Massachusetts Water Resources Authority
Boston, Massachusetts

A WATER QUALITY MODEL FOR MASSACHUSETTS AND CAPE COD BAYS: CALIBRATION OF THE BAYS EUTROPHICATION MODEL (BEM)

Job Number: NAIC0103

Prepared by:

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ABSTRACT

This report documents the development, calibration, and application of a water quality model of Massachusetts and Cape Cod Bays. The report summarizes the evaluation of existing data; describes the development of a time-variable eutrophication model of the Bays system and its calibration to existing water quality data; and analyzes the results of model projections made for various Massachusetts Water Resources Authority (MWRA) wastewater treatment alternatives using the calibrated model.

The water quality model uses the results of a three-dimensional time-variable hydrodynamic model of the Bays system, developed for MWRA by the United States Geological Survey. The hydrodynamic model was used to develop realistic circulation patterns for the water quality model calibration periods of October 1989 through April 1991 and January through December 1992. As judged by model versus observed data comparisons, the water quality model provides a realistic representation of the physical, chemical, and biological processes that determine eutrophication within the study area. The water quality model has been used to investigate and define the relationships between bay circulation, nutrient loadings, primary productivity, and dissolved oxygen in Massachusetts and Cape Cod Bays.

Sensitivity analyses have been performed to investigate the relative impact of anthropogenic nutrient inputs, the influx of nutrients from the Gulf of Maine, and atmospheric sources on primary production within the Bays system. The calibrated water quality model has also been used to project future water quality conditions to be expected when the new MWRA wastewater treatment facilities have been completed and the effluent wastewaters are discharged to Massachusetts Bay. The results of these projection runs indicate: the upgrade to secondary treatment and outfall relocation will provide significant improvement to water quality within Boston Harbor; the outfall will have localized impacts on water quality within the immediate vicinity of the outfall, but will not result in serious deterioration of present water quality; the relocation of the outfall will have almost imperceptible affects on water quality in Cape Cod Bay and Stellwagen Basin.

ACKNOWLEDGEMENTS

The work detailed in this report was conducted for the Massachusetts Water Resources Authority (MWRA) Harbor Studies Program, as part of the Marine Environmental Sciences Technical Assistance Task Order Contract, while under sub-contract to Normandeau Associates. Many people contributed to the material in this report and the research effort which it describes. In particular, the authors wish to acknowledge Ms. Wendy Leo, who was the MWRA project manager for this study, Dr. Michael Connor, Director, Harbor Studies Department, and Dr. Michael Mickelson, project manager for the Outfall Monitoring Program. We wish to thank them for their program assistance and technical input throughout the conduct of this study. The authors are also grateful to Mr. John Shipman of Normandeau Associates for providing liaison with MWRA during the course of this study.

The authors acknowledge the significant contribution of Dr. Richard Signell (USGS), who was responsible for the development and calibration of the hydrodynamic model, which is a key underpinning to the water quality model. His enthusiasm for this project and his willingness to perform "one more model run" to assist the water quality modeling effort was much appreciated. The authors also express their appreciation to the Model Evaluation Group, consisting of Dr. Robert Beardsley (Chairperson), Dr. Eric Adams, Dr. Anne Giblin, Dr. Donald Harleman, Dr. Jay O'Reilly, Dr. John Paul, and Dr. Jack Kelly, for their constructive criticism and valuable recommendations.

Much of the field data was obtained from data bases on the MWRA computer systems, however, we gratefully acknowledge the sediment flux data that was provided in a timely fashion by Dr. Anne Giblin. Recognition is also given to those unsung faces in the field, who are responsible for the collection and analysis of the field data; the scientists, technicians and field crews and support staff, without whom the water quality data for calibration purposes would not have been available.

Finally, recognition and appreciation are extended to the members of the HydroQual, Inc. staff who contributed to this study: Mr. James Hallden and Mr. Zheng Lu, who provided valuable assistance in the preparation of computer-based graphics, and Ms. Carol Ford, who typed this report.

Mr. James Fitzpatrick served as Project Manager for this study and was responsible for the data analysis presented herein and for the development of the water quality model. Dr. Dominic DiToro provided consultation and overall technical direction of the project. Mr. Richard Isleib served as Project Engineer on this study and was responsible for the development of model inputs and post-processing of model output.

