

Wastewater Management Validation and Design Committee

Subject: Summary Chapter V (Hydrodynamic Modeling)

Massachusetts Estuaries Project - Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Pleasant Bay System - Final Report May 2006¹

Key Issues:

1. Treatment of model attributes impacting the behavior of constituents, such as nitrogen, when introduced into the Pleasant Bay estuary (e.g. flushing, residence times, dispersion coefficients, mixing currents, etc.).
2. Adequacy of two dimensional model (Ref¹ p110 ¶ 1).
3. Adequacy of tidal and bathymetry data to modeling the behavior of constituents in Pleasant Bay estuary waters.
4. Impact of the North Breach of the Nauset Spit which opened in April 2007, both current and future, on the behavior of constituents and water quality in the Pleasant Bay estuary.

Tasks to Be Undertaken to Address the Key Issues:

Task 1. Conduct a critical review of the hydrodynamic model described in the SMAST-MEP report¹ and its application to the Pleasant Bay estuary with a focus on the following:

- a. The methodology and assumptions used in the development and application of the model;
- b. The methods used in the model to treat model attributes impacting the behavior of constituents, such as nitrogen, when introduced into the Pleasant Bay estuary (e.g. flushing, residence times, dispersion coefficients, mixing currents, etc.);
- c. Adequacy of the two dimensional model to describe the behavior of constituents, such as nitrogen, when introduced into the Pleasant Bay estuary. (Ref¹ p110 ¶ 1);
- d. Adequacy of tidal and bathymetry data used to model the impact of tidal phenomenon on the behavior of constituents in Pleasant Bay estuary waters.

Task 2. In April 2007, the North Breach (Kelley and Ramsey²) opened a new inlet connecting Pleasant Bay to the Atlantic Ocean. Conduct a critical review to assess the impact, current and projected over the next 20-50 years, of the North Breach of the Nauset Spit and the combined Pleasant Bay inlet system on the behavior of constituents and water quality in the Pleasant Bay estuary.

The purpose of conducting these tasks is to identify any significant problems or gaps in the design and operation of the hydrodynamic model that may result in significant differences in the expected behavior of water quality constituents, such as nitrogen.

Expertise and Experience Required to Complete the Tasks:

1. Hydrology and finite element analysis.
2. Two and three dimensional hydrological model development and application.
3. Coastal geologist (evaluation of issue 4. above) [preferred]

¹ Howes B., Kelley, S.W., Ramsey J.S., Samimy, R., Schlezinger, D., Eichner, E. (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Pleasant Bay, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

² Kelley, S.W., and Ramsey, J.S. (July 2008) Hydrodynamic Model of Chatham Harbor/Pleasant Bay including 2007 North Breach. Applied Coastal Research and Engineering, Inc., Mashpee, MA.

APPENDIX

Commentary:

Estuarine Circulation

Most of Pleasant Bay does not behave physically in the characteristic manner of estuaries, i.e. dominated by the mixing of saline and fresh water. The salinity gradient between the mouth and the head of the Pleasant Bay itself is minimal (only a few ppt), indicating very little mixing of water bodies. Thus, density driven estuarine circulation is not a significant factor in the hydrodynamics of the major portion of Pleasant Bay.

However, this is not the case in several of the small sub-embayments (drowned kettle ponds) at the northern extremity of the Pleasant Bay system. These sub-embayments are often cited as being eutrophic and containing the most degraded benthic habitats in the entire Pleasant Bay. A major portion of the fresh water that enters Pleasant Bay enters through these sub-embayments, and accordingly they typically display the lowest salinities in the Pleasant Bay. The analysis of tidal exchange between these sub-embayments and Pleasant Bay proper in the SMAST-MEP report does not seem to consider the significant influence of density driven gravitational flow in the flushing of the sub-embayments. This point is discussed in the section titled Residence Times and Flushing Rates below.

