CHILMARK POND HYDRODYNAMIC STUDY

1 INTRODUCTION

This section summarizes field data collection effort and the development of hydrodynamic models for the Chilmark Pond system (Figure 1). For this system, the model offers an understanding of water movement from the pond during a breach, and provides the first step towards evaluating water quality, as well as a tool for later determining nitrogen loading "thresholds". Nutrient loading data combined with measured environmental parameters within the system become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing water quality parameters, as well as determining the likely positive impacts of various alternatives for improving health of the pond, facilitating the understanding of how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

In general, water quality studies of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

Coastal ponds like Chilmark Pond are the initial recipients of freshwater flows (i.e., groundwater and surfacewater) and the nutrients they carry. An embayment's shape influences the time that nutrients are retained in them before being flushed out to adjacent open waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increase the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development are tied together through inputs of pollutants in runoff, rainfall and groundwater flows. Excess nutrients, especially nitrogen, promote phytoplankton blooms, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

1.1 System Physical Setting

Chilmark Pond is situated along the southern shoreline of Martha's Vineyard. The layout of the Chilmark Pond system is shown in the aerial photograph detail of Figure 1. The pond has a surface area of approximately 260 acres. The pond is fully enclosed, but is periodically opened by means of a trench dug across the beach to drain the pond into the Atlantic Ocean.

Similar systems, sometimes referred to as "blind", "intermittently open", or "seasonally open" estuaries, are also found in Australia, on the west coast of the United States, South America, and India (Stretch and Parkinson, 2006). Perched estuaries are those that have water levels consistently above mean sea level (MSL) and tend to occur on coastlines that have an energetic wave climate with steep beaches and coarse sediments. It is common practice to artificially breach closed ponds/estuaries when water levels become high, typically to prevent flooding of upland properties and to flush the systems from a build-up of contaminants adversely impacting water quality. Other coastal ponds along the south coast of Martha's Vineyard, Nantucket, and the southern shoreline of Massachusetts/Rhode Island are local examples of where periodic breaching is a regular method employed to manage water quality.

Figure 1. Aerial photograph of Chilmark Pond on Martha's Vineyard, Massachusetts.

1.2 System Hydrodynamic Setting

In Chilmark Pond, the hydrodynamic regime is dominated by freshwater inputs to the system from groundwater recharge, surface flow run-off from the watershed, and direct precipitation to the pond's surface. The volume of water in the pond is governed by the balance between additions from freshwater inflow and losses due to evaporation and flow through the southern beach face into the ocean. On average, the inputs are greater than the losses and the pond elevation gradually rises.

When the pond level is deemed high enough, a trench is cut across the southern barrier beach. The opening is made during favorable tide conditions to ensure the greatest potential to create a successful breach. The initial outflow from the pond causes a relatively small channel to be scoured through the beach and the water level in the pond drops. The ephemeral channel across the beach is a balance between the scouring effect of water flowing through it and the filling effect of sediment transport along the beach. Although Chilmark Pond is large relative to other regional coastal ponds, the wave climate on the southern coast of Martha's Vineyard is one of the most energetic in Massachusetts. As a result, the breach channel typically closes very quickly, sometimes after only minimal tidal exchange has occurred. The result is that these short or failed breaches only remove the top layer of water from the pond. For these failed breaches, there is very little inflow of water from the ocean and little mixing of the nutrient rich water from the pond with low nutrient inflow. As a result, openings that do not allow influx of ocean waters simply lower the water levels and do little to improve the water quality inside the pond, and only lower the pond.

2 HYDRODYNAMIC FIELD DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of Chilmark Pond. Bathymetry data were collected throughout the system so that it could be accurately represented as a computer hydrodynamic model, and so that flushing rates could be determined for the system. In addition to the bathymetry, tide data were also collected at three locations, to run the circulation model with real tides, and also to calibrate and verify its performance.

2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Chilmark Pond system were assembled from a April 2011 boat based hydrographic survey. The survey was designed to cover the entire main basin of Chilmark Pond, as well as the various coves within the pond. The survey was conducted from a 14' skiff with an installed precision fathometer (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide horizontal position measurements accurate to approximately 1-3 feet. As the boat was maneuvered around the pond, digital data output from both the echo sounder fathometer and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position.

