AR-404

Great Bay Estuary Restoration Compendium

The Nature Conservancy
SAVING THE LAST GREAT PLACES ON EARTH

New Hampshire Estuaries Project

New Hampshire Coastal Program
NHCP

University of New Hampshire

September, 2006

Table of Contents

Note for readers viewing this document digitally: This report contains numerous hyperlinks, allowing the viewer to click on the document text and directly access a related webpage. Hyperlinks typically show up as underlined blue font (i.e., hyperlink).

Acknowledgements

This report was funded by the New Hampshire Coastal Program and the New Hampshire Estuaries Project.

This project was made possible by several generations of scientists who made the study of the Great Bay estuary their life's work and the 'authors' mentioned below were primarily compilers of the work of others. This report was immeasurably improved by the contributions of many people who apply their expertise and energy on a daily basis to help meet conservation, restoration, and management challenges while moving the state of science and understanding forward, and who also somehow found time to supply us with their data and answer our questions. In particular we would like to thank Mike Dionne (NHF&G), Dr. Ray Grizzle (UNH-JEL), Joanne Glode (TNC), Jennifer Lingeman (UNH-CSRC), Dr. Richard Langan (UNH-CICEET), Alyssa Novak (UNH-JEL), Cheri Patterson (NHF&G), Dr. Fay Rubin (UNH-CSRC), Brian Smith (NHF&G / Great Bay NERR), Bruce Smith (NHF&G), and Dr. Frederick Short (UNH-JEL). Many of these people had the opportunity to share their information and data without adequate opportunity to see what we did with it and any mistakes or wrong conclusions need not be laid at *their* feet. Adam Finkelman, an intern from Colby-Sawyer College, assisted with data development. Alison Bowden and Arlene Olivero (TNC) provided good counsel regarding fish ecology and GIS data processing methods. Special thanks to Eric Aldrich (TNC) for formatting assistance.

Mark Zankel (TNC) provided the initial ideas that launched this project, and essential guidance along the way.

This report is dedicated to Colonel Cyrus and Barbara Sweet, whose unflagging enthusiasm and support for conservation in New Hampshire both inspired and made this work possible.

Primary Authors: Jay Odell (The Nature Conservancy), Alyson Eberhardt (University of New Hampshire), Dr. David Burdick (University of New Hampshire) and Pete Ingraham (The Nature Conservancy).

Cover credits: Oyster drawing, Matthew Squillante; Eelgrass photo courtesy of Fred Short; Salt marsh photo, Jay Odell; Alewife image courtesy of Maryland Dept. of Natural Resources. Cover design by Abigail Odell

Introduction

Single species approaches to natural resource conservation and management are now viewed as antiquated and oversimplified for dealing with complex systems. Scientists and managers who work in estuaries and other marine systems have urged adoption of ecosystem based approaches to management for nearly a decade, yet practitioners are still struggling to translate the ideas into practice. Similarly, ecological restoration projects in coastal systems have typically addressed one species or habitat. In recent years, efforts to focus on multiple species and habitats have increased. Our project developed an integrated ecosystem approach to identify multi-habitat restoration opportunities in the Great Bay estuary, New Hampshire. We created a conceptual site selection model based on a comparison of historic and modern distribution and abundance data, current environmental conditions, and expert review. Restoration targets included oysters and softshell clams, salt marshes, eelgrass beds, and seven diadromous fish species.

Spatial data showing the historical and present day distributions for multiple species and habitats were compiled and integrated into a geographic information system. A matrix of habitat interactions was developed to identify potential for synergy and subsequent restoration efficiency. Output from the site selection models was considered within this framework to identify ecosystem restoration landscapes.

The final products of these efforts include a series of maps detailing multi-habitat restoration opportunities extending from upland freshwater fish habitat down to the bay bottom. A companion guidance document was created to present project methods and a review of restoration methods. The authors hope that this work will help to stimulate and inform new restoration projects within the Great Bay estuarine system, and that it will serve as a foundation to be updated and improved as more information is collected.

Great Bay Estuarine System
Project Area Description

We define the Great Bay estuarine system to include the entire tidal basin inshore from the confluence of the Piscataqua River and the Gulf of Maine, and all of the uplands and freshwater systems that drain to these salty waters. This area is comprised of Great Bay proper, Little Bay, and the Piscataqua River. Approximately 1/3 of the area is within the state of Maine, the remainder in New Hampshire (Figure 1).

A custom watershed was created using standard United States Geological service (USGS) Hydrologic Cataloguing Units (HUC 12 codes), modified as required to exclude land areas that drain directly to the open coast. Additionally, the HUC 12 watersheds were split to recognize natural ecological boundaries that differentiate the estuaries' tidal shorelines, and extended to include the project area's subtidal lands, to provide integrated upland, intertidal, and subtidal project areas. For example, the standard HUC 12 watershed includes the entire shoreline of Great Bay proper, yet the south, east, and west shores have very different wind, current and shoreline sediment regimes and are naturally divided by the deep channel in the center of the bay.

Figure 1: Great Bay Estuarine System Project Area

Twice daily the tide rushes in from the Gulf of Maine, bringing full strength seawater through the Piscataqua River to Little Bay and Great Bay, to blend with the flow from eight primary rivers: the Winnicut, Squamscott-Exeter, Lamprey, Oyster, Bellamy, Cocheco, and the Salmon Falls. The Salmon Falls has a major tributary river, the Great Works. This approximately 1,000 square mile watershed is drained by over 2,000 stream and river miles.

Making the Case for Restoration

Great Bay is one of New Hampshire's greatest natural treasures, a unique estuarine system often noted for being less impacted by human activities than most other estuaries on the east coast of North America, particularly compared to those to the south. About 150 miles of shoreline border and buffer relatively healthy salt marshes and eelgrass meadows growing in vigorously mixed tidal waters that provide habitat for several hundred different resident and seasonal fish and invertebrate species. Seven rivers and their tributaries connect the surface and groundwater flows from over 1,000 square miles of coastal New Hampshire and Maine watersheds to the estuary, and provide critical habitat for a suite of diadromous fishes, including river herring, rainbow smelt, and eels. These migratory fish, along with waterfowl, shorebirds, osprey, and eagles, link Great Bay to the Gulf of Maine, and to other ecosystems around the world.

A close look at the history and current condition of the Great Bay estuarine system reveals that although it is relatively intact and remarkably resilient, it has been significantly altered and degraded. Prior to 1900, all of the rivers and many of the tributaries were dammed, extensive logging throughout the watershed brought tons of silt into tidal rivers, the bay bottom was covered in sawdust up to a foot deep and poisoned with industrial wastes, and aquatic resources were over harvested. Since that time, significant human population growth and development throughout the Great Bay watershed have created new stresses – notably habitat loss, and new levels and types of point and non-point source pollution.

In many cases we are only able to find scant records prior to the mid-1950s. In 1922, C.F. Jackson, namesake of the University of New Hampshire's Jackson Estuarine Laboratory, wrote of steady and troubling declines in several key species that had occurred over a period of about 30-40 years. Nowadays we are apt to consider losses that have occurred since the 1970s and consider that period as a reference point. Perhaps if we are mindful of the tendency to evaluate loss in the context of only one or two generations (described as "shifting baselines" in 1995 by Daniel Pauly), and the accumulated error compounding nature we will be less apt to set our restoration goals too low.

Although there is ample evidence that because of shifting baselines we tend to lose track of just how much ecosystems have really changed, there also seems to be a basic human tendency to mythologize the past, to superimpose upon the past a vision equivalent to what we desire in the present. We have all heard stories about how much better things were in the good old days. In this report we seek to define what has actually been lost, as precisely as possible given the available information.

Many years past, well trained ecologists subscribed to the notion of "the balance of nature", the idea that nature, undisturbed by people, has an ideal state (*e.g.* old growth forest). This ideal balanced ecosystem could be defined as a particular set of species with specific distributions, biomass, and average ages.

Today we are more inclined to recognize that ecosystems are dynamic, with multiple possible states and ever changing mosaics of diverse habitats. Natural disturbances like 100 year floods and hurricanes help to produce a diversity of habitat types and expressions, which in turn gives rise to biodiversity. The goal of restoration should not, therefore, be to reproduce the exact conditions that existed before humans disturbed the mythological balance of nature.

With that caveat in mind, we also recognize that human activities have unintentionally altered many of the ecological processes that are necessary for the long term persistence of estuarine habitats and all the species that depend on them. Left unchecked, these alterations can drive ecosystems into alternate and relatively stable states that are clearly undesirable, with hypoxic dead zones, and food webs simplified by the loss of formerly dominant species. These potential states are being realized in estuaries and other marine ecosystems around the world and they do not produce the kinds of natural resources, aesthetic riches, and ecological services desired and required by human communities in the Great Bay region.

The goal of estuarine restoration should therefore be to abate the threats that degrade and simplify the estuary ecosystem and at the same time take actions that help to build ecological resilience – the ability of an ecosystem to rebound from disturbances instead of shifting into new, oversimplified states. The emerging science and policy goals around the concept of resilience explicitly recognize humans as integral *parts of* ecosystems.

In a variety of useful ways, many people living and working in the Great Bay watershed are working to abate the threats that have led to habitat and species loss, the impacts that have given rise to the need for restoration. Restoration methods are usually considered to be primarily about planting things (*e.g.* oysters, eelgrass), or very directly improving structural conditions (*e.g.* removing dams, recreating natural stream channels). Some critics of restoration ecology note that restoration practitioners subscribe to a "field of dreams" myth – the idea that if we build it they (the species) *will* come. On the other hand, if we don't build it, they *definitely won't* come. Making maps to guide restoration efforts to plant and improve structural conditions for multiple species and habitats is the focus of this report, and these actions are necessary but not sufficient.

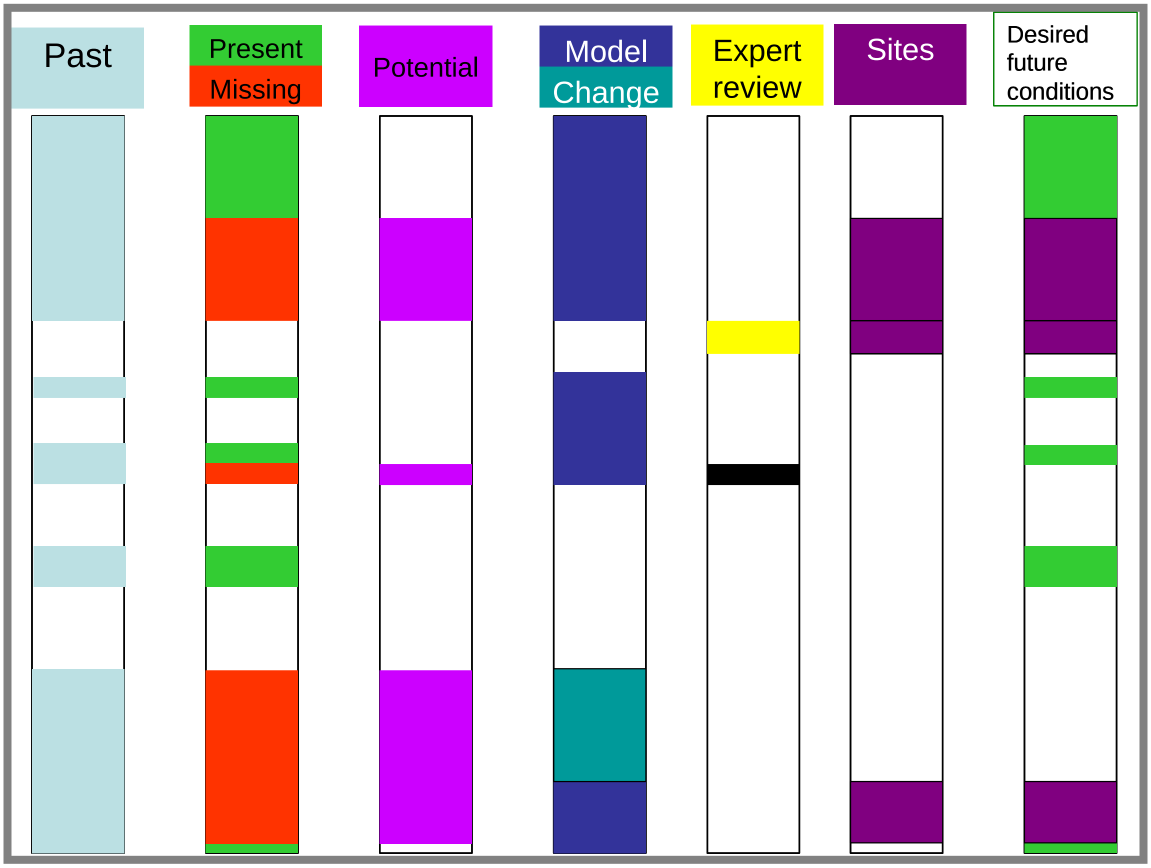
Ecosystem restoration cannot be successful without continued land protection, abatement of threats from municipal wastewater and non-point source pollution, and adoption of best practices to minimize negative impacts from development and natural resource use – this work should rightly be considered part of the restoration method.

References:

Hilderbrand, R. H., A. C. Watts, and A. M. Randle. 2005. The myths of restoration ecology. Ecology and Society 10(1): 19.

Pauly, Daniel. 1995. Anecdotes and the shifting baseline syndrome of fisheries. Trends in Ecology and Evolution 10(10): 430.

Overview of Project Methods



Conceptual Model for Site Selection.

Each vertical bar represents a detailed map showing the physical distribution of a hypothetical species or habitat type. The first bar (**Past**) indicates the locations inhabited by the species in the past, prior to loss. The second bar (**Present/Missing**) combines the known current distribution with that of the past. The third bar (**Potential**) indicates locations where the species used to be, but no longer is found. The fourth bar (**Model Change**) shows the output from a site suitability model, indicating areas where current environmental conditions are expected to support the species of interest (shown in blue), and areas where conditions have changed and are no longer suitable. The fifth bar (**Expert Review**) incorporates expert review, which is essential because models are, by definition, not perfect. The yellow segment represents an area that the model predicts incorrectly as unsuitable and the black segment indicates an area where the model incorrectly predicts a species will survive. The sixth bar (**Sites**) presents areas of known loss, as filtered by the model and expert review. Finally, the last bar (**Desired Future Conditions**) indicates desired future conditions—maintenance of existing populations combined with expansion into successful restoration sites.

The model provided a framework for data compilation, analysis, and expert review. Sophisticated site suitability models for most species in the project area are not available due to the lack of spatial data on elevation and substrate quality at fine enough scales. This fact places more burden on the expert review steps of site selection, and subsequently on site level project planning and post-restoration monitoring.

This compendium is designed to help practitioners identify and prioritize restoration projects based on ecological factors. However, the best projects may be the ones that get done, and additional social factors should be given due consideration – community values, legal considerations, and funding sources.

Introduction to Restoration Targets

We selected salt marsh, eelgrass, shellfish, and seven diadromous fish species as the primary targets for this report. These habitats and species are arguably the most important overall in terms of the ecological function of the estuary.

Salt marsh (*Spartina patens* and *S. alterniflora*) and **eelgrass** (*Zostera marina*), with assistance from flat diatoms and phytoplankton, form the base of the food web that supports all estuarine invertebrates, fish, and birds. In addition to capturing and storing the sun's energy and powering the food web these plants provide important, often essential habitat for hundreds of other species. The list of ecological services provided by eelgrass and salt marsh is long (and likely still being discovered), and includes protection from shoreline erosion, nutrient and sediment trapping, and pollution filtration.

There are several species of **shellfish** that currently or formerly were integral to the estuaries' diversity and function; herein we focus on two of them, the eastern oyster (*Crassostrea virginica*), and to a lesser extent the softshelled clam (*Mya arenaria*). The ecological services provided by oysters and other filter feeding bivalves are critically important – one adult oyster can filter up to fifty gallons of water an hour, removing particles down to about three microns. Healthy oyster beds and reefs clarify the water, improving conditions for eelgrass and other species. They are thought to offer resilience to eutrophication effects by cropping down excessive plankton blooms and sequestering nutrients, and the structure provided by their shells creates excellent habitat for other invertebrates and juvenile fish, and can also help to buffer shorelines from erosion.

Diadromous fish species continue to migrate between salt and fresh water through fish ladders on Great Bay's seven rivers, but conditions are far from optimal. In this report we focus on Atlantic salmon (*Salmo salar*), Atlantic sturgeon (*Acipenser oxyrhynchus*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), American shad (*Alosa sapidissima*), rainbow smelt (*Osmerus mordax*), and American eel (*Anguilla rostrata*). An eighth species, the sea lamprey (*Petromyzon marinus*) also migrates between Great Bay and the ocean. Detailed data on sea lamprey was not collected; measures taken to benefit the other species will likely improve conditions for sea lamprey as well. These species were all formerly abundant within the Great Bay estuary, and are now either locally extinct (*e.g.*, salmon and sturgeon), showing declining trends (*e.g.,* rainbow smelt), or at low levels (*e.g.,* shad and eel). Formerly the eggs, juvenile stages and adults of these species would have provided significant forage for many other species in both fresh and salt water habitats throughout the estuary. Predation, competition and other ecological interactions by robust diadromous fish populations had unknown but significant effects on the entire estuarine plant and animal community. The abundance and health of top level predators (*e.g.*, osprey, eagles, striped bass, seals) is linked to their ability to forage on juvenile and adult diadromous fishes in Great Bay. Similarly, the rich cultural heritage associated with fishing and eating seafood is linked to the fate of these iconic species.

Restoration Target Information

Conservation and restoration work around the Great Bay estuary is made possible and enhanced by ample historic and current output from several centers of research and management excellence, including the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), the Jackson Estuarine Laboratory, many other programs under the umbrella of the University of New Hampshire's Marine Program, and the Great Bay National Estuarine Research Reserve. The New Hampshire Estuaries Project and the New Hampshire Coastal Program serve a critical role in synthesizing and translating science, setting conservation and restoration goals, and providing grant opportunities. It is beyond the scope of this project (and perhaps not particularly useful) to comprehensively paraphrase and present the wealth of existing information for each restoration target. Several existing documents provide such a summary, notably:

- *The Ecology of the Great Bay Estuary*, New Hampshire and Maine: An Estuarine Profile and Bibliography, edited by Frederick T. Short in 1992.

- *A Technical Characterization of Estuarine and Coastal New Hampshire*, edited by Stephen H. Jones in 2000.

- The New Hampshire Estuaries Project Management Plan, published in 2000 and updated several times since.

- Cross Grained and Wily Waters, edited by Jeffrey Bolster in 2002, provides a nice overview of the maritime history of the estuary, and was instrumental in pointing out primary historical sources for this report.

These and other documents served as the foundation for this report and will undoubtedly continue to serve as useful references for restoration practitioners.

Additionally, New Hampshire's conservation and restoration work is served very well by access to Geographic Information Systems (GIS) data and analysis provided by UNH's Complex Systems Research Center and made available on the GRANIT website. Much of the data used in this report was obtained from GRANIT; exceptions where data was created for this project or obtained from other sources are noted. The project data on the CD can be overlaid with other useful layers easily obtained from GRANIT, particularly geo-referenced aerial photographs and USGS topographic maps. Similarly, the State of Maine's GIS website MEGIS, contains many very high resolution photos and other useful data.

Salt Marsh

Salt marshes are one of the world's most productive ecosystems. Above, Great Bay from Greenland. Eric Aldrich/TNC photo.

Salt marshes are intertidal wetlands typically located in low energy environments such as estuaries. They exist both as expansive meadow marshes and as narrow fringing marshes along shorelines. Salt marshes are considered one of the most productive ecosystems in the world due to high rates of plant growth. Numerous ecological functions are provided by salt marshes, including shoreline stabilization, wildlife habitat, and nutrient cycling. They also serve as important breeding, refuge and forage habitats for many species of crustaceans and other invertebrates, and fish. These organisms help to export nutrients and energy from salt marshes to support coastal food webs through their regular movements from salt marshes into other estuarine and marine habitats.

In the past few centuries, much of the salt marsh habitat in New England has been altered or destroyed. Historically, salt marshes were first ditched and drained for salt marsh hay farms and later for mosquito control. Furthermore, coastal development for roadways, homes, and industry resulted in extensive dredging and filling of salt marshes. As human understanding of salt marsh functions has improved, efforts have increased to conserve and restore these habitats. Although wetland regulations have reduced many impacts, salt marshes continue to be degraded and destroyed as coastal development persists. Salt marshes are a scarce habitat type, occupying only about 0.1% of the land area of New Hampshire.

Current threats to salt marshes include reduced tidal flow due to undersized culverts under roadways and train beds, loss of the upland buffer due to coastal development, excess nutrient inputs from stormwater runoff, and colonization by invasive species. The New Hampshire Coastal Program and others have led efforts to abate the threats to NH salt marsh persistence through conservation and restoration projects. The largest of these projects have been where the need is perhaps greatest along the open coastline between Odiorne Point and Hampton-Seabrook. Current salt marsh restoration projects in the Great Bay estuarine project area include Bulltoad Pond in Newcastle, Fresh Brook in Dover, and Odiorne Point Landing in Rye where half of the parking lot, built on the marsh, has recently been removed.

Salt Marsh Restoration Methods

Hydrologic Restoration

Construction of transportation corridors over marshes often filled them directly, but also reduced or eliminated tidal flow to the upstream areas. Also, agricultural activities sometimes diked and drained marshes to convert them to fresh pasture. Many areas that were healthy marshes are now deteriorating and not providing important functions such as fish production as a result of tidal restrictions. To restore the health and function of restricted marshes, culverts large enough to support flow of the full tidal range can be placed through the corridors at old or current creek locations. In 1994, the U.S.D.A. Natural Resources Conservation Service (NRCS), then the Soil Conservation Service, developed an atlas of marsh restrictions and tentative solutions for sites covering over 1,200 acres in the state (20% of New Hampshire's remaining salt marshes). By 2006, just 12 years after the NRCS atlas was produced, adequate tidal flow has been restored to most of the sites. Of those that remain, some are not cost effective to restore at this time, while successful partnerships to restore other important sites have not yet developed (*e.g.*, Stubbs Pond).

Hydrologic restoration can be an extremely effective method of restoring salt marshes because it addresses overall marsh function. Response to restoration is often very rapid, and includes increased saltwater and sediment inputs, increases in salt marsh vegetation, and decreases in invasive plant species. Furthermore, the method requires little maintenance. However, hydrologic restoration of salt marshes is often expensive and requires a great deal of time to plan, design and coordinate. Hydrologic analyses must be conducted to ensure that restoration of the tidal regime does not create flooding conflicts with adjacent land uses.

Excavation of Fill

Marshes have been filled by coastal development and disposal of dredge spoil. Most of the filled marsh in the Great Bay estuary is associated with transportation corridors (roads and railroads) and berms built to convert salt marsh to fresh water ponds. Infrastructure and recreational resources prevent fill removal of most sites in the estuary (*e.g.*, Exeter and Newfields Wastewater Treatment Plants; Durham Town Landing), but the potential does exist at some sites (*e.g.*, Jackson Landing).

Excavation is effective for lowering the elevation of marshes to ensure adequate tidal inundation. It is also an effective method for removing invasive species such as *Phragmites australis* (common reed). However, it can be difficult to obtain the proper elevation to restore a functioning salt marsh, particularly if coarse sediments are found at the target elevation. Excavation requires the use of heavy earth moving equipment as well as a suitable location for the disposal of dredge spoil.

Open Marsh Water Management

Two periods of ditching salt marshes have caused most of our larger marshes to be unnaturally drained. From European settlement until about 100 years ago, small ditches were created in marshes to facilitate harvest and enhance the growth of salt hay.

Beginning in the1930s, new knowledge that mosquitoes could carry disease and the onset of the Great Depression combined to send crews of previously unemployed men to ditch the marshes. With regard to mosquito control, the ditching was a failure – mosquitoes still bred in small water pockets and their main predators (small fish) were effectively eliminated from the marsh surface by the drainage ditches. Although the precise effects of the ditches are not clear, there has been some effort to reverse the drainage of the marsh surface. Such projects plug ditches using the spoil from the excavation of small ponds. These efforts may result in more habitat for small fish and are relatively low in cost per acre restored. However, OMWM requires heavy machinery and may require periodic maintenance. Furthermore, the impacts of OMWM are currently not fully understood.

Invasive Plant Removal

A variety of factors, including reduced tidal flow and increased stormwater runoff have resulted in the colonization of salt marshes in New Hampshire by invasive, exotic species such as *P. australis* and *Lythrum salicaria* (purple loosestrife). Multiple methods have been developed to remove invasive species and restore salt marsh vegetation with varying degrees of success.

Mowing is effective at reducing invasive plant biomass and can increase sunlight available to competing native species, but the dense stands of the invasive plants return in one to two years. Mowing is labor intensive and typically requires annual cutbacks with heavy machinery. Mowed clippings and dredge spoil must be properly disposed of to prevent growth of invasive species elsewhere. Due to low success rates, mowing is often used in combination with other invasive plant removal methods.

Burning is an efficient removal method for large areas of invasive plants and increasing soil nutrients. Because the prior year's plant material is needed to serve as fuel, burning can only occur every other year. Opportunities for burning are also limited by condition requirements for season, precipitation, and wind. Burning does not eliminate the perennial invasive plants, and colonization by other invasive plants in encouraged; therefore, burning is often used in conjunction with other methods.

Application of herbicide to invasive vegetation in salt marshes can effectively decrease invasive growth to allow native plants to establish. Herbicide can be used over a large area, or can be applied as a spot treatment in areas where desirable vegetation exists. However, glyphosate, the most widely used herbicide, is a broad-spectrum herbicide that will kill all vegetation it contacts. Although glyphosate biodegrades quickly, it can affect aquatic organisms. Furthermore, multiple applications of herbicide are required. The success of each application is dependent on the plant growth stage, so is most effective during short periods in late summer. Herbicide is most effective when sprayed several weeks after cutting or mowing.

In order to facilitate colonization by salt marsh vegetation following removal of invasive species, seeds, bare root seedlings, or plugs of native salt marsh vegetation can be planted. Although labor intensive, planting efforts may be effective at establishing native vegetation that will outcompete invasive species. Furthermore, planting efforts provide opportunities for community involvement.

Erosion controls

Salt marshes exist as a dynamic balance between erosion and marsh building. When erosion exceeds marsh building, marsh loss occurs. The placement of barriers such as filtration enhancement devices (FEDs) seaward of salt marsh edges can reduce exposure and aid sediment accretion by reducing re-suspension of sediments. FEDS are cost effective, easily constructed, and biodegradable; however, they often require maintenance and annual reconstruction.

Salt Marsh – Spatial Data Compilation & Analysis

Data Layers

1. Historical USGS topographical maps are available online courtesy of the UNH Dimond Library. Maps covering the project area are available for a variety of years, including 1893, 1916, 1918, and 1941. The 1918 series was selected because it had much more accurate and detailed shorelines than the 1893 maps, and unlike either the modern maps or those produced in 1893 and 1941, the 1918 maps use different symbol patterns to differentiate between freshwater and salt water marshes. The 1918 maps were superior to the 1916 maps in color and resolution, but utilized the 1916 survey data. Six images (Dover NE, NW, SE & SW; Exeter NW, and York SW) were imported and rectified to 1:24,000 New Hampshire Hydrography Dataset (NHHD) shorelines using the ArcView 9.1 georeferencing tool. After this step, all salt marsh areas were carefully traced onscreen and saved to a single polygon shapefile (1916_Marsh.shp). This file is contained on the project CD; the georeferenced topographical map images are available from The Nature Conservancy upon request.
2. A shapefile containing salt marsh data from 1962 was obtained courtesy of Stephen M. Dickson at the Maine Geological Survey (MGS). It was created to represent the distribution of salt marsh, eelgrass, and five other habitat types for the entire shoreline of Maine. Salt marsh patches larger than 150 m^2 were drawn using aerial photographs taken during low tide in May of 1962. These data were clipped to include the all tidal shorelines within the Maine side of the project area. Note: The MGS has additional historical photographs (not currently geo-referenced) that could potentially be made available to NH state agencies for conversion to GIS formats).
3. 1991 National Wetlands Inventory (NWI) data for the project area codes wetland types areas greater than three acres based on pre-1991 imagery. These data were filtered and clipped to remove non-salt marsh wetlands and salt marsh outside the project area. This data was published in 1991 but was created using photos taken earlier (dates unknown to authors at time of writing, presumed late 1980s).
4. Dr. Larry Ward and colleagues (UNH 1993) mapped tidal wetlands and produced shapefiles using aerial photographs taken from 1990 to 1992 in the New Hampshire portion of the project area.

5. Under contract from the Hampshire Coastal Program, Normandeau Associates Inc. created a shapefile with detailed coding for coastal wetland types and invasive species using aerial photography collected in August of 2004. The photographs used for this project were not digitized and this dataset does not extend to the Maine side of the project area.
6. Joanne Glode (TNC) created a new shapefile using the 1998 black and white orthophotos available on GRANIT to detect salt marsh ditches and create a new shapefile using onscreen digitization. These photos were in general more useful for ditch detection than the more recent color sets.
7. Alyson Eberhardt and Dr. David Burdick (UNH) visually examined orthophotos in combination with the salt marsh layers described above to identify areas where salt marsh has been lost to fill, and created a new shapefile of these areas using onscreen digitization. Onscreen digitization and existing unpublished GIS data was used to create a shapefile showing a few areas where marsh has been created, and a few areas where ditch plug restoration efforts are ongoing.
8. The areas identified in Alan Amman's 1994 NRCS tidal restriction evaluation report were digitized on screen and coded as either restored or not.
9. Shapefiles associated with the Bozek and Burdick (2003) report on impacts of seawalls on salt marshes were re-located and included on project maps.

Summary of project area salt marsh coverage:

The 1916 USGS data and the 1990-92 NWI data covers both Maine and New Hampshire, the 1962 MGS data only covers Maine, and the Ward 1992 and Normandeau 2004 data covers only New Hampshire. At the time of this report, the most recent available data for the Maine side of the GBERC project area is from the NWI 1991 survey.

