

TABLE OF CONTENTS

I. INTRODUCTION 1

 I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH 5

 I.2 SITE DESCRIPTION 8

 I.3 NUTRIENT LOADING 10

 I.4 WATER QUALITY MODELING 11

 I.5 REPORT DESCRIPTION 12

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT 14

III. DELINEATION OF WATERSHEDS 18

 III.1 BACKGROUND 18

 III.2 MODEL DESCRIPTION 18

 III.3 LEWIS BAY SYSTEM AND HALLS CREEK CONTRIBUTORY AREAS 20

 Watershed Area (acres) 23

 % contributing to Estuaries 23

IV. WATERSHED NITROGEN LOADING TO EMBAYMENT: LAND USE, STREAM INPUTS, AND SEDIMENT NITROGEN RECYCLING 25

 IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS 25

 IV.1.1 Land Use and Water Use Database Preparation 28

 IV.1.2 Nitrogen Loading Input Factors 29

 IV.1.3 Calculating Nitrogen Loads 38

 IV.2.1 Background and Purpose 50

 IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Halls Creek to Outer portion of Lewis Bay 54

 IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Stewart’s Creek to the Outer portion of Lewis Bay 57

 IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge Snow’s Creek to Inner Lewis Bay 60

 IV.2.5 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Hospital Bog to Hyannis Inner Harbor 63

 IV.2.6 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Mill Pond to Mill Creek 64

 IV.2.7 Surface water Discharge and Attenuation of Watershed Nitrogen: Chase Brook Discharge to Mill Creek 68

 IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS 69

 IV.3.1 Sediment-Watercolumn Exchange of Nitrogen 72

 IV.3.2 Method for determining sediment-watercolumn nitrogen exchange 73

 IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments 75

V. HYDRODYNAMIC MODELING 79

 V.1 INTRODUCTION 79

 V.2 FIELD DATA COLLECTION AND ANALYSIS 81

 V.2.1 Bathymetry 82

 V.2.2 Tide Data Collection and Analysis 85

 V.2.2.1 Lewis Bay 85

 V.2.2.1 Halls Creek 92

 V.2.3 ADCP Data Collection and Analysis 96

 V.3 HYDRODYNAMIC MODELING 97

V.3.1 Model Theory	97
V.3.2 Model Setup	98
V.3.2.1 Grid Generation	98
V.3.2.2 Boundary Condition Specification	98
V.3.3 Calibration	99
V.3.3.1 Friction Coefficients	103
V.3.3.2 Turbulent Exchange Coefficients	104
V.3.3.3 Wetting and Drying/Marsh Porosity Processes	105
V.3.3.4 Comparison of Modeled Tides and Measured Tide Data	105
V.3.4 ADCP verification of the Lewis Bay system	114
V.3.5 Model Circulation Characteristics	117
V.3.5.1 Lewis Bay	117
V.3.5.2 Halls Creek	118
V.5 FLUSHING CHARACTERISTICS	121
VI. WATER QUALITY MODELING	125
VI.1 DATA SOURCES FOR THE MODEL	125
VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment	125
VI.1.2 Nitrogen Loading to the Embayment	125
VI.1.3 Measured Nitrogen Concentrations in the Embayment	125
VI.2 MODEL DESCRIPTION AND APPLICATION	125
VI.2.1 Model Formulation	128
VI.2.2 Water Quality Model Setup	129
VI.2.3 Boundary Condition Specification	130
VI.2.4 Model Calibration	130
VI.2.5 Model Salinity Verification	135
VI.2.6 Build-Out and No Anthropogenic Load Scenarios	138
VI.2.6.1 Build-Out	139
VI.2.6.2 No Anthropogenic Load	143
VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH	148
VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS	148
VII.2 BOTTOM WATER DISSOLVED OXYGEN	149
VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS	162
VII.4 BENTHIC INFAUNA ANALYSIS	166
VIII. CRITICAL NUTRIENT THRESHOLD DETERMINATION AND DEVELOPMENT OF WATER QUALITY TARGETS	171
VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY	171
VIII.2. THRESHOLD NITROGEN CONCENTRATIONS	176
VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS	182
IX. ALTERNATIVES TO IMPROVE WATER QUALITY	188
IX.1 EXISTING LOADING SCENARIO A	189
IX.2 EXISTING LOADING SCENARIO B	191
IX.3 EXISTING LOADING SCENARIO C	193
IX.4 BUILD-OUT LOADING SCENARIO A	195
IX.5 BUILD-OUT LOADING SCENARIO B	197
IX.6 BUILD-OUT LOADING SCENARIO C	199
IX.7 EXISTING LOADING SCENARIO D	201
IX.8 EXISTING LOADING SCENARIO E	203