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the North American Vertical Datum 1988 (NAVD88). Once rectified, the finished processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The tracks followed by the boat during the bathymetry survey are presented in Figure 2.

2.2 Tide Data

Tide data records were collected at three stations in the Chilmark Pond system: 1) the north end of the main basin, 2) the west end of the main basin, and 3) the western sub-embayment. The locations of the stations within the pond are shown in Figure 3. The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 49-day period between April 26 and June 14 2011. The elevation of each gauge was leveled relative to NAVD88. Available data from the Martha's Vineyard Coastal Observatory (MVCO) offshore of Katama Beach was utilized as the offshore boundary condition for the hydrodynamic model.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. Hourly atmospheric pressure readings were obtained from the NOAA C-MAN station in Buzzards Bay, interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in variations in water pressure above the instrument. Further, a constant water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gauge). The sensors were surveyed into local benchmarks to provide vertical rectification of the water level; these survey values were used to adjust the water surface to a known vertical datum. The result from each gauge is a time series record representing the variations in water surface elevation relative to the NAVD88 vertical datum. A plot of the observed tide signals is shown below in Figure 4, where the two stations in the main basin yielded identical tide signals.

3 HYDRODYNAMIC MODEL DEVELOPMENT

The scour of a channel through the beach and the flow of water between the pond and ocean through this channel cannot be directly simulated with the RMA suite of models. Therefore, a computer model independent of RMA-2 was used to simulate the flow through the breached channel. Using this breach model, time varying boundary conditions were developed for RMA-2 model runs of the main portion of Chilmark Pond, up through the inlet channel.

3.1 Modeling flow through a breach

When the pond is first opened, the initial trench cut through the beach is scoured out by the rush of water leaving the super-elevated pond. The channel increases width and depth during this time and over the first few tides cycles if the breach remains open. It would be beyond the scope of this study to model the dynamic growth of the channel during the breach event itself. However, the width and depth of the channel are important variables needed to model the flow between the ocean and Chilmark Pond. To parameterize variables pertinent to the Chilmark Pond breach, *in situ* data from a breach event in May 2011 were analyzed.

Based on aerial imagery, the channel width was estimated to be 80 feet. To estimate the channel scour depth, the flow rate through the channel is needed. Using the data from the May 2011 breach event, the water levels following the initial opening could be observed (Figure 4). This plot shows the elevated water level in the pond at about 4.9 feet NAVD. Around mid-day on May 2nd, the pond level drops steeply, indicating that the breach had been opened at this time. The pond continued to drain until the tide offshore was higher than the pond elevation. At this time ocean water flowed into the pond. When the tide lowered again, the pond drained until the next rising tide. This continued until approximately May 20th, at which time the channel had almost closed and the pond level changed at a much slower rate. Around May 24th, tide data indicates that the breach had been completely filled in with sand and there was no longer exchange between the pond and the ocean.

