m NAVD88) Pilgrim Lake comprises 85.5 % of the area, Moon Pond about 2 % and Salt Meadow the remaining 12.5 %. At higher elevations (above 1m), Pilgrim Lake makes up 72 % of the area, Moon Pond 4 % and Salt Meadow 24 %. Salt Meadow will serve as the principal storage basin if exchanges between Pilgrim Lake and the ocean are increased by restoration.

Freshwater input to system

The input of freshwater to Pilgrim Lake and Moon Pond, from ground water and runoff, is responsible for maintaining the salinity of the two bodies of water below that in the adjacent ocean. R. Masterson from the US Geological Survey (USGS) (personal communication) provided estimates of the mean freshwater input to the Pilgrim Lake and adjacent Moon Pond and Salt Meadow. These estimates are based on a calibrated ground and surface water discharge model of the system (Masterson, 2004) and represent mean annual inputs. The annual average freshwater input rates are summarized in Table 1.

Table 1 Annual average freshwater input rates to the Pilgrim Lake- Moon Pond – Salt Meadow system (provided by J. Masterson, US Geological Survey)

Direct ground water discharge to pond:	0.0266 m ³ /sec (0.94 ft ³ /sec) (43.1%*)
Discharge to marshes adjacent to pond:	0.0351 m ³ /sec (1.24 ft ³ /sec) (56.9%)
Total discharge to pond:	0.0617 m ³ /sec (2.18 ft ³ /sec) (100%)
Direct discharge to northwest corner of pond:	0.0150 m ³ /sec (0.53 ft ³ /sec)
Discharge to marsh in northwest corner of pond:	0.00198 m ³ /sec (0.07 ft ³ /sec)
Total discharge to northwest corner of pond:	0.01698 m ³ /sec (0.6 ft ³ /sec)
(Note this is part of the total discharge to the pond given above)	
Total discharge to Salt Meadow:	0.01132 m ³ /sec (0.4 ft ³ /sec)

Total discharge to entire system: 0.07302 m³/sec (2.576 ft³/sec)
(Pilgrim Lake and Salt Meadow)

* Percent of total discharged.

4. Analysis of data from collection programs

Presented below is a summary of the analyses performed of the field data collected during the experimental program. The analyses focused on the long-term water level data collected in Pilgrim Lake, Moon Pond, and Provincetown and the intensive tidal cycle surveys.

Analysis of water level time series data

An analysis was performed of the water level time series records collected in Provincetown, Moon Meadow, and Pilgrim Lake to determine the amplitude and phases for the largest tidal constituents and the low frequency behavior of the water level. Figures 11, 12, and 13 show the times series of water level for the Provincetown, Moon Meadow, and Pilgrim Lake observation stations, respectively. The Provincetown record is from March 1, 2004 to October 7, 2004, with data missing between June 2 and July 15, 2004. The Moon Meadow record is from February 27, 2004 to October 7, 2004. There were two large data gaps between April 2 and 25, 2004 and July 5 and July 14, 2004. Data for the period from July 15 to August 15, 2004 had one digit left off the digital record and hence displays a step function like behavior during this period. The Pilgrim Lake record extended from May 15, 2004 to October 7, 2004. The record is continuous over the period, except for September 11 to 16, 2004.

In analyzing the data provided by NPS several problems were noted. These are summarized below along with efforts taken to adjust the records to account for the problems.

- *Provincetown: Issue:* The mean value for the second half of the record (0.44 m) was substantially higher than the first half (0.21 m). The mean value for the first half of the record was consistently higher (25 cm) than similar averages for the NOAA Boston Harbor water elevation record for the same period. *Correction:* mean value of the second half of record was adjusted (subtract 0.23 m) to be the same as the first half of the record and then the entire record was shifted down by 25 cm to be consistent with the low frequency variations at Boston Harbor. (Note if the water level data remain at the current mean value, after the correction for the differential for the second half of the record, it was impossible to calibrate the hydrodynamic model).
- *Moon Pond: Issue:* The water level record was about 25 cm higher than the water levels measured during the intensive tidal cycle surveys and similarly higher than the mean values in Pilgrim Lake. *Correction:* subtract 0.25 m from the record.

- *Pilgrim Lake: Issue:* The water level record displayed discrete jumps between one deployment and the next. *Correction:* set water levels at the beginning of the next deployment to be the same as the values at the end of the prior deployment as long as gap between deployments was less than a few days.

Figures 11, 12, and 13 show both the original data (lower panel), as well as the data after the above corrections were made (upper panel). The above adjustments make the data sets internally consistent and also ensure consistency with water level records in adjacent water bodies and with low frequency water level data from the NOAA station at Boston Harbor. Appendix A contains both the *as received* and *corrected* data sets.

Harmonic analysis

A tidal harmonic analyses of the three time series records were performed using Foreman's (1996) method. The results are reported in Table 2 for the twelve largest tidal constituents. The subscript of the constituent denotes the approximate number of cycles per day. The amplitudes are given in meters and the phases in degrees relative to Greenwich Mean Time (GMT) and Local Standard Time (LST). Tidal constituent speeds (degrees/hr), amplitudes and phases for Boston Harbor, derived from NOAA/NOS web site (<http://tidesandcurrents.noaa.gov>), are provided for reference. This is the closest permanent NOAA station to Provincetown. The tidal constituents with the largest amplitudes are, in order, M_2 , N_2 , S_2 , K_1 , and O_1 at Provincetown. This is the same as the ranking at Boston Harbor. The amplitudes at both stations are very close to one another. As an example, for the dominant M_2 tides the amplitude at Boston Harbor is 1.398 m and 1.34 m at Provincetown (96% Boston Harbor). The amplitudes for the other principal tidal constituents are similarly very close. The tides in Provincetown for the M_2 component lag those in Boston Harbor by 6.55 degrees or 13.56 minutes. The standard offset for time of high tide in Provincetown, referenced to Boston Harbor, is 16 minutes (www.maineharbors.com).

Table 2 Tidal constituent amplitudes and phases for Boston Harbor, Provincetown, Moon Meadow and Pilgrim Lake

Harmonic Component	Component Speed (degrees/hr)	Component period (hrs)	Boston Harbor *			Provincetown			Moon Meadow			Pilgrim Lake		
			Amplitude (m)	Phase (Degrees GMT)	Phase (Degrees LST)	Amplitude (m)	Phase (Degrees GMT)	Phase (Degrees LST)	Amplitude (m)	Phase (Degrees GMT)	Phase (Degrees LST)	Amplitude (m)	Phase (Degrees GMT)	Phase (Degrees LST)
Q1	13.4	26.8685	0.021	171.1	104.1	0.0197	179.8	112.82	0.003	243.6	176.61	5E-04	211.6	144.63
O1	13.94	25.8194	0.119	186.7	116.9	0.1134	192.9	123.19	0.011	217.8	148.07	0.001	15.97	306.25
P1	14.96	24.0659	0.047	202.1	127.3	0.0489	209.7	134.86	0.003	173.1	98.343	0.003	106.8	32.025
S1	15	24	0.004	122.8	47.8	0.0065	255.6	180.59	0.008	195.8	120.85	0.01	203.7	128.74
K1	15.04	23.9346	0.143	205.2	129.9	0.1472	207.9	132.72	0.012	230.8	155.62	0.001	146.8	71.546
N2	28.44	12.6584	0.309	78.9	296.7	0.2843	91.46	309.26	0.014	110.5	328.33	0.002	228.2	86.033
M2	28.98	12.4206	1.398	109.4	324.4	1.3423	116	331.03	0.153	126.7	341.74	0.008	240.4	95.505
L2	29.53	12.1917	0.055	156.2	8.5	0.0402	129	341.35	0.018	158.8	11.132	5E-04	245.2	97.571

T2	29.96	12.0165	0.019	123.9	334.1	0.0366	48.72	258.93	0.004	116.2	326.38	0.001	48.28	258.49
S2	30	12	0.213	146.2	356.2	0.2177	145.8	355.76	0.023	127.6	337.59	0.005	84.87	294.87
M4	57.97	6.2103	0.023	25.9	96	0.0204	11.96	82.122	0.024	232.5	302.62	7E-04	22.42	92.574
M6	86.95	4.1402	0.034	282.1	207.3	0.0379	302.5	227.72	0.015	179.2	104.49	3E-04	319.4	244.61

For the dominant M_2 tides, the amplitude decreases from 1.34 m at Provincetown to 0.153 m in Moon Pond (11% of the Provincetown amplitude). The M_2 phase in Moon Pond (126.7 degrees GMT) lags that at Provincetown (115.95 degrees GMT) by 10.75 degrees or 0.370 hrs (22.2 min). The other major tidal constituents (N_2 , S_2 , K_1 , and O_1) are seen to show amplitude reductions, on the order of a factor of 10, between Provincetown and Moon Pond. The tidal harmonic analysis of the water level time series in Pilgrim Lake indicates the absence of any tidal signal in the record. This is confirmed by looking at the time series record in Figure 13.

The lack of any tidal signal in Pilgrim Lake indicates that flux of water into the lake from the ocean via Moon Pond has no measurable impact on the lake's water level. This finding is very important in that it indicates it will be impossible to calibrate the inlet basin model for the system, since there is no measurable response to tidal forcing.

Plots of the sea surface elevation power spectral density versus frequency for Provincetown and Moon Pond are provided in Figures 14 and 15, respectively. The frequencies of the principal tidal constituents are noted on each figure. The figures clearly show the concentration of energy at the principal tidal forcing periods. These spectral energy plots are consistent with the harmonic analysis. The largest amount of energy is found for semi-diurnal periods, followed by the diurnal tides, and finally the tidal harmonics. No plot is provided for Pilgrim Lake since the energy is primarily non-tidal.

The water level data for each of the three stations were low pass filtered using a filter with a three day cut off to investigate the low frequency response of the system. The results are presented in Figure 16 for the original (lower panel) and corrected (upper panel) data sets, respectively. The corrected data sets show that the low frequency variations in water levels in Pilgrim Lake and Moon Pond have similar values and are higher than the values at Provincetown by about 20 cm. The Moon Pond and Pilgrim Lake records show substantial (about 10 cm) variability at time scales of numbers of days. There is no discernable relationship to local rainfall. These variations in water level may be due to local wind forcing.

Intensive tidal cycle measurements

Three experiments were performed on May 20, July 15, and August 5, 2004. Water elevation and velocity were measured every 15 minutes at Route 6 and High Head Road culverts. At High Head Road, measurements were performed on both sides of the culvert. Water elevation was measured from the top of the culverts and corrected to an NAVD88 reference using Slade's survey of the culvert inverts (Appendix D).

Figures 17 through 19 show the observed water levels versus time for the three intensive tidal cycle surveys over one complete tidal cycle. Water levels at the Rte 6 culvert and Moon Pond and Pilgrim Lake ends of High Head Road are shown. Water level data were not recorded for the May 20 and July 15, 2004 experiments at Rte 6 if the level was higher than the top culvert invert (culvert was completely full) and hence the water level is flat in both figures during this time. Water level data for Provincetown were not available for the May 20 and August 5, 2004 experiment but was available for the July 15, 2004 experiment.

Table 3: Summary of water level data for three intensive tidal cycle experiments (vertical reference: NAVD88) at Rte 6 culvert, High Head Road Moon Pond end (HH Moon) and High Head Pilgrim Lake end (HH Pilgrim).

Experiment #	Site	Mean (m)	Minimum (m)	Maximum (m)	Range (m)
May 20	Rte 6	-----	0.02	-----	-----
	HH Moon	0.22	0.14	0.35	0.21
	HH Pilgrim	0.22	0.15	0.34	0.19
July 15	Rte 6	-----	0.03	-----	-----
	HH Moon	0.28	0.20	0.40	0.20
	HH Pilgrim	0.28	0.19	0.39	0.20
Aug 5	Rte 6	0.26	0.07	0.45	0.38
	HH Moon	0.34	0.26	0.45	0.19
	HH Pilgrim	0.34	0.25	0.48	0.23

Table 3 presents a summary of the mean, minimum, maximum, and water level range for each of the three experiments. Data for the mean, maximum and range elevations are not available for the Rte 6 culvert for the first two experiments since water levels above the top of the culvert were not collected. Elevations are referenced to NAVD88.

The time series data show that the water levels at Rte 6 and High Head Road track one another closely for the high tide portion of the cycle but the water level in Moon Pond drops well below those at High Head Road at low tide. This is most clearly seen for the August 5, 2004 experiment but is apparent for the other two experiments as well. The tidal ranges for all experiments remain remarkably similar with values of about 20 cm at High Head Road (both ends of the culvert). The tidal range at the Rte 6 gauge in Moon Pond is almost twice this value.

Figures 20 to 22 show the water level and currents measured at Rte 6 and High Head (Moon Pond end) culverts for each of three experiments. The velocity statistics are provided in Table 4. Restricting our attention to the Rte 6 culvert we note that the current speeds are stronger at flood tide, especially at Rte 6, where they reach maximum values vary between 2.15 and 1.56 m/s versus 1.27 to 1.11 m/s, at ebb tide. The difference is particularly large (70 %) for the August 5, 2004 experiment. It is also noted that the

flood tide is of shorter duration (4.75 to 5.7 hrs) than the ebb (6.75 to 7.7 hrs)(Table 5). The flood tide currents display a sine like shape, whereas ebb tides are almost constant throughout the ebb tide. Tidal currents at High Head Road show a similar shape to those at Rte 6 but are about 2 to 3 times lower, decreasing to 0.71 to 0.59 m/s at flood tide and to 0.66 to 0.49 m/s at ebb tide.

Table 4 Mean and maximum ebb and flood velocities for each of the intensive tidal cycle surveys.

Experiment	Site	Mean (m/sec)	Maximum Ebb (m/sec)	Maximum Flood (m/sec)
May 20, 2004	Rte 6	1.04	-1.33	1.56
	HH Road	0.42	-0.49	0.59
July 15, 2004	Rte 6	1.03	-1.11	1.71
	HH Road	0.47	-0.58	0.59
August 5, 2005	Rte 6	1.25	-1.27	2.15
	HH Road	0.55	-0.66	0.71

Table 5 Summary of durations of flood and ebb tides, ratios of duration, and tidal range.

Experiment Date	Durations		Duration Ratio Ebb/flood	Tidal Range (m)
	Flood tide (hrs)	Ebb tide (hrs)		
20-May-04	4.75	7.67	1.61	2.98
15-Jul-04	5	7.42	1.43	2.33
5-Aug-04	5.67	6.75	1.2	3.11

Flows, Q (m^3/s), through the culverts were calculated at each time step as, $Q = A * U$, with A the cross-sectional area (m^2) and U the velocity (m/s). Velocities were assumed positive on flood flows and negative on ebb flows. The dimensions and geometry of the Rte 6 and High Head Road culverts are provided in Table 6. The Rte 6 culvert was free of any sediment and hence the full cross sectional area for a given water level was used. For the High Head Road culvert field observations showed that no flow occurred between 0 and 0.50 m as well as between 2.7 and 3.2 m of the side walls. Measurements of the depth to the culvert's opening showed an average height of 0.88 m. This compares to original box culvert height of 1.2 m. The difference is a result of sediment accretion on the culvert floor. The reported invert of the theoretical 1.2 m height culvert was assumed

to be shifted 32 cm upward, due to accretion, bringing the invert on the Moon Pond side of the box culvert to -0.39 m instead of -0.71 m as defined in Slade's measurements. Field data showed that the box culvert is tilted downward toward the lake, by 19 cm. The invert, as defined in Slade blueprint (-0.81 m), is adjusted accordingly. Table 6 presents a summary of the impacts of these various adjustments in terms of the box culverts "effective" width, depth and location of the invert.

Table 6 Rte 6 and High Head Road culvert characteristics.

	Shape	Diameter (m)	Width (m)	Height (m)	Effective Width (m)	Effective Height (m)	Invert (m/ navd88)	Effective invert (m/navd 88)
Culvert Rte 6	circular	1.2					(-1.04) -0.96	-0.96
Culvert Moon side	box		3.2	1.2	2.2	0.88	-0.71	-0.39
Culvert Pilgrim side							(-0.81) -0.90	-0.58

Table 7 provides a summary of the basic flow statistics for each experiment. The flows are largest at Rte 6 where we observe 1.46 to 1.14 m³/s on average, versus 1.03 to 0.70 m³/s in High Head Road, a 50% difference. Again, instantaneous maximal values are higher at flood tide, 2.51 to 1.82 m³/s versus 1.48 to 1.43 m³/s e at ebb tide, at Rte 6. A similar trend is seen at High Head Road.

Table 7 Mean and maximum ebb and flood flows for each of the intensive tidal cycle surveys.

Experiment	Site	Mean (m ³ /sec)	Maximum Ebb(m ³ /sec)	Maximum Flood(m ³ /sec)
May 20, 2004	Rte 6	1.14	-1.43	1.82
	HH Road	0.70	-0.77	1.14
July 15, 2004	Rte 6	1.14	-1.18	1.99
	HH Road	0.84	-0.95	1.14
August 5, 2004	Rte 6	1.46	-1.48	2.51
	HH Road	1.03	-1.21	1.37

Table 8 shows the integrated flow (volume of water) entering (flood) and exiting (ebb) for each of three intensive tidal cycle surveys for Rte 6 and High Head Road culverts. All estimates were based on the Marsh McBirney current observations. The imbalance between the flood and ebb fluxes is also provided both in terms of volume as well as percent differential. Fluxes are about 70 % higher at Rte 6 than at High Head Road. The flow imbalances are substantial, 15 to 25 %, and can be attributed to the lack of detailed measurements of the vertical and lateral current variability at each culvert. After source of imbalance is the differential flux of water on a given ebb and flood tide caused by diurnal inequalities in tidal forcing.

Table 8 Integrated flows for flood and ebb tide, differential flow and excesses at Rte 6 and High Head Road calculated using the Marsh McBirney current meter data for each of the intensive tidal cycle surveys.

Location	Total inflow Q_{flood} (1000 m ³)	Total outflow Q_{ebb} (1000 m ³)	Flow balance $Q_{\text{flood}} - Q_{\text{ebb}}$ (1000 m ³)	Flow excess $(Q_{\text{flood}} - Q_{\text{ebb}}) / Q_{\text{flood}}$ (%)
Rte 6				
May 20, 2004	23.8	27.85	-4.05	-17.0
July 15, 2004	26.18	25.366	0.81	3.1
August 5, 2004	37.35	29.03	8.33	22.3
High Head Road				
May 20, 2004	14.05	17.76	-3.71	-26.4
July 15, 2004	15.91	21.82	-5.91	-37.1
August 5, 2004	21.5	25.16	-3.66	-17.0

Table 9 Integrated flows for flood and ebb tide, differential flow and excesses at High Head Road calculated using various current meter data sets for selected intensive tidal cycle surveys.

High Head Road	Current meter	Total Inflow Q_{flood} (1000 m ³)	Total outflow Q_{ebb} (1000 m ³)	Flow balance $Q_{\text{flood}} - Q_{\text{ebb}}$ (1000 m ³)	Flow excess $(Q_{\text{flood}} - Q_{\text{ebb}}) / Q_{\text{flood}}$ (%)
May 20, 2004	Marsh McBirney	14.05	17.76	-3.71	-26.4
May 20, 2004	Aanderaa	8.46	11.29	-2.83	-33.4
July 15, 2004	Marsh McBirney	15.91	21.82	-5.91	-37.1
July 15, 2004	Swoffer	9.93	16.09	-6.16	-62.0
August 5, 2004	Marsh McBirney	21.5	25.16	-3.66	-17.0
August 5, 2004	Swoffer	19.53	21.36	-1.83	-9.4

In addition to the Marsh McBirney, currents were measured with the Aanderaa for the May 20, 2004 and with the Swoffer propeller current meter for the July 15 and August 5, 2004 experiments. Table 9 shows the integrated fluxes computed using these other sources of current data. Both the Swoffer and Aanderaa based estimates are substantially

lower than those based on the Marsh McBirney. The Aanderaa data are potentially suspect because of the interference of the culvert structure with the acoustic based measurement system used in the meter.

Hydrographic Surveys

The hydrographic data are provided in Appendix B1 to 3 for each of the three intensive tidal cycle survey dates. The data show mean salinities of 21, 24.5 and 25 ppt for the three experimental dates. The salinities were generally lowest at the northwestern end of the lake, consistent with the assumed enhanced freshwater input to this area (Table 1). There was no evidence of any significant stratification over the main body of Pilgrim Lake, nor any strong horizontal variability.

5 Hydrodynamic and salinity model application, calibration, and sensitivity analysis

Hydrodynamic model

The hydrodynamic model given in Section 2 was applied to the Pilgrim Lake system. The system was idealized as a two basin, two inlet system: Moon Pond connected to Cape Cod Bay by Rte 6 culvert and Moon Pond connected to Pilgrim Lake by the High Head Road culvert. This strategy allowed the impacts of modifications of the either inlet on both Moon Pond and Pilgrim Lake to be assessed. The two basins were characterized by their storage capacities (areas) vs elevations (Figure 10). The geometry of the inlets were determined from Slade's survey data and information collected during the intensive tidal cycle surveys. Model simulations were performed for the intensive tidal cycle experiments with forcing based either on data collected at Provincetown (May 20, 2004 and August 5, 2004) or values collected at Boston Harbor (July 15, 2004) and phase and amplitude adjusted to represent conditions at Provincetown.

