# APPENDIX A

## Commission Member Information

## A. House of Representatives

**Judith Spang (Commission Chair)**
55 Wiswall Road, Durham, NH 03824; phone: 659-5936
judith@kestrelnet.net

**Dennis Abbott**
199 Ash Swamp Road, Newmarket, NH 03857; phone: 659-3175
denevel@comcast.net

**Harry Merrow**
P.O. Box 94, Center Ossipee, NH 03814; phone: 539-2109
hcmerrow@verion.net

## B. Senate

**Martha Fuller Clark**
Home – 152 Middle St., Portsmouth, NH 03801; phone: 271-6933
martha.fullerclark@leg.state.nh.us

**Margaret Hassan**
48 Court Street, Exeter, NH 03833; phone: 271-4153 or 772-4187
maggie.hassan@leg.state.nh.us

## C. Pease Development Authority, Division of Ports & Harbors

**Tracy Shattuck, Harbor Master**
PDA-Division of Ports & Harbors, P.O. Box 369, Portsmouth, NH 03802-0369; phone: 436-8500
t.shattuck@peasedev.org

## D. University of New Hampshire

**Fred Short, Research Professor**
Jackson Estuarine Laboratory, 85 Adams Point Road, Durham NH 03824; phone: 862-5134
fred.short@unh.edu

**Larry Ward, Research Associate Professor**
Center for Coastal and Ocean Mapping, Jere A. Chase Ocean Engineering Lab, 24 Colovos Road, Durham NH 03824; phone: 862-2337
larry.ward@unh.edu

## E. The Nature Conservancy

**Ray Konisky**
Great Bay Field Office, 112 Bay Road, Newmarket, NH 03857; phone: 659-2678
rkonisky@tnc.org

## F. Department of Environmental Services

**Ted Diers, Program Manager**
NH Coastal Program, 50 International Dr., Suite 200, Portsmouth, NH 03801; phone: 559-0027
theodore.diers@des.nh.gov

**Christian Williams**
NH Coastal Program, 50 International Dr., Suite 200, Portsmouth, NH 03801; phone: 559-0025
christian.williams@des.nh.gov

## G. Strafford Regional Planning Commission

**Cynthia Copeland, Executive Director**
Strafford Regional Planning Commission, 2 Ridge St., Suite 4, Dover, NH 03820; phone: 742-2523
cjc@strafford.org

## H. Rockingham Planning Commission

**Bruce Dearborn**
156 Water Street, Exeter, NH 03833; phone: 778-0885
bldearborn@msn.com

## I. Representatives from Conservation Commissions in Estuarine Towns

**Alison Watts**
Newfields Conservation Commission, 65 Main Street, Newfields, NH 03856; phone: 772-5070
alison.watts@unh.edu

**Justin Richardson**
Newington Conservation Commission, 205 Nimble Hill Road, Newington, NH 03801; phone: 436-7046
jrichardson@upton-hatfield.com

## J. Great Bay National Estuarine Research Reserve

**Peter Wellenberger, Manager**
Great Bay National Estuarine Research Reserve, NH Fish & Game Dept., Region 3, 225 Main Street, Durham, NH 03824; phone: 868-1095
peter.wellenberger@wildlife.nh.gov

## K. Fish & Game Department

**Doug Grout, Marine Fisheries Division**
NH Fish & Game Dept., Region 3, 225 Main Street, Durham, NH 03824; phone: 868-1095
douglas.grout@wildlife.nh.gov

## L. Piscataqua Region Estuaries Partnership

**Jennifer Hunter, Director**
Piscataqua Region Estuaries Partnership, UNH, Nesmith Hall, Durham, NH 03824;
phone: 862-3948
jennifer.hunter@unh.edu

## M. Representatives of Water-Related Recreational Interests

**Ellen Griffin Saas**
Great Bay Marine, Inc., 61 Beane Lane, Newington, NH 03801; phone: 436-5299
ellen@greatbaymarine.com

**Peter Whelan, President**
NH Coastal Conservation Association, P.O. Box 4084, Concord, NH 03302; phone: 731-2669
pawhelan@comcast.net

## N. Other Interested Parties

**David Cedarholm**
Town of Durham, 100 Stone Quarry Drive, Durham, NH 03824; phone: 868-5578
dcedarholm@ci.durham.nh.us

**David Funk**
Great Bay Stewards, 43 Boston Harbor Road, Dover NH, 03820; phone: 749-6756
dtfunk@comcast.net

# APPENDIX B

## Sediment Load Report

# Sediment Loads from the Great Bay Estuary Watershed

## A Report to the Siltation Commission


**STATE OF NEW HAMPSHIRE**
**DEPARTMENT OF ENVIRONMENTAL SERVICES**
**29 HAZEN DRIVE**
**CONCORD, NEW HAMPSHIRE 03301**

**THOMAS S. BURACK**
**COMMISSIONER**

**HARRY T. STEWART, P.E.**
**DIRECTOR**
**WATER DIVISION**

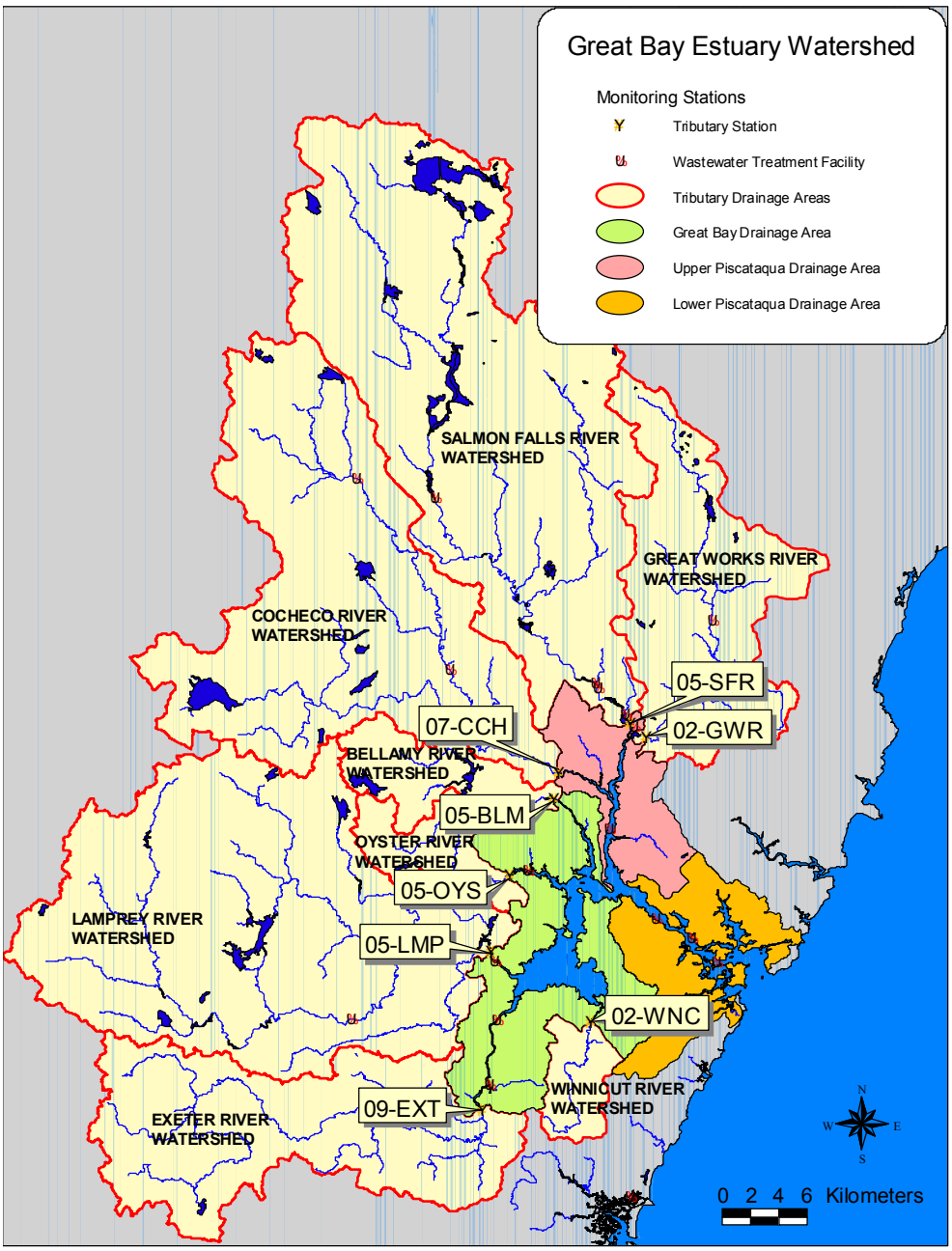
**PREPARED BY**
**PHILIP TROWBRIDGE, P.E.**
**WATERSHED MANAGEMENT BUREAU**


**October 22, 2009**

NEW HAMPSHIRE DEPARTMENT OF Environmental Services

At the request of the Siltation Commission, the Department of Environmental Services compiled data on suspended sediment loads from watersheds to the Great Bay Estuary. DES used the suspended sediment concentrations measured at the tidal dams along with streamflow to estimate the loads during three periods: 1993-1996, 2002-2005, and 2006-2008. The LOADEST software developed by the U.S. Geological Survey was used for the calculations (Runkel et al., 2004). The watersheds included in this study are shown in Figure 1.

**Figure 1: Watersheds of the Great Bay Estuary**

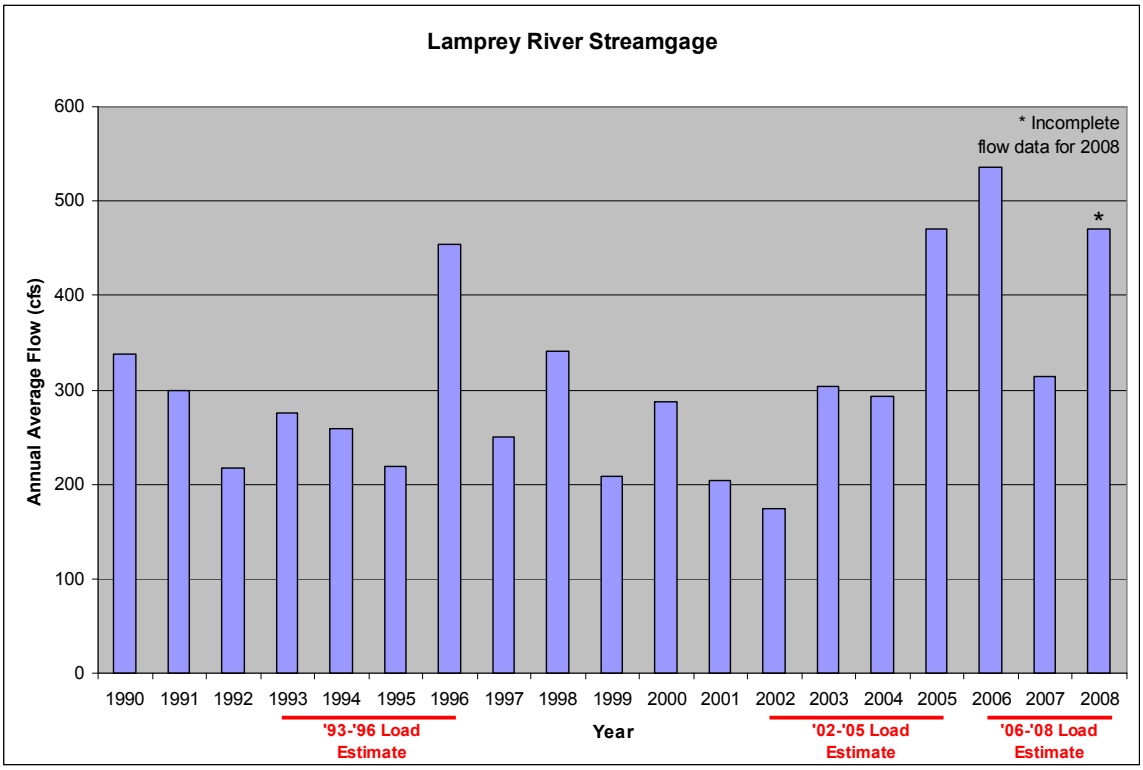


## Streamflow During Study Periods

The annual average streamflow at the Lamprey River gage was used as an indicator of rainfall and runoff during the study periods.

The annual average flows for each year between 1990 and 2008 are shown in Figure 2. The 1993-1996 and 2002-2005 periods represented low to moderate flows. The 2006-2008 period had higher than average flows.

**Figure 2: Annual Average Streamflow at the Lamprey River Gage**

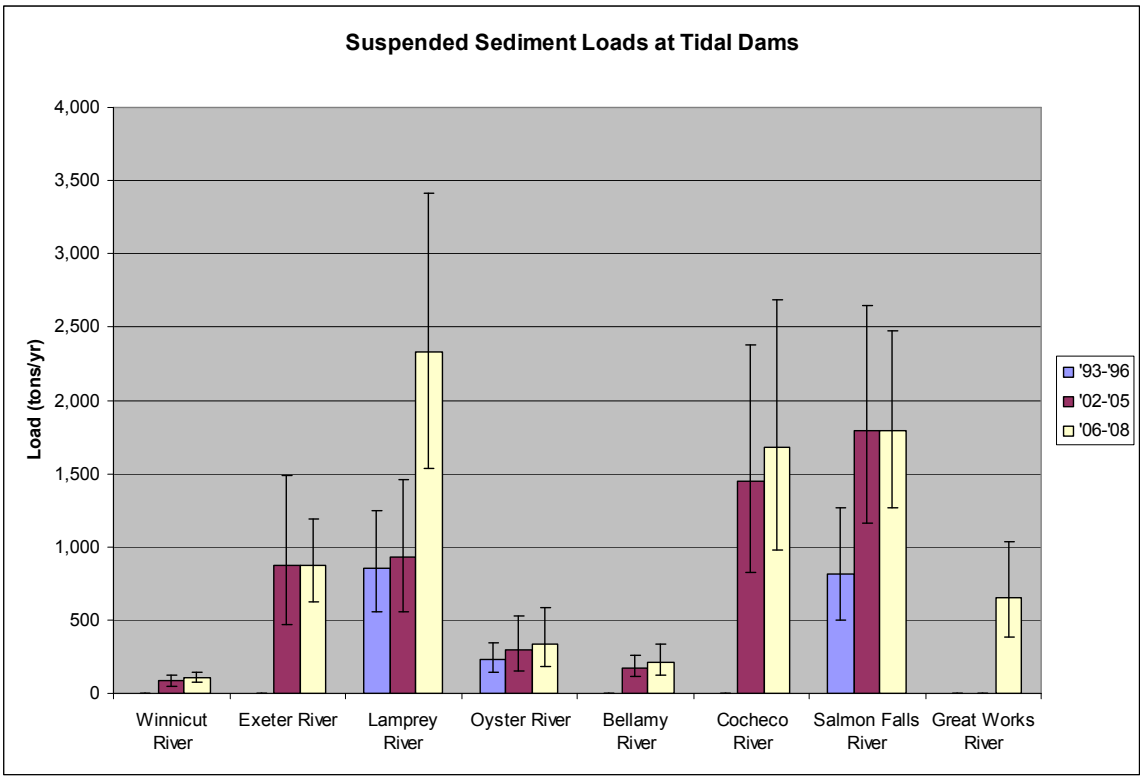


## Sediment Loads from Watersheds

The sediment loads from each of the watersheds predicted by LOADEST are shown on Figure 3. Gaps in the graph indicate that loading estimates were not available for that watershed during that period. The error bars are the 95th percentile confidence limits of the estimate.

The largest sediment loads were from the Exeter, Lamprey, Cocheco, and Salmon Falls rivers. The loads from the watersheds were relatively constant across the three study periods. The exception to this statement is the Lamprey River, for which the loads nearly doubled in 2006-2008 from the previous years.

**Figure 3: Average Loads of Suspended Sediments from Watersheds**



## Sediment Yields from Watersheds

The measured loads were normalized by the watershed drainage area to calculate the sediment yield for each watershed (Figure 4). The sediment yield for the Oyster River watershed was consistently higher than for the other watersheds. The yield for the Lamprey River doubled for the 2006-2008 period. For the earlier periods, the yield for the Lamprey River was lower than for the other watersheds. The overall sediment yield from Great Bay watersheds (i.e., sum of loads divided by sum of drainage areas) was 7.1 tons/year/mi$^2$ in 2002-2005 and 9.1 tons/year/mi$^2$ in 2006-2008. The variability in sediment yield between watersheds does not appear to be related to land use within the watersheds (Table 1) but could be related to land use and erosion along the riparian corridor.

**Figure 4: Average Yields of Suspended Sediments from Watersheds**

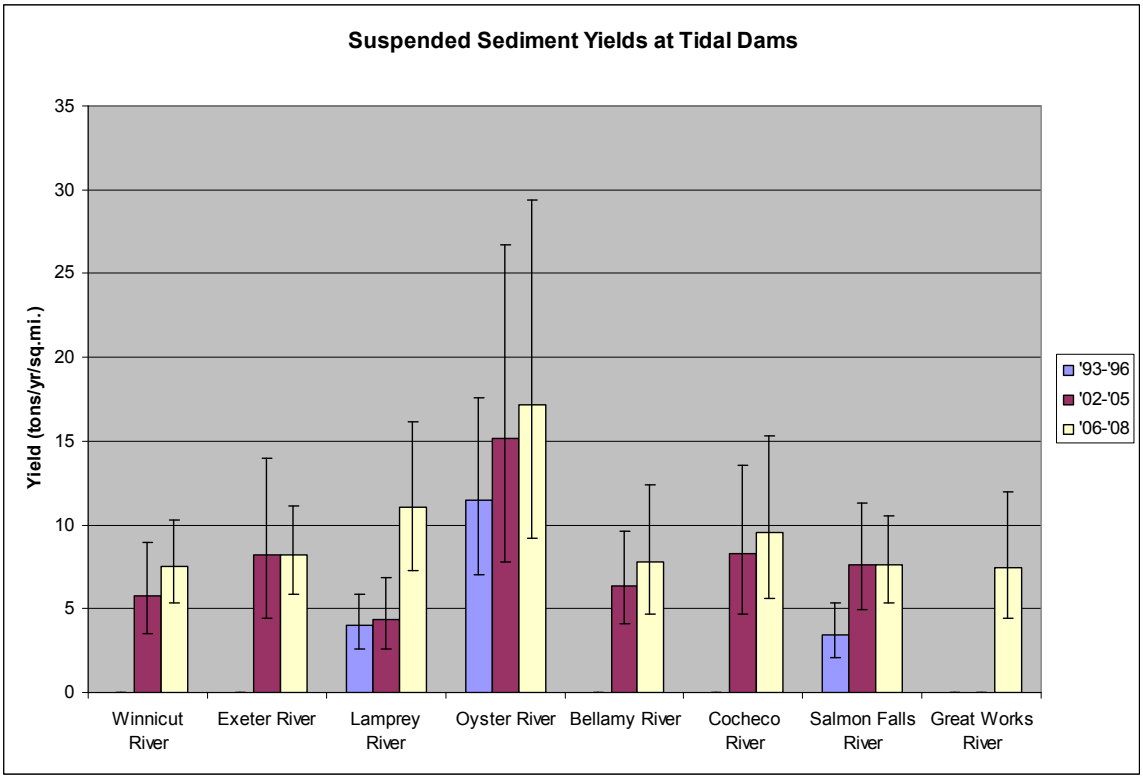



**Table 1: Percent of watershed drainage area in developed and agricultural land classes in 2006**

| | Winnicut River | Exeter River | Lamprey River | Oyster River | Bellamy River | Cocheco River | Salmon Falls River | Great Works River |
|---|---|---|---|---|---|---|---|---|
| Developed | 16.68% | 7.46% | 3.55% | 11.16% | 10.16% | 9.04% | 5.68% | 5.11% |
| Agriculture | 14.15% | 14.75% | 8.02% | 11.08% | 9.23% | 7.89% | 7.39% | 10.17% |
| Developed & Agriculture | 30.83% | 22.21% | 11.57% | 22.23% | 19.40% | 16.93% | 13.07% | 15.28% |
| Impervious Surfaces 2005 | 12.4% | 8.3% | 5.1% | 8.4% | 9.6% | 7.1% | 4.9% | 5.3% |
| Drainage Area (square mi.) | 14.16 | 106.90 | 211.90 | 19.85 | 27.26 | 175.28 | 235.00 | 86.69 |

**Sediment Yields from Other Watersheds**

DES performed a literature search for sediment yields in other watershed to provide context for the results in this report. Naiman (1982) measured sediment yields of 4.3 to 21.7 tons/year/$mi^2$ in five pristine, boreal watersheds in Quebec. Boomer et al. (2004) reported sediment yields between 28.5 and 342 tons/year/$mi^2$ in 45 watersheds in the coastal plain of the Chesapeake Bay. Finally, the average sediment yield for the entire Mississippi River basin was reported to be 149 tons/year/$mi^2$ by Turner and Rabalais (2004). These reports indicate that sediment yields from the Great Bay watersheds are at the low end of the range of yield observed in other watersheds. However, the methods for measuring sediment loads were not always consistent between the various reports. The sediment yields measured for the Great Bay watershed may be biased low due to the analytical and sampling methods used. The analytical method for measuring suspended sediments does not accurately measure fine sediment particles which would contribute to the total sediment load. Also, some sediment load monitoring programs collect samples across all hydrologic conditions, rather than on a fixed monitoring schedule.

DES also investigated models to predict sediment yields based on land use in the watersheds. The established models (AVGWLF, Universal Soil Loss Equation) require information on slope and other geomorphic factors in order to predict bank erosion for sediment yields. These models cannot be run with only land use classifications for a watershed. A simplified model of sediment yields devised by Jones et al. (2001) requires three input variables for a watershed: The percent of watershed with forest land cover adjacent to stream edge, the percent of watershed with urban land cover, and the percent of watershed with wetland land cover.

**Preliminary Findings**

1. The sediment yield from the Oyster River watershed is higher than the average for the Great Bay Watershed. In 2002-2005 and 2006-2008, the sediment yield from the Oyster River watershed was 15.1 and 17.1 tons/year/$mi^2$, respectively. The overall yield for the combined Great Bay watersheds during these periods was 7.1 and 9.1 tons/year/$mi^2$, respectively.

2. The sediment yield from the Lamprey River doubled from 4.4 tons/year/$mi^2$ in 2002-2005 to 11.0 tons/year/$mi^2$ in 2006-2008. The 2006-2008 period experienced far greater rainfall and runoff than the 2002-2005 period. There was also rapid development in this watershed over this decade. These two factors likely contributed to the change in sediment loads from the Lamprey River watershed between 2002-2005 and 2006-2008.

3. The sediment loads in this report may underestimate the actual sediment loads. The analytical method for measuring suspended sediments does not accurately measure fine sediment particles which would contribute to the total sediment load. However, relative changes in loading both between watersheds and between years are expected to be correct.

4. The measured sediment yields for the Great Bay watershed in this report are at the low end of those that have been observed in other watersheds. However, as stated previously, the sediment loads included in this report likely underestimate the actual sediment loads. Therefore, comparisons to published values for other watersheds may not be appropriate.

5. Models to predict sediment yields require detailed geomorphic information in order to calculate bank erosion.

6. The sediment load estimates could be improved with investments in monitoring programs that are specifically designed for this purpose. Analytical methods that quantify the concentration of suspended sediment of all particle sizes should be used. The monitoring design should collect data across the full range of the hydrograph.

## References

Boomer, K.B., D.E. Weller, and T.E. Jordan. 2008. Empirical models based on the Universal Soil Loss Equation fail to predict sediment discharges from Chesapeake Bay catchments. *J. Environ. Qual*. **37**: 79-89

Jones, K.B., A.C. Neal, M.S. Nash, R.D. Van Remortel, J.D. Wickham, K.H. Riitters, and R.V. O'Neill. 2001. Predicting nutrient and sediment loadings to streams from landscape metrics: A multiple watershed study from the United States Mid-Atlantic Region. *Landscape Ecology* **16**: 301-312.

Naiman, R.J. 1982. Characteristics of sediment and organic carbon export from pristine boreal forest watersheds. *Can. J. Fish. Aquat. Sci*. **39**: 1699-1718.

Runkel, R.L., Crawford, C.G., and Cohn, T.A. (2004) Load Estimator (LOADEST): A FORTRAN Program for Estimating Constituent Loads in Streams and Rivers: U.S. Geological Survey Techniques and Methods Book 4, Chapter A5, 69 p. Published online: http://pubs.usgs.gov/tm/2005/tm4A5/

Turner, R.E., and N.N. Rabalais. 2004. Suspended sediment, C, N, P, and Si yields from the Mississippi River basin. *Hydrobiologia* **511**: 79-89.

## Data Sources

DES Ambient River Monitoring Program Data between 2001 and 2007. Department of Environmental Services, Watershed Management Bureau, Concord, NH. Published Online: http://www2.des.state.nh.us/OneStop/.

