Nitrogen Modeling to Support Watershed Management: Comparison of Approaches and Sensitivity Analysis

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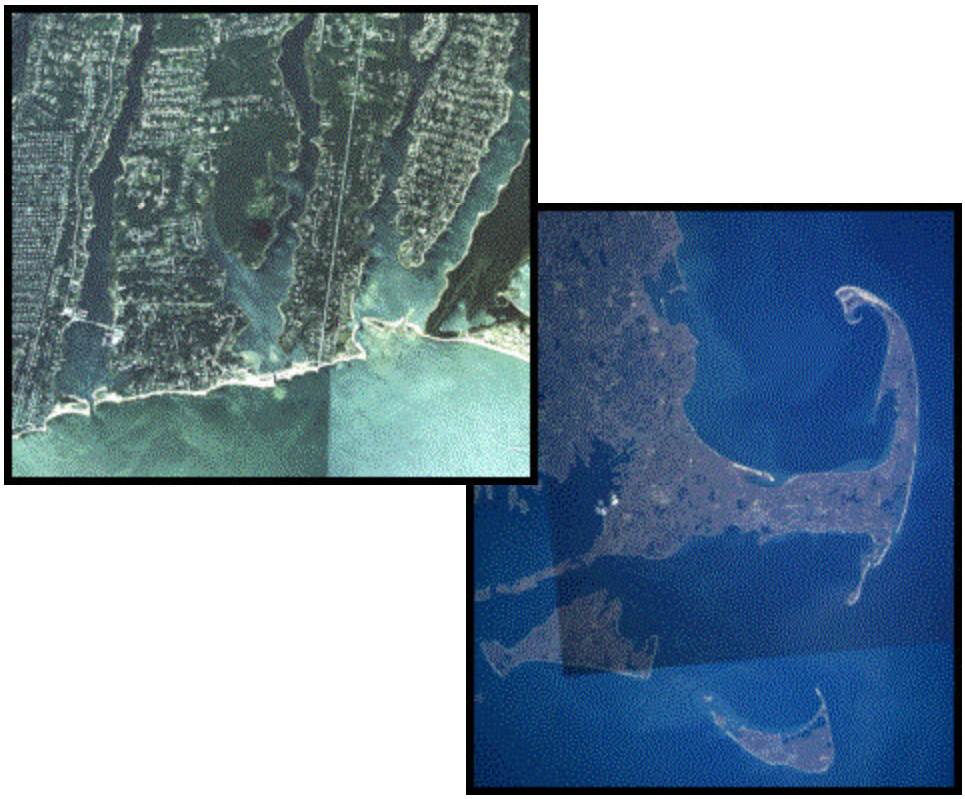

EXECUTIVE SUMMARY

Overview: Coastal embayments throughout the State of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over their assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At its higher levels, enhanced loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational use of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing, and other activities as a result of bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However, like nutrients, bacterial contamination is related to changes in land-use as watershed become more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities. DEP, SMAST, and others have partnered under the Estuaries Project to address these embayment management and planning issues.

A central component of the Estuaries Project is the task of providing a quantitative tool for watershed-embayment management throughout Southeastern Massachusetts. The Estuaries Project is founded upon science-based management. The Project will use a consistent, state-of-the-art approach throughout the region's coastal waters and provide technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the project is to provide technical guidance to DEP in support of policies regarding nitrogen loading to embayments and to conduct nitrogen TMDL's. In appropriate estuaries, TMDL's for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). However, the goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation. As part of the overall effort, the evaluation approach will be used to assess available options for meeting selected nitrogen goals protective of embayment health. The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in southeastern Massachusetts,
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning, and
- keep each embayment's model "alive" to address future regulatory needs.

The Estuaries Project is comprised of four phases relating to project design, project development, implementation of approach, and application of management models to on-going management issues. The project phases are:

- *Phase I:* Assemble a working group, design the project organizational framework, evaluate existing management models and select appropriate approach for regional implementation, and survey existing data sources with regard to potential to support selected approach.
- *Phase II:* Determine the prioritization procedure and select initial embayments, promote water quality data collection in embayments with insufficient baseline data, educate local stakeholders as to Project goals, approach, results and data needs and complete the assessment of existing data and data gaps. Also, establish necessary regulatory and

stakeholder committees and increase the analytical capability of the Project Team relative to collection of field data needed to support the management approach.