Salt Marsh Change Analysis

The Ward data was combined with the NWI data (excluding non-salt marsh polygons) because the survey times were relatively close, and together they approximate recent past conditions in both Maine and New Hampshire.

The 2004 data was compared to the 1916 USGS data, and to the combined NWI/Ward data using the XTools erase function. Two new shapefiles were created, one showing potential salt marsh loss between 1916 and 2004, and one showing potential loss between 1992 and 2004.

Similarly, the 1916 data was analyzed in comparison with the 1962 MGS data and the NWI data to produce two shapefiles showing potential loss from 1916 to 1962, and from 1962 to the most recent dataset from NWI. Figure 2 shows a comparison of the historical and current salt marsh occurrence data.

All shapefiles containing polygons with potential marsh loss were combined. This combined file represents the fourth step in the project conceptual model described above,

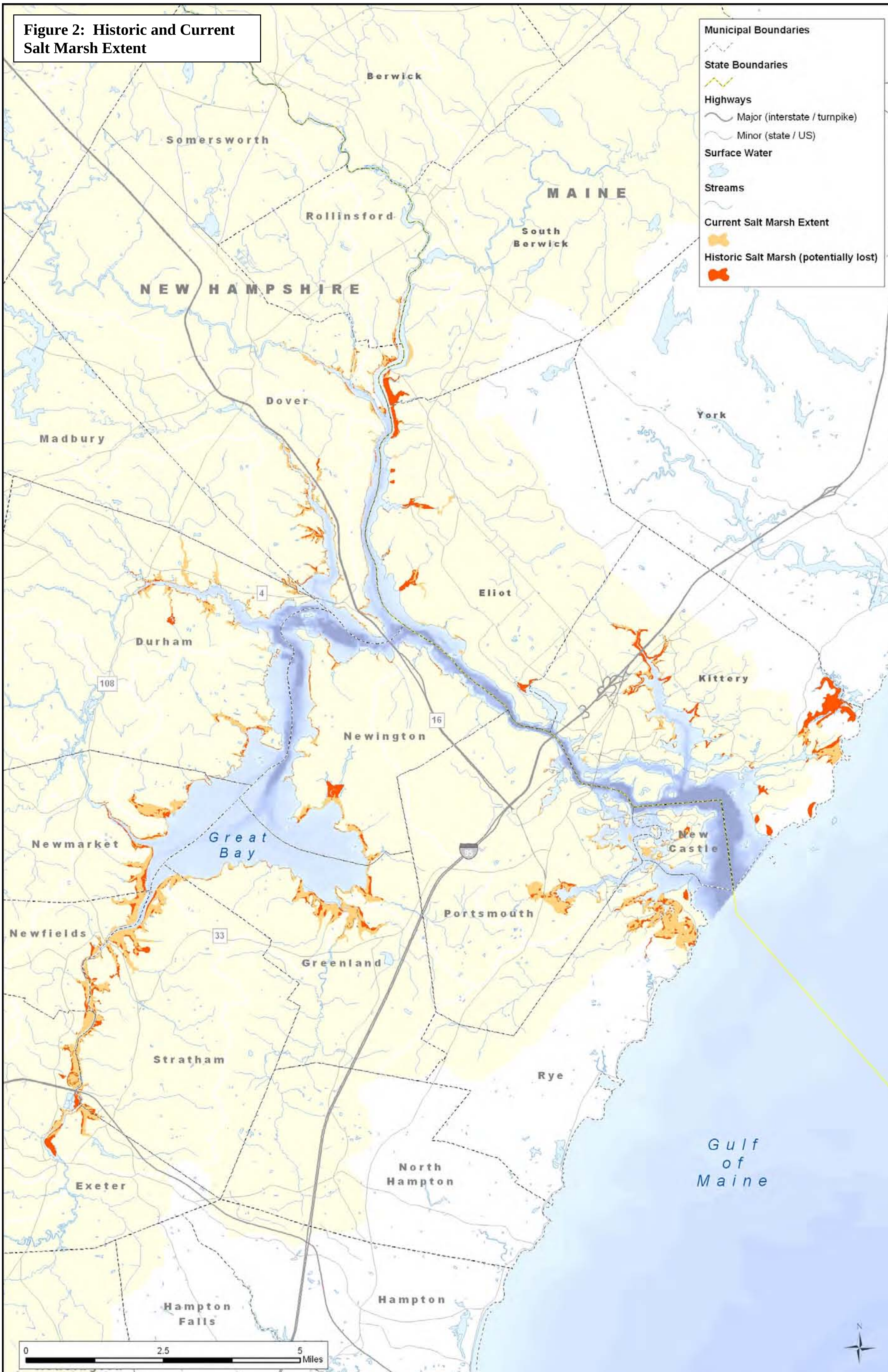


Figure 2: Historic and Current Salt Marsh Extent

areas formerly but no longer occupied by salt marsh. There are over 2,500 polygons totaling about 2,500 acres in this file but it should *not* be considered an accurate representation of salt marsh loss because of several sources of error.

Examination of the source data reveals many areas where salt marsh polygons with the same basic marsh extent and shape are offset from each other due to poor registration of the different datasets to a common shoreline. The registration error is likely the result of different base maps and projection methods used. Finally, the five different mapping projects used different survey and photo interpretation protocols. In combination, these factors led to production of many very small polygons that likely do not represent actual loss. In a similar exercise using some of the same data, Trowbridge (2006) discusses similar analysis challenges.

It should also be noted that the 1916 maps do not include fringing marshes, and often lack the marsh "tails" that extend upland into tidal creeks. These features are captured very well in the Normandeau data, and this difference does not indicate that there has been marsh gain in these areas.

Given the caveats described above, the analysis yields many clear indications of significant marsh loss. The analysis methods described above easily and precisely detected areas of well known marsh loss along with new ones.

Each polygon in the file containing areas of potentially lost marsh with a size greater than or equal to 3 acres was individually evaluated. It was clear that the majority of the smaller polygons were the result of registration errors and the 3 acre filter reduced the number to individually scrutinize (130 instead of 2,562) to a more tractable level. There were 2,111 acres in the in the unfiltered file, compared to 1,561 acres after polygons less than 3 acres were removed. Average size of polygons in the filtered and unfiltered files is 12.0 and 0.8 acres, respectively. Because it is quite possible that this method excluded areas of slight marsh loss from consideration, and that the cumulative effect of many small losses could be significant, the entire dataset is included on the project CD for future evaluation in the context of sea-level rise and other impacts.

The 130 polygons greater than or equal to 3 acres were displayed onscreen, and evaluated at fine scales using georeferenced orthophotos, primarily the NAIP 2003 set available on GRANIT and the 1 foot resolution color photos for the Maine side of the project area, available at MEGIS.

Each polygon was assigned one of the following codes:

0 – Likely does not represent actual marsh loss (note all polygons less than 3 acres have this code, although each was not carefully evaluated)

1 – Likely is actual loss but restoration is impractical due to current infrastructure (houses, parking lots, buildings, roads)

2 – Appears to be actual loss but site investigation needed

3 – Past loss or damage with partial restoration completed (more work may be needed)

4 – Restoration candidate, need site visit to confirm, assess feasibility, and develop strategy

This coding exercise was conservative in the sense that when there was doubt about whether a polygon should be assigned a '2' or a '0,' it received a '0', and a '2' was entered when there was doubt as whether or not a '4' was indicated. Most areas coded as 1, 2, 3, or 4 were also evaluated for the following four types of stress: tidal restrictions, fill, ditches, and invasives. The database contains a field for each. A one digit code was entered in these fields to indicate the probable presence (1) or absence (0) for each stress type.

There were 5 areas totaling 94 acres coded with a '4'; 51 areas totaling 431 acres were coded with a '2'.

The polygons coded as invasive species types in the Normandeau 2004 data were extracted, evaluated, and coded in a similar fashion. Some of the *Phragmites australis* that occurs in the project area is a native, non-invasive variety. Based on David Burdick's field experience polygons known to represent native Phragmites were coded with a '0', those known to be invasive were given a '4', and those where the Phragmites type is unknown were given a '2'.

The results of this analysis are shown, in combination with the other marsh impact layers described above, in Figure 3.

It must be stressed that while these areas coded as "lost" indicate specific areas where loss has occurred, in many cases the shape and size are partly influenced by artifacts of the spatial analysis (*e.g.* source data registration errors) and are not likely to be exact representations lost marsh size and area.

Salt marsh references:

Bozek, C.M. and D.M. Burdick. 2003. Impacts of seawalls on salt marsh plant communities in the Great Bay Estuary of New Hampshire. Report to the Great Bay National Estuarine Research Reserve, Durham, NH. Grant Number NA160R2395.

Breeding, C.H.J., F.D. Richardson, and S.A.L. Pilgrim. 1974. Soil survey of New Hampshire tidal marshes. NH Agricultural Experiment Station, Durham, NH.

Bromberg, K.D. and M.D. Bertness. 2005. Reconstructing New England Salt Marsh Losses Using Historical Maps *Estuaries* 28(6): 823–832.

Burdick, D.M., M. Dionne, R.M. Boumans and F.T. Short. 1997. Ecological responses to tidal restorations of two northern New England salt marshes. *Wetland Ecology and Management* 4:129-144.

Chase, J. and L. Merrill. 2000. *The State of New Hampshire's Estuaries*, NH Estuaries Project, November, 2000.

Irlandi, E.A. and M.K. Crawford. 1997. Habitat linkages: the effect of intertidal salt marshes and adjacent subtidal habitats on abundance, movement, and growth of an estuarine fish. *Oecologia* 110:222-230.

Jackson, C. F. 1944. A Biological Survey of Great Bay, New Hampshire. No. 1. Physical and Biological Features of Great Bay and the Present Status of its Marine Resources.

Minello, T.J., K.W. Able, M.P. Weinstein, and C.G. Hays. 2003. Salt marshes as nurseries for nekton: testing hypotheses on density, growth, and survival through meta-analysis. *Marine Ecology Progress Series* 246: 39-59.

Mitsch, W. J., and J.G. Gosselink. *Wetlands*. John Wiley and Sons, 2000. New York.

Morgan, P.A. 2000. Conservation and ecology of fringing salt marshes along the southern Maine/New Hampshire coast. Dissertation, University of New Hampshire, Durham.

NAI 2005. Normandeau Associates, Inc. New Hampshire wetland cover mapping project.

Roman, C.T., W.A. Niering, and R.S. Warren. 1984. Salt marsh vegetation change in response to tidal restriction. *Environmental Management* 8:141-150.

Roman, C.T., R.W. Garvine, and J.W. Portnoy. 1995. Hydrologic modeling as a predictive basis for ecological restoration of salt marshes. *Environmental Management* 19:559-566.

Short, F.T. 1992. (ed.) The Ecology of the Great Bay Estuary, New Hampshire and Maine: An Estuarine Profile and Bibliography. NOAA - Coastal Ocean Program Publ 222 pp.

Short, F.T., R.G. Congalton, D.M. Burdick, and R.M.J. Boumans. 1997. Modelling Eelgrass Habitat Change to Link Ecosystem Processes with Remote Sensing. Final report: NOAA Coastal Ocean Program and NOAA Coastal Change Analysis Program.

USDA Soil Conservation Service. 1994. Evaluation of Restorable Salt Marshes in New Hampshire. U.S. Department of Agriculture, Durham, NH.

Valiela, I., and M.L. Cole 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. *Ecosystems* 5:92-102.

Valiela, I., S. Mazzilli, J.L. Bowen, K.D. Kroeger, M.L. Cole, G. Tomasky, and T. Isaji, T. 2004. ELM, an estuarine nitrogen loading model: formulation and verification of predicted concentrations of dissolved inorganic nitrogen. *Water, Air, and Soil Pollution* 157(1-4): 365-391.

Ward, L.G., A.C. Mathieson, and S.J. Weiss. 1993. Tidal wetlands in the Great Bay/Piscataqua River estuarine system" location and vegetational characteristics. Final Report to the New Hampshire Office of State Planning Coastal Program, Concord, NH.

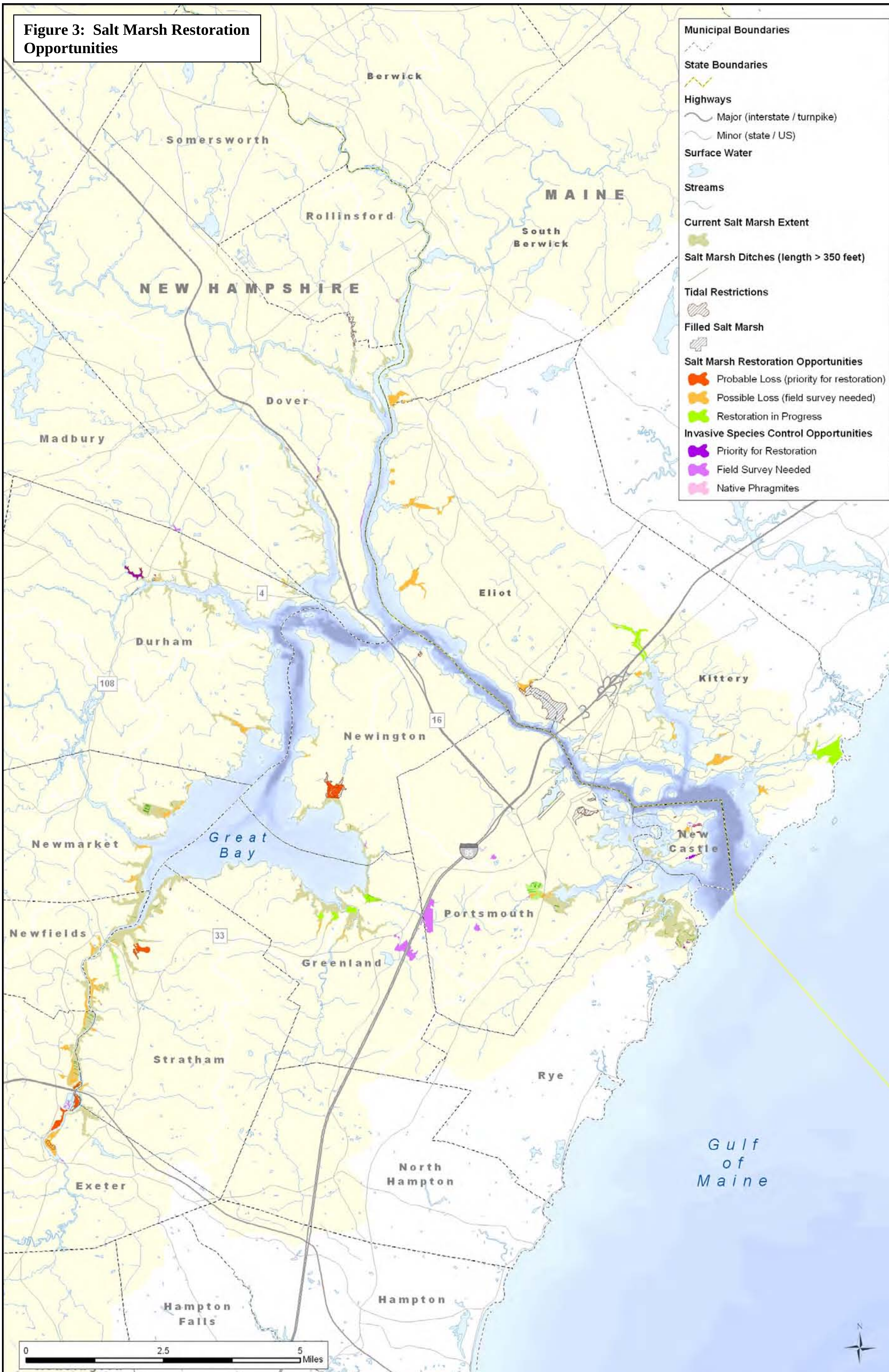


Figure 3: Salt Marsh Restoration Opportunities
Municipal Boundaries
State Boundaries
Highways
Major (interstate / turnpike)
Minor (state / US)
Surface Water
Streams
Current Salt Marsh Extent
Salt Marsh Ditches (length > 350 feet)
Tidal Restrictions
Filled Salt Marsh
Salt Marsh Restoration Opportunities
Probable Loss (priority for restoration)
Possible Loss (field survey needed)
Restoration in Progress
Invasive Species Control Opportunities
Priority for Restoration
Field Survey Needed
Native Phragmites
Berwick
Somersworth
MAINE
Rollinsford
South Berwick
NEW HAMPSHIRE
Dover
Madbury
Eliot
Durham
Kittery
Newington
Great Bay
Newmarket
New Castle
Portsmouth
Newfields
Greenland
Stratham
Rye
Gulf of Maine
North Hampton
Exeter
Hampton
Hampton Falls
0
2.5
5
Miles

Eelgrass

Eelgrass provides refuge, forage, and critical nursery habitat for many fish and invertebrate species. Frederick Short photo.

Eelgrass (*Zostera marina* L.) is the major seagrass in the western North Atlantic. Eelgrass is a marine flowering plant that grows in subtidal and intertidal regions of coastal waters in both protected and exposed systems. Eelgrass provides numerous ecological functions, including food, spawning and refuge locations for fish and shellfish. In addition, the complex networks of leaves, roots and rhizomes serve to trap nutrients and sediments, protect shorelines from erosion, and filter pollution. In northern latitudes eelgrass typically exhibits a seasonal change in abundance, with low biomass in winter months and rapid increases in the spring and early summer.

Eelgrass has undergone drastic fluctuations in distribution within the Great Bay estuary with evidence of a slow overall decline in the past decade. In the late 1980s, a marine slime mold, or wasting disease, infected eelgrass populations in Great Bay. It is estimated that approximately 80% of the eelgrass population in Great Bay was destroyed by the wasting disease outbreak, although populations recovered in the mid-90s. Currently, eelgrass meadows persist in Great Bay, Portsmouth Harbor, and Little Harbor. Parts of Little Bay such as Broad Cove and the Bellamy River formerly supported extensive eelgrass beds, but these beds did not recover after the 1980s and no longer exist. Increased development in New Hampshire and southern Maine continues to threaten Great Bay estuary eelgrass populations by increasing the amount of nutrients and suspended sediments entering waterways. These impacts have resulted in the steady decline in eelgrass biomass documented by the New Hampshire Estuaries Program. Both nutrient enrichment and suspended sediments decrease water clarity, resulting in a reduction in light availability and eelgrass decline. Physical disturbance from dredging, boat moorings and propellers and ice scour can also decrease eelgrass populations. Furthermore, natural factors such as bioturbation and wasting disease can harm eelgrass beds.

In Little Bay and the upper Piscataqua River, eelgrass has not returned naturally to areas where it was found in the early 1980s. In 1993-1994 an eelgrass transplant effort to mitigate for the Port of New Hampshire expansion successfully restored 2.5 hectares of eelgrass to the Piscataqua River. In 2001, 2.2 hectares of eelgrass were transplanted in Little Harbor, Portsmouth Harbor, and the Piscataqua River to mitigate for a dredging project in Little Harbor. The seagrass ecology laboratory at UNH is currently restoring 3 acres (approximately 1.2 hectares) of eelgrass in a 3-year project in the lower Bellamy River.

Eelgrass Restoration Methods

Natural Recolonization

Restoration via natural recolonization is the creation of suitable conditions for increasing eelgrass distribution. It requires an understanding of the causes of eelgrass decline. Those causes much then be remediated, which can include such as efforts identifying and addressing point and non-point nutrient discharges. By restoring the overall ecological health of the system, eelgrass restoration via natural recolonization results in long-term improvements. Furthermore, improving the health of the system will also benefit other habitats and organisms within the system. However, natural recolonization approaches often require extensive time and money resources. Projects such as repairing malfunctioning sewage systems (or upgrading inadequate systems) require the coordination of multiple groups and government agencies. Even with improved overall estuarine conditions, the natural recolonization of eelgrass may be very slow or never happen, due to the lack of available eelgrass propagules.

Transplanting

Transplanting eelgrass involves the movement of viable plants from a sustainable donor population to a target restoration site. Eelgrass may also be grown in aquaria for transplanting. A variety of methods are used to transplant eelgrass, including TERFS ™, sprigs and the horizontal rhizome method.

The TERFS ™ (Transplanting Eelgrass Remotely with Frame Systems) method involves attaching eelgrass shoots onto a reusable wire frame with biodegradable ties. The frames are placed on top of the substrate at the restoration site and are retrieved after the eelgrass roots into the sediment. The TERFS ™ method is an efficient restoration method that is relatively inexpensive. The use of TERFS ™ allows for community involvement because it is "low-tech", does not require SCUBA, and was developed as a method for volunteer restoration projects. The TERFS ™ method has proven to effectively anchor plants and allow roots to stabilize into the sediment, as well as protect against bioturbation.

The TERFS ™ method requires the construction or rental of TERFS frames as well as storage and transport capabilities for managing the frames. If shoots are harvested from donor beds for transplant, care must be taken not to adversely impact the donor bed. Studies have shown that the collection of individual shoots in a thinning process has no adverse effect on donor beds.

Other transplant methods include directly planting eelgrass shoots into the substrate. The horizontal rhizome method (HRM) involves anchoring two bare shoots into the sediment with a biodegradable bamboo skewer. HRM is a low cost transplant method;

however, it requires a great deal of effort, use of SCUBA, and does not protect against bioturbation.

Seeding

Eelgrass can also be restored by directly sowing seeds, a method that has shown potential in some areas (e.g,, Granger et al. 2002). Thus far, the success rate of seeding appears to be low, with a few notable exceptions. The utility of this approach will likely be highly site-specific, with wave action, sediment characteristics and tidal currents being significant factors affecting the overall success relative to other methods.

Various methods for seeding exist and continue to be developed. Researchers at the University of Rhode Island are developing a towable sled to deposit seeds directly within the substrate. Other methods involve encapsulating the seeds in a biodegradable coating to reduce predation and facilitate sinking to the substrate. The Buoy Deployed Seeding (BuDS) method involves attaching netting filled with flowering shoots to a buoy anchored in the target restoration area. As seeds develop in the flowering shoots, they drop to the surrounding area.

Seeding has the potential for restoring large areas. However, in many cases, efforts to establish thriving eelgrass beds from seeds have failed. Although the seeding methods can distribute eelgrass seeds which sprout and form seedlings, rarely have these seedling beds reached adult plant size. Efforts by the University of New Hampshire to reestablish eelgrass beds from seeds in the Great Bay Estuary have resulted in no success. Seeding may not be an appropriate method for high energy sites due to the likelihood of seed resuspension and drift to other areas. Furthermore, seeds and developing plants are more vulnerable than mature transplants to bioturbation. Seeding requires harvest, storage, sorting and cleaning of the seeds, making it comparable to other methods in labor and expense. The impacts on donor beds from seed harvest and removal have not been documented, so we are not able to offer a comparison of this approach with thinning of donor sites for transplant methods that require harvesting whole adult eelgrass shoots.

Eelgrass – Spatial Data Compilation & Analysis

Data Layers

1. A 1949 University of New Hampshire M. Sc. thesis by Stanley Krochmal, contained a carefully drawn eelgrass map that was scanned and rectified to the NHHD 1:24,000 shoreline data. Polygons with density codes were traced onscreen from this image. The original map closely matches modern hydrology data and shows extensive eelgrass beds in the Oyster River and other areas where it is no longer found; some areas, notably the south east shore of Great Bay, apparently did not contain eelgrass at the time of his survey. He indicated that he did survey these areas. Krochmal was likely using primarily shore based methods at low tide and the absence of eelgrass beds from deeper areas on his maps should be interpreted accordingly.

2. The eelgrass polygons from the same 1962 Maine Geological Survey data described above for salt marsh were also used to help represent historical conditions.

3. A map of “Major Eelgrass Beds in the Great Bay Estuary” (Nelson 1981) was scanned and georeferenced to the NHHD 1:24,000 shoreline layer. Because of substantial differences in shorelines between the two sources, this process was accomplished in six steps, working in one area of the estuary at a time and tracing the shapes onscreen to create a new shapefile. Rectifying smaller sections provided relatively good fits, as compared to trying to adjust the entire hand drawn map to the modern shoreline.
4. MEGRASS is a polygon coverage available from the MEGIS site, created with the assistance of Dr. Frederick Short. This coverage contains data for the Maine side of the project area from aerial photographs taken in July to October period during 1993 to 1997. Metadata from this file: “When possible, photography was at the time of extreme low tides, low wind velocity, good water clarity, and maximum biomass of eelgrass. These factors aid in the detection of the subtidal portion a bed. Transparencies from the 1993-1997 flights were oriented beneath and eelgrass bed locations compiled on stable-base manuscripts containing the coastline and other basemap features from the 1:24,000 scale USGS topographic maps. Polygons delineating stands of eelgrass were digitized and coded using a four category scale of percent cover. Verification has been carried out by boat, on foot, and by plane. Though dense patches of eelgrass approximately 6 meters in diameter and less can be identified under good conditions, a conservative estimate of the minimum mapping unit is 150 square meters. This represents a stand of approximately 14 meters in diameter.”
5. The extensive eelgrass survey data collected by Dr. Frederick Short, and already converted to shapefiles, was used to represent modern conditions. Because of the (partly naturally) dynamic nature of the eelgrass “foot print” in the bay, summaries of Dr. Short’s data produced by Dr. Phil Trowbridge that are coded based on the number of years eelgrass has been found in a particular location are very useful (Figure 4). For the purposes of following the project conceptual model to select restoration sites, one year to represent current conditions, all locations within the project area where eelgrass has been found between 1990 and 2002 were considered as part of the “current” distribution. It must be noted that in light of the troubling trends of declining eelgrass density that have become evident in recent years, some of these so-called “current” areas may be well on a path to being restoration candidates. Updating the grid-coded eelgrass persistence layers with the most recent year’s surveys, and analyzing the results with respect to temporal trends on a cell by cell basis would help to clarify the extent of the current distribution and to identify additional problem areas.

The older data layers (1-3) described above were combined into a single file to represent the historic distribution, and the more recent layers (4-5) were combined to approximate the current distribution (Figure 5). The XTools 3.0 erase function was used to create a new shapefile containing only polygons showing areas unique to the historical data file, areas of loss.

Dr. Short has developed a site suitability model (Figure 6) that utilizes information on historical eelgrass distribution, salinity, depth, substrate, and pollution levels. The model produces spatially explicit output that ranks areas of the estuary for their ability to support eelgrass growth at five levels – best, good, fair, poor, or unsuitable. The new shapefile showing areas of eelgrass loss was clipped with a copy of the model output that excluded areas coded as poor or unsuitable. This produced a final shapefile that showing priority restoration sites – the sites where eelgrass historically occurred but has been lost *and* can still be expected to support eelgrass following restoration efforts (See Figure 7).

Historic data sets do not provide a complete picture of historic eelgrass coverage. In particular, the Krochmal data ends abruptly a short distance upstream from the mouths of the Bellamy and Piscataqua Rivers because that was the geographic extent of his survey. Consequently, there are additional eelgrass restoration opportunities not revealed using our data and methods.

Eelgrass references:

Davis, R.C. and F.T. Short. 1997. Restoring eelgrass (Zostera marina L.) habitat using a revised transplanting technique: the horizontal rhizome method. *Aquatic Botany* 59: 1-16.

Granger, S., M. Traber, S.W. Nixon, and R. Keyes. 2002. A practical guide for the use of seeds in eelgrass (Zostera marina L.) restoration. Part I. Collection, processing, and storage. M. Schwartz (ed.), Rhode Island Sea Grant, Narragansett, R.I. 20 pp.

Grizzle, R.E., F.T. Short, C.R. Newell, H. Hoven, and L. Kindblom. 1996. Hydrodynamically induced synchronous waving of seagrasses: 'monami' and its possible effects on larval mussel settlement. *Journal of Experimental Marine Biology and Ecology*. 206: 165-177.

Jones, S. H. 2000. A Technical Characterization of Estuarine and Coastal New Hampshire. Jackson Estuarine Laboratory, University of New Hampshire, Durham, NH.

Nelson, J.I. 1981. Inventory of natural resources of Great Bay Estuarine System. New Hampshire Fish and Game Department, Concord, NH.

Pickerell, C.H., S. Schott and S.W. Echeverria. 2005. Buoy Deployed Seeding: Demonstration of a new eelgrass (*Zostera marina* L.) planting method. *Ecological Engineering* 25: 127-136.

Short, F.T. 1992. (ed.) The Ecology of the Great Bay Estuary, New Hampshire and Maine: An Estuarine Profile and Bibliography. NOAA - Coastal Ocean Program Publ 222 pp.

Short, F.T., C.A. Short and C.L. Burdick-Whitney. 2002. A manual for community-based eelgrass restoration. Report to the NOAA Restoration Center. Jackson Estuarine Laboratory, University of New Hampshire, Durham, NH. 54 pp.

Short, F.T. and D.M. Burdick. 1996. Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. *Estuaries* 19:730-739.

Short, F.T., D.M. Burdick, S. Granger and S.W. Nixon. 1996. Long-term decline in eelgrass, Zostera marina L., linked to increased housing development. pp. 291-98. In J. Kuo, R.C. Phillips, D.I. Walker, & H. Kirkman (eds.). Seagrass Biology: Proceedings of an International Workshop, Rottnest Island, Western Australia, 25-29 January 1996. Nedlands, Western Australia: Sciences UWA.

Short, F.T. and C.A. Short. 2003. Seagrasses of the western North Atlantic. pp. 207-215. In: Green, E.P. and Short, F.T. (eds.). *World Atlas of Seagrasses: Present Status and Future Conservation*. University of California Press, Berkeley, USA.

Short, F.T., C.A. Short and C.L. Burdick-Whitney. 2002. A manual for community-based eelgrass restoration. Report to the NOAA Restoration Center. Jackson Estuarine Laboratory, University of New Hampshire, Durham, NH. 54 pp.