Jones, S.H., and R. Langan. 1995. Assessment of Nonpoint Source Pollution in Tributaries Entering Great Bay. A final report to the New Hampshire Office of State Planning, NH Coastal Program. University of New Hampshire, Durham, NH.

NOAA Coastal Services Center, Northeast Land Cover Analysis. Published Online: http://www.csc.noaa.gov/crs/lca/northeast.html.

PREP. 2009. Nitrogen, Phosphorus, and Suspended Solids Concentrations in Tributaries to the Great Bay Estuary Watershed in 2008. Piscataqua Region Estuaries Partnership, University of New Hampshire, Durham. NH. Published Online: http://prep.unh.edu/resources/pdf/nitrogen_phosphorus_and-prep-09.pdf. Accessed August 6, 2009.

USGS Daily Average Streamflow Data. Published Online: http://waterdata.usgs.gov/nh/nwis/current/?type=flow.

# APPENDIX C

## Great Bay Bathymetric Report

# Development and Analysis of a Bathymetric Database for Great Bay Estuary, New Hampshire

**Final Report to**

**New Hampshire Department of Environmental Services**
**Coastal Program**

**Submitted by**

**Larry G. Ward**
**University of New Hampshire**
**Center for Coastal and Ocean and Mapping**
**24 Colovos Road**
**Durham, NH 03824**

**December 15, 2009**

**This project was funded in part by a grant from the NOAA to the New Hampshire Department of Environmental Services Coastal Program**
**(Award # NA07NOS4190081)**

**Important Notice**

**The bathymetric surveys included in the database constructed for this study are:**

# NOT TO BE USED FOR DEVELOPMENT OF NAVIGATION CHARTS OR NAVIGATION PURPOSES.

**Abstract**

Bathymetric surveys have been conducted in Great Bay Estuary (GBE) for more than a century, largely for navigation purposes, using a variety of technologies for soundings (e.g., leadlines, single beam and multibeam sonars) and positioning (e.g., sextant, RTK GPS). In order to maximize existing information of Great Bay Estuary, a project was undertaken to assemble all useful and assessable bathymetric surveys in a database, convert them to a common projection and datum, develop bathymetric maps of representative time periods, and, based on the assembled database, conduct comparisons to assess changes in bathymetry over time in selected locations. In addition, the archives would be available for future research projects. Furthermore, a goal of this project was to define and prioritize where new, high resolution bathymetric surveys are needed to better understand rates and patterns of sedimentation in GBE.

Major accomplishments and results of this project include the following.

1. Development of a bathymetric database that presently includes 16 surveys of GBE, but will continue to grow as new surveys are uncovered or occur. For instance, two relatively recent surveys by the US Army Corps of Engineers (a 2006 survey of the Exeter (Squamscott) River and a 2007 survey of Little Harbor) have just been acquired and will be added to the database.
2. Digitizing of the 1898 and 1903 U.S. Coast and Geodetic Survey (predecessor to the National Ocean Service) bathymetric survey smooth sheets (H2360 and H2656) which cover the area from the entrance to Portsmouth Harbor to Dover Point. In total, 13,331 soundings were entered. Prior to digitizing these early surveys, the bathymetry of Portsmouth Harbor and the Piscataqua River at the turn of the 20$^{th}$ century was not available in digital form for construction of bathymetric maps and analysis.
3. Conversion of the soundings in the bathymetric database to a common projection (Universal Transverse Mercator - UTM Zone 19 North), horizontal datum (World Geodetic System 1984 - WGS84) and units (minus meters below mean low water or mean lower low water).
4. Development of an ArcGIS project with all bathymetries from the database entered and layers included for developing bathymetric maps.
5. Development and testing of a methodology to compare bathymetric surveys from various time periods.
6. Determination of the difficulties of quantifying depth changes between the historical bathymetric surveys chosen for this study (1913 and the 1953-1955 NOS surveys) due to inherent limitations of the data sets that were discovered when the surveys were examined in detail. The problems are related to the fact that the historical surveys used tidal datums derived from tide gages located at very different locations and thus quantitative comparisons between the historical surveys include a bias due to datum differences. Nevertheless, assessments of morphologic changes can be done as they are not affected by the datum bias. For example, comparison of the 1913 and 1953-1955 NOS surveys of the eastern half of Great Bay indicate that reaches of the northern channel became shallower over the 40 year period indicating shoaling occurred.

**Table of Contents**

Abstract ..... iii

List of Tables ..... v

List of Figures ..... v

1 Introduction ..... 1

2 Bathymetric Surveys Archive ..... 1

2.1 Digitizing of Hydrographic Survey Sheets ..... 7

2.2 Conversion of Bathymetric Surveys to Common Coordinate System ..... 7

3 Bathymetric Maps ..... 8

4 Bathymetric Change Analyses ..... 15

4.1 Potential Errors ..... 15

4.2 Selection of Bathymetric Surveys and Time Periods ..... 16

4.3 Methodology ..... 16

4.4 Results ..... 17
4.4.1 Upper Great Bay Estuary ..... 17
4.4.2 Upper Piscataqua River (Dover Point to Salmon Falls River) ..... 20
4.4.3 Upper Piscataqua River (Dover Point to ~43° 10') ..... 20
4.4.4 Little Bay ..... 23
4.4.5 Great Bay ..... 23

5 Analysis of Channel Cross Sections in Eastern Great Bay ..... 28

6 New Bathymetric Survey of Great Bay (2009) ..... 31

7 Summary ..... 33

8 Acknowledgements ..... 33

9 References ..... 34

## List of Tables

Table 1. Bathymetric surveys included in historical database for this project. ..... 3

Table 2. Channel depths in the northern channel in eastern Great Bay. ..... 31

## List of Figures

Figure 1. Composite bathymetric map of surveys done in Great Bay Estuary between 1898 and 1913. ..... 4

Figure 2. Seamless bathymetric map of the NOS survey conducted in Great Bay Estuary between 1953 and 1955. ..... 5

Figure 3. Composite bathymetric map of the surveys conducted in Great Bay Estuary between 2000 and 2007. ..... 6

Figure 4. Bathymetric map of Portsmouth Harbor based on the 1898 NOS survey produced as an ArcGIS TIN model. ..... 9

Figure 5. Bathymetric map of Portsmouth Harbor based on the 1898 survey produced in ArcGIS as a gridded TIN model. ..... 10

Figure 6. Bathymetric map of Portsmouth Harbor based on the 1898 and 1903 surveys produced in IVS 3D Fledermaus..... 11

Figure 7. Bathymetric map of Little Bay and Great Bay based on the 1913 NOS survey produced in IVS 3D Fledermaus..... 12

Figure 8. Bathymetric map of Little Bay and Great Bay based on the 1953-1955 NOS survey produced in IVS 3D Fledermaus. ..... 13

Figure 9. Bathymetric map of Little Bay and Great Bay based on the 2000 NOS and the 2002 CCOM surveys produced in IVS 3D Fledermaus. The bathymetry for the Bellamy River is from the 2006 USACE survey. ..... 14

Figure 10. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the upper Great Bay Estuary segment. ..... 18

Figure 11. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the the Piscataqua River (Dover Point to Salmon Falls) segment. ..... 21

Figure 12. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the Piscataqua River (Dover Point to ~43° 10') segment. ..... 22

Figure 13. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the Little Bay segment. ..... 25

Figure 14. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the Great Bay Estuary segment. ..... 26

Figure 15. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the western Great Bay Estuary segment. ..... 27

Figure 16. Approximate locations of channel cross sections on the northern channel in the eastern half of Great Bay. The channel cross sections are shown in Figure 17.. 29

Figure 17. Channel cross sections from eastern Great Bay (see Figure 16). ..... 30

Figure 18. Survey lines for the 2009 bathymetric survey conducted in Great Bay Estuary by UNH CCOM/JHC. ..... 32

## 1 Introduction

Estuarine systems such as Great Bay Estuary (GBE) are natural sediment traps, collecting and depositing sediments from landward, seaward, and internal (i.e., shoreline erosion or primary productivity) sources. As a result, periodic dredging and engineering alterations are required resulting in monetary costs, as well as conflicts between human needs and environmental concerns. Therefore, informed and environmentally responsible management of GBE requires a sound understanding of the sources, transport pathways and mechanisms, as well as interim and long-term depositional sites of sediment. Essentially, this knowledge base constitutes a sediment budget for the estuary. However, understanding sedimentation processes and budgets within GBE is complex due to multiple interactions between physical, biological, and chemical processes. Fortunately, GBE has been the focus of numerous research programs over the last five decades that have studied a number of processes and have developed several important databases. Included are a number of bathymetric surveys that have been conducted over the years primarily for navigation purposes.

As a first step in an effort to develop an understanding of the morphology and sedimentology of GBE, a project was undertaken to assemble all useful and assessable bathymetric surveys in a single database. The purpose of developing the bathymetric archive was to create a database that could be used to study historical changes in the system. The archive also would be available for future research projects. Furthermore, a major goal of this project was to define, based on a review of existing surveys, where new, high resolution bathymetric surveys are needed in order to better understand rates and patterns of sedimentation in GBE and to create a baseline for future bathymetric comparisons.

Therefore, the objectives of this project include: developing a database containing as many available and relevant bathymetric surveys as possible; converting the assessable surveys to digital form (if necessary); converting each bathymetric survey obtained for the archives to a common projection and horizontal datum; assembling the bathymetric surveys in a GIS environment; developing bathymetric maps of representative time periods displaying the coverage; and conducting comparisons of the bathymetry to assess changes with time at selected locations.

## 2 Bathymetric Surveys Archive

To date, four sources of bathymetric data have been utilized for this project including the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS), the New England District of the US Army Corps of Engineers (USACE), the University of New Hampshire Center for Coastal and Ocean Mapping (CCOM) – NOAA Joint Hydrographic Center (JHC), and a bathymetric survey conducted by RESON as part of the Shallow Survey 2008 5$^{th}$ International Conference on High-Resolution Surveys in Shallow Water hosted by UNH CCOM/JHC.

The bathymetric surveys acquired during this study conducted by NOS, along with electronic copies of hydrographic sheets and descriptive reports, are available from the National Geophysical Data Center (NGDC) web site (http://www.ngdc.noaa.gov/). The following surveys were obtained: hydrographic or smooth sheets for bathymetric surveys conducted in 1898 (H2360), 1903 (H2656), and 1913 (H3524 and 3525); digital data for four bathymetric surveys carried out from 1953 to 1955 (H08090, H08092, H08093 and H08094); and two relatively recent multibeam echo sounder (MBES) surveys including a 1997 survey of the entrance to Portsmouth Harbor (H10763) and a 2000 survey of Portsmouth Harbor to Newington (H11014).

The soundings from the 1898, 1903, and 1913 surveys were not available in digital form from NGDC. Therefore, the four hydrographic sheets had to be digitized. The two surveys from 1913 (H3524 and H3525) were previously digitized at CCOM (Jakobsson et al. 2005). The other two hydrographic surveys (1898; H2360; 1903: H2656) had to be digitized as part of this study. This process is described in section **2.1 Digitizing of Hydrographic Survey Sheets**. Though the metadata available with these surveys is somewhat limited and incomplete, sufficient information is available to identify the projection, horizontal datum, vertical reference and tide gage locations for each survey.

The 2000 survey of Portsmouth Harbor to Newington is a high resolution multibeam survey that is available in xyz format, as well as gridded at 1 m. The full multibeam dataset is not available from NGDC for the 1997 NOS survey of Portsmouth Harbor.

The bathymetric surveys obtained from USACE were provided by the New England District and include portions of Little Harbor (2001) and the channels of the Lamprey River (1997), Bellamy River (2006), Cocheco River (2007) and the lower Piscataqua River from Portsmouth Harbor to Newington (2007). These datasets include single beam and multibeam acoustic surveys. Some of these bathymetric surveys conducted by the USACE were available on the following web site for the New England District.

http://www.nae.usace.army.mil/navigation/navigation2.asp?mystate=nh

However, most of the digital data of the full edited xyz bathymetry was supplied directly by the New England District of the USACE. Only the shoalest soundings were available for the 1997 Lamprey River which is a subset of the full edited database that depicts the shallowest depths. Although this is useful for defining navigation channels and assessing their location, it cannot be used for evaluating depth changes. Therefore, the 1997 Lamprey survey is not included in this study.

**Notice: The surveys conducted by the US Army Corp of Engineers are public information. However, it is recommended that the New England District of the USACE be contacted <u>before</u> their surveys are used.**

CCOM-JHC provided a mulitbeam survey of GBE extending from the Piscataqua River at Dover Point through Little Bay to Furber Strait. This survey is archived as a bathymetric map gridded at 1 m. The bathymetric survey of the entrance to Portsmouth Harbor conducted in 2007 by RESON is available as part of the Common Dataset associated with the Shallow Survey 2008 conference.

Collectively, these surveys provide the main bathymetric data for the GBE utilized for this project that have the minimal required horizontal and vertical datum control. The database has been brought together and is stored along with available metadata in an archive (Table 1). The coverage provided by these surveys are shown in Figures 1 to 3.

**Notice: The bathymetric surveys included in the database constructed for this study are not to be used for development of navigation charts or navigation purposes.**

**Table 1. Bathymetric surveys included in historical database for this project.**

| | |
|---|---|
| 1898 NOS Survey (H2360) | Portsmouth Harbor Approach |
| 1903 NOS Survey (H2656) | Portsmouth Harbor to Dover Pt. |
| 1913 NOS Survey (H3524) | Upper Piscataqua R. |
| 1913 NOS Survey (H3525) | Little Bay and Great Bay |
| 1953-1955 NOS Survey (H8090) | Portsmouth Harbor Area |
| 1953-1955 NOS Survey (H8092) | Portsmouth Harbor Approach to Dover Pt. |
| 1953-1955 NOS Survey (H8093) | Great Bay, Squamscott R., Lamprey R. |
| 1953-1955 NOS Survey (H8094) | Dover Point to Upper Piscataqua River, Bellamy R. |
| 1997 NOS Survey (H10763) | Portsmouth Harbor Approach |
| 2000 NOS Survey (H11014) | Portsmouth Harbor to Dover Pt. |
| 2001 USACE Survey | Little Harbor |
| 2006 USACE Survey | Bellamy R. |
| 2007 USACE Survey | Cocheco R. |
| 2007 USACE Survey | Piscataqua R. from Bridges to Dover Pt. |
| 2002 CCOM Survey | Dover Pt. to Great Bay |
| 2007 RESON Survey | Portsmouth Harbor Entrance |

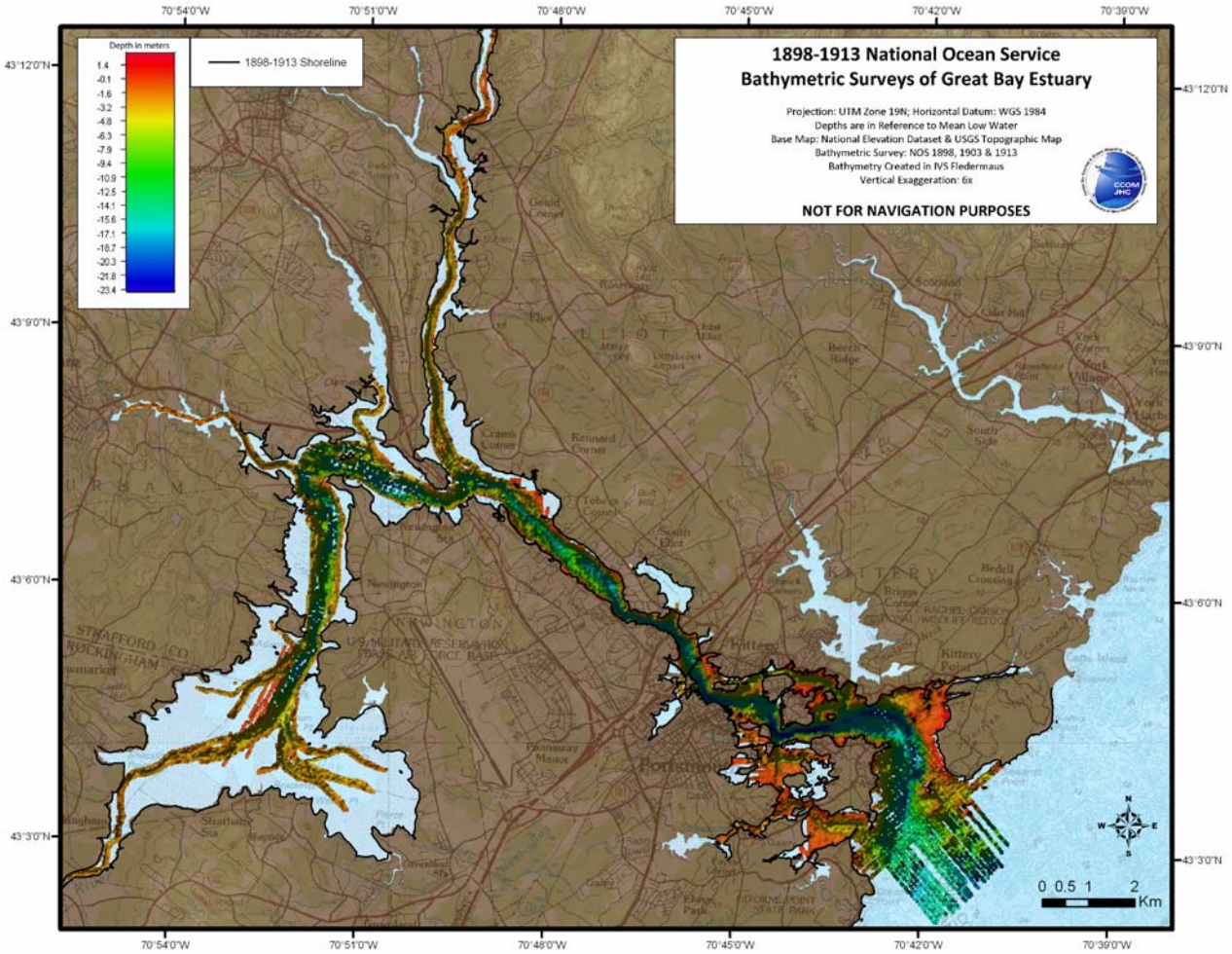



**Figure 1. Composite bathymetric map of surveys done in Great Bay Estuary between 1898 and 1913.**

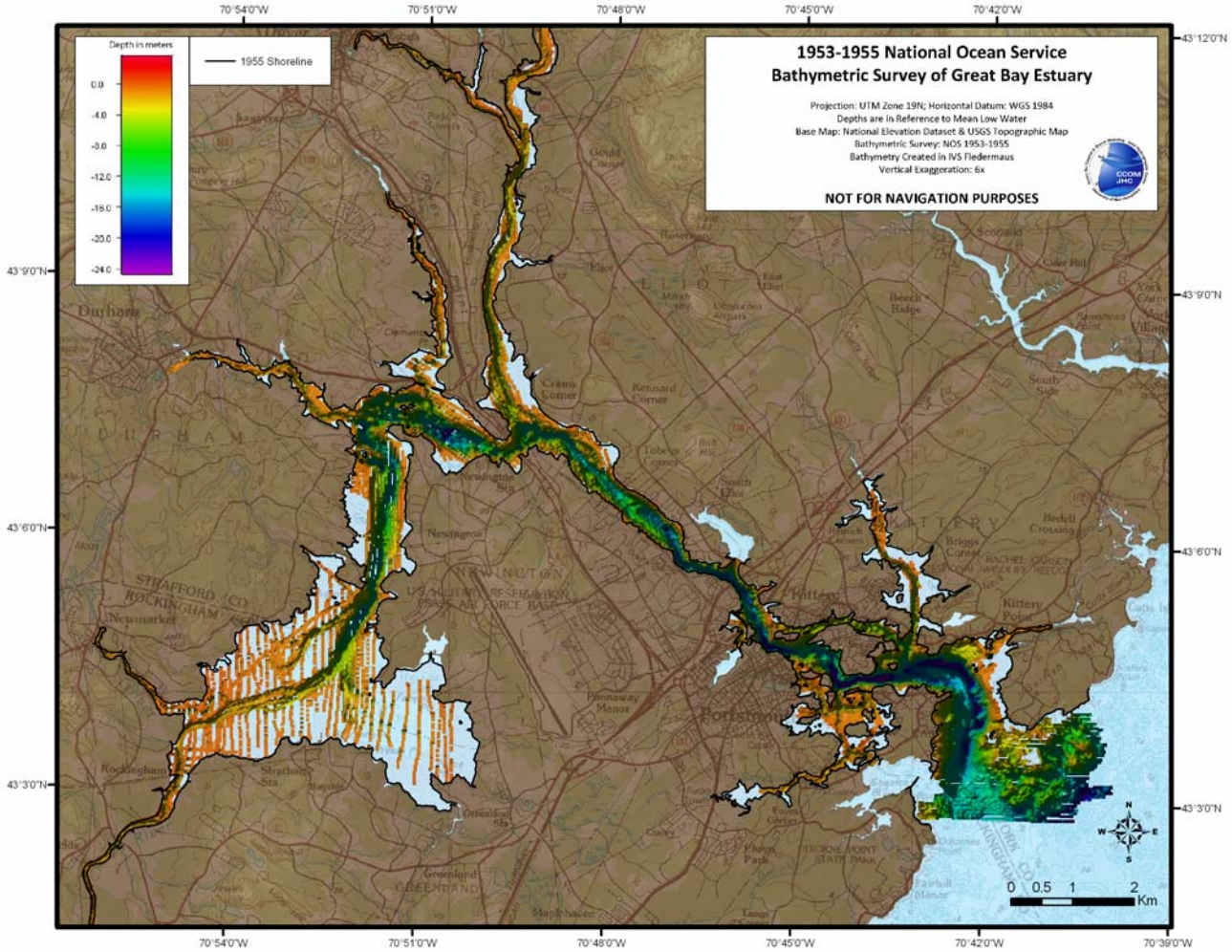



**Figure 2. Seamless bathymetric map of the NOS survey conducted in Great Bay Estuary between 1953 and 1955.**

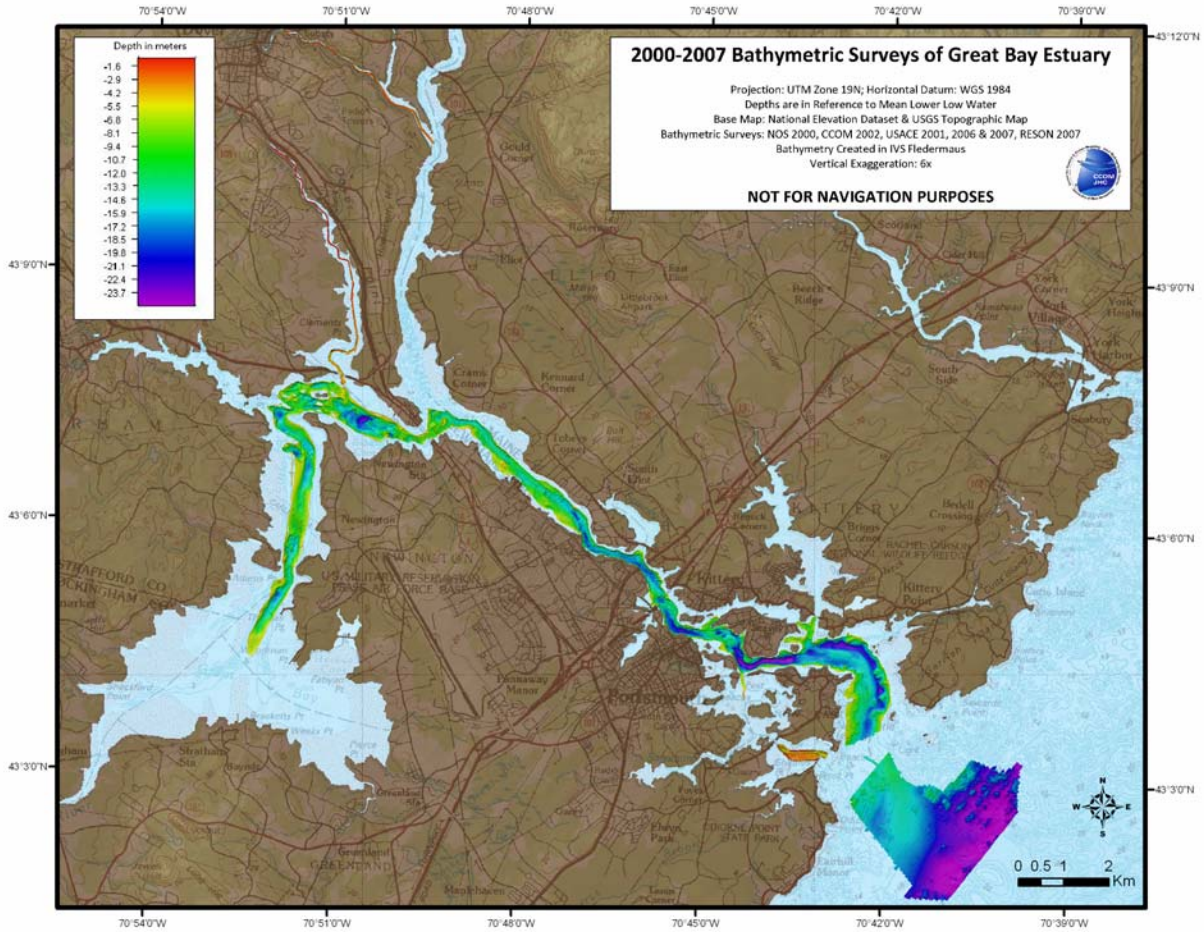



**Figure 3. Composite bathymetric map of the surveys conducted in Great Bay Estuary between 2000 and 2007.**

### 2.1 Digitizing of Hydrographic Survey Sheets

The soundings from the 1898 NOS survey of Portsmouth Harbor approach (H2360) and the 1903 NOS survey of Portsmouth Harbor and the Piscataqua River to Dover Point (H2656) were digitized directly from scans of the original smooth sheets which were downloaded from the NGDC web site. The U.S. Coast and Geodetic Survey (predecessor to the National Ocean Service) added graticules to the smooth sheets (at a later date) that referred to NAD 1927 coordinate system. The smooth sheets were then geo-registered directly using the graticules to NAD 1927. The original coordinate systems on the smooth sheets were not determined, although the Clarke 1866 spheroid was cited. The depth soundings were digitized in ArcGIS with the heads up display using the Editor tool to locate and enter a value for each sounding that was legible. Due to the age and relatively poor quality of some areas of the original smooth sheets that were scanned, a number of the soundings were not legible. If the sounding was not reasonably clear, the value was omitted during the digitizing. The digitized soundings were then edited by printing out the digitized smooth sheets with the entered soundings. If the entered values could not be verified they were deleted from the database. The digitized soundings then were obtained from the created dbf files. A major effort was made to determine the correct sounding value. However, undoubtedly digitizing errors still occurred. In total, 6,569 soundings were entered for the 1898 survey and 6,762 soundings for the 1903 survey.