- *Phase III:* Implement embayment management approach on a 2-year cycle, which includes field data collection, modeling, reporting, and a significant level of public outreach. Year 1 focuses on site-specific data collection to fill data gaps, Year 2 focuses on modeling, synthesis, and evaluation of management options.
- *Phase IV:* Keep quantitative models and embayment specific management approaches "alive" for future DEP and other management/planning needs. Also, provide a platform (upon request) for tracking embayment changes.

This Report is part of Phase I of the Estuaries Project. Before implementing a specific approach to support nitrogen management, it is necessary to evaluate current watershed and embayment nitrogen management models as to their accuracy, data needs, comparability, and applicability across embayment types observed in southeastern Massachusetts. At present, three approaches have been relatively widely applied: the Buzzards Bay Project Nitrogen Loading Methodology (BBP), the Cape Cod Commission Nitrogen Loading/Critical Loads Methodology (CCC), and the Linked Watershed-Embayment Modeling Approach (Linked).

A Case Study approach was used to evaluate and compare the available nitrogen management models. The Case Studies were selected from among the ca. 15 embayments in Southeastern Massachusetts for which we have developed the data to support the higher level Linked Modeling Approach. The Case Study embayments selected were within the Towns of Falmouth and Chatham on Cape Cod. These embayments were selected for the following reasons:

- the embayments had sufficient data to parameterize each of the management models;
- the embayments used are similar in structure, nitrogen loading, and hydrodynamics to those throughout Southeastern Massachusetts;
- the results from evaluation of these embayments are immediately transferable to other embayments throughout the region.

The overall assessment of the management models included:

- comparison of watershed nitrogen loading results from each model and the resultant embayment nitrogen distribution based upon the Linked Model;
- evaluation of predicted critical nitrogen loading thresholds (BBP) relative to the resultant embayment nitrogen distribution based upon the Linked Model;
- sensitivity analysis for the Linked Watershed-Embayment Approach.

The Linked Model was used to portray the nitrogen distribution within each embayment resulting from the BBP and CCC methodologies, because only the Linked Model has this capability. In addition the Waquoit Model for watershed nitrogen loading was utilized to portray embayment nitrogen distribution for the one case study available. In general construct, the Linked Model uses a watershed land-use loading approach similar to the other models, but it also is coupled to a numerical hydrodynamic/water quality model, which encompasses the circulation and dispersion of nitrogen within the receiving waters. This linkage of watershed and embayment not only provides for assessment of specific areas within embayments, but also allows for calibration and validation approaches not available for the other methodologies.

The comparative application of the various methodologies to the case study embayments also provided an analysis of the consistency of model results between systems. This latter point is critical in evaluating a model for use by the Estuaries Project, that will cover all 89 embayments of Southeastern Massachusetts. Given the specific regional nature of the project (all embayments in Massachusetts from Duxbury to Mt. Hope Bay, including Cape Cod, Nantucket,

and Martha's Vineyard), the evaluation and selection of an appropriate model must focus on its utility in these specific systems. The models, in this evaluation are directly applicable to shallow (generally <5m), primarily vertically mixed (only supporting periodic short term stratification), enclosed or semi-enclosed embayments, surrounded by permeable watersheds with significant groundwater discharges. The approaches can also be used in Mt. Hope Bay, a deeper estuary, which supports periodic strong salinity stratification. However, this analysis will require additional parameterization and complexity of the underlying hydrodynamic model component, as well as development of a separate system-specific uncertainty analysis. Therefore, the results of the various model evaluations are directly applicable to 88 of the 89 embayments within the project area.

In addition to the comparison of the various management models and sensitivity analyses, specific management applications of the Linked Watershed-Embayment Model are also presented which address the utility of the Linked Model for "real-world" embayment management issues. Four examples are presented of specific management scenarios related to the Case Studies. These management alternatives included the determination of estuarine nitrogen levels resulting from: removal of Title 5 septic loads, increased watershed nitrogen loading at build-out, and modifications of tidal inlets (e.g. improvements to tidal flushing).