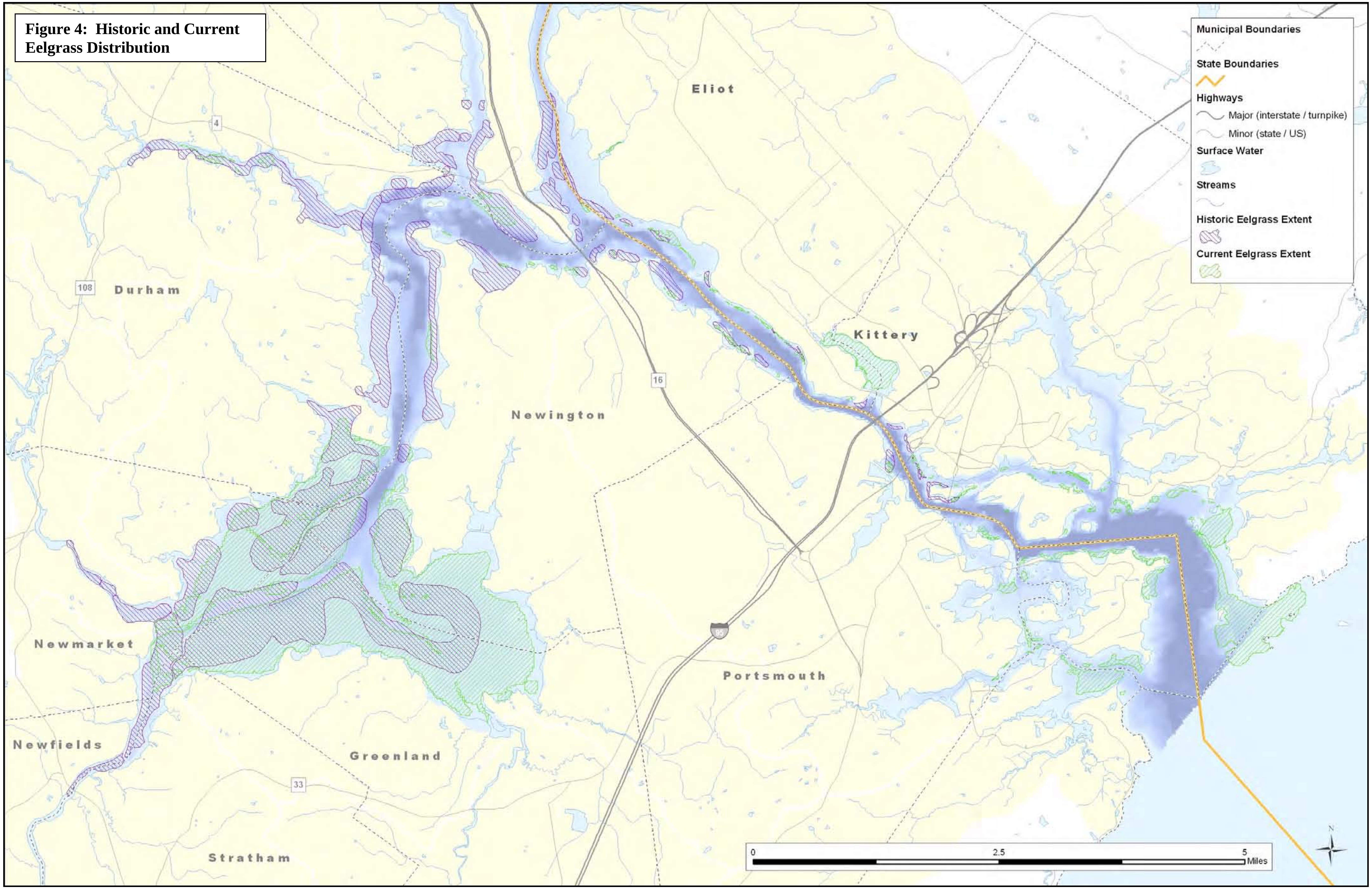


Figure 4: Historic and Current Eelgrass Distribution
Municipal Boundaries
State Boundaries
Highways
Major (interstate / turnpike)
Minor (state / US)
Surface Water
Streams
Historic Eelgrass Extent
Current Eelgrass Extent
Eliot
Durham
Kittery
Newington
Newmarket
Portsmouth
Newfields
Greenland
Stratham
4
108
16
33
0
2.5
5
Miles
N

Figure 5: Current Eelgrass Distribution

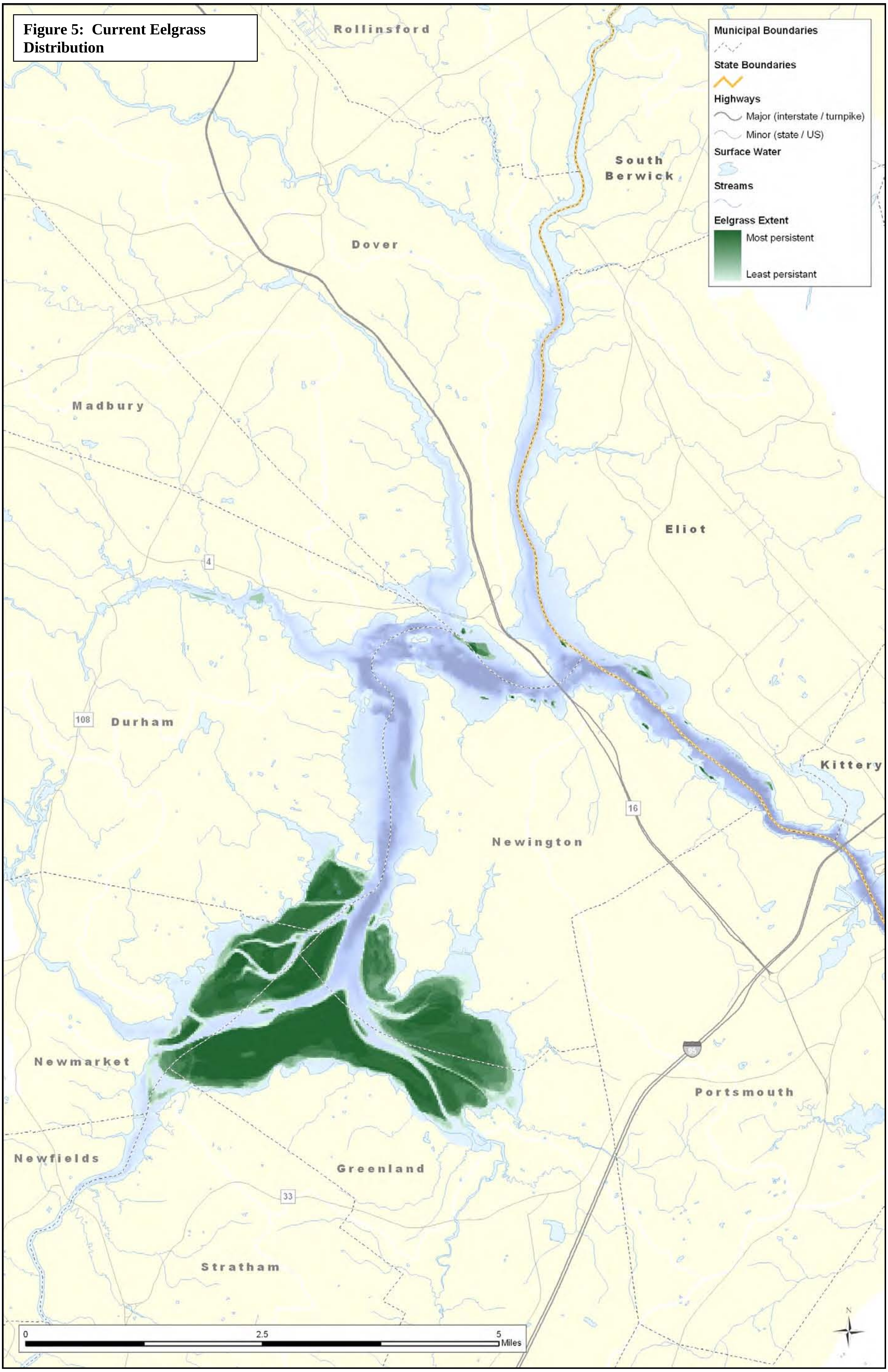


Figure 6: Eelgrass Habitat Suitability Model

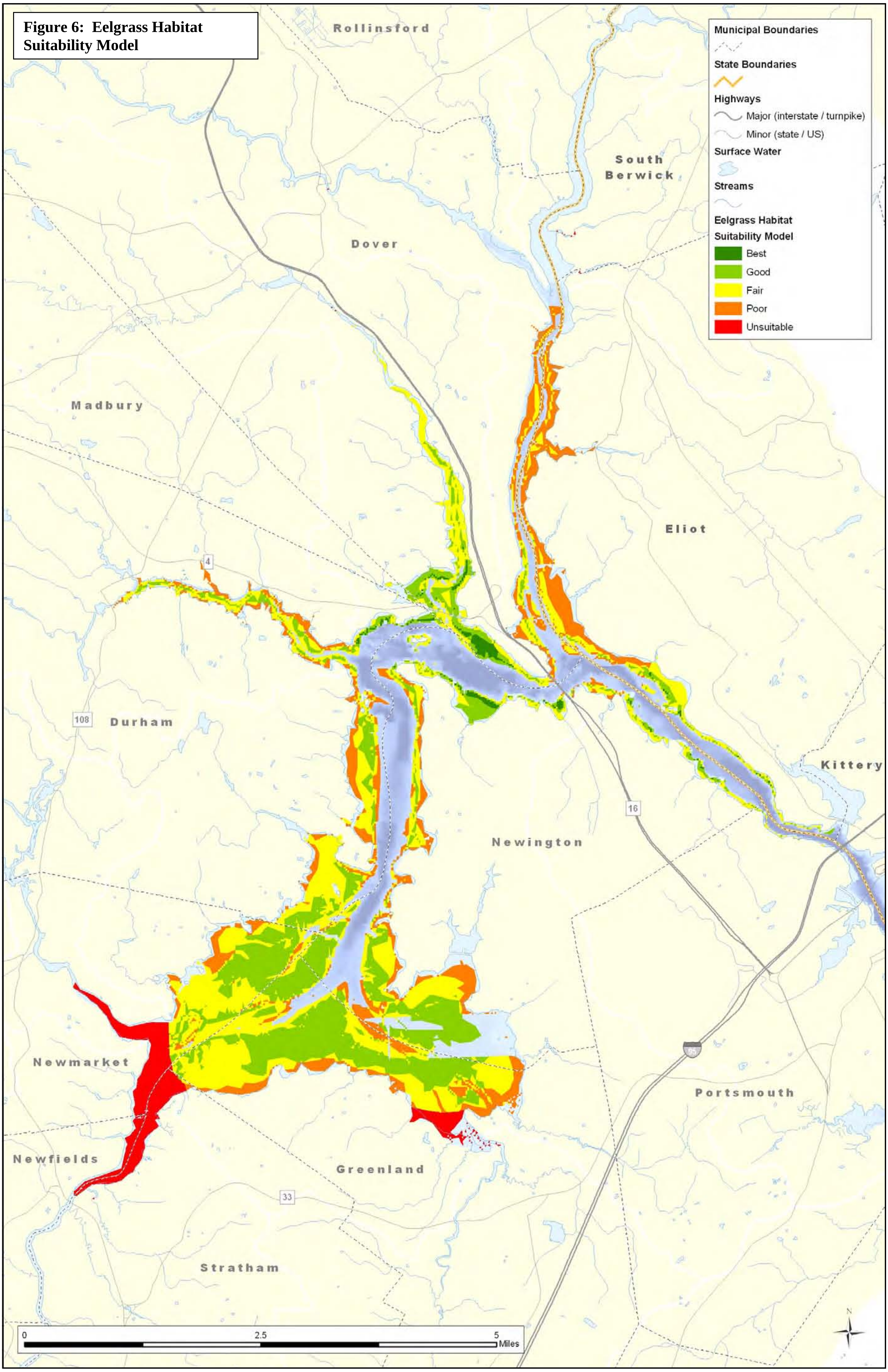
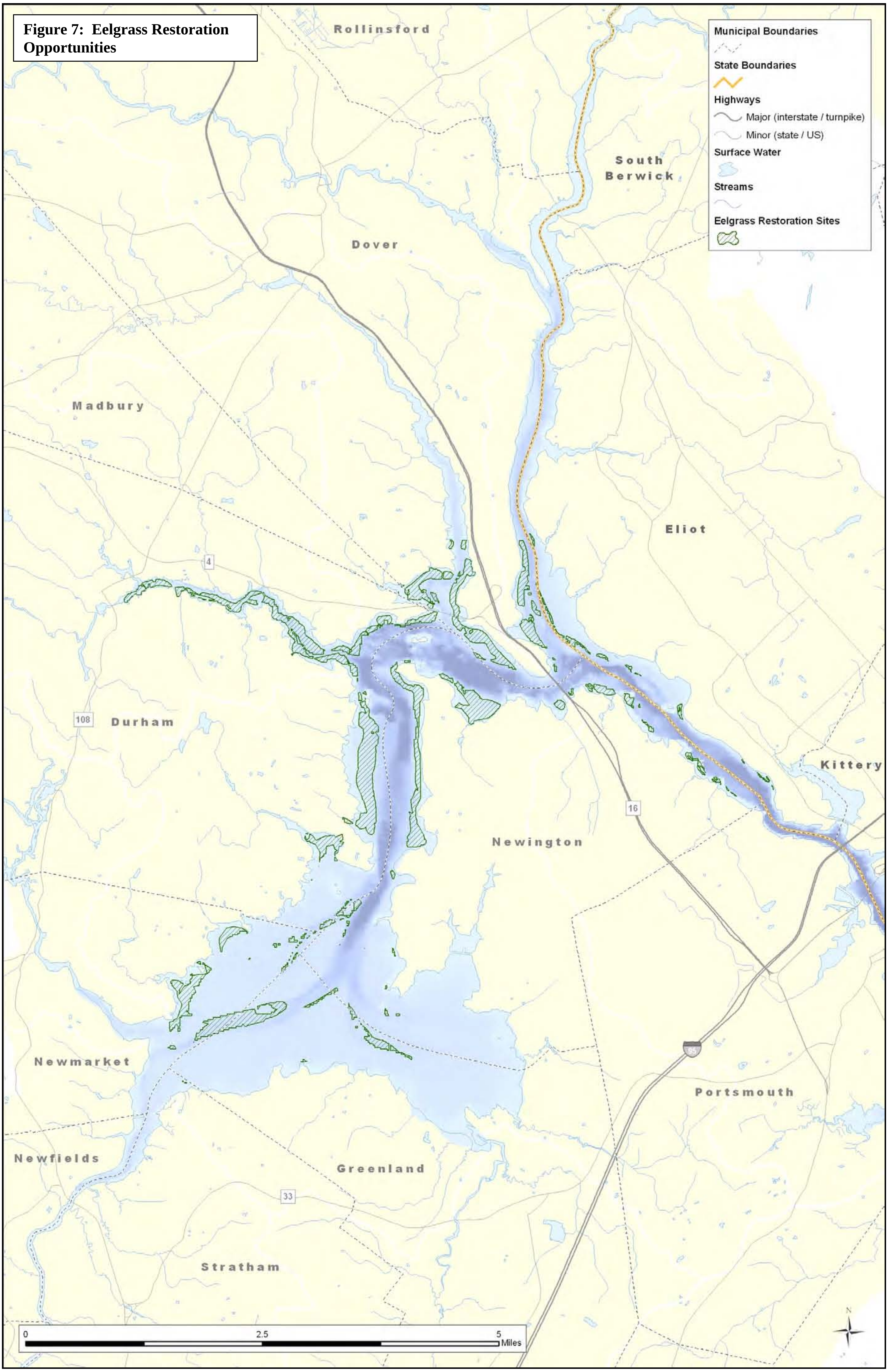


Figure 7: Eelgrass Restoration Opportunities



Oyster Reefs

Coral reef systems around the world have received much attention, bringing to bear many resources for their protection and conservation.

The coral reef's temperate analogues are reefs formed by oysters and other shellfish – shellfish reefs historically provided critical habitat and benefits quite similar to coral. Unfortunately, it is difficult to identify any intact oyster reefs or shellfish beds anywhere in the northern hemisphere. Globally, native shellfish are not just highly threatened, they are functionally extinct in most bays.

Spat covered oyster shells for placement at Great Bay restoration sites. Ray Grizzle photo.

Eastern oysters (*Crassostrea virginica*) are an intertidal and shallow subtidal species throughout its range, but remain mainly subtidal in the northeastern US. They are found predominantly on hard substrates in areas of increased water velocity. Eastern oysters can tolerate a range of salinities and are found predominantly in the brackish water of estuaries. An overview of previous research (prior to 2000) on oyster distributions in Great Bay can be found in *A Technical Characterization of Estuarine and Coastal New Hampshire* (Jones 2000). Langan (2000) provides recommendations for shellfish restoration strategies in *Shellfish Habitat Restoration Strategies for New Hampshire's Estuaries*.

There is ample credible historic information indicating that oysters were formerly much more abundant in Great Bay than they are today. Jackson (1944) quotes Scales (*History of Dover* 1923) as saying that in 1623 "there were all the oysters they could use and clams were so abundant in the Bellamy that they fed them to their hogs". A Smithsonian Institution report from 1887 indicates that around the mouths of the Lamprey and Squamscott Rivers there were "considerable shell heaps" and that the area was "renowned among the Indians" for oysters. A major decline in oysters likely occurred in the 17th and 18th centuries due to pollution and sedimentation from the construction and operation of mills and logging. While the extent and abundance of oysters may have decreased, Great Bay oysters continued to grow large in size; a passage from the Exeter Newsletter in 1876 refers to Great Bay oysters that weighed over 3 pounds. The Smithsonian report provides a post-mortem of a classic gold-rush style fishery. It indicates that following a Coast Survey exploration in 1874 that found oysters in Great Bay, a former Chesapeake Bay oysterman moved to the Great Bay region and brought the first oyster tongs to the area. This apparently helped to catalyze an intensive commercial oyster fishery that over-harvested oysters for Boston markets for about seven years, with harvesters even going so far as to cut holes in the ice of the bay during winter and using horse drawn dredges to very effectively remove oysters. Apparently it was also common not to return small oysters and debris (rock and shell important for maintaining effective spat settlement) because the State eventually passed a regulation forbidding this practice. Other regulations restricting harvest followed, but too late. The 1887 report states that by that time (1879) the average daily harvest had dropped to about a bushel and a half a day (for each of about 7 harvesters who remained in the fishery). Today there is no commercial fishery allowed but the recreational catch limit is still measured in bushels – one per person per day, though it is probably quite rare now to attain a limit.

Jackson (1944) describes depleted populations relative to the formerly extensive beds found in nearly all Great Bay rivers and channels and attributes this decline to pollution and siltation. He reported that the Oyster River bed that used to produce "hundreds of bushels a season" had shrunk from nearly half a mile to a few hundred feet in length. Both Jackson and the Smithsonian report indicate that the remaining opportunity to harvest oysters was highest at Nannie Island, and this is the same case today.

An outbreak of the oyster disease causing parasite MSX (*Haplosporidium nelsoni*) in 1995, in combination with another protozoan parasite known as Dermo (*Perkinsus marinus)*, contributed to very sharp oyster populations in the upper Piscataqua River and Great Bay estuary locations. MSX was first identified in Great Bay system oysters in 1983 and Dermo was first found in 1996. However it is likely that both were present somewhat earlier. The pathogen MSX persists in Great Bay, and further oyster mortalities can be expected. A general consensus exists among the many recent reports monitoring oysters in Great Bay that oyster populations continue to decline. In fact, oyster populations may be at a historic low. The current poor status of oysters in Great Bay is attributed to multiple factors, including accumulation of fine sediments, mortality due to MSX, removal of shell and lack of preferred substrate for settlement, and poor recruitment. It is not clear what role the continuing low level of recreational harvest plays in the dynamics of the struggling oyster population. One of the most intact and healthy reefs remaining is located in an area closed for pollution concerns.

According to UNH Jackson Estuarine Laboratory (JEL) researchers, oyster restoration efforts for the Salmon Falls River, Piscataqua River, Bellamy River, Oyster River, Adams Point, and Nannie Island should include: the periodic assessment of oyster populations (including density, age structure, areal cover, and spatfall), continued monitoring for oyster disease, shell planting to provide additional substrate for larval settlement, predator removal or eradication, hatchery-reared, disease-resistant seed, and encouraging recreational harvesters to return shell to the harvest areas or to the shell recycling program. Researchers at the JEL currently have ongoing oyster restoration projects in the Salmon Falls River, the Bellamy River, in Great Bay (Adams Point and Nannie Island), and South Mill Pond.

Oyster Restoration Methods

Spawner Sanctuaries

Establishing spawner sanctuaries, or areas where oyster harvest is prohibited, can be an effective method of oyster conservation and restoration. A sanctuary serves to alleviate fishing pressure on a designated reef or a portion of a reef. This can provide a continual source of larvae and allows the potential for natural selection for disease tolerant strains. Although no large scale oyster sanctuaries currently exist in the Great Bay estuary, there are two small closed areas where experiments are ongoing. The establishment of sanctuaries may be an important management tool in the future, to complement and enhance strategies to overcome threats from the MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*) parasites in the bay to improve the current low oyster abundance. If restoration is truly successful there will be enough oysters to maintain adequate recruitment, provide increased filtration capacity and other ecological services, and also provide for a sustainable harvest for people. The benefits of setting aside areas to help ensure that long term reproductive capacity is maintained should be assessed in consideration of impacts to current recreational harvest opportunity. Improved understanding of oyster metapopulation dynamics in the estuary– identifying the specific areas that contribute the most and least (sources and sinks) to production of young oysters would be helpful in the design of an efficient network of open and closed areas that might eventually provide improved and sustainable harvest opportunity.

Reef Restoration

Restoration via reef creation typically involves planting oyster cultch, or substrate, to provide suitable conditions for larval settlement. Restoration using unseeded cultch relies on natural larval settlement because it only involves placement of dead shell onto the restoration area. Oyster reef restoration can also involve remote setting techniques, where larval oysters are introduced into a tank of clean cultch and held until the larvae settle to the substrate. The colonized cultch is then transplanted ("spat seeding") to the restoration area. Due to the prevalence of MSX and Dermo parasites, hatchery reared disease-resistant seed is sometimes used to increase the likelihood of oyster survival in the long-term.

Reef creation with seeded cultch is a method currently employed in the Great Bay estuary. Previous efforts have met with success, suggesting that this is a locally effective method of restoring oyster reefs. Reef creation with unseeded cultch, while potentially more cost and time effective than remote setting, does not currently occur in the Great Bay estuary due to a shortage of available cultch material. A shell recycling program at the University of New Hampshire is currently underway to address this shortage and increase the opportunities for reef creation in the future. Furthermore, potential conflicts may arise if planting cultch in areas where other habitats are present or were known to historically exist. Such instances may provide opportunities for multi-habitat restoration projects.

Transplanting

Transplanting involves moving healthy adult oysters from areas of high density to a restoration site. Because transplants occur with adult oysters, they are less susceptible to mortality from predation or parasitism. Adult oysters also serve as a source of larvae as well as substrate for future spatfall. Furthermore, remote monitoring of transplanted oysters is easier than methods using spat due to the higher visibility of adult oysters.

Due to the scarcity of high density oyster reefs in Great Bay, this restoration method is not commonly employed. Furthermore, collection of adult oysters can be destructive to the donor bed.

"Oyster Conservationists"

Oyster conservationists (called "oyster gardeners" in other areas) are volunteers who raise small oysters in cages. Through this community based restoration approach, community members that live on the water are provided with spat on shell from remote setting or other sources. The community partners look after the spat, and are given the responsibility of raising the oysters for the next 2-3 months. Community partner responsibilities include cleaning the oysters, removing any fouling organisms, and monitoring the oysters for growth and mortality.

Community oyster gardening programs provide a source of settled cultch for reef creation projects. Perhaps the greatest benefit of such programs is that they connect the community to the resource and raise awareness of issues of oyster habitat degradation. Difficulty in locating potential partners can serve as a limitation to community gardening; furthermore, such programs are limited by the number of people that meet the criteria for raising oysters (*i.e.* live on the water with a suitable dock). However, The Nature Conservancy and the Jackson Estuarine Laboratory (with funding from NOAA's Community Based Restoration Program) recently initiated a new volunteer based oyster conservationist program and signed up fifteen households to assist in 2006.

Shellfish – Spatial Data Compilation & Analysis

Data Layers

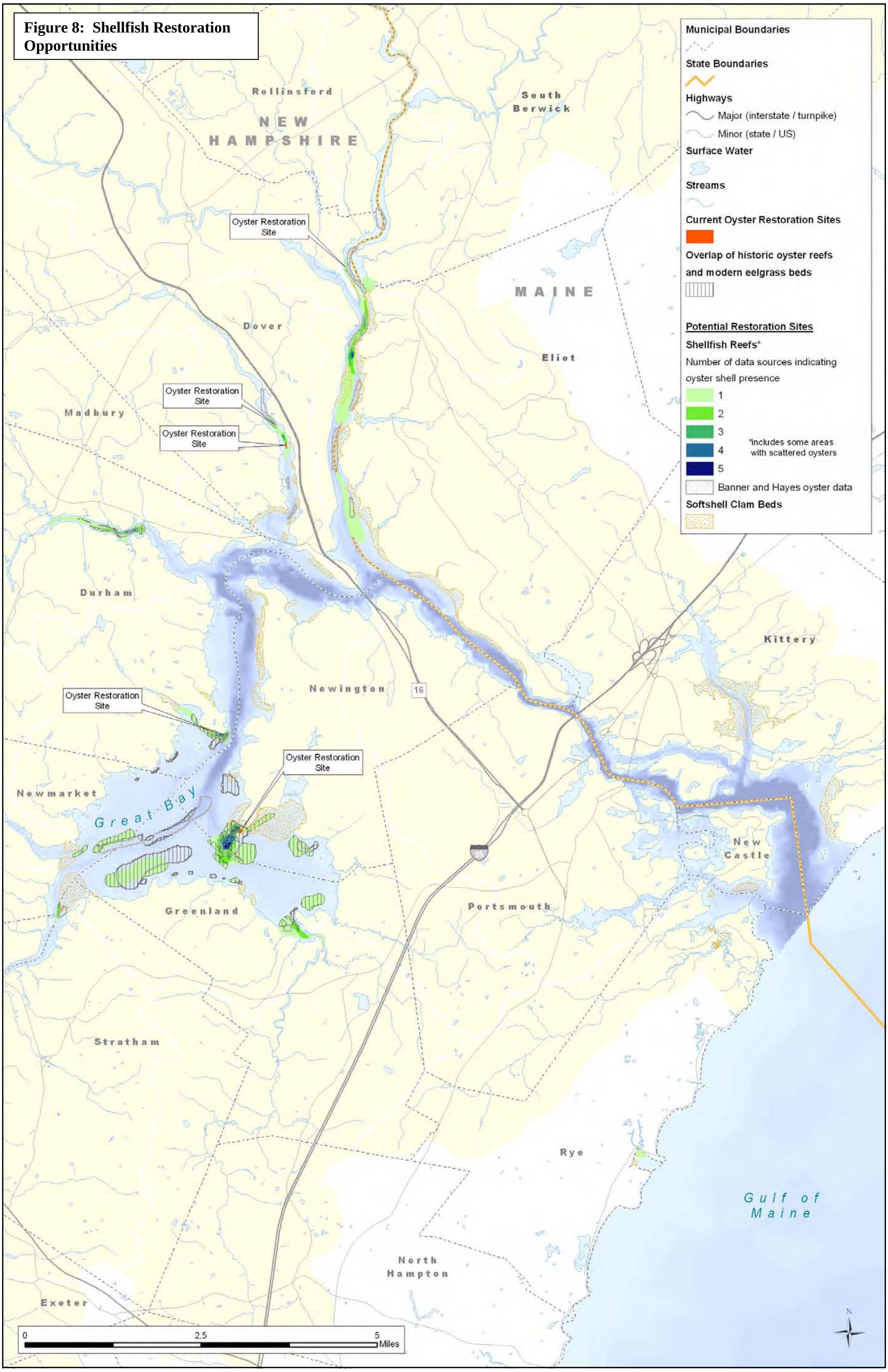
1. Ayer, W, Bruce Smith, and Richard Acheson. 1970. *An Investigation of the Possibility of Seed Oyster Production in Great Bay*, New Hampshire. This report includes a map showing results of oyster surveys conducted in 1966 (Oyster River survey from 1968). The map was scanned and geo-referenced for this project, in multiple sections to obtain a rough fit to the NHHD 1:24,000 shoreline data.
2. Maine Department of Marine Resources 1995. *Molluscan shellfish habitat in Maine* (1977 distribution). This layer was obtained from MEGIS. It shows distribution of oysters *in 1977* on Maine side of Piscataqua River. Seth Barker of Maine DMR is the primary author of this data (extracted for this project from MESHELL.shp) which includes distributions for several shellfish species for the entire Maine coastline.

3. Nelson 1981, 1982. *Inventory of the Natural Resources of the Great Bay Estuarine System/Great Bay Estuary Monitoring Survey, 1981-1982*. The map contained in this report was scanned and georeferenced as described above. This report was cited as a source for the Banner and Hayes oyster layer described below but is represented there somewhat differently.
4. Banner and Hayes, 1996. *Important Habitats of Coastal New Hampshire*. Distributions for most of the species mapped for this report were generated using habitat models, but the oyster map is cited as being created from Nelson 1981 & 1982 (above), in combination with maps obtained from by Dr. Richard Langan (CICEET). The report indicates that the authors "…field verified many locations using GPS to measure their geographic coordinates". This layer contains small patch reefs and a deepwater reef not found in other spatial data sources.
5. Langan, 1997. *Assessment of Shellfish Populations in the Great Bay Estuary*. The report included several shapefiles with information on clam and oyster distributions throughout the estuary. This is the earliest layer for New Hampshire shellfish created using modern survey methods.
6. Smith, 2002. *Shellfish Population and Bed Dimension Assessment in the Great Bay Estuary*. The shapefile associated with this report accurately maps oyster distribution for the Oyster River, Adams Point, and Nannie's Island reefs (this data set is merged with Dr. Ray Grizzle's oyster data from 2004)
7. Grizzle, R. and M. Brodeur. 2004. *Oyster (*Crassostrea virginica*) Reef Mapping in the Great Bay Estuary, New Hampshire* – 2003. Contains accurately mapped oyster shell bottom areas at several locations in the estuary.