In addition to digitizing the soundings of the 1898 and 1903 NOS surveys, the shorelines and the mean low water lines (0 ft contour) were digitized for the smooth sheets for the 1898 NOS survey (H2360), the 1903 NOS survey (H2656) and the 1953-1955 NOS surveys (H08090, H08092, H08093 and H08094) in ArcGIS with the Editor tool. Again, due to the age of the original smooth sheets that were scanned, portions of shorelines or the mean low water lines that were blurry or unclear were omitted.

### 2.2 Conversion of Bathymetric Surveys to Common Coordinate System

The bathymetric surveys that are included in the database were conducted over a time period ranging from 1898 to 2007 by multiple agencies. As a result, the original surveys are in a number of different projections and datums. Therefore, it was necessary to transform all of the surveys to a common coordinate system (projection and datum). In view of data management and facilitating comparisons, it was decided to use the following global system.

Projection: Universal Transverse Mercator (UTM Zone 19 North)
Horizontal Datum: World Geodetic Survey 1984 (WGS84)

The conversions were done in Global Mapper Software, LLC.

Vertical datums could not be reliably adjusted and were left as reported.

## 3 Bathymetric Maps

Bathymetric maps from the soundings were developed in ArcGIS and IVS 3D Fledermaus using the following general approach. First, the soundings for the surveys were converted to the standard projection (UTM Zone 19N) and horizontal datum (WGS84) for this project. For the 1898, 1903, 1913 and 1953-1955 bathymetric surveys, the soundings were brought into ArcGIS as shape files. Subsequently, the point data for each survey were used to create a Digital Elevation Model (DEM) using a Triangulated Irregular Network (TIN) algorithm. The TINs were constructed in ArcGIS using the 3D Analyst TIN Creation tool. The TINs were set up using the smallest edge (facet) length that facilitated the construction of TINs with maximum use of data while still maintaining open areas such as islands or areas where no soundings occurred as much as possible. Each TIN was then gridded in ArcGIS 3D Analyst at 3 m using the Convert TIN to Raster tool. In addition, each survey was brought into IVS 3D Fledermaus and gridded at the smallest reasonable size to display the soundings as a bathymetric map. The advantage of the bathymetry created in Fledermaus is the three-dimensional character that can be observed. The most recent bathymetries obtained from 2001 to 2007 are largely high resolution and consequently are displayed only as Fledermaus maps to take advantage of the three-dimensional quality of the database. However, these modern bathymetric maps were brought into the ArcGIS project as both TIFFs and gridded binary files. The most recent bathymetry is limited in spatial coverage.

The bathymetric surveys archived in the database developed for this project group into three general time periods: 1898 to 1913, 1953 to 1955, and 2001 to 2007 (Table 1). Bathymetric maps were developed for each of these time periods in ArcGIS and Fledermaus. The earliest composite map includes the 1898, 1903, and 1913 NOS surveys (Figure 1). The 1950s era seamless bathymetric map includes the 1953-1955 NOS surveys (Figure 2). The most recent composite map includes the 2000 NOS survey, the 2002 CCOM/JHC survey, the 2006 and 2007 USACE surveys, and the 2007 RESON survey (Figure 3). The quality and detail of these bathymetric maps largely reflect the spatial converges and density of soundings within that coverage. Examples of bathymetric maps made with a TIN, a gridded TIN, and a gridded TIN transported into Fledermaus and displayed in three dimensions for Portsmouth Harbor are shown in Figures 4, 5, and 6, respectively. Bathymetric maps made in IVS 3D Fledermaus and ArcGIS for Little Bay and Great Bay are shown in Figures 7 to 9.

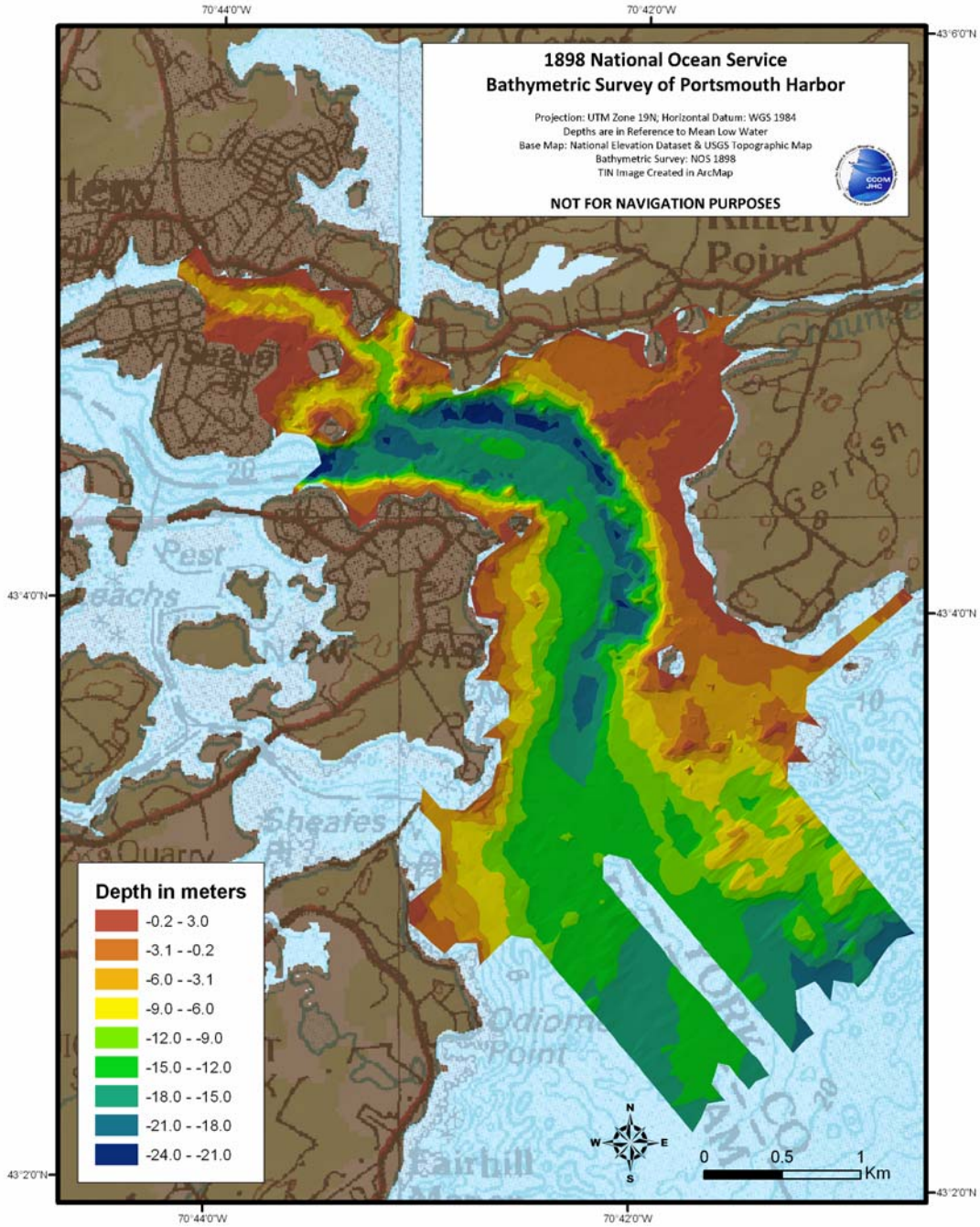



**Figure 4. Bathymetric map of Portsmouth Harbor based on the 1898 NOS survey produced as an ArcGIS TIN model.**

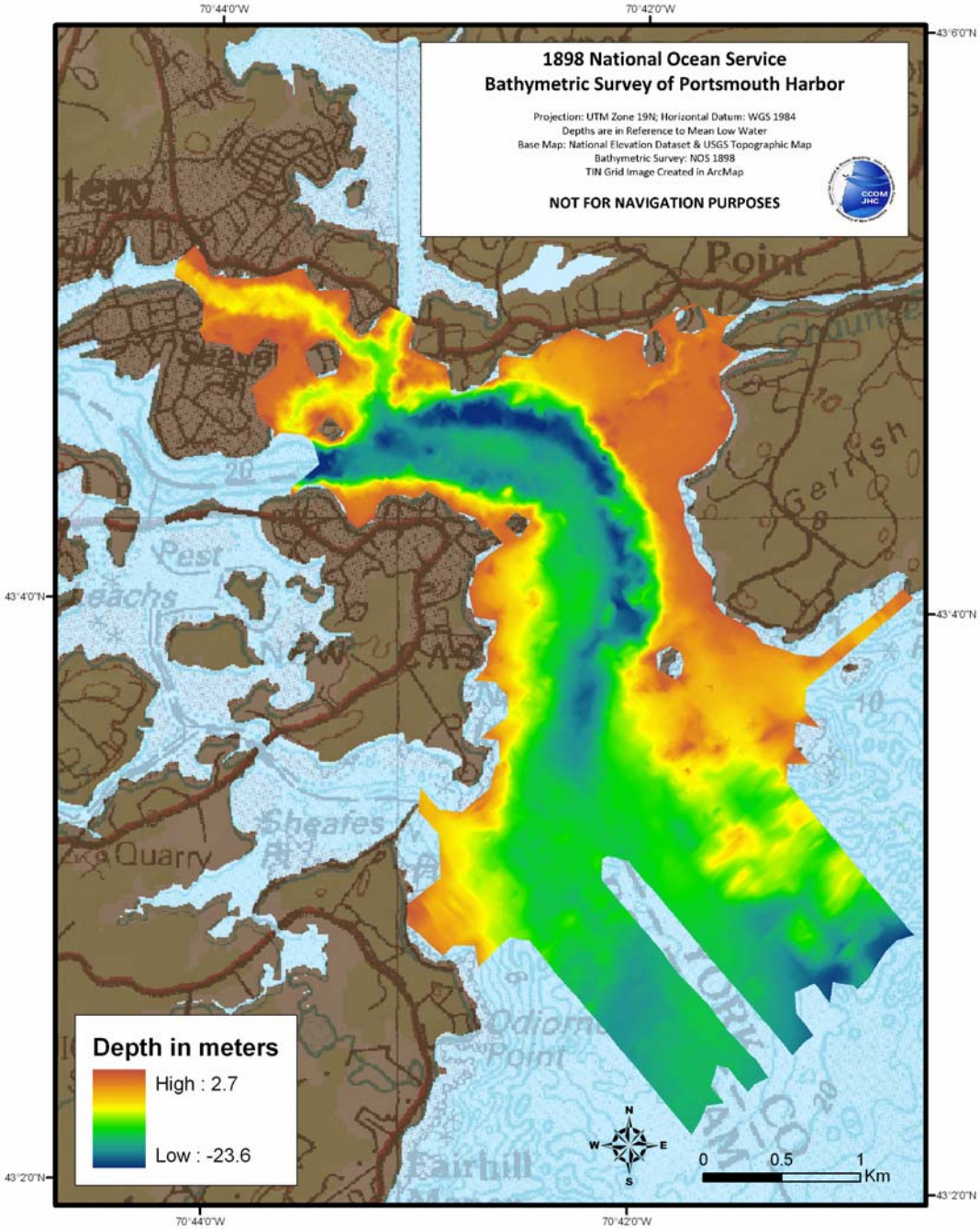



**Figure 5. Bathymetric map of Portsmouth Harbor based on the 1898 survey produced in ArcGIS as a gridded TIN model.**

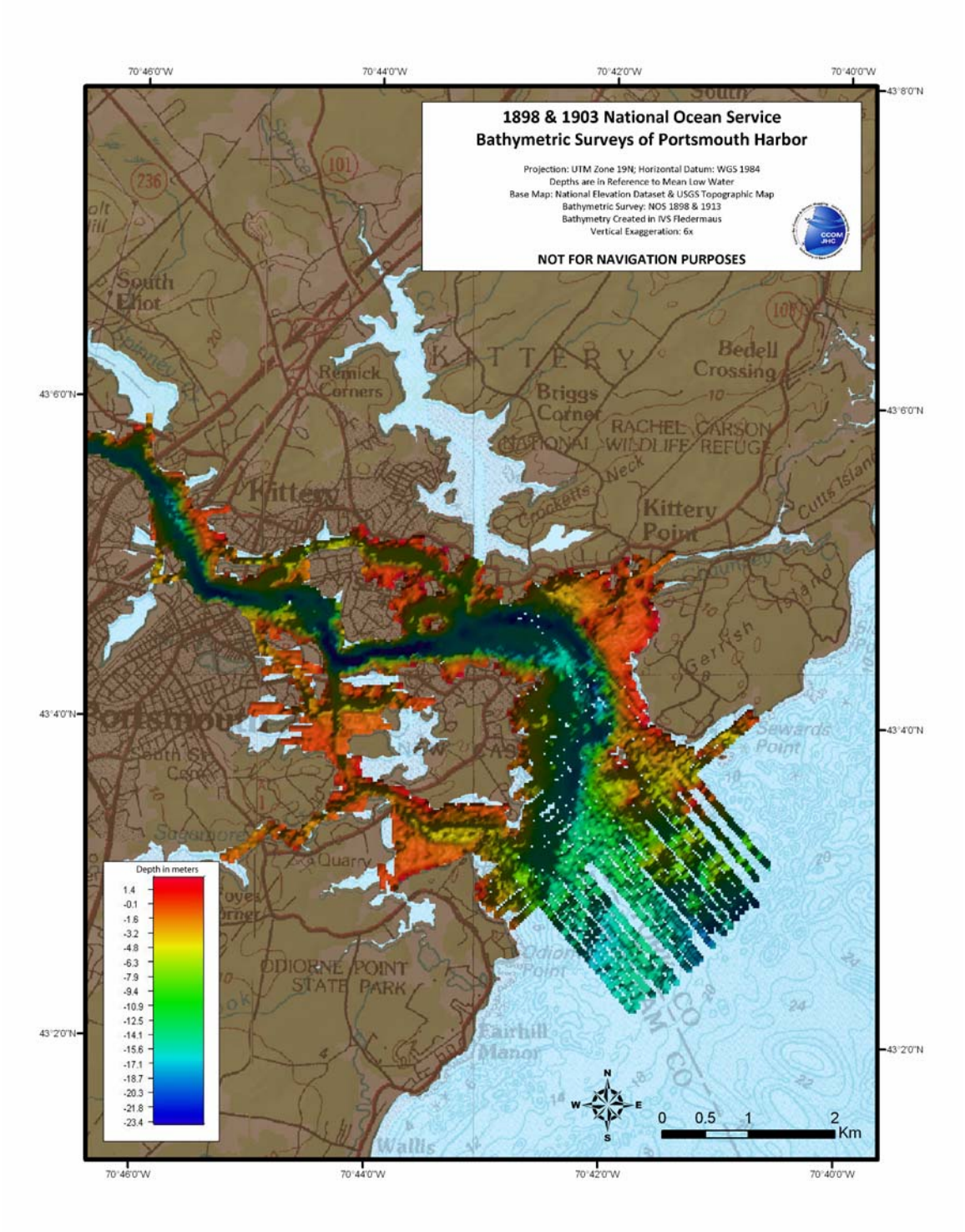



**Figure 6. Bathymetric map of Portsmouth Harbor based on the 1898 and 1903 surveys produced in IVS 3D Fledermaus.**

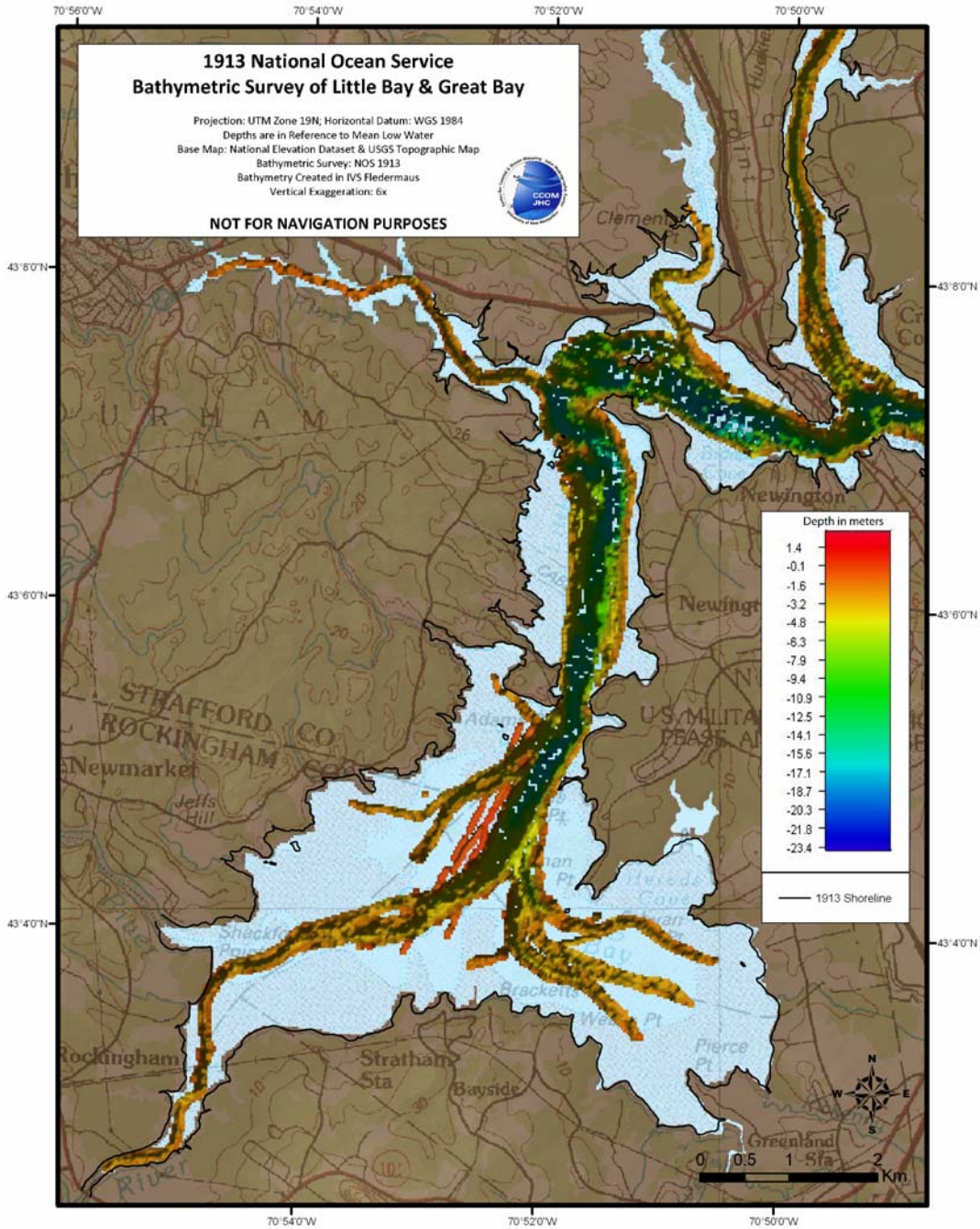



**Figure 7. Bathymetric map of Little Bay and Great Bay based on the 1913 NOS survey produced in IVS 3D Fledermaus.**

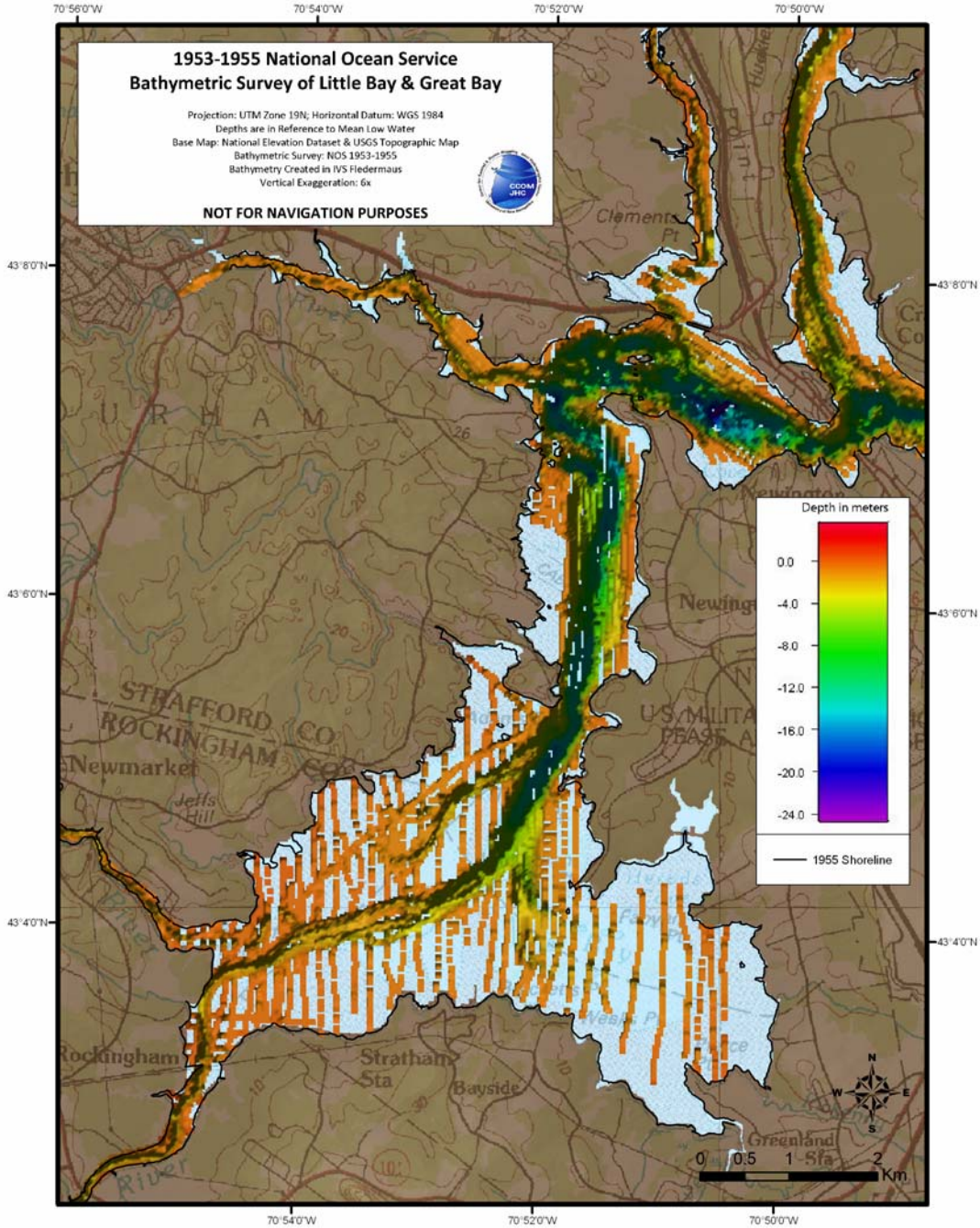



**Figure 8. Bathymetric map of Little Bay and Great Bay based on the 1953-1955 NOS survey produced in IVS 3D Fledermaus.**