Figures 23 through 25 show observed and model predicted sea surface elevations (Moon Pond, Pilgrim Lake) versus time for each of the intensive tidal cycle surveys, respectively. The water level in Provincetown or Boston Harbor surrogate is also provided. For Moon Pond, water levels collected during the intensive tidal cycle surveys at Rte 6 culvert and the Moon Pond end of High Head Road are provided, as is the data collected from NPS Moon Pond monitoring station. Simulations were performed assuming a Manning coefficient of 0.09 in the inlets and a friction factor of 0.03 in the culverts. The Manning coefficient is higher than normally used for open natural channel flows ($n = 0.03$ to 0.07) (White, 1999) but is attributed to additional losses in the structures used to hold the weir boards downstream of High Head Road. The value of the friction factor for the culvert is consistent with Colebrook's formula assuming typical rough concrete pipes (White, 1999). These values accounted for the losses associated with the inlet-culvert system at High Head Road and the complicated flows through the culvert system connecting Moon Pond to the ocean. These values were determined by performing a sensitivity study to determine the impact of (Manning/friction factor)

frictional losses on the difference between model predicted and observed water levels in Moon Pond and Pilgrim Lake. Model predictions showed water level variations of 1 cm (range) in Pilgrim Lake. These values are below the resolution of the water level measurements in Pilgrim Lake.

Comparing model predictions with observations we see that model correctly predicts the dramatic reduction in water level between Cape Cod Bay and Moon Pond and associated phase lag. Model predicted peak values are within several centimeters of observations in Moon Pond. The model predicts a slightly earlier rise in water level in Moon Pond than observed but accurately reproduces the decrease in water level with time. The coefficient of determination (R^2) between model predicted and observed water levels were very good for each experiment (0.79, Experiment #1; 0.88, Experiment #2; and 0.88, Experiment #3). Model predictions are in good agreement with observations in Pilgrim Lake (under predict by several centimeters), both showing no water level variation over the tidal cycle. The R^2 for Pilgrim Lake hence are very low (< 0.50). These simulations show a dramatic reduction of tidal variations between Provincetown and Moon Pond and no tidal signal in Pilgrim Lake. The large differentials in water levels are a direct result of the frictional losses in the Rte 6 culvert system and the large differential in storage capacities of the Moon Pond and Pilgrim Lake basins (Figure 10). The amount of water entering/exiting Moon Pond on the flood/ebb tide is sufficient to raise/lower the water level in the pond because of its very small storage capacity. The amount of water that enters/exits Pilgrim Lake over a tidal cycle however is very small compared to the storage capacity of the basin and hence doesn't measurably affect the water level in the lake.

Salinity model

The salinity model described in Section 2 was applied to the Pilgrim Lake System. The system consisted of Moon Pond, Pilgrim Lake, Salt Meadow, and the marshes around the edge of these areas. Inputs to the model that were specified included mean annual freshwater input, mean volumes of the system, the ebb and flood tidal volumes for each tidal cycle, and the exchange coefficient representing the percent of the water volume exiting the system on the flood tide that returned on the following flood tide.

The mean annual freshwater input to the system was estimated by Masterson (2004) and is reported in Table 1. The best estimate is $0.0732 \text{ m}^3/\text{sec}$. Masterson (personal communication) suggests at $\pm 10\%$ uncertainty in this value with the majority of the uncertainty associated with the recharge rate. The volume of the system, as a function of water level, was obtained from the National Park Service's storage capacity versus elevation (Figure 10) and is based on their high-resolution topographic map. To determine the tidal volume exchanges, model predicted fluxes through the culvert were integrated numerically to determine the flood and ebb tide fluxes for each tidal cycle and used as input to the salinity model. This numerical integration scheme eliminates concerns about the inequality in the durations of high and low tide and the exact shape of the tidal volume curve, inherent in assuming a harmonic representation for the tidal volume fluxes. Data to estimate the exchange efficient, b , is not available and hence this

must be determined by using this as a model calibration parameter. The ocean salinity was set at 31 ppt, based on flood tidal salinities observed during the intensive tidal cycle surveys.

To calibrate the model it was applied to predict the temporal evolution of the salinity for the period from November 1, 2002 to March 30, 2004. At the beginning of this period the NPS opened the tidal gates and removed the weir boards from High Head Road thus allowing seawater to enter the system. NPS tracked the surface and bottom salinities, at biweekly intervals at six stations located along the central axis of Pilgrim Lake and in Salt Meadow. The mean salinity in the lake at the start of the simulation was approximately 10 ppt. This salinity was a result of prior openings of the tidal gates.

The model requires a time series of water elevations at the mouth of the system. Unfortunately such a record was not available at Provincetown for the period corresponding to the salinity record. An analysis of the Provincetown (NPS) and Boston (NOAA/NOS) water elevation time series however shows they are very similar, except for a shift in their mean value and a slight shift in time (16 minutes). A water elevation time series at Provincetown was therefore estimated during the period covering the salinity record using observed water elevation data from Boston's, by applying a simple shift to the mean value, in order to ensure consistency with the local vertical reference level NAVD88. A simulation was performed from November 1, 2002 to March 30, 2004 with a mean freshwater input of $0.0732 \text{ m}^3/\text{sec}$ (base case). Model predictions are shown in Figure 26. For comparison the observed values from the NPS survey are shown for Stations S1 (High Head Road) and eastern (S3), central (S4), and western (S5) sections of the lake. S2 was located in a drainage ditch in Salt Meadow and hence is not of interest in this model calibration exercise. The simulation assumed a return factor of 0 % ($b=0$). Model predictions are in general agreement with the observations showing rapidly increasing salinity in the lake early in the simulation, asymptotically approaching a fixed value (about 24.5 ppt) by the end of the simulation. Model predictions are consistent with the highest values of salinity reported at the end of the simulation but about 5 ppt higher than the lowest values. A sensitivity study was performed varying the freshwater input to the lake by ± 10 and 20 %. As expected the predicted salinity decreases/increases as the freshwater input rate increases/decreases. Variations are on the order of 0.5 ppt. If the freshwater is increased by 100 % then the salinity decreases by 5 ppt.

Next a series of simulations were performed where the freshwater input rate was held fixed at the mean value and the return parameter, b , varied between 0 and 1. If $b = 1$, all the water entering the system has just exited at the end of the previous tidal cycle. If $b = 0$, then none of the water exiting the system on ebb re-enters on flood and hence all the water is new oceanic water at the reference salinity. Predictions were made for $b = 0, 0.2, 0.4, 0.6$, and 0.8 (Figure 27). The case for complete return was not run since this would result in little change in the system salinity with time. The model shows that the higher the amount returned the lower the salinity in the lake. For $b = 0.8$ the salinity is about 17 ppt at the end of the simulation compared to a value of 25 ppt for $b = 0$. Model predictions with a $b = 0.4$ appear to give the best agreement with the average of all the station data at the end of the experiment. This value appears reasonable given the fact it is

likely that most of the water exiting the marsh during ebb tide is transported away from the inlet and hence can't reenter the marsh on the following flood tide.

The salinity time series shows substantial variations over time scales of weeks to months that are not reflected in the model predictions. To determine the extent to which these variations might be related to variations in freshwater input, Figure 28 shows model predicted salinity vs time for the base flow and base plus 100 % of base freshwater flow conditions. Observations at NPS monitoring stations are also shown as S1, S3, S4, and S5. The lower line gives the freshwater flow rate for Jones River, Kingston, MA. This is the closest USCG gauged stream in the same climatic system. Comparing observed flow rates to the NPS data it appears that there is an inverse correlation between freshwater flow and salinity levels. This is particularly noticeable at the peak flow events (marked on the plot).

6 Application of hydrodynamic and salinity model to proposed restoration options

Representatives of the National Park Service, the US Army Corp Engineers New England District, and the State of Massachusetts, Office of Coastal Zone Management and the authors formulated a variety of remedial options for the system. The primary focus of the options was to increase high water levels, lower low water levels and increase the tidal range in Pilgrim Lake and Salt Meadow. The options are summarized in Table 10. The table provides the case number, assumptions about the openings at the southeastern and northwestern ends of the lake, the width and depth of the proposed inlets, and whether the Salt Meadow dikes were assumed to be present or removed. Two major sets of options were considered. The first option assumes that the current culvert system continues to exist and that a new inlet is constructed at the location of the historic inlet on the northwestern end of the lake. The second option assumes that a new inlet replaces the current culvert system, with Sub-option 1 (2-1) assuming that the Salt Meadow Dikes are removed and Sub-option 2 (2-2) that it continues to exist. The new inlet at northwestern end of the lake is assumed to have a length of 150 m and inlet at the southwestern end of the lake to be 600 m long. This is the distance from the ocean, via Moon Pond and through High Head Road to Pilgrim Lake. This inlet length was assumed to eliminate any restrictions imposed by depth or the culvert at High Head Road. This approach is also consistent with the fact that the principal flow path from the Rte 6 culvert to Pilgrim Lake is via a channel. For Option 1 simulations it was assumed that the current culvert under High Head Road remains in place, while for Option 2 cases all restrictions have been removed. In each case the impact of varying the width of the inlet and the depth of the bottom of the inlet (relative to NAVD88) were investigated. Width variations for the northwestern inlet (50, 100, 200, and 300 m) are based on exploring a reasonable range of widths that would allow the lake water levels to replicate those in the ocean. For the southwestern inlet, the widths vary from 5 to 50 m, with the upper bound being the largest inlet width that can be accommodated within the existing Town of Truro open space at Noon's Landing for the current culvert system. For convenience in referring to the cases in the report, each case has been given a Case Number as shown in Table 10. The first letter, R, refers to restoration. The first number in the sequence refers to option

number (1- new inlet at northwestern end of lake, existing culvert system at southwestern end; 2- replace existing culvert system with new inlet at southwestern end of lake). The next number (1 to 4) refers to the width of the proposed inlet (as noted in the table) and the final letter denotes the depth of the inlet bottom (A = 0.0, B = -0.5, and C = -1.0 m). As an example, Case Number R111-2C is for a restoration option with a new inlet at the northwestern end of the lake with a width of 100 m and a depth of -1.0 m. The High Head Road culvert remains in place and the Salt Meadow dikes and culverts have been removed.

Table 10 Restoration Options for Pilgrim Lake

Date: July 26, 2005

		Openings		Modifications to		Inlet
		Southern end:	Northern end:	High Head Rd	Salt Meadow	Invert
Case Number	Option Number	Ocean to Moon Pond	Ocean to Pilgrim Lake	Culvert System	Dikes Culverts	Depth (m, NAVD88)
R11-1A	1	Existing	New inlet width 50 m	Existing	Remove	0
R11-1B						-0.5
R11-1C						-1
R11-2A		Existing	width 100 m	Existing	Remove	0
R11-2B						-0.5
R11-2C						-1
R11-3A		Existing	width 200 m	Existing	Remove	0
R11-3B						-0.5
R11-3C						-1
R11-4A		Existing	width 300 m	Existing	Remove	0
R11-4B						-0.5
R11-4C						-1
	2	New inlet				
R21-1C		width 5 m	None	Remove	Remove	-1
R21-2A		width 10 m	None	Remove	Remove	0
R21-2B						-0.5
R21-2C						-1
R21-3C		width 25 m	None	Remove	Remove	-1
R21-4A		width 50 m	None	Remove	Remove	0
R21-4B						-0.5
R21-4C						-1
R22-1A		width 5 m	None	Remove	Existing	0
R22-1B						-0.5
R22-1C						-1
R22-4A		width 50 m	None	Remove	Existing	0

R22-4B						-0.5
R22-4C						-1

Present Conditions

4 ft= 1.22 m, 6 ft = 1.83 m

Ocean - Moon Pond

Oval culvert (4 ft X 6 ft) from ocean to tidal gate chamber (two flapper type tidal gates in series, cabled open) just east of Rte 6A; oval culvert (4 ft X 6 ft) from tidal gate chamber to transition chamber west of Rte 6 (two 1 ft diameter, 100 ft long lateral (N and S) culverts drain into transition chamber);
4 ft diameter culvert from transition chamber to Moon Pond
Total distance from ocean to Moon Pond, 213 m (700 ft)
Maximum width of right of way 65 m

Ocean- Pilgrim Lake

No present connection, historical 1000 ft wide inlet

High Head Road

3.2 m wide by 1.1 m high box culvert under High Head Road
Weir gate on Pilgrim Lake end of the culvert (all boards removed)

Salt Meadow

Two earthen dikes oriented across the meadow with 2 ft (lower) and 1 ft diameter (upper) culverts

Hydrodynamic simulations were forced by water elevation data derived from Provincetown for the period from August 15 to 30, 2004. These simulations were sufficiently long for the model predictions to reach approximate steady state and to develop an accurate estimate of mean tidal conditions. The simulations used the storage capacity data provided in Figure 10, with exact formulation depended on whether the Salt Meadow dikes were in place or removed. Figure 29 shows the model predicted water levels in Moon Pond and Pilgrim Lake versus time for the period from August 15 to 30, 2004 for Case R11-1A. Also shown in the figure is the water level time series used to force the simulation from Provincetown as well the model predicted water levels in Moon Pond and Pilgrim Lake under existing conditions. The figure shows that steady state conditions are achieved within several days of the start of the simulation.

The model predictions for Pilgrim Lake show a rapidly rising water level during flood tide, resulting in a sharp peaked high tide, and a more slowly declining water level as the tide ebbs. This is followed by an abrupt rise in water level as the tide floods again. This behavior is consistent with strong ocean forcing on flood tide and a slow draining of water from the lake throughout the ebb. The lake is still draining when the next flood tide begins, thus the sharp transition from falling to rising water levels. Time series of the other cases (not shown, but provided in Appendix G) show similar behavior to those illustrated for R11-1A.

Table 11 presents a summary of the impact of restoration option R11-1A on the low and high tide levels and tidal range in Pilgrim Lake. The values of these same parameters for the ocean forcing are provided for comparison. Finally the tidal range in the lake, as a percent of the range in the ocean, is given. For case R11-1A the high tide level reaches 1.06 m compared to 1.34 m in the ocean, while the low tide level decreases to 0.43 m compared to a value of -1.46 m in the ocean. The tide range in the lake is hence 22.5 % of that in the ocean. For this case high tide is lower than that in ocean because of restrictions imposed by the cross sectional area of the inlet. The low tide water level in the lake is substantially higher than in the ocean. This is a result of the slow draining of the lake during ebb flow, which in turn is caused by the relatively shallow depth of the inlet and the decreasing cross section of the inlet as the lake water level lowers.

Model results for all other cases are presented in Table 11. Rather than discuss each case separately the major trends are summarized below.

For Option 1 cases (R11) the model results show the following trends. Histograms of the high and low tide levels and tidal range in Pilgrim Lake are also shown in Figure 30 and 31, respectively for each case. Time series data for one tidal cycle are provided in Appendix G

- Low tide levels decrease (lower levels) with increasing inlet width and depth and reach their lowest values for a width of 200 m or greater and depths of -1.0 m.
- High tide levels increase (higher levels) with increasing inlet width and reach their highest value for a width of 200 m or greater. The depth of the inlet has little impact on high tide levels. For inlet widths greater than 200 m high tides in the lake are the same as in the ocean.

Table 11 Restoration Options for Pilgrim Lake - Moon Pond
Model simulations results

OPTION 1: NEW INLET													
INLET PARAMETERS													
Width (m)		50	50	50	100	100	100	200	200	200	300	300	300
Depth (m) NAVD88		0	-0.5	-1	0	-0.5	-1	0	-0.5	-1	0	-0.5	-1
CASE #	OCEAN	R11-1A	R11-1B	R11-1C	R11-2A	R11-2B	R11-2C	R11-3A	R11-3B	R11-3C	R11-4A	R11-4B	R11-4C
TIDAL LEVEL NAVD88 (m)													
Low tide	-1.46	0.43	0.03	-0.3	0.23	-0.26	-0.71	0.08	-0.42	-0.91	0.04	-0.5	-0.96
High tide	1.34	1.06	1.05	1.07	1.23	1.29	1.32	1.34	1.35	1.35	1.34	1.35	1.35
Tidal range	2.8	0.63	1.02	1.37	1	1.55	2.03	1.26	1.77	2.26	1.3	1.8	2.31
% ocean range	100.0	22.5	36.4	48.9	35.7	55.4	72.5	45.0	63.2	80.7	46.4	64.3	82.5

OPTION 2: CULVERT SYSTEM REPLACED BY INLET												
INLET PARAMETERS												
Width (m)			5	5	5	10	10	10	25	25	25	50
Depth (m) NAVD88			0	-0.5	-1	0	-0.5	-1	0	-0.5	-1	0
OPTION 2-1 Salt meadow culverts removed												
CASE #	OCEAN	R21-1A	R21-1B	R21-1C	R21-2A	R21-2B	R21-2C	R21-3A	R21-3B	R21-3C	R21-4A	R21-4B
TIDAL LEVEL												
NAVD88 (m)												
Low tide	-1.46			0.29	0.55	0.36	0.22			0.02	0.42	0.04
High tide	1.34			0.42	0.65	0.53	0.48			0.65	0.86	0.84
Tidal range	2.8			0.13	0.1	0.17	0.26			0.63	0.44	0.8
% ocean range	100.0			4.6	3.6	6.1	9.3			22.5	15.7	28.6
OPTION 2-2 Salt meadow culverts maintained												
CASE #	OCEAN	R22-1A	R22-1B	R22-1C	R22-2A	R22-2B	R22-2C	R22-3A	R22-3B	R22-3C	R22-4A	R22-4B
TIDAL LEVEL												
NAVD88 (m)												
Low tide	-1.46	0.7	0.39	0.28							0.37	-0
High tide	1.34	0.77	0.50	0.43							0.92	0.92
Tidal range	2.8	0.07	0.11	0.15							0.55	0.93
% ocean range	100.0	2.5	3.9	5.4							19.6	33.2

- Tidal range increases with inlet width and reaches a maximum for a width of 200 m or greater. The lower the depth of the inlet the larger the tidal range. The depth of the inlet restricts the tidal range for the case with the largest width (300 m) and depth (-1.0 m).

The simulations show that the high tide levels are primarily controlled by the inlet width. If the inlet width is 200 m or larger then high tide in the lake and the ocean are essentially the same. Low tide levels are principally controlled by the inlet bottom depth; the deeper the depth the lower the low tide level. For widths greater than 200 m the low tide water levels in the pond decrease to the bottom depth of the inlet. The tidal range in the lake asymptotically approaches the range in the ocean as the inlet width and depth increase (Table 11, Figure 31). Since the lake depths are on the order of -1.0 m the lake is fully drained at low tide for inlet widths greater than 200 m and inlet depths of -1.0 m.

For Option 2 cases (R2) the model results show the following trends. Histograms of the high and low tide levels in Pilgrim Lake for Sub option 2-1 and 2-2 cases are shown in Figure 32 and 33, respectively. The associated tidal range histograms are shown in Figures 34 and 35.

For the Option 2-1 and 2-2 (R21 and R22) cases the dependency of high and low tide levels and tidal range on inlet width and depth are the same as observed for Option 1 cases. The principal difference is that the range of inlet widths explored is substantially lower in Option 2 than for Option 1 (R11). The results of Option 2 cases are broadly consistent with those explored in Option 1. Where direct comparisons are possible (R21-1C versus R22-1C and R21-4C versus R22-4C) removal of the Salt Meadow dikes is predicted to reduce the Pilgrim Lake tidal range slightly compared to the retain Salt Meadow dikes case (tidal range percentage 5.4 % with dikes, 4.6 % without dikes for 1C; 46.4% with dikes, 41.8% without dikes for 4C). This difference is a direct result of the differential storage capacity for the lake with and without Salt Meadow dike restrictions (Figure 10). With Salt Meadow dikes removed the storage capacity of the lake is increased at water levels above 0.0 m NAVD88. This increase in storage capacity lowers the high tide level compared to that for the dikes maintained case as the water is distributed over a larger area.

Predictions for R21-4C and R11-1C should be similar given that they assume the same inlet width and depth and that the Salt Meadow dikes are removed. Case R21-4C gives a tidal range reduction of 41.8 % compared to 48.9 % for R11-1C. The differences between the two cases can be explained by the fact that R11-1C assumes that the existing culvert system to the ocean and High Head Road culvert still remain, as at present, and that the inlet length for Option 2 cases is longer (600 m) than for Option 1 (150 m). Both factors favor a larger tidal range for R11-1C than for R21-4C.

Studying cases R21-2A, B and C it is noted that as the inlet is deepened, high and low tide levels decrease and the tidal range increases. The decrease in low tide levels is a result of the ability of additional water to drain from the wetland as the inlet depth increases. The reduction in high tide levels, with increase in inlet depth, is due to enhanced frictional losses as ever-increasing volumes of water are transported through the inlet. Note the frictional losses increase as the square of the velocity.

Given constraints of access to Pilgrim Lake via the current Town of Truro Park, in which the existing culvert is located, NPS has requested that three cases be explored in additional depth (Cases R21-1C, R21-4C, and R22-4C). For a reference they have also requested that additional simulations be performed for R11-4C. This case represents a potential optimal restoration as it allows the maximum tidal range to be achieved in the lake and Salt Meadow (see Table 11) of any of the cases considered.

For these four cases simulations were performed with salinity model described earlier to determine the mean salinity in the lake assuming mean freshwater input rates. The salinity in the ocean was assumed to be 31 ppt. The maximum water levels in the lake were also determined for 100-year storm conditions. The 100 year storm water level is the same as that used by Spaulding and Grilli (2001) for nearby Herring River. Finally plan view plots of the wetted surface area of the Pilgrim Lake system were prepared for each case. These plots were generated by use of the hypsographic curve for the lake system (Figure 10) and an associated digital topographic map (Figure 9). It was assumed

the water level in the lake was constant across the entire lake. These plots were generated at hourly intervals throughout the tidal cycle.