These files were all converted to a standard NH State Plane projection and combined into a single file that preserves the original boundaries of the source data and includes a new attribute ("VALUE" field) that shows how many of the individual data sources indicated oysters were found in a particular location. This approach was used to provide both a measure of confidence and to some extent a measure of persistence (Figure 8). It is difficult to ascertain the health and condition of the oysters in question represented by the various polygons, which at the very least represent former (dead shell) oyster locations, and in some cases represent viable populations. Figure 8 also shows sites where restoration activities and monitoring are currently underway. All of the remaining areas should be considered as potential restoration opportunities. Practitioners may want to concentrate their efforts at sites where oysters have been most frequently noted, but sites where only one or two surveys have found oysters may also be promising for various reasons.

Some of the data sets used to create Figure 8 include areas with only scattered oysters that may not have had dense or well-developed reefs in past years, and some are based on survey methods that are considered relatively crude by more modern standards. The Banner and Hayes oyster data is treated separately because some of the oyster locations it shows may be duplicative of data gleaned from other sources. However, it is included because it shows several small oyster areas that are not indicated in any other source.

Figure 8: Shellfish Restoration Opportunities



An additional map of unknown origin was found in Jackson Estuarine Laboratory (JEL) files. The author and date of this map remains uncertain. It shows fairly detailed clam and oyster locations, hand drawn onto a topographic map, and includes several small reefs dotting the shorelines of Great Bay that are not represented in the other sources. According to Bruce Smith it appears to represent select oyster distributions from dates between 1991 and 1995 (MSX disease outbreak). This map was not scanned into GIS format because we were unable to confirm its source; a copy is available upon request.

The oyster data shown here indicates the likely extent of oysters after significant losses due to overfishing, pollution, and siltation that occurred during the 1800s, and before the MSX and Dermo disease outbreaks during the mid-1990s. This map shows 1,302 acres of oyster shell bottom, extant from 1970 to 2006. If the Banner and Hayes data is not included (on the basis that it duplicates Nelson 1981), the number of acres drops to 929. However, the approach also removes several areas that are unique to this data set.

Today, nearly all the areas shown on this map contain much lower density than they did in the early 1990s, and some reefs have only very small remnant populations. Local researchers suspect that the total live reef areas are between 50 and 100 acres, scattered throughout the estuary.

Using a conservative estimate of the historic extent of oysters in the project area (929 acres), conservative estimates of pre-disease density (200/m^2, all sizes) based on UNH and New Hampshire Fish and Game data, and a conservative filtration rate estimate (20 gallons/day per oyster), the historic filtration capacity of oysters in Great Bay is calculated at 15.038 billion gallons per day. This amount of water is equivalent to 27% of the high tide volume of the Great Bay estuary project area. *In other words, the historic oyster population is estimated to have been capable of filtering a volume of water equivalent to the entire bay in less than four days.*

Using arguably generous area (100 acres) and density (50/m^2) estimates, the current oyster filtration capacity is estimated to be 404.69 *thousand* gallons per day, or about 0.7% of the project area's high tide volume. The current oyster population may be capable of filtering a volume of water equivalent to the entire estuary in about 137 days.

Estimates for historic and current filtration capacity are only relevant for the six warmest months of the year when oysters are actively feeding. These are the same months when eutrophication leads to anoxic conditions in other estuaries.

Less is currently known about the status of softshell clam populations in the Great Bay estuarine system and to what extent they have declined. Jackson (1944) reported that Great Bay's clam population had steadily declined over the last 30 years until there was "only a vestige of their former abundance". He indicated the reason for this was "…pollution and the smothering of clams by silt *as a result of the dying of the eelgrass* being the chief factors rather than over-digging" (emphasis added). He provides a detailed assessment of the potential clam production beds within the estuary, noting that hundreds of acres were covered in sawdust and sewage.

The softshell clam beds shown in (Figure 8) include data from 3 sources, from 1977 (Maine DMR), 1980 (Nelson), and 2005 (Grizzle), and total about 1,540 acres. A recent University of New Hampshire survey in areas south of Adam's Point in Great Bay found extremely low abundances at all six locations sampled. Clam populations may be reduced relative to historic levels due to increased fine sediments from runoff that smother young clams, increases in populations of clam predators like the invasive green crab, disease, and possibly past harvests. Information on softshell clam restoration methods employed at Hampton-Seabrook can be obtained from CICCET, JEL, NHF&G, and the DES shellfish program

Shellfish & Eelgrass Overlap Zones

Analysis of the spatial data for historical presence of oysters and eelgrass revealed several areas where eelgrass and oysters coincide. In some cases this is likely due to coarse mapping protocols for some oyster data sets, and issues of mapping scale and registration (as described above for salt marsh data). However, in other cases it is more likely that oysters and eelgrass have both occupied either the same general or exact areas at different points in time. That is to say, at the same point in time the two species could have been in the same general vicinity (and this could even include being 12 inches apart), while at different points in time they could have been in the same exact areas. Oysters can live within eelgrass habitat although oysters do not typically form reefs in these areas. The scale issues and uncertainty of certain data sources preclude being able to know for sure whether they were in the exact same places, but it seems probable given the overlaps that include the center of patches of both species.

There are two general types of overlap: 1) historic oyster areas (some with remnant live oysters) that coincide with current eelgrass areas, and 2) historic oyster areas that coincide with historic eelgrass areas where eelgrass is no longer present.

In the first case, we believe that oyster restoration projects that would damage existing eelgrass should not be conducted. However, we suggest that oyster restoration projects conducted adjacent to existing eelgrass beds (*e.g.* in deep water where eelgrass is unlikely to occur) may enhance eelgrass viability.

In the second case, we believe that practitioners and researchers should deploy and test the concept of integrated oyster and eelgrass restoration projects, whereby patches of each are interspersed in the same general area. Integrated oyster and eelgrass projects may result in synergistic cost-effective benefits due to facilitative interactions - oysters remove light-limiting fine particulates to potentially benefit eelgrass, while eelgrass may help to trap sediments that would otherwise smother young oysters. In some cases, site specific surveys will indicate hard bottom areas appropriate for oysters within a matrix of softer bottom historic eelgrass habitat (or vice-versa). If oyster or eelgrass restoration projects in these areas are conducted separately, such projects should be done in a manner that does not preclude opportunity for restoration of the other species in the same general area.

For oyster and eelgrass projects in areas with either type of overlap, restoration plans should be developed jointly by shellfish and eelgrass experts, striving for consensus plans that increase areal coverage, density, and viability for both species.

Shellfish References:

Adams, J.P. 1976. Drowned Valley: The Piscataqua River. University Press of New England. Hanover, New Hampshire.

Ayer, W.C., B. Smith and R.D. Acheson. 1970. An Investigation of the Possibility of Seed Oyster Production in Great Bay, New Hampshire. Marine Survey Report No. 2. New Hampshire Fish and Game Department, Concord, NH.

Brown Goode, G. 1887. The Fisheries and Fishery Industries of the United States. United States Commission of Fish and Fisheries. Government Printing Office, Washington, D.C.

Grabowski, J.H. A.R. Hughes, D.L. Kimbro, and M.A. Dolan. 2005. How habitat setting influences restored oyster reef communities. *Ecology* 86(7): 1926-1935

Grizzle, R. E. and M. Brodeur. 2003. Oyster (*Crassostrea virginica*) reef mapping in the Great Bay Estuary, New Hampshire. Final Report to the New Hampshire Estuaries Project. August 2004.

Haven, D. and R. Morales-Alamo. 1970. Filtration of particles from suspension by the American oyster *Crassostrea virginica*. *Biological Bulletin* 139: 248-264.

Jackson, C. F. 1944. A Biological Survey of Great Bay, New Hampshire. No. 1. Physical and Biological Features of Great Bay and the Present Status of its Marine Resources.

Jones, S. H. 2000. A Technical Characterization of Estuarine and Coastal New Hampshire. Jackson Estuarine Laboratory, University of New Hampshire, Durham, NH.

Langan, R. 1997. Assessment of shellfish populations in the Great Bay Estuary. Final Report. Office of State Planning, New Hampshire Estuaries Project. 34 pp.

Langan, R. 2000. Shellfish Habitat Restoration Strategies for New Hampshire’s Estuaries. Final Report Submitted to the New Hampshire Estuaries Project . USEPA/NHEP. Jan. 2000. 16 pp.

Lehnert, R.L. and D.M.Allen. 2002. Nekton use of subtidal oyster shell habitat in a southeastern US estuary. *Estuaries* 25(5): 1015-1024.

Meyer, D.L. E.C. Townsend, and G.W.Thayer. 1997. Stabilization and erosion control value of oyster cultch for intertidal marsh. *Restoration Ecology* 5(1): 93-99.

Newell, R.I. 2004 Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: A review. *Journal of Shellfish Research* 23: 51-61.

Newell, R. E. and E.W. Koch. 2004. Modeling Seagrass Density and Distribution in Response to Changes in Turbidity Stemming from Bivalve Filtration and Seagrass Sediment stabilization. *Estuaries* 27(5): 793-806.

Smith, B. 2002. Shellfish population and bed dimension assessment in the Great Bay Estuary. Final Report, New Hampshire Estuaries Project. Concord, NH.

Trowbridge, P. 2005. Environmental indicator report, shellfish. Final Report, New Hampshire Estuaries Project. Concord, NH.

University of New Hampshire Oyster Restoration Program http://www.oyster.unh.edu/, 7 July 2006.

Diadromous Fishes

Years ago there were so many salmon that, as an enthusiastic old friend once assured me, "you could walk across on them below the falls;" but now they are unknown, simply because certain substances which would enrich the farms are thrown from factories and tanneries into our clear New England streams. Good river fish are growing very scarce. The smelts, and bass, and shad have all left this upper branch of the Piscataqua, as the salmon left it long ago, and the supply of one necessary sort of good cheap food is lost to a growing community, for the lack of a little thought and care in the factory companies and saw-mills, and the building in some cases of fish-ways over the dams. I think that the need of preaching against this bad economy is very great. The sight of a proud lad with a string of undersized trout will scatter half the idlers in town into the pastures next day, but everybody patiently accepts the depopulation of a fine clear river, where the tide comes fresh from the sea to be tainted by the spoiled stream, which started from its mountain sources as pure as heart could wish. Man has done his best to ruin the world he lives in, one is tempted to say at impulsive first thought; but after all, as I mounted the last hill before reaching the village, the houses took on a new look of comfort and pleasantness; the fields that I knew so well were a fresher green than before, the sun was down, and the provocations of the day seemed very slight compared to the satisfaction. I believed that with a little more time we should grow wiser about our fish and other things beside. Sarah Orne Jewett. 1890

Juvenile Atlantic salmon spend up to three years in freshwater habitats. Eric Aldrich/TNC photo.

Diadromous fishes are those that migrate between fresh and salt water in their life cycle. These species are further classified as either anadromous, those fishes that live predominantly in saltwater and move to freshwater to reproduce (*e.g.* alewife, blueback herring, American shad, rainbow smelt, Atlantic salmon, Atlantic sturgeon, and sea lamprey) or catadromous, species that spend the majority of life in freshwater and migrate seaward to spawn (*e.g.* American eel). Within both riverine and coastal environments these species have specific habitat requirements for feeding, spawning and refuge. These requirements and stress associated with the physiological changes required to transition between fresh and salt water render these species extremely vulnerable to habitat impacts within freshwater and marine migratory corridors. In particular, juvenile salmonids, shad, and river herring are very sensitive to low dissolved oxygen levels, with altered behavior and severe stress at levels around 5 ppm, with near total mortality possible as levels approach 3 ppm. Low oxygen levels in impoundments behind dams that have fish ladders may currently be limiting diadromous fish populations in the Great Bay system. Low oxygen conditions can occur due to excessive nutrients and are exacerbated by low flow conditions that occur in part because of freshwater withdrawals for diverse human needs. In addition to the negative impacts of high water temperature and subsequent lowered oxygen levels, reduced summer flows can also leave juvenile fish trapped in small impoundments and unable to migrate downstream to the estuary.

While quantitative data on historic distributions are scarce, there is more than ample anecdotal information to indicate that diadromous fishes were very abundant within the tributaries of the Great Bay estuary prior to the construction of dams. A pamphlet by Christopher Leavitt to England in 1623 cites abundant fish resources as the primary reason the region was settled by colonists in the early 17th century. Shad and herring were reported to be so abundant that settlers not only dried and smoked them for food over winter, but also used them as fertilizer for corn fields and were almost certainly found in every river system and nearly every large brook connected to the estuary. There are numerous historical records that attest to the former abundance of Atlantic salmon. Jackson (1944) writes "All accounts are in agreement that these early settlers found the rivers teeming with fish…should those settlers return now they would face real hardship in getting enough food from the river to carry them through a New England winter…Gone are the salmon which once crowded the mouth of the Salmon Falls, Exeter, and Lamprey Rivers…only a vestige of the shad, herring, and other fishes remain." Historic reports from C. F. Jackson and others also indicate that Atlantic sturgeon were once common in the Great Bay estuary. Jackson reported that they were harvested in abundance in the early 1800s, occasionally in the late 1800s and were only "accidentally" found at the time of writing, 1948. Town histories of Great Bay communities refer to the abundance of salmon in the Cocheco, Salmon Falls, and Lamprey Rivers and the drastic decline in this species following the installation of head of tide dams on each of the rivers. In addition to the construction of mill dams on New Hampshire waterways as early as the 17th century, other sources cite the abundant sawdust input from mills, sewage, agricultural runoff, other fish passage constraints such as culverts, fishing pressure and habitat alteration as causes of the decline of diadromous species.

Many dams still exist today, blocking fish movement between upstream and downstream areas. Restoration of diadromous fishes began in the 1960s and 1970s with the construction of fish ladders to facilitate fish movement across dams. Runs of several diadromous fish species currently move through fish ladders at seven dams on tributaries of Great Bay including alewives and blueback herring, American eels, lamprey, and, at some sites, American shad. While fish ladders improve access to upstream areas for some species, overall conditions are far from optimal. Salmon and sturgeon populations are virtually extinct in the region

Diadromous fish are an important part of Great Bay's web of life. John Canfield photo.

due to degraded habitat and fragmentation.

Dams are not the only barriers to fish passage. Many culverts used for road-stream crossings serve as barriers because of inadequate size, shape, design, installation, and maintenance. Historical stressors combined with rapid development and associated water and habitat quality issues threaten all diadromous species in the Great Bay region.

Both new and continuing efforts are being made to restore diadromous fishes to the region. American shad are transported from the Connecticut and Merrimac Rivers in Massachusetts and stocked above the Pickpocket dam on the Exeter River; this program has been in place since 1972. Intra and inter-basin transfers of river herring occur in the Lamprey, Cocheco, Winnicut, and Salmon Falls river systems. Projects to remove dams are in various stages on multiple rivers. The Bellamy IV dam was removed on the Bellamy River in 2004 opening up 0.25 miles of potential habitat to alewives, blueback herring, American eels, and rainbow smelt. The construction of a nature-like bypass channel is currently in the planning stages for the Wiswall dam on the Lamprey River. The Gonic Sawmill dams on the Cocheco River and the Winnicut River dam are currently under consideration for removal.

Diadromous Fish Restoration Methods

Dam Removal

Dam removal involves the removal or breach of an instream structure that diverts or impounds water. Dam removal can benefit all fish species that use riverine habitats. In addition to restoring fish passage to upstream areas, dam removal can increase fish habitat quality by restoring water flows, and in turn, sediment and nutrient flow. It may also restore a brackish salinity region that is important to the life histories of many fishes, including rainbow smelt. Furthermore, dam removal is a permanent restoration that will not require ongoing maintenance or attention.

Dam removal requires a large investment of resources, including time and money. Due to the changes in streamflow and sedimentation patterns that follow dam removal, such a project may not be feasible in developed areas due to adjacent and downstream land and/or water use. The resuspension of sediments that accumulate behind dams, which may contain toxins, can cause significant alteration and contamination of downstream habitats. The presence of rare or endangered species must be evaluated prior to dam removal. Increased flow rates downstream and lowered water levels upstream following dam removal may remove habitats important to the persistence of rare species.

Nature-Like Fishways

Nature-like fishways (NLF) have been constructed in Europe, Canada, Australia, and Japan and have recently become more accepted as a dam removal alternative in the United States. Each NLF is carefully designed to mimic the natural conditions in the river reach that has been blocked. Unlike fish ladders, successfully designed and constructed NLF can pass most or all naturally occurring species and also provide good quality stream habitat for the plants and invertebrates that help to support migratory fish.

Fish Ladder

A fish ladder is a series of ascending pools or steps with flowing water that allows some fish species to pass over barriers such as dams. Installation of fish ladders is often a more practicable restoration option when barrier removal is not feasible. Fish ladder installation is typically more economically feasible than barrier removal, and does not significantly correct altered hydrologic regimes. While this may be considered a limitation in terms of fish restoration, fish ladders may be the only practical way to provide passage over dams that are not practical to remove.

Because fish swimming ability varies by species and life history, fish ladder design flow requirements are species specific; therefore, one fish ladder cannot pass all species. Fish ladders have proven successful at passing species such as river herring, and to lesser degrees for American shad; however, fish ladders have not yet been designed to attract all diadromous species. Fish ladders act as filters, allowing passage for certain species during specific flow conditions. Creating appropriate flow strength and orientation to attract target species can be difficult, and real-world performance often falls short of engineering design goals. While fish ladders are less expensive than dam removal, they still require a substantial monetary investment, often correlated with the height of the barrier. Furthermore, fish ladders typically require maintenance such as debris removal and flow control.

Fish Lift

A fish list is an elevator-like mechanism where fish are attracted by species specific water flows to a hopper and are mechanically lifted up and released over a structure. Fish lifts can potentially accommodate all fish species and are most effective in bringing fish over very large structures such as large hydroelectric dams.

Fish lifts can be expensive to design, install, and maintain. Due to the complexity of the mechanisms, they require consistent maintenance. As with fish ladders, success is dependent on the ability to create flows to attract target fish species.

Culvert Enhancement or Replacement

Scientists and resource managers are increasingly looking at culverts as a source of stream habitat fragmentation. New Hampshire is currently conducting the first comprehensive, watershed-scale assessment of the impacts of culverts on stream habitat continuity in the Ashuelot River watershed (located in southwestern New Hampshire), so there is now well-developed methodology for field assessment and analysis that could be readily applied to Great Bay tributaries. Additionally, new tools and guidelines have been developed to promote fish- and stream-friendly culvert design. The Massachusetts Stream Crossing Handbook is one good example.

Stocking

Fish stocking involves the release of adult and juvenile fishes into a river targeted for restoration. Fishes may be captured and transported from rivers supporting healthy, sustainable runs, or may be trapped in the lower reaches of a river and moved above an impoundment. Fishes may also be hatchery produced and introduced into the target river in the juvenile stage. Stocking programs can serve to accelerate the recovery rate of target species, particularly when transported within basin where fishes are more likely to be adapted to local conditions. Furthermore, stocking may restore ecological functions supported by diadromous fishes such as secondary production.

When stocking hatchery reared fish, hybridization of hatchery reared with native fishes may serve to dilute the native gene pool. Furthermore, the movement of fishes from one system to another may introduce diseases and parasites into the recipient system. Because fish stocking does not address the causes of fish population decline, stocking must continue to occur to maintain a large population.

Habitat Restoration

Diadromous fish restoration can occur through efforts to improve water and substrate quality. Examples of habitat restoration projects include shoreland buffer restoration to address runoff and erosion issues, storm water runoff treatment to improve water quality, and restoration of stream channel morphology to increase floodplain habitat. Removing sources of habitat degradation promotes the long-term re-establishment of fish populations. Furthermore, habitat restoration addresses the overall ecological health of a system and therefore, will benefit many species in addition to the target species.

Particularly in more developed watersheds, the factors contributing to habitat degradation are often numerous and complex. These causes are often non-point sources and therefore, efforts to identify and address them can be costly and time consuming. Habitat restoration projects require scientific guidance, as well as continued monitoring and management following completion of the project.

Diadromous Fish References:

Adams, J.P. 1976. *Drowned Valley: The Piscataqua River*. University Press of New England. Hanover, New Hampshire.

Brown Goode, G. 1887. The Fisheries and Fishery Industries of the United States. United States Commission of Fish and Fisheries. Government Printing Office, Washington, D.C.

Connecticut River Watershed Council, Inc. 2000 A Fishway for your Stream. The Connecticut River Watershed Council, Inc., Easthampton, MA.

Grout, D., C. Patterson, C. McBane, B. Smith, M. Dionne, S. Maxwell, K. Sullivan, M. Carpenter, J. Carloni, S. Moriarity, and K. Jolles. 2004. New Hampshire’s Marine Fisheries Investigations Final Report. Hew Hampshire Fish and Game Department.

Jackson, C. F. 1922. Ecological Features of Great Bay, New Hampshire, and a Preliminary Checklist of its Fish. January, 1922. vol. III no. 1 (publisher unknown)

Jackson, C. F. 1944. A Biological Survey of Great Bay, New Hampshire. No. 1. Physical and Biological Features of Great Bay and the Present Status of its Marine Resources.

Jackson, C. F. 1948. Fishes of Great Bay. Unpublished manuscript found in University of New Hampshire's Milne Archives.

Haerel-Borer, S.S. D.M. Allen, and R.F. Dame. 2004. Fishes and shrimps are significant sources of dissolved inorganic nutrients in intertidal salt marsh creeks. *Journal of Experimental Marine Biology and Ecology*. 311 (1): 79-99.

Leavitt, C. 1623. Pamphlet to New England.

New Hampshire Department of Environmental Services. 2005. Lamprey River Baseline Fish Sampling August 25-29, 2003.

Noon, J. *Fishing in New Hampshire: A History*. New Hampshire Fishing Series Vol. II. Moose Country Press, Warner, NH.

Scales, J. 1923. *Colonial Era, History of Dover*, New Hampshire. Manchester, NH.

Warfel, H.E., T.P. Frost, and W. H. Jones. 1942. The Smelt, *Osmerus mordax*, in Great Bay, New Hampshire. *Transactions of the American Fisheries Societ*y. 77: 257-262.

Stream Network Analysis

A stream network analysis was used to identify restoration needs for each of the seven focal diadromous species.

The NHHD 1:24,000 scale stream network (flowline feature), was obtained from the UNH Complex Systems Research Center (CSRC), as enhanced by CSRC to include routing information and other attributes.

The New Hampshire dams database, a database of Maine dams from MEGIS, and a project area selection from the National Inventory of Dams were combined and filtered to eliminate duplicates. The resulting file contained over 500 dams, with many coded as inactive or never built. The combined file was edited to eliminate most dams not coded as active, resulting in a file with 190 dams in the project area. Most dams were not located exactly coincident with the NHHD streams layer and so they were "snapped" to it using a tolerance of 100 feet. Following snapping, the relevant NHHD reach codes were added to each record.

Attributes to represent the upstream and downstream occurrence for each species were added to the dams database. A large 3 by 4 foot format map was printed and marked by hand with colored pens to capture the results of the project literature search for fish. Subsequently, the map was reviewed by local fish experts who provided corrections, additions, caveats, and detailed information regarding each river system. The final map was then used to "code up" the dams database, so that each of the 190 dams had data to indicate which species were likely currently and historically up and downstream of it.

Fish distribution coding rules for dams database:

Mainstem rivers:

H probable or known that fish were historically present and are currently absent, based on historical records or expert review

C probable or known that fish are currently present, based on historical records or expert review

0 probable or known that fish are not currently present and were not historically present, based on historical records or expert review

1st order tributaries or higher:

H same as above *or* the segment is contiguous with a section coded H

C same as above *or* the segment is contiguous with a section coded C

HU probable that fish were historically present (based on expert opinion), but no specific record exists *and* the stream segment is not contiguous with a section coded H

CU probable that fish are currently present (based on expert opinion), but no specific record exists *and* the stream segment is not contiguous with a section coded C

0 same as above

Note: The "U" suffix is used to denote uncertainty.

The NHHD data was exported to a shapefile format (GBERCStreams.shp) to provide a more accessible and easily editable format. Stream reaches in this file were split as needed at dams so upstream lengths could be more easily calculated. Using the network utility analyst tool in ArcView 9.1 (see Appendix 1 for methods), the total number of unobstructed upstream miles was hand calculated for each dam.

Fields for each of the seven species were added to the streams shapefile, and attributes for each species were added using the same codes used for dams. Again, coding each of the approximately 9,000 segments was made somewhat easier by using the network utility tool. Results of this analysis are presented in Figures 9-15.

Figures 9 through 15 provide detailed information on potential habitat *quantity*. A proxy index for habitat *quality* was developed using the USGS SPARROW model. The SPARROW data was clipped to the project area, resulting in 1,193 individual catchments (fine scale watersheds). Information that can be derived for each catchment includes the percentage of land area in each of the National Land Cover Database (NLCD) classifications. These classifications include categories for forested, suburban, urban, agriculture, and combined categories like "developed". Additionally, the SPARROW model provides the ability to query any catchment to determine the area or percentage of land upstream in any of these categories.

The NHHD reach code field was used to join the SPARROW model to our fish-coded streams database. Assuming that instream habitat quality is influenced both by land use upstream *and* land use and buffer condition directly adjacent to a reach of interest, metrics for each were incorporated in a series of test algorithms, in search of an index that would be predictive.

The data presented in this report uses a habitat impact index, with lower numbers indicating lower impact and better quality stream habitat. The portion of a stream that lies within a SPARROW catchment is given a value calculated using the percentage of land in the catchment that is developed in the developed category (weighted 0.6), plus the percentage in the agricultural category (weighted 0.1), plus the percentage of land in the *sum* of all the hydrologically connected catchments upstream of the catchment of

Figure 9: Historic and current distribution of alewife (*Alosa pseudoharengus*)
Prior to dam construction alewife were most likely present in nearly every stream connected to the estuary, except where limited by natural barriers or inadequate stream flow.

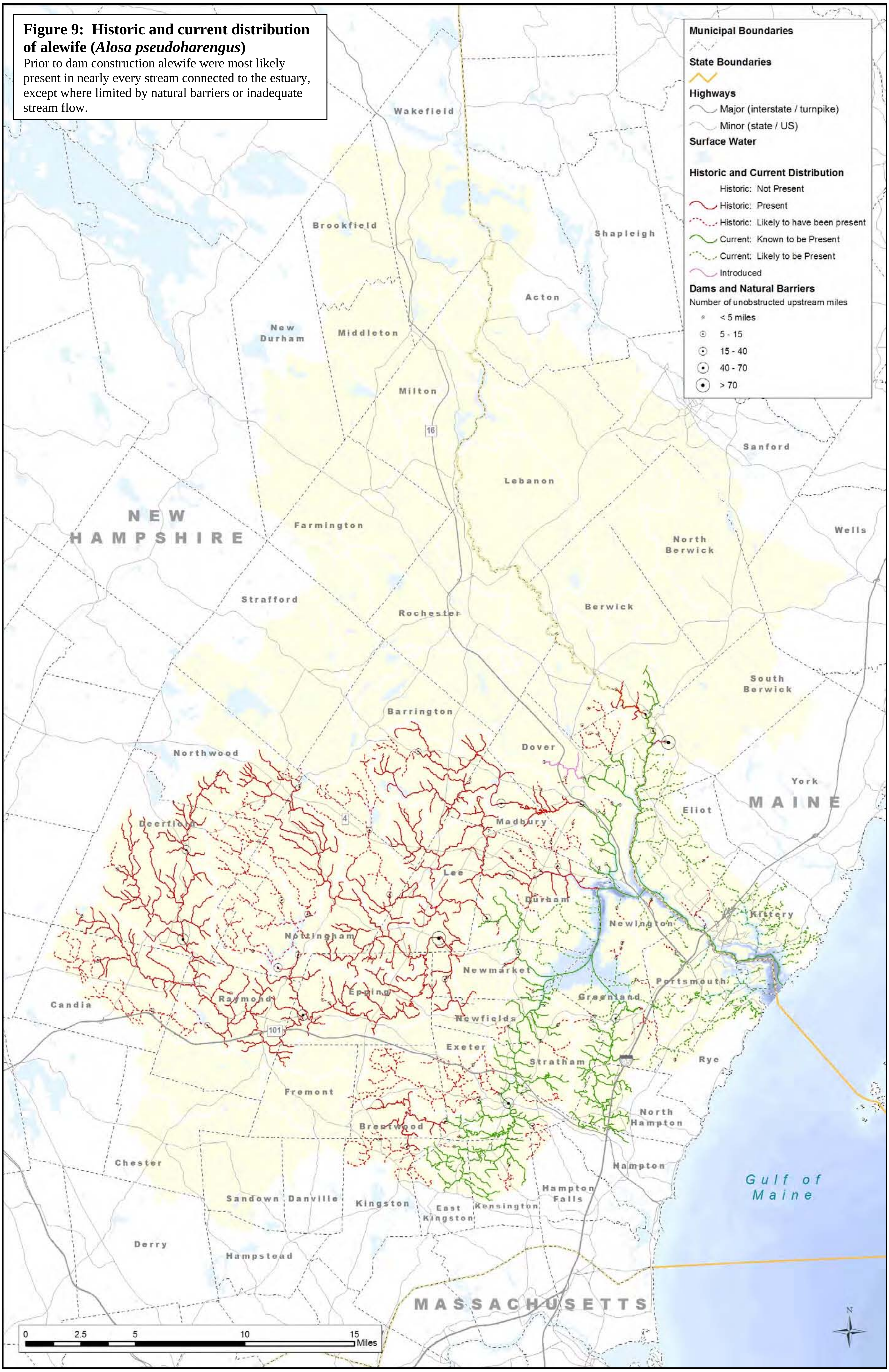


Figure 10. Historical and current distribution of blueback herring (*Alosa aestivalis*)
Blueback herring are very similar in appearance to alewives, and collectively the two species are often referred to as river herring. Like the alewife, blueback herring formerly utilized many miles of stream habitat that they no longer have access to.