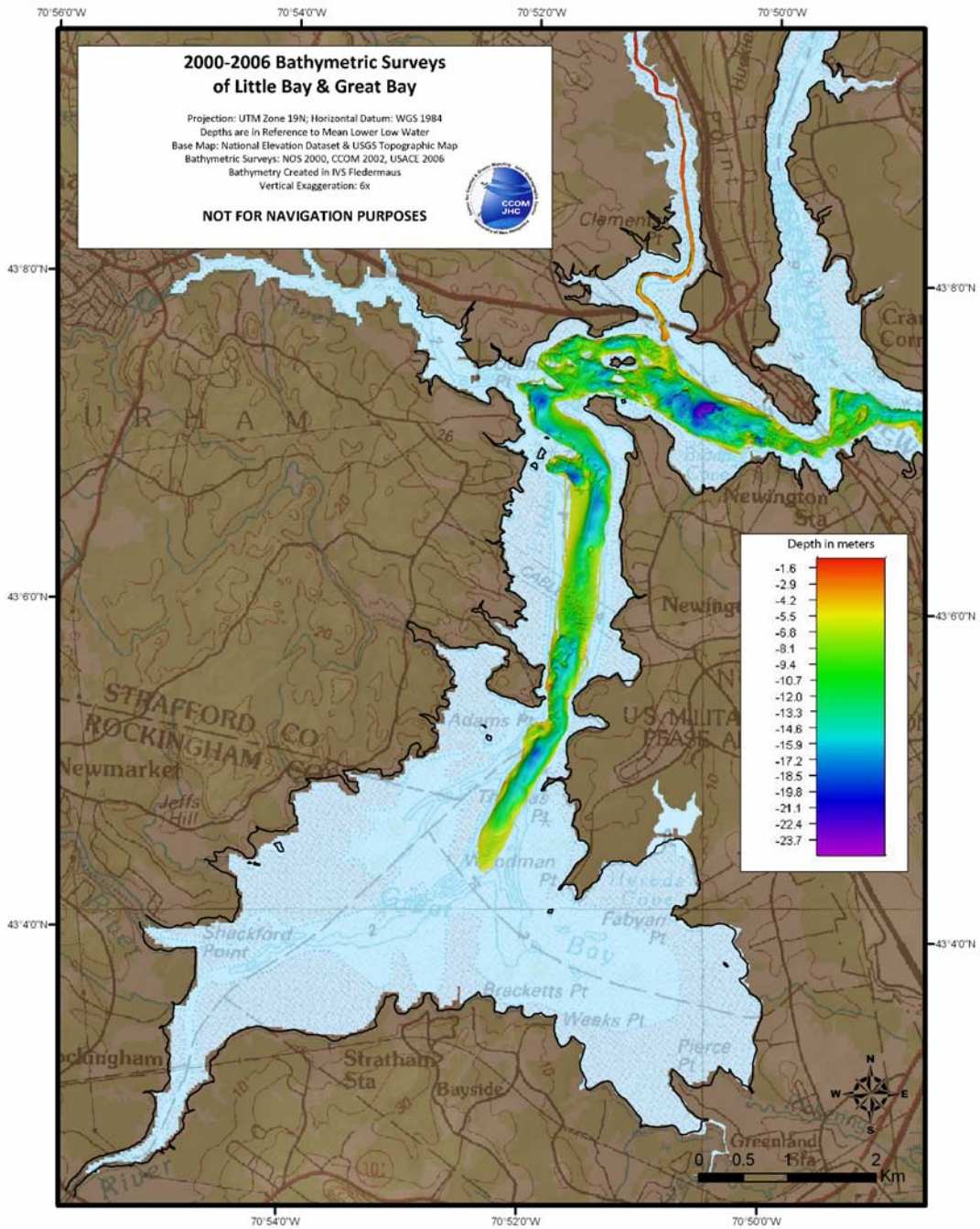



**Figure 9. Bathymetric map of Little Bay and Great Bay based on the 2000 NOS and the 2002 CCOM surveys produced in IVS 3D Fledermaus. The bathymetry for the Bellamy River is from the 2006 USACE survey.**

## 4 Bathymetric Change Analyses

As indicated earlier, several major bathymetric surveys have been conducted in GBE over the last century for navigational purposes. Since these surveys can potentially provide important insights into changes in bathymetry in GBE, the existing surveys assembled during this study were thoroughly examined and analyzed to determine if reasonable trends or patterns could be discerned. At a minimum, this type of investigation would identify areas where high resolution bathymetric surveys need to be undertaken in the future to resolve fundamental questions concerning sedimentation in GBE. However, before this is discussed, it is important to understand the potential errors associated with comparing soundings or depths from different surveys. This is especially the case when considering historical bathymetric surveys.

### 4.1 Potential Errors

Comparisons of bathymetric surveys across different time periods have been used frequently in the past as a means of determining changes in depth that are then interpreted as evidence of bottom deposition, erosion, or stability. However, assessing changes in depth over time using historic bathymetric data must be done with considerable caution (van der Wal and Pye 2003; Jakobsson et al. 2005; Calder 2006).

Comparing soundings from different time periods often results in comparing depth measurements made using very different technologies that may include leadlines, poles, single beam echosounders, or multibeam echosounders. Positioning or location of soundings from different time periods has also changed significantly from using sextants to Real Time Kinematic (RTK) GPS systems. As a result, soundings, depth measurements, and positioning have associated errors that can vary with the survey and the technology (Jakobsson et al. 2005; Calder 2006). Extremely important when comparing different bathymetric surveys is the location of the tide gage or tide gages and the tide zones used to reduce the soundings and to establish the vertical datum (common vertical reference). However, when comparing different bathymetric surveys, often conducted some decades apart, differences in tide gage locations or the vertical datum can lead to large differences in soundings (van der Wal and Pye 2003). Other issues that lead to errors or create problems when comparing bathymetric surveys from different time periods include the relatively low density of soundings from many earlier surveys, the focusing of soundings on channels, the frequent paucity of depth measurements on adjacent flats, and the lack of overlapping soundings between surveys being compared.

All of these factors can significantly affect the outcome of accurately determining changes in depth between surveys (van der Wal and Pye 2003; Jakobsson et al. 2005; Calder 2006). In fact, the errors often exceed the magnitude of the differences in depths making observations of net changes invalid.

### 4.2 Selection of Bathymetric Surveys and Time Periods

After review of the existing bathymetry and historical records of GBE, it was decided to focus on the upper estuary landward of Dover Point due to the extensive anthropogenic alterations and frequent dredging that has occurred in the lower estuary. It was also decided to focus primarily on the 1913 and the 1953-1955 surveys due to their wider spatial coverage. The recent surveys, although conducted at a much higher resolution with improved technology (frequently multibeam echosounders), tend to focus on the channels only and are very limited in their overall spatial coverage. As a compromise, the 1913 and 1953-1955 surveys were selected for the bathymetric comparisons despite the relatively wide spacing of soundings. It should be noted that the 1913 NOS survey focuses on the channel areas, while the 1953-1955 NOS survey covers larger reaches, but at the expense of wider spacing between survey lines. In addition, the 1913 NOS survey was primarily conducted with leadlines and poles, while the 1953-1955 NOS survey utilized narrow beam echosounders. A potential error between these technologies could arise in areas where the bottom is covered with eelgrass. Acoustic data, if not processed properly, can underestimate depths in areas vegetated with eelgrass and other types of submerged aquatic vegetation.

### 4.3 Methodology

Bathymetric comparisons between surveys were done using a modification of the method presented by Jakobsson et al. (2005). The following method was used for all of the analyses.

1. The soundings for all surveys being analyzed were converted to the same projection (UTM 19N), horizontal datum (WGS84), and units (meters) and brought into ArcGIS.
2. Soundings from the areas of estuary chosen for comparisons were clipped (separated from the larger database) in ArcGIS into individual files for each survey period (in this case 1913 and 1953-1955) using the Analysis Tool Extract.
3. The point data for each segment was converted to a TIN model in ArcMAP using the 3D Analyst TIN Creation tool by using the smallest maximum edge length (facet) possible, while still including a reasonable percentage of the survey points. The maximum edge length for the TIN for the analysis of the entire upper Great Bay was 150 m. The remaining segments (upper Piscataqua River area, Little Bay, and Great Bay) used 100 m maximum edge lengths.
4. Each TIN model was gridded in ArcGIS 3D Analyst at 3 m using the Convert TIN to Raster tool.
5. Subsequently, the gridded TINs were brought into IVS 3D Fledermaus and converted to a three-dimensional bathymetric map (sd file). This was done for both the 1913 and 1953-1955 soundings.
6. Similarly, the individual soundings that were clipped from the larger surveys for the areas being analyzed were brought into Fledermaus as ungridded data and were gridded at 1 or 2 m. The 1 or 2 m grid size was much smaller than the

distance between the points, so each grid essentially represented a single sounding (although converted to an area).

7. To determine the difference in depths between the two surveys the gridded surface made in Fledermaus from the 1953-1955 converted TIN to raster was used as a base or a continuous surface. The 1913 soundings that were gridded at 1 or 2 m in Fledermaus were then subtracted from the 1953-1955 surface to determine the change in depth at that location using the IVS 3D Fledermaus Surface Differencing tool. The differences for each location were then averaged in Fledermaus for the entire segment to determine the net change. The reverse process was also done as a comparison. In this case the 1913 converted TIN to raster was used as a continuous surface and the 1953-1955 survey gridded points subtracted. The results were similar varying within 0.08 m.

The difference in bathymetry was also assessed using a second method which was done largely for display purposes. The subtraction of the 1913 point soundings (gridded at 1 or 2 m in Fledermaus) from the 1953-1955 TIN model (gridded and brought into Fledermaus) is considered to give the best representation of the actual change based on the soundings. However, the results are difficult to visualize. Therefore, each segment was also analyzed by creating a TIN model of the 1913 soundings, gridding, and bringing into Fledermaus. Subsequently, the 1913 gridded TIN model was subtracted from the 1953-1955 gridded TIN model using the Fledermaus Surface Difference tool. This results in a isopach map of the difference of the two surveys which can be more easily visualized. Although the results obtained using this method are usually similar to those obtained using the methods described above in number 7, the subtraction of the gridded TINs is for visualization and the numeric results are not reported here.

### 4.4 Results

A review of the acquired bathymetries was conducted in order to assess the potential for bathymetric comparisons. This analysis involved: 1) developing TIN models (and subsequently converting to a grid and transporting into Fledermaus) for several of the tributaries including the Oyster, Bellamy, and Cocheco Rivers based on the 1913 or the 1953 NOS surveys; and 2) gridding more recent high resolution USACE multibeam surveys in Fledermaus (2006 USACE Bellemy River survey and 2007 USACE Cocheco River surveys). Initial analyses of these systems showed that there was not enough overlap or intersections of soundings to produce reliable results. In addition, there were concerns about the tide control of the earlier surveys. Therefore, these tributaries were not analyzed.

#### 4.4.1 Upper Great Bay Estuary

The comparison between the 1953-1955 and the 1913 NOS surveys extended from the Upper Piscataqua River and Salmon Falls area in the north to Great Bay and Squamscott River to the south (Figure 10). This area is essentially the entire upper estuary and is the same as the coverage of the 1913 NOS survey. One of the reasons for examining this area

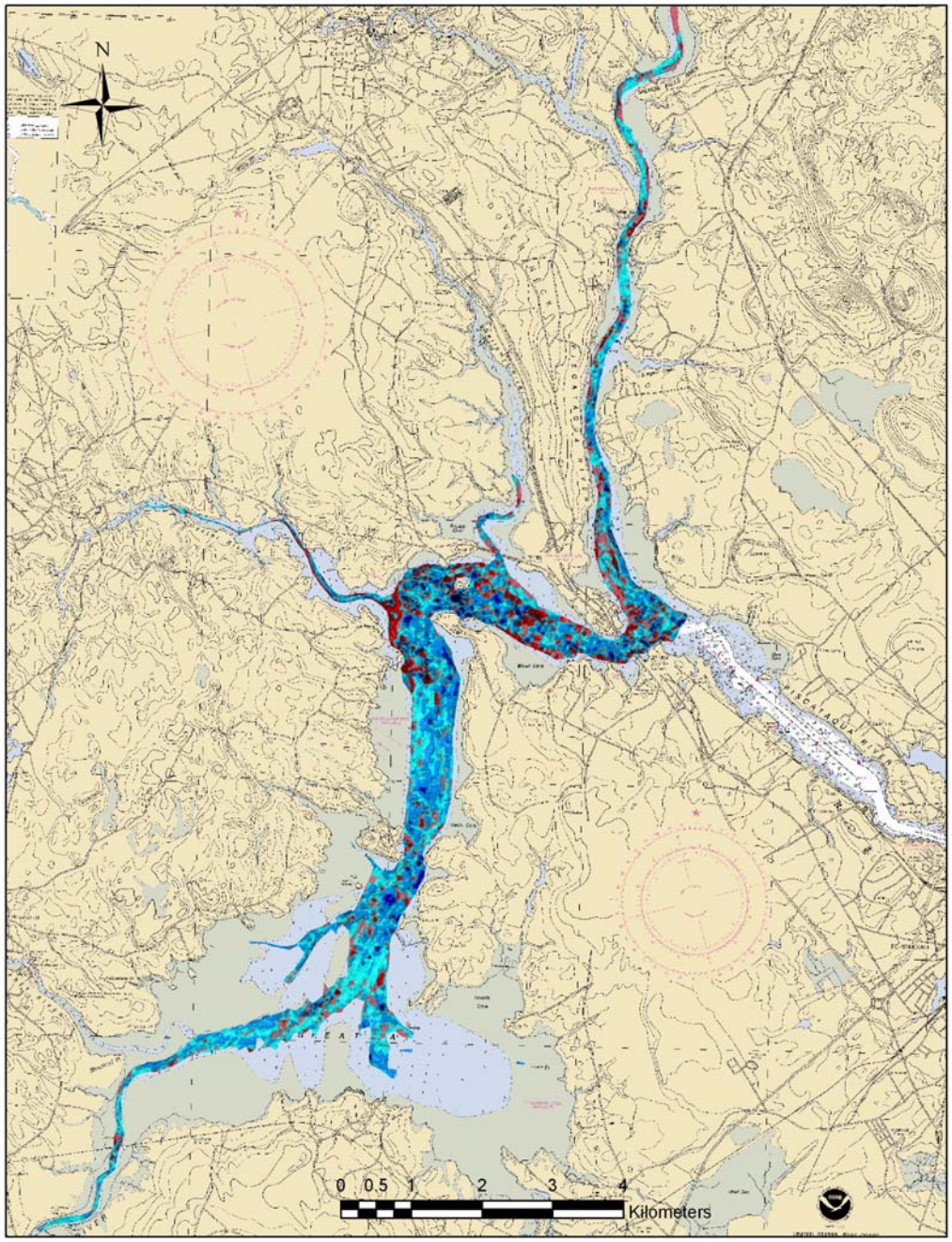



**Figure 10. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the upper Great Bay Estuary segment. The shaded area represents the difference between the TINs for each survey created in ArcGIS, converted to a grid and then brought into IVS 3D Fledermaus. Blue indicates where the 1953-1955 TIN model depths are less than the 1913 TIN model depths; red indicates where they are greater.**

was to compare the methodologies utilized during this study with those of Jakobsson et al. (2005) who conducted a comparison between the 1953-1955 and the 1913 bathymetric surveys for largely the same area. Although the approach and overall methodologies used in our study were similar to those of Jakobsson et al (2005), differences in software and modifications of the procedures warranted a comparison. While the objective of this study was to examine smaller sections of GBE than Jakobsson et al. (2005), it was still important to compare the studies to determine if the approaches were compatible and to verify the approach used in the present study.

The results of the comparison of the 1953-1955 and 1913 NOS bathymetric surveys using the procedures outlined in section **4.3 Methodology** indicated that an average decrease in depth occurred in the upper GBE where the two surveys intersected (Figure 10). Subtraction of the 1913 two meter grids from the 1953-1955 TIN model (converted to a grid and brought into Fledermaus) surface had a mean change of 0.46 m ±1.36 with a range of -12.04 to 8.48 m over the ~40 year period. However, it should be noted that there was significant variability in the amount and direction of change across the comparison area. It also should be noted that the comparison covered a very large area.

Jakobsson et al. (2005) reported an average difference between the 1913 point data and their 1953-1955 TIN model as 0.45 m with a symmetric distribution of depth differences about the mean. In general the outcomes of the two methods (Jakobsson at al. 2005 and the approach presented here) are very consistent, both in average change and in the locations of the seafloor changes.

Important to this project, Jakobsson et al. (2005) also reviewed potential errors associated with the horizontal positioning of the soundings and the depth measurements for the 1913 and 1953-1955 NOS bathymetric surveys. Their estimation (using several assumptions) of the maximum horizontal positioning error of soundings was ±18 m, while the maximum error of the depth measurements was ±0.34 m [based on a ±0.3048 m (1 ft) maximum depth measurement error and a ±0.1524 m (0.5 ft) tide control error]. However, Jakobsson et al. (2005) also pointed out that the most significant potential source of error was the uncertainty associated with tide reducers. In fact, very different locations were used for tide gage stations during the two surveys, likely creating significant issues in vertical control as tidal datums vary spatially. In both surveys adjustments were made to the soundings during processing and verification by the Coast and Geodetic Survey (predecessor to the NOS). Finally, the descriptive report which accompanied the 1953-1955 survey specifically mentions the potential sounding problems in Little Bay and Great Bay indicating problems with tide reducers that would increase the error. This is discussed in more detailed in sections **4.4.4 Little Bay** and **4.4.5 Great Bay**.

As stated above, the results reported for the upper GBE for this study are consistent with those of Jakobsson et al. (2005), indicating that the methodologies are compatible and the results comparable (0.46 m and 0.45 m, respectively). Also, the error analysis reported for the 1913 and 1953-1955 NOS surveys by Jakobsson et al. 2005 apply to this study as well. As a result, the differencing of the surveys has to take into account the potential

influence of positioning errors, vertical measurements errors, and tide control. With this in mind, it is not possible to judge a net difference of 0.46 m ±1.36 as being significant without further verification.

### 4.4.2 Upper Piscataqua River (Dover Point to Salmon Falls River)

The Salmon Falls and Cocheco Rivers form the upper reaches of the Piscataqua River and provide both freshwater and fluvial sediment input to GBE. The upper Piscataqua River, as defined for this study, extends from approximately the confluence of the Salmon Falls and Cocheco Rivers southward to Dover Point. The Cocheco River was dredged between 2005 and 2007 in order to restore the channel depths into the city of Dover. Additional dredging for completion of the project is slated for 2010. Prior to the most recent dredging, the Cocheco River was last dredged in the late nineteenth century, which indicates a shallowing of the channel and the deposition of sediments during the intervening years.

Subtraction of the 1913 one meter grids from the 1953-1955 TIN model (gridded and brought into Fledermaus) from the upper Piscataqua River from Dover Point to the Salmon Falls River (Figure 11) indicated an average decrease in depth between the surveys of 0.25 m ±1.16 (ranging from -4.65 to 8.00 m). The net change for this segment of GBE is small when considering the magnitude of the potential errors involved in making these kinds of assessments (see section **4.4.1 Upper Great Bay Estuary)**. Consequently, it is not possible to make a general statement as to an overall trend for this reach.

### 4.4.3 Upper Piscataqua River (Dover Point to ~43° 10')

In order to examine the upper Piscataqua River area in somewhat more detail, the segment was clipped in ArcGIS from Dover Point to ~1.5 km north of Sturgeon Creek at ~43° 10' (~5.3 km up estuary from Dover Point) (Figure 12). Subtracting the 1913 points gridded at one meter from the 1953-1955 TIN model (converted to a grid and imported into Fledermaus), the segment from ~1.5 km north of Sturgeon Creek to Dover Point had an average decease in depth between the surveys of 0.28 m ±1.24 with a range of -4.65 to 7.97 m. Again, the net change in this segment is small compared to the potential errors (see section **4.4.1 Upper Great Bay Estuary Comparison)** and it is not possible to determine if this represents actual change.

Although the quantitative analysis of the bathymetric changes based on the 1913 and 1953-1955 surveys is not conclusive, it appears that the Dover Point area may be an important site for future study in order to gain a better understanding of channel movements and sediment exchange between the upper Piscataqua River area and the rest of the estuary (Figure 12). This site is recommended for high resolution bathymetric mapping if possible.

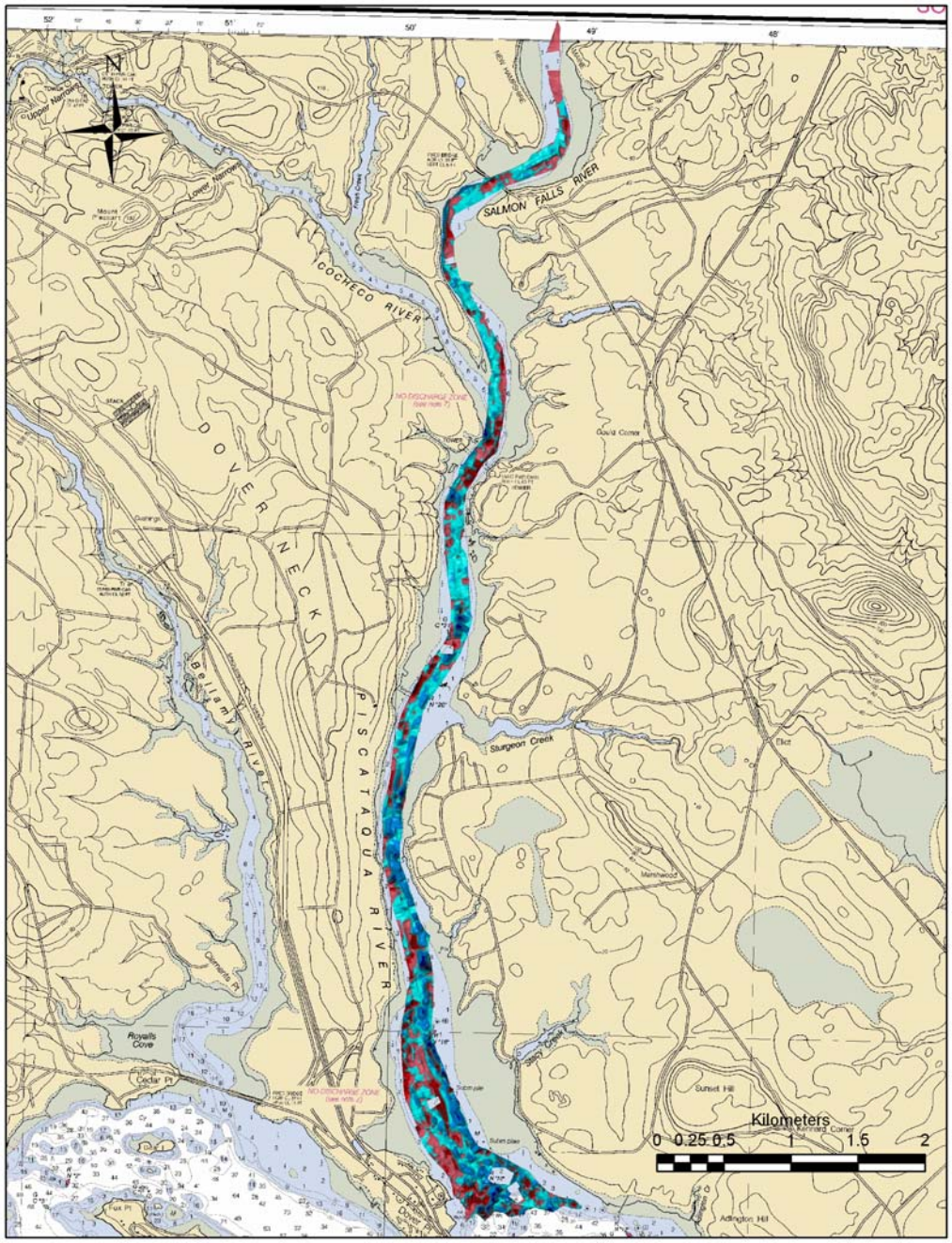



**Figure 11. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the the Piscataqua River (Dover Point to Salmon Falls) segment. The shaded area represents the difference between the TINs for each survey created in ArcGIS, converted to a grid and then brought into IVS 3D Fledermaus. Blue indicates where the 1953-1955 TIN model depths are less than the 1913 TIN model depths; red indicates where they are greater.**