Predictions for the high and low tide water levels, tidal range, maximum water level in 100 yr storm, and mean salinity are presented in Table 12 for each of the four cases. Values for the ocean and existing conditions in Pilgrim Lake are provided for comparison. Results from Table 11 for the relevant cases are also provided to facilitate comparison. Restricting attention to three remedial option cases of prime interest we see that increasing the inlet width increases the high water level, decreases the low water level and increases the tidal range in Pilgrim Lake. For the widest inlet the tidal range in the lake is 45.4 % of its value in the ocean. This compares to 82.5 % for the potential optimum inlet (300 m wide). Similar results are seen from the 100 yr storm forcing cases. The wider the inlet, the higher the maximum storm surge height. For the 300 m width case the water levels in the pond are the same as in the ocean, 2.89 m. For the 50 m width cases (R21-4C and R22-4C) the levels are approximately 75 to 80 % of those in the ocean. The case with the existing Salt Meadow dikes (R22-4C) in place has the higher value because of the more limited basin storage capacity. For existing conditions and the narrowest inlet (5 m) the storm surge height in the lake is restricted by frictional losses through the culvert and inlet systems. Simulations with the salinity model show the salinity increases as the inlet width increases and asymptotically approaches the levels in the ocean. For the widest width case the salinity reaches 30.6 ppt compared to a value in the ocean of 31 ppt. Model predicted salinities are slightly higher in Pilgrim Lake (30.8 ppt) if the Salt Meadow dike is in place compared to the no dike case (30.6 ppt). This is a direct result of the larger tidal range and hence increased volume of ocean water entering Pilgrim Lake when the dike is closed.

Table 12 Summary of model results for selected restoration options for Pilgrim Lake - Moon Pond System

Estimated Tidal parameters are based on observed forcing,

August 15 to September 10 2004

Storm surge forcing for the 100 yr storm is from Spaulding and Grilli (2001)

PARAMETERS

CASE Name	Ocean	Current	R11-4C	R21-1C	R21-4C	R22-4C
INLET PARAMETERS						
Width (m)		culvert	300	5	50	50
Depth (m) NAVD88		system	-1	-1	-1	-1
Length (m)		235	150	*600	600	600
RESTRICTIONS						
Salt Meadow dikes		Existing	Removed	Removed	Removed	Existing
High Head Rd culvert		Existing	Existing	Removed	Removed	Removed
TIDAL LEVEL						

NAVD88 (m)						
Low tide	-1.46	0.17	-0.96	0.29	-0.28	-0.33
High tide	1.34	0.2	1.35	0.42	0.89	0.97
Tidal range	2.8	0.03	2.31	0.13	1.17	1.3
Tidal range (% ocean)	100	1.1	82.5	4.60	41.8	46.4
100 Year Storm NAVD88 (m)						
Maximum level	2.89	0.23	2.89	0.54	2.16	2.36
Mean Salinity (ppt)	31	24.5	31	27	30.6	30.8 (27.4)**

* For R2 cases it has been assumed that the inlet extends from the Ocean to Pilgrim Lake and passes through Moon Pond. This assumption was made to remove either depth or width restrictions imposed by Moon Pond or High Head Road culvert

** Value in parentheses is for Salt Meadow since that system is modeled separately

Figure 36 shows a plan view of the model predicted wetted surface area at low and high tide for the existing conditions. This will serve as a reference for comparison to the remedial options. Model predictions at high and low tide for the optimum case and each of the three remedial cases are shown in Figures 37 to 39 (R11-4C, R21-1C, R21-4C, and R22-4C). It is noted that the low tide surface area is also covered with water at high tide. A vertical elevation reference bar (NAVD88 reference) is provided at the bottom of each plot. The top-side of the bar gives the contour intervals for Pilgrim Lake. For cases where the study region has been divided into more than one basin (existing – Pilgrim Lake and Moon Pond and R22-4C – Pilgrim Lake and Salt Meadow) the lower portion of the bar gives the contour elevation for the additional basin. For existing conditions (Figure 36) there is no noticeable difference in surface area between high and low tide, except for a very small difference in Moon Pond. For the narrowest opening case (R21-1C, Figure 37) the results are very similar to the existing conditions. This is a direct result of the very limited increase in tidal range in the lake (10 cm) between the two cases (Table 12). The high tide surface area increases dramatically, compared to existing conditions, as the width of the inlet increases (R21-4C (high tide = 0.89 m) and R22-4C (high tide = 0.97 m), R11-4C (high tide = 1.34 m)). There is little difference in high tide surface area between the 50 and 300 m inlet width cases however since the storage capacity curve (Figure 10) shows a substantially reduced increase in surface area with elevation for elevations larger than 0.8 m. There is also little difference in high tide surface area between cases R21-4C and R22-4C in Pilgrim Lake but of course substantial differences in Salt Meadow, where the former case assumes existing conditions and the later that the dikes have been removed. Low tide surface areas increase substantially for the 50 and 300 m width cases (R21-4C, R22-4C and R11-4C), compared to existing or the limited inlet width case of 5 m (R21-1C). While the low tide level for the optimum case (R11-4C) (-0.96 m) is significantly lower than that for 50 m width cases (about - 0.30 m) the

differences in low tide surface area are moderated by the bowl like shape of Pilgrim Lake.

7. Summary and conclusions

As part of this study to investigate the impact of selected remedial options on the Pilgrim Lake system a variety of field collection efforts were performed to characterize the existing system. Intensive tidal cycle survey data were collected on May 19-20, 2004; July 15, 2004; and August 5, 2004, to characterize the currents/flows, sea surface elevations, salinity, and temperature field in the Pilgrim Lake system and adjacent Cape Cod Bay over a lunar, semi-diurnal (M_2) tidal cycle (period-12.42 hrs). Measurements were made at the Rte 6 and High Head Road culverts, with an accompanying hydrographic survey of Pilgrim Lake. In addition time series data on the water levels at Provincetown, Moon Pond, and Pilgrim Lake were collected simultaneously for period of about 7 months.

Analysis of the data resulted in the following insight into the lake dynamics.

- For the dominant M_2 tides, the amplitude decreases from 1.34 m at Provincetown to 0.153 m in Moon Pond (11% of the Provincetown amplitude). The M_2 phase in Moon Pond (126.7 degrees GMT) lags that at Provincetown (115.95 degrees GMT) by 10.75 degrees or 0.370 hrs (22.2 min). The other major tidal constituents (N_2 , S_2 , K_1 , and O_1) are seen to show amplitude reductions, on the order of a factor of 10, between Provincetown and Moon Pond. For comparison the intensive tidal cycle surveys showed a reduction in tidal range from the ocean (2.8 m) to Moon Pond (0.2 m) of about a factor of 14. The tidal range at Provincetown is approximately 96% of the Boston with high tide lagged by about 16 minutes.
- Water level fluctuations in Pilgrim Lake are dominated by low frequency non-tidal forcing. No water level variations at tidal time scales were observed in the lake. This is a direct result of the very limited tidally induced flux of water into the lake and the very large volume of the lake.
- Tidal current speeds are 40 % to 70 % stronger at flood than at ebb tide at the Rte 6 culvert. The flood tide however is of shorter duration (5.1 hrs) than the ebb (7.3 hrs). The flood tide currents display a sine like shape, whereas ebb tides are almost constant throughout the ebb tide. Tidal currents at High Head Road culvert show a similar shape to those at Rte 6 but are about 2 to 3 times weaker. The shape of the tidal current curve is a direct result of strong ocean forcing on flood tide followed by draining of the system on the ebb.
- Hydrographic surveys show that lake waters are vertically and horizontally well mixed throughout the system. The exception is that in the northwestern end of the lake the water is stratified due to a local source of ground water entering the

system. Since there were no observed tidal currents in the lake the lack of vertical or horizontal stratification seems likely due to wind mixing.

An inlet basin hydrodynamic model was applied to the Pilgrim Lake system. Two basins, Moon Pond and Pilgrim Lake, connected to each other by High Head Road culvert, and to the ocean via Moon Pond by the Rte 6 culvert, were used to represent the system. Input data on the culvert system geometry and elevations were based on a survey of the infrastructure and the *as built* drawings. The storage capacity of the basin was determined by NPS personnel based on an analysis of existing data, supplemented by a topographic survey of selected sections of the system, and in particular Salt Meadow, performed by Slade Associates Inc. as part of this study. The model was forced by the ocean water level. The model was calibrated by comparison of model predictions to data collected during the intensive tidal cycle surveys and the time series measurement program. A Manning coefficient was used to characterize losses in the culvert under High Head Road and a relative roughness coefficient was used for the same purpose for the culvert system from the ocean to Moon Pond.

The simulations show a dramatic reduction of tidal variations between Provincetown and Moon Pond and essentially no tidal signal in Pilgrim Lake; both consistent with the observations. Predicted water levels in Moon Pond were within several centimeters of the observed values. The model predicts a slightly earlier rise in water level in Moon Pond than observed but accurately reproduces the decrease in water level with time. The large differentials in water levels between Moon Pond and the ocean are a direct result of the frictional losses in the Rte 6 culvert system and the large differential in storage capacities of the two basins. At elevations typical of those currently observed in the field measurement program, Moon Pond comprises 2 % and Pilgrim Lake and Salt Meadow the remaining 98% of the surface area of the combined system. The amount of water entering/exiting Moon Pond on the flood/ebb tide is sufficient to raise/lower the water level in Moon Pond because of its relatively limited storage capacity. The amount of water that enters/exits Pilgrim Lake over a tidal cycle however is extremely small compared to the storage capacity of the basin and hence doesn't measurably affect the water level in the lake.

A tidal prism based model was applied to Pilgrim Lake System to predict the mean salinity in the system. The model used output from the hydrodynamic model to specify the volume exchanges between the lake and the ocean. A mean freshwater input rate of $0.073 \text{ m}^3/\text{sec}$ was assumed based on a groundwater and runoff model developed by Masterson (2004). The ocean salinity was set at 31 ppt. Model predictions were compared with data collected by NPS at four monitoring stations that they occupied in the lake following the opening of the tidal gates. At approximate steady state conditions the model predicted a salinity of 24.5 ppt, compared to a mean of the observations of about 23.5 ppt.

A sensitivity study was performed varying the freshwater input to the lake by +/- 10 and 20 %. As expected the predicted salinity decreases/increases as the freshwater input rate

increases/decreases. Variations are on the order of 0.5 ppt. If the freshwater input is increased by 100 % then the salinity decreases by 5 ppt.

Next a series of simulations were performed where the freshwater input rate was held fixed at the mean value and the return parameter, b , varied between 0 and 1. The return parameter specifies the amount of water exiting on the ebb tide that re-enters on the next flood. The model shows that the higher the amount returned the lower the salinity in the lake. For $b = 0.8$ the salinity is about 17 ppt at the end of the simulation compared to a value of 25 ppt for $b = 0$. Model predictions with $b = 0.4$ result in a salinity of 23.5 ppt in good agreement with the average of all the station data.

Based on input from NPS, the State of Massachusetts, and the US Army Corp of Engineers a total of 26 restoration options were investigated. The options were divided into two major classes. Option 1 (12 cases) assumed that the current culvert system at the southwestern end of the lake continues to exist, connecting the ocean to Moon Pond, and that a new inlet is constructed at the location of the historic inlet on the northwestern end of the lake. Option 2 (14 cases) assumes that a new inlet replaces the current culvert system, with Sub-option 1 (2-1) assuming that the Salt Meadow Dikes are removed and Sub-option 2 (2-2) that they continue to exist. Within each option the impact of inlet width and bottom depth were investigated. For the new inlet on the northwestern end of the lake widths of 50, 100, 200, and 300 m were investigated. For the replacement inlet on the southwestern end of the system widths of 5, 10, 25, and 50 m were studied. The maximum width of the southwestern inlet was constrained by the existing Town of Truro Park. Inlet depths of 0.0, -0.5 and -1.0 m (NAVD88) were explored. For reference the mean depth of Pilgrim Lake is about -1 m. Simulations were performed for each case using the hydrodynamic model and results summarized in terms of the high and low water levels and tidal range in Pilgrim Lake compared to equivalent values in the ocean. In broad overview, model predictions show that

- Low tide levels decrease (lower levels) with increasing inlet width and depth and reach their lowest values for a width of 200 m or greater and depths of -1.0 m.
- High tide levels increase (higher levels) with increasing inlet width and reach their highest value for a width of 200 m or greater. The depth of the inlet has little impact on high tide levels. For inlet widths greater than 200 m high tides in the lake are the same as in the ocean.
- Tidal range increases with inlet width and reaches a maximum for a width of 200 m or greater. The lower the depth of the inlet the larger the tidal range. The depth of the inlet restricts the tidal range for the case with the largest width (300 m) and depth (-1.0 m).
- Removal of the Salt Meadow dike and culvert system decreases the tidal range slightly (about 15 %) compared to existing conditions. This difference is a direct result of the differential storage capacity for the lake with and without Salt Meadow dike restrictions.

To achieve the maximum tidal exchange with the ocean and hence the largest tidal range (approximately 80 % of the ocean range) in the lake requires an inlet with a width of 200 m or larger and an inlet depth of -1 m. The tidal range in this case is restricted by low tide levels and in turn the depth of the lake. At ebb tide much of the lake bottom would be exposed.

For the maximum width of the southern inlet of 50 m and an inlet depth of -1.0 m the tidal range in the lake is approximately 46% of that in the ocean. Restrictions in this case are imposed both by the high and low tide levels.

For three of the most probable remedial option cases (R21-1C (5 m width), R21-4C (50 m width), and R22-4C (50 m width), all with inlet depths of -1 m, predictions were made for the salinity and water level in the lake from 100 yr storm forcing. These simulations show that as the inlet width increases the lake salinity is predicted to increase and asymptotically approach the oceanic value. The maximum water level in the lake also increases as the width of the inlet increases. For the 50 m case maximum storm levels are about 75 % of those in the ocean. For reference, if an optimal inlet is constructed with a width of 300 m and a depth of -1.0 m, the salinity, high water and the maximum 100 yr water level will be the same as in the ocean. The tidal range in the lake will be about 82.5 % of the oceanic value and restricted by the depth of the lake. Plan view plots of the high and low tide water surface area were prepared for existing conditions and the most probable and optimum remedial options. High tide surface areas are shown to increase as the inlet widths increase (for widths of 50 and 300 m). The differential high tide surface area between the 50 m and 300 m width cases is quite modest and is a direct result of the change in slope of the storage capacity vs elevation curve, reflecting a more vertical sided basin. The low tide surface areas are predicted to decrease as the inlet width increases (for widths of 50 and 300 m). The bowl shaped geometry of the lake limits the change between the two cases.

The simulations show that the tide range, surface area at high tide, and mean salinity can all be substantially increased, compared to existing conditions, by construction of a 50 m wide, -1.0 m deep inlet, within the existing right of way, at southwestern end of the Pilgrim Lake system. With Salt Meadow dikes removed this case results in flooding of the majority of the Salt Meadow system. The optimum inlet, as defined by the largest tidal range, largest high and smallest low tide surface areas, and highest salinity is achieved for inlet widths greater than 200 m with a depth of -1.0 m.

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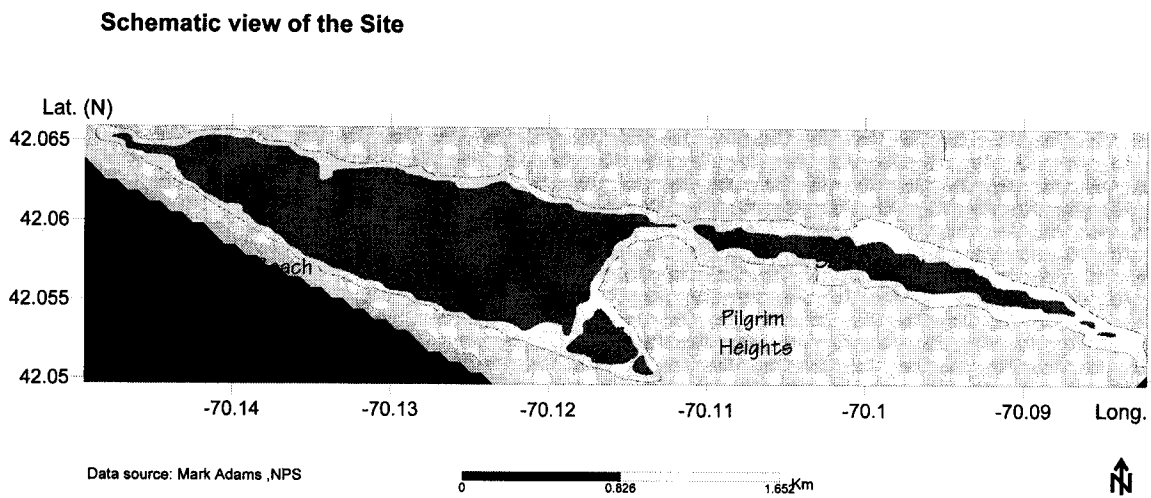


Figure 1 East Harbor system including Pilgrim Lake, Salt Meadow, and Moon Pond.

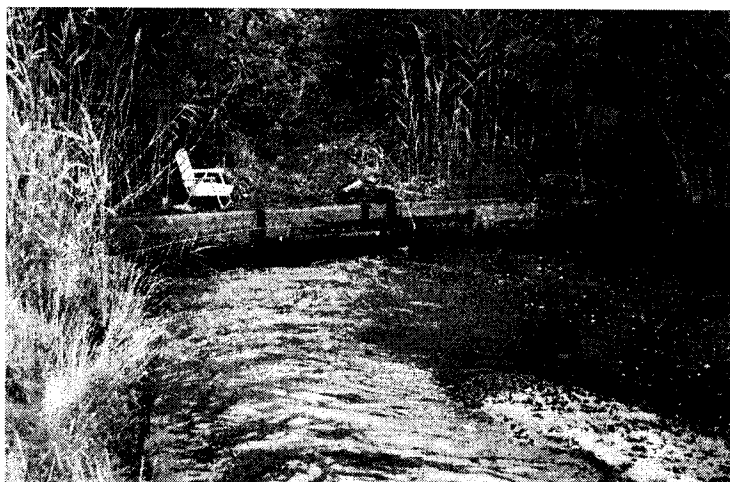


Figure 2 Rte 6 culvert bulkhead viewed from Moon Pond looking toward the ocean.

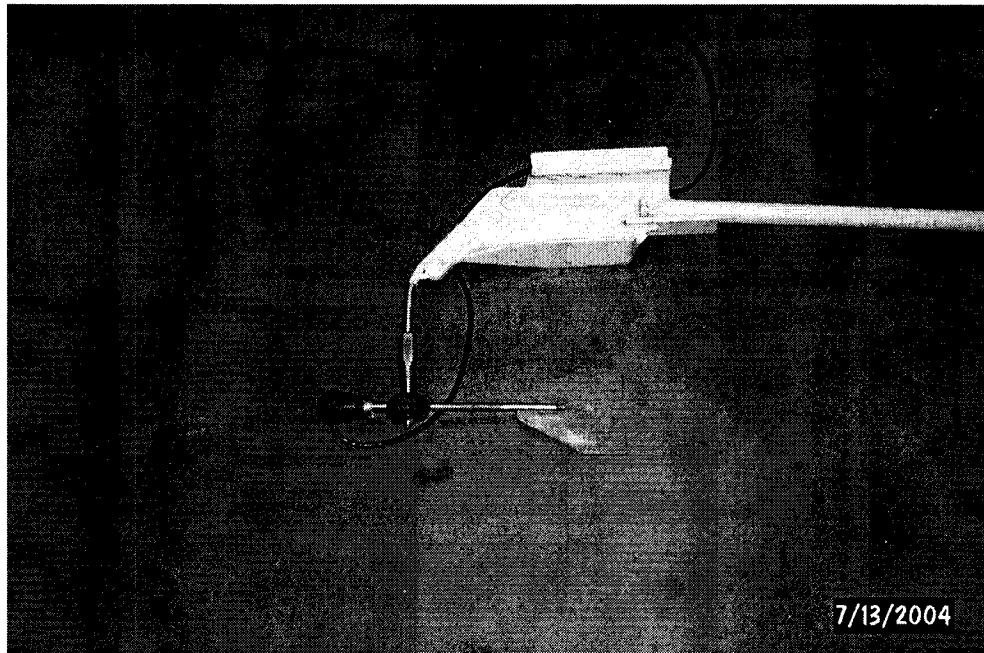
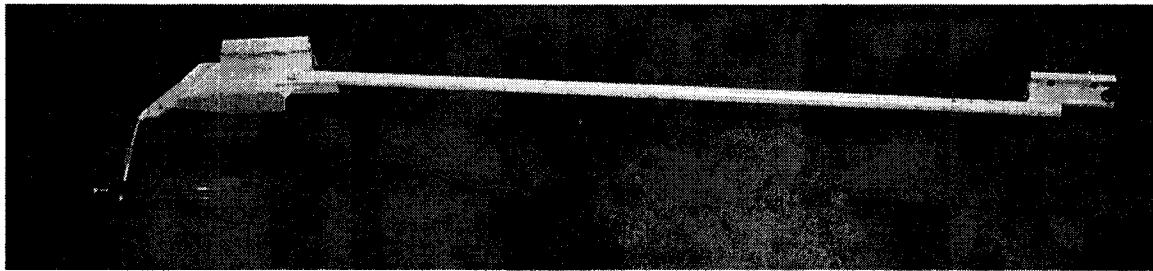


Figure 3 Current meter (Marsh McBirney) mounting bracket. The sensor head and guide vane are noted on the left of the photographs.



Figure 4 View from High Head Road looking toward Rte 6 culvert.

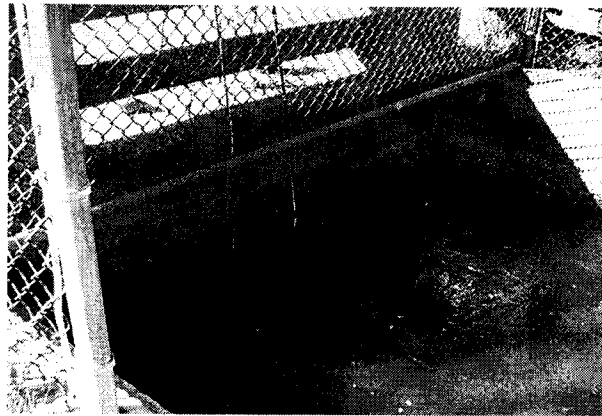


Figure 5 View of box culvert at High Head Road from Pilgrim Lake end showing deployment of electromagnetic (left) and acoustic current meters (right).