Conclusions Based Upon Model Comparisons and Sensitivity Analysis: The specific results of the comparative analysis of the models, the sensitivity analysis of the Linked Model, and the management application Case Studies are summarized below. *The overall conclusion from the evaluation was that the Linked Watershed-Embayment Model was the best available model for use in the 89 embayments within the Estuaries Project.* The Linked model outperformed the various other management models in predicting estuarine nitrogen levels, was the only model to include a quantitative (both calibrated and validated) embayment component, was robust relative to the watershed model component, and included both nitrogen attenuation during transport, nitrogen regenerated within the estuary, and considers groundwater transport time. In addition, the Linked Model Approach provides for independent calibration and validation at each level of assessment, thus increasing the certainty of the results and the confidence needed to guide management.

1. Watershed-embayment nitrogen management requires an approach that can accurately portray nitrogen levels within receiving waters and relate them to habitat quality. The approach needs to be holistic and allow evaluation of the effects of spatially altering nitrogen loads, determine the effects associated with changes in key determinants (e.g., tidal exchange, source waters, freshwater flows), and allow evaluations of all spatial scales of the embayment (tributary, upper, lower, coves, etc.). The Linked Watershed-Embayment Model is consistent with these management needs.

2. Of the Models evaluated, only the Linked Model provides output as to the nitrogen distribution throughout an embayment resulting from determined watershed load. In general construct, the Linked Model uses a watershed land-use loading approach similar to the BBP and CCC models, but also is coupled to a numerical hydrodynamic/water quality model which encompasses the circulation and dispersion of nitrogen within the receiving waters. This linkage of watershed and embayment not only provides for assessment of specific areas within embayments, but also allows for calibration and validation approaches not open to the other models. The BBP and CCC Models typically distribute bulk nitrogen loads to sub-embayments or to entire embayment systems, since they do not have a spatially dependent embayment component.

3. The Linked Watershed-Embayment Nitrogen Management Model requires additional data, not needed by the BBP and CCC Models, to support its embayment component that includes

both hydrodynamic and ecological parameters. However, the BBP and CCC do require measurement of embayment flushing rates for determination of critical nitrogen loads.

4. In almost all cases, the standard nitrogen loading terms are consistent among the BBP, CCC, and Linked Models. This is not surprising, since they are based upon the same studies and base data. However, the septic loading term is about 25% lower in the Linked Model than the BBP or CCC Models. This results from the use of Title 5 design flows for the BBP and CCC methodologies (with 35 mgN/L), while the Linked Model is based upon regional septic system discharge and transport studies. In addition, while all methods correct for occupancy, this is deemed a major error in some applications that have not properly evaluated occupancy rates in seasonal communities. Errors in occupancy create a proportional error in residential wastewater loading. Although the error in final nitrogen load due to incorrect occupancy data is "project specific" (and cannot be evaluated here), the resulting error that it generates in the final watershed loading is relatively significant, due to the preponderance of on-site wastewater in most Southeastern Massachusetts coastal watersheds.

5. In contrast to the land-use nitrogen loading terms, there is not consistency among the various methodologies as to the extent of nitrogen attenuation within the watershed as nitrogen moves via groundwater or surface water from the source to the receiving waters. The Linked Model includes attenuation, based upon site-specific measurements. The BBP Model did not use attenuation prior to 2000 and now uses a generic attenuation of 30% for surface and groundwater transport (>1 km). The CCC Model does not include attenuation during transport.

6. The similarity in construct of the BBP and CCC watershed nitrogen loading models and the watershed portion of the Linked Model suggests that previous watershed loading databases might be easily modified to support the Linked Watershed-Embayment Approach.

7. The overall calibration process for the hydrodynamic modeling generally produces errors in tidal elevation and phase of less than 3%. For the more complex embayments, current measurements provide additional model validation data. A comparison of the measured and computed volume flow rates at the Stage Harbor Inlet based upon the hydrodynamic component of the Linked Model showed remarkably good agreement. The calibrated model accurately describes both the general conditions and the irregularities of the discharge through the inlet.

8. Water quality models of estuaries are typically calibrated using salinity data, though the ultimate purpose of the model is to model total nitrogen concentrations. Since salinity and total nitrogen are dissolved constituents, they both will exhibit similar dispersion characteristics. Salinity measurements are commonly used to determine the dispersion coefficients of estuaries (e.g., as in the general method and examples provided by Fischer, et al, 1979). This is a valid assumption because the modeled systems do not have strong gradients in salinity or nitrogen concentrations, which makes turbulent mixing the dominant dispersive phenomenon in the modeled estuaries. Therefore, dispersion coefficients determined for salinity are appropriate for total nitrogen.

