DRAFT 12/22/2017

Great Marsh Barriers Assessment

Regional Inventory and Assessment of Risk and Impact of

Barriers to Flow in Coastal Watersheds of the North Shore of Massachusetts

A Component of the Great Marsh Resiliency Project

Overview

This report summarizes work conducted as part of the Barriers Assessment component of the Great Marsh Resiliency Project. The Resiliency Project was funded by the National Fish and Wildlife Foundation through the Hurricane Sandy Coastal Resiliency Competitive Grant Program and led by the National Wildlife Federation. The project included five separate sub-projects aimed at increasing the resiliency of the Great Marsh and the PIE-Rivers Region.

The term “barriers” in this report refers to human-made structures that may impede flow, fluvial and coastal processes (dams, non-tidal stream/river crossings, tidal crossings, and coastal stabilization structures). The interruption of important physical, chemical and ecological processes can reduce the overall resilience of our coastal watersheds, making our communities more vulnerable to extreme weather events and our ecological resources less sustainable.

As our region has become more developed, waterways and coastlines have been dotted with more infrastructure and more aquatic barriers. Many of these structures have aged past their design life and are in need of replacement or removal, while others were not designed to effectively pass wildlife or to manage high flows associated with extreme weather. New England has experienced more frequent floods since 1970 (Armstrong, Collins, & Snyder, 2011), increasing the risk of failure for aging and/or undersized structures. The extreme damage caused by recent large storms, including the Mother’s Day Storm (2006), Hurricane Irene (2011) and Hurricane Sandy (2012) has highlighted these risks. These weather events have also drawn attention to the importance of some of the ecosystem services provided by naturally functioning aquatic systems, including flood attenuation and protection against storm surge. The presence of aquatic barriers limits the ability of the system to serve some of these functions.

The Ipswich River Watershed Association (IRWA) inventoried and assessed 1,020 potential barriers across the 280 square mile region as part of the most comprehensive effort we are aware of in this portion of New England. The inventory included an extensive desktop GIS analysis, thorough review of information from previous reports and on-the-ground surveys of more than 500 road-stream crossings to supplement existing IRWA data sets. The structures were then assessed and prioritized using screening tools that considered both ecological impact and infrastructure risk. This comprehensive approach provides a novel, regional assessment of barriers in the Great Marsh and its contributing watersheds. This report and the combined results of the screening analyses are intended to be used as tools for local governments, private owners and restoration practitioners to identify sites that warrant further investigation, especially where infrastructure and ecological risk appear to overlap. We hope this will identify opportunities for projects to be initiated and implemented that achieve dual benefits with respect to community resilience and ecological integrity. This framework will allow municipal officials, restoration practitioners and others to identify and further pursue work at sites while considering the position of the site and relative importance within the landscape and watershed.

Table of Contents

Acknowledgments

This report is the culmination of a multi-year process that would not have been possible without the support of an excellent team of funders, partners, staff and volunteers. The National Fish and Wildlife Foundation (NFWF) provided generous funding to support the project through the Hurricane Sandy Coastal Resilience Grant Program. We are grateful to our project partners including the National Wildlife Federation, Trout Unlimited, Meridian Associates, the Great Marsh Resiliency Partnership and members of the broader Parker-Ipswich-Essex-Rivers Partnership (PIE-Rivers).

Colin Lawson and Erin Rodgers with Trout Unlimited were instrumental to the project, providing the methodology for and implementing the Hydraulic Capacity model. Thanks to Chris Ryan (Meridian Associates) for the many hours and phone calls developing conceptual designs for road-stream crossing replacements. George Comiskey of the Parker River Clean Water Association helped locate a hard-to-find copy of a 1996 tidal crossings report that we used in our review.

We would also like to thank a number of staff members at the Massachusetts Division of Ecological Restoration (DER) for their support in various aspects of the project. Beth Lambert and Kris Houle provided early access and technical support allowing us to incorporate DER's dam restoration potential model into our analysis. Hunt Durey provided a copy of and technical support for the Draft Great Marsh Plan (2006). Tim Chorey provided critical technical support to guide crossing design and contribute materials to guide next steps in the crossing replacement process.

The field component of this project was extensive and sometimes demanding, including work in all weather conditions and battles with ticks, mosquitos and poison ivy. Our seasonal team members who did the bulk of the survey work included Kelsey Davison, Kayla Dorey, Shannon Gentile, Aaron Hume, Emily Korman, Meghan Sullivan, Cassie Tragert and Joanna Yelen. We are also very grateful to the many volunteers who accompanied us and assisted with surveys over the course of the project.

This project could not have been completed without the support of the entire staff at the Ipswich River Watershed Association. A particularly big thanks to Ryan O'Donnell for his help with surveys and managing seasonal staff. Finally, thank you to Wayne Castonguay and Kristen Grubbs for their help connecting with municipalities and reviewing this document.

The Region

The geographic scope of this project includes the watersheds of the Parker, Ipswich and Essex Rivers (PIE-Rivers) as well as some additional areas in the coastal municipalities of Newburyport and Salisbury, MA. The PIE-Rivers watersheds are the principal contributing watersheds to the Great Marsh Area of Critical Environmental Concern (ACEC) and include much of the city of Newburyport. The study also includes the portion of Newburyport that is within the Merrimack River watershed and the Town of Salisbury in its entirety. These additional areas were incorporated so that the study region includes all of the municipalities included in the Great Marsh Coastal Adaptation Planning effort associated with our work. In total, the project area includes approximately 280 square miles and all or parts of 29 towns (Figure 1).