Figure 6 Weir gate guides located inside metal fence cage on Pilgrim Lake end of High Head Road culvert - flume system.

Salinity and elevation stations measurements

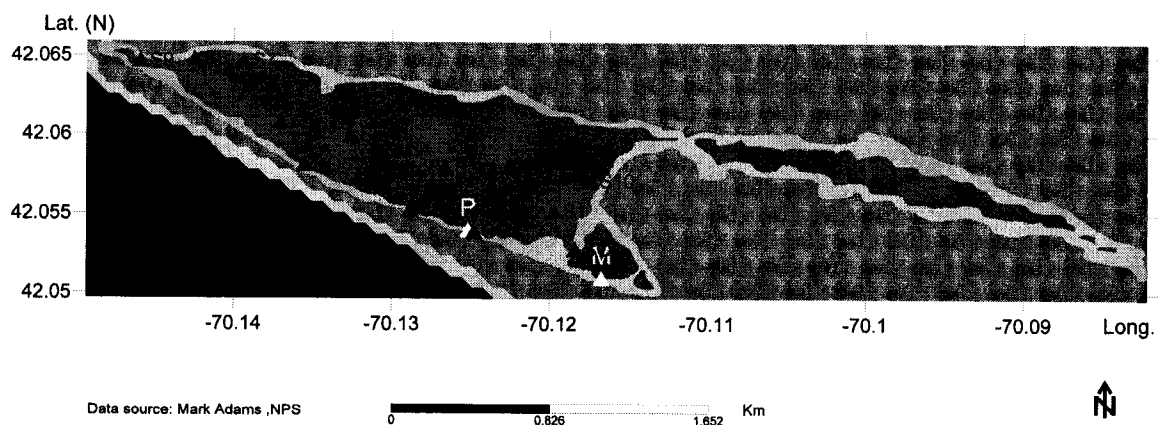


Figure 7 Location of the hydrographic stations occupied during the intensive tidal cycle surveys on May 20, July 15, and August 5, 2004. Also shown are the locations of the NPS water level measurements (P – Pilgrim Lake and M – Moon Pond).

Proposed Survey Transects - East Harbor Basin

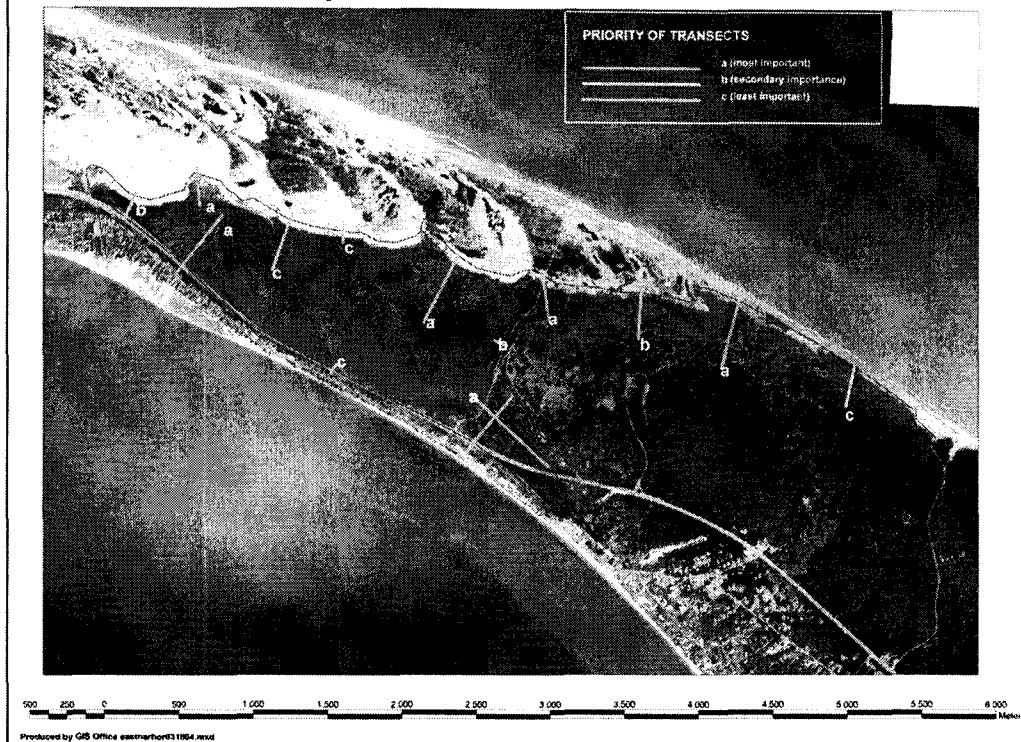


Figure 8 Proposed Slade transect survey lines in Pilgrim Lake, Moon Pond, and Salt Meadow (prepared by Mark Adams, National Park Service).

Topography of Pilgrim Lake, Moon Pond and Salt Meadow

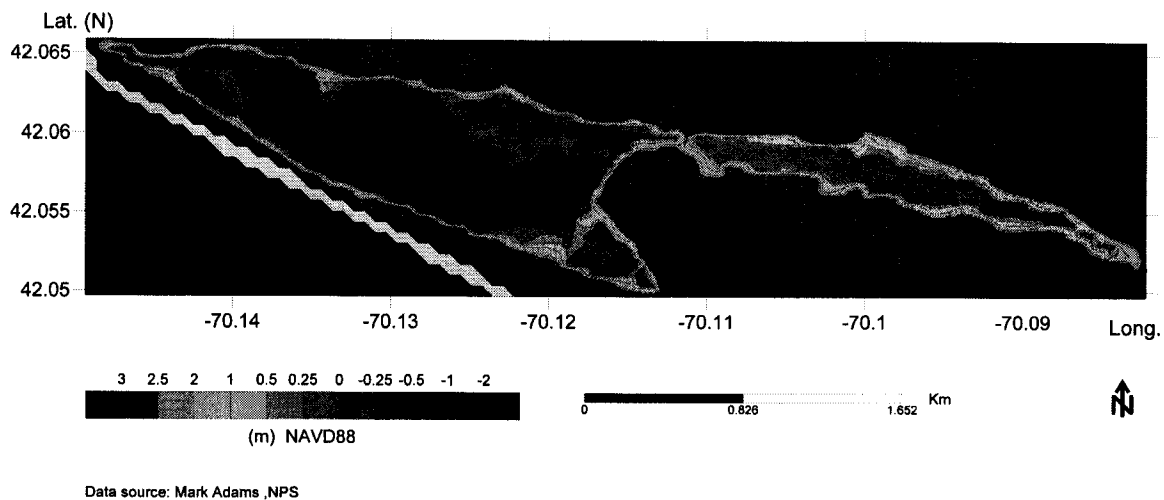


Figure 9 Topographic map of the study area prepared by NPS.

Area versus elevation Moon Pond, Pilgrim Lake and Salt Meadow

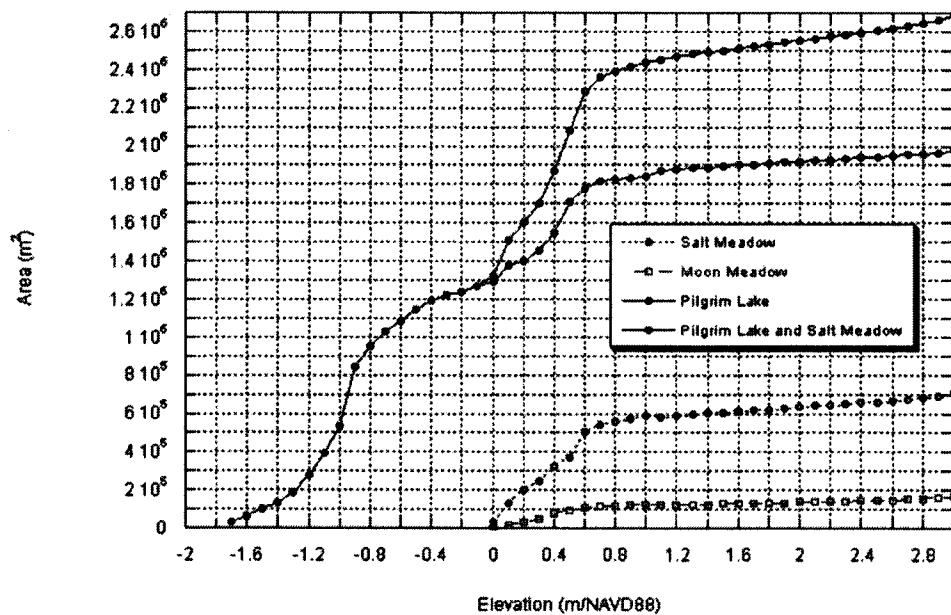


Figure 10 Hypsographic (area versus elevation) curves for Pilgrim Lake, Moon Pond, Salt Meadow and Pilgrim Lake and Salt Meadow combined.

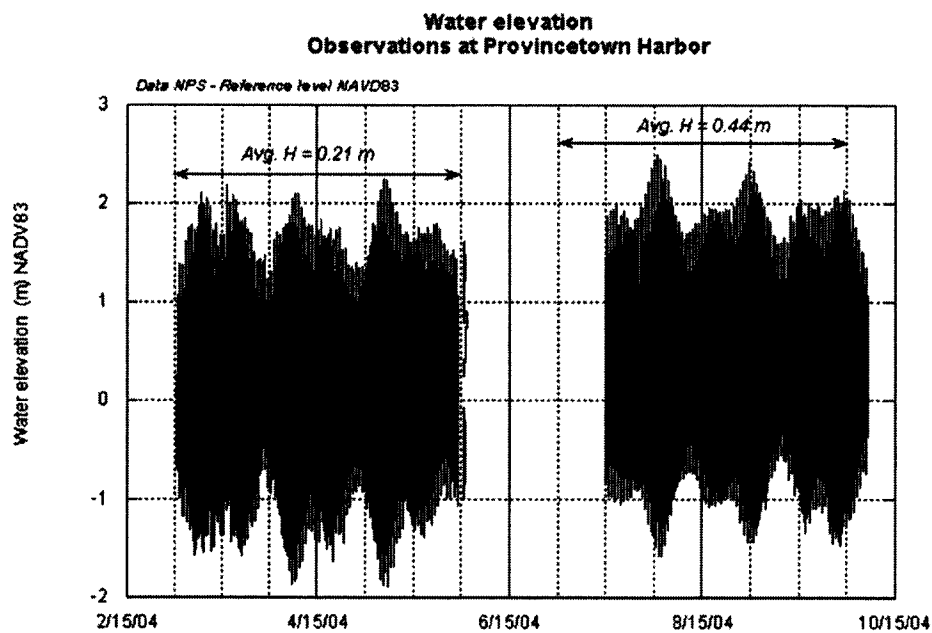
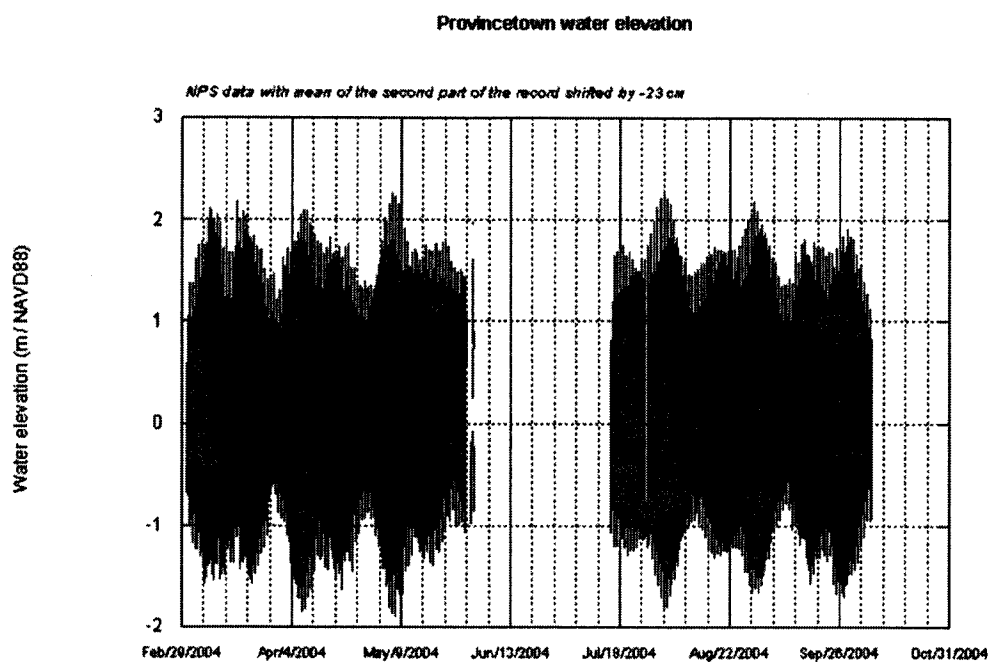


Figure 11 Water level time series at Provincetown Harbor (upper panel corrected, lower panel as received).

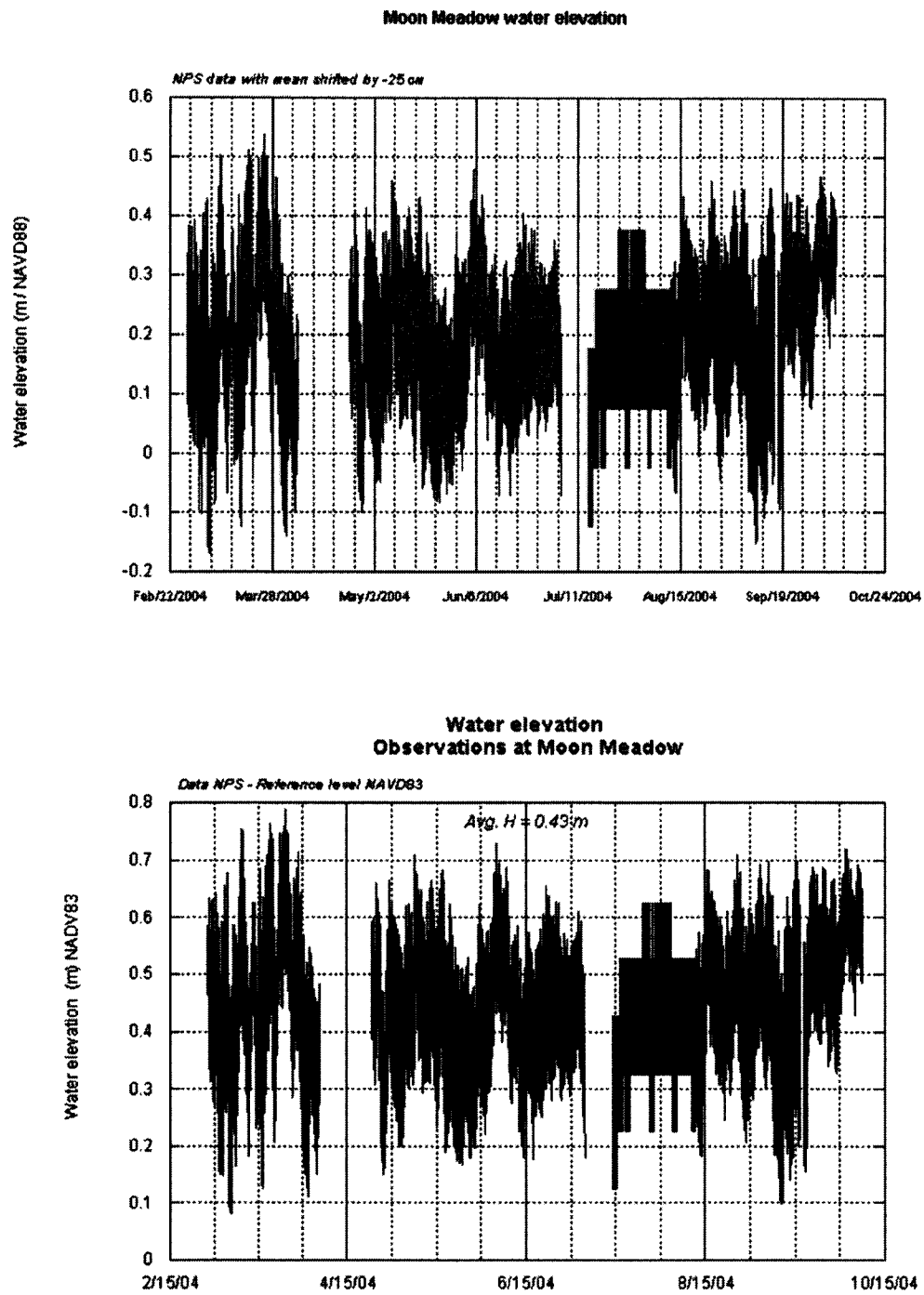


Figure 12 Water level time series in Moon Pond (upper panel corrected, lower panel as received).

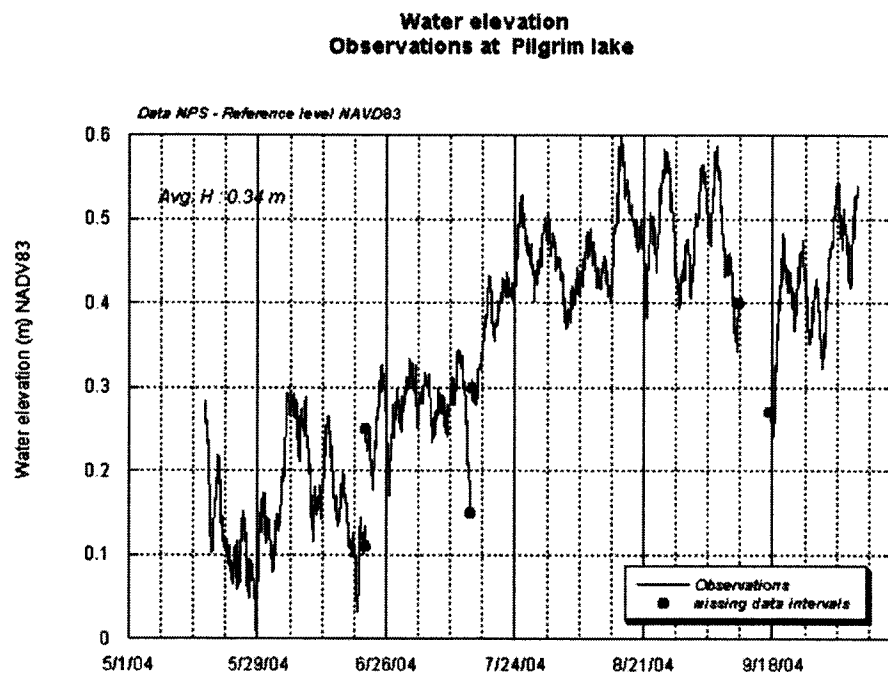
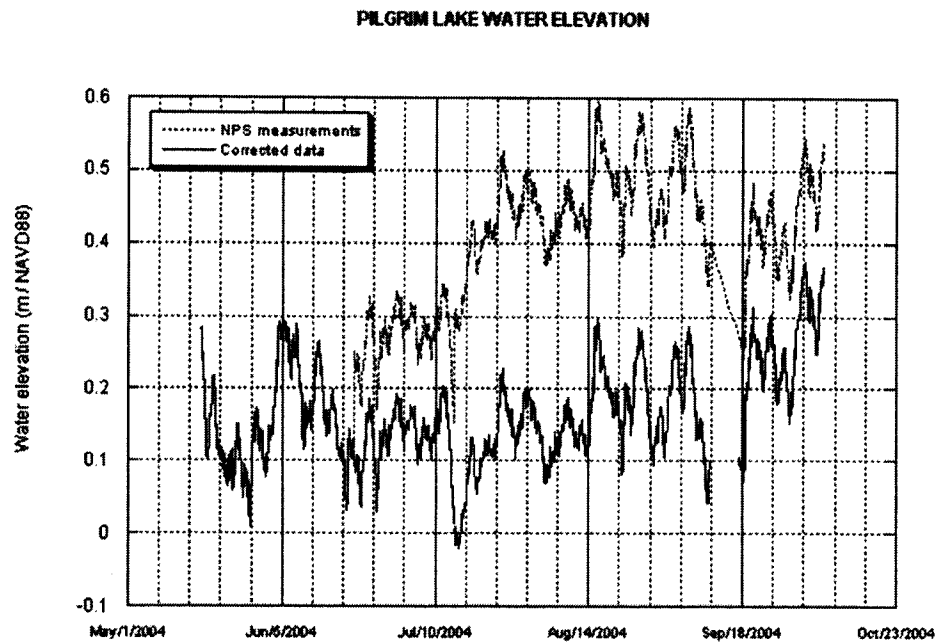


Figure 13 Water level time series in Pilgrim Lake (upper panel corrected, lower panel as received).