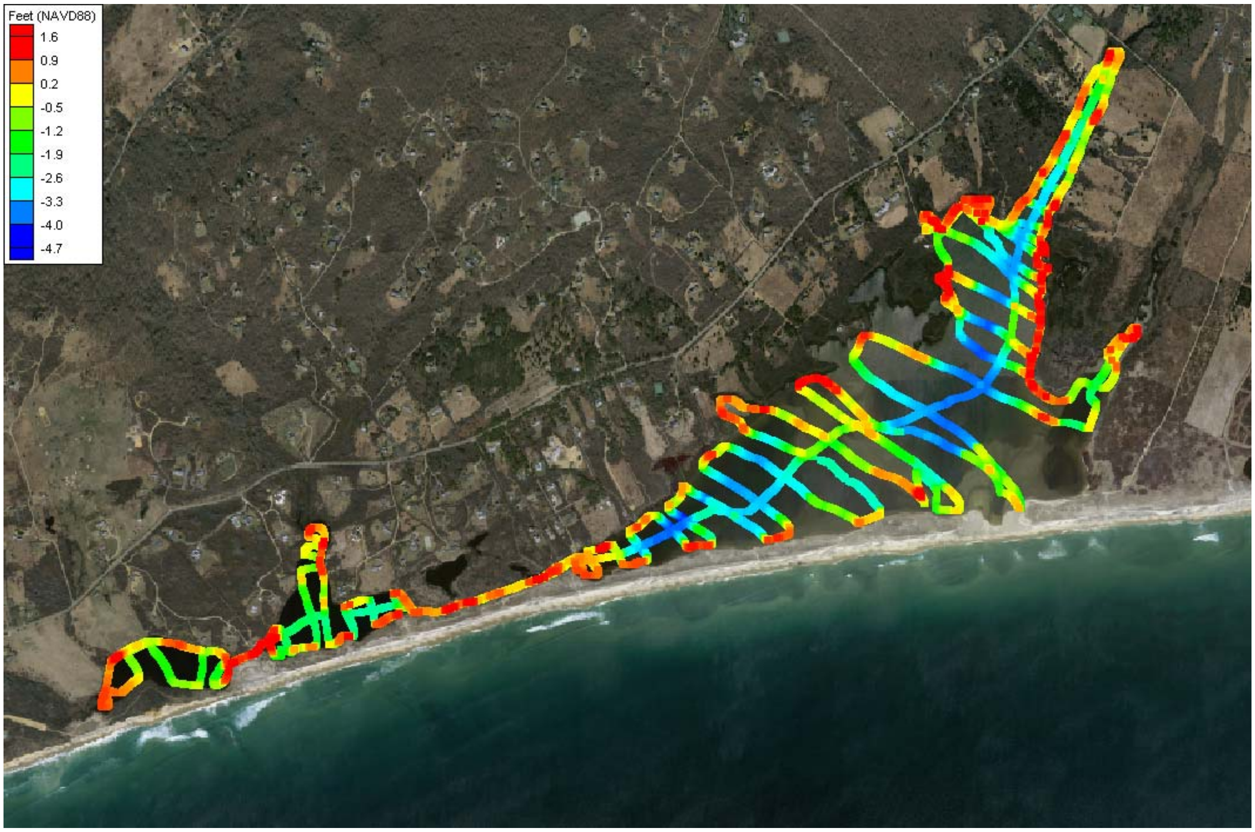

Figure 2. Bathymetry survey lines and depths for Chilmark Pond.

Using these data, an average flow rate out of the pond was calculated. The first four times that the pond level was falling after the initial opening were examined to determine the drop in pond elevation and the time over which this drop occurred. Together with the surface area of the pond (approximately 260 acres), these values led to a calculation of 360 ft^3/s of water leaving the pond on average.

With the flow rate and channel width established, the channel depth was calculated using an approach described by the U.S. Army Corps of Engineers (USACE) for the analysis of scour depth at tidal inlets (Hughes, 1999). This equation predicts the depth of the channel, given the flow rate, sediment type and channel width as

$$h = \frac{0.234 q^{8/9}}{\left[g(S-1)\right]^{4/9} d^{1/3}}$$

where *h* is the elevation of the channel bottom relative to the high water level, *q* is the flow rate divided by the channel width, *S* is the specific gravity of the sand and *d* is the average diameter of the sand. A quartz sand (*S* = 2.65) of diameter 0.5mm was used to represent the sand in this case.

Figure 3. Aerial photograph of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. The gage locations are shown in red: (S-1) represents the north end of the main basin, (S-2) represents the west end of the main basin, and (S-3) represents the sub-embayments to the west.