Tidal Exchange

The SMAST-MEP report (V, p.85) indicates that mean tidal range in the Pleasant Bay at the time the study was conducted was about half that in immediate offshore waters. Nevertheless, Pleasant Bay does contain well defined and relatively strong tidal currents. The SMAST study employed seven tide gauges to input differential water surface data into its hydrodynamic model (V, p.96). Of these, one station was located off the mouth of the inlet at the south end of the Pleasant Bay, two were located within the northernmost sub-embayments of the system, and the remaining four were distributed along the western margins of the Pleasant Bay system between the north and south ends of the Pleasant Bay (see Fig. V-8, p.97). Consequently, the model generated from this data set treated flooding and ebbing tidal amplitudes linearly and roughly longitudinally, as a wave propagated from south to north and sloshing back to the south. For instance, see Fig. VI-2, p.137 and Fig. VIII-1, p.216, for the modeled tidal effects on nitrogen concentrations. Evidence of this is shown by the SMAST study description of the main basin of Pleasant Bay as "relatively quiescent" and the use low dispersion coefficient values. The method of tidal modeling employed may bear significantly on the flushing characteristics within the Pleasant Bay.

Earlier studies by Horne and Horne³ documented compelling circumstantial evidence indicating that tidal circulation within Pleasant Bay is more complex. The distribution, size, shape, and orientation of macro-bedforms (megaripples, subaqueous dunes, and sand waves) on the substrate indicate the direction and relative magnitude of bed shear produced by currents working on that substrate. The fields of bedforms within Pleasant Bay clearly showed that the eastern half of the Pleasant Bay (just west of the Nauset barrier spit) was dominated by flood currents flowing northerly, while the western half of the Pleasant Bay (to the east of the embayed mainland shore) was dominated in contrast by ebb currents flowing southerly (see Horne and Horne, fig. 9). Both the size of the bedform fields and of the individual bedforms indicated that competent flow (and bed shear) was stronger and more widespread in the shallower eastern part of the Pleasant Bay than in the deeper western part. These lines of

³ Horne, G. S. and C. F. Horne, 2001, Reconnaissance hydrography of the upper reaches of Little Pleasant Bay, Orleans, MA: report to the Pleasant Bay Resource Management Alliance, 10 p., 9 figs., 2 tables.

evidence suggested that residual tidal circulation integrated over the course of full tidal cycle within the Pleasant Bay approximated a counterclockwise gyre. This interpretation could be anticipated from the influence of the Coriolis Effect deflecting both flood and ebb flow to the right, and it was corroborated by east-west temperature contrasts during the flooding tide, cooler water to the east. Furthermore, such an interpretation would suggest that mutually evasive and opposing tidal currents could co-exist during the change of tidal state.

This type of gyric circulation through a tidal cycle is also supported by current studies reported in the SMAST-MEP analysis (V, p.105). Cross-channel current measurements during peak flood flow across the mouth of The River between Namequoit Point and Old Field Point (Fig.V-16, p.126) show waning ebb flow at the western margin of the cross-section while most of the section to the east is strongly flooding, with a significant cross-channel component of flow from west to east. Ebb tidal currents were much weaker and relatively uniform.

Residence Times and Flushing Rates

The SMAST-MEP study employed the basic geochemical concept of residence time to evaluate the period of time required for tidal currents to replace a parcel of water within the Pleasant Bay with refreshed sea water from the open coastal ocean, often called flushing rate (V, p.125). Residence time usually compares the resident standing concentration of a component within a geochemical system with the rate of input (or output) of that component into (or from) the same system. In the case of the Pleasant Bay system the concept was applied to the tidal prism entering the Pleasant Bay relative to the mean volume of the Pleasant Bay. Similarly, in order to evaluate local flushing in various sub-embayments of the Pleasant Bay system, local residence time compared the tidal prism in the sub-embayment with the mean volume of the sub-embayment. However, SMAST attempted to quantify the flushing of sub-embayments out of the entire Pleasant Bay system by comparing the tidal prism in the sub-embayment with the mean volume of the entire Pleasant Bay system, yielding flushing rates two orders of magnitude greater than for the entire system (Table V-8, p.128). A concept referred to as "system residence time" in the SMAST-MEP report. The system residence time concept suggests that the northern sub-embayments of Pleasant Bay, such as Arey's, Lonnie's, and Pah Wah Ponds, would require between one and two years to be flushed by semi-diurnal tidal prisms that are more than a third of the volume of the entire sub-embayment.