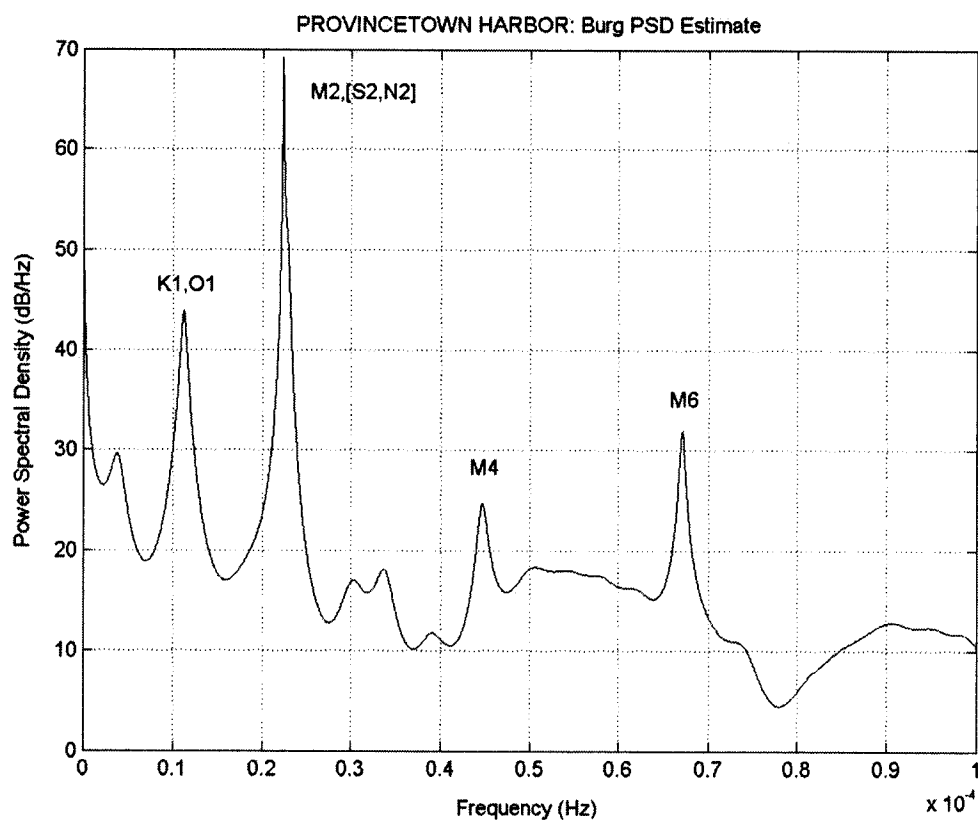


Figure 14 Power spectral density of sea surface elevation time series vs frequency (Hz) for Provincetown. The principal diurnal, semi-diurnal and harmonics are noted.

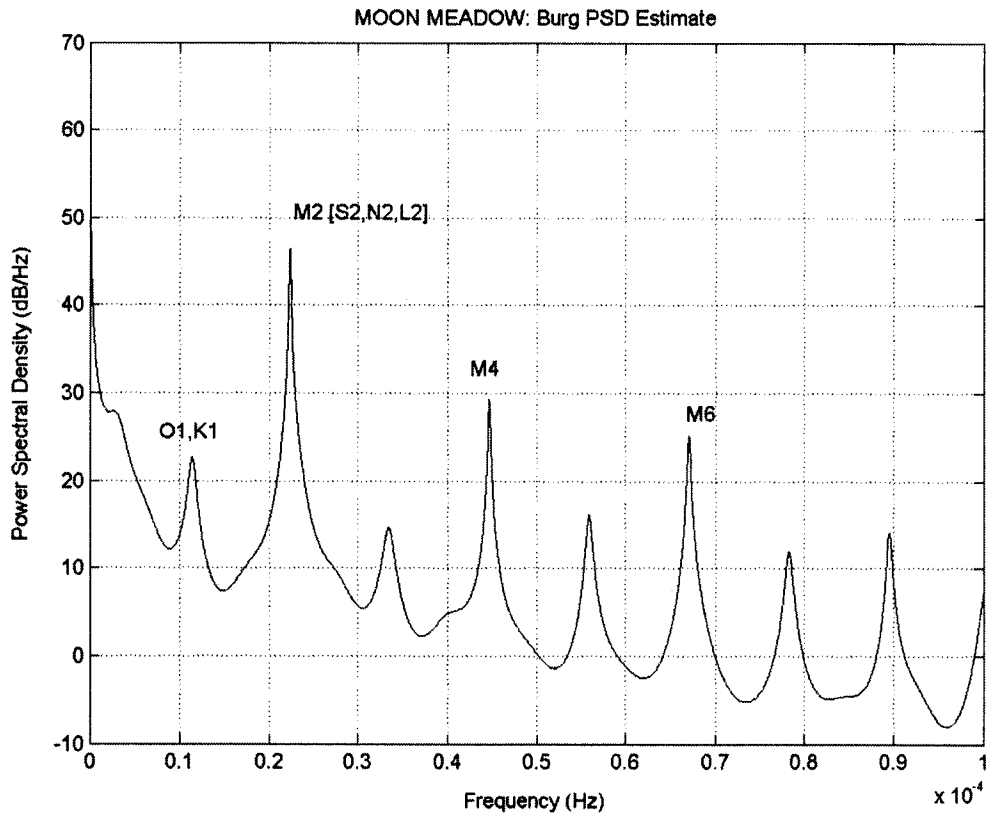


Figure 15 Power spectral density of sea surface elevation time series vs frequency (Hz) for Moon Meadow. The principal diurnal, semi-diurnal, and harmonics are noted.

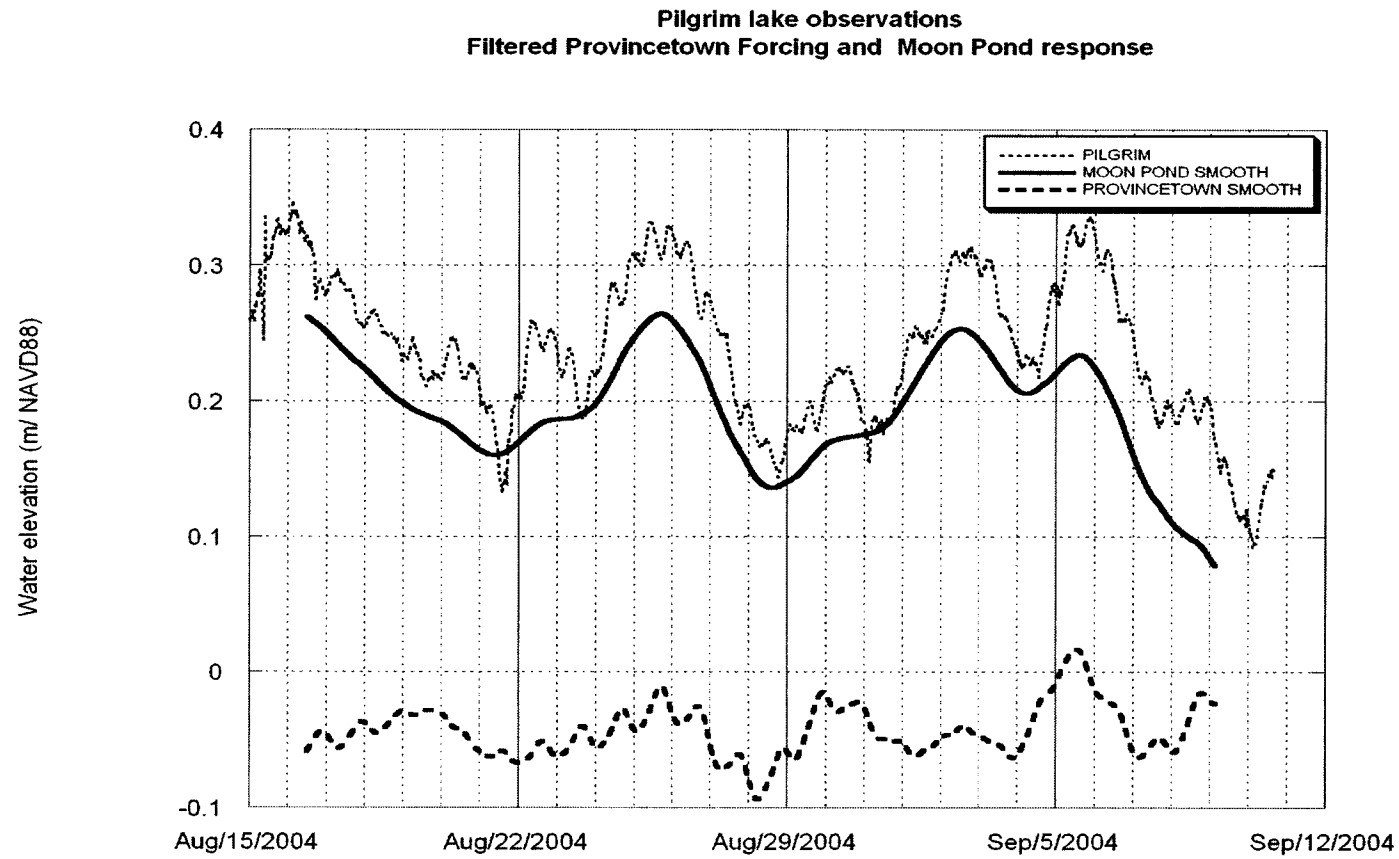


Figure 16 Low frequency variation in water level for Provincetown, Moon Pond, and Pilgrim Lake from mid August to early September 2004.

Water elevation - Experiment 1, May 20, 2004
Rt. 6 and High Head Rd. culverts, Moon pond and Pilgrim sides

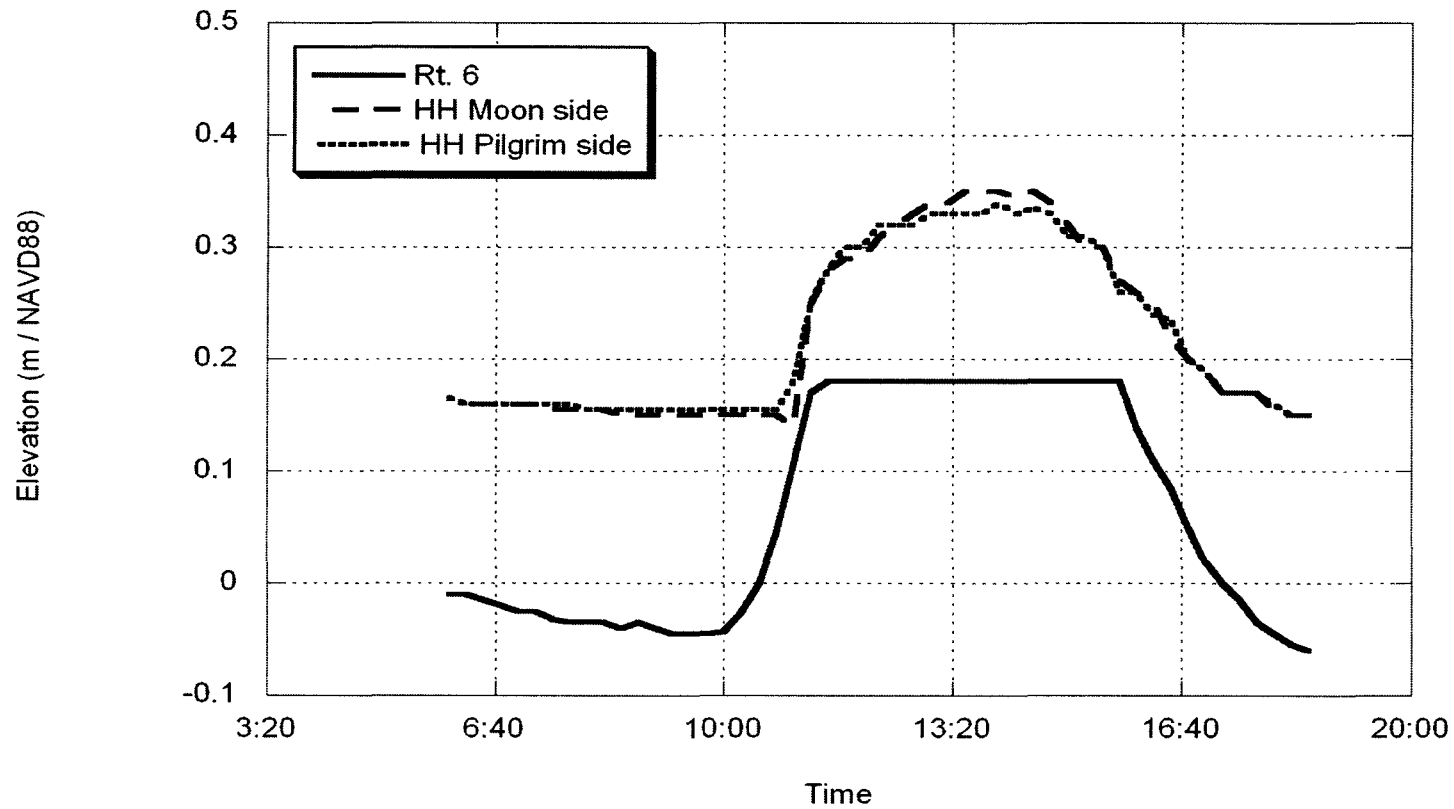


Figure 17 Water level for the May 20, 2004 intensive tidal cycle survey for Moon Pond adjacent to the Rte 6 culvert and at the Moon Pond and Pilgrim lake ends of High Head Road.

Water elevation - Experiment 2, July 15, 2004
Rt. 6 and High Head Rd. culverts, Moon pond and Pilgrim sides

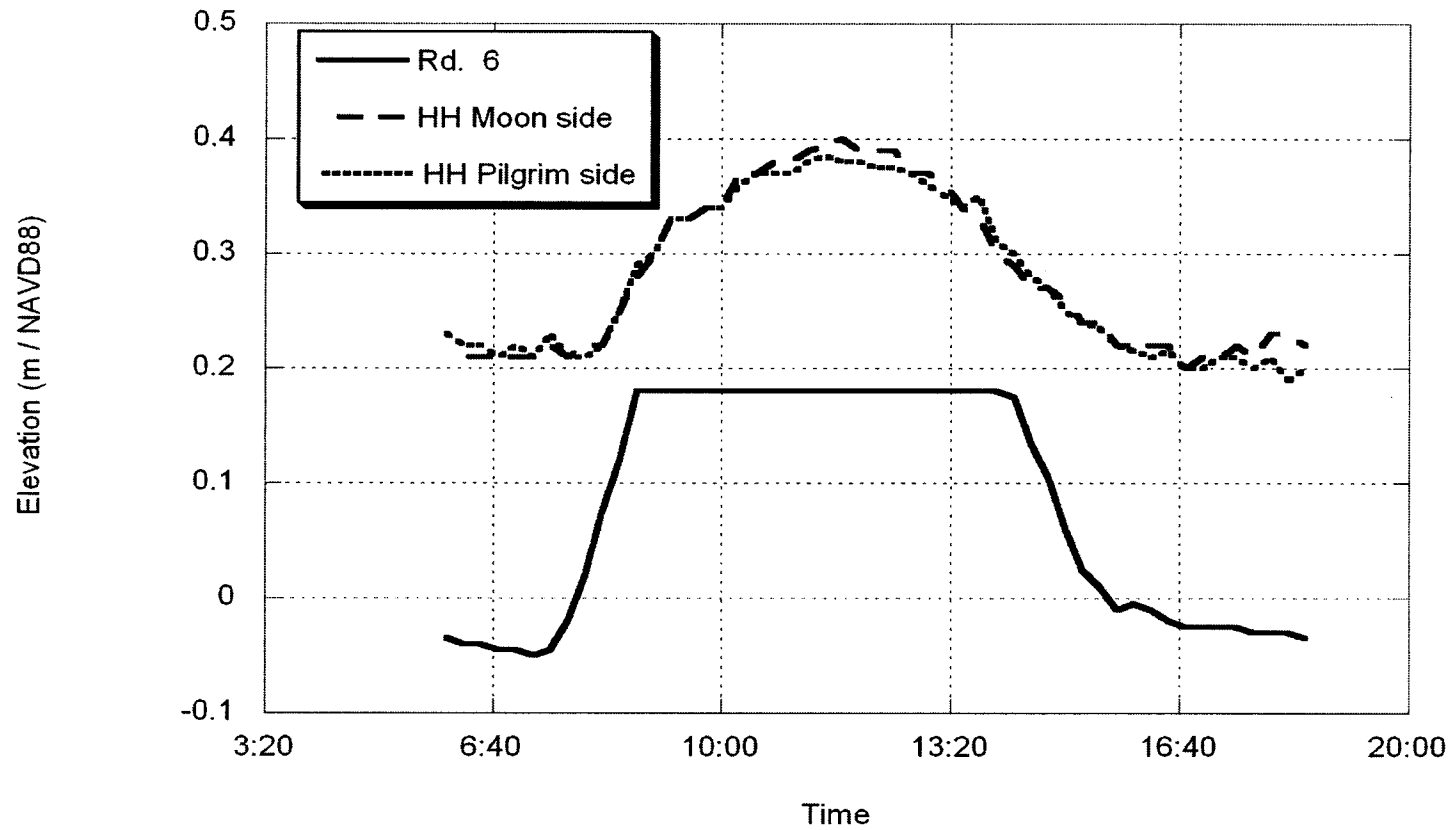


Figure 18 Water level for the July 15, 2004 intensive tidal cycle survey for Moon Pond adjacent to the Rte 6 culvert and at the Moon Pond and Pilgrim lake ends of High Head Road.

Water elevation - Experiment 3, August 5, 2004
Rt. 6 and High Head Rd. culverts, Moon pond and Pilgrim sides

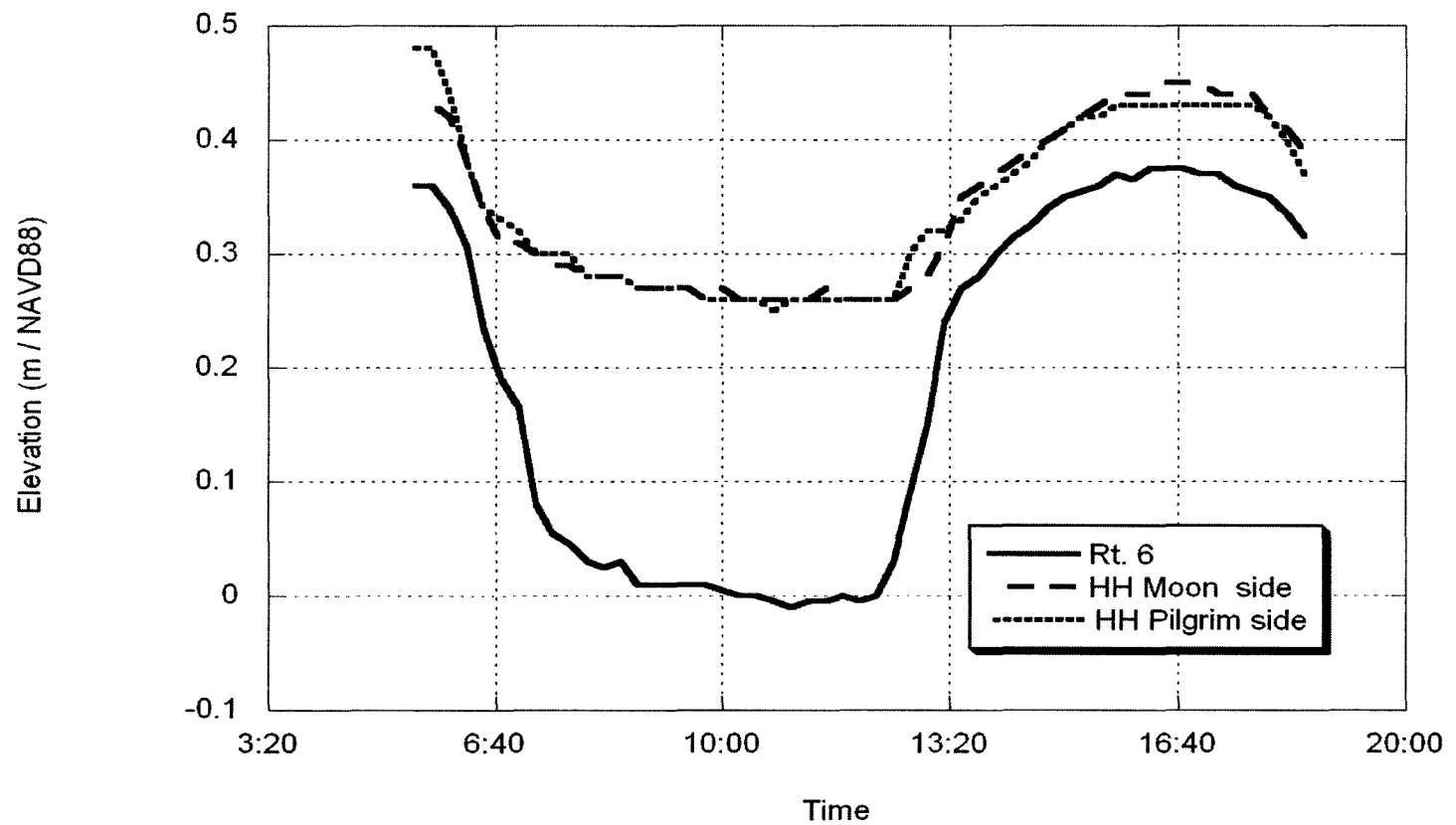


Figure 19

Water level for the August 5, intensive tidal cycle survey for Moon Pond adjacent to the Rte 6 culvert and at the Moon Pond and Pilgrim lake ends of High Head Road.