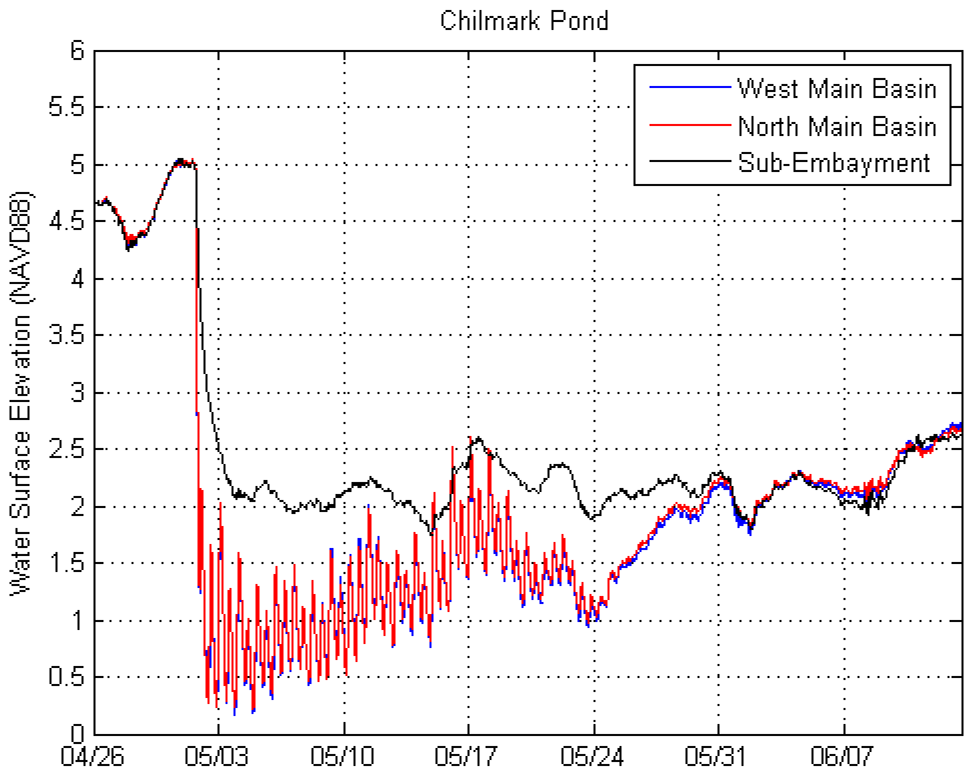

Figure 4. Tide gage signals measured within Chilmark Pond. The figure represents the entire 49-day record (April 26 to June 14 2011). Elevations are referenced to NAVD88.

With the initial pond elevation, offshore tides, channel width, and channel depth established, the final step was to estimate the flow in and out of Chilmark Pond during the breach event. To compute this volume exchange, the equation of flow over a broad-crested weir was employed. This equation relates the flow rate through the channel to the channel width and height of water above the channel bottom as

$$Q = 3.0bH^{3/2}$$

where Q is the predicted flow rate, b is the channel width and H is the difference in elevation between the high water and the channel bottom.

Using the starting pond level of 4.9 feet NAVD88 and the recorded offshore tides, a computer model was created to calculate the time-varying flow through the channel. The pond level and offshore tide every 10 minutes was input into the model and the flow rate was calculated. Multiplying the flow rate by the time step yields the total volume of water moving through the channel. If the pond level is higher than the offshore tide, this water is leaving the pond, while a higher water level in the ocean means that water is entering the pond. Knowing the surface area of the pond, the change in pond surface elevation was calculated at each time step. The comparison between the field data and the broad-crested weir model is shown in Figure 5.