Portions of seven of the municipalities fall within tidally influenced coastal areas of the Great Marsh study region. These are the Towns of Essex, Ipswich, Newbury, Rowley, and Salisbury as well as the Cities of Gloucester and Newburyport (Table 1). These coastal municipalities may have all four of the barrier types assessed in this report. The rest of the municipalities are in the non-coastal portion of the study region and therefore by definition have no tidal crossings or coastal stabilization structures (Table 2). These “inland towns” include a number of municipalities that are located on the coast (e.g. Manchester, Beverly), but their coastal zones are not part of the study region.

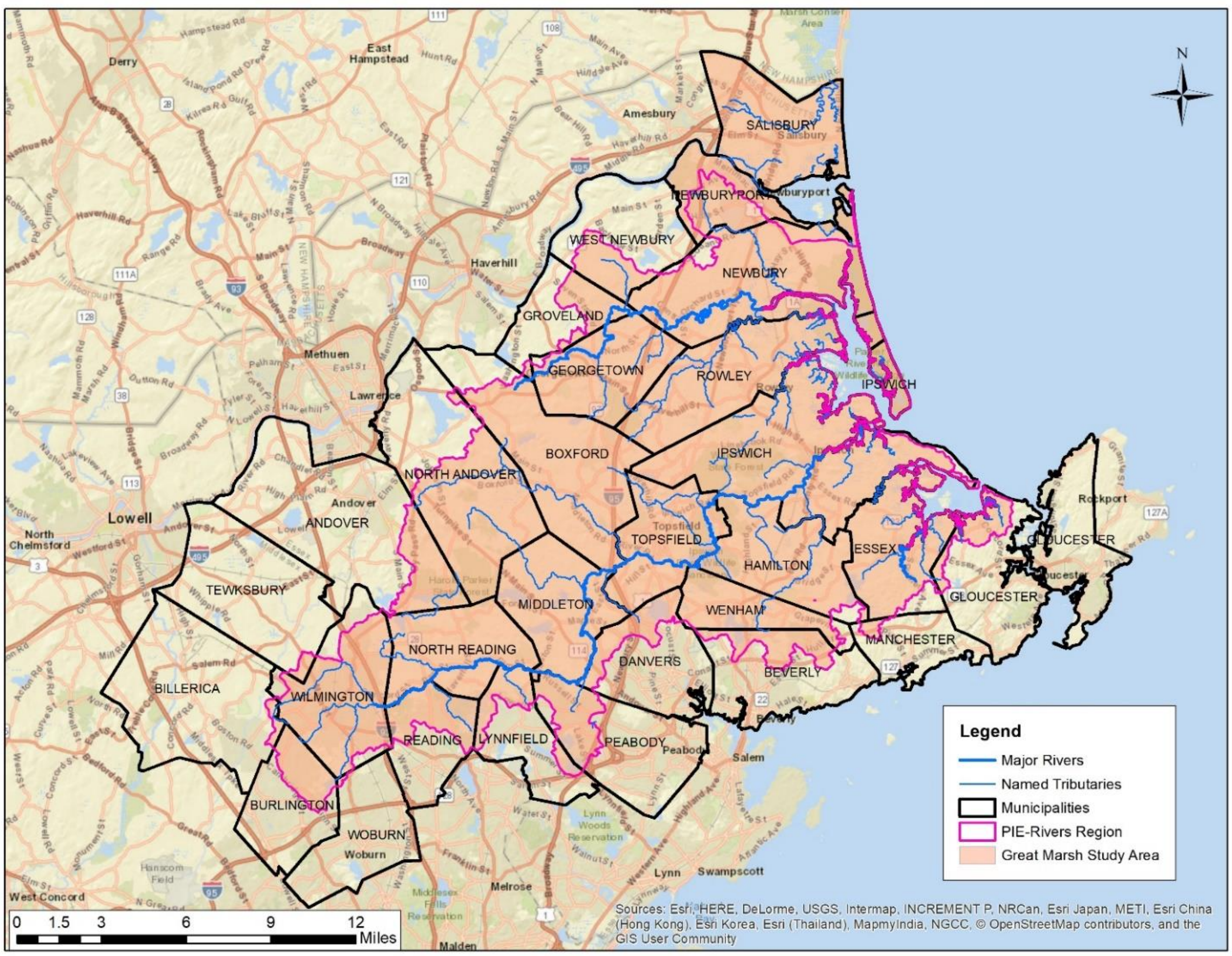

Figure 1. Map showing the region covered by the Great Marsh Barriers Study.

Table 1. List of coastal municipalities in the Great Marsh study region showing total land area falling within the study region and number of barriers of each barrier type expected to exist based on existing data sets and GIS analysis.

Town	Area (square miles)	Dams	Non-Tidal Stream Crossings	Tidal Crossings	Shoreline Stabilization
Essex	13.0		38	12	
Gloucester	2.9		3	3	1
Ipswich	32.4	6	87	17	25
Newbury	23.4	9	80	27	21
Newburyport	8.8	4	34	4	31
Rowley	18.6	6	76	9	
Salisbury	16.0		20	15	9

Table 2. List of inland municipalities in the Great Marsh study region showing total land area falling within the study region and number of barriers of each barrier type expected to exist based on existing data sets and GIS analysis. Numbers of road-stream crossings and dams located within the surveyed portions of each municipality. The area column represents the land area of the municipality that falls within the study region.

Town	Area (square miles)	Non-Tidal Crossings	Dams
Andover	5.4	28	7
Beverly	3.7	16	1
Billerica	0.6	1	
Boxford	21.2	158	11
Burlington	3.5	9	3
Danvers	3.9	21	3
Georgetown	12.9	90	1
Groveland	3.4	10	
Hamilton	14.4	61	
Lynnfield	3.4	5	1
Manchester	0.4	3	
Middleton	14.5	62	10
North Andover	16.6	83	7
North Reading	13.5	50	2
Peabody	4.6	30	6
Reading	4.8	9	
Tewksbury	0.5		
Topsfield	12.8	83	11
Wenham	7.4	34	1
West Newbury	3.6	11	
Wilmington	14.2	62	
Woburn	0.1	1	

Project Description

This project was conducted by the Ipswich River Watershed Association (IRWA) as a component of the Great Marsh Resiliency Project. The Resiliency Project was funded by the National Fish and Wildlife Foundation through the Hurricane Sandy Coastal Resiliency Competitive Grant Program and led by the National Wildlife Federation. The project included five separate sub-projects aimed at increasing the resiliency of the Great Marsh and the PIE-Rivers Region.