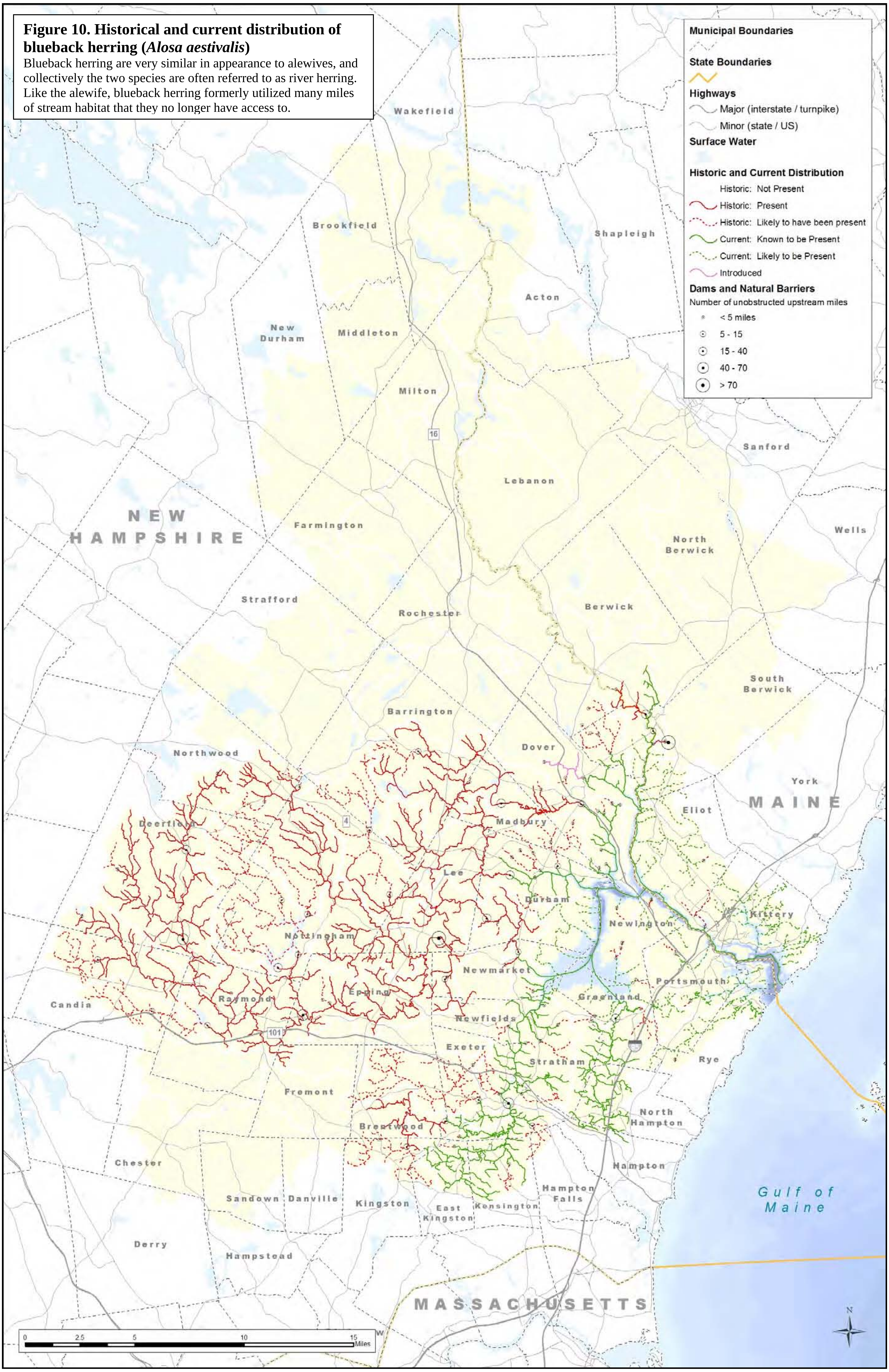
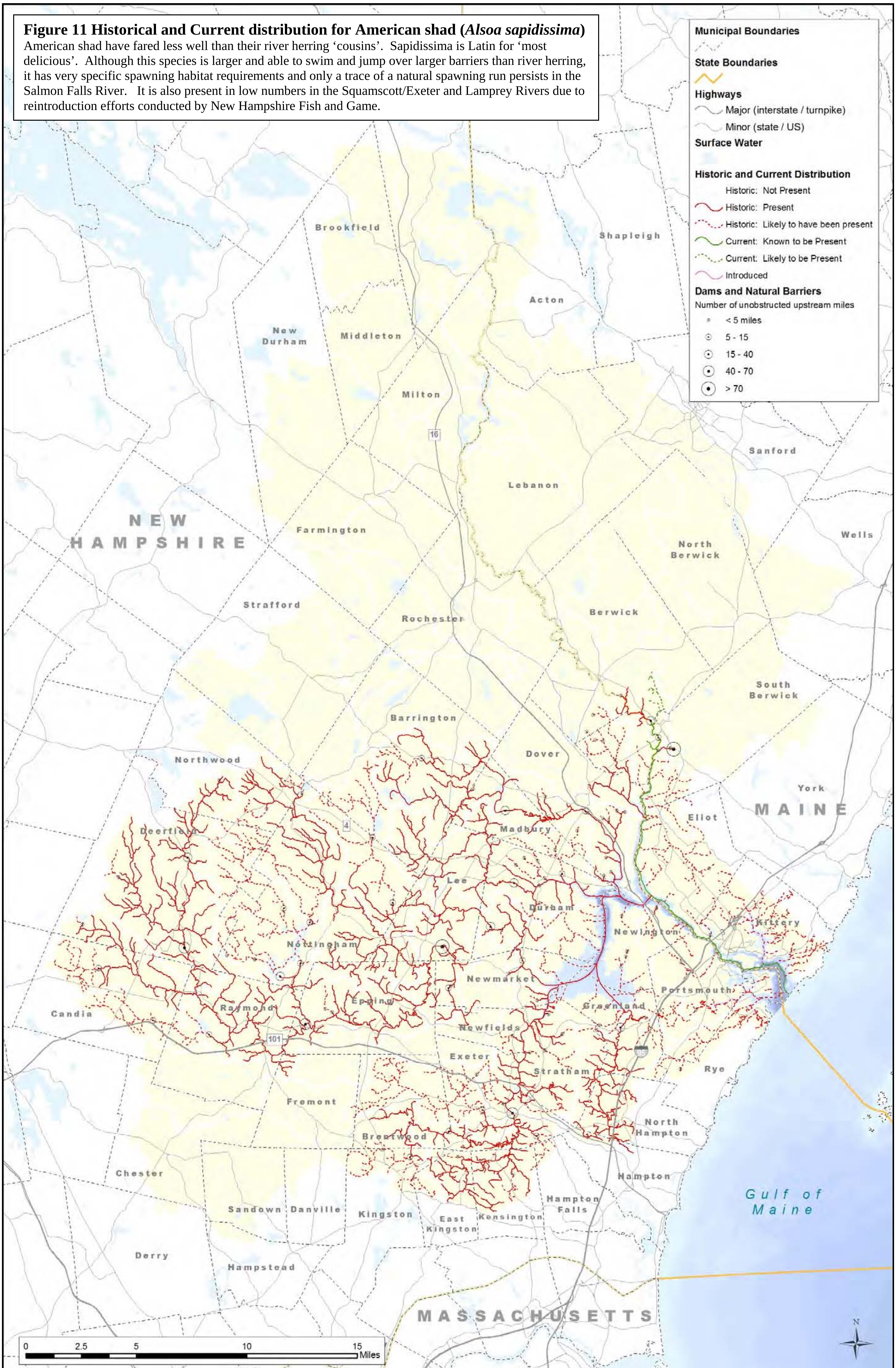


Figure 11 Historical and Current distribution for American shad (*Alsoa sapidissima*)
American shad have fared less well than their river herring 'cousins'. Sapidissima is Latin for 'most delicious'. Although this species is larger and able to swim and jump over larger barriers than river herring, it has very specific spawning habitat requirements and only a trace of a natural spawning run persists in the Salmon Falls River. It is also present in low numbers in the Squamscott/Exeter and Lamprey Rivers due to reintroduction efforts conducted by New Hampshire Fish and Game.



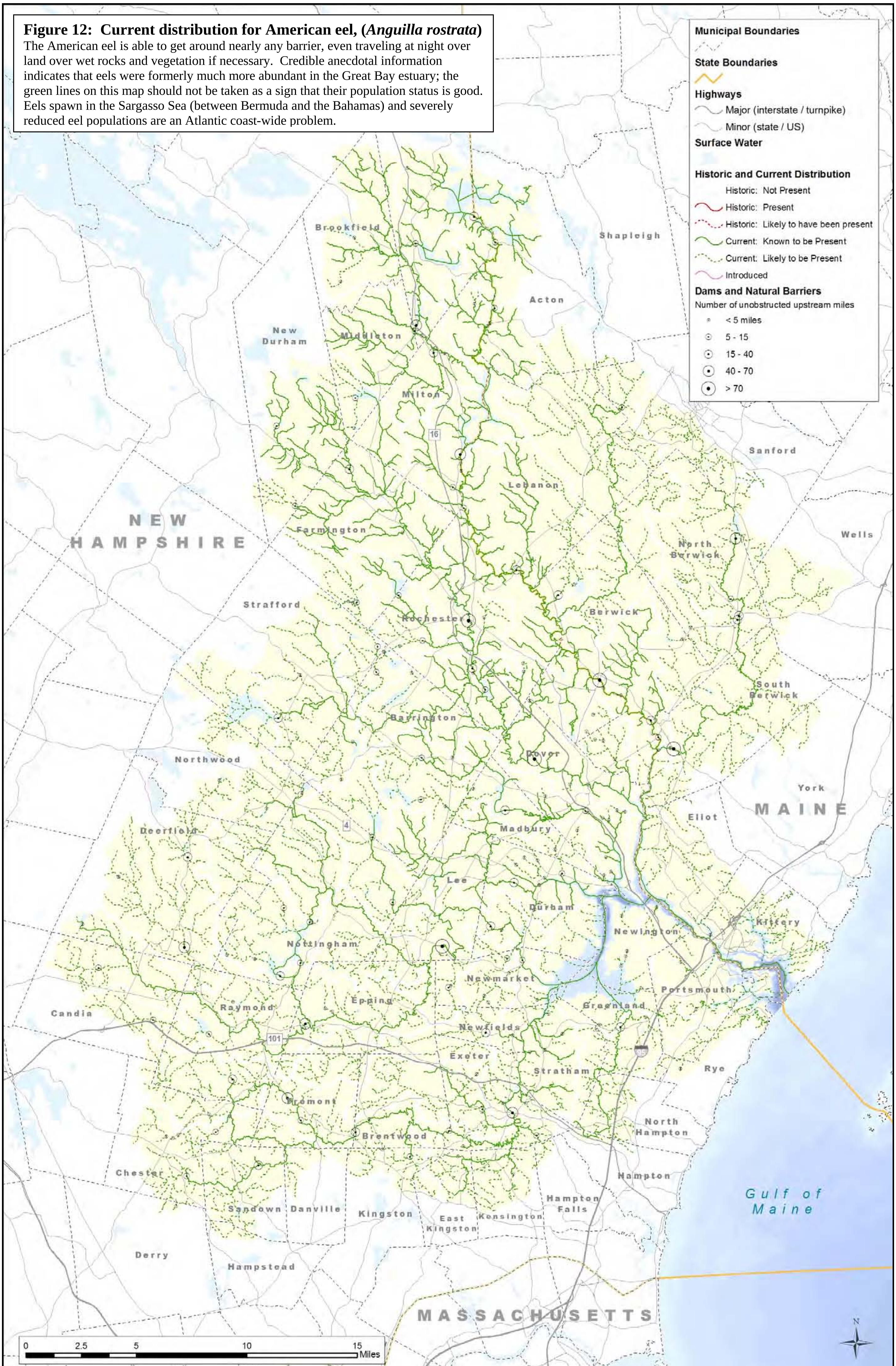
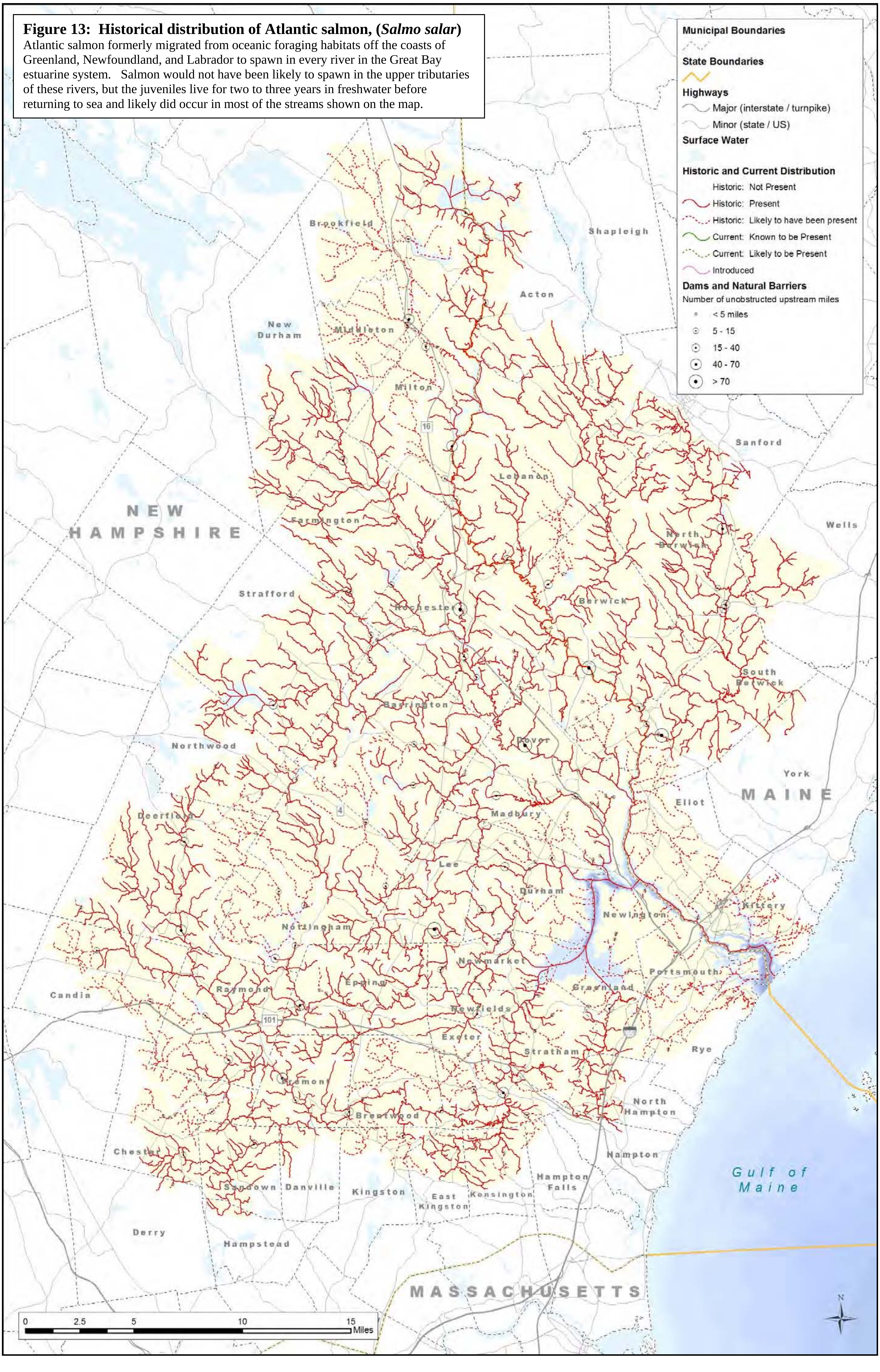


Figure 12: Current distribution for American eel, (*Anguilla rostrata*)
The American eel is able to get around nearly any barrier, even traveling at night over land over wet rocks and vegetation if necessary. Credible anecdotal information indicates that eels were formerly much more abundant in the Great Bay estuary; the green lines on this map should not be taken as a sign that their population status is good. Eels spawn in the Sargasso Sea (between Bermuda and the Bahamas) and severely reduced eel populations are an Atlantic coast-wide problem.

Figure 13: Historical distribution of Atlantic salmon, (*Salmo salar*)
Atlantic salmon formerly migrated from oceanic foraging habitats off the coasts of Greenland, Newfoundland, and Labrador to spawn in every river in the Great Bay estuarine system. Salmon would not have been likely to spawn in the upper tributaries of these rivers, but the juveniles live for two to three years in freshwater before returning to sea and likely did occur in most of the streams shown on the map.



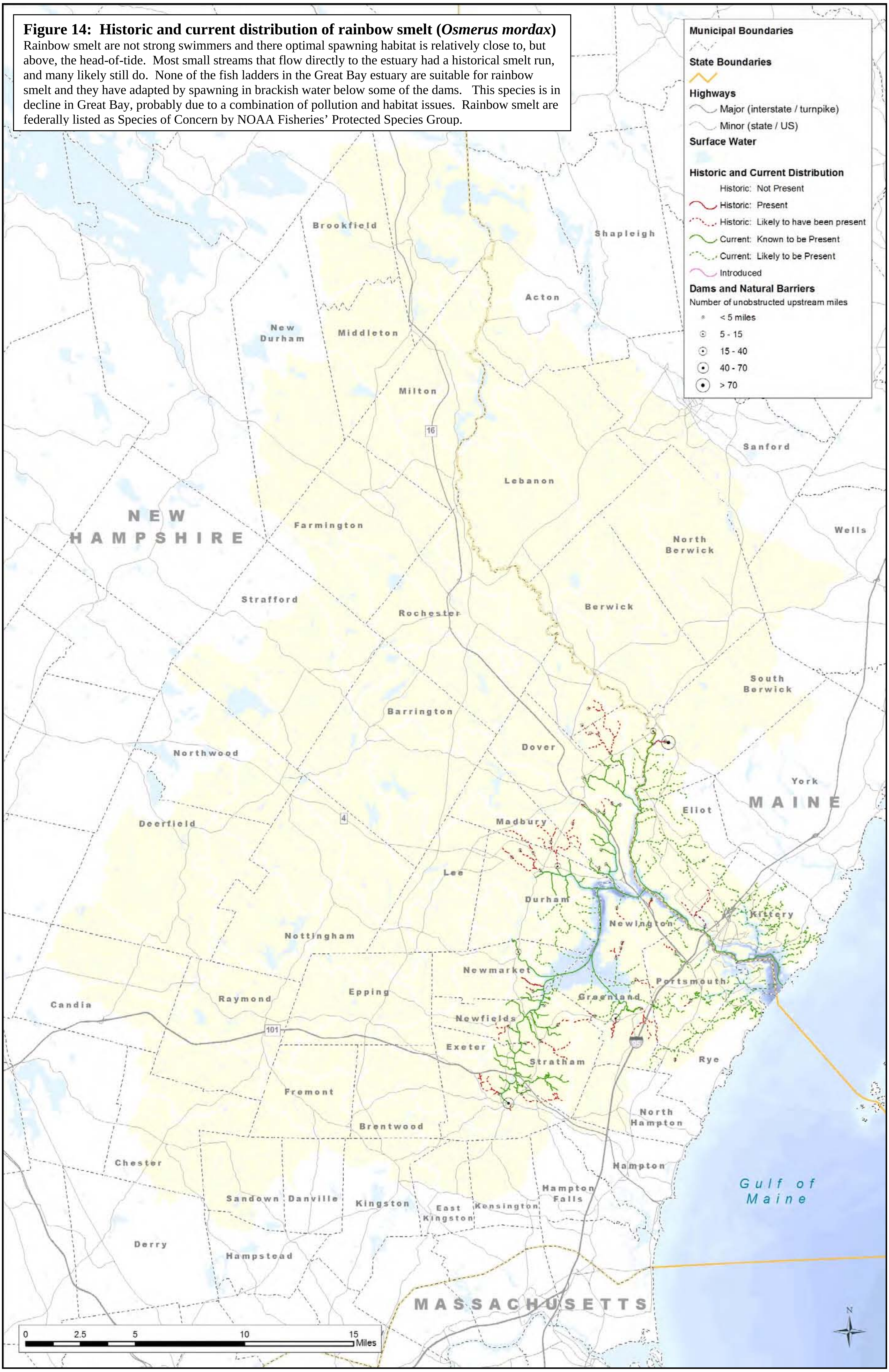


Figure 14: Historic and current distribution of rainbow smelt (*Osmerus mordax*)
Rainbow smelt are not strong swimmers and there optimal spawning habitat is relatively close to, but above, the head-of-tide. Most small streams that flow directly to the estuary had a historical smelt run, and many likely still do. None of the fish ladders in the Great Bay estuary are suitable for rainbow smelt and they have adapted by spawning in brackish water below some of the dams. This species is in decline in Great Bay, probably due to a combination of pollution and habitat issues. Rainbow smelt are federally listed as Species of Concern by NOAA Fisheries' Protected Species Group.

Figure 15: Historical distribution of Atlantic sturgeon (*Acipenser oxyrhynchus*)
Atlantic sturgeon can live for 60 years and reach a size of up to 800 pounds. They were formerly abundant in many Atlantic coast rivers but due to dams, overharvest, and pollution they are now locally extinct with the exception of a few rivers. Historical reports indicate that Atlantic sturgeon were abundant in the Great Bay estuary in the 1800s and nearly lost by the early 1900s.

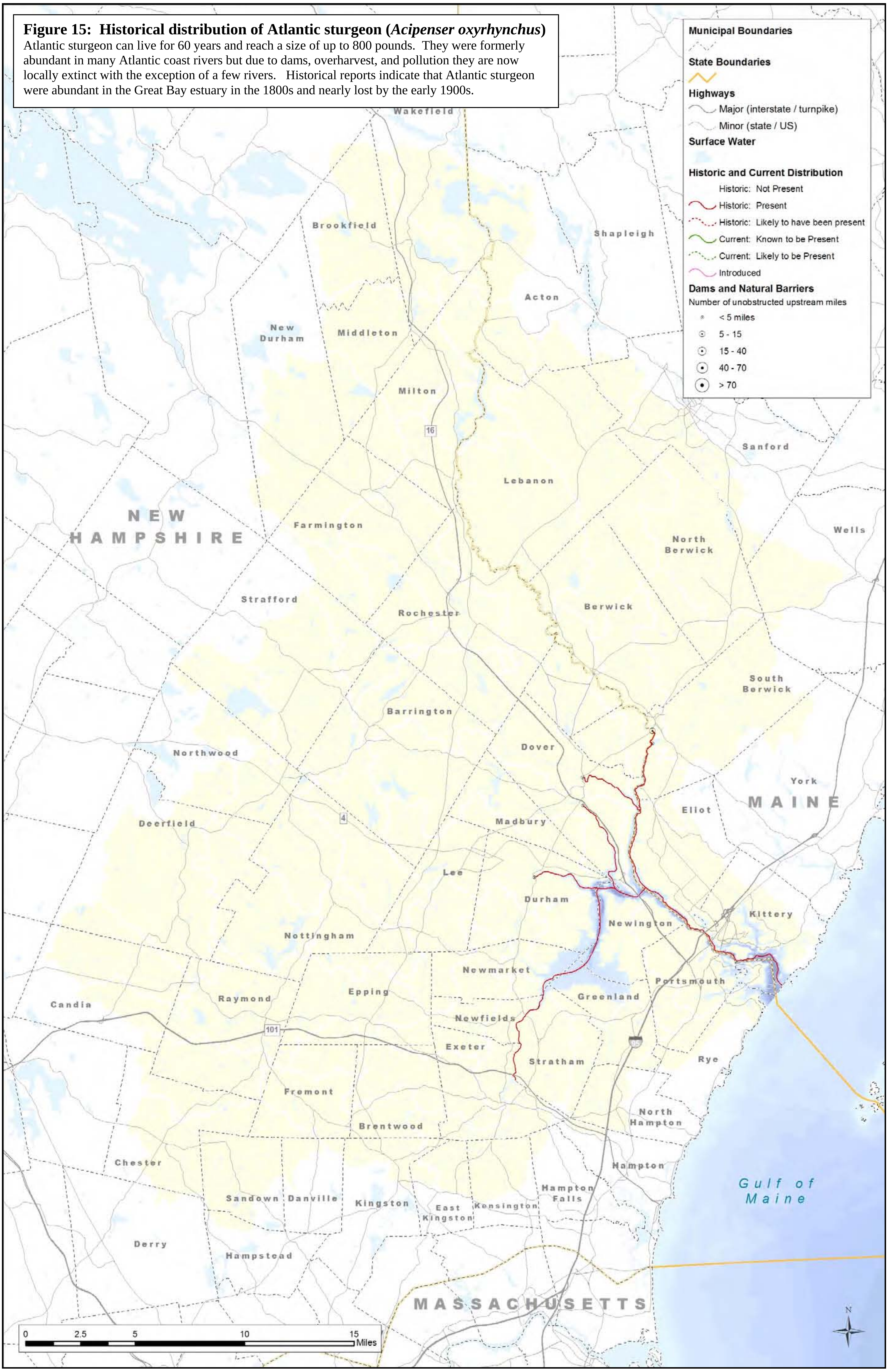
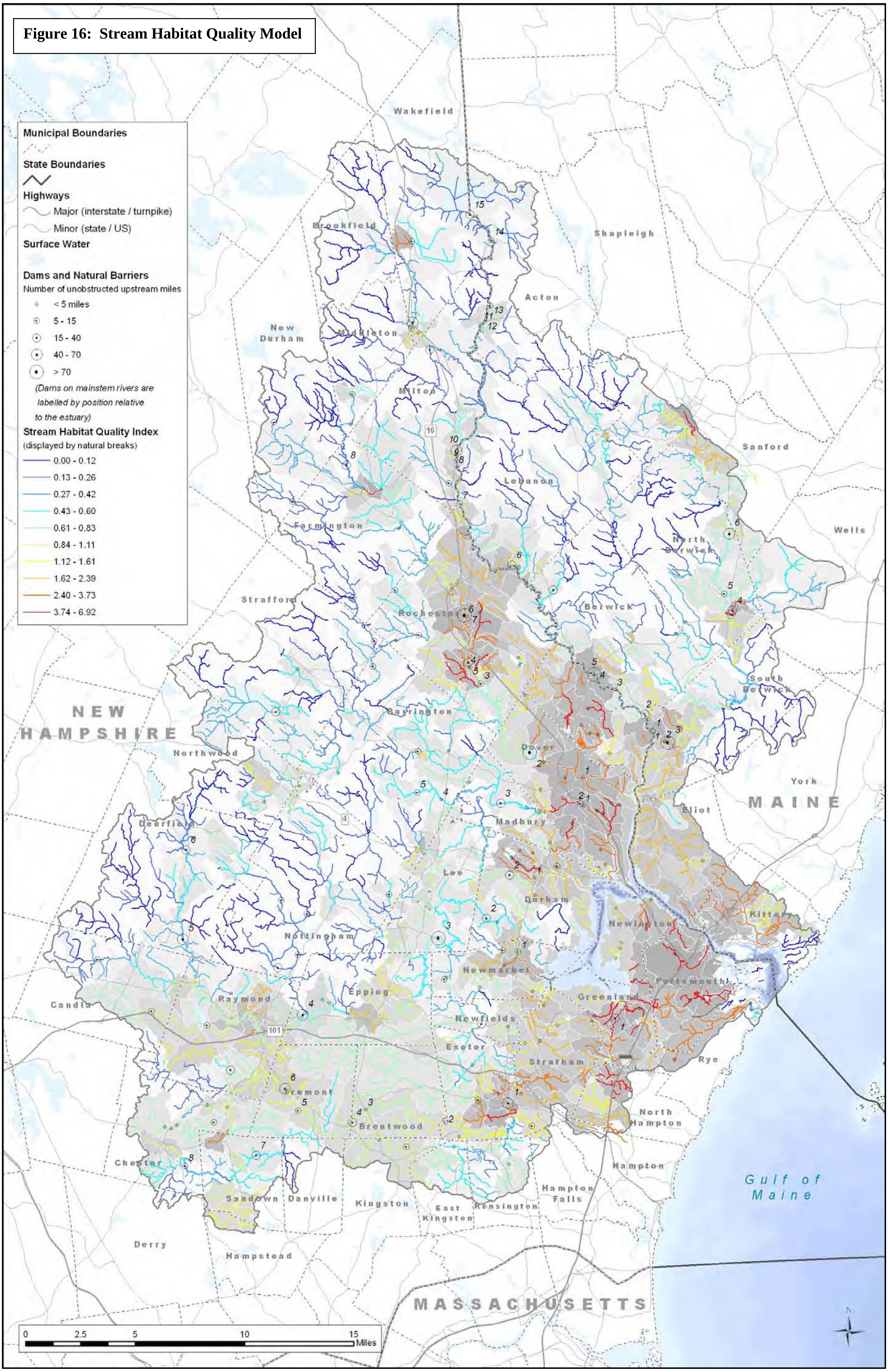


Figure 16: Stream Habitat Quality Model



interest (weighted 0.3). The percent of the upstream watershed that is developed is used as a proxy for water quality impacts and alteration of natural flow and sediment regimes in the downstream reach of interest, and the percentage of the local catchment in a developed status is a used as a more direct proxy for these same factors. It is weighted higher with the assumption that the more local land based impacts will tend to be more direct with less sequestration and assimilation of pollutants, and because we expect this metric may also serve as a very rough proxy for riparian buffer quality. This index may overestimate habitat impacts in stream reaches in urban areas with extensive natural buffers.