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SUMMARY

Introduction

The City of Boston and Boston Harbor are located in the northwest portion of Massachusetts Bay. Together Massachusetts Bay and Cape Cod Bay combine to form a roughly 100 X 50 km semi-enclosed basin in the western Gulf of Maine. Serving a population of over two million people in the Greater Boston Metropolitan Area, the waters of Boston Harbor and nearshore Massachusetts Bay provide an important recreational as well as commercial resource. The waters of Boston Harbor have also served as a recipient of the region's sewage. Historically, the input of this sewage had an adverse impact on the water quality of Boston Harbor. Significant efforts to improve the water quality of the Harbor were begun in 1952 when a primary sewage treatment plant was built on Nut Island. This facility treated at least a portion of the sewage that had been previously discharged untreated into the Harbor. In 1968, construction of a much larger facility on Deer Island was completed. The completion of these two facilities permitted the major portion of the region's sewage to receive disinfection, thus reducing the input of disease-causing microorganisms to the Harbor's waters.

However, the discharge of other wastewater constituents, such as solids, oxygen-consuming organic material, and nutrients, still presented a problem to the water quality of the Harbor. After a series of lawsuits were filed in the early 1980's against the City of Boston and the Metropolitan District Commission (the agency then responsible for the sewage system), the Massachusetts Water Resources Authority (MWRA) was created and charged with a mandatory schedule for meeting the secondary treatment standards of the Clean Water Act, and hence improving the water quality of Boston Harbor. To date, as part of this clean up effort, the MWRA has ceased the discharge of scum and sludge associated with wastewater and wastewater treatment and completed construction of a new primary treatment facility.

Also on the federally court mandated schedule is the construction of a new secondary treatment facility on Deer Island and a new outfall tunnel to carry the treated effluent out to the deeper waters of Massachusetts Bay. It is expected that these improvements in wastewater treatment and effluent outfall relocation will provide improvements to water quality within Boston Harbor. Concerns have been raised, however, about the effect that the outfall relocation will have on water quality within Massachusetts and Cape Cod Bays. While previous modeling efforts suggest that the discharge of effluent organic carbon and nutrients to northwest Massachusetts Bay will have little effect on the environment of the Bays, these studies used relatively simple frameworks for their analyses and are therefore subject to some uncertainty.

In an effort to develop a more rigorous and detailed understanding of the potential impact of the outfall relocation on the water quality of Massachusetts and Cape Cod Bays, the MWRA has funded a number of studies within Boston Harbor and Massachusetts Bay. Included in these efforts have been a number of hydrographic and water quality surveys of the Bay. Also included is funding to support the development of time-variable three-dimensional hydrodynamic and water quality models of the Bay. The hydrodynamic model is being developed by the U.S. Geological Survey (USGS) under a cooperative agreement with the MWRA.

This work is directed primarily towards the development of a mathematical model of the eutrophication processes of Boston Harbor and Massachusetts and Cape Cod Bays. The resulting water quality model can then be used as a management tool to address questions concerning the water quality impacts in Boston Harbor and Massachusetts and Cape Cod Bays resulting from the outfall relocation. The purpose of the Bays Eutrophication Model (BEM) is twofold: (1) to obtain further understanding of the processes relating eutrophication, nutrients, and dissolved oxygen within the Bays system, and (2) to use the resulting modeling framework as an aid in understanding the potential impacts of wastewater treatment and outfall relocation. The BEM is developed herein on the basis of (a) incorporation of known relationships of phytoplankton growth and nutrients, and (b) calibration of the model to observed data for the period October 1989 through April 1991 and January through December 1992.

Point and Nonpoint Source Inputs

Other than exchange with the Gulf of Maine, the principal inputs of oxygen demanding material and nutrients entering Boston Harbor and the Bays system are:

1. Point source discharges from municipal wastewater treatment plants,
2. Inputs from combined sewer overflows (CSOs),
3. Loadings associated with the various tributaries draining to Boston Harbor,
4. Nonpoint source inputs from study area rainfall runoff,
5. Groundwater loadings, and
6. Atmospheric inputs impinging directly on the water surface.