Although the "system residence time" concept is developed in the SMAST-MEP report, it is not clear how it is employed in the hydrodynamic model. The concept of system residence time as a ratio of the volume of a small sub-embayment to the volume of the entire Pleasant Bay estuary system seems illogical. It depends on the unstated and implicit assumption that water flushed from a sub-embayment into the Pleasant Bay itself on the ebbing tide, does not mix appreciably with the Pleasant Bay water, and sloshes partially back into the sub-embayment on the next flooding tide, as though driven by a standing wave or surge (see Fig. VI-2, p.137 again). This assumption ignores the abundant evidence indicating gyric tidal circulation within the Pleasant Bay, which would mix and flush sub-embayment water much more efficiently. In addition, if this implicit assumption was true, the volume of fresh water flowing into the sub-embayments would make it impossible for the sub-embayment salinity to remain in equilibrium at a level not much different from Pleasant Bay itself. Traditionally, systems such as Pleasant Bay estuary are viewed as a series of well mixed 'reactors' and the resulting system residence time is the sum of the residence times in the reactors. The 'series of reactors' applied to the estuary considers stepwise flushing of sub-embayment water to tributaries (so-called rivers), then to the Pleasant Bay proper, and then out of the Pleasant Bay system. Using this traditional analysis, Kescayo Gansett (Lonnies) Pond has a system residence time of 2.8 days versus 375.3 days stated in the SMAST-MEP report.

Moreover, this concept of flushing of sub-embayments seems not to consider the importance of density driven estuarine circulation within the northern sub-embayments of Pleasant Bay.

For example, detailed three dimensional measurements of salinity and temperature inside and outside of Arey's Pond on the flooding tide¹ show that the flooding tidal prism is measurably both cooler and more saline, thus significantly denser than residual water in the Pond. As the more dense flooding water spills over the sill at the entrance to the Pond, clearly it must convect under the fresher and warmer water in the Pond, causing the Pond to turn over and mix. Conversely, on the ebbing tide the less dense water at the surface of the Pond (most diluted by ground water discharge) must be the first to drain out of the Pond and is decanted through The River, mixing into Pleasant Bay. This happens twice a day with each tide cycle. If this were not the case, the continual discharge of fresh ground water into the Pond would cause the Pond water to continually freshen. In fact, the long term salinity level in Arey's Pond is constant and static, indicating a condition of "dynamic equilibrium" with regard to both groundwater discharge and tidal exchange.

Effects of 2007 Breach of Nauset Spit

In April 2007, the Patriot's Day Storm breached Nauset Spit opposite Allen Point (Chatham). Applied Coastal Research & Engineering (ACRE) collected, analyzed and reported on the hydrodynamic data in the SMAST-MEP report. In August 2008 ACRE issued an update² on the earlier study based on data collected in November 2007, 7 months after the opening of the new inlet (North Breach).

As shown in the August 2008 ACRE report², the North Breach has had a significant impact on Pleasant Bay. The North Breach occurred about 1.8 miles north of the Chatham south inlet and initially was only a few hundred feet wide. Since its formation it has widened to more than ½ mile and is still widening. Consequently, it is modifying the bathymetry of the southern portion of Pleasant Bay and strongly affecting the circulation in the entire Pleasant Bay system.

The following is a brief summary of the major changes that have occurred, as summarized at the Pleasant Bay Alliance symposium on the topic in Chatham on June 26, 2008.

Bathymetric information which reflects tidal circulation has been observed by frequent and recent aerial surveillance. Tidal exchange through the new inlet is bifurcated by a flood tidal delta just inside the inlet, with strong flood currents dominating the northern part of the inlet and turning right or north just inside the west side of the spit. As would be expected, the flooding currents have intercepted the southerly longshore drift of foreshore sediment, and transported it through the inlet, forming the flood tidal delta and burying a large (tens of acres) bed of eelgrass behind the spit and extending to the north. Flooding currents continue to the north between Nauset Spit and Strong Island, bypassing the major part of Pleasant Bay and flushing directly into Little Pleasant Bay. The returning ebb flow is predominantly through the western part of the Pleasant Bay system, flowing through The Narrows, turning right through Pleasant Bay and following a path south into Chatham Harbor and out the south inlet. Part of the ebb flow escapes through the new inlet on the south side of the flood tidal delta, but most of it continues to the south and out of the Pleasant Bay system through the south inlet.