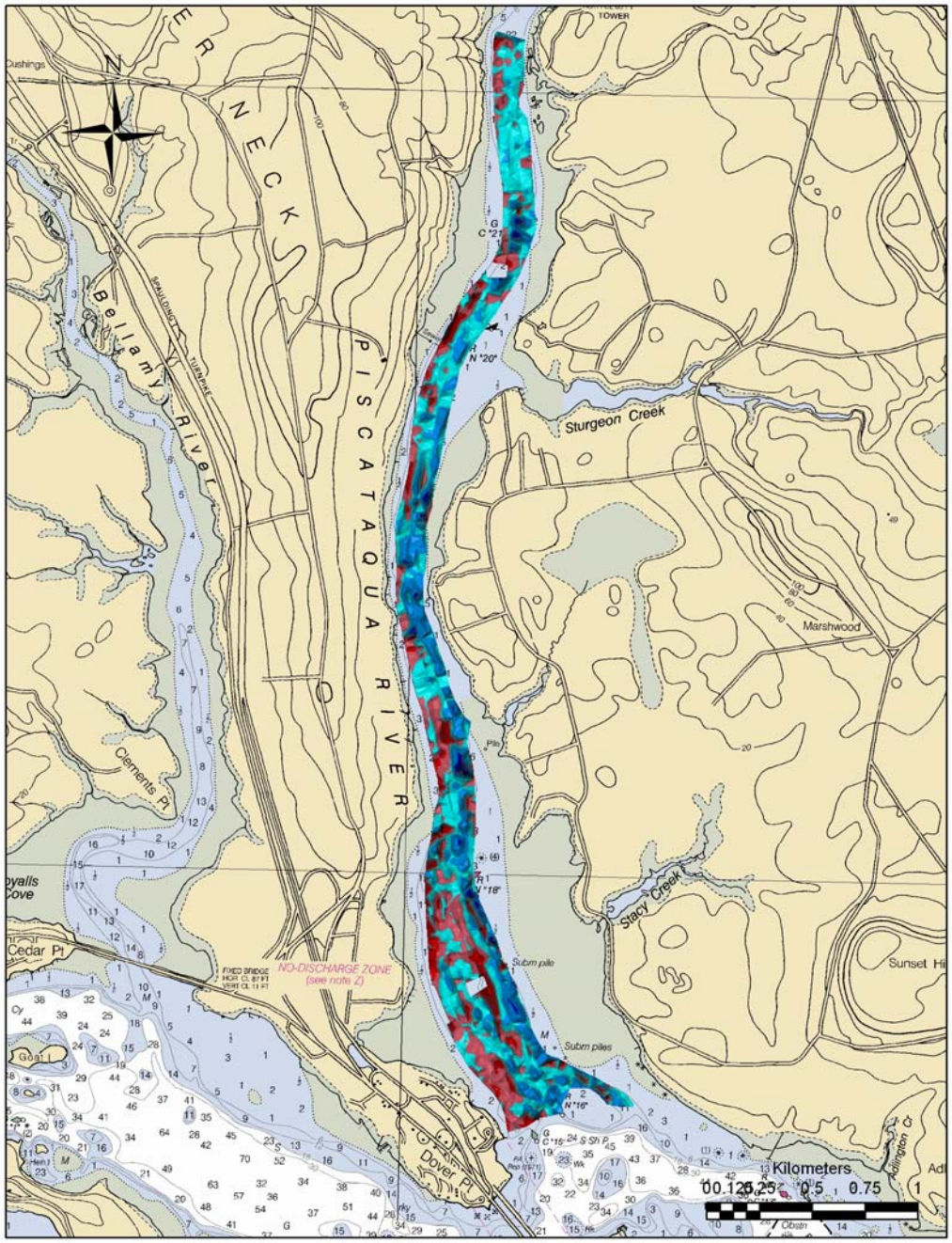



**Figure 12. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the Piscataqua River (Dover Point to ~43° 10') segment. The shaded area represents the difference between the TINs for each survey created in ArcGIS, converted to a grid and then brought into IVS 3D Fledermaus. Blue indicates where the 1953-1955 TIN model depths are less than the 1913 TIN model depths; red indicates where they are greater.**

### 4.4.4 Little Bay

The Little Bay segment analyzed for changes in depth between the 1913 and 1953-1955 NOS surveys extended from Fox Point to Furber Strait. As was typical for the 1913 NOS survey, the soundings were largely restricted to the channel area with little coverage of the large subtidal and intertidal flats. This is unfortunate because these flats appear to be important to the overall sediment budget of the upper estuary. More detailed higher resolution bathymetric surveys are warranted in this area if possible.

The results of the analysis (subtracting the 1913 point data gridded at one meter from the 1953-1955 TIN model gridded and brought into Fledermaus) indicated that the average change between the surveys was a decrease in depth of 0.70 m ± 1.51 with a range of -12.03 to 6.69 m (Figure 13). Although the magnitude of the net change in depth between the 1913 and the 1953-1955 surveys is larger than measured in the previous segments, there are several areas of concern regarding the analysis conducted in this area. The first concern stems from information provided in the descriptive report which accompanied the 1953-1955 NOS survey citing that soundings in Little Bay were reduced during the survey from a tide gage located at Newington on the Piscataqua River. The descriptive report also points out that the tides in Little Bay are likely more closely related to tidal characteristics in Great Bay. As a result some soundings were adjusted by 1 to 2 feet. The location of the tide gages and its effect on the comparison of the bathymetry is discussed in section **4.4.5 Great Bay Comparison**.

As a test of the potential problems with reducing soundings and vertical datum issues between the 1913 and 1953-1955 NOS surveys, the interior of the channel in Little Bay was isolated (clipped) and the surveys were differenced using the described method. It is assumed that this area would not change in any major way due to erosion or deposition as the 2002 CCOM survey indicated frequent outcropping bedrock and a relatively hard bottom. Differencing of the 1953-1955 and the 1913 NOS surveys indicated a positive change of 1.20 m ±1.35 with a range of -9.27 to 4.19 m. Assuming the premise that the seafloor changed little during the period between the 1913 and 1953-1955 NOS surveys is correct, then the apparent decrease in depth is likely due to tidal datum issues.

Therefore, due to the problems associated with the measurement of the level of the tides (necessary to establish a common vertical reference or datum) at very different locations, quantitative comparisons between the historical surveys for Little Bay are limited and it is hard to draw a conclusion from the present comparison.

### 4.4.5 Great Bay

Great Bay is a major sediment deposition center in GBE and is therefore critical in understanding depositional processes throughout the system. Subtraction of the 1913 NOS survey from the 1953-1955 NOS survey indicated an average decrease in depth between the surveys for the area in Great Bay where there was adequate bathymetric coverage (Figure 14). The net change was 0.67 m ±1.03 over the ~40 year period. Similar to the other comparisons, the range of change was very large (-5.40 to 7.02 m) which is

likely due to channel migrations or positioning errors between surveys. As can be seen in Figure 14, large areas of Great Bay were not included in the analysis. This resulted from the use of 100 m for maximum edge length for the development of the TIN model of the 1953-1955 bathymetric survey. The line spacing during the 1953-1955 survey was very wide, often exceeding 200 m. In order to include this area, the TIN model would have extended across very large areas where no soundings occurred, which would lead to questionable results.

Additional analyses were done by subdividing Great Bay into a western and eastern segment. The western segment includes the main channel that runs through the Bay and into the Squamscott and Lamprey Rivers (Figure 15). The eastern half of Great Bay was also isolated, but again due to the very wide spacing of the survey lines the TIN model covered a very limited area and precluded analysis. The results of the analysis for the western half of Great Bay indicate that the average change was a decrease in depth of 0.66 m ±0.98 with a range from -5.40 to 6.96 m over the ~40 year period between the 1913 and 1953-1955 NOS surveys.

The descriptive report for the 1953-1955 NOS survey (hydrographic survey sheet H-8093) reported significant changes in the shallow channels in Great Bay. The same descriptive report describes changes in the channels in the lower Squamscott River and the main channel that runs through Great Bay as being 1 to 3 feet less in 1953-1955 than in 1913. However, the descriptive report also stated that "these differences may be partially due to the fact that the 1913 survey depths were reduced from tides observed at Dover Point on the north in the Piscataqua River which may differ by as much as 3 feet with actual tides in Great Bay as used in the present survey" (U.S. Coast and Geodectic Survey descriptive report for Great Bay and Squamscott River, H08093). The tides during the 1953-1955 survey were monitored at the railroad bridge on the Squamscott River.

The change in depth in this segment is strongly influenced by the major differences in the location of tide gages between the 1913 and the 1953-1955 NOS surveys which were used for reducing the soundings and establishing the tidal datums. Therefore, quantitative analysis of the difference in depths between the surveys is not possible in Great Bay. This is also true for Little Bay, as well as some of the tributaries such as the Oyster, Bellamy, and Squamscott Rivers that used the same tide gage locations.

Results from the comparison of the historic bathymetric surveys in Great Bay indicate that a high resolution survey with a common referencing system is needed. Furthermore, it is critical that the survey cover the entire Great Bay including the shallow regions and extensive subtidal and intertidal flats. As a result of this recognition, a new survey was conducted in Great Bay in summer 2009 by CCOM/JHC [discussed in section **6 New Bathymetric Survey of Great Bay (2009)**].

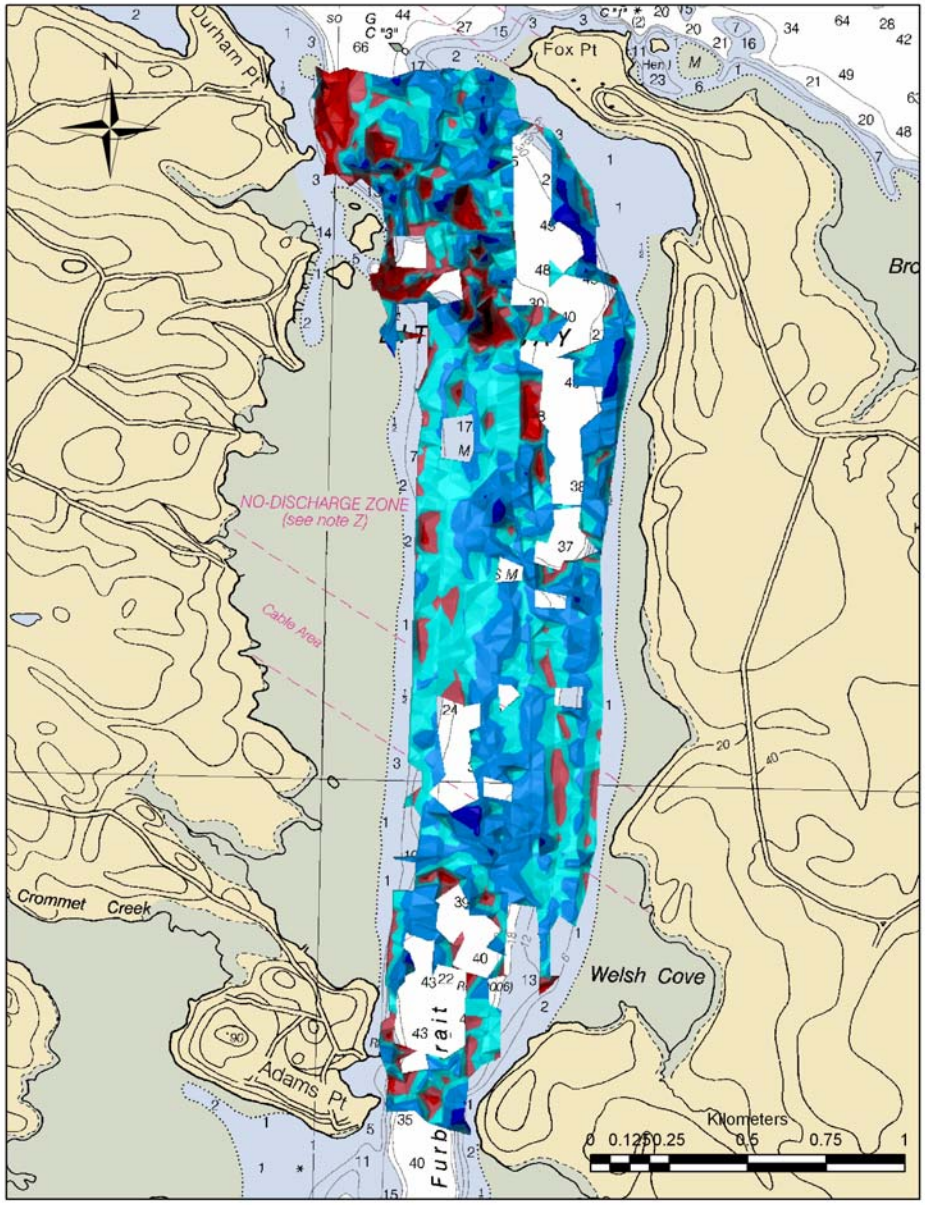



**Figure 13. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the Little Bay segment. The shaded area represents the difference between the TINs for each survey created in ArcGIS, converted to a grid and then brought into IVS 3D Fledermaus. Blue indicates where the 1953-1955 TIN model depths are less than the 1913 TIN model depths; red indicates where they are greater.**

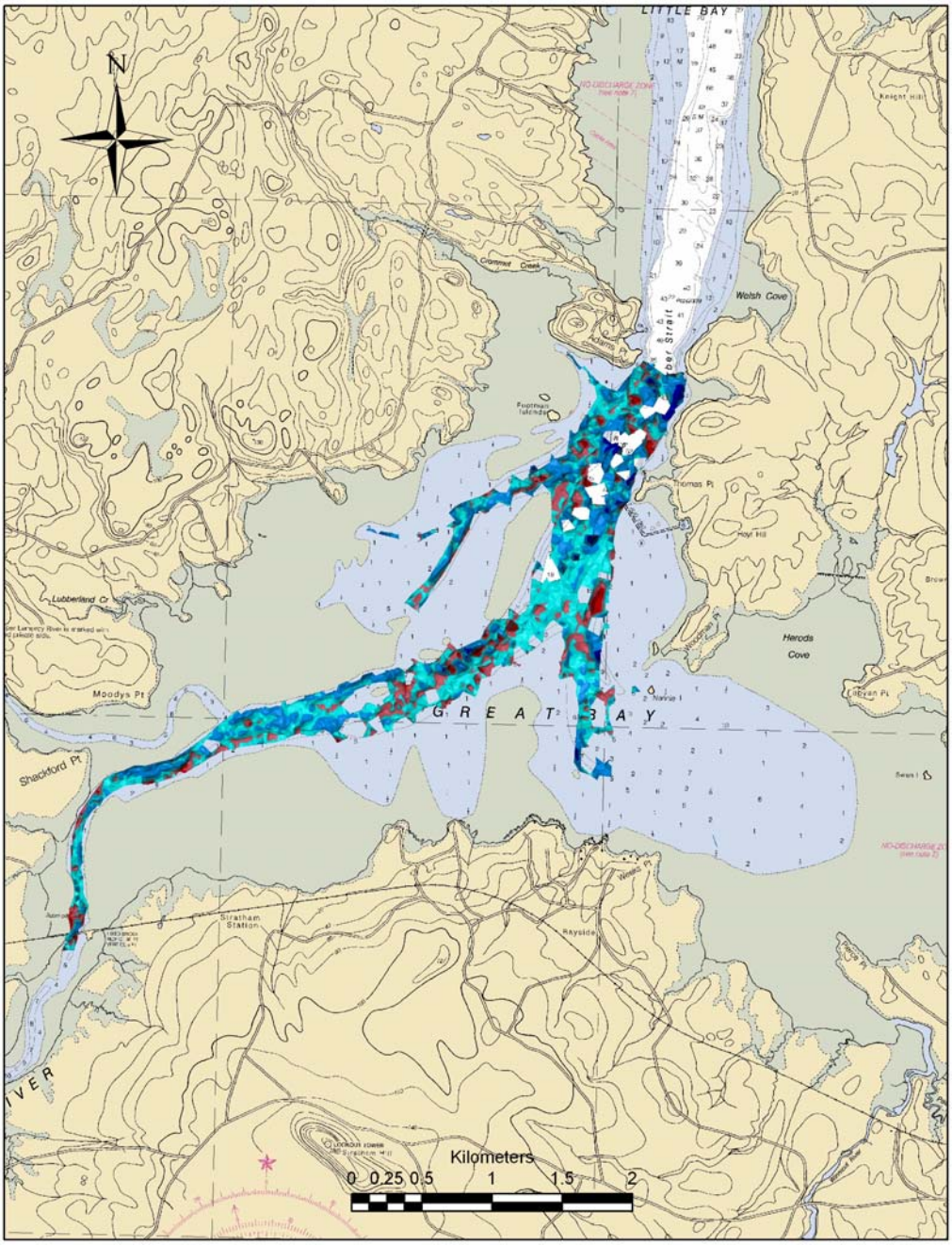



**Figure 14. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the Great Bay Estuary segment. The shaded area represents the difference between the TINs for each survey created in ArcGIS, converted to a grid and then brought into IVS 3D Fledermaus. Blue indicates where the 1953-1955 TIN model depths are less than the 1913 TIN model depths; red indicates where they are greater.**

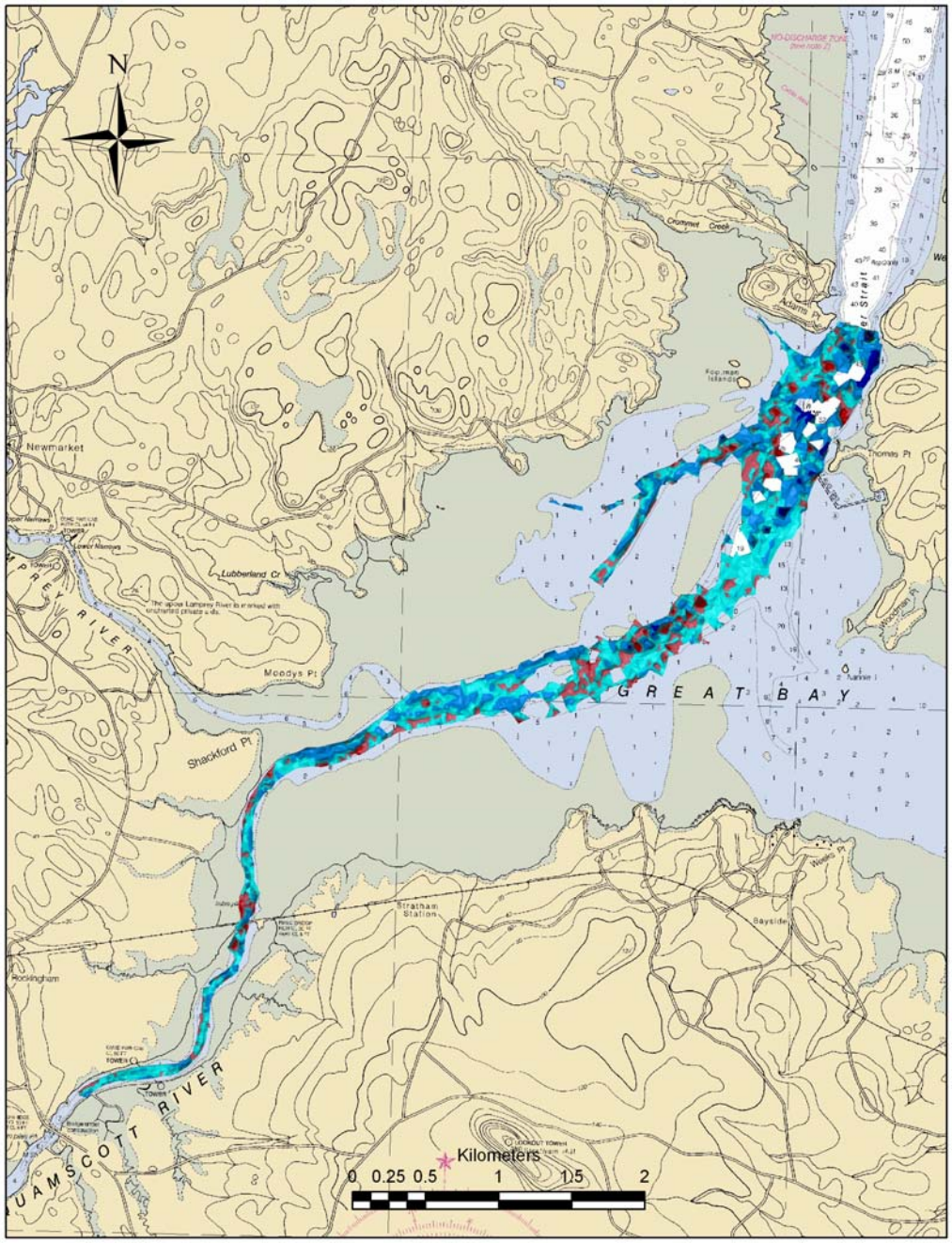



**Figure 15. Area of bathymetric comparison between the 1953-1955 and 1913 NOS surveys for the western Great Bay Estuary segment. The shaded area represents the difference between the TINs for each survey created in ArcGIS, converted to a grid and then brought into IVS 3D Fledermaus. Blue indicates where the 1953-1955 TIN model depths are less than the 1913 TIN model depths; red indicates where they are greater.**

## 5 Analysis of Channel Cross Sections in Eastern Great Bay

The eastern half of Great Bay had three channels flowing in an easterly direction in 1913 (Figure 7) and in 1953-1955 (Figure 8). In order to determine if the morphology and depth of the northern most channel had changed between these periods, a series of cross sections were constructed where the 1953-1955 survey lines crossed the 1913 survey lines (Figure 16). The 1953-1955 survey lines ran approximately north-south, while the 1913 survey lines were largely restricted to the channel. A total of eight cross sections were constructed at these crossings. For each survey (1913 and 1953-1955) and each crossing, the soundings lying along a line following the 1953-1955 survey (or reasonably close to the line) were recorded along with its distance from a reference line. The soundings were then plotted as depth versus distance from the reference line (Figure 17). Once the cross sections were constructed, the depth of the channel was estimated from the cross section. It is important to note that the channel depth was measured by the distance from the shallowest sounding to the deepest sounding for that cross section and for that survey. This type of comparison is not affected by the bias or issues related to the vertical datum.

The 1953-1955 channel depths were reasonable easy to determine due to the survey lines crossing the channels approximately orthogonally and extending onto the adjacent flats. The 1913 survey lines tended to map the channels and did not extend onto the adjacent flats. Therefore, in the case of the 1913 soundings, the maximum channel depth could not be determined because the top of the channel was not mapped. However, a minimum difference could be estimated. To determine if there had been a change in the channel depth between the surveys and hence shoaling or erosion, the maximum depth of the 1953-1955 bathymetric survey was compared to the 1913 minimum depth for each cross section.

Comparison of the cross sections from the northern channel based on the 1913 and 1953-1955 NOS surveys of the eastern half of Great Bay reveal that 6 out of 8 cross sections (cross sections 1 to 6) became shallower over the 40 year period (Table 2; Figure 17). Although the 1913 channel cross sections only tend to contain a few soundings, it is appears that the 1913 channel was deeper along much of its length indicating deposition of sediment in the channel. In addition, the slope of the channel walls decreased significantly in cross sections 1 to 6, also indicating shallowing of the channel.