The habitat impact index is presented as a hypothesis for testing and improvement using additional parameters and/or different weighting (see Figure 16) and is combined with the habitat quantity metrics in the tables below. The SPARROW model is based on the coarser 1:100,000 scale National Hydrography Dataset (NHD) streams data and although we used it to code all streams, strictly speaking it should only be valid for stream segments common to both NHD and NHHD scales (all major rivers and most major streams). Figure 16 also shows SPARROW catchments shaded darker in areas with more development. The red to blue color coding scheme used to display the streams should, perhaps, not be taken too literally until more review of the data and its predictive value can be made. While dark blue coded streams can reasonably be expected to provide very good habitat, and dark red is likely the poorest, various shades of yellow may or may not signify “fair”.

It must be noted that merely reporting on the number of stream miles in various categories and referring to miles as “habitat” overstates the power of the methods. Each species has specific requirements. Alewives have evolved to spawn in lakes and though they may often be found spawning in streams and rivers, they prefer lakes. The stream miles metrics reported below provide a quantitative measure of the access that fish currently have to their preferred habitats, and how that access could be improved, not an exact measure of habitat quantity. Also note that even though a dam has a fish ladder, it will still act as a partial barrier, filtering out two (rainbow smelt and sturgeon) or more species. All of the project area’s fish passage facilities potentially present a barrier to some or all species, depending on flow conditions.

It must be stressed that this project does not include an assessment of the impact of road-stream crossings on fish habitat availability. Inadequate culverts act as additional filters, blocking passage for one or more species, either continuously or during specific flow conditions. Barriers may occur due to excessive culvert height, accelerated stream velocity, and other factors. Assessment of relevant culverts will need to be included in initial feasibility studies for fish passage improvement at dams. In some cases, correction of one or more inadequate culverts may be required to realize any benefits from improving passage at an adjacent upstream dam.

Stream Network Analysis Table Structure

Each of the following tables contains the same basic structure. The first row of each table shows the total number of *unobstructed* miles (combined mainstem and tributaries) that lie downstream of the first dam that does not have fish passage installed. Each table contains a row for each mainstem dam, with the dam's position relative to the lower estuary (Great Bay, Little Bay, Piscataqua River) indicated in the first column. The second column lists the dam's location in terms of the number of mainstem (not including tributaries) river miles upstream from the estuary. The third column contains the habitat impact score (described above) for each section. This is the average score for all stream segments, for each section of interest. The fourth column accumulates the average impact score, from the dam of interest downstream to the estuary.

The fourth column is the first column in the table with metrics on the total number of river/stream miles upstream of each dam. This is the number of miles which would become accessible to fish if the mainstem dam were removed. Significant additional tributary miles could be added with projects at tributary dams. The dams database on the project CD also contains the number of unobstructed miles upstream of each tributary dam. The fifth column, Cumulative Connectivity Potential (CCP) is simply a cumulative accounting of the number of unobstructed miles shown in column four, plus the number of miles that are already unblocked. The last column expresses the CCP in terms of system percent – the percentage of the river system reopened compared to the total number of miles in the system. Entries at the lower right of each table for 'blocked tributary miles' represent additional miles upstream of tributary dams that are not reflected in the CCP values.

Squamscott/Exeter River

The Exeter River begins in Chester, NH and flows 45.7 miles east and north to the southwest corner of Great Bay. Where the river is tidal, below String Bridge in downtown Exeter, it is called the Squamscott River. Denil fishways are located at the two downstream-most dams – the Great dam in Exeter and the Pickpocket dam in Brentwood. A velocity barrier to smelt currently exists on the left channel below the String Bridge, although eggs have been found on the right channel. Fish passage monitoring conducted at the Great Dam by New Hampshire Fish and Game (NH F&G) has found that river herring using the fishway have been predominantly alewives in recent years. In addition to alewives, the Great dam fishway also passes resident species, blueback herring, American eels, lamprey, and American shad. Adult shad have been stocked in the Exeter River since 1982 with the goal of restoring a self-sustaining run. Gravid adults are transported from either the Connecticut and/or Merrimack rivers in Massachusetts and released above the Pickpocket Dam. A ledge located upstream of the Pickpocket dam below route 125 in Brentwood serves as a natural barrier to passage of all species other than lamprey and American eels. Prior to the decline of Atlantic salmon, they likely would have passed this ledge.

Squamscott/Exeter River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential*	System percent
		n/a		Unobstructed below 2nd dam	104.1	32%
First	7.4	1.8		53.6 included in first row	104.1	32%
Second	21.7	1.2	1.4	14.3 included in first row	104.1	32%
Third	27.8	1.1	1.4	3.7	107.8	33%
Fourth	28.9	0.9	1.3	16.3	124.1	38%
Fifth	33.1	1.0	1.3	6.0	130.1	40%
Sixth	34.5	1.1	1.3	41.5	171.6	52%
Seventh	47.1	1.0	1.2	30.0	201.5	61%
Eighth	51.9	0.5	1.1	14.9	216.4	66%
Upstream terminus	54.7	1.2	1.1	n/a		
				Blocked tributary miles	111.3	34%
				Historically connected	327.7	100%

Third "dam" is a waterfall and a natural barrier to all species except salmon and eel.

Lamprey River

The Lamprey River flows from the town of Northwood 45.3 miles to discharge into the western side of Great Bay in Newmarket. The Macallen dam, located at the head of tide, was the site of the first falls on the Lamprey. Historically only salmon, lamprey and eels would have passed this point consistently. A Squamscott Indian settlement was located on the east bank below the first falls; it is presumed that the location was chosen due to the plentiful salmon, river herring, shad and smelt found there. A denil fishway on the Macallen Dam passes alewives, American eels, sea lamprey, and American shad. Blueback herring do not use the ladder and have been observed spawning below the dam. While the Macallen dam fishway was not designed specifically for shad, it passes more shad than the other fishways in the NH coastal region. Three and a half miles upstream of the Macallen dam is the Wiswall dam, originally constructed in 1835. Because no fishway currently exists at this site, it serves as a barrier to all diadromous species other than American eels. A project to install a nature-like bypass channel around the dam has been proposed. The third dam, at Wadleigh Falls has been breached, but under typical flow conditions, its remnants still constitute a barrier. While Atlantic salmon and American eel are capable of easily passing this location, NHF&G staff suspect that under the right flow conditions American shad, sea lamprey, and possibly river herring could pass over Wadleigh Falls. In November of 1996, the section of the Lamprey River between Bunker Pond in Epping and the confluence with the Piscassic River was designated a Wild and Scenic River by the National Park Service.

Lamprey River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential*	System percent
		n/a		Unobstructed below 1st dam	13.7	3%
First	2.4	2.1		10.6 included in first row	13.7	3%
Second	5.9	0.9	1.4	36.6	50.3	11%
Third	13.7	0.6	0.9	121.6	171.9	37%
Fourth	26.8	1.0	1.0	68.6	240.5	51%
Fifth	40.0	0.8	0.9	46.4	286.8	61%
Sixth	45.3	0.4	0.9	18.8	305.6	65%
Upstream terminus	49.7	0.1	0.8	n/a		
				Blocked tributary miles	163.0	35%
				Historically connected	468.6	100%
Third dam at Wadleigh Falls is breached but still presents barrier to all species except salmon and eels. One tributary, the Piscassic River, includes 47.15 miles with natural barrier to all species except salmon and eels.						

Oyster River

The Oyster River flows through the towns of Barrington, Lee, Madbury, Nottingham, and Durham before discharging into Little Bay. The Oyster River dam is the first main stem dam on the Oyster River. A denil fishway passes American eels, sea lamprey, and blueback herring over the dam. Alewives were likely historically present in the Oyster River but are no longer found there. Blueback herring spawn in tributaries upstream of the Oyster River dam as well as at the base of the next upstream obstruction, the Durham Reservoir dam. In 1940, Jackson observed smelt eggs on rocks in the Oyster River. By the late 40s the same rocks were covered with slime and silt deposits and no eggs were found. Jackson attributed the decline in smelt to sewage accumulation. Unfortunately, the Oyster River continues to be plagued with poor water quality. Low dissolved oxygen levels were recorded over 5 days in the impoundment upstream of the Oyster River dam in 2005. Furthermore, a wastewater treatment plant discharges into the Oyster River downstream of the Oyster River dam. Because of its proximity to the dam, the degraded water is backed up at the dam and concentrated on flood tides.

Oyster River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential*	System percent
		n/a		Unobstructed below 2nd dam	12.5	20%
First	3.4	1.9		4.8 included in first row	12.5	20%
Second	5.2	1.3	1.7	34.2	46.7	74%
Johnson Creek 1	n/a	n/a	n/a	5.8	52.5	83%
Beards Creek 1	n/a	n/a	n/a	3.5	56.0	89%
Longmarsh Brook	n/a	n/a	n/a	1.6	57.6	91%
Hamel Brook	n/a	n/a	n/a	0.9	58.5	93%
Upstream terminus	11.7	0.5	1.0	n/a		
				Remaining blocked tribs.	4.6	7%
				Historically connected	63.1	100%
Only one mainstem dam on this system, first dams on select lower river tributaries included in this summary.						

Bellamy River

The mainstem of the Bellamy River flows almost 20 miles from its headwaters in Barrington to discharge into Little Bay in Dover. The first saw and gristmills were constructed on the Bellamy River as early as 1650. A dam removal project in 2004 opened up ¼ mile of habitat to river herring, American eels and smelt. The Sawyer Mill dams are located approximately ¼ mile above the head of tide and are the lowest downstream impediments to fish passage. Due to a lack of fish passage at these dams, it is currently passable to only American eels. Removal or improved passage at the first two dams would restore diadromous fish access to 34% of the total stream habitat in this system.

Bellamy River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score*	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential**	System percent
	n/a	n/a	Unobstructed below 1st dam (no ladder)		12.7	18%
First	4.8	3.2		0.1	12.8	18%
Second	4.9	3.7	3.2	11.2	24.0	34%
Third	11.8	1.8	2.4	28.2	52.2	75%
Fourth	17.1	0.4	1.8	3.5	55.7	80%
Fifth	18.7	0.5	1.7	6.2	62.0	89%
Upstream terminus	21.8	0.4	1.5			
				Blocked tributary miles	8.0	11%
				Historically connected	69.9	100%

<u>Cocheco River</u>

The Cocheco River joins the Salmon Falls River in Dover to form the Piscataqua River. Located in downtown Dover at the head of tide, the Central Ave dam is a hydroelectric facility. A denil fishway passes both species of river herring, American eels, sea lamprey, and American shad. As the site of the first falls on the river, the Central Ave dam historically served as a barrier to all diadromous species other than American eels, sea lamprey and, in certain flow conditions, Atlantic salmon. Upstream of the Central Ave Dam is a natural barrier passable to sea lamprey, American eels and salmon. A second hydroelectric dam, the Watson Waldron, exists upstream of the natural barrier. For 15 years, salmon fry were stocked in the Cocheco watershed to enhance recreational fishing opportunity by NH F&G. The program was discontinued in 2003 due to low returns. American shad were stocked in the Cocheco watershed by NH F&G between 1980 and 1988, before concentration of restoration efforts focused on the Exeter River. Significant tributaries to the Cocheco River include the Mad River and the Isinglass River.

Cocheco River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score*	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential**	System percent
		n/a		Unobstructed below 2nd dam	13.79	4%
First	3.9	2.84			13.8	4%
Second	6.3	3.0	2.9	118.5	132.3	35%
Third	14.7	0.9	1.7	6.3	138.6	37%
Fourth	15.4	2.2	1.8	0.3	138.9	37%
Fifth	15.7	2.8	1.8	20.0	158.9	42%
Sixth	19.4	2.8	2.0	0.1	159.0	42%
Seventh	19.5	3.5	2.0	83.1	242.1	64%
Eighth	32.6	1.8	1.9	20.8	262.8	69%
Upstream terminus	38.0	0.1	1.7			
				Blocked tributary miles	115.4	31%
				Historically connected	378.3	100%

Salmon Falls

The Salmon Falls River flows approximately 33 miles from its headwaters to the confluence with the Cocheco River in Dover to form the Piscataqua River. It serves as the boundary between New Hampshire and southern Maine. According to Jackson (1944), the Salmon Falls River sustained the most productive diadromous fish runs in the region prior to the construction of dams. The South Berwick dam, located at the head of tide, is a hydroelectric facility. In 2002, a denil fishway was constructed at the Salmon Falls dam to target diadromous fish passage. While a shad run exists on the Salmon Falls River, it is not yet clear whether shad are using the fishway as there is little monitoring data available. River herring have been observed using the fishway although there is no confirmation of which species. Also an American eel fish passage system allows passage over the dam. The next dam upstream, the Rollinsford dam, is also a hydroelectric facility. Because the dam does not have a fishway, it serves as an upstream barrier to all species other than American eels. Restoration of fish passage at this site would provide potential fish access to about 10% of the total stream miles in this system. In 1990, a 216 pound female Atlantic sturgeon was captured in the Salmon Falls river at the head of tide in an illegal gill net.

Salmon Falls River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential*	System percent
		n/a		Unobstructed below 2nd dam	26.1	5%
First	4.3	1.8		6.1 (included in first row)	26.1	5%
Second	5.3	2.2	1.8	21.9	47.9	10%
Third	7.7	1.3	1.7	1.1	49.0	10%
Fourth	8.7	3.4	1.9	0.4	49.4	10%
Fifth	9.1	3.4	2.0	169.4	218.8	45%
Sixth	20.0	1.0	1.5	23.6	242.4	49%
Seventh	25.9	2.0	1.6	10.3	252.7	52%
Eighth	28.0	1.0	1.5	0.3	253.1	52%
Ninth	28.3	1.2	1.5	0.4	253.5	52%
Tenth	28.8	1.2	1.5	45.0	298.5	61%
Eleventh	37.5	0.4	1.3	0.2	298.7	61%
Twelth	37.7	0.7	1.3	2.1	300.8	61%
Thirteenth	38.5	0.3	1.2	11.3	312.2	64%
Fourteenth	42.8	0.3	1.1	13.0	325.2	66%
Fifteenth	44.6	0.2	1.1	29.5	354.6	72%
Upstream terminus	48.8	0.3	1.0	n/a		
				Blocked tributary miles	135.8	28%
				Historically connected	490.4	100%
Distance to estuary calculated to upstream end of Piscataqua River.						

Great Works

The Great Works River is a major tributary of the Salmon Falls River. Anecdotal evidence suggests that there were historic runs of shad and alewife in this system. The first dam on the Great Works River is located 0.1 miles upstream of its confluence with the Salmon Falls, and serves as a barrier to the upstream migration of all species but American eels and sea lamprey. The second dam, the Great Works dam, was originally built to power a sawmill in 1634. Restoration of fish passage at the first three dams on the Great Works River would provide fish access to 85.2 miles of stream habitat in this system.

Great Works River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score	Cumulative Score	Currently unobstructed upstream miles, including tributaries	Cumulative Connectivity Potential*	System percent
		n/a	Unobstructed below 1st dam (no ladder)		0.1	0%
First	0.1	3.6		0.6	0.7	0%
Second	0.7	2.7	2.8	0.2	0.9	0%
Third	0.9	3.6	3.0	85.2	86.1	43%
Fourth	15.2	1.4	1.5	24.7	110.8	55%
Fifth	17.0	1.6	1.5	11.1	122.0	61%
Sixth	20.8	1.1	1.4	50.1	172.1	86%
Upstream terminus	30.7	1.1	1.3	n/a		
				Blocked tributary miles	27.7	14%
				Historically connected	199.8	100%

Winnicut River

The Winnicut River discharges into southeastern Great Bay in Greenland, NH. The only mainstem dam on the Winnicut River, owned by NH F&G, is located at the head of tide. A step-weir fish ladder currently exists on this dam; however, it is minimally effective in passing anadromous fish. The dam is currently proposed for removal with planned construction of a technical fishpass system to enhance passage after dam removal, to be installed underneath the route 33 bridge.

Winnicut River Mainstem Dams	Mainstem river miles upstream from estuary	Habitat Impact Score	Cumulative Score	Currently unobstructed upstream miles, including tributaries*	Cumulative Connectivity Potential*	System percent
		n/a	Unobstructed below 1st dam		2.7	6%
First	1.2	5.2		39.1	41.8	89%
Upstream terminus	11.4	2.0	2.3	n/a		
				Blocked tributary miles	5.1	n/a
				Historically connected	47.0	100%

The only mainstem dam on the this river currently has a relatively ineffective fish ladder and the dam is being scheduled for removal. It is considered as a barrier for purposes of this summary table. GRANIT data shows 3 dams on lower tributaries.

River System Comparison

Comparison between rivers	Impact of sequential mainstem passage improvement projects (cumulative open miles including tributaries)				Cumulative Habitat Impact Score	Percent of System Connected to Estuary	
	First	Second	Third	Fourth		Current	After up to 4 projects
Squamscott/Exeter	3.7	20.0	26.0	67.5	1.3	32%	52%
Lamprey	36.6	226.8	273.1	291.9	0.9	3%	65%
Oyster	34.2	n/a	n/a	n/a	1.7	20%	74%
Bellamy	0.1	11.3	39.5	43.0	1.8	18%	80%
Cocheco	118.5	124.8	125.1	145.1	1.8	4%	42%
Salmon Falls	21.9	22.9	23.4	192.7	2.0	5%	45%
Great Works	0.6	0.8	86.0	110.8	3.0	0%	43%
Winnicut	39.1	n/a	n/a	n/a	2.3	6%	89%

Habitat Interactions

Habitat Interaction Matrix

	Eelgrass bed	Oyster reef	Salt marsh	Diadromous fish
Eelgrass bed		+	?	+
Oyster reef	+		?	?
Salt marsh	+	?		+
Diadromous fish	?	?	?	

Eelgrass may provide benefits to oysters and other shellfish, in several different ways. Eelgrass meadows trap and sequester suspended sediments that might otherwise smother shellfish larvae and reduce habitat quality for adults. Eelgrass beds also create eddies in currents that can affect larval retention and settlement, and also provide potential attachment sites for some the planktonic larval stages of some shellfish. Less well studied and understood are interactions that may occur within microbial loop cycles, as nutrients are sequestered, transformed into different states, (*e.g.* nitrate to ammonia) and potentially transferred between oyster and eelgrass habitats. Eelgrass may also dampen currents that could otherwise lead to salt marsh erosion.

The importance of eelgrass to many fish species for refuge, nursery and feeding habitats is well documented. The near disappearance of the formerly abundant winter flounder from the project area is conceivably linked in part to the loss of eelgrass “stepping stones” between Little Bay and the Gulf of Maine (this is a hypothesis and has not been studied). In turn, predation pressure and interspecies competition within robust fish communities found in eelgrass beds may have indirect positive (or possibly negative) effects on eelgrass viability (*e.g.* potentially reducing numbers of green crab that prey upon eelgrass epiphyte grazers or bioturbators).

Salt marshes serve as an important nursery habitat for many species of migratory fish. Estuarine fish density and growth was found to be higher in salt marshes adjacent to seagrass beds than in marshes adjacent to unvegetated bottom. Furthermore, salt marsh peat is thought to reduce and delay eutrophication impacts to estuaries. The marshes take up nutrients and prevent epiphytes and algae from flourishing in adjacent subtidal habitats where they compete with and can eliminate seagrasses.

Oysters, softshell clams, and other bivalves filter large volumes of water, removing nutrients and algae from the water column and in turn, improving water quality. A major cause of seagrass decline is reduced light penetration due to eutrophication and turbidity. Oyster feeding increases light penetration due to reduction of phytoplankton concentrations and suspended inorganic particulate matter. A model developed by researchers at the University of Maryland predicted that oyster restoration can facilitate restoration of seagrasses via filtration of suspended sediments reducing turbidity and improving light clarity. Oyster growers in Virginia recently began to document the absence of eelgrass adjacent to new lease sites because they found that eelgrass begins to grow in directly adjacent areas as soon as oysters are established. There is a growing body of anecdotal and published scientific information that strongly suggests that oysters have positive effects on eelgrass growth and survival.

In estuaries where oysters are principally found in the intertidal zone their reefs have been shown to protect salt marsh shorelines from erosion. Large, shallow subtidal reefs could potentially have similar effects in this system.

Subtidal oyster shell is an important habitat for many nekton species and has been shown to be essential fish habitat for juvenile seabass, groupers, and snappers. Because both oyster and fish populations in the Great Bay estuary are so diminished, the value of oyster reefs to a variety of fish species is expected (as documented in other estuaries), but specific benefits to individual species in this system is difficult to quantify. It is a well established ecological axiom that habitat complexity gives rise to biodiversity, and oyster reefs offer substantial complexity in comparison to the dominant mud flats of this system. Oyster reefs adjacent to mud flats in other systems have been found to increase juvenile fish abundances on the mud flats, likely due to the increased food availability for fish on reefs.

Fishes serve as major sources of inorganic nutrients in salt marshes, via excretion and bioturbation. Furthermore, migratory behavior of fishes is known to be an important vector of secondary production across habitats (*e.g.* diadromous fishes exchange nutrients and energy between ocean habitats and coastal uplands).

All of the flora and fauna of the estuary require sufficient shoreland buffers (tidal and freshwater riparian) with sufficient natural vegetation. Whether alongside major tidal rivers like the Piscataqua, or on the banks of “step-across” streams high in the watershed, these critical transition zones benefit both adjacent and all downstream habitats. Natural buffers are essential for mediating water flows, accreting sediments and organic matter, cycling and sequestering nutrients, and providing the allochthonous inputs (large and small woody debris and other material) necessary for maintaining diverse habitats and food webs to support fish populations.

Selected References:

Haven, D. and R. Morales-Alamo. 1970. Filtration of particles from suspension by the American oyster *Crassostrea virginica*. Biological Bulletin 139: 248-264.

Dame, R.F. 1996. Ecology of Marine Bivalves: An Ecosystem Approach CRC Preass, Inc. Boca Raton, Florida.

Newell, R.I. 2004 Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: A review. Journal of Shellfish Research 23: 51-61.

Newell, R. E. and E.W. Koch. 2004. Modeling Seagrass Density and Distribution in Response to Changes in Turbidity Stemming from Bivalve Filtration and Seagrass Sediment stabilization. Estuaries 27(5): 793-806.

Zostera may increase *Mytilus edulis* settlement due to eelgrass blade movement and contact with larvae, and directed settlement of larvae toward seagrass beds ("monami"). Grizzle, R.E., F.T. Short, C.R. Newell, H. Hoven, and L. Kindblom. 1996. Journal of Experimental Marine Biology and Ecology. 206: 165-177.

Jones III, E.B.D., G.S. Helfman, J.O. Harper, and P. V. Bolstad. 1999. Effects of riparian Forest Removal on Fish Assemblages in Southern Appalachian Streams. Conservation Biology 13(6): 1454-1465.
Meyer, D.L. E.C. Townsend, and G.W.Thayer. 1997. Stabilization and erosion control value of oyster cultch for intertidal marsh. Restoration Ecology 5(1): 93-99.

Grabowski, J.H. A.R. Hughes, D.L. Kimbro, and M.A. Dolan. 2005. How habitat setting influences restored oyster reef communities. Ecology 86(7): 1926-1935.

Lehnert, R.L. and D.M.Allen. 2002. Nekton use of subtidal oyster shell habitat in a southeastern US estuary/ Estuaries 25(5): 1015-1024.

Haerel-Borer, S.S. D.M. Allen, and R.F. Dame. 2004. Fishes and shrimps are significant sources of dissolved inorganic nutrients in intertidal salt marsh creeks. Journal of Experimental Marine Biology and Ecology. 311 (1): 79-99.

Minello, T.J., K.W. Able, M.P. Weinstein, and C.G. Hays. 2003. Salt marshes as nurseries for nekton: testing hypotheses on density, growth, and survival through meta-analysis. Marine Ecology Progress Series 246: 39-59.

Minello, T.J., K.W. Able, M.P. Weinstein, and C.G. Hays. 2003. Salt marshes as nurseries for nekton: testing hypotheses on density, growth, and survival through meta-analysis. Marine Ecology Progress Series 246: 39-59.

Critical transition zones, such as riparian buffers, benefit adjacent habitats by mediating water flows, accreting sediments and organic matter, and cycling nutrients.
Ewel, K.C. C. Cressa, R.T. Kneib, P.S. Lake, L.A> Levin, M.A. Palmer, P. Snelgrove, and D.H. Wall. 2001. Managing critical transition zones. Ecosystems 4(5): 452-460.

Restoration Landscapes

The final maps in this report integrate the restoration opportunities described above. Figure 17 provides an overview of the entire project area and includes the legend for Figures 18-27. These maps are focused on geographically and, to a large extent, ecologically distinct zones of the estuary. It was not possible to visually display all relevant information collected and created for this project, and GIS users will likely find additional value in exploration of the project's data CD.

Conclusion

This report presents diverse data, of varying detail and quality (relative to modern standards) and attempts to make some sense of it. The authors are mindful that this compilation and analysis has limitations, and that different readers may draw different conclusions. Corrections and improved analyses are warmly welcomed wherever they are indicated. The report is presented as a foundation for improving the knowledge of the past distribution for critically important Great Bay estuary habitats and species, and not as a hard and fast blueprint for how things were, or exactly how they should be. Rather, we hope that the report will be a useful decision *support* tool and a jumping off point for embarking on the sorts of ambitious restoration projects we think are needed to rebuild biodiversity, resilience, and enduring productivity for the Great Bay estuarine system.

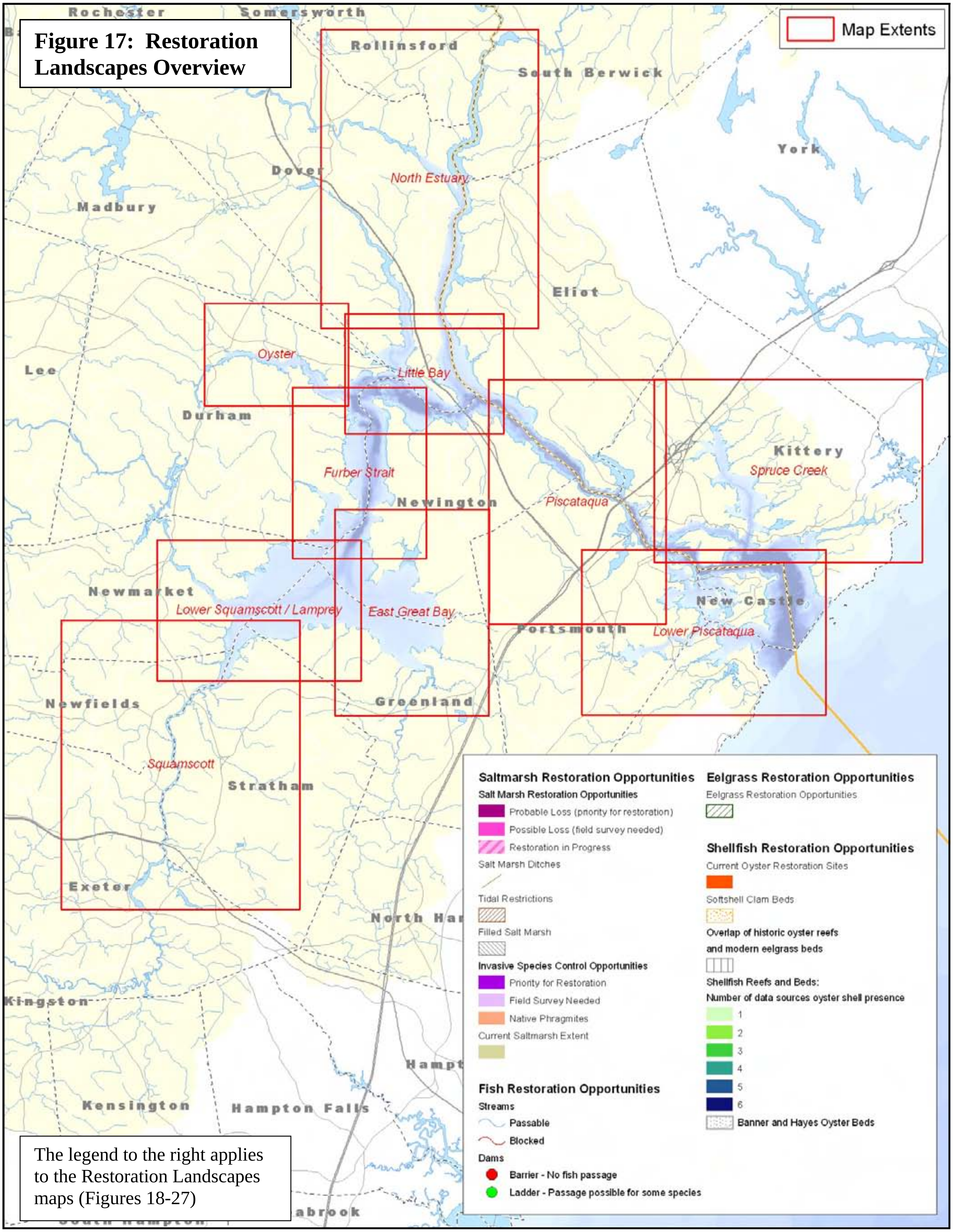
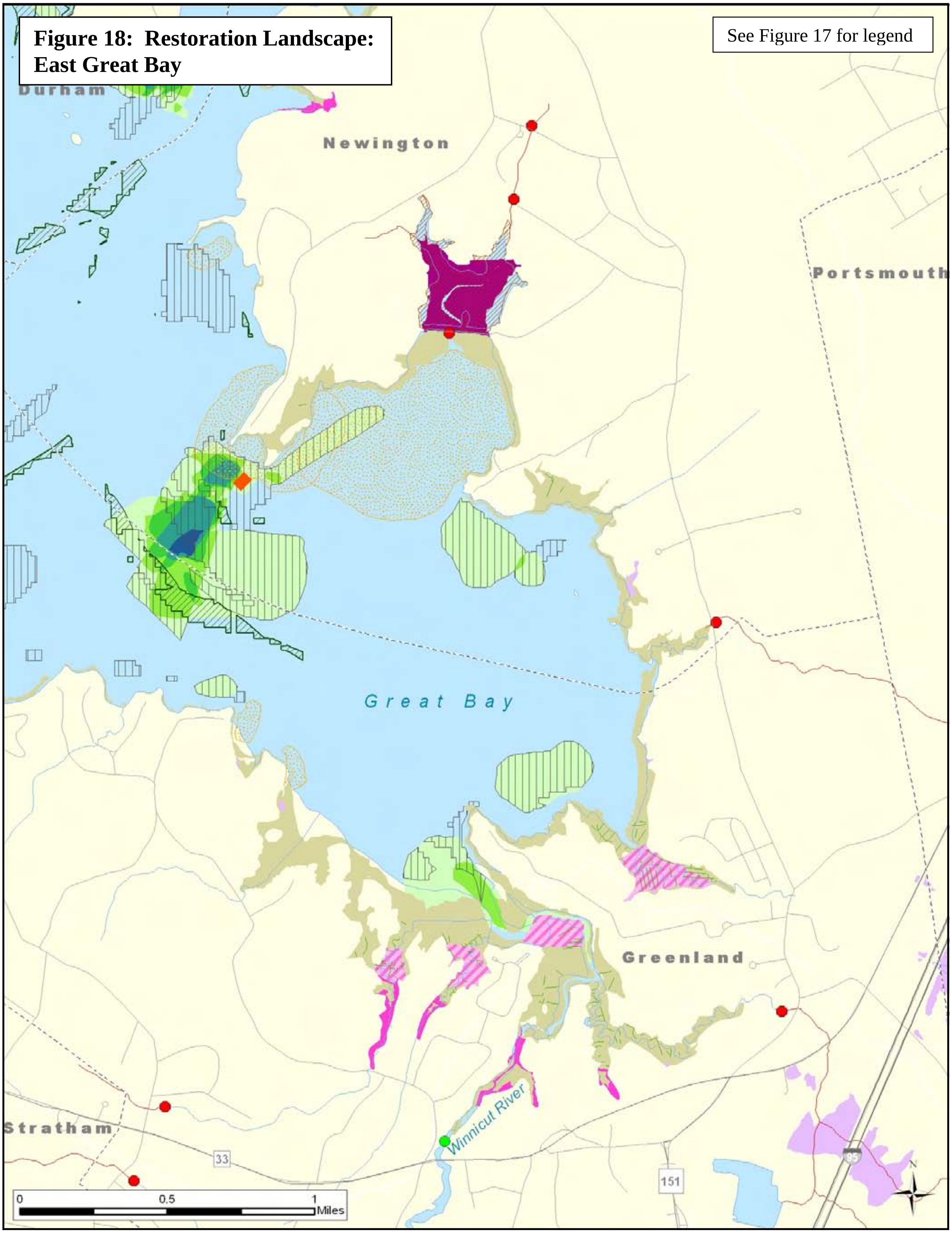