IX.9 EXISTING LOADING SCENARIO F205
IX.10 BUILD-OUT LOADING SCENARIO D207
IX.11 BUILD-OUT LOADING SCENARIO E209
IX.12 BUILD-OUT LOADING SCENARIO F.....211
X. REFERENCES.....214

LIST OF FIGURES

Figure I-1. Study area for the Massachusetts Estuaries Project analysis of the Lewis Bay Embayment System. Tidal waters enter to the main basin of Lewis Bay through a single large inlet from Nantucket Sound. Freshwaters enter from the watershed primarily through direct groundwater discharge and 4 surface water discharges (Snows Creek, a creek from Hospital Bog, a stream from Mill Pond and Chase Brook) and discharge through the Stewarts Creek Salt Marsh adjacent the outer basin, Hyannis Harbor.2

Figure I-2. Topographic Map of the Lewis Bay System depicting major geographic features. Note the barrier spit that joined Great Island to the mainland and created Lewis Bay.3

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach9

Figure II-1. Town of Barnstable/Yarmouth Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Town and volunteers. Stream water quality stations sampled weekly by the MEP. Halls Creek along the eastern shore of Centerville Harbor will be assessed in a future MEP Technical Report on the Lewis Bay System.17

Figure III-1. Watershed and sub-watershed delineations for the Lewis Bay estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).21

Figure III-2. Comparison of 1998 Cape Cod Commission and current Lewis Bay watershed and sub-watershed delineations.22

Figure IV-1. Land-use in the Lewis Bay and Halls Creek system watersheds. The Halls Creek system watershed is completely contained within the Town of Barnstable, while the Lewis Bay system watershed is split between the Town of Barnstable and the Town of Yarmouth. Land use classifications are based on assessors’ records provided by the towns.27

Figure IV-2. Distribution of land-uses within the major sub-watersheds and whole watershed to the Lewis Bay estuary system and the watershed to Halls Creek. Only percentages greater than or equal to 4% are shown.30

Figure IV-3. Total effluent discharge and median effluent total nitrogen concentration at the Hyannis Water Pollution Control Facility (2002-2006).36

Figure IV-4. Parcels, Parcelized Watersheds, and Developable Parcels in the Lewis Bay and Halls Creek watersheds.40

Figure IV-5 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Lewis Bay System watershed, (b) Mill Creek sub-watershed, and (c) Hyannis Inner Harbor sub-watershed. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control.42

Figure IV-5 (d-f). Land use-specific unattenuated nitrogen load (by percent) to the (d) Snows Creek sub-watershed, (e) Stewarts Creek sub-watershed and (f) the Halls Creek system. “Overall Load” is the total nitrogen input within the watershed, while the “Local Control Load” represents only those nitrogen sources that could potentially be under local regulatory control.43

Figure IV-6. Lewis Bay Sewer Scenario Collection Area. Potential sewer collection area is shown in pink. Potential Scenario C discharge areas are shown based on Barnstable Facilities Plan (2007).....49

Figure IV-7. Location of Stream gages (red symbols) in the Lewis Bay embayment system.....52