The Great Marsh Barriers Assessment inventoried, assessed, and prioritized human made structures that may impede flow, fluvial and coastal processes. These structures, collectively called barriers in the report, include dams, non-tidal stream/river crossings, tidal crossings, and coastal stabilization structures. We assessed these structures based on both ecological impact and infrastructure risk using a combination of existing analyses, newly applied screening tools and local knowledge. This report and the combined results of the screening analyses are tools for local governments, private owners and restoration practitioners to identify sites warranting further investigation, especially where infrastructure and ecological risk overlap. This report identifies opportunities for projects to be initiated and implemented that achieve the dual benefits of improved community resilience and ecological integrity.

Municipal jurisdictions end at town boundaries, despite clear hydrologic and ecological links across those boundary lines. Since a primary focus of this project was to provide useful and easily accessible information for municipal partners, we have summarized the results and available information for each municipality in separate sections appended to this report. The town-specific summaries go into greater detail and are intended to give local officials, staff and residents maps, study results and other information specific to the town in which they are working as a supplement to this regional analysis. The summaries for individual towns can be found in the Appendix of this report.

This project also provides assistance to communities and infrastructure owners with efforts to remove or mitigate ecological and infrastructure risk at sites where it is feasible and cost effective. This project developed conceptual design plans for the replacement of 103 of the high priority road crossings in the region (101 non-tidal crossings plus two tidal sites in Salisbury) to improve storm resilience and ecological connectivity. These sites were chosen based on preliminary results from the screening analysis and conversations with staff at many of the region's municipalities. The conceptual design plans and supporting materials are available and appended to this report.

Structure Types

Our analysis considers four basic categories of structures that intercept or redirect water; dams, non-tidal road-stream/river crossings, tidal crossings and coastal stabilization structures. These structures all have limited life spans and, depending on their design, location and maintenance history, their failure may present significant risk to people and other infrastructure. This risk is elevated during extreme storm and high tide events, which are becoming more common in northeastern Massachusetts.

These structures also often severely alter natural flow, flooding and sediment transport regimes of rivers and coastal areas that can result in significant negative impacts to the ecology and resilience of those systems. For example, the downstream transport of sediments and nutrients from the watershed provides important nourishment to coastal food webs and helps salt marshes keep pace with erosion and sea level rise. Also, downstream transport of wood and other material helps build and re-shape river and stream habitat, providing important complexity and habitat niches to support a wide range of aquatic and semi-aquatic species.

The biological and ecological impacts of these changes to the river system can be profound. For example, sea-run migratory (diadromous) fishes such as river herring can have their entire life cycle interrupted. If aquatic barriers keep adult river herring from returning from the ocean to access their freshwater spawning grounds, the fish stocks are quickly depleted. River herring are an important forage fish in the estuary and ocean, providing food for species such as striped bass, cod and tuna. Thus, low river herring abundance can have a negative effect on these prized game and food fishes. The exclusion or reduction of river herring from the freshwater system also removes an important annual source of marine-derived food and nutrients, in the form of adult fish and their eggs, to the coastal rivers and ponds. This change greatly alters the food web and nutrient cycle, with impacts on everything from bugs to birds that live in or frequent these freshwater habitats.

The risk to roads and other infrastructure associated with barriers are also significant. This has been highlighted quite frequently over the last decade or so during large rain events such as the Mother’s Day Storm (2006), Hurricane Irene (2011) and Hurricane Sandy (2012). Flooding events such as these test aging and undersized infrastructure with sometimes dangerous and often costly results as roads, railways and other infrastructure is damaged and destroyed as structure fail or underperform.

In light of aging infrastructure, increasing storm severity and shrinking budgets municipalities and other government entities have an increased need to prioritize the riskiest structures for upgrade and replacement. At the same time, in recent decades, ecological restoration practitioners have given greater attention to the impact some of these structures have on valuable ecosystems and ecosystem services. Restoration practitioners too have identified the need to prioritize the structures with the highest cost-benefit ratios for improvements. In many cases, there is considerable overlap between ecosystem impact and infrastructure risk, but rarely are these two concerns considered together. This study utilizes a variety of data sets and screening analyses to summarize and assess the relative effects of these structures on infrastructure and aquatic ecology in the region. This study integrates prioritization efforts for infrastructure and ecological concerns to identify sites where both can be addressed, benefitting communities by promoting more resilient infrastructure and ecosystems.

This comprehensive approach provides a novel, regional assessment of barriers in the Great Marsh and its contributing watersheds. This framework will allow municipal officials, restoration practitioners and others to identify and further pursue work at sites while considering their position and relative impact within the landscape and watershed.

Dams

Massachusetts has nearly 3,000 known dams, most of which have roots as power sources for small mills built in the 18th and 19th centuries. On average, there are more than 10 dams per 100 stream miles across New England and New York (Anderson & Olivero Sheldon, 2011). There are currently 84 dams within the Great Marsh study region, the majority of which are relatively small mill dams that have long since outlived the purpose for which they were built. As a result of their age, many of these dams are also in some level of disrepair, increasing the risk of an eventual structure failure.