Data necessary to make estimates of the various pollutant loadings to the system were obtained from reports prepared by MWRA and by Menzie-Cura and Associates. These data allowed the generation of monthly estimates of the point source inputs associated with the Nut Island and Deer Island facilities and atmospheric inputs. Although these data were not sufficient to generate monthly estimates of pollutant inputs for the other municipal facilities, CSOs, tributaries, rainfall runoff, or groundwater loadings, they were sufficient to provide yearly-average estimates. Figure S-1 provides a comparison of the annually-averaged daily inputs of organic carbon, total nitrogen and total phosphorus delivered to the study area from each of the aforementioned sources. As can be seen the major sources of these

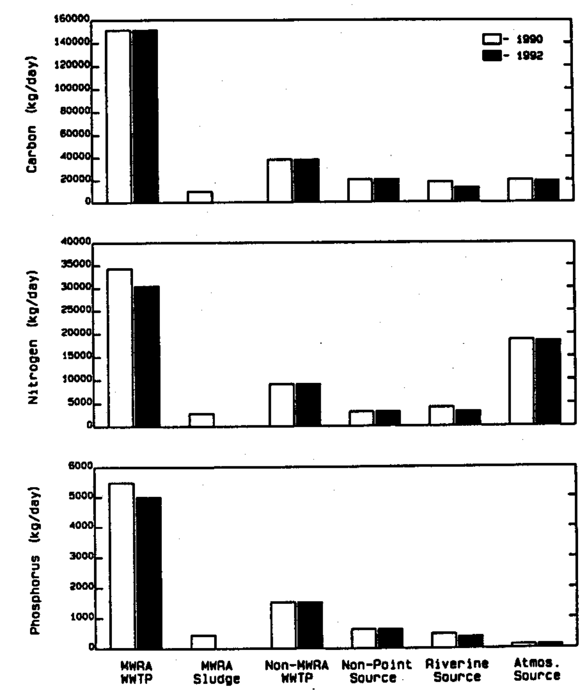

Figure S-1. LOADING COMPARISONS OF POLLUTANT SOURCES FOR 1990 VERSUS 1992 pollutants are the wastewater treatment plants, and the MWRA facilities in particular. With the exception of atmospheric nitrogen, the remaining sources of these inputs are distributed, approximately equally, between non-point sources, riverine sources and atmospheric sources. It should also be noted that in December of 1991, the MWRA ceased discharging sludge into the Harbor, and therefore, this loading input is not included in the organic carbon and nutrient loading estimates for the 1992 period.

Database

The credibility of model calculations are judged, to a large degree, by their agreement with observed data. Besides the obvious constraints that a eutrophication model should behave reasonably well and predict general patterns such as spring-summer phytoplankton growth, comparison of model calculations against observed data is perhaps the only external criterion which is available to determine the validity, and hence the utility, of a complex eutrophication model. The comparison of model computation to actual data indicates whether the assumptions and approximations used in the model adequately represent the "real world."

The principal sources of data for this study were:

1. For the period October 1989 through April 1991, the Bigelow Laboratory for Ocean Sciences; a joint University of Massachusetts at Boston (UMB)/Woods Hole Oceanographic Institution (WHOI)/University of New Hampshire (UNH) team; the New England Aquarium; and

2. For the period January through December 1992, the MWRA funded outfall monitoring program conducted by researchers from the Battelle Ocean Sciences, the University of Rhode Island, the University of Massachusetts at Dartmouth and the Marine Biological Laboratory located in Woods Hole, Massachusetts.

Although the purpose and scope of each of the hydrographic and water quality studies conducted by these researchers differed from one another, the data from these efforts provided sufficient coverage with respect to the space and time scale of the water quality model calculation. The spatial coverage of these surveys ranged from 1 to 10 km within the immediate vicinity of Boston Harbor and the proposed outfall location, to 5 to 20 km for the remaining portions of Massachusetts Bay and Cape Cod Bay. The temporal coverage varied considerably between the early Bigelow and UMB/ WHOI/UNH cruises and the MWRA outfall monitoring program. The latter sampling program was conducted on an approximately monthly basis for stations located in the nearfield vicinity of the proposed outfall and on a semi-monthly basis at farfield stations. The MWRA monitoring program also included more measurements of the principal state-variables considered in the water quality model framework, than did the earlier water quality surveys.