Figure IV-8. Halls Creek discharge (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Halls Creek Marsh (Table IV-6).....56

Figure IV-9. Stewart’s Creek discharge (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to outer Lewis Bay (Table IV-6).....59

Figure IV-10. Discharge from Snow’s Creek (solid blue line), nitrate+nitrite (yellow diamonds) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Lewis Bay (Table IV-6).....62

Figure IV-11. Discharge from Hospital Bog (solid blue line), nitrate+nitrite (yellow diamonds) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Hyannis Inner Harbor (Table IV-6).....65

Figure IV-12. Discharge from Mill Pond (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Mill Creek (Table IV-6).....67

Figure IV-13. Discharge from Chase Brook (solid blue line), nitrate+nitrite (yellow diamond) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Mill Creek (Table IV-6).....70

Figure IV-14. Lewis Bay and Halls Creek embayment system sediment sampling sites (green symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.....74

Figure IV-15. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.....76

Figure V-1. Map of the Lewis Bay and Halls Creek estuary systems (from United States Geological Survey topographic maps).....80

Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. Eight (8) gauges were deployed for the 55-day period between May 27, and July 21, 2004. The colored triangles represents the approximate locations of the tide gauges: (LB1) represents the gage in Nantucket Sound (Offshore), (LB2) inside the Uncle Roberts Cove, (LB3) in Sweetheart Creek, (LB4) in Snows Creek, (LB5) Hyannis Inner Harbor at Hyannis Marine, (LB6) at Bayview Beach, (LB7) lower end of Mill Creek, and (LB8) upper reach of Mill Creek. Two (2) gauges (LB9 and LB10) were deployed at Stewarts Creek for a 16-day period between May 12, and May 31, 2007.....83

Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.....84

Figure V-4. Transects from the bathymetry survey of the Halls Creek. The yellow marker shows the location of the tide data recorder deployed inside the Creek for this study.85

Figure V-5. Water elevation variations as measured at the seven locations within the Lewis Bay system, between June 1 and July 21, 2004.87

Figure V-6. Plot showing two tide cycles tides at seven stations in the Lewis Bay system plotted together. Demonstrated in this plot is the amplitude reduction in Snows Creek caused by the propagation of the tide through the culvert under Ocean Street.88

Figure V-7. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.90

Figure V-8. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Nantucket Sound (LB1).92

Figure V-9. Plots of observed tides for Halls Creek, for the 56-day period between May 27 and July 21, 2004. The top plot shows tides offshore Halls Creek inlet, in Nantucket Sound. The bottom plot shows the gauge record measured in Halls Creek. All water levels are referenced to NGVD 29.93

Figure V-10. Plot showing two tide cycles tides from the Halls Creek and Nantucket Sound tide data records, plotted together. Demonstrated in this plot is the minor frictional damping effect caused by flow restrictions at the inlets. The damping effects are seen only as a lag in time of high and low tides from Nantucket Sound. The maximum time lag of low tide between the Sound and Halls Creek in this plot is 103 minutes.93

Figure V-11. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 23 individual tide constituents determine in the harmonic analysis of the Halls Creek gauge data. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series ($r=m-p$).95

Figure V-12. The model finite element mesh developed for Lewis Bay estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained in Nantucket Sound.100

Figure V-13. Depth contours of the completed Lewis Bay finite element mesh.101

Figure V-14. Plot of hydrodynamic model grid mesh for Halls Creek. Colors designate the different model material types used to vary model calibration parameters and compute flushing rates.102

Figure V-15. Plot of interpolated finite-element grid bathymetry of the Halls Creek system, shown superimposed on 2005 aerial photos of the system locale. Bathymetric contours are shown in color at one-foot intervals.103

Figure V-15. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the offshore gauging station. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.106

Figure V-16. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Uncle Roberts Cove gauging station (LB2). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.107