The following hydrographic and hydrodynamic data were updated in November 2007¹; newer information is not yet available:

1. The average tidal range in the northern extremities of the Pleasant Bay system has increased by 0.7 foot or 19% to about 2/3 of that in the adjacent open ocean.
2. The asymmetry in tidal phase had also increased so that the flood duration is only about half of that for the ebb.
3. The tidal prism in the entire Pleasant Bay has increased by about 15%, proportionally shortening the residence time and increasing the flushing rate.

4. The North Breach shares the flood and ebb tidal exchange with the south inlet. Flood flow rates into the north inlet in 2007 were 40% of the flow in both inlets, but ebb flow to the north was only 30% of the sum of both; the tidal flux through the north inlet accounted for about 35% of the total tidal prism in Pleasant Bay.
5. Comparison of the new total flow rates with the increase in tidal range show that the post-breach estuarine system is hydraulically more efficient.

These recent studies of tidal circulation in Pleasant Bay after the new breach in Nauset Spit in April, 2007, have substantiated the presence of evasive tidal currents strongly flooding on the east and ebbing to the west. Thus, tidal flushing within the Pleasant Bay system clearly is not simply a function of water sloshing north and south, but appears to circulate counterclockwise through a full tidal cycle around the entire Pleasant Bay system. The result of all of these post-breach hydrodynamic changes is much more efficient flushing of the northern portion of Pleasant Bay by refreshed sea water on the flooding tide. At the symposium in Chatham on the new breach it was stated by John Ramsey (ACRE), one of the principles of the SMAST analysis, that Pleasant Bay probably now has the best tidal flushing it has experienced over the past 150 years.

Reviewer Questions

Page numbers refer to the SMAST-MEP report¹ on Pleasant Bay.

Pg. 95-96. Data Collection and Analysis.

Para. 1. Fig. V-8. The bathymetry surveys were conducted in 1997, 2000, and 2004. Would there have been any significant changes to depth in the upper ponds between 1997 and 2004?

Para. 3 and 4. Seven tide gauges were located in the Pleasant Bay System, figure V-8. Why weren't any tide gauges located along the eastern edge of Pleasant Bay, that is, along the Barrier Beach? How does the hydrodynamic model interpret the tidal rise in the eastward direction for the tide gauges in the Western section of Pleasant Bay, i.e., PLB4 and PLB5?

Pg. 104. Tide Data Collection and Analysis.

Fig. V-13. Explain the reason for the difference between "Measured Tide" and the "Predicted Tide". How do these data relate to the July-August time-frame?

Why were the measurements made in October-November, rather than in July-August, when most of the remainder of the report was addressed? Are the local velocities and gradients different in the summer months due to solar heating of the bottom sands and other materials?

Pg 105. ADCP Data Analysis.

Fig. V-14. The data in the middle chart show some negative cross-current velocities in the middle of the channel, showing significant mixing patterns.

Fig. V-15. From the middle chart, it appears that there was mixing in the cross-channel direction.
Are the cross channel currents included in the model?

Fig. V-16. The top chart for the West Bay channel (entrance to The River from Little Pleasant Bay) velocities through the main channel of 1 to 2 ft/sec, but at the southwest bank of "backflow". Does the hydrodynamic model reflect these types of flows as well?

Fig. V-17. The ebb flow in the West Bay Channel seems to be of moderate velocity. The middle chart appears to show reasonable cross current velocities, or good mixing. The charts also seem to show very low velocities along the bottom surface.

Pg 110. Hydrodynamic Modeling

Para. 1. Is the “two-dimensional” modeling sufficient throughout the Pleasant Bay System?

Para. 6. “Various friction and eddy viscosity coefficients were adjusted...” These parameters, or constants, were selected by trial and error, until a solution was obtained that satisfied the boundary conditions? Is there necessarily a single solution? There were no tide gauges on the east side of larger Pleasant Bay; would this cause a deficiency in the analysis?

Pg. 113. Calibration

Para 2. The model was calibrated in November 2004. This is a period where the bottom surface is colder than during July and August. Would all of the coefficients used in the “model” be temperature sensitive, and therefore be different in July and August?

Para 4. Table V-5. The Manning roughness coefficients were fairly close, except for Pleasant Bay and the culverts at Frost Fish and Muddy Creek. Is there an explanation?