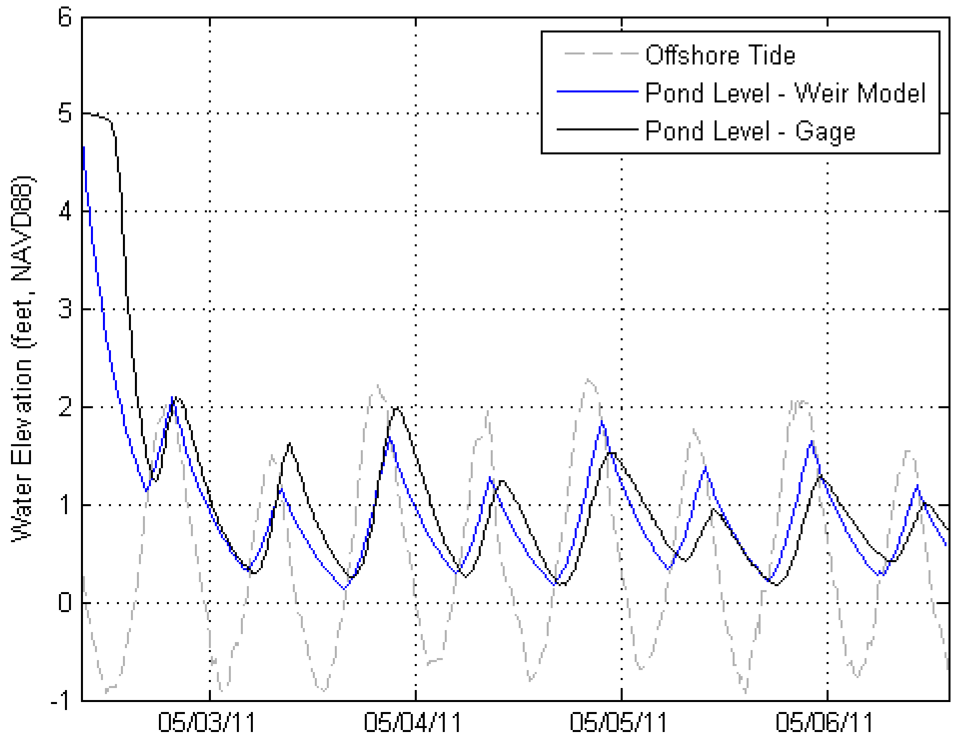

Figure 5. A comparison of the broad-crested weir model results with the recorded pond elevations during the breach event at Chilmark Pond.

This simple modeling approach has been used in the Massachusetts Estuary Project for both Edgartown Great Pond on Martha's Vineyard and Sesachacha Pond on Nantucket Island and yielded excellent agreement with the field data, with an rms error of 0.28 feet. From these reports it has been determined that this approach is best for the first five or so days while the channel is fully open, after which the model starts to deviate further from the observed signal. This indicates that the water was not traveling through the channel freely, suggesting that the opening was beginning to shoal. This is a good reminder that the weir model assumes a fully open channel and makes no approximations for the natural shoaling and eventual closure of the breach. With that caveat in mind, the broad-crested weir model was used to simulate the first four (4) days of the breach event, and it yielded a very good approximation of flow in Chilmark Pond. The resulting pond elevations were used as the boundary condition for the RMA2 model.

3.3 RMA2 Model Development and Theory

A two-dimensional hydrodynamic model of Chilmark Pond was developed using inputs of bathymetry and modeled water surface elevations determined using the broad-crested weir model (Figure 5). The RMA-2 model was utilized based upon its successful implementation in the Massachusetts Estuary Project.

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2 is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the system. Element boundaries may either be curved or straight.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore it is unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

The finite element mesh with interpolated bathymetry is shown in Figure 6. The grid is composed of 2282 quadratic finite elements (both triangular and quadrilateral elements) and 7048 computational nodes. The grid has a maximum depth of -4.8 ft NAVD88, which is located in the deep area in the central region of the main basin. The bathymetry in the area around the breach in the southeast edge of the pond was edited to be deeper than actually occurs there. This small change was made to ensure model stability and has little impact on the modeled pond elevations.