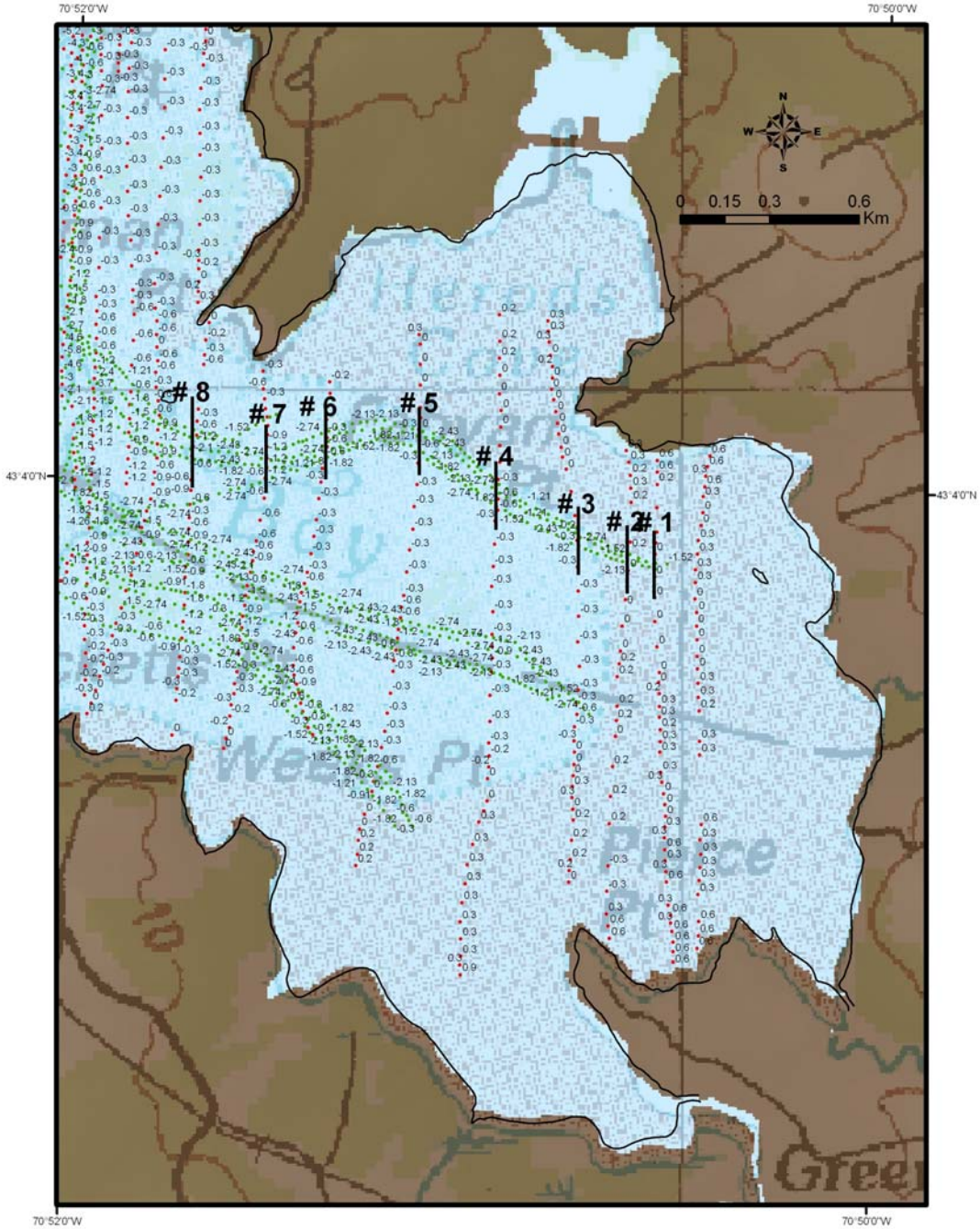



**Figure 16. Approximate locations of channel cross sections on the northern channel in the eastern half of Great Bay. The channel cross sections are shown in Figure 17.**

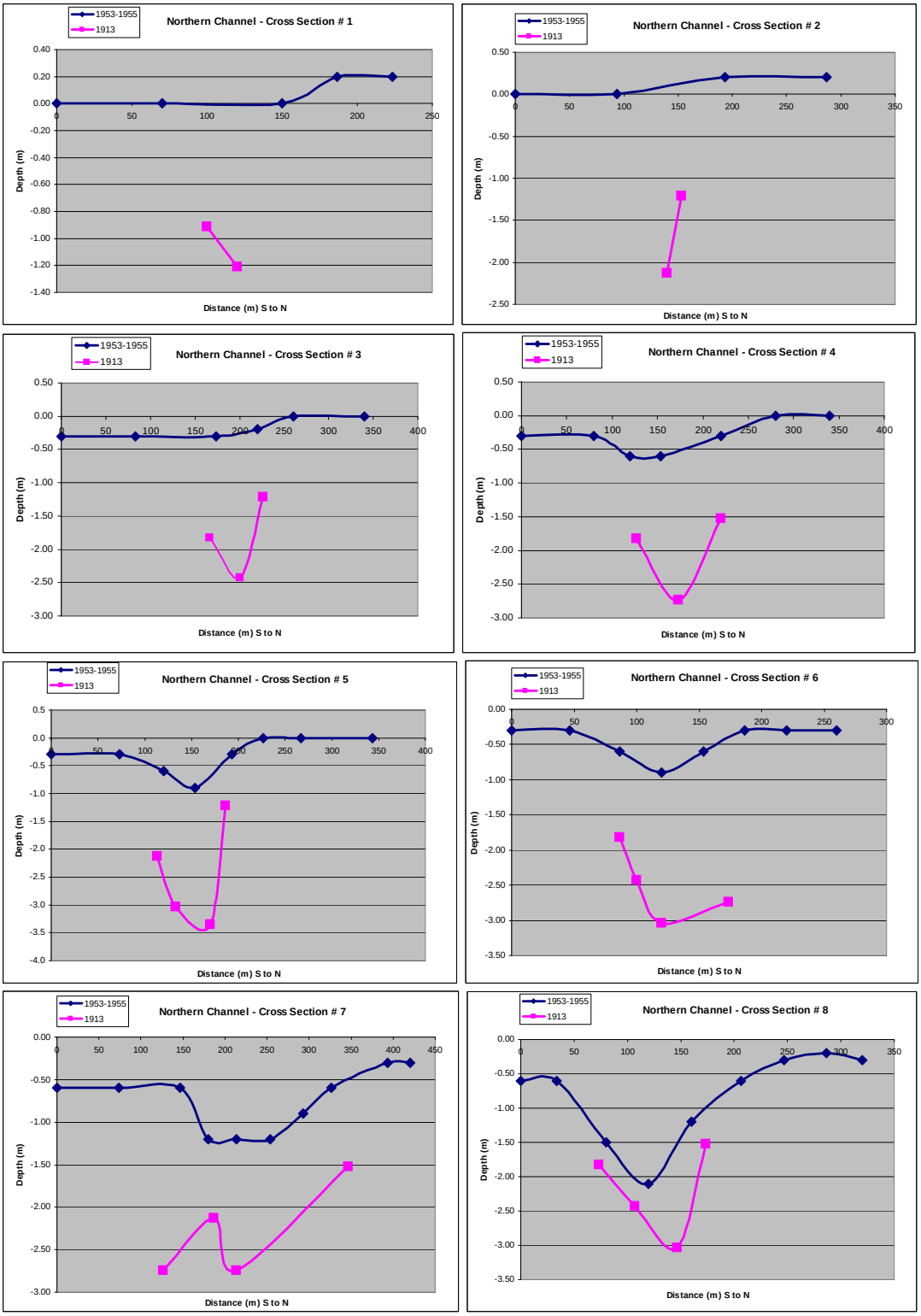



**Figure 17. Channel cross sections from the northern channel in eastern Great Bay (see Figure 16).**

**Table 2. Channel depths in the northern channel in eastern Great Bay.**

| Cross Section Number | 1953-1955 Channel Depth Meters | 1913 Channel Depth (Minimum) Meters |
|---|---|---|
| 1 | No channel to 0.2 | 0.3 |
| 2 | No channel | 0.9 |
| 3 | 0.3 | 1.2 |
| 4 | 0.6 | 1.2 |
| 5 | 0.9 | 2.1 |
| 6 | 0.6 | 1.2 |
| 7 | 0.9 | 0.6 to 1.2 |
| 8 | 1.9 | 1.5 |

## 6 New Bathymetric Survey of Great Bay (2009)

Great Bay is a major depositional feature and central to understanding sedimentation processes in GBE. Despite its importance, the bathymetry of Great Bay is poorly defined. The two earlier surveys (1913 and 1953-1955 NOS surveys) that cover Great Bay lack spatial coverage and adequate density of soundings. In addition, issues with the vertical datums make comparison of these surveys problematic. Therefore, in summer 2009, UNH CCOM – NOAA JHC conducted a bathymetric survey of Great Bay in order to address this critical gap.

The survey was done with single beam acoustic systems. The survey line spacing was typically 50 m and frequently 25 m. In total, ~461 km of survey lines were run (Figure 18). RTK GPS positioning was used assuring highly accurate horizontal control (on the order of 10 cm). Vertical control was provided by RTK GPS systems on the survey vessels allowing all depths to be directly referenced to the WGS84 ellipsoid. In addition, water levels were monitored at three fixed tide stations with pressure sensors and at a mid-bay location with a RTK GPS buoy for establishing the relationship between WGS84 vertical datum and the tidal datum in various locations. Although the 2009 Great Bay bathymetric survey was not funded as part of this project, the information will provide an extremely valuable contribution to the objectives of this study.

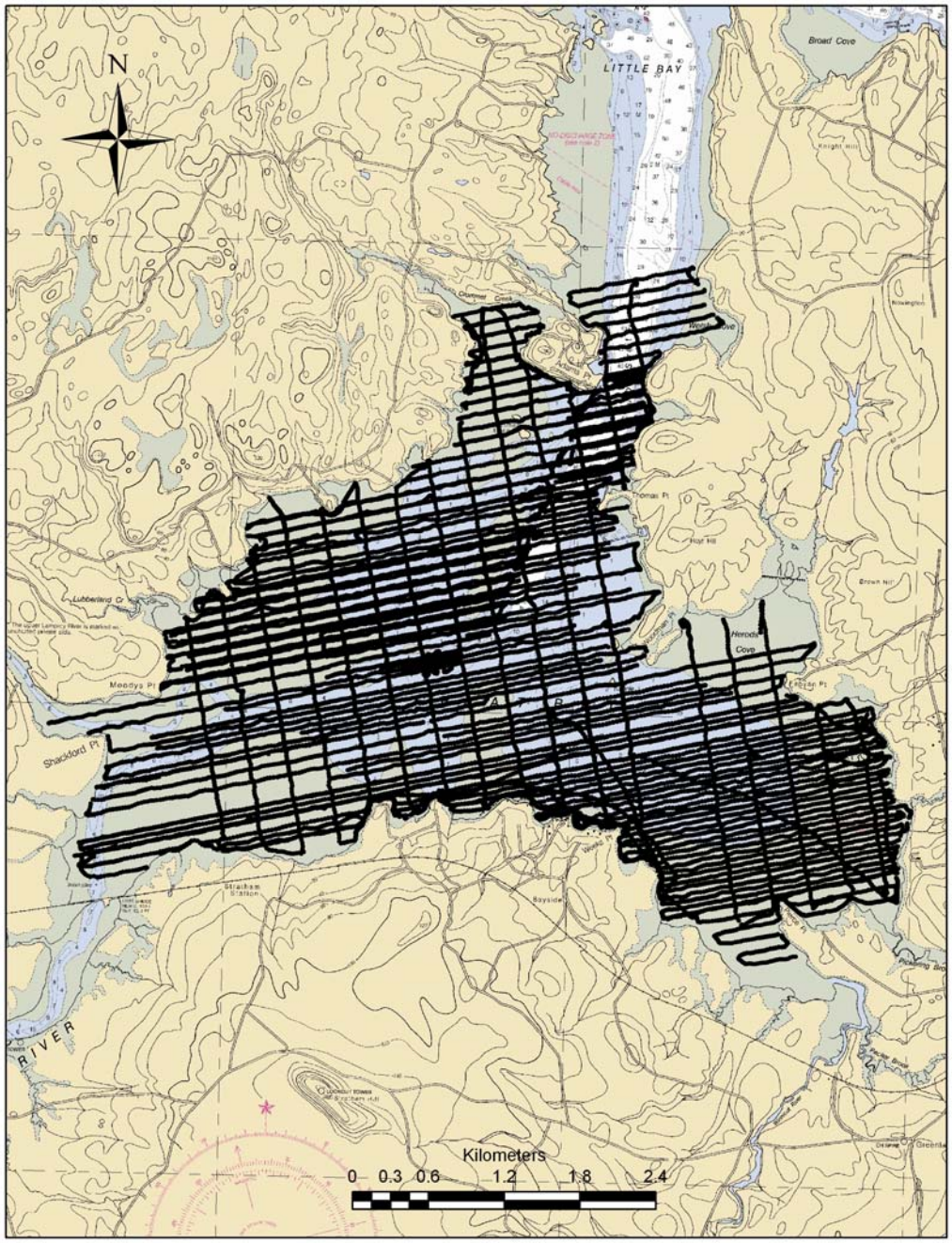



**Figure 18. Survey lines for the 2009 bathymetric survey conducted in Great Bay Estuary by UNH CCOM/JHC.**

## 7 Summary

The primary products and results of this study include: the development of a bathymetric database that contains the major surveys conducted between 1898 and 2007 in Great Bay Estuary (presently known and assessable) archived in a standardized format; the development of an GIS project that displays the bathymetric surveys; the development and testing of a procedure to compare the bathymetry from the different surveys; and the determination that quantitative analysis of depth changes between the 1913 and the 1953-1955 NOS surveys is problematic due to tidal datum issues. Detailed analysis indicates the problems with quantitative determinations of depth changes between the 1913 and the 1953-1955 surveys are due to limitations of the data sets related to the historical surveys using very different locations to measure the level of the tides (necessary to establish a common vertical reference or datum) and thus quantitative comparisons of depths between the historical surveys are limited. However, morphologic comparisons, which are not affected by the tidal datum bias, of the northern channel in eastern Great Bay reveal channels depths decreased between 1913 and 1953-1955 indicating shoaling occurred.

## 8 Acknowledgements

This study was funded by NOAA Office of Ocean and Coastal Resource Management (Coastal Zone Management Act) through the New Hampshire Department of Environmental Services Coastal Program (Award # NA07NOS4190081). Support was also provided by NOAA National Ocean Service (Award # NA05NOS4001153) through the University of New Hampshire Center for Coastal and Ocean Mapping – NOAA Joint Hydrographic Center. The New England District of the US Army Corps of Engineers provided bathymetric data for recent surveys in GBE to the study. Dr. Semme Dijkstra provided guidance in study design, troubleshooting, as well as helped construct the bathymetric database and GIS. Mashkoor Malik provided guidance in the early stages of the study and expertise in Fledermaus and ArcGIS. Andrea LeBarge helped with the digitizing of the smooth sheets, construction of the database, development of the GIS projects and preparation of the figures.

## 9 References

Calder, B. 2006. On the uncertainity of archive hydrographic data sets. *IEEE Journal of Oceanic Engineering*, Vol. 31, No. 2, p. 249-265.

Jakobsson, M., A. Armstrong, B. Calder, L. Huff, L. Mayer and L. Ward. 2005. On the use of historical bathymetric data to determine changes in bathymetry. *International Hydrographic Review,* Vol. 6, No. 3 (New Series), p. 25-41.

van der Wal, D. and K. Pye. 2003. The use of historical bathymetric charts in a GIS to assess morphological changes in estuaries. *The Hydrographic Journal*, No. 110, p.3-8.

# APPENDIX D

## Effects of Siltation Matrix

# Great Bay Siltation Commission Effects Subcommittee
# Effects of Siltation Matrix

| Ecosystem | Focus | Expected Impact | References |
|---|---|---|---|
| Estuarine Habitat | Eelgrass Beds | Eelgrass is light-limited and cannot survive in sediment-enriched waters. Siltation reduces light reaching the bottom, limiting eelgrass distribution and sediments can bury eelgrass beds. Several hundred acres of historic eelgrass beds have been lost in Great Bay estuary, especially along the tidal tributaries and Little Bay. This is a loss of fish and waterfowl habitat, a loss of food web support, and also a loss of the filtering capacity of eelgrass as well as the nutrient uptake capacity. Loss of eelgrass means loss of its capacity to filter suspended sediments from the water column (a negative feedback loop). SUMMARY PROVIDED | Short, F.T., D.M. Burdick and J.E. Kaldy. 1995. Mesocosm experiments quantify the effects of eutrophication on eelgrass, Zostera marina L., Limnology and Oceanography 40:740-749; Beem, N. and F.T. Short. 2009. Subtidal Eelgrass Declines in the Great Bay Estuary, NH-ME. Estuaries and Coasts. 32: 202-205. |
| | Oyster Reefs | Oysters require hard-substrate for larval settlement. Sediment deposits eliminate suitable hard-bottom areas and reduce feeding ability (Loosanoff 1948, 1962). Hundreds of acres of historic oyster beds have been lost in Great Bay estuary (Odell et al 2006) and recovery may be limited due to a lack of suitable settlement locations. Oysters provide water filtration services and create reef habitat for fish and other species. SUMMARY PROVIDED | Loosanoff, V.L. 1962. Effects of turbidity on some larval and adult bivalves. Proc. Gulf Caribb. Fish. Inst. 14:80-95; Loosanoff, V.L. & F.D. Tommers. 1948. Effects of suspended silt and other substances on rate of feeding of oysters. Science 107:69-70; Odell et al. 2006. Great Bay Estuary Restoration Compendium. |
| | Subtidal Bottom and Intertidal Mudlfats | Sediment and organic matter loading to the rivers and estuarine bottom decreases grain size and increases organic content of the sediment (Jones 2002). Decrease in grain size increases resuspension. Sediment changes will influence invertebrate community composition, but may or may not lead to anoxic conditions and/or lower invertebrate diversity. Sediment deposits accumulate and form intertidal mud flats. Invertebrates as food sources for shorebirds are locally associated with "medium-grained sandy mud" and may be reduced in areas of unconsolidated silt and muck. SUMMARY PROVIDED | Oyster River Channel Restoration Task Group. 2002. Chemical and physical analysis of sediments, from Feasibility Study for Re-establishing a Navigation Channel in the Oyster River, Durham, NH; McKinley, P. and P. Hunt. 2008. Avian Use of the Hampton-Seabrook Estuary: 2006-2007. Report to New Hampshire Fish and Game Department. Durham, NH. |
| | Salt Marsh | Sediments deposited on the salt marsh at high tides may provide substrate for brackish invasive plants, but also allow marshes to gain elevation as sea level rises. Great Bay salt marshes appear to be tracking sea level rise with little evidence of submergence. | Anecdotal and/or observational evidence only |
| Estuarine Species | Diadromous Fish | Lack of hard or sandy bottom limits egg development habitat for smelt. Suspended sediments reduce success of larval stage development for herring, shad. Loss of diadromous fish disrupts the local food web, affecting many higher organisms. | |

| | | | |
|---|---|---|---|
| | Estuarine Resident Fish | Fish suffer from gill irritation (Wilber and Clarke) and reduced availability of benthic food sources due to sediments, but turbidity may increase protection from predators (Bruton). Loss of eelgrass decreases food source availability and habitat. SUMMARY PROVIDED | Wilber, D.H. and D.G. Clarke. 2001. Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. North American Journal of Fisheries Management 21:855-875. Bruton, M.N. 1985. The effects of suspended solids on fish. Hydrobiologia 125:221-241.; Summarized by J. Fischer, 2008. NH Fish and Game Department. |
| | Oysters and Clams | Sediment deposits eliminate suitable hard-bottom areas and reduce feeding ability (Loosanoff 1948, 1962). SUMMARY PROVIDED | Loosanoff, V.L. 1962. Effects of turbidity on some larval and adult bivalves. Proc. Gulf Caribb. Fish. Inst. 14:80-95; Loosanoff, V.L. & F.D. Tommers. 1948. Effects of suspended silt and other substances on rate of feeding of oysters. Science 107:69-70. |
| | Horseshoe Crab | Horseshoe crabs may prefer sandy shoreline bottom substrate for spawning that might be limited by sedimentation (horseshoe crab spawning in Great Bay shows high numbers of spawning individuals in mud/sand and mud/shell habitat). | Anecdotal and/or observational evidence only |
| Water Quality Regime | Contaminant Nutrient Transport | Suspended sediments transport metals, nutrients, and contaminants from land-based sources into the estuary. Nutrients from tributaries are on the rise. Contaminants have been shown to accumulate in local estuarine mussel and eelgrass beds. SUMMARY PROVIDED | Chase M.E., S.H. Jones, P. Hennigar, J. Sowles, G.C.H. Harding, K. Freeman, P.G. Wells, C. Krahforst, K. Coombs, R. Crawford, J. Pederson, and D. Taylor. 2001. Gulfwatch: monitoring spatial and temporal patterns of trace metal and organic contaminants in the Gulf of Maine (1991-1997) with the blue mussel, *Mytilus edulis* L. Marine Pollution Bulletin 42:491-505; Piscataqua Region Estuaries Partnership. 2009. State of the Estuary, NH. |

| **Recreational** | **Focus** | **Expected Impact** | **References** |
|---|---|---|---|
| Structures | Docks | As the system fills in and gets more shallow, people along the shore will want longer docks to reach navigable water. There will be less room for the existing users and growth, resulting in crowding the mooring fields further and greater demand for new areas. This leads to greater dock and mooring impacts to eelgrass and salt marsh habitat. | |
| | Moorings | Moorings must be moved into open water, clogging navigable channels and making it further to reach for boaters. New moorings may further impact eelgrass beds. High demand for choice deepwater moorings results in multi-year waiting lists. | |

| | | | |
|---|---|---|---|
| Activities | Boating | Mudflats amended by sediment deposits hinder access to open water and complicate navigation around the bay. | Anecdotal and/or observational evidence only |
| | Rowing | Narrowing channels limit rowing routes for shells and launches. Access to open channel limits the access time to 3.5/hr on each side of high tide from all-tide access 25 yrs ago (at Oyster River, Great Bay Rowing). | L. Hafner, Rowing Director, Great Bay Rowing |
| | Clamming | Locations may be limited for access; siltation over beds may reduce populations, although some new beds may be formed by deposits. | Anecdotal and/or observational evidence only |
| | Fishing and Oystering | Species may be relocating due to mud flat expansion; loss of eelgrass habitat may reduce fish populations, although NH Fish & Game juvenile fish survey results cannot confirm; old oyster beds become buried. | Anecdotal and/or observational evidence only |
| | Waterfowl Hunting | Loss of eelgrass removes food source for ducks and geese, causing flocks to go elsewhere. Mussel beds are another important forage area that could potentially get silted over. | Anecdotal and/or observational evidence only |

| **Social** | **Focus** | **Expected Impact** | **References** |
|---|---|---|---|
| Aesthetics | Scenery | Marsh sediment deposits allow for new vegetation, change of scenery. | Anecdotal and/or observational evidence only |
| Connectivity | Cultural | Changes in Great Bay influence our landscape, habitat, recreational, educational, and commercial perspectives; interactions become more passive than active. | Anecdotal and/or observational evidence only |
| Shoreland Living | Bay Geomorphology | Possible changes in water table/channel morphology as parts of estuary silt in. | Anecdotal and/or observational evidence only |

| **Commercial** | **Focus** | **Expected Impact** | **References** |
|---|---|---|---|
| Aquaculture/Fishing | Oyster Farming/Lobsters | Excess sediments may slow growth, eliminated desirable sites, and impact quality of shellfish product. | Anecdotal and/or observational evidence only |
| Marinas | Boating | Less water depth in some areas may impede recreational users. | Anecdotal and/or observational evidence only |

| | | | |
|---|---|---|---|
| | Moorings | Marina moorings become harder to manage in mucky sediments. | Anecdotal and/or observational evidence only |
| Infrastructure | Sanitation | Silting in of sanitation outflows lowers dilution. SUMMARY PROVIDED | Oyster River Channel Restoration Task Group. 2002. Chemical and physical analysis of sediments, from Feasibility Study for Re-establishing a Navigation Channel in the Oyster River, Durham, NH. |
| | Energy | Cooling tunnels, and possible future tidal energy sites may be compromised by excess siltation; possible diminishment of tidal currents with filled-in estuary. | |

# APPENDIX E

## Effects of Suspended Solids on Fish and Shellfish

# Summary of Effects of Suspended Solids on Estuarine Fish and Shellfish

Prepared By: Jessica Fischer
New Hampshire Fish & Game Department

Suspended solids in marine environments can occur from a variety of natural and anthropogenic sources. Tidal flows, terrestrial/river run-off, rainfall, and plankton blooms are all naturally occurring processes that increase the turbidity of the water. Anthropogenic sources include discharge of sewage and industrial waste, dredging, agriculture, boating, and marine construction projects (Au et al., 2004, Grant and Thorpe, 1991, Martens and Servizi, 1993, Wilber and Clarke, 2001).

Suspended solids have varying effects on the marine ecosystem. There have been a variety of studies that examine the effects of suspended solids on fish and shellfish. The most common effects of suspended solids on fish are: reduced visibility of pelagic food, reduced availability of benthic food, clogging of gill rakers and gill filaments, reduced predation risk, and reduction in the amount of light penetration in the water column which causes a decline in photosynthesis (Bruton 1985). Further investigations of these effects have been done almost exclusively on salmonids in various stages of their life cycle. Suspended solids have been shown to reduce the success of fertilization, decrease feeding rates, cause abrasions on gills, stimulate cough responses, increase the susceptibility to disease, and produce alarm reactions which cause migration downstream to areas of lower concentrations of coho (*Oncorhynchus nerka*) and sockeye (*Oncorhynchus kisutch*) salmon (Galbraith et al., 2006, Berg and Northcote 1985). Surprisingly, there are some positive aspects of having increased suspended solids in the water column. Bruton (1985) found that moderate levels of turbidity appear to be beneficial to fish in estuarine environments because the reduced visibility offers protection from predators in shallow, food rich areas.

Few studies have been done on the effects of suspended solids on estuarine fish. Species of freshwater fish have been found to withstand suspended solid loads greater than 100,000 mg/L for a week or longer, but mortality occurred when the load surpassed 175,000 mg/L (Bruton 1985). Wilber and Clark (2001) reviewed papers that examined the lethal response of estuarine fish to suspended solids. Tolerant species were found to be striped killifish (*Fundulus majalis*), common mummichog (*Fundulus heteroclitus*), spot (*Leiostomus xanthurus*), oyster toadfish (*Opsanus tau*), hogchoker (*Trinectes maculates*), and striped cusk eel (*Rissola marginata*). Sensitive species were white perch (*Morone americana*), bay anchovy (*Anchoa mitchilli*), juvenile Atlantic menhaden (*Brevoortia tyrannus*), striped bass (*Morone saxatilis*), Atlantic croaker (*Micropogonias undulatus*), and weakfish (*Cynoscion regalis*). Atlantic silversides (*Menidia menidia*), juvenile bluefish (*Pomatomus saltatrix*), and age-0 white perch were classified as highly sensitive to suspended solids. Atlantic silversides and white perch exhibited the highest mortality rate (10%) at suspensoid concentrations less than 1,000 mg/L for one and two days. The green grouper (*Epinephelus coioides*) however, has been found to be more tolerant of suspended solids than all species listed above (Au et al. 2004). Due to the variation of

sensitivity among species, more studies are needed to clearly indicate the lethal level of suspended solids among each species.