Dams have a profound impact on river processes and ecology. They interrupt natural downstream sediment transport, alter nutrient cycles and temperature regimes, block fish and wildlife migration corridors and change free flowing (lotic) habitat to more pond-like (lentic) habitat altering the species the system can support. The combination of these and other factors associated with dams has resulted in a drastic change in species composition and abundance throughout the region. Removing a dam can quickly remove many of the negative effects and begin to restore a river to a more natural state. For this reason, river restoration experts have become more and more focused on removing dams when they are no longer needed or when their costs outweighs their benefits.

In recent decades, more and more dam owners in Massachusetts and across the country are reevaluating the risk, cost and ecological impact of outdated dams. Forty-five dams have been removed in Massachusetts since 2000[1], including two in the Great Marsh study region. In many cases they are choosing to remove rather than maintain dams they no longer need. In cases where dams are still actively used there are sometimes options to reduce risk and ecological impact during maintenance and renovation. With such a large number of dams it is important for both dam owners and restoration practitioners to have a way to prioritize structures for further consideration.

Non-Tidal Road-Stream Crossings

"Road-stream crossing" is a general term that includes structures that carry roads or railways over streams or rivers. Most often these crossings are either culverts or bridges. When crossings are undersized, improperly installed (e.g. too high relative to the stream bed), or in disrepair, they can cause serious problems for the roadway, the waterway, or both. As the name implies, non-tidal crossings are those bridges and culverts that span waterways that are not influenced by ocean tides. Public works departments are often dealing with maintenance and replacement of these structures which are ubiquitous throughout the temperate northeast. In

[1] Rivers, American (2017): American Rivers Dam Removal Database. figshare. https://doi.org/10.6084/m9.figshare.5234068.v2, Retrieved: 4:00 pm, 11/17/2017.

recent years, restoration practitioners have been giving increased attention to the impact of improper crossing design on river function and aquatic ecology.

The Massachusetts Stream Crossing Standards (Jackson, Bowden, Lambert, & Singler, 2011) were developed to guide design of new and upgraded stream crossings that allow natural fluvial processes to take place through a crossing, thus allowing for better habitat connectivity. Crossings designed to meet these standards have also proven more resilient to high storm flows, reducing failure risk and increasing structure life.

Tidal Crossings

Tidal crossings are bridges and culverts located within the tidally influenced portion of streams and rivers as well as tidal creeks. The tidal water flowing through these structures may be saltwater, brackish or freshwater depending on its position in the watershed and streamflow rates, but all sites are subject to two-way water flow at regular tidal intervals. Undersized tidal crossings can impact aquatic and salt marsh systems in many ways, including alteration of natural tidal inundation cycles, salinity gradients and species movement. In some cases, historic presence of an undersized tidal crossing can have long-term (potentially permanent) repercussions that negatively affect salt marsh health.

Tidal crossings are analogous to non-tidal crossings in many ways; however the twice daily fluctuation of water level, bi-directional flow, and exposure to coastal storm surges makes them a special case for both prioritization and design. Because of these rapid and extreme fluctuations in variables including velocity, water depth and salinity, it is very challenging to make judgments about both the ecological impact and the flooding or failure risk based on a single site visit and assessment. Due to these factors, acceptable rapid assessment methods have not yet been developed for this type of structure.

Coastal Stabilization Structures

Like the other three structure types, coastal stabilization structures can have deleterious effects on aquatic systems. While these structures differ from the first three in that they do not block or constrict the flow-through of water in the same way, they can and do have large impacts on energy and sediment transport regimes in the nearshore and estuarine environments of the Great Marsh. Hardened coastal structures[2] often increase the risk of storm impacts on adjacent sites, scour important shallow water and intertidal habitat, and alter natural tidal flooding cycles on salt marsh and beach ecosystems. The physics governing these impacts are complex and highly site specific, but in general it can be assumed that the more armored a coastline is the more impacted the coastal ecosystem. In places where infrastructure needs to be protected, the proper design and maintenance of the structures is extremely important to ensure minimal impacts on ecosystem function and storm protection associated with natural dune, beach and marsh features.

Methods

Below is a summary of the methods the Ipswich River Watershed Association (IRWA) team used to identify and prioritize potential barriers throughout the study region. The methods are organized by the four barrier types listed above. This study leverages a variety of existing data sets and prioritization efforts for the various structure types and attempts to integrate them into a more comprehensive, screening level assessment of these structures. Because of the inherent differences among the structure types and the variation in available data and screening tools for them, we assessed and prioritized each structure type separately. Structures were prioritized across the region as well as within each individual municipality. The priority scores produced in this report, while often presented as numerical values, should not be considered a quantitative assessment of importance. Important considerations including cost, ownership and historic value were not systematically evaluated. In addition, the screening analysis was not able to consider many site-specific factors including specific species presence, rare species habitat and existing utilities. These priority scores are intended to be used as a tool to identify sites that warrant further investigation and to provide a decision support tool to assist municipal managers and other structure owners.

In addition to the inventory and prioritization effort described above, this project developed conceptual plans for the replacement and upgrade of a subset of structures that we identified as high priority. We identified a subset of high priority road-stream crossings for potential design based on our initial prioritization effort, meetings with municipal representatives, and position relative to other structures. For example, some structures that had moderate priority scores were included for design if they either opened up a large portion of river to upstream access or were part of a series of nearby high priority structures. Similarly, some high-scoring

[2] Human-made structures consisting of material such as rock, concrete or steel that are designed to resist shoreline erosion and movement of coastal sand and sediment.

structures were removed from consideration if their upgrade would not reconnect a large segment of habitat and were not on an important roadway.

Dams

We identified dam locations in the region using the Massachusetts Office of Dam Safety (ODS) Dams layer[3] as our base data set. The ODS Dams layer was checked against our local knowledge of dam locations and dam removals that had taken place since the last update of the database in February, 2012. Records of dam locations that we knew to be incorrect or redundant, or where dams had been removed, were withdrawn from the data set prior to our final analysis.