Figure V-17.	Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Sweetheart Creek gauging station (LB3). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.....	107
Figure V-18.	Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Snows Creek gauging station (LB4). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.....	108
Figure V-19.	Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Hyannis Inner Harbor gauging station (LB5). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.	108
Figure V-20.	Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period for the Lewis Bay gauging station (LB6). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.....	109
Figure V-21.	Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Lower Mill Creek gauging station (LB7). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.....	109
Figure V-22.	Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Upper Mill Creek gauging station (LB8). The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.....	110
Figure V-23.	Comparison of model output and measured tides for the TDR location offshore Hyannisport, in Nantucket Sound for the modeled calibration period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.	112
Figure V-24.	Comparison of model output and measured tides for the TDR location in Halls Creek, for the modeled calibration period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.....	113
Figure V-25.	Comparison of model output and measured tides for the TDR location offshore Hyannisport, in Nantucket Sound, for the modeled verification period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.	115
Figure V-26.	Comparison of model output and measured tides for the TDR location in Halls Creek, for the modeled verification period. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.....	115
Figure V-27.	Comparison of measured volume flow rates versus modeled flow rates (top plot) across Mill Creek inlet transect (A-3), over a tidal cycle on June 23, 2004 ($R^2 = 0.84$). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Nantucket Sound.....	116
Figure V-28.	Comparison of measured volume flow rates versus modeled flow rates (top plot) across the entrance to Lewis Bay (A-1), over a tidal cycle on	

June 23, 2004 ($R^2 = 0.91$). Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Nantucket Sound..... 117

Figure V-29. Example of hydrodynamic model output in Lewis Bay for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow. 118

Figure V-30. Example of Halls Creek hydrodynamic model output for a single time step during an ebbing tide. Color contours indicate velocity magnitude, and vectors indicate the direction of flow. Material type boundaries are also shown as the solid black lines within the model domain. 119

Figure V-31. Time variation of computed flow rates for Halls Creek. Plotted time period represents the seven-day period that includes the model calibration period. Positive flow indicated flooding tide, while negative flow indicates ebbing tide. 120

Figure V-32. Relative velocity phase relationship of M2 and M4 tidal velocity constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M_2 phase and the M_4 phase ($2M_2 - M_4$). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant..... 120

Figure VI-1. Estuarine water quality monitoring station locations in the Lewis Bay system. Station labels correspond to those provided in Table VI-1..... 126

Figure VI-2. Estuarine water quality monitoring station locations in the Halls Creek estuary system. Station labels correspond to those provided in Table VI-2. 128

Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Lewis Bay estuary system. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate \pm one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented..... 133

Figure VI-4. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Halls Creek. Plots are interpreted similarly as those for Lewis Bay in Figure VI-3..... 133

Figure VI-5. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for the Lewis Bay system. The approximate location of the sentinel threshold station for the Lewis Bay system (BHY-3) is shown. 134

Figure VI-6. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Halls Creek system. 135

Figure VI-7. Comparison of measured and calibrated model output at stations in the Lewis Bay system. For the left plot, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period

(triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate \pm one standard deviation of the entire dataset. For the plot to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented. 136

Figure VI-8. Comparison of measured salinity and calibrated model output at stations in Halls Creek. Plots are interpreted similarly as those for Lewis Bay in Figure VI-7. 136

Figure VI-9. Contour plots of modeled salinity (ppt) in the Lewis Bay system. 137

Figure VI-10. Contour Plot of modeled salinity (ppt) in the Halls Creek system. 138

Figure VI-11. Contour plots of modeled total nitrogen concentrations (mg/L) in the Lewis Bay system, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for the Lewis Bay system (BHY-3) is shown. 142

Figure VI-12. Contour plot of modeled total nitrogen concentrations (mg/L) in the Halls Creek system, for projected build-out loading conditions. 143

Figure VI-13. Contour plots of modeled total nitrogen concentrations (mg/L) in the Lewis Bay system, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for the Lewis Bay system (BHY-3) is shown. 146