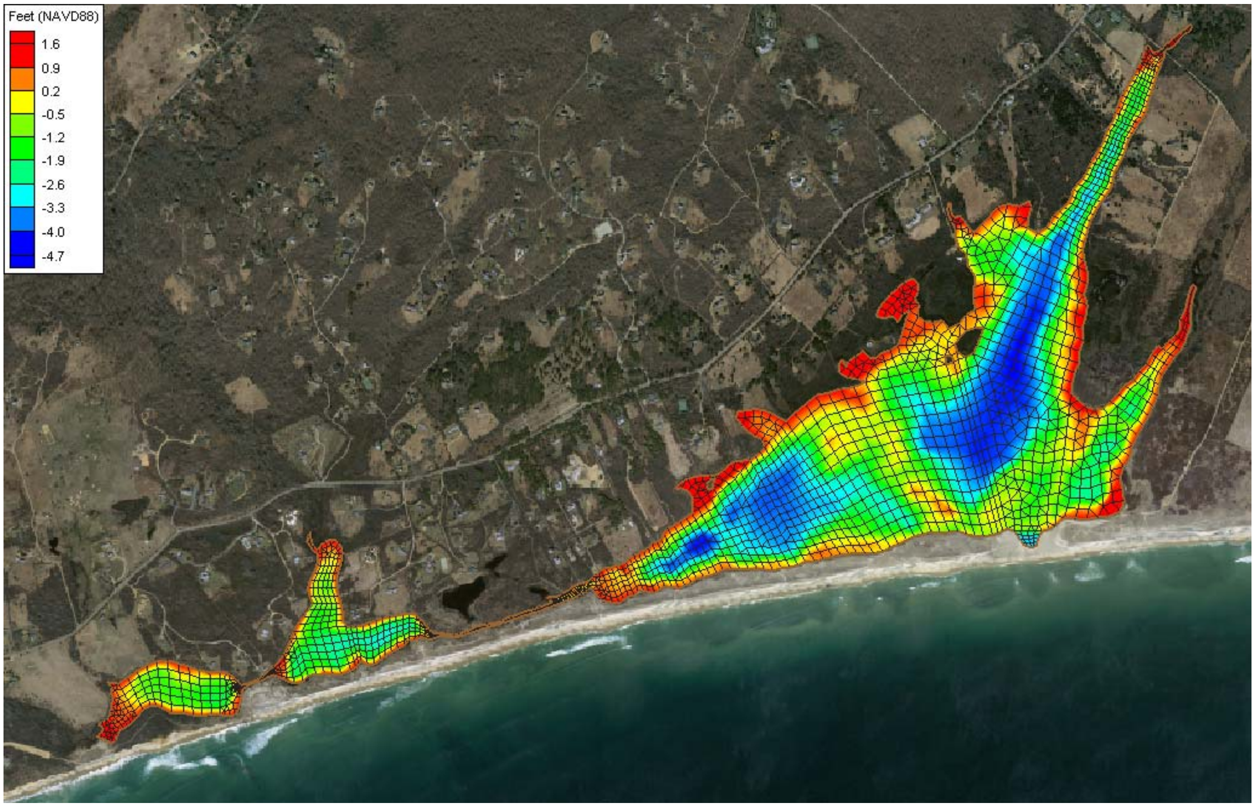

Figure 6. Interpolated bathymetric contours (feet) of the final RMA2 computational mesh of Chilmark Pond. Depth contours are relative to the NAVD88.

4. FLUSHING CHARACTERISTICS

During a sustained breach event, the freshwater inflow would be negligible in comparison to the tidal exchange through the temporary inlet. A rising tide in the Atlantic Ocean creates a slope in water surface from the ocean into the pond. Consequently, water flows into (floods) the pond. Similarly, the pond drains on an ebbing tide. This exchange of water between the pond and ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to quantitatively evaluate the tidal flushing of the system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of a pond from points within the system. For this study, a **system residence time** was computed as the average time required for a water parcel to migrate from a point within the pond to the entrance of the channel. System residence times are computed as follows:

$$T_{system} = \frac{V_{system}}{P} t_{cycle}$$

where T_{system} denotes the residence time for the system, V_{system} represents volume of the pond at mean tide level, P equals the tidal prism (or volume entering the pond through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days).

Residence times are provided as a first order evaluation of estuarine water quality. Lower residence times generally correspond to higher water quality; however, residence times may be misleading depending upon pollutant/nutrient loading rates and the overall quality of the receiving waters. As a qualitative guide, system residence times are applicable for systems where the water quality within the entire estuary is degraded and higher quality waters provide the only means of reducing the high nutrient levels. This is a valid approach in this case, since it assumes the ocean has higher quality water relative to the pond.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the system faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the pond is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing water quality in the Chilmark Pond system.

The average volume calculated for Chilmark Pond is 26,550,000 ft^3 with a tidal prism of 13,100,000 ft^3 when the inlet is open. This results in a residence time of approximately 1.1 days. This modest residence time provides some confidence that the temporary channel allows enough exchange to significantly improve water quality during a typical breach event.