One of the most adverse effects suspended solids pose on fish is damage to the gills. Fish gills are the major organ for respiration, osmoregulation, ion transport, and excretion of nitrogenous wastes. Damage to them could reduce the ability for oxygen transfer, saltwater transport, and ammonia excretion (Eckert & Randall 1983). Structural gill damage was identified in the green grouper when exposed to various concentrations of suspended solids (50 to 2000 mg/L). Symptoms observed were epithelial lifting, reduction of epithelial thickness, and hyperplasia in the pillar system which suggests that the fish were under hypoxic stress (Au et al. 2004). Martens and Servizi (1993) observed intracellular lodging of sediment particles in the gill epithelia of juvenile Pacific salmon (*Oncorhynchus* spp.) when exposed to concentrations of 16-41 mg/L for 96 hours.

Shellfish appear to tolerate the effects of suspended solids better than some fish species in the literature even though they are more susceptible to high levels due to their filter feeding in the water column (Shin et al. 2002). Grant and Thorpe (1991) found that the soft-shell clam (*Mya arenaria*) copes with low values of turbidity by reducing its oxygen consumption, but if exposed for long periods of time, this reaction will cause starvation. The green-lipped mussel (*Perna viridis*) was found to have a very high tolerance of suspended solids (up to 2000 mg/L for 96 hours) (Shin et al. 2002).

In most estuaries, the average range of concentrations of total suspended matter generally ranges from a few mg/L to several tens of mg/L. Higher values are observed near the bottom due to active resuspension of solids. During high rain events and in the immediate vicinity of dredging activities, concentrations may exceed several thousand mg/L (Auld and Schubel 1978). In exploring the impact to hatching success and larval development of fishes Kiorboe (1981) found that the embryonic development of Atlantic herring (*Clupea harengus*) was unaffected by suspended silt and that there was no correlation between silt concentration and egg mortality. Auld and Schubel (1978) found that concentrations of up to 1,000 mg/L did not significantly affect the hatching success of yellow perch (*Perca flavescens*), blueback herring (*Alosa aestivalis*), alewife (*Alosa pseudoharengus*) or American shad (*Alosa sapidissima*), but did affect the hatching success of white perch and striped bass at concentrations of 1,000 mg/L. The survival of larvae of striped bass and yellow perch (*Perca flavescens*) exposed to concentrations of ≥500 mg/L for 48-96 hours was also reduced. American shad larvae were less tolerant with even lower levels (≥100 mg/L) reducing their survival. The variability among species creates a challenge for biologists when making management decisions based on the literature. More studies are needed to further broaden the understanding of how suspended solids affect the egg survivability and hatching success of different fish species.

## Literature Cited

Au D.W.T, Pollino, C.A., Wu, R.S.S., Shin, P.K.S., Lau, S.T.F., Tang, J.Y.M. 2004. Chronic effects of suspended solids on gill structure, osmoregulation, growth, and triiodothyronine in juvenile green grouper (*Epinephelus coioides*). Marine Ecology Progress Series 266: 255-264.

Auld, A. H., Schubel, J. R. 1978. Effects of suspended sediment on fish eggs and larvae: A laboratory assessment. Estuaries and Coastal Marine Science 6:153-64.

Berg, L., Northcote, T.G. 1985. Changes in territorial, gill flaring, and feeding behavior in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. Canadian Journal of Fisheries and Aquatic Science 42:1410-1417.

Bruton, M.N. 1985. The effects of suspended solids on fish. Hydrobiologia 125:221–241.

Eckert, R. and Randall, D.J. Animal Physiology: Mechanisms and Adaptations, Second Edition. New York: W.H. Freeman and Company, 1983.

Galbraith, R.V., MacIsaac, E.A., MacDonald, J.S., Farrell, A.P. 2006. The effect of suspended sediment on fertilization success in sockeye (*Oncorhynchus nerka*) and (*Oncorhynchus kisutch*) salmon. Canadian Journal of Fisheries and Aquatic Science 63:2487-2494.

Grant, J., Thorpe, B. 1991. Effects of suspended sediment on growth, respiration, and excretion of the soft-shell clam (Mya arenaria). Canadian Journal of Fisheries and Aquatic Science 48: 1285–1292.

Kiørboe, T. 1981. Effects of Suspended Sediment on Development and Hatching of Herring (*Clupea harengus*) Eggs. Estuarine, Coastal and Shelf Science 13:107-111.

Martens, D.W., Servizi, J.A. 1993. Suspended sediment particles inside gills and spleens of juvenile Pacific salmon (*Oncorhynchus* spp.). Canadian Journal of Fisheries and Aquatic Science 50:586–590.

Shin, P.K.S., Yau, F.N., Chow, K.K., Tai, K.K., Cheung, S.G. 2002. Responses of the green-lipped mussel (*Perna viridis*) to suspended solids. Marine Pollution Bulletin 45:157-162.

Wilber, D.H., Clarke, D.G., 2001. Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. North American Journal of Fisheries Management 21:855–875.

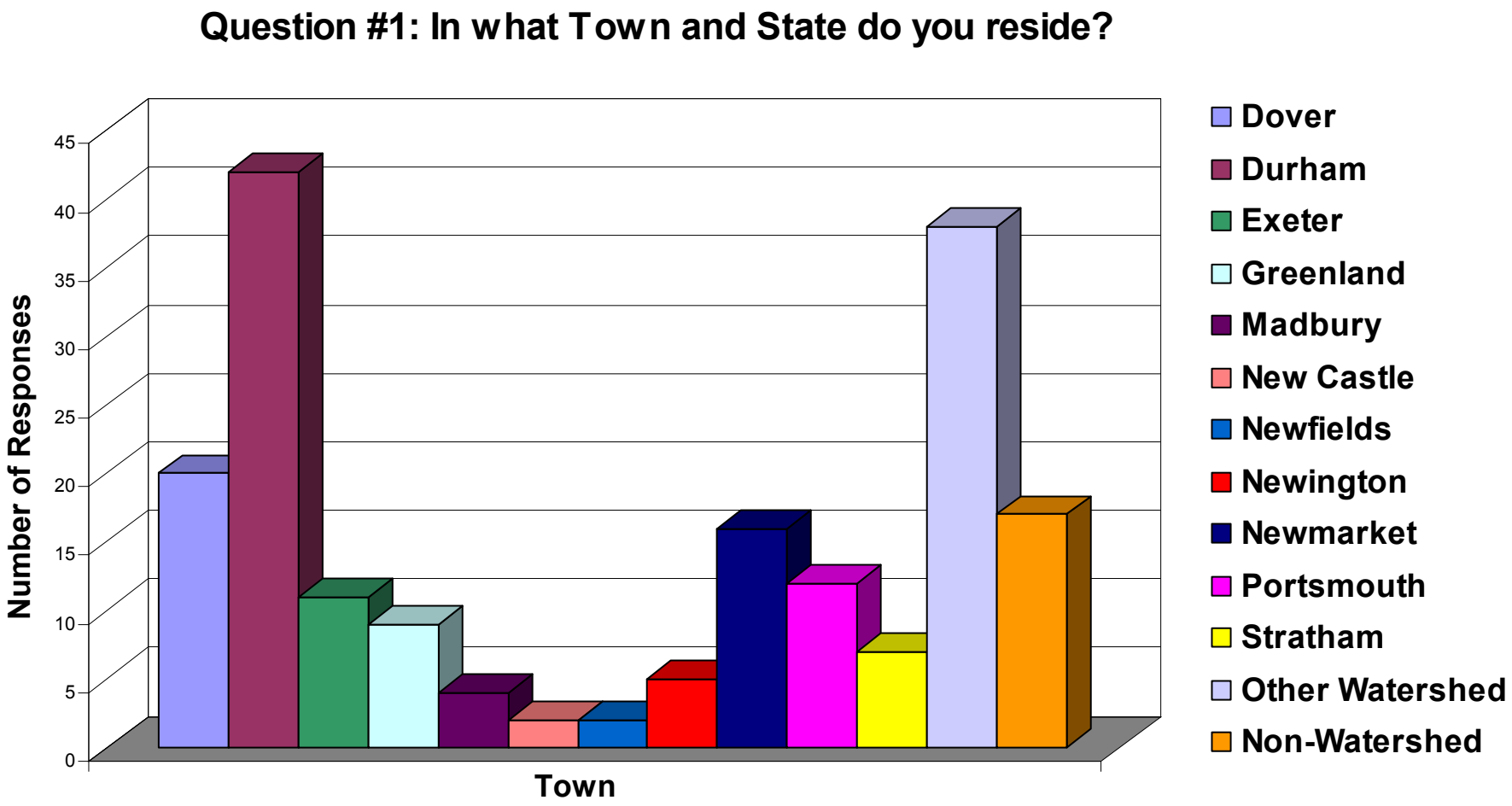
# APPENDIX F

## Recreational Use Survey Results

# Great Bay Recreational Use Survey Results

Survey Period: August 21 – September 25, 2009

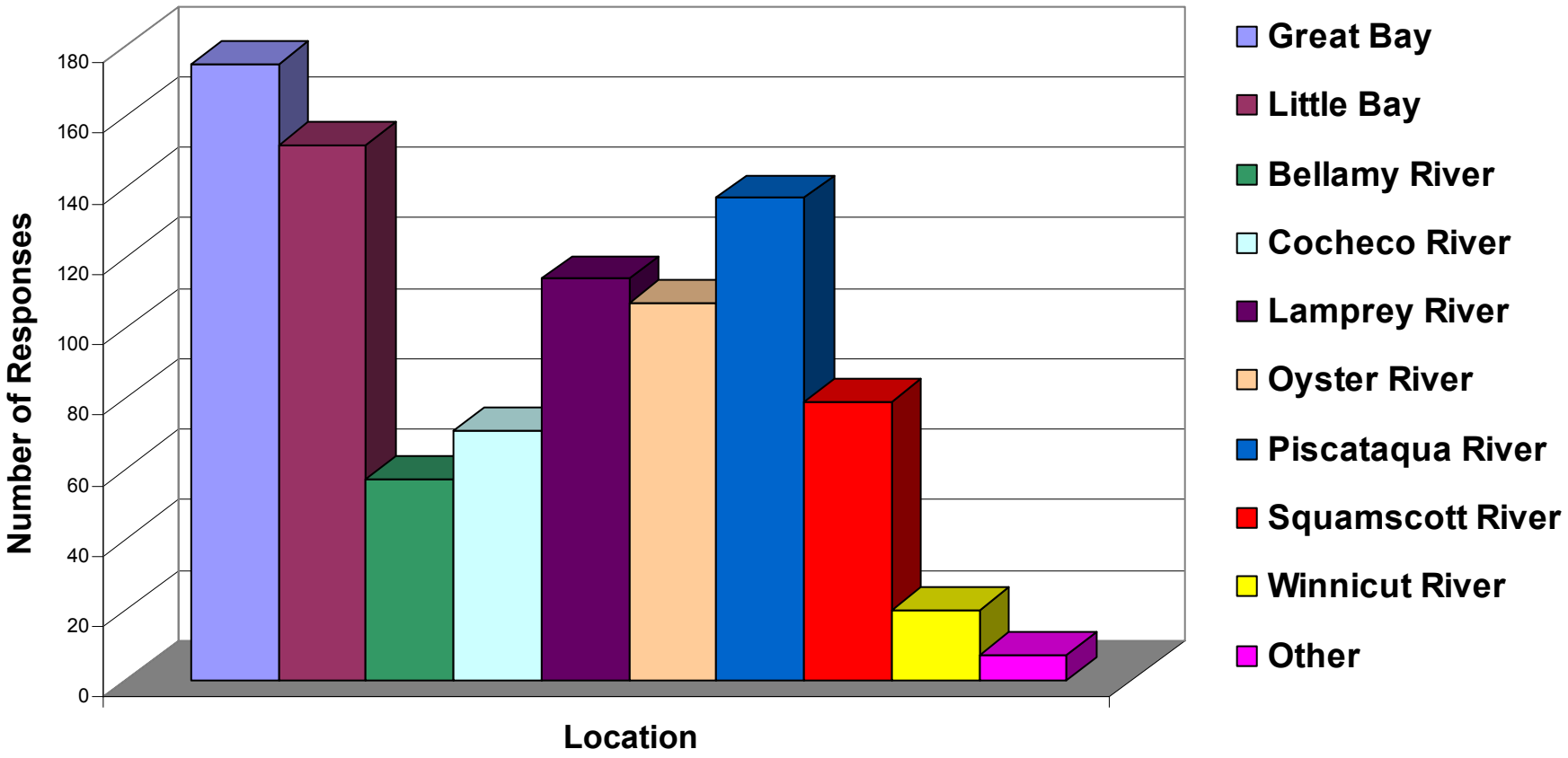
Number of Responses: 198


Question #1: In what Town and State do you reside?
Number of Responses
0
5
10
15
20
25
30
35
40
45
Town
Dover
Durham
Exeter
Greenland
Madbury
New Castle
Newfields
Newington
Newmarket
Portsmouth
Stratham
Other Watershed
Non-Watershed

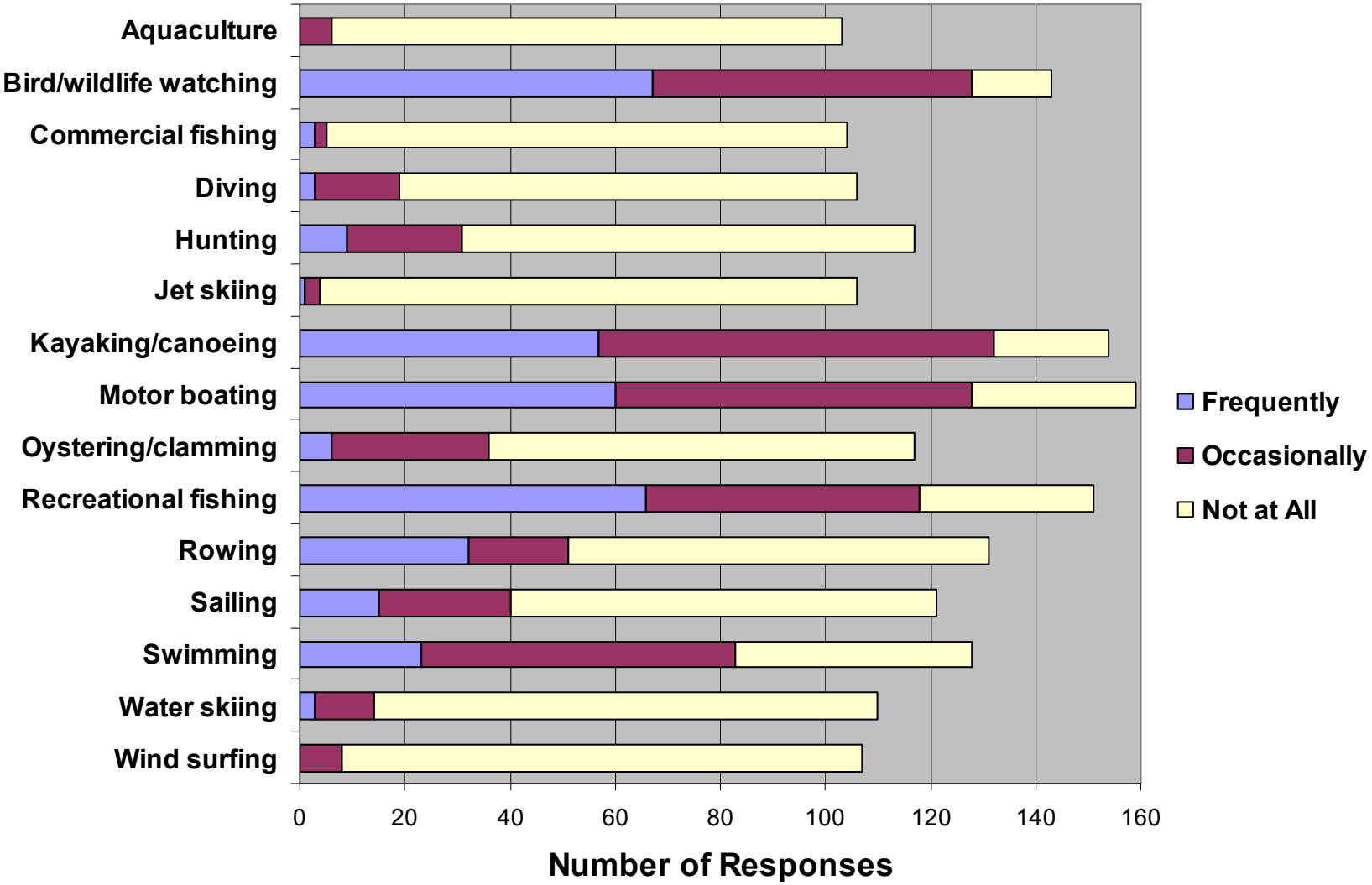
Question #2: How many years have you been involved in recreation in the Great Bay Estuary?

Average number of years = 19

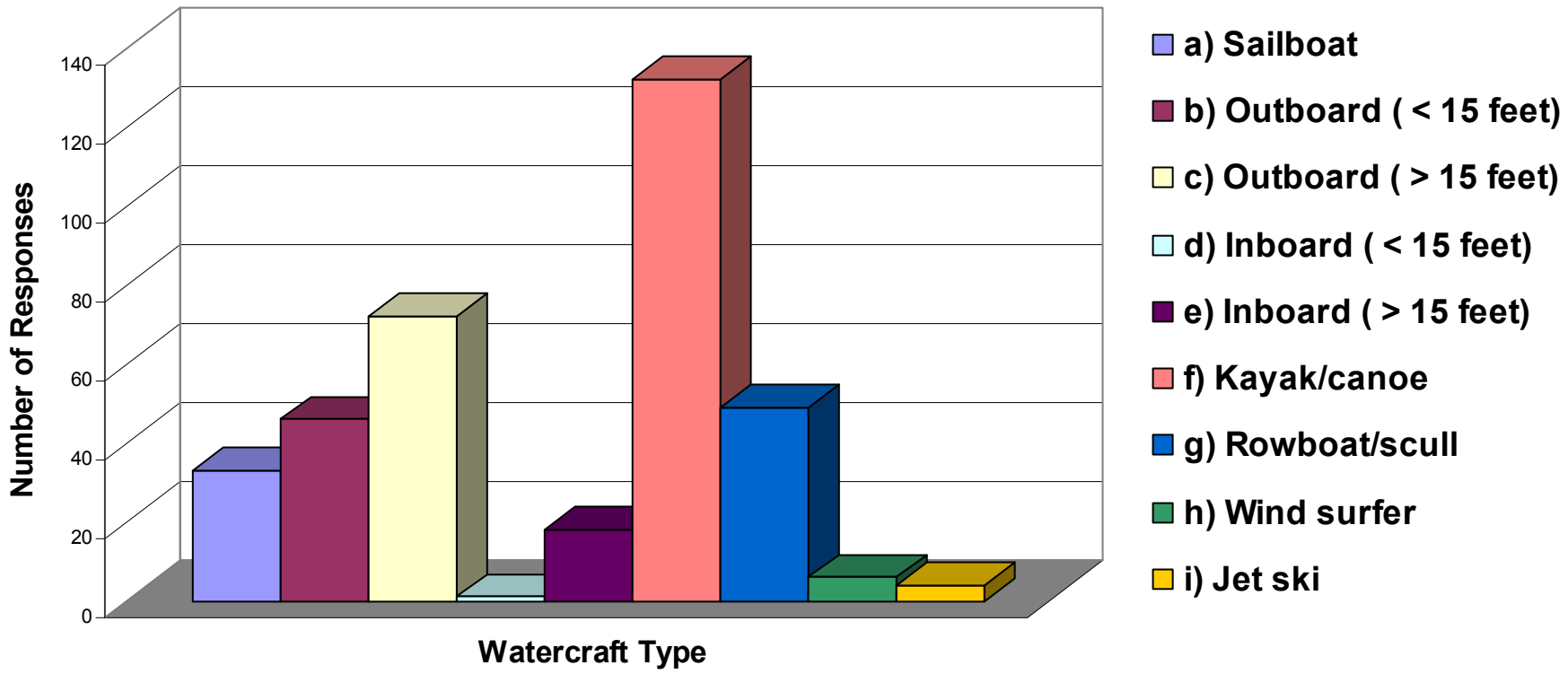
## Question #3: In what areas of the Great Bay Estuary do you recreate?