Chlorophyll-a -- An important measure of the eutrophication status of the Massachusetts and Cape Cod Bays system is the concentration of chlorophyll-a. Chlorophyll-a is an indirect measure of the overall phytoplankton population, and as such it does not distinguish between desirable phytoplankton groups that are important to the Bays' food chain and nuisance groups such as toxic dinoflagellates. Nevertheless, it is a widely accepted indicator of the standing algal crop.

Within the Boston Harbor and Massachusetts and Cape Cod Bays study area there is marked temporal and spatial variability in chlorophyll-a levels. This variability is due not only to the spatial variability of available nutrients, but is also dependent on the temporal and spatial variability of other environmental parameters. These parameters include water temperature, incident solar radiation, light transparency, and grazing pressure from higher trophic levels. Two of the more important parameters which influence phytoplankton growth, water temperature and solar radiation, have strong annual cycles.

Figure S-2 presents the annual cycle of chlorophyll-a and chlorophyll fluorescence for three stations within the study area. These data are from the 1992 MWRA monitoring program. Panel (a) shows surface (0 to 5 meter depth) chlorophyll-a for a station located near the entrance to Boston Harbor. As can be seen for this station the annual cycle of chlorophyll-a has its maximum concentrations during the summer months. This is in contrast to panels (b) and (c), which show the annual cycles of chlorophyll-a for stations located in northern Massachusetts Bay and southern Cape Cod Bay. The chlorophyll-a data for the Massachusetts Bay station, panel (b), indicate a small algal bloom in late February; followed by a decline in March and April; low concentrations during the summer months; and, finally a fairly large bloom in early October. Data for the Cape Cod Bay station, panel (c), indicate a similar pattern, except that the February bloom is much larger in Cape Cod Bay than in Massachusetts Bay and the fall bloom is much smaller.

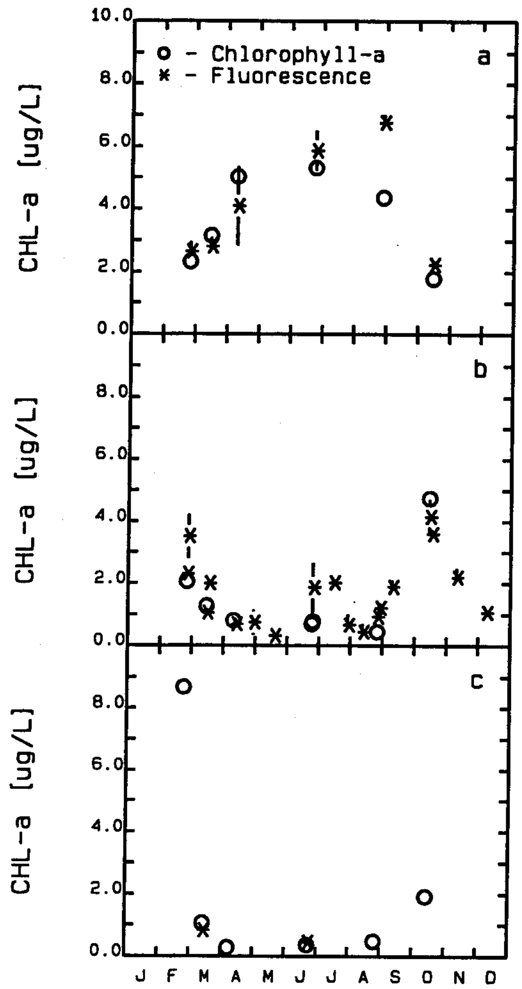

Figure S-2. Annual Cycle of Chlorophyll-a
(a) Boston Harbor
(b) northern Mass. Bay
(c) southern Cape Cod Bay