Figure 17: Restoration Landscapes Overview

The legend to the right applies to the Restoration Landscapes maps (Figures 18-27)

Figure 18: Restoration Landscape: East Great Bay



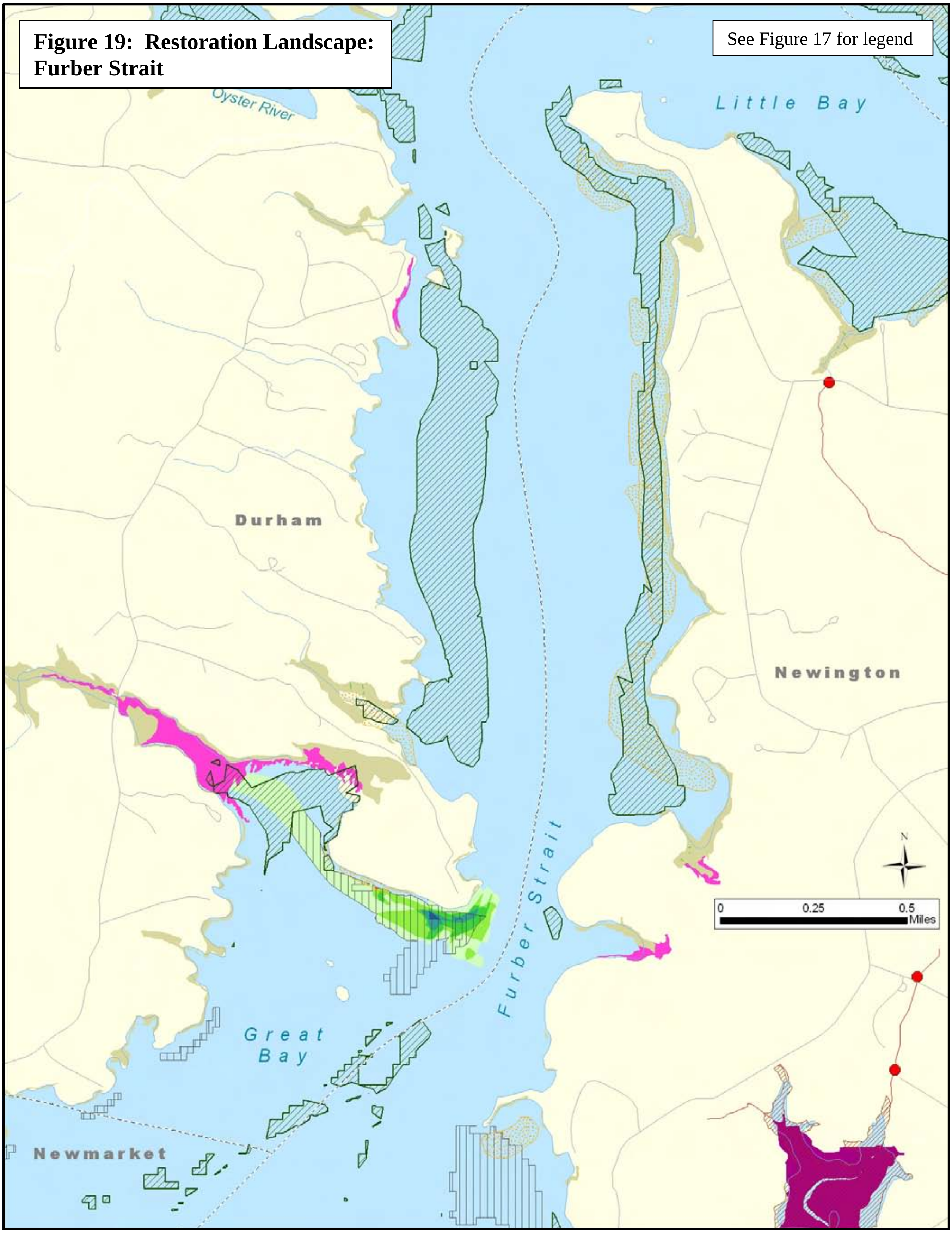


Figure 19: Restoration Landscape: Furber Strait

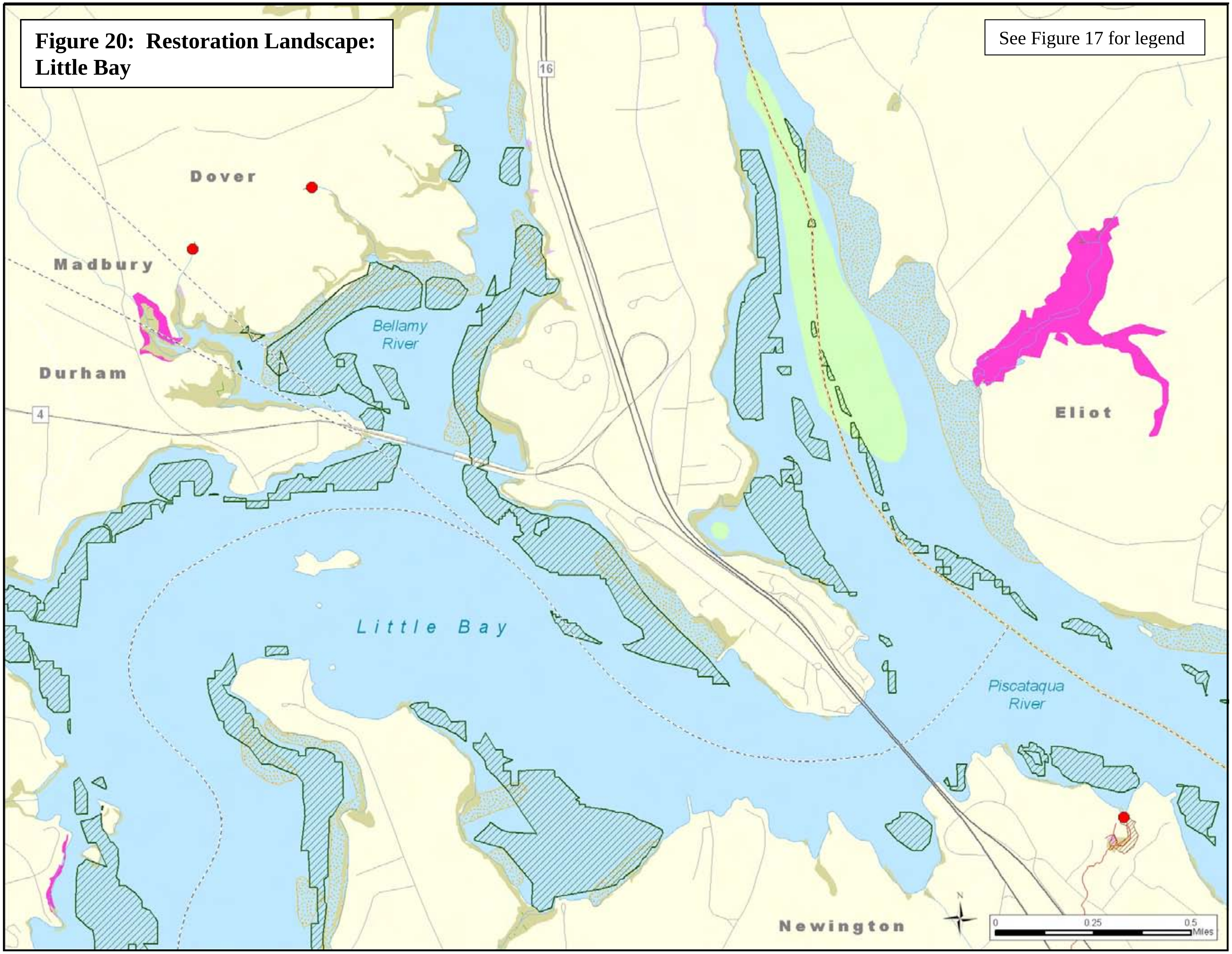


Figure 20: Restoration Landscape: Little Bay
See Figure 17 for legend
Dover
Madbury
Durham
Bellamy River
Little Bay
Eliot
Piscataqua River
Newington
16
4
0
0.25
0.5
Miles

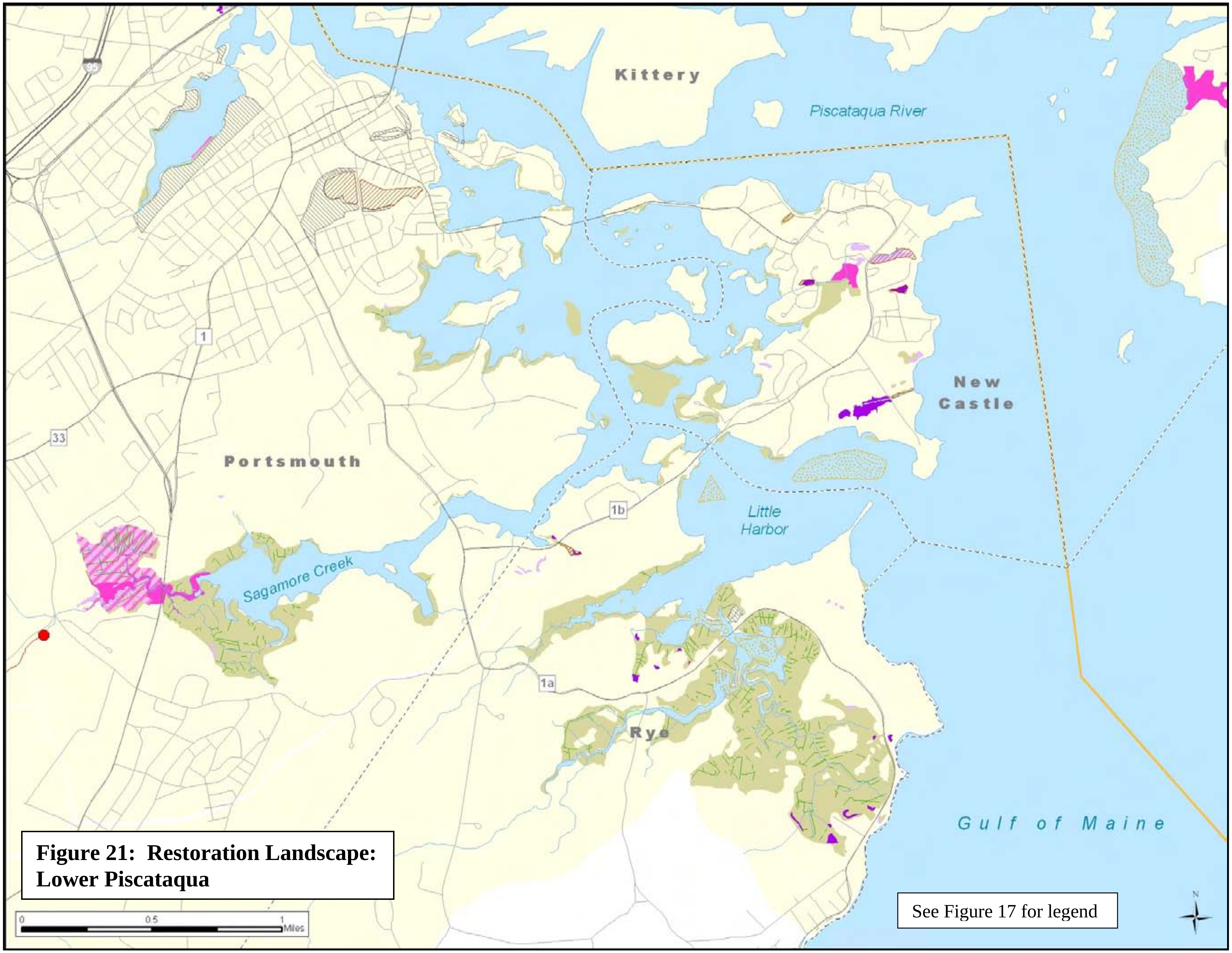


Figure 21: Restoration Landscape: Lower Piscataqua

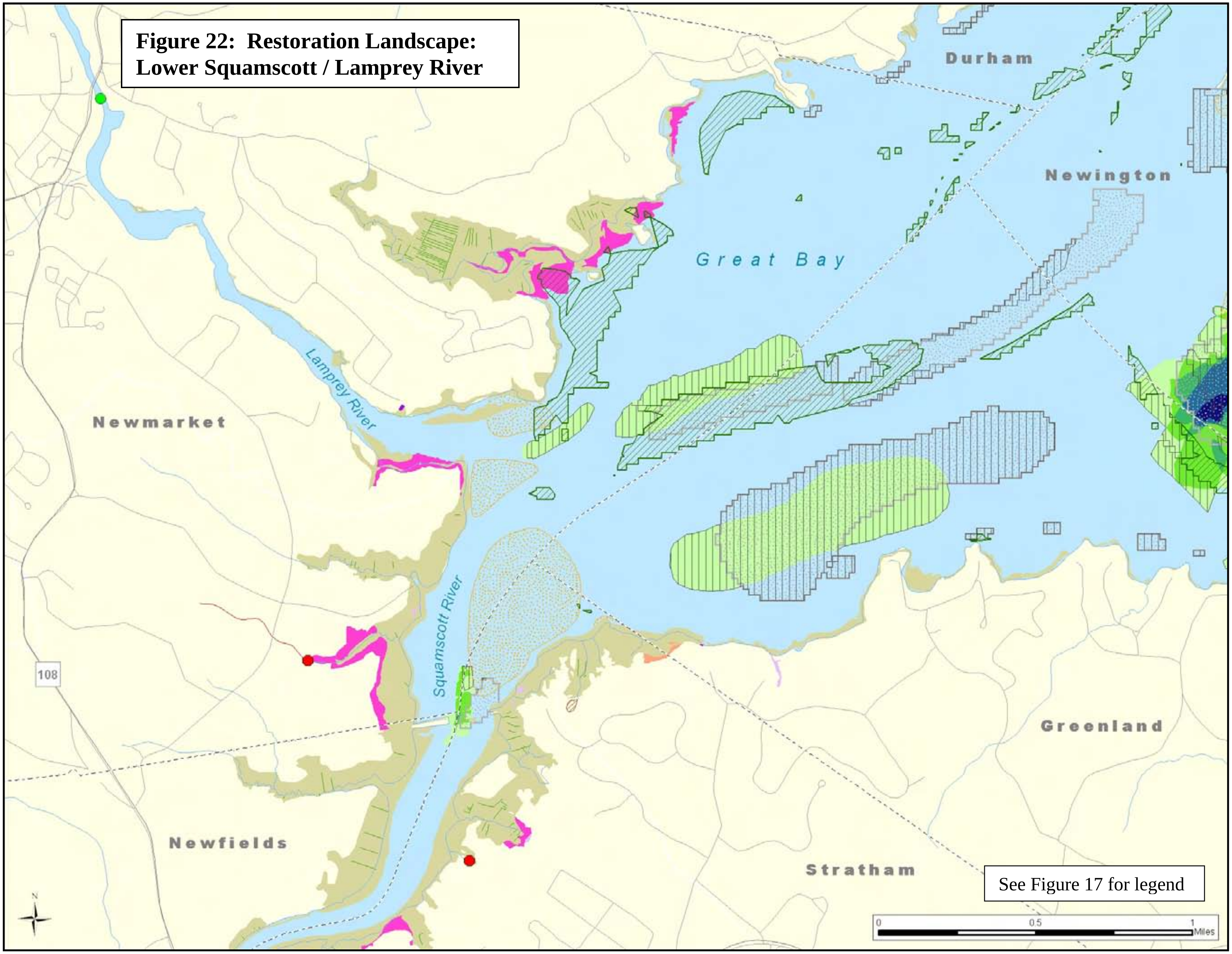
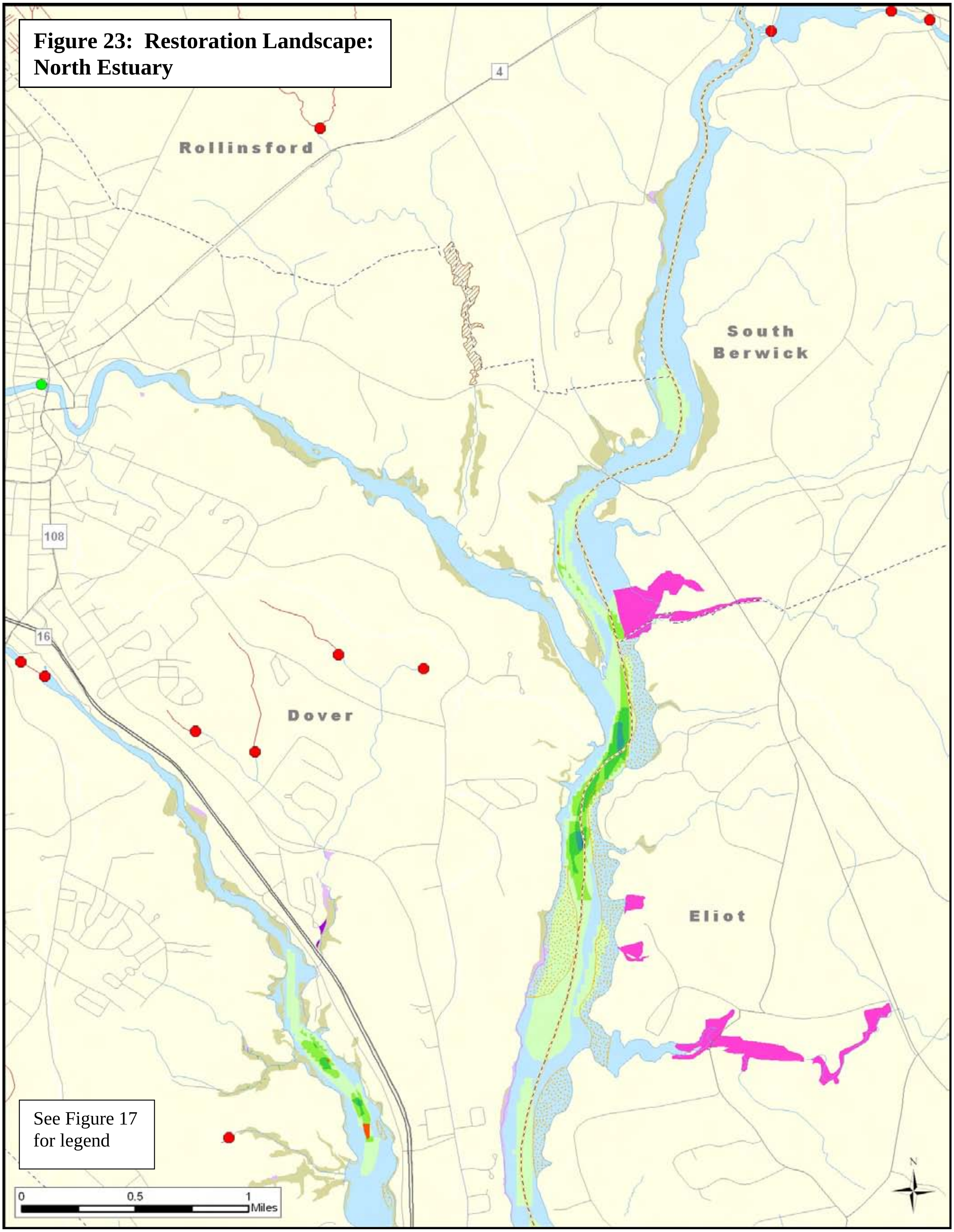


Figure 22: Restoration Landscape:
Lower Squamscott / Lamprey River
Durham
Newington
Great Bay
Lamprey River
Newmarket
Squamscott River
108
Greenland
Newfields
Stratham
See Figure 17 for legend
0
0.5
1
Miles
N

Figure 23: Restoration Landscape: North Estuary



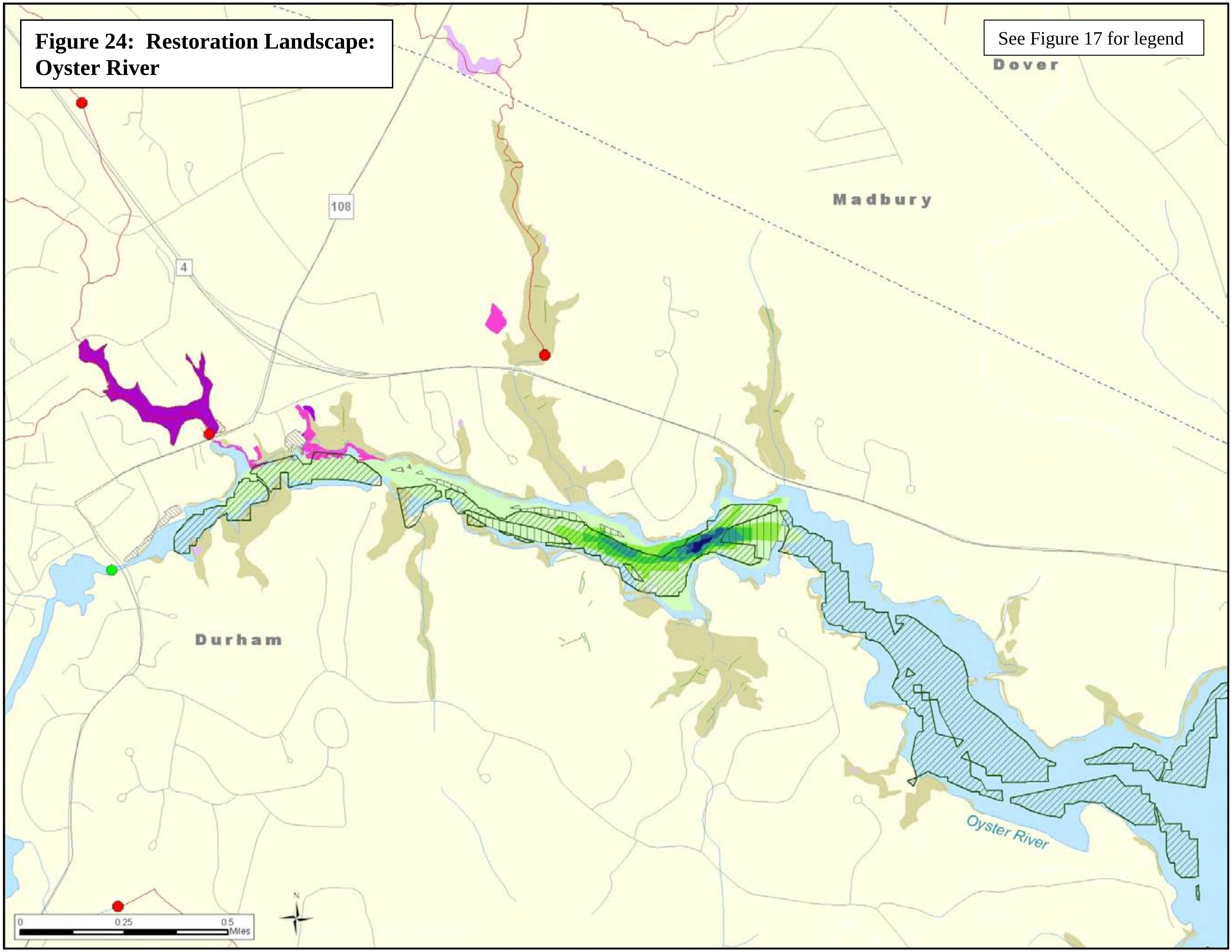


Figure 24: Restoration Landscape:
Oyster River
See Figure 17 for legend
Dover
Madbury
108
4
Durham
Oyster River
0
0.25
0.5
Miles
N

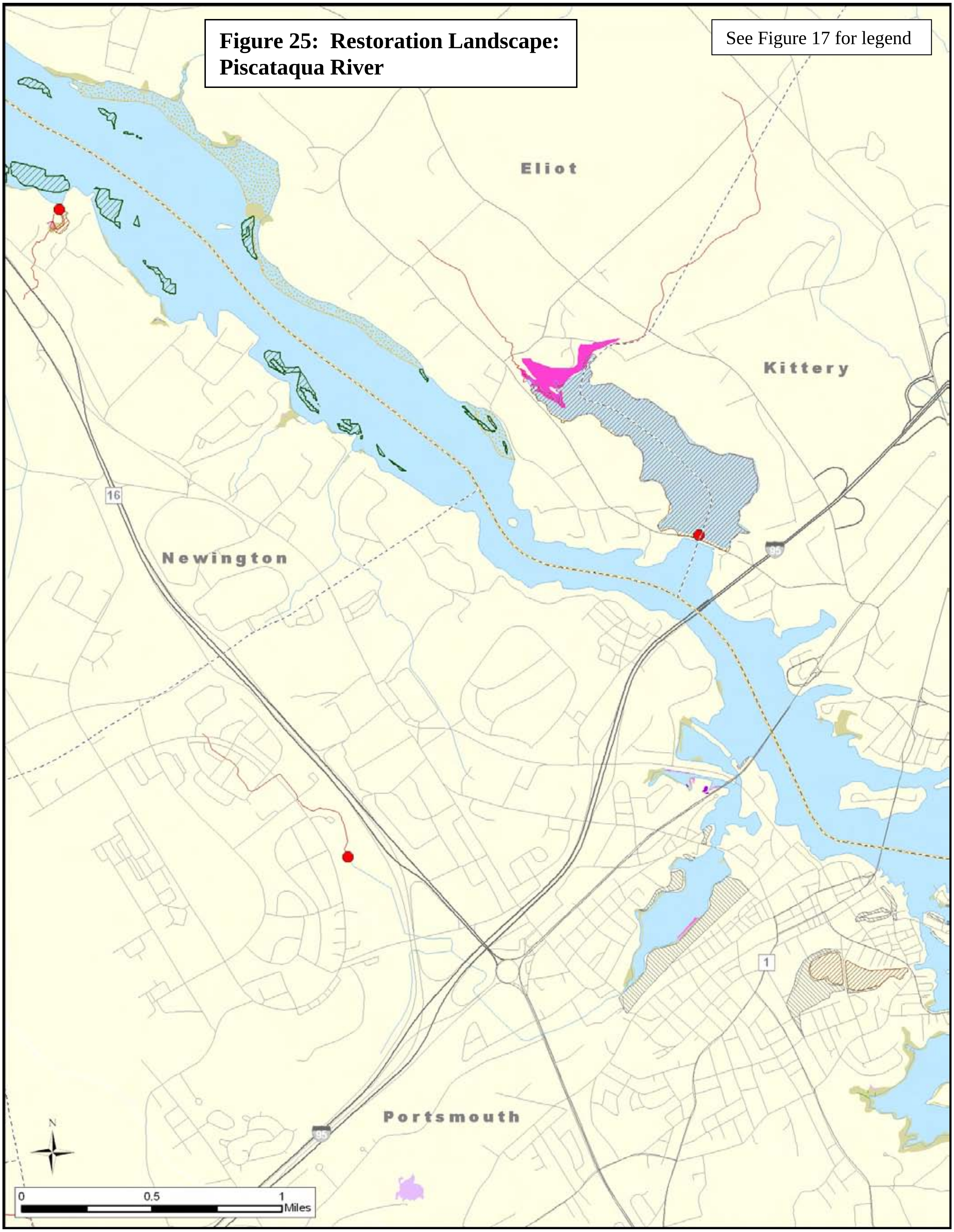


Figure 25: Restoration Landscape: Piscataqua River
See Figure 17 for legend
Eliot
Kittery
Newington
Portsmouth
16
95
1
N
0
0.5
1
Miles