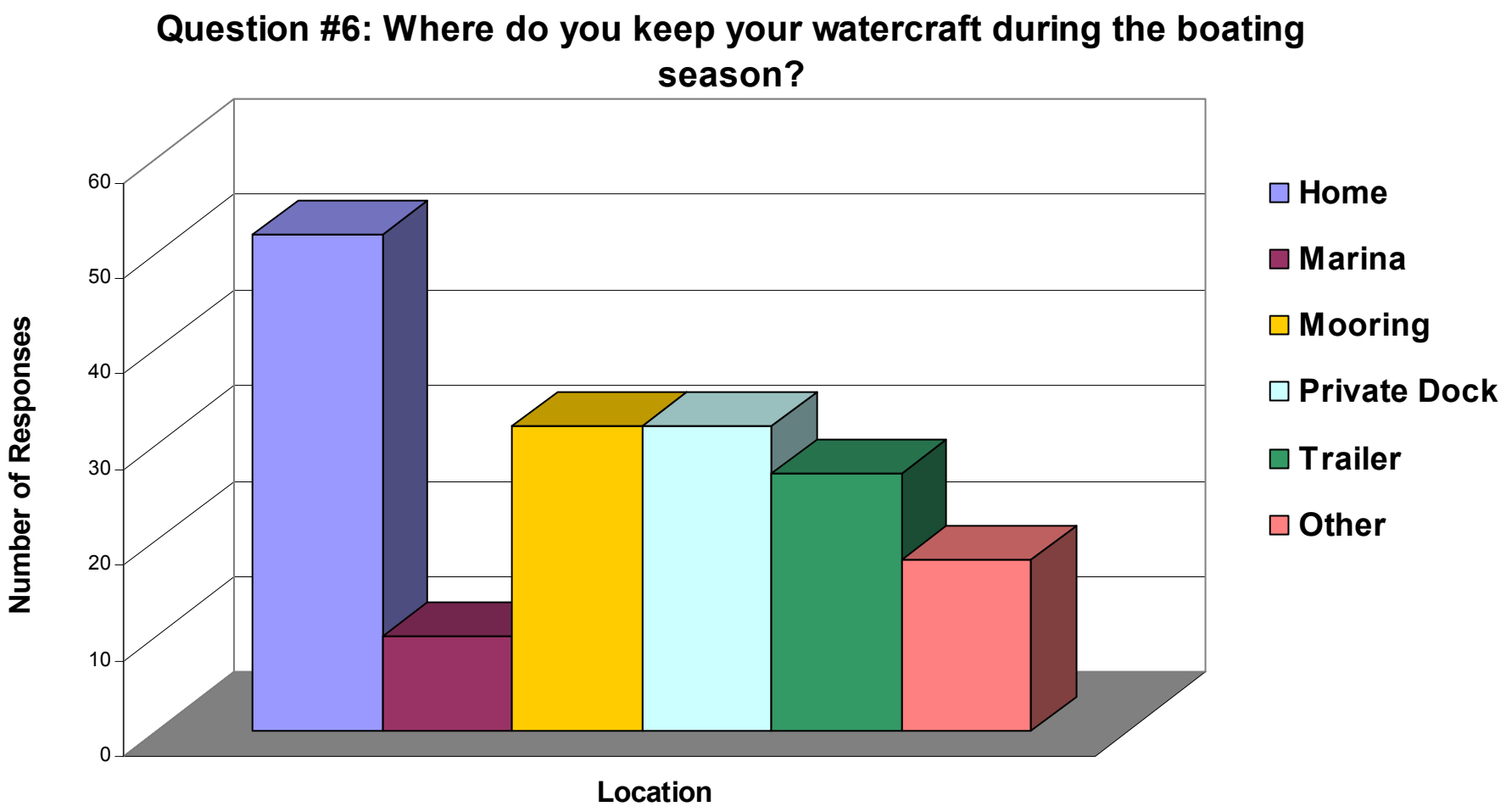


## Question #4: Please indicate how frequently you engage in the following activities within the Great Bay Estuary

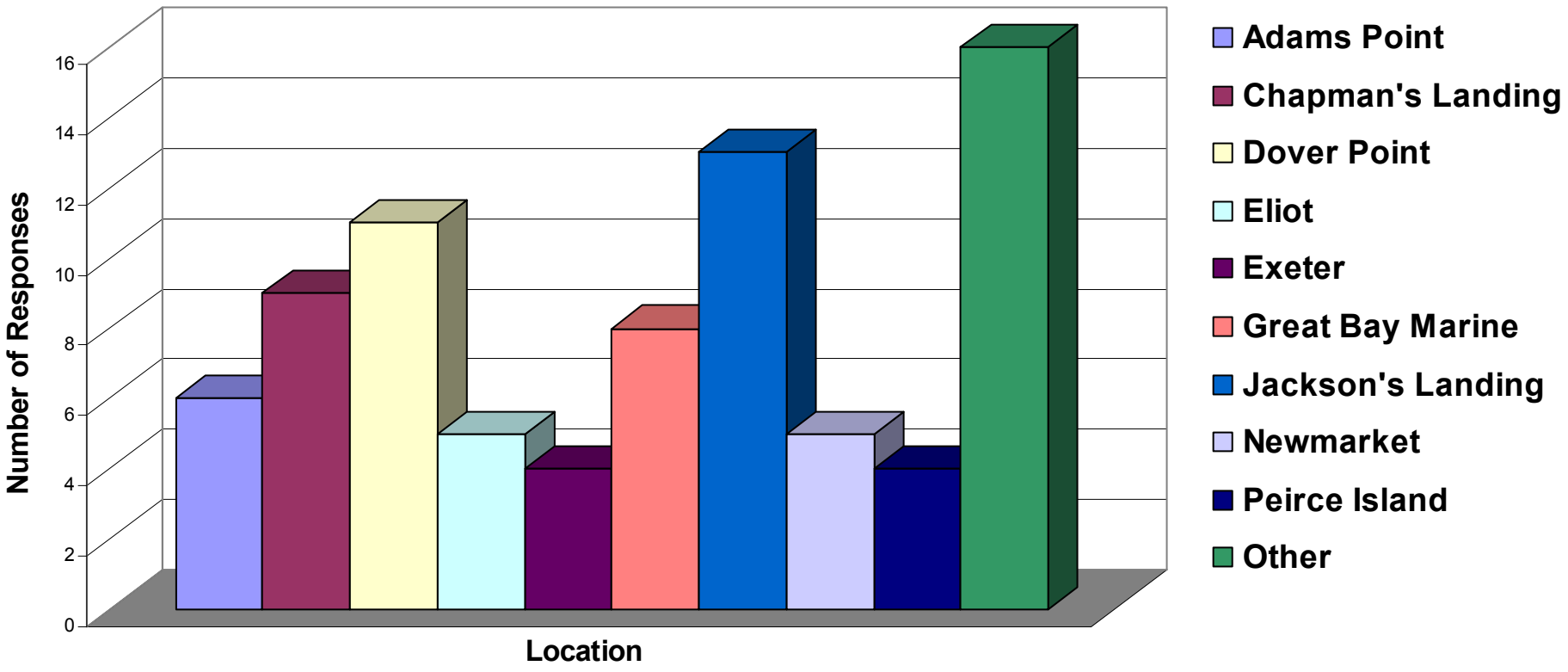


## Question #5: What types of watercraft do you use in the Great Bay Estuary?

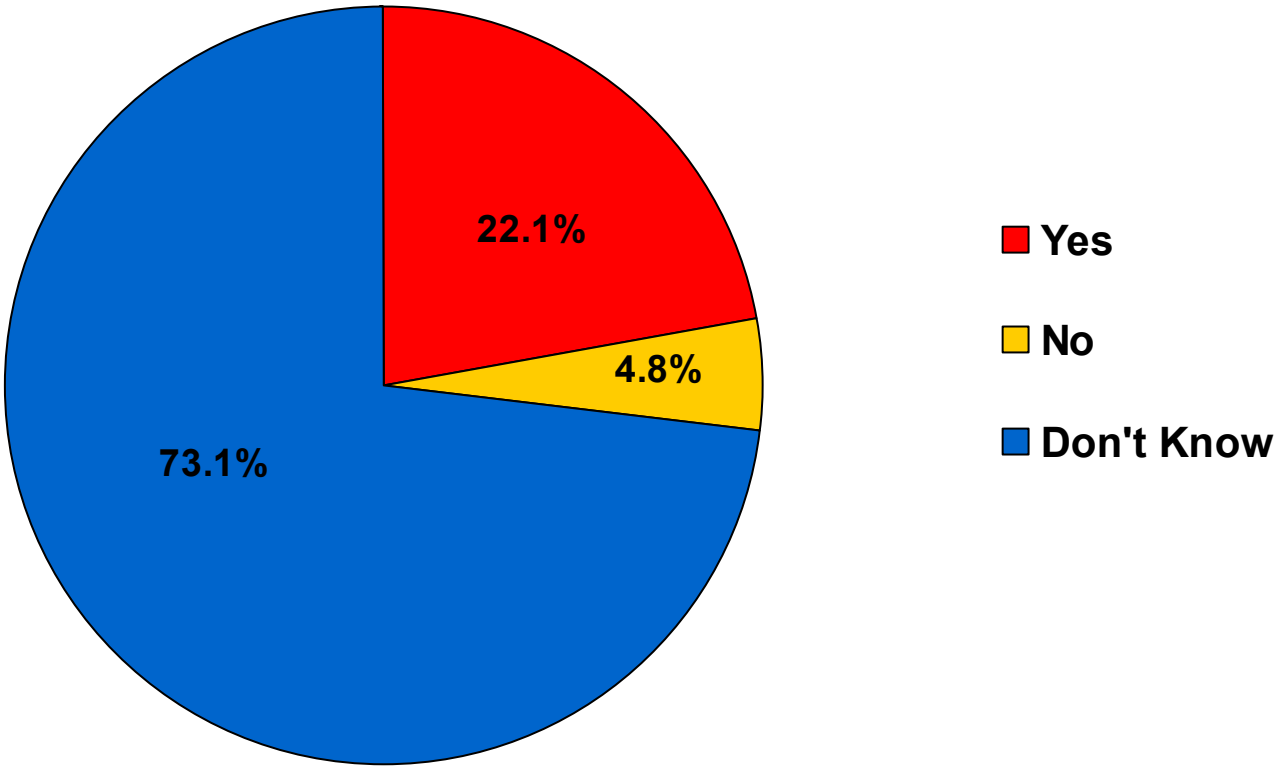



Question #6: Where do you keep your watercraft during the boating season?
Number of Responses
0
10
20
30
40
50
60
Location
Home
Marina
Mooring
Private Dock
Trailer
Other

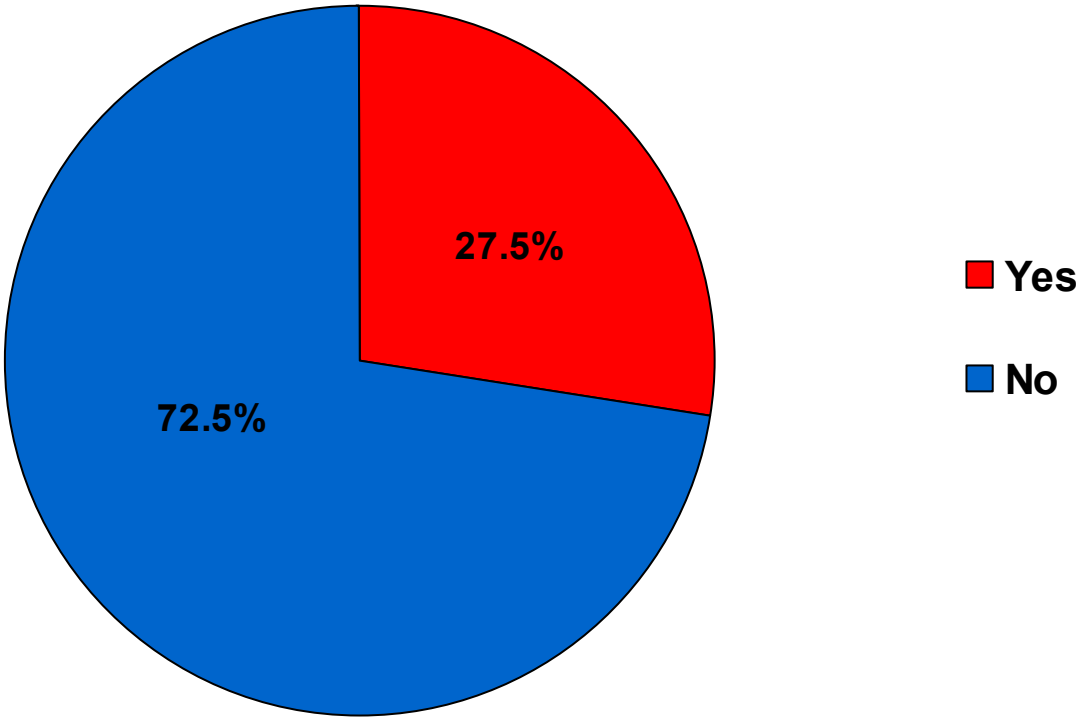
## Question #7: If you trailer your watercraft, where do you most often launch it?

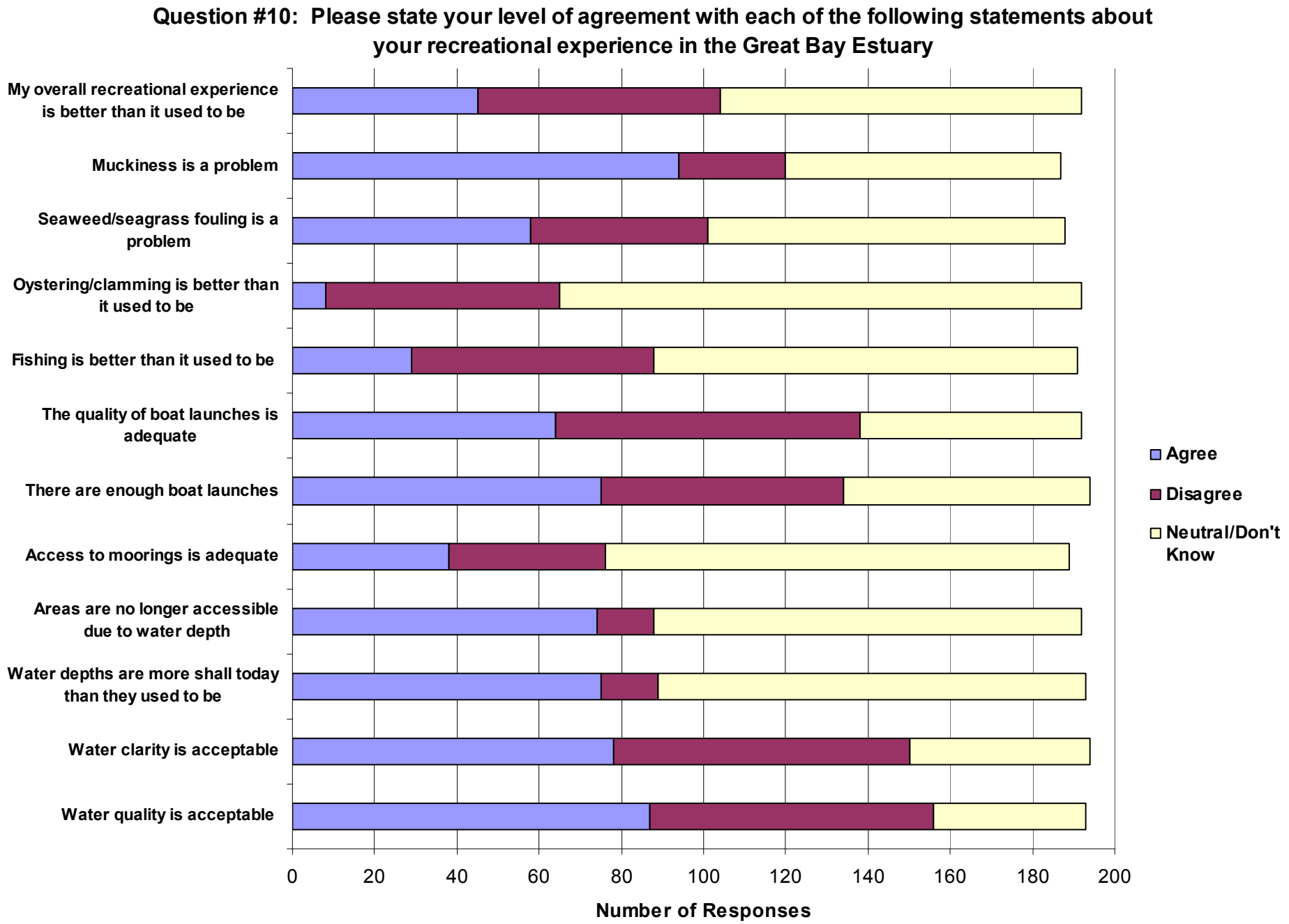


**Question #8: Are there enough sewage pumpout facilities for you to comply with the state's "No Discharge" requirements?**



**Question #9: Are you aware of the state's sewage pumpout boat?**

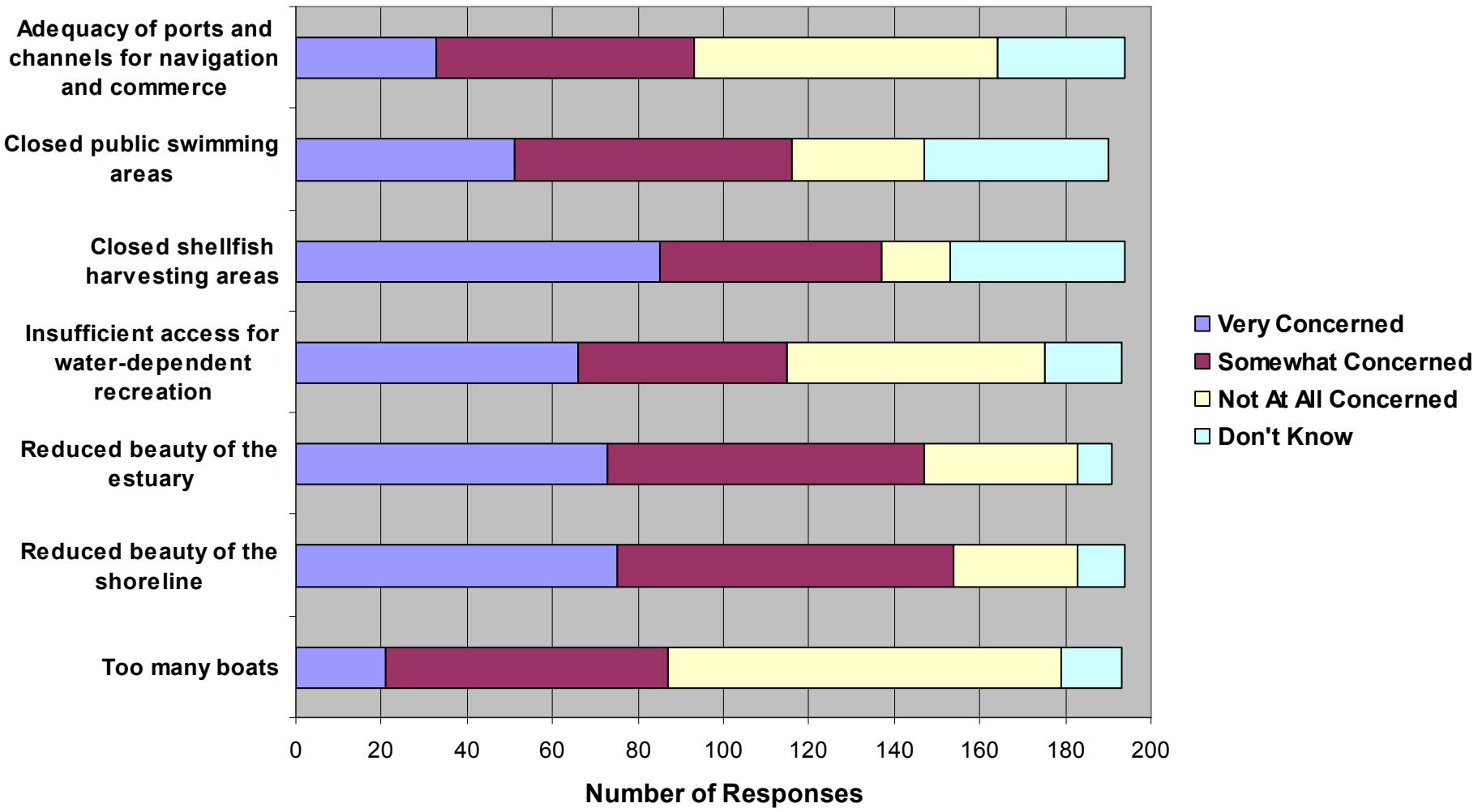



Question #10: Please state your level of agreement with each of the following statements about your recreational experience in the Great Bay Estuary
My overall recreational experience is better than it used to be
Muckiness is a problem
Seaweed/seagrass fouling is a problem
Oystering/clamming is better than it used to be
Fishing is better than it used to be
The quality of boat launches is adequate
There are enough boat launches
Access to moorings is adequate
Areas are no longer accessible due to water depth
Water depths are more shall today than they used to be
Water clarity is acceptable
Water quality is acceptable
0
20
40
60
80
100
120
140
160
180
200
Number of Responses
Agree
Disagree
Neutral/Don't Know

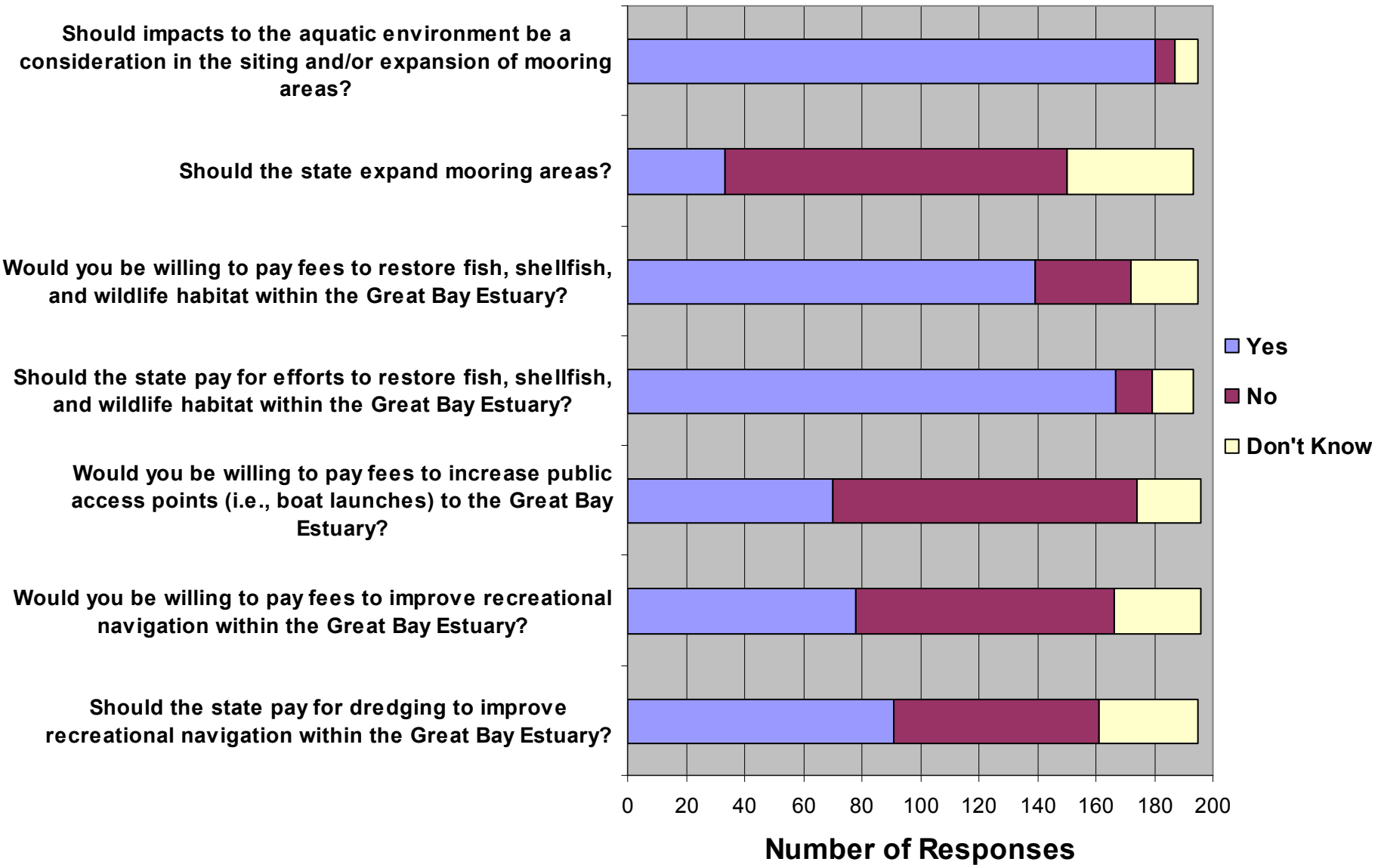
**Question #11: What other issues relative to the recreational experience in the G.B. Estuary are of concern to you? (Top 10 most common responses)**

- Limited public access
- Discharge from wastewater treatment facilities
- Boat traffic
- Boat wakes & lack of wake enforcement
- Nutrient loading
- Declining eelgrass populations
- Siltation in rivers, particularly the Oyster River
- Reduced water quality
- Stormwater runoff
- Lack of all-tide boat launches

## Question #12: Please indicate how concerned you are with each of the following issues related to recreation and navigation in the areas of the Great Bay Estuary



## Question #13: Please answer each of the following questions



**Question #14: Is there anything else you would like to share with the Commission? (Top 5 most common responses)**

- Increase all-tide access
- Increase oyster restoration efforts
- Improve “no wake zone” enforcement
- Increase public access sites
- Conduct more surveys like this

# APPENDIX G

## PROS AND CONS OF A STATE-OWNED DREDGE

As stated in Section IV of the Report, the majority of the tidal dredging in New Hampshire's seacoast is related to the maintenance of federal navigation channels. The U.S. Army Corps of Engineers (ACOE) maintains eight federal navigation projects in New Hampshire, five of which are located in Great Bay Estuary: the Bellamy, the Cocheco, the Lamprey and the Squamscott Rivers, as well as the Piscataqua River/Portsmouth Harbor.

Due to the high costs of dredging activities, the Commission briefly explored whether the state could reduce costs by purchasing its own dredge equipment. The Commission's findings are listed below:

**PROS:**

- Were the state to purchase its own dredge, it would reduce the high costs associated with mobilization and demobilization of dredging equipment. Based on cost information provided by the ACOE for four different dredging projects located in New England, mobilization and demobilization costs varied from 15% to more than 50% of total project costs.

- Owning a dredge would reduce the lengthy ACOE bureaucratic process involved in funding and project management for dredging projects.

- Owning a dredge would give the state the ability to stay ahead of sedimentation issues rather than waiting for them become problems. Current practices are such that dredging projects typically don't occur until after sedimentation has created conditions that pose significant navigational and/or safety concerns. This would necessitate a change in philosophy from conducting periodic, large-scale projects to smaller, routine maintenance projects, not unlike snow removal.

- Owning a dredge would allow the state to undertake multi-objective projects, rather than strictly ACOE navigation improvement/maintenance projects. In addition, the state contribution to purchase and maintain the dredge could constitute non-federal match to leverage federal restoration grants.

**CONS:**

- The state would have to assume full responsibility for the eight existing federal navigation projects in New Hampshire because the ACOE cannot use a publicly-owned or subsidized dredge to service federal channels. Doing so would be deemed as competing with private sector bidding on federal work.

- Owning a dredge would, therefore, eliminate any federal funding associated with dredging projects. Maintenance of existing federal navigation projects is fully paid for with federal dollars while "improvements" to federal navigation projects, such as the proposed expansion of the upper-most turning basin in the Piscataqua River, are generally cost-shared between the federal government and the state. On balance, it is not clear that eliminating that cost share would balance the costs of owning the dredge.

- The initial cost to purchase a new dredge would exceed $1 million and maintenance costs would have to be budgeted on an annual basis.

- When purchasing a new dredge, the state would have to choose a single dredge type (e.g., cutter-head dredge). Specific dredge types are more effective than others in certain substrates. Due to the varying composition of the substrate in the Great Bay Estuary (and its tidal rivers) the selected dredge type would likely not be effective for all substrate types.

- It is unknown whether there are enough dredging projects in New Hampshire to keep the dredge and the crew necessary to operate the dredge busy. It is also unknown whether dredging projects in southern Maine might utilize a state-owned dredge.

It should be noted that many of the same complications regarding the timing of dredging (e.g., dredge "windows" for migrating fish), disposal issues and permitting requirements and timeframes that cause delays in the current dredge management process would continue despite the state owning a dredge. This has been a consistent issue in Barnstable County, MA, which owns a dredge.