We then assessed dams in ESRI ArcGIS using a prioritization system that considered screening indices for both infrastructure risk (RI) and ecological impact (EI) to derive a numeric dam priority (DP) score for each dam in the region. The generalized process for deriving these DP scores is outlined in Figure 2. More detail on how the DP score and its various components were calculated is discussed below. Dams across the whole region were sorted and ranked according to their calculated DP scores to provide an initial priority list.

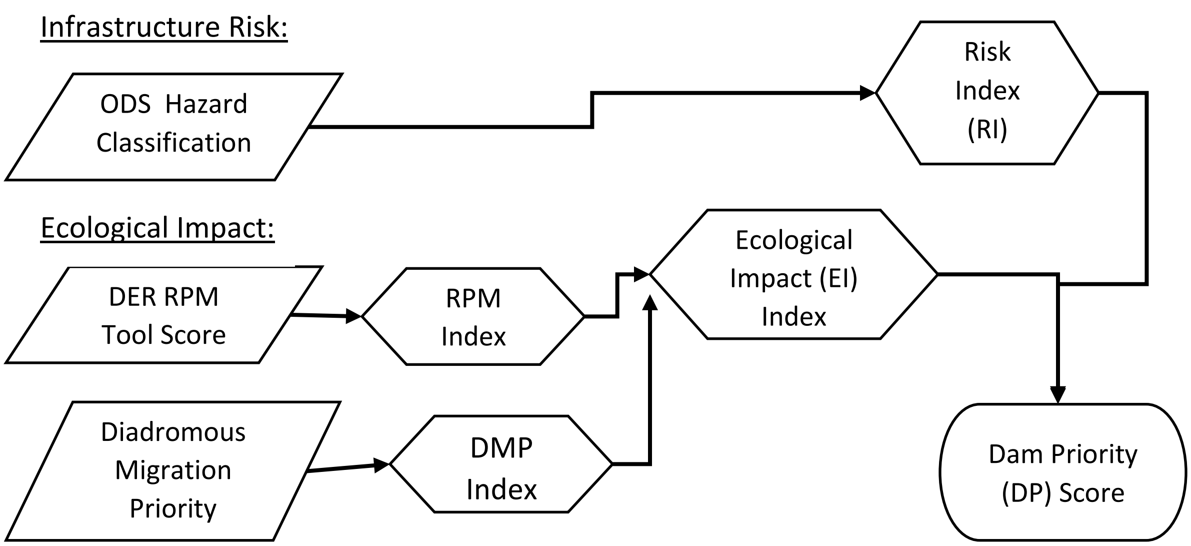

Figure 2. Generalized barrier prioritization scoring process for dams[4]. Explanations of model inputs and sub-components are fully explained in the Infrastructure Risk, Ecological Impact and Dam Priority Score sections below.

A number of dams in the region are directly associated with reservoirs that provide drinking water to local communities through surface water withdrawals. While it is conceivable that a municipality or water provider may decide to decommission and remove one of these structures, we assumed it was quite unlikely in most cases due to the ongoing, important function these dams are providing. We conducted a second round of prioritization using the same process as above, but removing dams that are known to be associated with active municipal surface water reservoirs.

[3] http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/dams.html

[4] Explanation of abbreviations in Figure 2: ODS (Massachusetts Office of Dam Safety), DER RPM (Massachusetts Division of Ecological Restoration – Dam Restoration Potential Model)

The final step in prioritizing dams was consideration of any available local information on factors including community priority, safety concerns and restoration interest that we were able to obtain from conversations with residents or municipal officials. Dams with active or planned restoration projects, specific community concerns, or those that are known to be in poor condition were flagged and added to the priority list. While this step is inherently more subjective than calculating numerical priority scores, it can provide critically important information affecting restoration potential of a site.

Infrastructure Risk (RI)

The ODS assigns hazard codes to dams under its regulatory jurisdiction based on the severity of hazards presented to communities in the event of dam failure. Jurisdictional dam owners are responsible for periodic inspection of their dams on a schedule set by the hazard code. Hazard codes do not relate in any way to probability of failure since these codes are not tied to the maintenance condition of the dam.

For our analysis, we chose to use the hazard code for the dams as our screening metric for infrastructure risk. We considered all dams to be in similar condition and focused solely on the risk in the event of failure according to the ODS categorization. Each dam in the study region was assigned a risk index value based on its ODS hazard code as shown in Table 3.

Table 3. Dam Infrastructure Risk Index (RI) scoring system.

Office of Dam Safety Hazard Class	Risk Index Score
Non-Jurisdictional	0
Low Hazard	0.5
Significant Hazard	1
High Hazard	2

Ecological Impact (EI)

To screen for the ecological impact of dams, we used the Massachusetts Division of Ecological Restoration's (DER) Restoration Potential Model (RPM) Tool[5] and priority restoration paths for anadromous fish identified by the Massachusetts Division of Marine Fisheries (DMF) (Reback, Brady, McLaughlin, & Milliken, 2004) and the Ipswich River Watershed Association.

The RPM Tool displays information that can be used to evaluate the relative ecological benefit of removing a dam based on a scoring system that considers a variety of dam and watershed characteristics including indicators of watershed position, ecological integrity and aquatic habitat connectivity. It does not account for many other variables that must be considered when assessing the priority and potential impacts of dam removal.