Experiment #1 May 20 2004
 Velocities and water elevation at Rt. 6 and High Head Rd. culverts

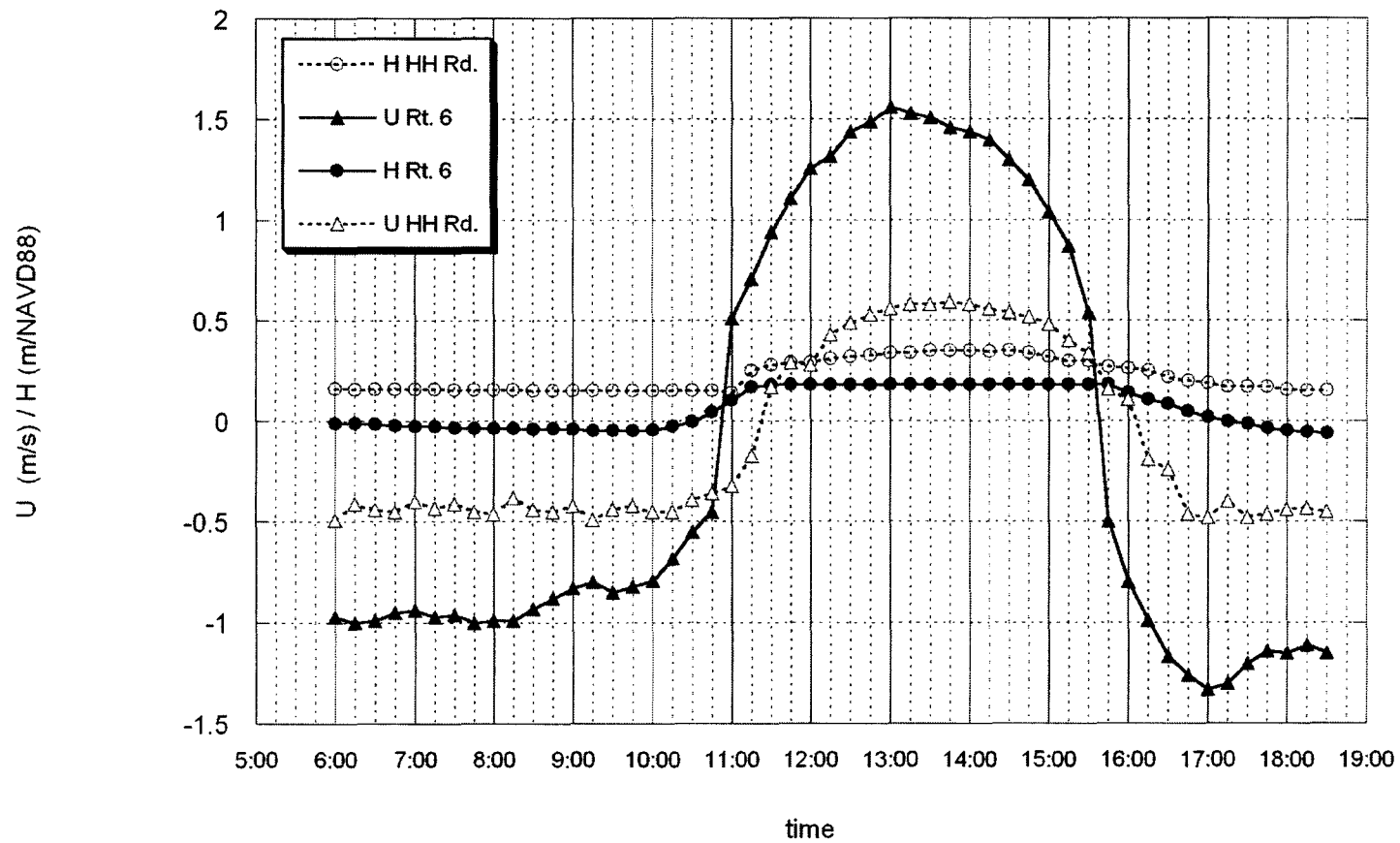


Figure 20 Current speed (m/sec) and water level (m) at Rte 6 culvert and High Head Road for the May 20, 2004 experiment.

Experiment #2 July 15 2004

Velocities and water elevation at Rt. 6 and High Head Rd. culverts

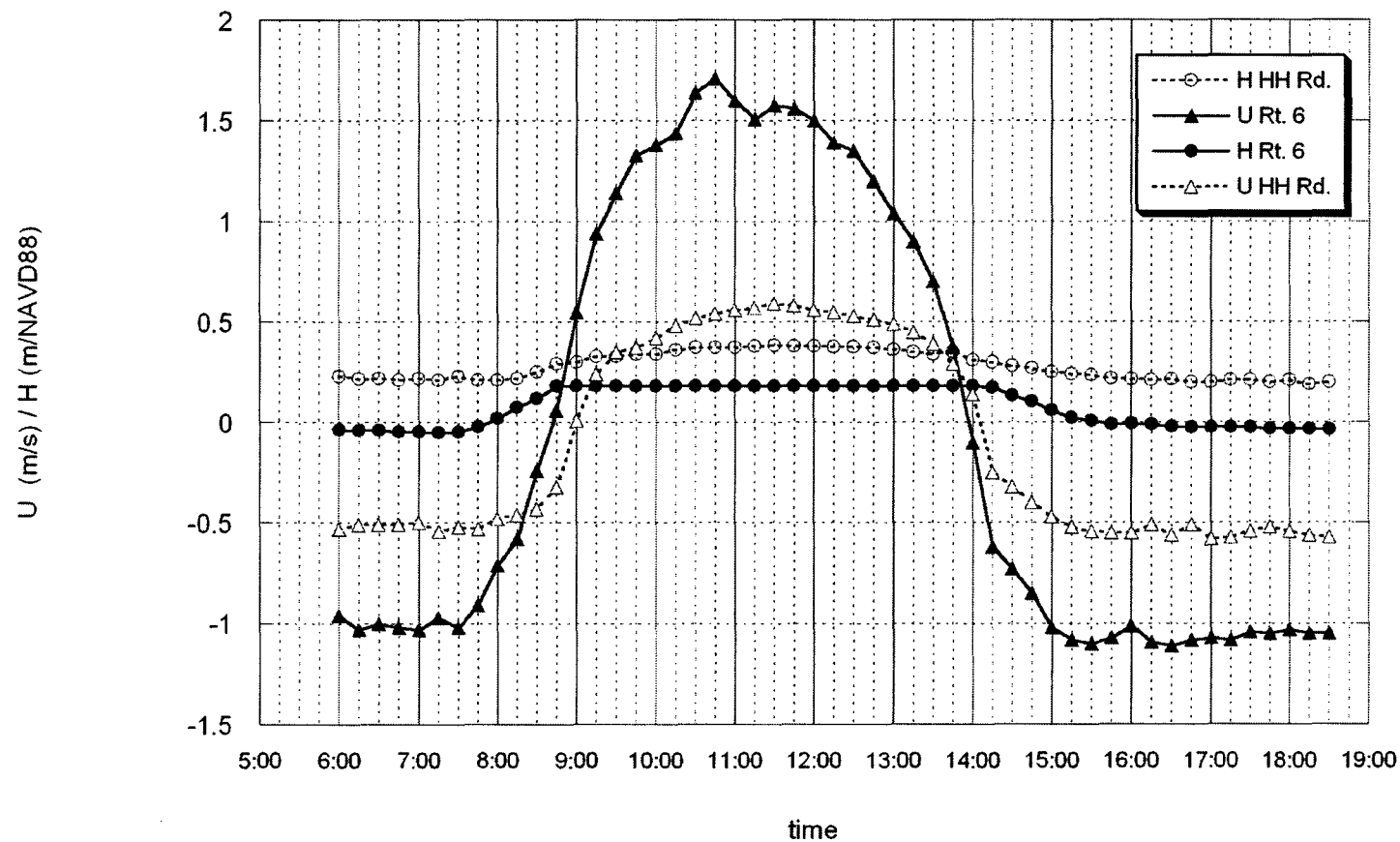


Figure 21 Current speed (m/sec) and water level (m) at Rte 6 culvert and High Head Road for the July 15, 2004 experiment.

Experiment #3 August 5 2004

Velocity (U) and water elevation (H) at Rt. 6 and High Head Rd. culverts

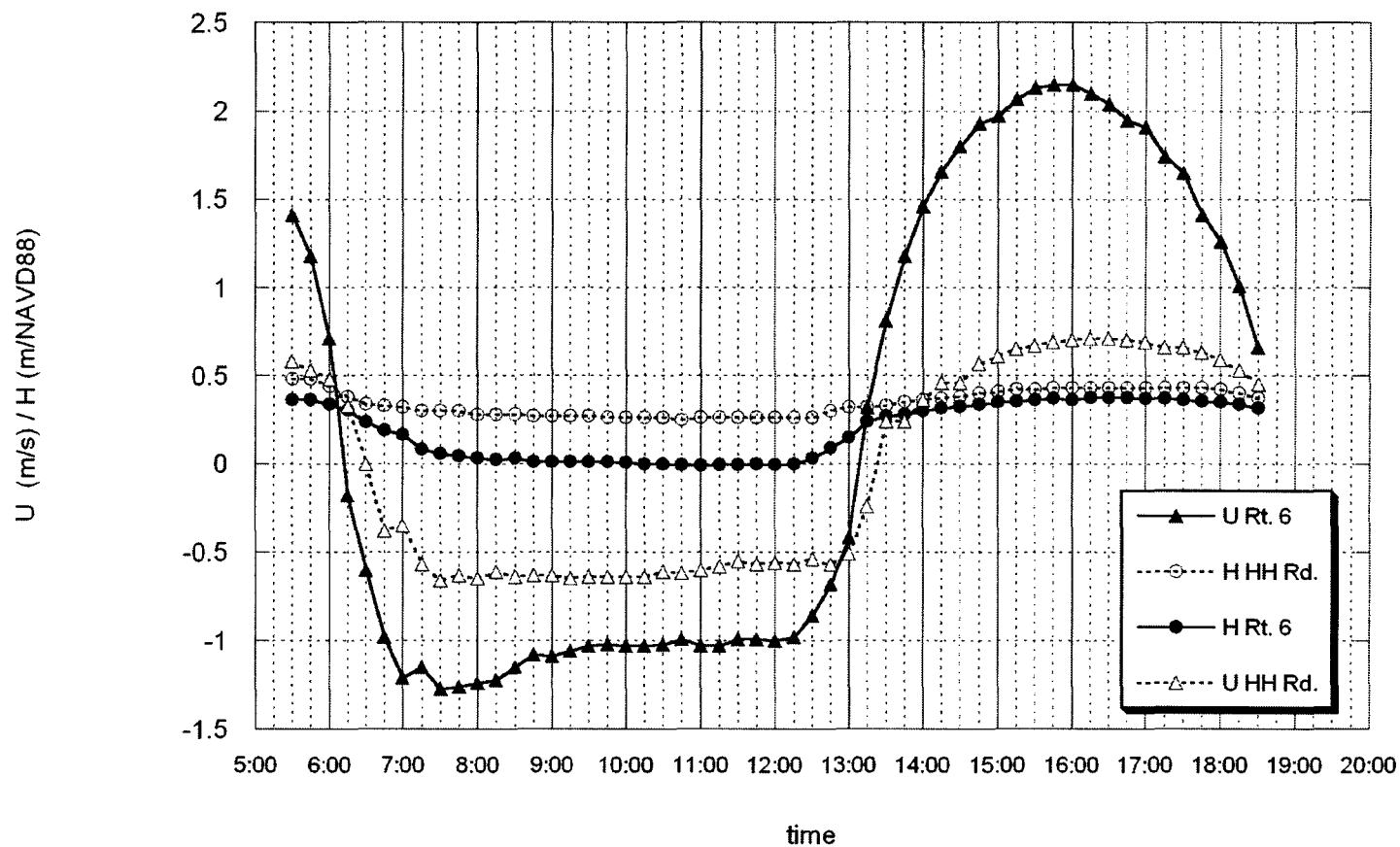


Figure 22 Current speed (m/sec) and water level (m) at Rte 6 culvert and High Head Road for the August 5, 2004 experiment.

Field experiment #1, May 20, 2004
Comparison simulations and observations

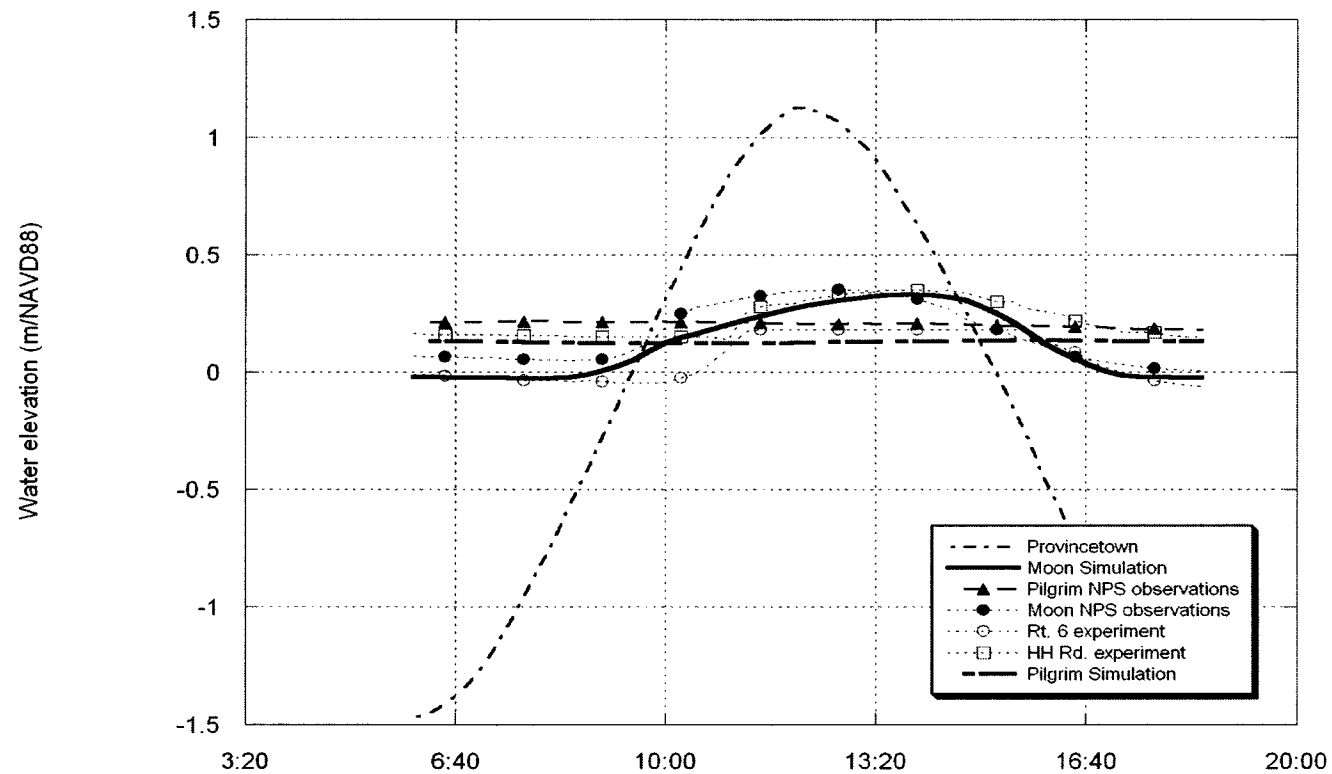


Figure 23 Comparison of model predictions and observations for sea surface elevations in Moon Pond and Pilgrim Lake for the May 20, 2004 experiment.

Field experiment #2, July 15, 2004
Comparison simulations and observations

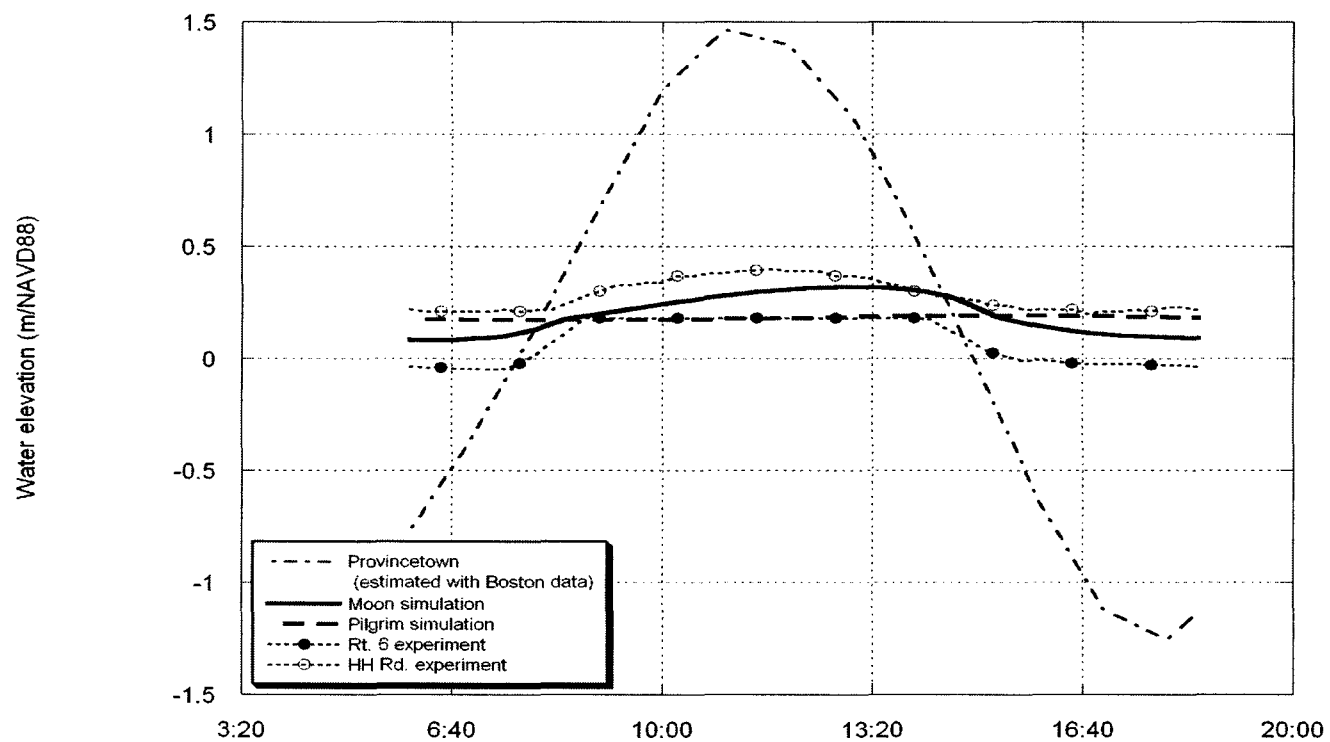


Figure 24 Comparison of model predictions and observations for sea surface elevations in Moon Pond and Pilgrim Lake for the July 15, 2004 experiment.

Field experiment #3, August 5, 2004
Comparison simulations and observations

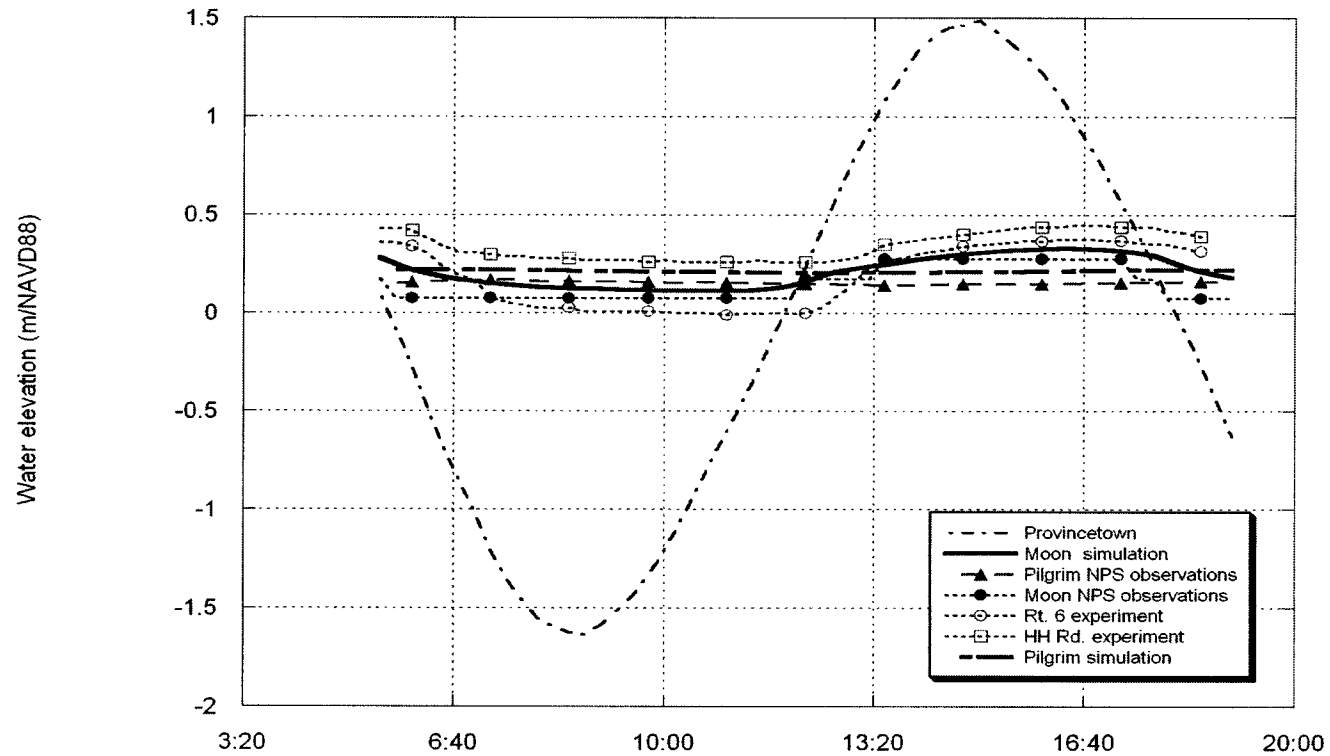
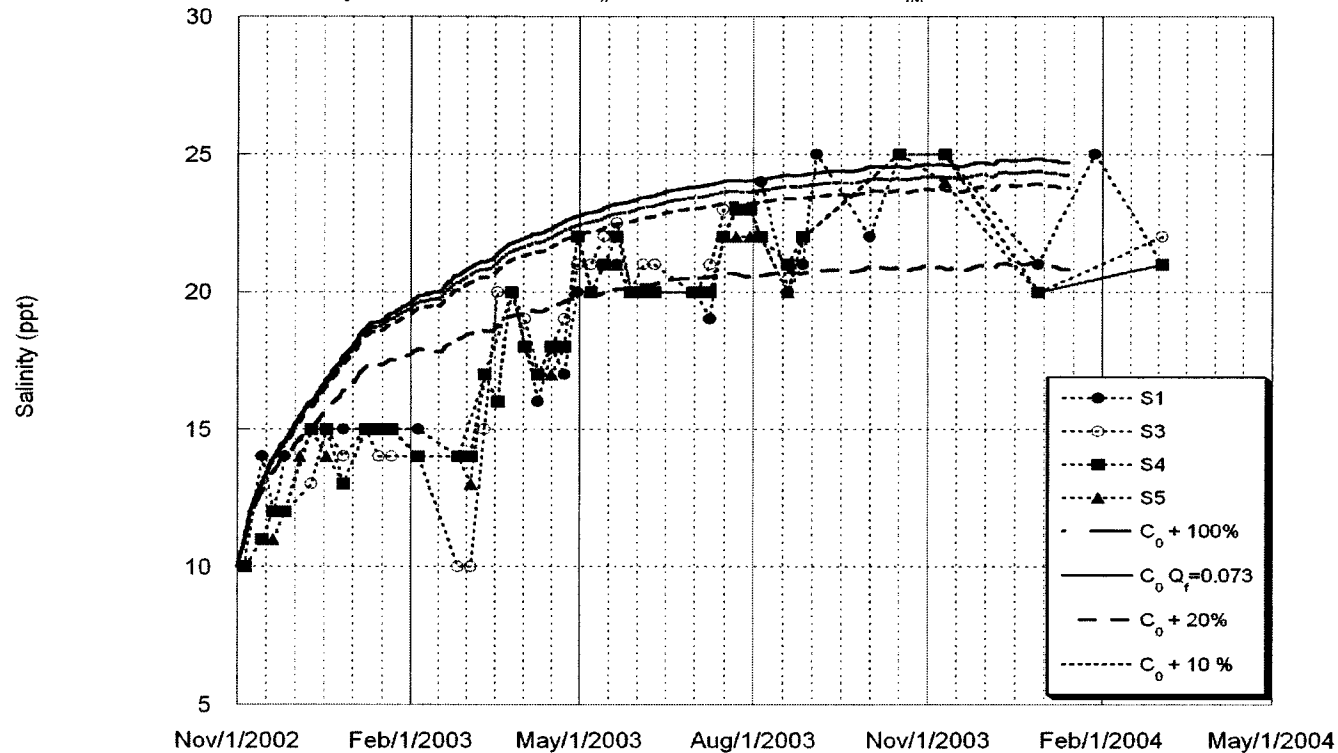


Figure 25 Comparison of model predictions and observations for sea surface elevations in Moon Pond and Pilgrim Lake for the August 5, 2004 experiment.