The coefficients were changed to make the model represent the tidal motion; are there multiple values that would make the model work?

Pg. 114. Comparison of modeled tides and measured tides.

In Figures V-19 through V-25, the report shows a comparison of the model computed tides and the observed water levels at various locations throughout Pleasant Bay. All this is based on measurements taken over five days beginning November 13, 2004. THIS WAS THE PERIOD OF CALIBRATION. How did the model predict the tidal behavior in a time period in future years?

Pg. 119 – 120. ADP Verification of the Pleasant Bay System

Para. 1. The calculations were checked with the velocity measurements made on November 16 and 23, 2004. Figure V-26 shows the flow through the “Cotuit Bay Inlet”. Why is Cotuit Bay discussed here?

In Figure V-27, the data are presented for the “mouth of the River” on November 23, 2003. Is the “mouth of The River” referred to here the same channel referred to in Fig V-17 as the “entrance to West Bay”.

Pg. 125. Flushing Characteristics.

The “system residence time” seems to be a strange measurement. Does this measurement mean to imply that it will take over a year to completely flush out Muddy Creek, Round Cove, Pah Wah Pond, Areys Pond and Lonnie's Pond [Table V-8]? Doesn't this parameter suggest that the fluid from these ponds just move in and out with very little exchange with the incoming tide?

Pg. 126 Flushing Characteristics (continued)

Para. 1 Develops a concept of “system residence time” for sub-embayments (e.g. Arey’s Pond). It defines “system residence time” as a ratio of the sub-embayment volume to the volume of the entire Pleasant Bay system. . In other words, “system residence time” has been defined as the length of time required for the entire volume of Pleasant Bay to pass through Arey’s Pond. Using this method results in a “system residence time” for Arey’s Pond of 410 days or 13.5 months although the local residence time is 1.1 days. This says that, although it takes just 2 complete tidal cycles (~1.1days) for all of the nitrogen in located in the volume of Arey’s Pond today to move out of Arey’s Pond and into The River, it takes more than a year before all of the “today’s” Arey’s Pond nitrogen moves out of the Pleasant Bay system and into the Atlantic.

Does this imply an assumption of plug flow in the embayments and sub-embayments? It does not seem to be logical. Does the Pleasant Bay system work this way? How is “system residence time” used in the hydrodynamic model? Is this an appropriate way to describe the transport of nitrogen from a sub-embayment to the Atlantic Ocean?

Pg. 128. Flushing Characteristics (continued).

Para. 4. Minor errors in residence times may result from simplifying assumptions (in the model?). How does one know?

Pg. 134 Model Calibration

Para. 1 “Generally, the relatively quiescent main basin of Pleasant Bay and its tributary sub-embayment systems required values of E that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of E in these calmer areas typically range between order 10 and order 0.001 m²/sec (US Army Corps of Engineers, 2001).” (Note: Dispersion coefficient for plug flow is zero ($E=0$).) This indicates (low E values used) that the model for the main basin of Pleasant Bay has it in a very quiet state (lacking significant current flow and mixing). Figures VI-2 (p137) and VIII-1 (p216) seem to confirm this. Ahmad Ali Tavakoly Zadeh and Seyed Mahmood Kashefipour, Department of Hydraulic Structures, Shahid Chamran University, Ahwaz, Iran reported: “The accuracy of the solution to the numerical scheme, which is usually used to solve the Advective-Diffusion Equation (ADE), is highly dependent upon the accuracy of longitudinal Dispersion coefficients (E values).

Is Pleasant Bay quiescent? Are there not significant currents producing mixing? If there were significant currents, would higher dispersion coefficients be needed to reflect the currents in Pleasant Bay?

Question regarding Reference 2 (ACRE Report):

A new report² indicates that the North Breach has increased the tidal prism by 14.9% and significantly impacted the current velocities and flow rates in the Orleans region of Pleasant Bay. This is readily observed by comparing Figs V-28 and V-29 (Pages 123-124) with Figs 9 and 10 of the new report. System residence time (for the entire Pleasant Bay estuary) has been reduced. How does the above referenced study change use of the model described in Chapter V? What is the impact of the study’s forecast of the future impact of the South Inlet and the North Breach?