While the RPM tool does give some priority to head of tide dams and structures that have fewer downstream barriers to the ocean, it does not specifically prioritize structures that are important migration paths for diadromous fish. Since restoration of diadromous fish stocks (especially river herring) is a major regional priority, we chose to give extra weight to dams that block migration paths to critical spawning and rearing habitats. We began to identify high priority restoration paths using an analysis of anadromous fish passage conducted by DMF which discussed anadromous fish restoration potential for all major streams in the study region and provided

[5] Restoration Potential Model Tool and description available at: https://www.mass.gov/service-details/ders-restoration-potential-model-tool-description

information on the presence/absence of fish passage structures at various dams (Reback et al., 2004). Ipswich River Watershed Association staff reviewed these paths and added additional priority routes leading to some historical alewife spawning ponds that we deemed to have restoration potential based on recent habitat surveys and conversations with DMF staff. The final network of priority migration corridors is shown in magenta in Figure 3. All dams located along these priority migration corridors were categorized as migration priorities and further split based on whether they have existing fish passage structures.

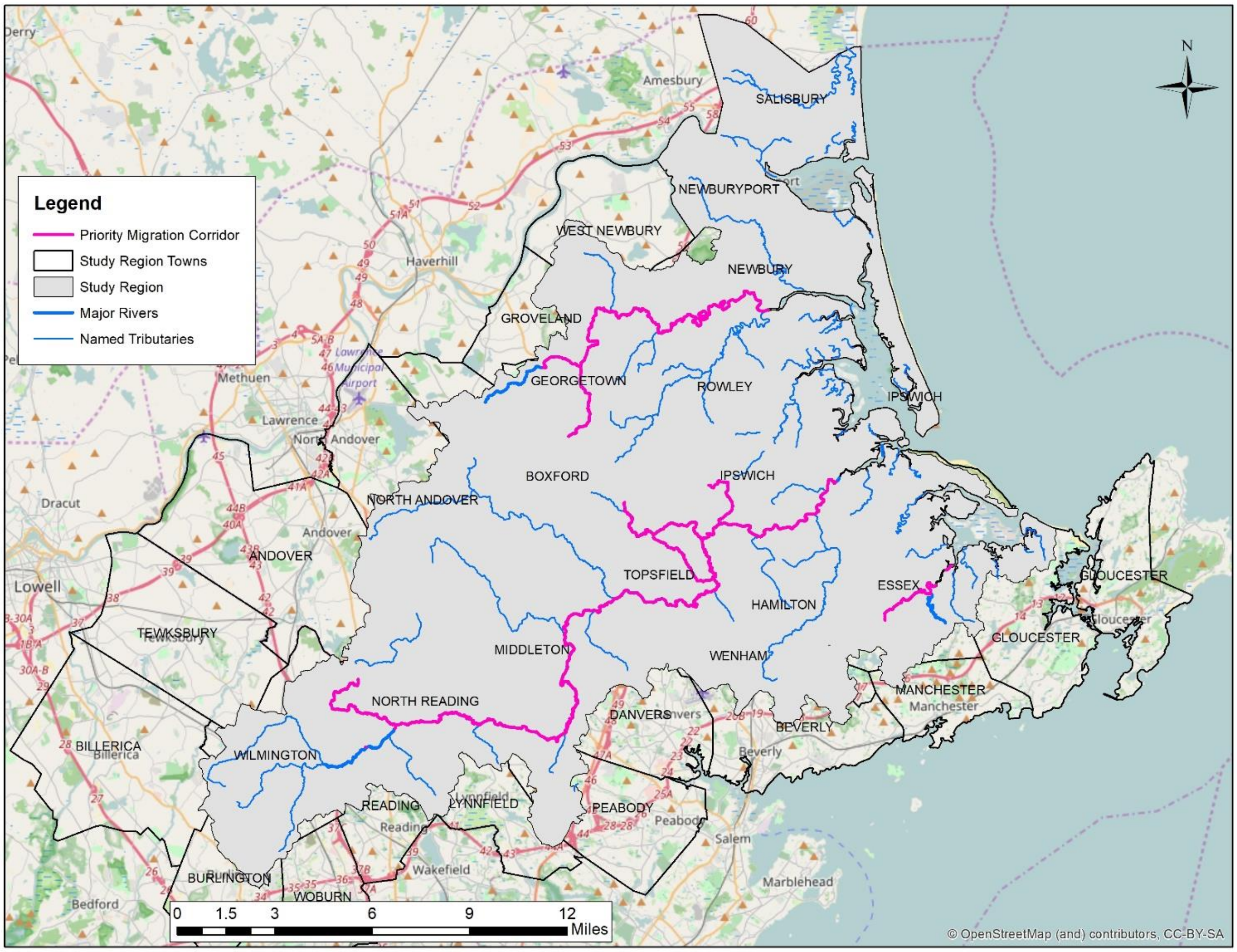

Figure 3. Map of Great Marsh Barriers Assessment study region showing priority migration corridors for anadromous fish.

We combined the information from the RPM tool score and the DMP categories into an Index of Ecological Impact (EI). The EI Index is a score ranging from 0 to 2 with lower scores indicating structures that are likely causing less negative ecological impact to their watersheds (i.e. are lower priority for removal or other restoration) and higher scores being structures that should be higher restoration priorities based on ecological criteria. It is important to note that this is just a screening tool that does not consider many factors that might increase or decrease a dam's impact on its watershed. Removal of dams with EI Index scores of 0 may still provide significant ecological benefits.

The EI Index score is calculated as:

$$\text{EI Index} = \ (RPM\ Index + \ DMP\ Index\ )/2 \qquad (1)$$

where:

The RPM Index is derived from Table 4 and the DMP Index is derived from Table 5.