Nitrogen -- Nitrogen is an important nutrient for phytoplankton growth. In excessive amounts, however, nitrogen can stimulate growth until excessive quantities of algae accumulate. The potential exists for the water column to be depleted of dissolved oxygen when these algae die and decompose. An analysis of the available data within Massachusetts and Cape Cod Bays indicates that nitrogen is the key nutrient limiting phytoplankton growth within these waters. Figure S-3 presents time series plots of surface (0 to 5 meter) dissolved inorganic nitrogen and the ratio of dissolved inorganic nitrogen (DIN) to dissolved inorganic phosphorus (DIP) for two locations within Massachusetts Bay; one station (panels (a) and (b)) is near the entrance to Boston Harbor, while the other station (panels (c) and (d)) is in northern Massachusetts

Bay. The DIN/DIP ratio indicates the potential for either nutrient to limit algal growth. Based on an analysis of phytoplankton cellular composition (the Redfield ratio), DIN/DIP ratios less than or equal to seven, generally indicate that nitrogen is the potentially limiting nutrient; ratios of DIN/DIP greater than seven, indicate phosphorus as the potentially limiting nutrient.

As can be seen in panel (a) for the station near the entrance to Boston Harbor concentrations of DIN are, with the exception of August, above the levels (i.e., 10 μg N/L) that would limit algal growth. Panel (b) indicates that nitrogen is the potentially limiting nutrient with DIN/DIP ratios less than seven. A very low DIN/DIP ratio was observed in June, the period of time corresponding to the near depletion of DIN. The concentrations of DIN observed for the northern Massachusetts Bay station, panel (c), are at or near levels which limit algal growth during the summer months and in October. As can be seen in panel (d) the DIN/DIP ratios are almost always less than three and are less than one during the summer months, indicating a strong nitrogen limitation. Therefore, concerns have been raised about the possible stimulation of phytoplankton growth in Massachusetts Bay

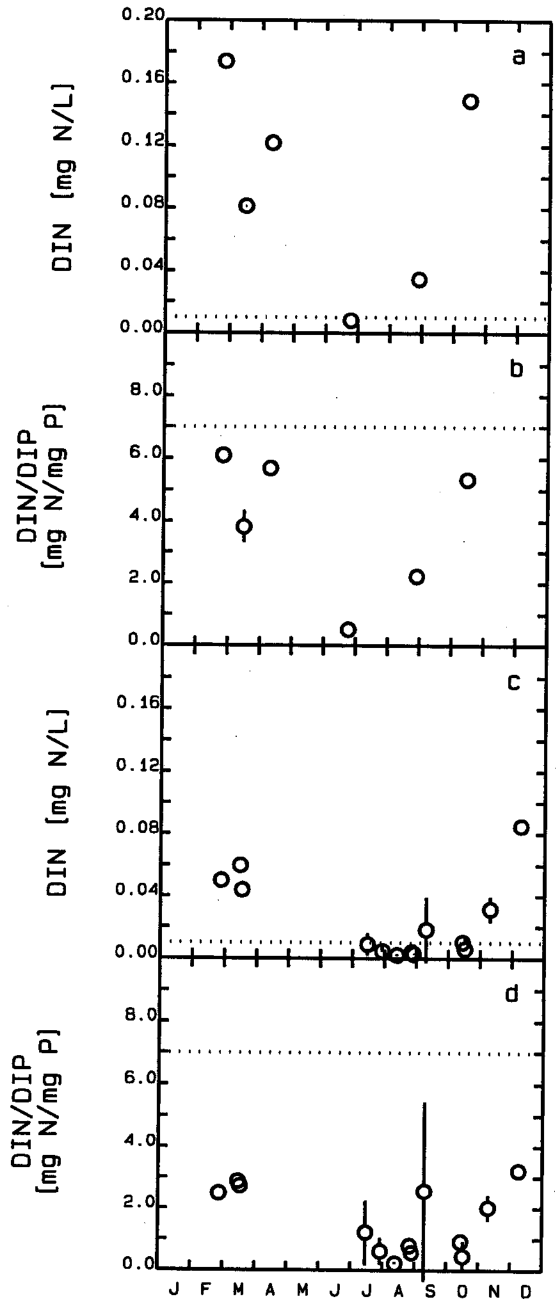

Figure S-3. Surface DIN and Ratio of DIN to DIP

(a), (b) near Boston Harbor entrance
(c), (d) northern Mass. Bay