Figure VI-14. Contour plot of modeled total nitrogen concentrations (mg/L) in Halls Creek, for no anthropogenic loading conditions. 147

Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability. 150

Figure VII-2. Aerial Photograph of the Lewis Bay system in the Town of Barnstable showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003. No moorings were placed in Halls Creek, due to the near complete drainage of the creeks and basin at low tide. 153

Figure VII-3. Bottom water record of dissolved oxygen at the Hyannis Harbor (west) station, Summer 2003. Calibration samples represented as red dots. 154

Figure VII-4. Bottom water record of dissolved oxygen at the Hyannis Harbor (east) station, Summer 2003. Calibration samples represented as red dots. 154

Figure VII-5. Bottom water record of dissolved oxygen at the Mill Creek station, Summer 2003. Calibration samples represented as red dots. 155

Figure VII-6. Bottom water record of dissolved oxygen at the Lewis Bay (inner) station, Summer 2003. Calibration samples represented as red dots. 155

Figure VII-7. Bottom water record of dissolved oxygen at the Lewis Bay (outer) station, Summer 2003. Calibration samples represented as red dots. 156

Figure VII-8. Bottom water record of dissolved oxygen at the Uncle Robert's Cove station, Summer 2003. Calibration samples represented as red dots. 156

Figure VII-9. Bottom water record of Chlorophyll-a in Hyannis Harbor (west) station, Summer 2003. Calibration samples represented as red dots. 157

Figure VII-10. Bottom water record of Chlorophyll-a in Hyannis Harbor (east) station, Summer 2003. Calibration samples represented as red dots. 157

Figure VII-11. Bottom water record of Chlorophyll-a in Mill Creek station, Summer 2003. Calibration samples represented as red dots. 158

Figure VII-12. Bottom water record of Chlorophyll-*a* in Lewis Bay (inner) station, Summer 2003. Calibration samples represented as red dots. 158

Figure VII-13. Bottom water record of Chlorophyll-*a* in Lewis Bay (outer) station, Summer 2003. Calibration samples represented as red dots. 159

Figure VII-14. Bottom water record of Chlorophyll-*a* in Uncle Roberts Cove station, Summer 2003. Calibration samples represented as red dots. 159

Figure VII-15. Eelgrass bed distribution within the Lewis Bay System. The 1995 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The yellow (2001) areas were mapped by DEP. All data was provided by the DEP Eelgrass Mapping Program..... 164

Figure VII-16. Eelgrass bed distribution within the Lewis Bay System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were field verified. All data was provided by the MassDEP Eelgrass Mapping Program..... 165

Figure VII-17. Aerial photograph of the Lewis Bay system showing location of benthic infaunal sampling stations (red symbol). 169

Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Lewis Bay system, for threshold conditions (0.38 mg/L at water quality monitoring station BHY-3, and less than 0.5 at water quality monitoring station MC-1 and the average of stations BH-1 and BH-2). The approximate location of the sentinel threshold station for Lewis Bay (BHY-3) is shown. 180

Figure VIII-2. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Halls Creek system, for threshold conditions (maximum concentration of 2.0 mg/L at monitoring station BC-13 and 1.0 mg/L at BC-14). 182

LIST OF TABLES

Table III-1. Daily groundwater discharge to each of the sub-watersheds in the watershed to the Lewis Bay system estuary and Halls Creek estuary, as determined from the USGS groundwater model.23

Table IV-1. Nitrogen Loads from the Wastewater Treatment Facilities to Estuary Watersheds in the Lewis Bay/Halls Creek Study Area.....34

Table IV-2. Primary Nitrogen Loading Factors used in the Lewis Bay MEP analyses. General factors are from MEP modeling evaluation (Howes and Ramsey 2001). Site-specific factors are derived from Barnstable and Yarmouth data. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.39

Table IV-3. Lewis Bay and Halls Creek Nitrogen Loads. Attenuation of Lewis Bay and Halls Creek system nitrogen loads occurs as nitrogen moves through up-gradient ponds and streams during transport to the estuary. All values are kg N yr⁻¹.....41