Table 4. RPM Index scoring system

RPM Score Range	RPM Index Score
0-20	0
21-35	1
36-65	2

Table 5. DMP Index scoring system

DMP Category	DMP Index Score
No Priority	0
Priority - Existing Passage	1
Priority - No Passage	2

Dam Priority Score (DP)

The DP Score, as outline in Figure 2, is the final numeric value we calculated to prioritize dams based on the infrastructure and ecological indices were used as inputs. The DP Score is calculated using the following equation:

$$\text{DP} = (\text{EI} + \text{RI}) + 0.01(\text{RI} - \text{EI}) \qquad (2)$$

The DP score ranges from 0 to 4 with higher numbers representing dams that are higher priority for removal based on our screening methods. The DP score gives near equal weight to both the ecological (EI) and risk (RI) scores. In cases where the sum of the two scores is equal, it gives priority to dams that derive more of their score from the RI index score.

Non-Tidal Road-Stream Crossings

We identified expected stream crossing locations using GIS data downloaded from the North Atlantic Aquatic Connectivity Collaborative (NAACC) stream crossing database[6]. This data set includes stream crossings predicted by GIS desktop analysis (intersecting stream networks with road and rail networks across the state) and known locations verified by previous field studies. Because this data set is based on a state-wide desktop GIS analysis some crossings were not in their originally expected place and some did not exist at all. Additionally, some crossings were identified during field visits and added to the data set by our field crews. Our goal was to conduct a complete survey of the crossings in the watershed, knowing that a considerable number of sites would be

[6] www.streamcontinuity.org/cdb2

inaccessible for a variety of reasons including private property and crew safety (e.g. Interstate highway, active railroad).

A large number of the crossings included in our analysis had been previously verified, surveyed and scored based on ecological criteria in an earlier study conducted by IRWA as part of the NAACC program (Kelder, 2014). We conducted a secondary desktop analysis to remove incorrect, redundant, or removed structures and also added some structures that were not in the original data set. We also flagged and removed known tidal stream crossings from this analysis because the prioritization system described below is designed for non-tidal stream crossings only[7].

As part of this study, we collected additional field measurements of elevation and geomorphology variables at road stream crossings using a protocol developed by Trout Unlimited (TU). This included an extensive field effort over the course of three years where teams conducted one or more site visits to more than 500 road-stream crossings, an effort that required well over 3,000 hours of staff and volunteer time. Using the information collected during this survey as well as information from the NAACC surveys noted above, TU conducted a screening-level analysis of each crossing's expected ability to pass peak flows generated by five storm scenarios (50%, 10%, 4%, 2% and 1% likelihood storms)[8]. The full results of the TU analysis are summarized in the appended report (Trout Unlimited, 2017).

We prioritized field efforts using our best professional judgment regarding the relative importance of getting results for a crossing based upon factors including watershed position, proximity to known barriers and relationship to critical migration habitat. For example, a crossing located on private property immediately downstream from a water supply dam high in the watershed and without a fish ladder would likely not warrant further investigation if it was not easily accessible. On the other hand, a crossing on private property, but along a priority migration corridor would be flagged for follow up and we would make extra effort to gain access to conduct a survey at a later date. As a result of the logistical challenges of a study of this scope, the percentage of sites visited may appear low, but this effort represents a far more complete understanding of road-stream crossings than in almost any other watershed system in the Commonwealth.

We assessed non-tidal road-stream crossings using a prioritization system that considered screening indices for both infrastructure risk and ecological impact to derive a numeric Crossing Priority (CP) score for each crossing. The generalized process for deriving the CP scores is outlined in Figure 4. More detail on how the CP score and its components were calculated is outlined in the sections below. Crossings across the whole study region were mapped in ESRI ArcGIS and ranked according to their calculated CP scores to allow for visual assessment of their potential impact on watershed and municipal scales. We also produced maps showing the distribution of crossings based on their component infrastructure risk (CRI) and ecological impact (CEI) scores.

[7] Field data was collected at a number of tidal crossings, but any results from the screening tools would be of questionable value since both the NAACC and Hydraulic Capacity tools do not consider two-way flow.

[8] Storm likelihood is the calculated percent chance of at least one 24-hour rainfall event of that size or larger occurring on any given year. This concept is sometimes presented as a return interval where the return interval is the number of times, on average, this magnitude of rainfall is expected to happen over a fixed time period (e.g. 1% likelihood storm = 100 year return interval storm). – 1% = 100 yr, 2% = 50 yr, 4% = 25 yr, 10% = 10 yr, and 50% = 2 yr.

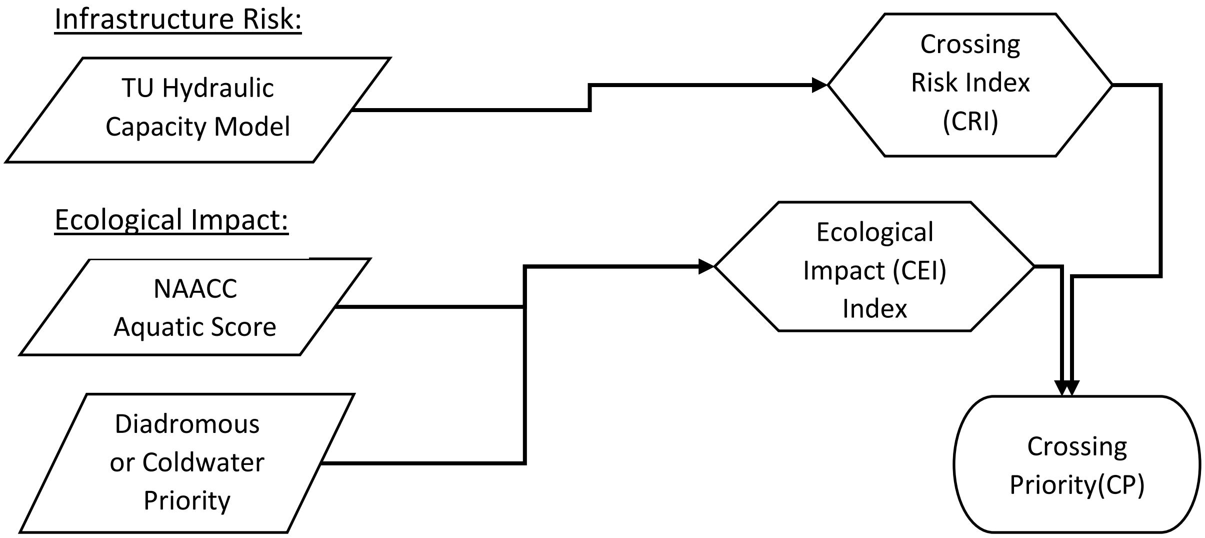

Figure 4. Generalized barrier prioritization scoring process for non-tidal road-stream crossings. Explanations of model inputs and sub-components are fully explained in the Infrastructure Risk, Ecological Impact and Crossing Priority Score sections below.