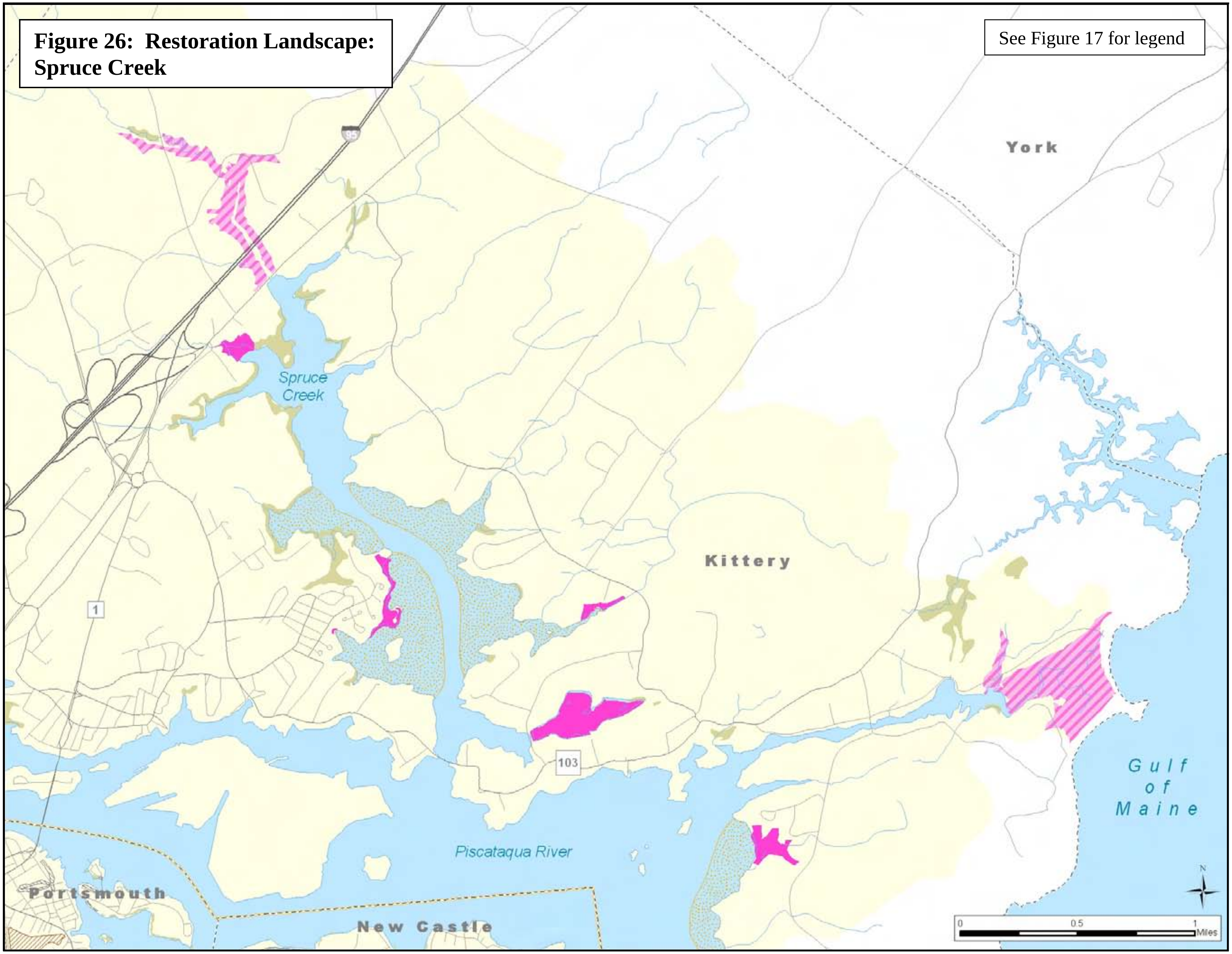


Figure 26: Restoration Landscape: Spruce Creek
See Figure 17 for legend
York
Spruce Creek
Kittery
95
1
103
Gulf of Maine
Piscataqua River
Portsmouth
New Castle
0
0.5
1
Miles
N

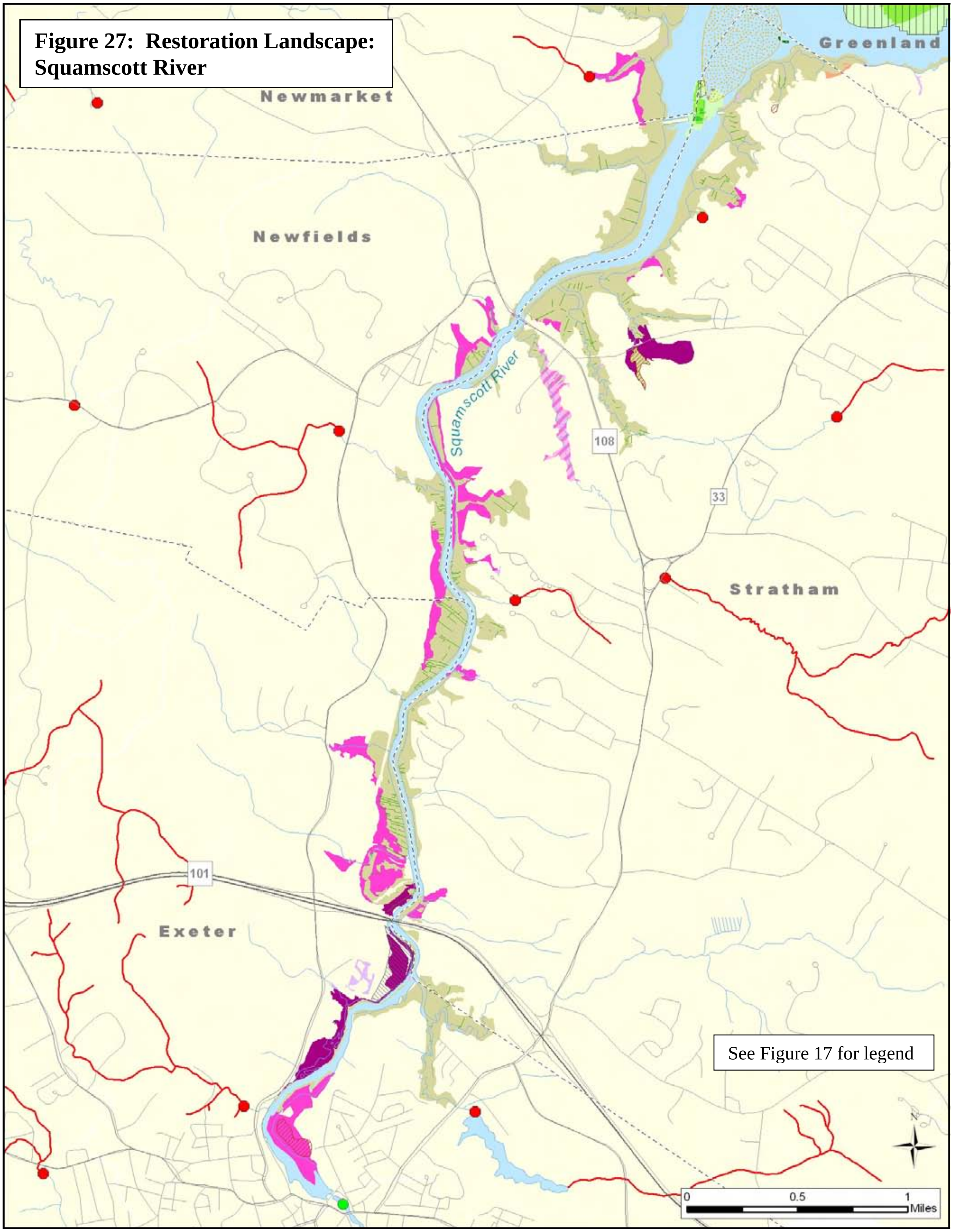


Figure 27: Restoration Landscape:
Squamscott River
Newmarket
Greenland
Newfields
Squamscott River
108
33
Stratham
101
Exeter
See Figure 17 for legend
0
0.5
1
Miles
N

Appendix 1. Dissolved Oxygen Thresholds

Published Oxygen Threshold Values for Select Species			
Species	**DO level (mg/L)**	**Consequence**	**Reference**
American shad	4-5	minimum for adult migration and spawning	Walburg and Nichols 1967, Jessop 1975
	4-5	suitable for juveniles	Burdick 1954
	4-5	successful hatch of healthy larvae	Bradford et al. 1968
	5	lethal barrier to adult migration	Ellis et al. 1947
	<5	total egg mortality	Marcy 1976
	3.5	sublethal effects	Chittenden 1973
	<3	loss of equilibrium (adult and juveniles)	Chittenden 1969
	2-3	33% mortality	Dorfman 1970
	2.5-2.9	LD_{50} of eggs and larave	Bradford et al. 1968
	<2	high adult mortality	Tagatz 1961, Chittenden 1969
	0.6	immediate adult death	Chittenden 1969
American eel	11+ ppm	adults and elvers sensitive below this level	Sheldon 1974
		* fair better in air than in low oxygen	
Atlantic sturgeon	2.8-3.3	87.5% mortality to 150-200 day old at 26C (37-44% sat)	Secor and Gunderson 1998
	2.3-3.2	22% mortaity for 150-200 day old at 20C (27-37% sat)	Secor and Gunderson 1998
	4.3-4.7	YOY (~30-200 days old) - lost production at 60% sat	Secor and Niklitschek 2001
	=3.3	acute and chronic lethal effects	Secor and Niklitschek 2001
	>5	0% mortality fo 150-200 day old at 20-26degC	Secor and Gunderson 1998
Atlantic salmon		oxygen requirements are greatest just prior to hatching	Crisp 1993
	7+	~100% egg survival	Crisp 1996
	5.0-5.5	general YOY requirement (80% sat) but varies by activity, feeding, & temp	Crisp 1993
	<6	low hatching/embryo survival	Lacroix 1985
Blueback herring	1.3 ppm @ 24.6C	Mass mortality	Moss et al 1976
	3.6 ppm @ 27.6C	Mass mortality	Moss et al 1976
Sea-run brook trout	<5	trout avoid area	Spoor 1990
River herring	>5 ppm	threshold levels required to prevent sublethal and lethal effects	NHF&G 2006 (pers.comm)
Rainbow smelt	>5 ppm	threshold levels required to prevent sublethal and lethal effects	NHF&G 2006 (pers.comm)

References

Bradford, A.D., J.G. Miller, and K. Buss. 1968. Bioassays on eggs and larval stages of American shad, Alosa sapidissima. Pages 52-60 in F.T. Carlson, 1968. Suitability of the Susquehanna River for the restoration of shad. U.S. Department of the Interior, Maryland Board of Natural Resources, New York Conservation Department,

Burdick, G.E. 1954. An analysis of the factors, including pollution, having possible influence on the abundance of shad in the Hudson River. N.Y. Fish Game Journal 1:188-205.

Chittenden, M.E. Jr. 1969. Life history and ecology of the American shad, Alosa sapidissima, in the Delaware. Ph.D. dissertation. Rutgers University, New Brunswick, NJ. 458 pp.

Chittenden, M.E. Jr. 1973. Effects of handling on oxygen requirements of American shad, *Alosa sapidissima*. J. Fish. Res. Bd. Can. 30:105-110.

Crisp, D.T. 1993. The environmental requirements of salmon and trout in fresh water. Freshwater Forum 3:176–202.

Crisp, D.T. 1996. Environmental requirements of common riverine European salmonid fish species in fresh water with particular reference to physical and chemical aspects. Hydrobiologia 323:201-221.

Dorfman, D. 1970. Responses of some anodromous fishes to varied oxygen concentrations and increased temperatures. Ph.D. dissertation, Rutgers University, New Brunswick, 76 pp.

Ellis, M.M., B.A. Westfall, D.K. Meyer, and W.S. Platner. 1947. Water quality studies of the Delaware River with reference to shad migration. U.S. Fish and Wildlife Service Spec. Sci. Rep. No. 38. 19 pp.

Jenkins, W.E., T.I.J. Smith, L.D. Heyward, and D.M. Knott. 1993. Tolerance of Shortnose Sturgeon, Acipenser brevirostrum, Juveniles to Different Salinity and Dissolved Oxygen Concentrations. Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies 47: 476-484.

Jessop, B.M. 1975. A review of the American shad (Alosa sapidissima) stocks of the St. John River, New Brunswick, with particular references of to the adverse effects of hydroelectric developmens. Can. Fish. and Mar. Serv. Resour., Dev. Branch Mar.-T. Reg. Tech. Rep. Ser. Mar./T. 75-6:1-23.

Lacroix, G.L. 1985. Survival of eggs and alevins of Atlantic Salmon (Salmo salar) in relation to the chemistry of interstitial water in redds in some acidic streams of Atlantic Canada, Canadian Journal of Fisheries and Aquatic Sciences 42(2): 292-299.

Marcy, B.C. Jr. 1976. Early life history studies of American shad in the lower Connecticut River and the effects of the Connecticut Yankee Plant. American Fisheries Society Monographs 1: 141-168.

Moss, S. A., Leggett, WC, Boyd, W. A. 1976. Recurrent mass mortalities of. the blueback herring, Alosa aestivalis, in. the Lower Connecticut River. Am. Fish. Soc. Mongr. 1:227-234

Secor, D.H. and T.E. Gunderson. 1998. Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon, *Acipencer oxyrhynchus,* in North America. Environmental Biology of Fishes 14:61-72.

Secor, D.H. and E.J. Niklitschek. 2001. Hypoxia and Sturgeons. Report to the Chesapeake Bay Program Dissolved Oxygen Criteria Team. Technical Report Series No. TS-314-01-CBL

Spoor, W.A. Distribution of fingerling brook trout, Salvelinus fontinalis (Mitchill), in dissolved oxygen concentration gradient. Journal of Fish Biology 36 (3): 363-373.

Sheldon, W.W. 1974. Elvers in Maine; techniques in locating, catching, and holding. Maine Department of Marine Resources, Augusta, ME. 27 pp.

Tagatz, M.E. 1961. Tolerance of striped bass and American shad to changes in temperature and salinity. U.S. Fish Wildlife Service Spec. Sci. Rept. Fish. No. 388. 8 pp.

Walburg, C.H. and P.R. Nichols. 1967. Biology and management of the American shad and status of the fisheries, Atlantic coast of the United States, 1960. US Fish and Wildlife Service. Spec. Sci. Rep. Fish. 550. 105 pp.

Appendix 2. Dissolved Oxygen Sampling

Objective

To evaluate the habitat quality of dam impoundments for fish.

Methods

A YSI 6000 datasonde was deployed at 7 sites in the downstreammost sections of 5 tributaries of the Great Bay estuary (Table A2.1). Datasondes were deployed in impoundments upstream of dams for 4-6 days and set to record at 15 minute intervals. Data were collected for dissolved oxygen (mg/L and percent saturation) and temperature. Detailed methods for datasonde calibration, programming, and deployment are described below. The dissolved oxygen criterion of 6.0 mg/L for Class A waters in NH (NH DES 1999) was used in this project. Dissolved oxygen conditions below this level can have harmful effects on the target species.

Table A2.1. Dissolved oxygen sampling sites

Dam name	River	Town	State	Longitude	Latitude
Rollinsford	Salmon Falls	Rollinsford	NH	-70.8183	43.2378
Central Ave.	Cocheco	Dover	NH	-70.8750	43.1967
Macallen	Lamprey	Newmarket	NH	-70.9347	43.0811
Wiswall	Lamprey	Durham	NH	-70.9633	43.1039
Pickpocket	Exeter	Exeter	NH	-71.0017	42.9694
Exeter	Exeter	Exeter	NH	-70.9444	42.9811
Oyster	Oyster	Durham	NH	-70.9194	43.1306

Results

Of the 7 sites sampled, 4 were found to violate the dissolved oxygen criterion of 6.0 mg/L. Seventy percent of the samples collected in the impoundment upstream of the Oyster River dam exceeded the dissolved oxygen criteria (Fig. A2.1). Samples collected from the Exeter River dam impoundment exceeded the dissolved oxygen criteria 39.2% of the time; while samples from the Macallen and Pickpocket dams exceeded the dissolved oxygen criteria in 19.0% and 20.0% of samples, respectively. The remaining sites had dissolved oxygen levels greater than 6.0 mg/L in all samples.

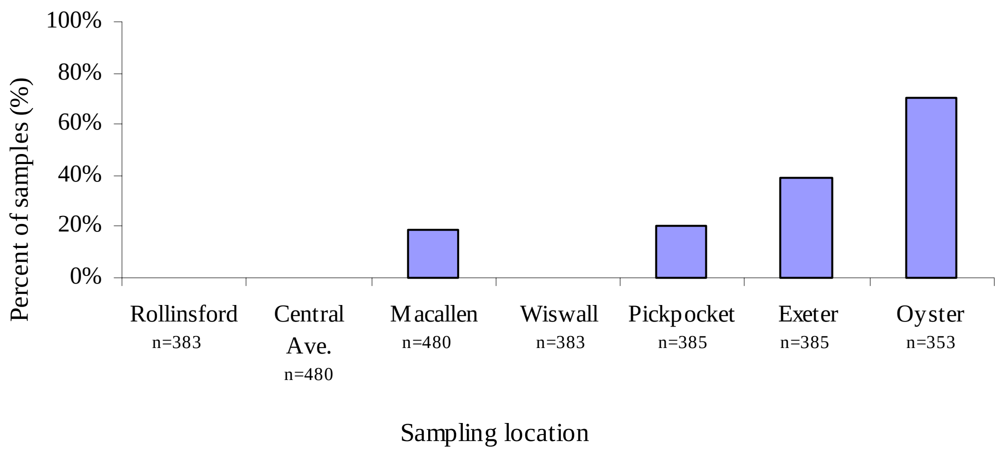


Figure A2.1. Proportion of samples violating dissolved oxygen criteria of 6 mg/L

Dissolved oxygen levels remained stable at all sites with the exception of the Oyster River Dam impoundment, where dissolved oxygen levels fluctuated greatly (Fig. A2.2). A trend of increasing dissolved oxygen during daylight, and decreasing levels at night was observed. While the overall trend followed a pattern typically associated with the occurrence of photosynthesis, the anoxic conditions at sundown are of concern. The very low oxygen levels suggest high rates of respiration and decomposition, possibly due to excessive algal growth resulting from a build-up of nutrients in this impoundment. A fish ladder exists to support the movement of river herring upstream of the Oyster River Dam; however, the low dissolved oxygen levels observed in the impoundment will likely result in high energetic costs to migrating fish, or even mortality.

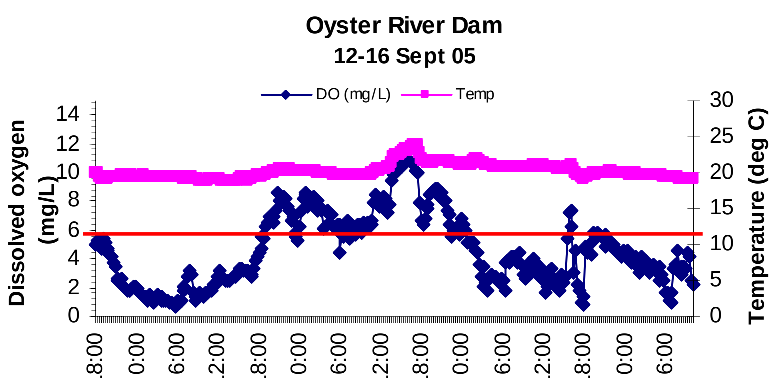


Figure A2.2. Dissolved oxygen levels upstream of the Oyster River Dam, Durham, NH.

GBERC DISSOLVED OXYGEN DATA COLLECTION METHODS
YSI 6000

CLEAN AND PREPARE THE DATASONDE (To be done 24 hours prior to calibration)

1. Rinse sensor with deionized water to remove debris. If necessary, dampen a lint-free cloth (*e.g.* Kimpwipe®) with methanol to remove accumulated materials.
2. Remove o-ring and membrane. Drain electrolyte.
3. Rinse sensor cavity with deionized water. Refill sensor cavity with new electrolyte until a perceptible meniscus of electrolyte forms above the electrode surface of the sensor. Ensure that air bubbles are not present in the sensor cavity.
4. Before installing a new membrane, make sure that the O-ring groove and the probe tip are clean and smooth. If the KCl electrolyte solution leaks from the probe surface during monitoring studies, the readings are likely to be less accurate in a shorter period of time.
5. Replace membrane and o-ring. Make sure that there are no air bubbles under the membrane and finger prints on the membrane. Trim the excess membrane material.
6. Place the datasonde in a calibration cup with a wet sponge and let it rest for 24 hours prior to calibration.

PRE-DEPLOYMENT PROGRAMMING (To be done prior to calibration)

1. Connect the communication cable to the computer and the datasonde.
2. Open the EcoWatch software and click on the datasonde icon, and 'Com 1' to access the main menu.
3. Select '6. Report set-up' and verify that the following parameters are slected (have an asterisk next to them): Temp (C), Cond (µS/cm), Sal (ppt), DO (%), DO (mg/L), Depth, Batt (V). Pres 'ESC' to save the settings and return to the main menu.
4. Select '1. Run' from the main menu.
5. Select '3. Unattended sample' from the Run menu. The current time and date, all active sensors, battery voltage and free flash disk space will be displayed.
6. Enter the following information for the sampling study:
    A. Starting date: (XX/XX/XX)
    B. Starting time: (XX:XX:XX)
    C. Duration in days: (XX.XXX)
    D. Interval in minutes: (15)
    E. Site description:
7. Note: The time entry must include hours, minutes, and seconds. Therefore, a study starting at 8 AM should be entered as 8:00:00.
8. Check the information carefully. If it is correct, press 'Y' when asked if the start-up information is correct.
9. From the main menu, select '4. Status' to check that the correct sensors are recording, the batteries have adequate power, and the flash disk has enough space.

PRE-DEPLOYMENT CALIBRATION

1. Ensure that there is 1/8 in (3mm) of water or a wet sponge in the bottom of the calibration cup. Place the probe end of the datasonde into the cup and make sure that the probe is not immersed in water. Prop the datasonde up in the cup so that the cup is vented to the atmosphere (*e.g.* unscrew the screws on the probe cover to prop it up on the cup).
2. Run the instrument in discrete sample mode (at an interval of 4 seconds) and record the first 10 DO % readings on papers.
3. The numbers must start at a high number and decrease with each 4 second sample. If the probe starts at a low number and steadily increases then the sensor has a problem and must be rejected. Allow the instrument to run until the numbers stabilize. It does not matter what the actual number is since the probe has not been calibrated yet. Make certain that *both the DO reading and the temperature* have stabilized (10-15 minutes) before starting the calibration sequence. A wet thermistor can indicate artificially low temperature readings due to evaporation and this situation will result in poor temperature compensation and inaccurate readings.
4. Record the DO charge from the 'Diagnostics' menu. The DO charge should be between 25-75. Counts below this range indicate low electrolyte or a tear in the membrane. Counts above this may be due to oxidation of the electrodes.
5. From the 'Calibrate' menu select '2. DO %'.
6. Enter the current barometric pressure in mm Hg (inches of Hg x 25.4 = mm Hg; millibars x 0.75 = mm Hg) Press 'Enter' and the computer will indicate that the calibration procedure is in progress.
7. After approximately 1 minute the calibration will be complete. Press any key, as instructed, and the screen will display the percent saturation value which corresponds to your local barometric pressure input (*e.g.* if the barometer reads 742 mm Hg, the screen will display 97.6% (742/760)).
8. NOTE: Calibration of dissolved oxygen in the DO % procedure also results in calibration of the DO mg/L mode and vice versa.
9. Rinse the datasonde in water and dry the datasonde.

DATASONDE DEPLOYMENT

1. Determine if the impoundment to be sampled is thermally stratified by collecting a depth profile of the impoundment with a handheld dissolved oxygen meter.
2. If stratified, deploy the datasonde at the bottom of the epilimnion.
3. If not stratified, deploy the datasonde at 25% of the depth of the impoundment (*e.g.* the datalogger should be placed at a depth of 5 feet in a 20 foot deep impoundment.)

POST-RETRIEVAL INSTRUMENT QUALITY ASSURANCE CHECK

1. Retrieve the datasonde from the water and visually examine the probes for fouling and damage.

2. Gently clean the datasonde of debris and place it in a secure container that will prevent any severe vibrations to the unit during transportation.
3. Connect the datasonde to the communication cable and open the EcoWatch software.
4. Carefully use a lint-free cloth to remove any water droplets from the dissolved oxygen membrane.
5. Place the datasonde in the calibration cup with a wet sponge. Prop the datasonde up in the cup so that the cup is vented to the atmosphere (*e.g.* unscrew the screws on the probe cover to prop it up on the cup). Allow adequate time for the air to become saturated and the temperature to stabilize (15 minutes to 2 hours depending on the datasonde temperature).
6. Record the dissolved oxygen concentration (mg/L) and saturation (%) and verify that the DO calibration has not strayed.

DATA RETRIEVAL

1. From the datasonde main menu select ‘1. Run’.
2. Select ‘3. Unattended sample.’ The screen will display a prompt asking if you wish to cancel the unattended sampling study. Press ‘Y’ and ‘Enter’ to stop the unattended study. Note: If unattended sampling has already stopped because the duration of the sampling has expired, pres ‘ESC’ twice to return to the main menu.
3. From the main menu select ‘3. File.’
4. From the file menu select ‘3. Quick upload.’ Note: Quick upload will automatically upload data from the most recent sampling event. If retrieving data from an earlier sampling, select ‘2. Upload’ and then select the file to upload.
5. Select ‘2. Comma & " " Delimited’ for the upload data format.
6. A File transfer status screen will display.
7. When the data have finished transferring, access the newly created file from the following folder: C:\Program Files\Ecowatch\data and open it in Excel.

INTERIM DATASONDE STORAGE

1. Place enough water in the calibration cup to provide humidity (~1/4 inch of water, or a wet sponge), but not enough to cover the probe surfaces. Any type of water can be used: distilled, deionized, or tap.)
2. Make sure the storage vessel is sealed to minimize evaporation.
3. Check the vessel periodically to make certain that water is still present. If the membrane appears to be damaged or has dried out, be sure to replace it prior to calibration and deployment.

Methods have been adapted from the following sources:

YSI Incorporated. 6000UPG Multi-Parameter Water Quality Monitor Instruction Manual. Revision E, April 1997.

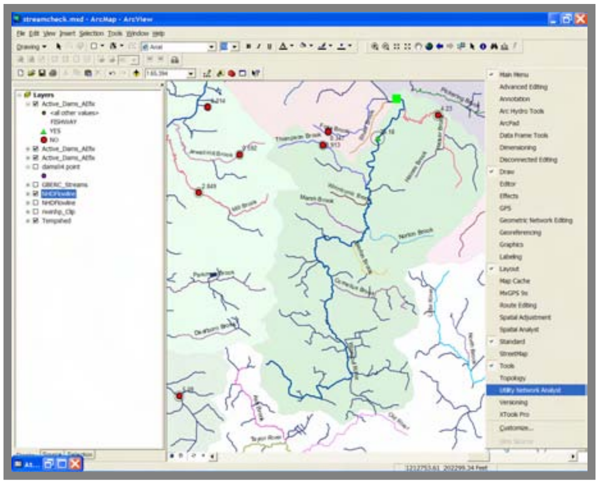
NH DES. Ambient River Monitoring Program Standard Operating Procedures (SOP) Datasonde 4a and MiniSonde 4a Multiprobe. Revision 3, March 2004.

National Estuarine Research Reserve System-Wide Monitoring Program (SWMP). YSI 6-Series Multi-Parameter Water Quality Monitor Standard Operating Procedure. Version 3.0, December 2000.

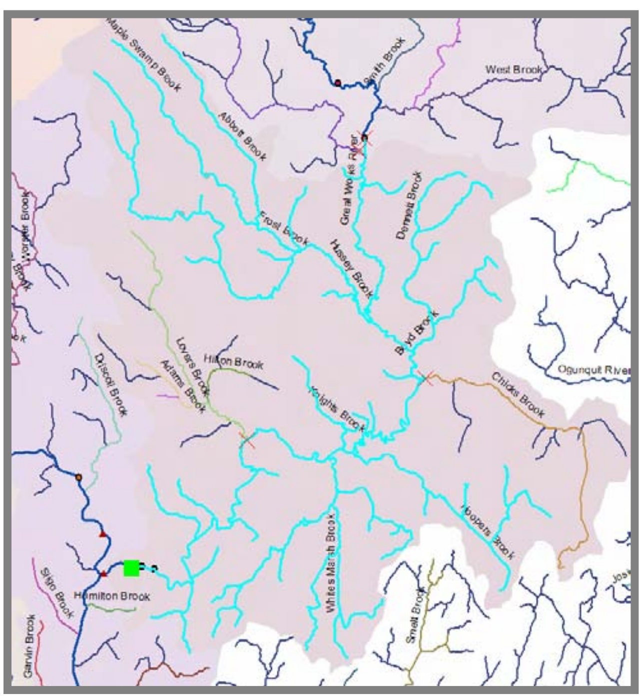
Appendix 3. Network Utility Analyst Tool

Using the Network Utility Analyst tool in ArcView 9.x to Evaluate Impact of Dams and other Barriers

1. Load NHHD flowline features (or another route-coded NHD stream geodatabase) to the table of contents.
2. Right click on the taskbar and select the Utility Network Analyst tool.



3. Select Analysis, Options, Return results as selection from the tool bar.
4. Click the drop down menu next to the little blue flag symbol to select “Edge flag tool”
5. Click the map at the stream section(s) you would like to start a trace from, this will leave a green square on the map
6. Click the drop down menu again and select “Edge barrier tool”
7. Click the map with this tool to indicate where traces should stop (*e.g.* dams and waterfalls), this will leave red Xs on the map.
8. Then select desired action (*e.g.* “Find upstream accumulation” from drop down menu and click the “Solve” icon. Manual selection adjustment may be necessary.



9. The resulting selection can be queried, saved as a layer file, or used to create a new selection from another file (*e.g.* Select by location, where line segments are coincident). The NHDflowline was exported to shapefile format to get around ArcMap geodatabase editing constraints. The “select by location” method, followed by right clicking field headings in shapefile tables is a useful and efficient way to change attribute codes for multiple stream segments.