Table IV-4. Nitrogen attenuation by Freshwater Ponds in the Lewis Bay and Halls Creek watersheds based upon 2001 through 2005 Cape Cod Pond and Lakes Stewardship (PALS) program sampling. These data were collected to provide a site-specific check on nitrogen attenuation by these systems. The MEP Linked N Model for Lewis Bay and Halls Creek uses a standard value of 50% for all the pond systems.....46

Table IV-5. Existing and buildout unattenuated nitrogen loading changes due to proposed scenarios for wastewater discharge from Town of Yarmouth potential sewer service area. Scenario A removes the wastewater nitrogen loads from the Lewis Bay watershed. Scenario B treats the wastewater at the Hyannis Water Pollution Control Facility. Scenario C treats the wastewater at the WPCF and discharges it at abandoned bogs to the east of Cape Cod Hospital. All values are kg N yr⁻¹.....48

Table IV-6. Comparison of water flow and nitrogen discharges from Rivers and Streams (freshwater) discharging to estuarine reach of Lewis Bay. The “Stream” data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.....55

Table IV-7. Summary of annual volumetric discharge and nitrogen load from the Rivers and Streams (freshwater) discharging to the Lewis Bay system based upon the data presented in Figures IV-6 through IV-9 and Table IV-6.71

Table IV-8. Rates of net nitrogen return from sediments to the overlying waters of the Lewis Bay Estuarine System and the adjacent Halls Creek Salt Marsh. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July -August rates.....78

Table V-1. Tide datums computed from records collected in the Lewis Bay system June 1 - July 21, 2004. Datum elevations are given in feet relative to NGVD 27.88

Table V-2. Tidal Constituents, Lewis Bay System June 1 - July 21, 2004.....89

Table V-3. M₂ Tidal Attenuation, Lewis Bay.....90

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Lewis Bay, 2004.....91

Table V-5.	Tide datums computed from a 28-day period from the tide records collected in the Halls Creek system. Datum elevations are given relative to NGVD 29.	94
Table V-6.	Major tidal constituents determined for gauge locations in Halls Creek, May 27 through July 21, 2004.	94
Table V-7.	Percentages of Tidal versus Non-Tidal Energy for Halls Creek gauging stations, May to July, 2004.	94
Table V-8.	Manning’s Roughness coefficients used in simulations of modeled systems.	104
Table V-9.	Turbulence exchange coefficients (D) used in simulations of the modeled embayment systems.	105
Table V-10.	Comparison of tidal constituents from the calibrated RMA2 model of Lewis Bay versus measured tidal data for the period June 1 to June 8, 2004.	111
Table V-11.	Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Halls Creek, during modeled calibration time period.	113
Table V-12.	Tidal constituents for measured water level data and model output, with model error amplitudes, for Halls Creek, during modeled validation time period.	114
Table V-13.	Halls Creek relative velocity phase differences of M ₂ and M ₄ tide constituents, determines using velocity records.	121
Table V-14.	Embayment mean volumes and average tidal prism of the Lewis Bay and Halls Creek system during the simulation periods.	124
Table V-15.	Computed System and Local residence times for sub-embayments of the Lewis Bay estuary and Halls Creek marsh.	124
Table VI-1.	Towns of Barnstable and Yarmouth water quality monitoring data, and modeled Nitrogen concentrations for the Lewis Bay system used in the model calibration plots of Figure VI-2. All concentrations are given in mg/L N. “Data mean” values are calculated as the average of the separate yearly means.	127
Table VI-2.	Measured data and modeled nitrogen concentrations for the Halls Creek estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. “Data mean” values are calculated as the average all samples. Halls Creek data represented in this table were collected in the summers of 2001 through 2006.	128
Table VI-3.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent present loading conditions	131
Table VI-4.	Sub-embayment and surface water loads used for total nitrogen modeling of the Halls Creek system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent present loading conditions for the listed sub-embayments.	131
Table VI-5.	Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Lewis Bay and Halls Creek systems.	132
Table VI-6.	Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic (“no-load”) loading scenarios of the Lewis Bay system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	139