9. The Linked Model Approach (standard protocol with attenuation) was able to predict observed embayment nitrogen levels with percent errors less than 10% in 13 of 15 cases. Similarly, for Great and Green Ponds, the BBP and CCC also yielded good fits to the measured nitrogen levels with percent errors generally less than 10%, but had difficulties in Bournes Pond, likely a result of not accounting for benthic regeneration. The Waquoit Model yielded an exceedingly poor fit to observed nitrogen levels. The Waquoit Model underestimated nitrogen levels by an average of 35% (range: 27%-57%). Based upon these

results the Waquoit Model is not recommended for use by the Estuaries Project. Based upon the ability to predict the actual nitrogen levels in a consistent fashion across all of the embayment the Models rank as follows (best to worst): Linked>BBP>CCC>>>Waquoit. The fit appears to be improved if benthic regeneration is added to the BBP and CCC Models.

10. The BBP Critical Nitrogen Loads were found to vary in near direct proportion with alteration of the residence time (r) employed (0-10 days). In addition, since the upper third of an estuary has no volumetric or functional significance, the focus on its flushing rate may not always yield protective or meaningful results. More significant is that almost all embayments are sub-embayments to a larger bay and some embayments have multiple upper sub-embayments. This approach is open to manipulation of the critical loading limit through selection of flushing rate (e.g., use of the flushing rate for a sub-embayment versus the flushing rate for the system).

11. The critical nitrogen limits based upon the BBP Approach do not consistently approximate measured habitat health conditions. Generally, the generated limits tend to over-estimate the loads which a system can tolerate. It is likely that the poor fit is due to the non-inclusion of benthic regeneration and the lack of the nitrogen load spatial distribution along the estuary.

12. The overall result of the sensitivity analysis is that the Linked Model predictions of embayment nitrogen level and distribution are relatively robust. The Model is most sensitive to (in the following order of most to least sensitive): watercolumn dispersion > source water nitrogen concentration > benthic regeneration, septic load > attenuation, fertilizer, impermeable surfaces. The effect of varying the watershed nitrogen loading or attenuation terms was largest in the upper reaches of the embayment and diminished toward the inlet. The effect is seen both as a reduction in the percent change and the nitrogen concentration change. Dispersion was also most sensitive to upper estuary processes. This pattern is due to the increasing dominance of inflowing tidal source waters near the inlet versus the dominance of watershed processes in the upper reaches of embayments. This latter effect is demonstrated by the results of varying the source water concentration, which results in large (20%) changes in nitrogen levels near the inlet and diminishing effects in the upper estuary. Benthic regeneration tended to show the largest changes at mid-estuary.

13. Once the Linked Model has been calibrated and validated to existing estuarine conditions, it provides a powerful management tool to evaluate various nitrogen loading scenarios. Example case studies indicate the expected nitrogen concentration changes, as well as the associated shifts in ecological health, for alterations to septic loading in Great, Green, and Bournes Ponds. The Linked Model can be run under user selected nitrogen management scenarios, to evaluate the most cost effective watershed management alternative for estuarine protection/restoration. These “what if scenarios” play a central role in both local decision making and the larger TMDL process. In addition, projected nitrogen concentration shifts associated with modifications to inlet channels can be used to assess potential impacts resulting from either dredging or structural modifications (e.g. jetty configuration or culvert redesign) to an estuary. This latter model application supports engineering design and feasibility analysis for both embayment and wetland restoration.

Next Steps:

1. A Quality Assurance Project Plan (QAPP) is being developed which will include the parameters required for the implementation, calibration, and validation of the model for an embayment system. As part of the QAPP, there will be the site-specific information required for the field data to be collected to fill data gaps for each of 89 embayments within the project area.

2. Embayments will be prioritized for model implementation generally based upon: the existence of appropriate water quality monitoring data, existing data on model parameters, current and future nutrient related health, local support (municipal, NGO, citizens), and regulatory needs (e.g. permit development, 303d listing).

3. Outreach to regional and local stakeholder groups and organization of stakeholder committees is being formalized and expanded.

4. The Estuaries Project is currently in its implementation phase (Phase III) and is initiating modeling of the first series of embayment systems.