Salinity restoration in Pilgrim Lake
Model sensitivity to fresh water inflow (m^3/s)
Comparison model simulations with measurements at stations S1,S3,S4,S5

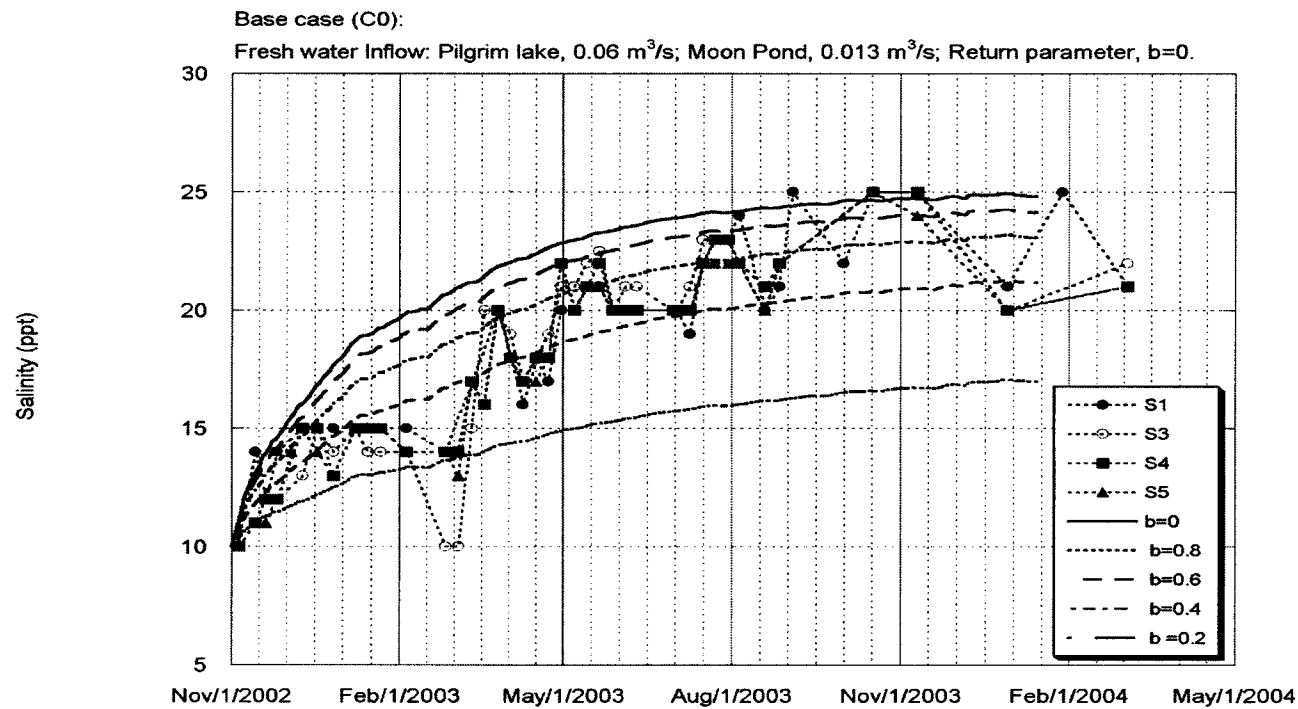
Base case C_0 : Pilgrim lake inflow, $Q_{TP}=0.06 \text{ m}^3/\text{s}$; Moon Pond, $Q_{TM}=0.013 \text{ m}^3/\text{s}$; Return parameter, $b=0$.



Data source
 Salinity :NPS (2004)
 Inflow :Materson (2005)

Figure 26 Model predicted salinity vs time for various freshwater input rates. Observations are NPS monitoring stations as shown as S1, S3, S4, and S5.

Salinity restoration in Pilgrim Lake
Model sensitivity to return parameter b
Comparison model simulations with measurements at stations S1,S3,S4,S5



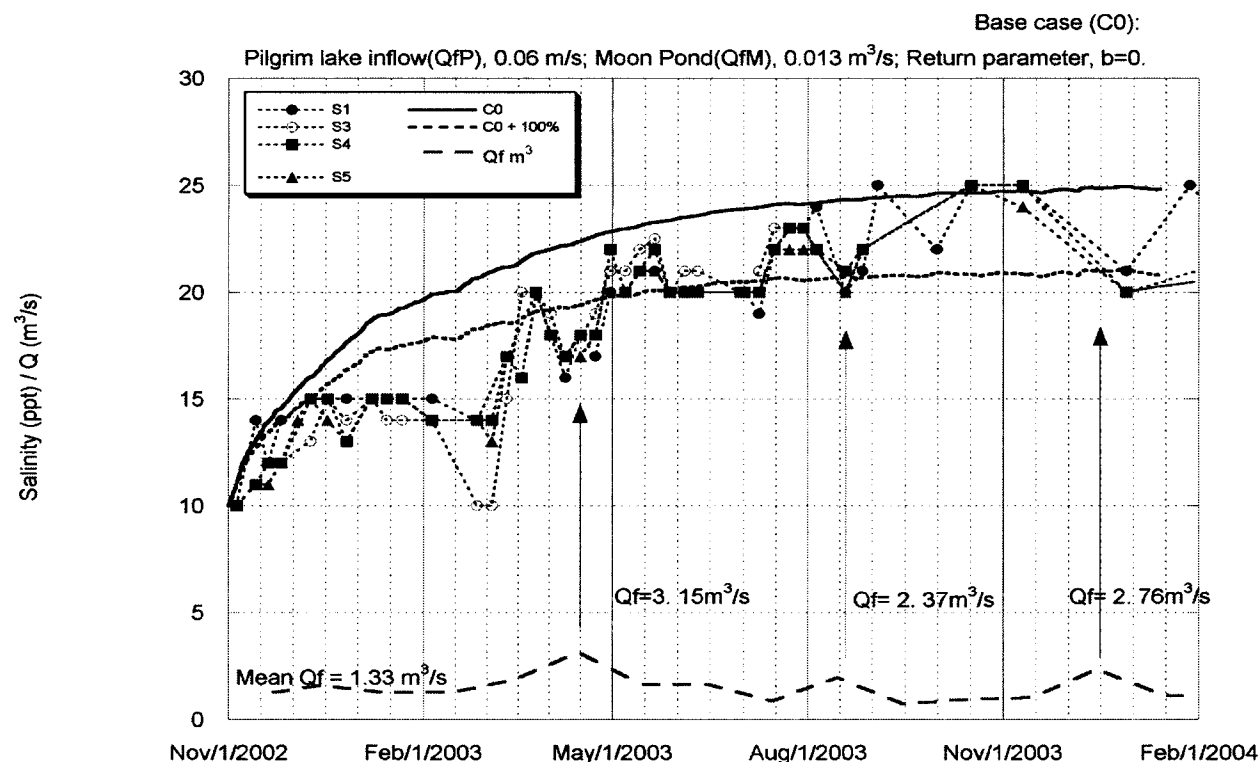
Data source
 Salinity :NPS (2004)
 Inflow :Materson (2005)

Figure 27 Model predicted salinity vs time for various return amounts. Observations are NPS monitoring stations as shown as S1, S3, S4, and S5.

Salinity restoration in Pilgrim Lake

Model sensitivity to fresh water inflow (m^3/s)

Comparison measurements and model simulations with mean monthly fresh water inflow, in Jones river, Kingston, Ma



Data source

Salinity :NPS (2004)

Inflow :Materson (2005)

Figure 28

Model predicted salinity vs time for base and twice base freshwater flow conditions. Observations at NPS monitoring stations are shown as S1, S3, S4, and S5. The lower line gives freshwater flow rate for Jones River, the closest gauged stream to the Pilgrim lake watershed.

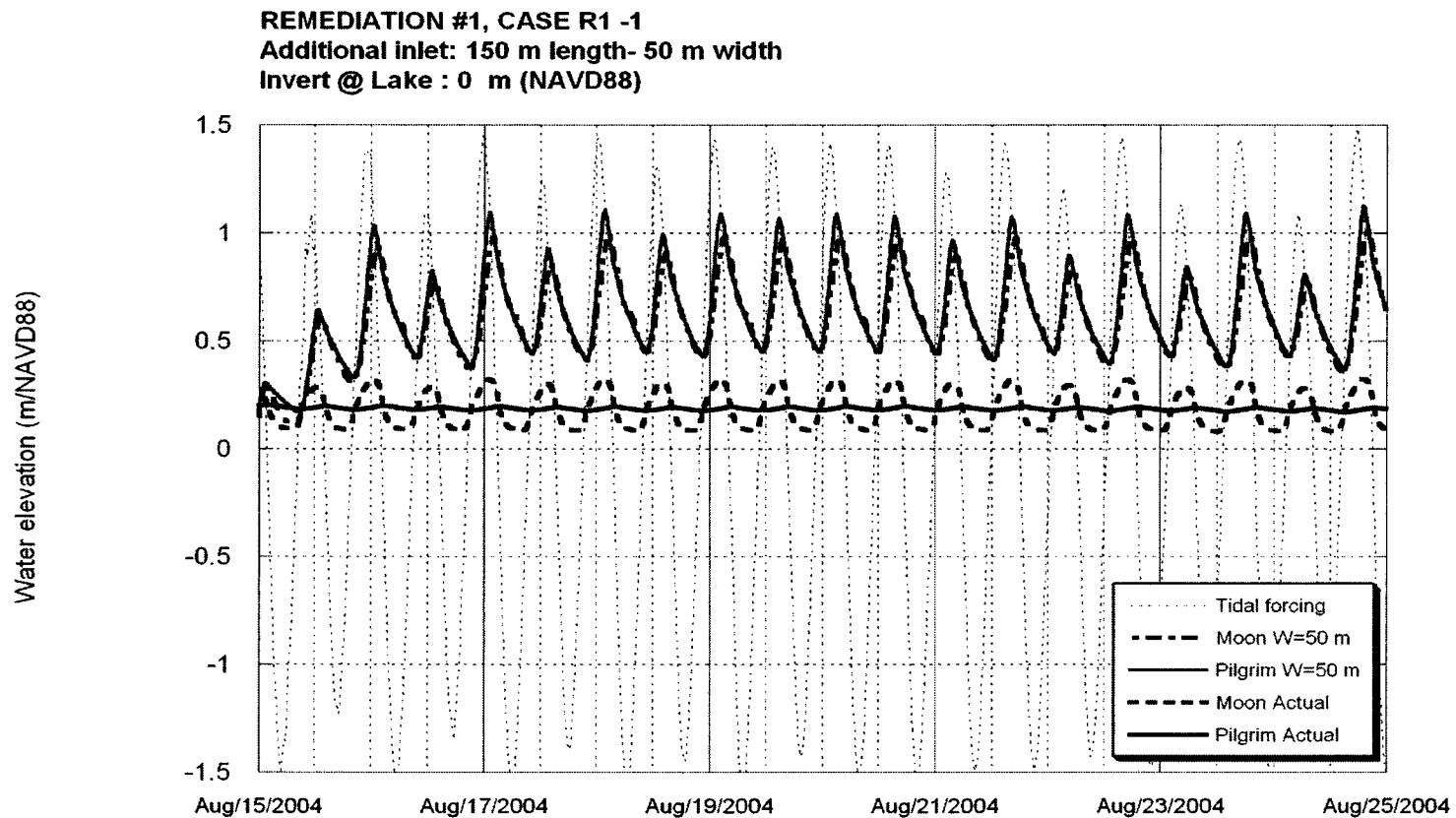


Figure 29

Model predicted water levels in Moon Pond and Pilgrim Lake for Case R1-1A a 50 m wide, 150 m long inlet (bottom set at 0.0 m NAVD88) on the northern end of the Lake. Pilgrim Lake and Salt Meadow are assumed as one system. Also shown are tidal forcing in Provincetown and the current water levels in Moon Pond and Pilgrim Lake.

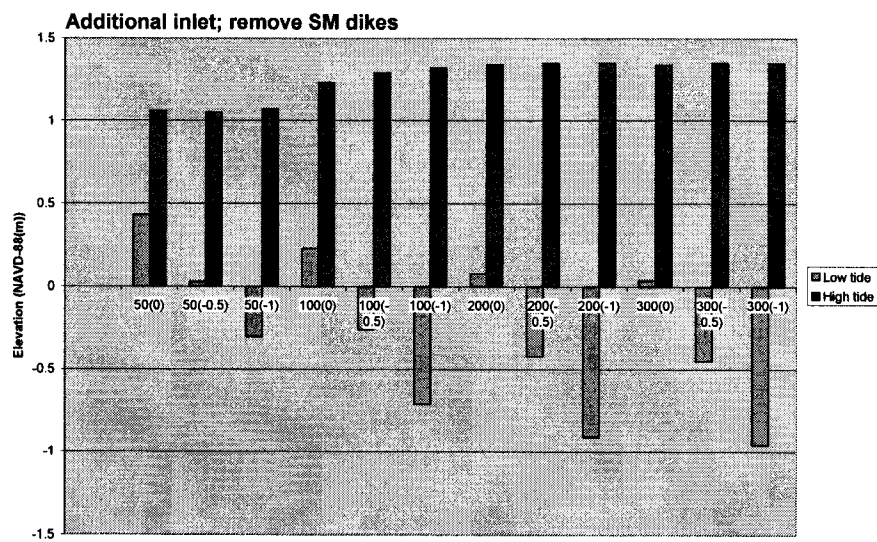


Figure 30 Histogram of the model predicted high and low tide water levels in Pilgrim Lake for Option 1 cases. The values of the inlet width (m) and depth (m, NAVD88) are provided for each case (e.g. 100 (-1.0) is 100 m wide inlet with a depth of -1.0 m)

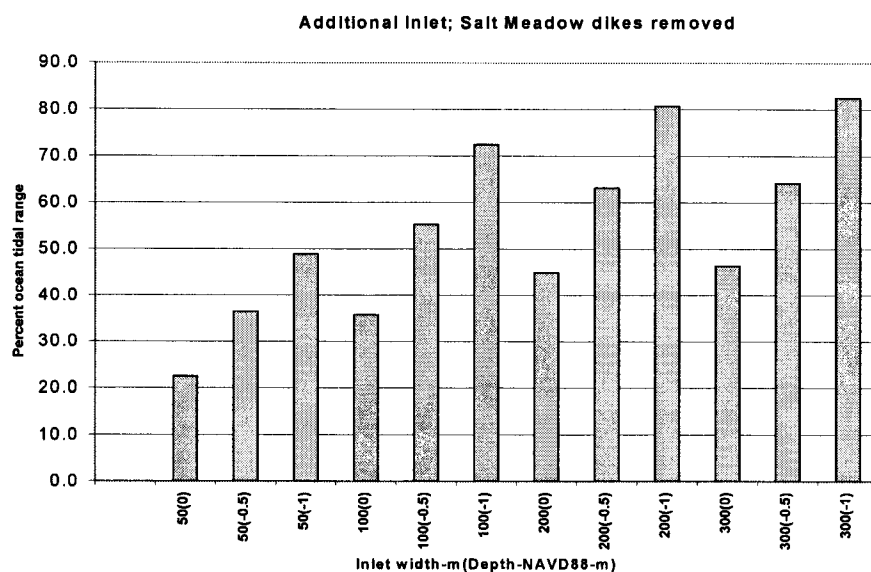


Figure 31 Histogram of the model predicted tidal range in Pilgrim Lake for Option 1 cases. The values of the inlet width (m) and depth (m, NAVD88) are provided for each case (e.g. 100 (-1.0) is 100 m wide inlet with a depth of -1.0 m).

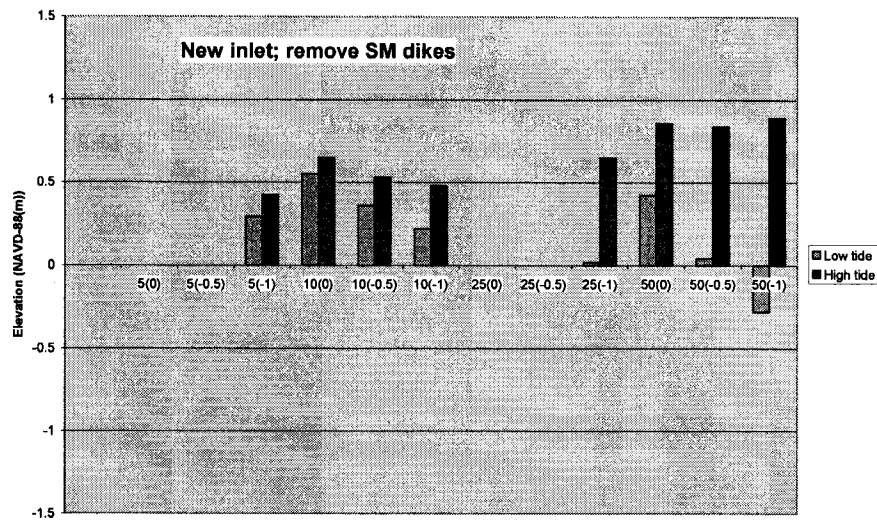


Figure 32 Histogram of the model predicted high and low tide water levels in Pilgrim Lake for Option 2-1 cases. The values of the inlet width (m) and depth (m, NAVD88) are provided for each case (e.g. 100 (-1.0) is 100 m wide inlet with a depth of -1.0 m).

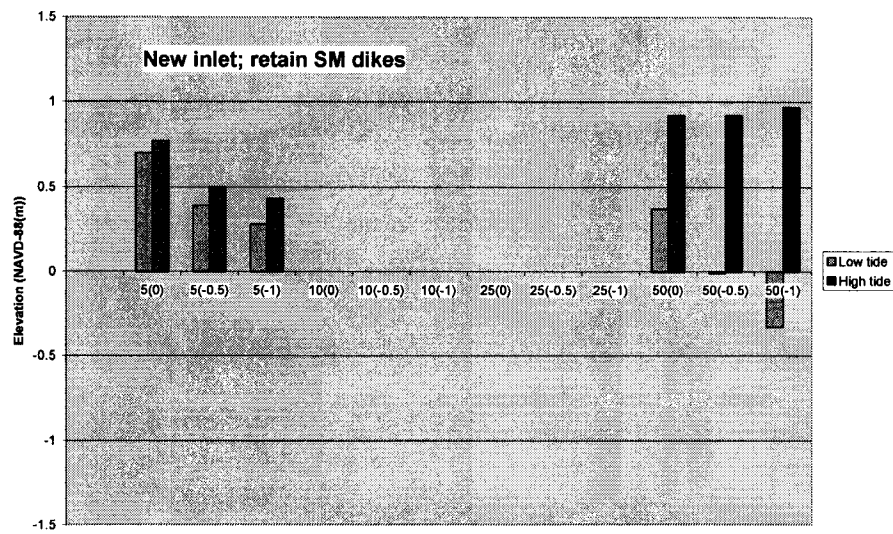


Figure 33 Histogram of the model predicted high and low tide water levels in Pilgrim Lake for Option 2-2 cases. The values of the inlet width (m) and depth (m, NAVD88) are provided for each case (e.g. 50 (-1.0) is 50 m wide inlet with a depth of -1.0 m).