Table VI-7.	Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic (“no-load”) loading scenarios of the Halls Creek system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	139
Table VI-8.	Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Lewis Bay system, with total watershed N loads, atmospheric N loads, and benthic flux.	140
Table VI-9.	Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Halls Creek system, with total watershed N loads, atmospheric N loads, and benthic flux.	140
Table VI-10.	Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Lewis Bay system. Sentinel threshold stations are in bold print.	141
Table VI-11.	Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Halls Creek system.	141
Table VI-12.	“No anthropogenic loading” (“no load”) sub-embayment and surface water loads used for total nitrogen modeling of the Lewis Bay system, with total watershed N loads, atmospheric N loads, and benthic flux.....	144
Table VI-13.	“No anthropogenic loading” (“no load”) sub-embayment and surface water loads used for total nitrogen modeling of the Halls Creek system, with total watershed N loads, atmospheric N loads, and benthic flux.....	144
Table VI-14.	Comparison of model average total N concentrations from present loading and the no anthropogenic (“no load”) scenario, with percent change, for the Lewis Bay system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold stations are in bold print.....	145
Table VI-15.	Comparison of model average total N concentrations from present loading and the no anthropogenic (“no load”) scenario, with percent change, for the Halls Creek system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold station is in bold print.	145
Table VII-1.	Percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels.	160
Table VII-2.	Duration (% of deployment time) that chlorophyll a levels exceed various benchmark levels within the embayment system. “Mean” represents the average duration of each event over the benchmark level and “S.D.” its standard deviation. Data collected by the Coastal Systems Program, SMAST.	160
Table VII-2a.	Duration (% of deployment time) that chlorophyll a levels exceed various benchmark levels within the embayment system. “Mean” represents the average duration of each event over the benchmark level and “S.D.” its standard deviation. Data collected by the Coastal Systems Program, SMAST.	161
Table VII-3.	Changes in eelgrass coverage in the Lewis Bay Embayment System within the Towns of Barnstable and Yarmouth over the past half century (MassDEP, C. Costello).	166
Table VII-4.	Benthic infaunal community data for the Lewis Bay embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison	

between locations (Samples represent surface area of 0.018 m²). Stations refer to map in figure VII-17, (N) is the number of samples per site. 170

Table VIII-1. Summary of Nutrient Related Habitat Health within the Lewis Bay Embayment System on Nantucket Sound within the Towns of Barnstable and Yarmouth, MA., based upon assessment data presented in Chapter VII. The main basin of Lewis Bay and its tributary sub-embayments of Hyannis Inner Harbor and Uncle Roberts Cove are typical coastal embayment basins. In contrast, Mill Creek is primarily a salt marsh basin. 175

Table VIII-2. Comparison of sub-embayment watershed **septic loads** (attenuated) used for modeling of present and threshold loading scenarios of the Lewis Bay system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms. 183

Table VIII-3. Comparison of sub-embayment **total attenuated watershed loads** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Lewis Bay system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms. 184

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Lewis Bay system, with total watershed N loads, atmospheric N loads, and benthic flux. 184

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Lewis Bay system. Sentinel threshold stations are in bold print. 185

Table VIII-6. Comparison of sub-embayment **total watershed loads** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Halls Creek system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms. 187

Table VIII-7. Threshold sub-embayment loads used for total nitrogen modeling of the Halls Creek system, with total watershed N loads, atmospheric N loads, and benthic flux. 187

Table VIII-8. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Halls Creek system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print. 187

Table IX-1. Comparison of sub-embayment watershed **septic loads** (attenuated) used for modeling present loading conditions for Existing Scenario A. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms. 189

Table IX-2. Comparison of sub-embayment **total attenuated watershed loads** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario A. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms. 190