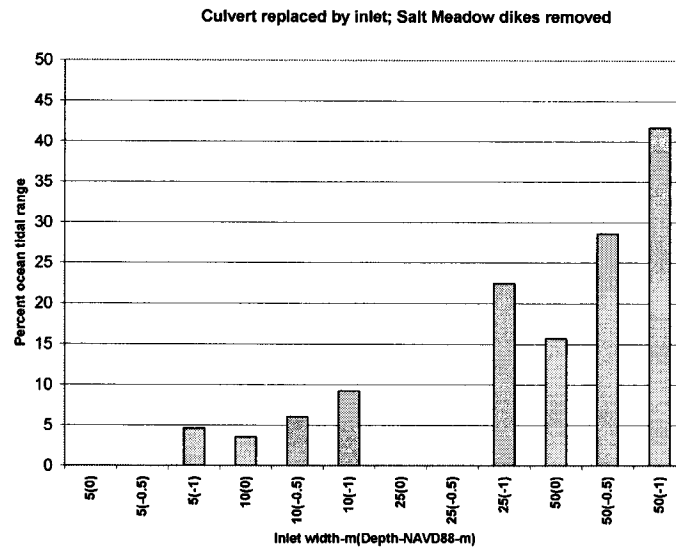


Figure 34 Histogram of the model predicted tidal range in Pilgrim Lake for Option 2-1 cases. The values of the inlet width (m) and depth (m, NAVD88) are provided for each case (e.g. 50 (-1.0) is 100 m wide inlet with a depth of – 1.0 m).

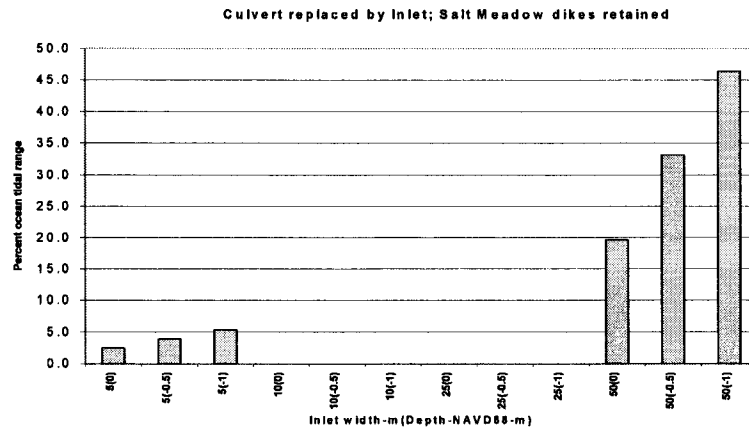
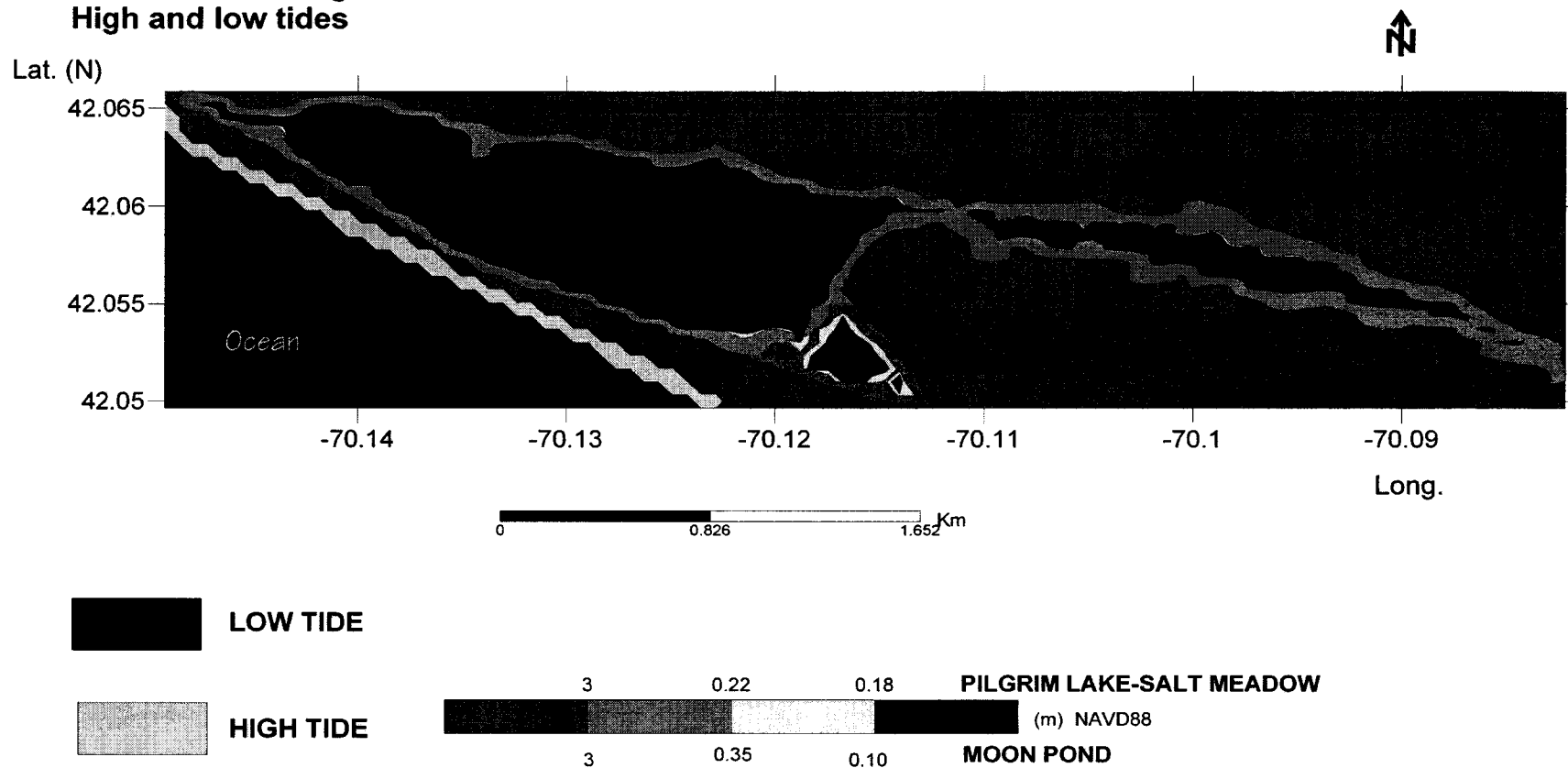


Figure 35 Histogram of the model predicted tidal range in Pilgrim Lake for Option 2-1 cases. The values of the inlet width (m) and depth (m NAVD88) are provided for each case (e.g. 50 (-1.0) is 50 m wide inlet with a depth of -1.0 m).

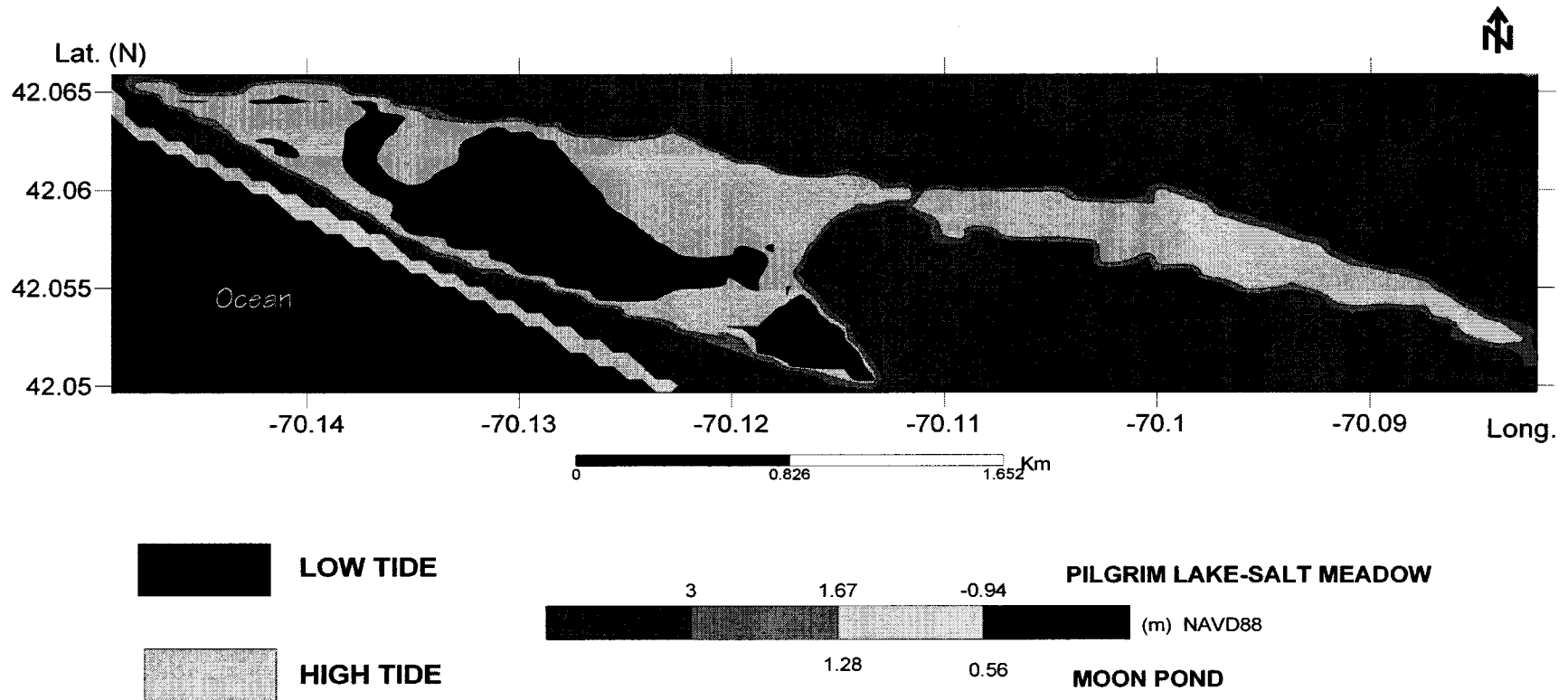
**Pilgrim Lake, Moon Pond, Salt Meadow
Simulated existing conditions
High and low tides**



Data source: Mark Adams, NPS

Figure 36 Plan views of the water surface at high and low tide for existing conditions. Note separate scales for Pilgrim Lake-Salt Meadow and Moon Pond.

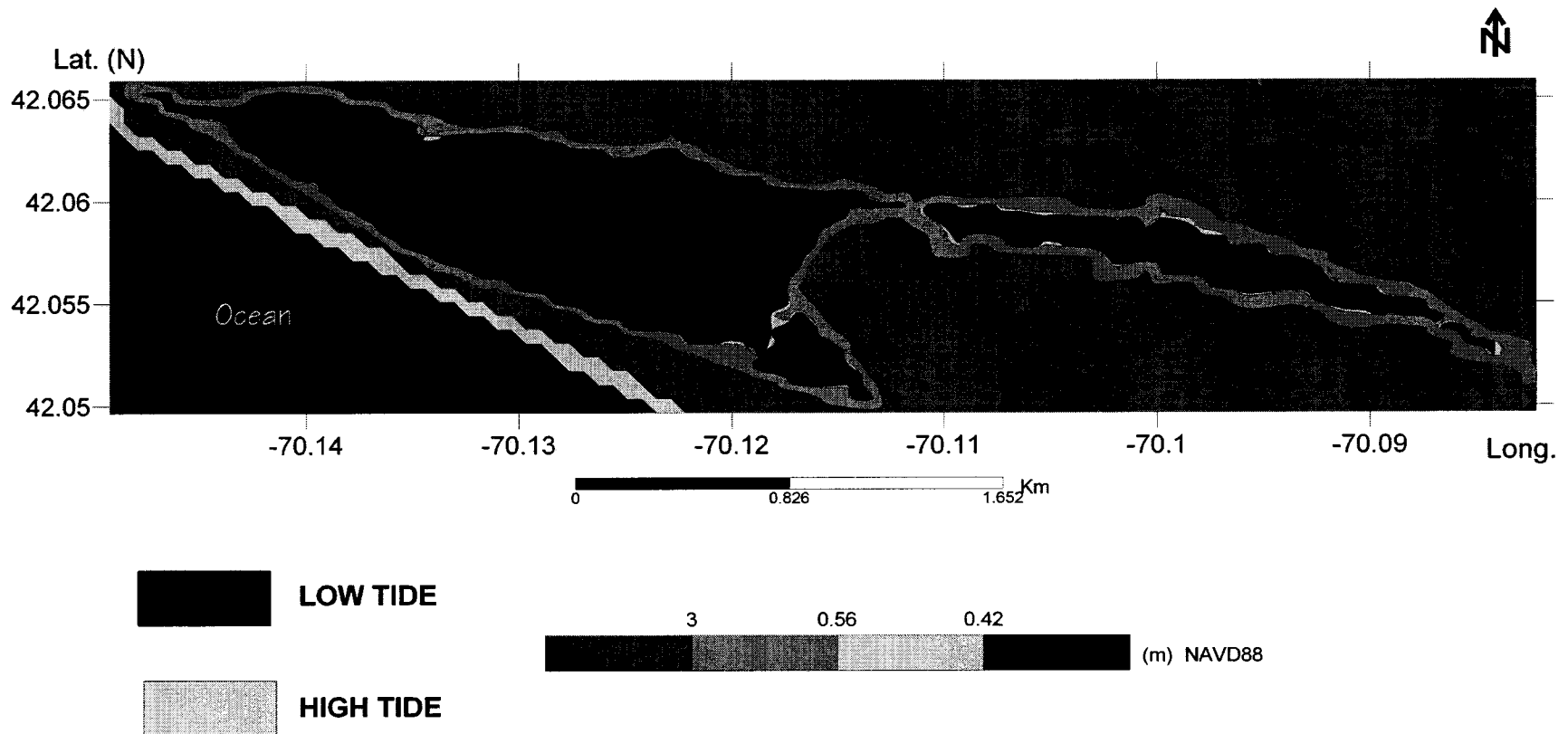
**Pilgrim Lake, Moon Pond, Salt Meadow
SIMULATED RESTORATION OPTION
300 M WIDTH ADDITIONAL INLET - SALT MEADOW CULVERTS REMOVED
High and low tides**



Data source: Mark Adams, NPS

Figure 37 Plan views of the water surface at high and low tide for case R11-4C.

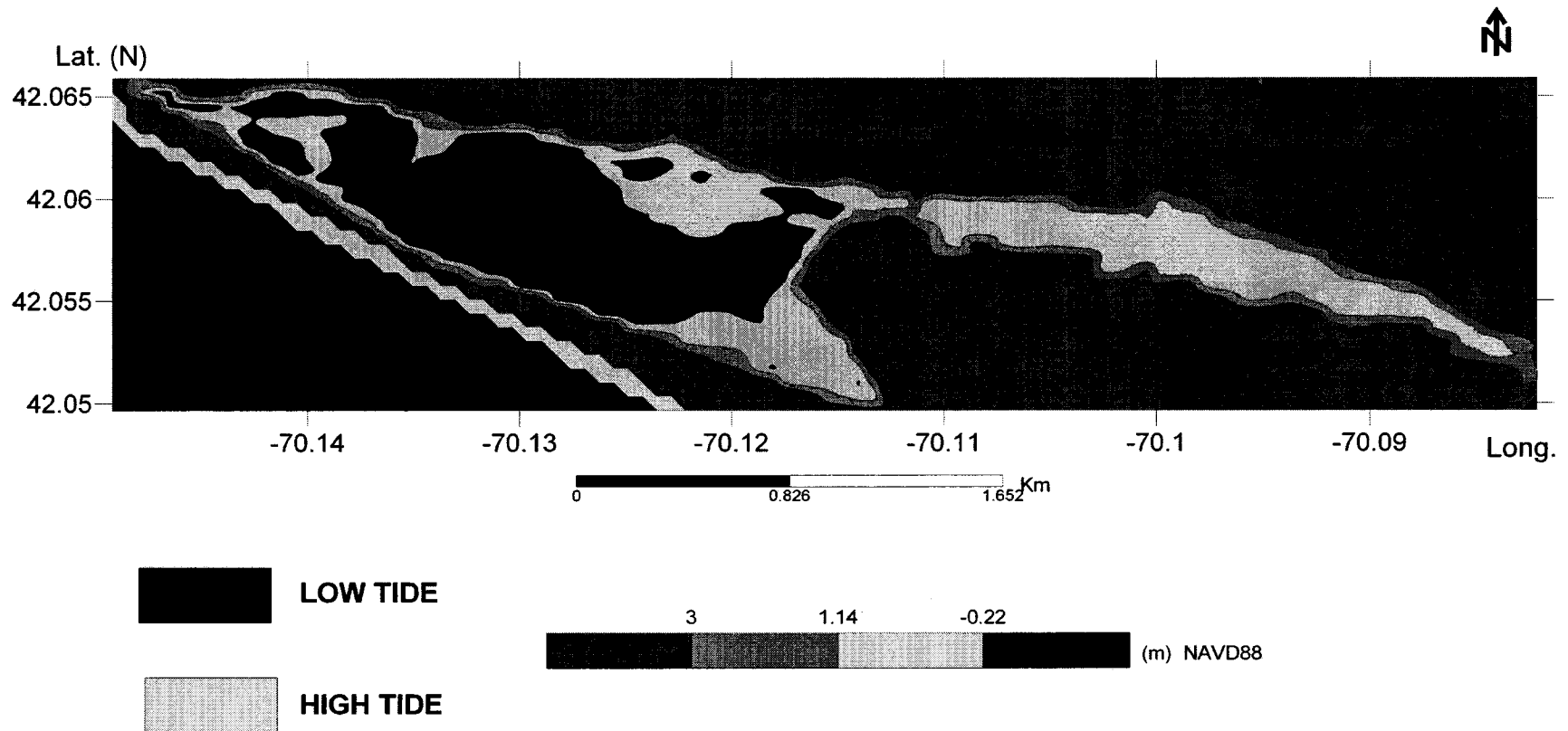
**Pilgrim Lake, Moon Pond, Salt Meadow
SIMULATED RESTORATION OPTION
5 M WIDTH INLET - SALT MEADOW CULVERTS REMOVED
High and low tides**



Data source: Mark Adams, NPS

Figure 38 Plan views of the water surface at high and low tide for case R21-1C.

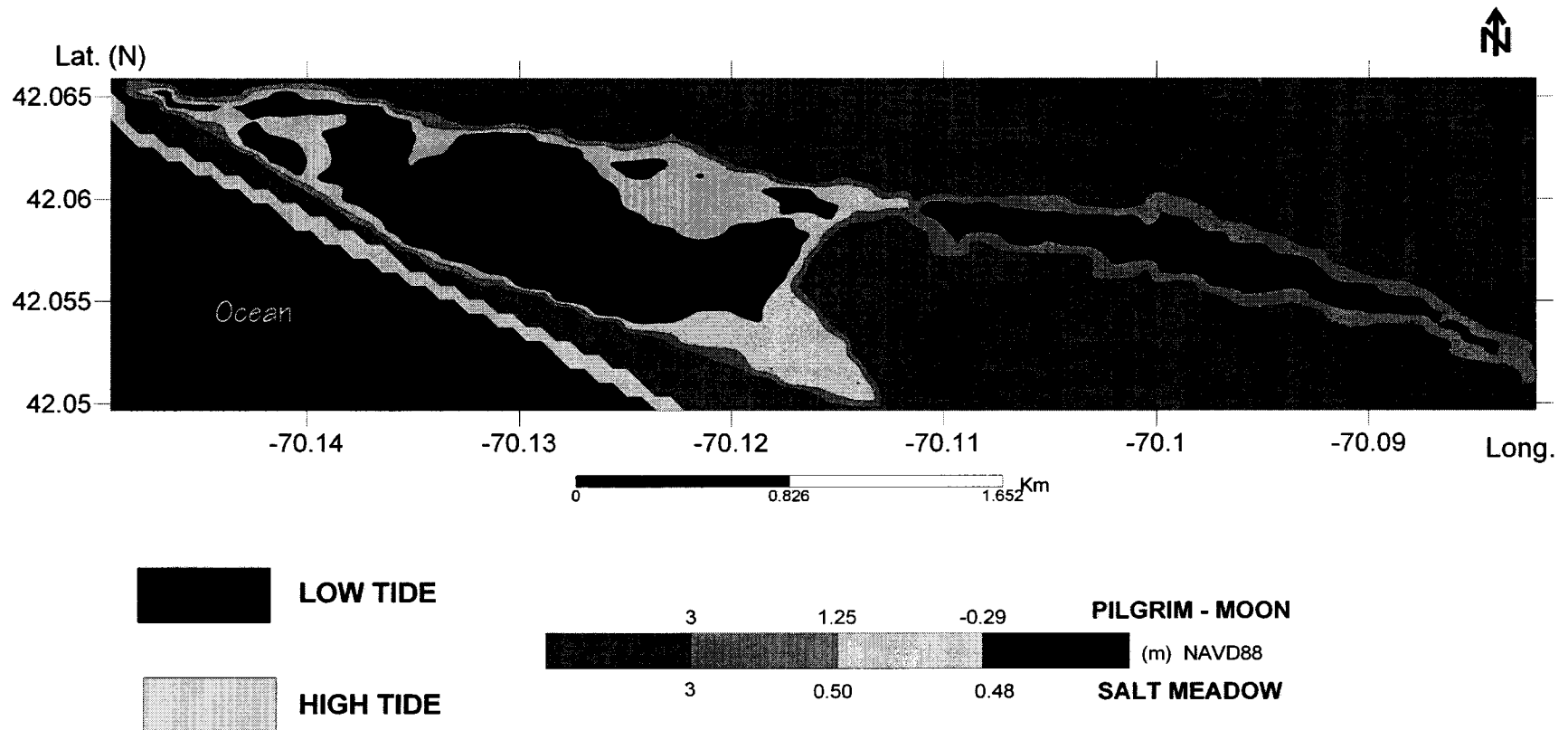
**Pilgrim Lake, Moon Pond, Salt Meadow
SIMULATED RESTORATION OPTION
50 M WIDTH INLET - SALT MEADOW CULVERTS REMOVED
High and low tides**



Data source: Mark Adams, NPS

Figure 39 Plan views of the water surface at high and low tide for case R21-4C.

**Pilgrim Lake, Moon Pond, Salt Meadow
SIMULATED RESTORATION OPTION
50 M WIDTH INLET - SALT MEADOW CULVERTS MAINTAINED
High and low tides**



Data source: Mark Adams, NPS

Figure 40 Plan views of the water surface at high and low tide for case R22-4C.