Table IX-3. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario A, with total watershed N loads, atmospheric N loads, and benthic flux. 190

Table IX-4.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario A), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.	191
Table IX-5.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Existing Scenario B. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	192
Table IX-6.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario B. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	192
Table IX-7.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario B, with total watershed N loads, atmospheric N loads, and benthic flux.	193
Table IX-8.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario B), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.	193
Table IX-9.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Existing Scenario C. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	194
Table IX-10.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario C. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	194
Table IX-11.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario C, with total watershed N loads, atmospheric N loads, and benthic flux.	195
Table IX-12.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario C), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.	195
Table IX-13.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Build-Out Scenario A. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	196
Table IX-14.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario A. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	196
Table IX-15.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario A, with total watershed N loads, atmospheric N loads, and benthic flux.	197

Table IX-16.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario A), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.....	197
Table IX-17.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Build-Out Scenario B. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	198
Table IX-18.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario B. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	198
Table IX -19.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario B, with total watershed N loads, atmospheric N loads, and benthic flux.	199
Table IX-20.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario B), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.....	199
Table IX-21.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Build-Out Scenario C. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	200
Table IX-22.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario C. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	200
Table IX-23.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario C, with total watershed N loads, atmospheric N loads, and benthic flux.	201
Table IX-24.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario C), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.....	201
Table IX-25.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Existing Scenario D. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	202
Table IX-26.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario D. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	202
Table IX-27.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario D, with total watershed N loads, atmospheric N loads, and benthic flux.	203

Table IX-28. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario D), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.203

Table IX-29. Comparison of sub-embayment watershed **septic loads** (attenuated) used for modeling present loading conditions for Existing Scenario E. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.204

Table IX-30. Comparison of sub-embayment **total attenuated watershed loads** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario E. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.204

Table IX-31. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario E, with total watershed N loads, atmospheric N loads, and benthic flux.205

Table IX-32. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario E), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.205

Table IX-33. Comparison of sub-embayment watershed **septic loads** (attenuated) used for modeling present loading conditions for Existing Scenario F. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.206

Table IX-34. Comparison of sub-embayment **total attenuated watershed loads** (including septic, runoff, and fertilizer) used for modeling of present conditions for Existing Scenario F. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.206

Table IX-35. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Existing Scenario F, with total watershed N loads, atmospheric N loads, and benthic flux.207

Table IX-36. Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Existing Scenario F), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.207

Table IX-37. Comparison of sub-embayment watershed **septic loads** (attenuated) used for modeling present loading conditions for Build-Out Scenario D. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.208

Table IX-38. Comparison of sub-embayment **total attenuated watershed loads** (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario D. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.208

Table IX-39. Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario D, with total watershed N loads, atmospheric N loads, and benthic flux.209

Table IX-40.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario D), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.....	209
Table IX-41.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Build-Out Scenario E. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	210
Table IX-42.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario E. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	210
Table IX -43.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario E, with total watershed N loads, atmospheric N loads, and benthic flux.	211
Table IX-44.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario E), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.....	211
Table IX-45.	Comparison of sub-embayment watershed septic loads (attenuated) used for modeling present loading conditions for Build-Out Scenario F. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.	212
Table IX-46.	Comparison of sub-embayment total attenuated watershed loads (including septic, runoff, and fertilizer) used for modeling of present conditions for Build-Out Scenario F. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.	212
Table IX-47.	Sub-embayment loads used for total nitrogen modeling of the Lewis Bay system for present loading scenario with present loading conditions for Build-Out Scenario F, with total watershed N loads, atmospheric N loads, and benthic flux.	213
Table IX-48.	Comparison of model average total N concentrations from present loading scenarios (with and without the reduction of septic loads for Build-Out Scenario F), with percent change, for the Lewis Bay system. The threshold station is shown in bold print.....	213