The CP score is an index value we calculated for prioritizing non-tidal road-stream crossings for upgrade based on our screening of infrastructure risk and ecological impact. The CP score ranges from 0 to 10 with larger numbers representing higher priority structures for replacement. It is important to point out that these priorities are based on our screening tools and don't consider all aspects of an eventual decision to prioritize a structure for replacement, including local priority, cost and other site-specific concerns.

Using preliminary results from the above analysis, we produced maps and tables showing high priority crossings for each municipality with ten or more scored crossings. We approached officials from each municipality to solicit their feedback on the results and inquire about any other sites that they deemed high priority (especially due to flooding or failure history). We used feedback from the municipalities to ground-truth our results and to adjust town-specific priority design lists as appropriate. Consistent with our approach to local knowledge regarding dams, sites prioritized based solely on local knowledge were included as priorities, but not explicitly ranked.

Infrastructure Risk (CRI)

The TU Hydraulic Capacity (HC) screening model calculates expected flow at the 2-yr, 10-yr, 25-yr, 50-yr, and 100-yr return interval storms at each crossing site based on its upstream watershed characteristics and tests whether the structure has the capacity to accommodate the peak flow. The inability of crossings to pass storm flows can result in water ponding on the upstream side of the road embankment and increased velocities and erosive forces at the downstream outlet. In general, we expect the roadway in areas around these crossings to be more likely to flood and fail over time and chose to use the results of the HC model to generate our Crossing Infrastructure Risk Index (CRI).

For each return interval, the HC screening model generates a value of Pass (enough capacity), Fail (not enough capacity) or Transitional (near capacity 85% - 115% of capacity). We used these results to generate a numeric CRI value scaled from 0-5 with 0 passing at all and 5 at none of the return intervals tested using the following formula:

$$\mathrm{CRI} = 1\mathrm{F} + .6\mathrm{T} \tag{3}$$

where:

F = the number of return intervals where the crossing fails

T = the number of return intervals where the crossing is transitional

Ecological Impact (CEI)

The NAACC program assesses non-tidal road-stream crossings based on their design with respect to ecological connectivity. Specifically the protocol measures a crossing's level of compliance with the MA Stream Crossing Standards which were developed to promote stream continuity, aquatic organism passage and wildlife passage at crossings (Jackson et al., 2011). Field collected data is submitted by trained individuals to the NAACC database which, among other things, calculates an NAACC Aquatic Score for each crossing. This Aquatic Score (AQ) is a value ranging from 0 to 1 with 0 representing no connectivity and 1 representing full connectivity at the crossing. We used this score as the primary component in our Crossing Ecological Impact Index (CEI).

As we did with dams, we wanted to incorporate some level of added importance to crossings located along high value stream reaches. In particular, we were interested in prioritizing crossings along priority migration paths for diadromous fishes and for coldwater stream habitat which is rare in the study region. For diadromous fish, we used the priority migration corridors described in the Dam Ecological Impact Index section above and shown in Figure 3. We then retrieved the MA DFW Coldwater Fisheries Resources[9] layer from MassGIS and attempted to add any coldwater habitat to our priority corridors. All of the mapped coldwater resources within the study region were already included in the stream reaches shown in Figure 3 so that was kept as the priority region. All crossings located along the priority migration corridors were categorized as migration priorities (MP) and assigned an MP value of 1. All other crossings were assigned a MP value of 0.

Using the above information, we calculated the CEI Index as described below.

If AQ is greater than 0.5:

$$\mathrm{CEI} = 5 - 5\mathrm{AQ} \tag{4}$$

If AQ is less than or equal to 0.5:

$$\mathrm{CEI} = 5 - 5\mathrm{AQ} + \mathrm{MP} \tag{5}$$

where:

AQ = NAACC Aquatic Score

MP = migration priority value described above (0 or 1)

[9] http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/dfwcfr.html

If CEI calculations returned a value of greater than 5 the score was rounded down to 5. The CEI score ranges from 0 to 5 with larger numbers indicating structures that are expected to have higher negative ecological impact based on this screening assessment and thus higher priority for improvement.

Crossing Priority Score (CP)

The CP score, as outlined in Figure 4, is the final numeric value we calculated for prioritizing non-tidal road-stream crossings for upgrade based on our screening of infrastructure risk and ecological impact. The CP score ranges from 0 to 10 with larger numbers representing higher priority structures for replacement. The score is obtained by summing the CRI and CEI scores as follows:

$$\mathrm{CP} = \mathrm{CRI} + \mathrm{CEI} \tag{6}$$

In cases where only CRI or CEI scores were available, CP was equivalent to the available component score.

Tidal Crossings

Because of the highly variable and complex conditions at tidal crossings and tidally restricted areas, no one has yet developed assessment methodologies comparable to those for non-tidal crossings. These structures are subject to two-way water flow as well as the variable effects from both upstream (e.g. river flow, stormwater) and downstream (e.g. tidal inundation, storm surge) directions. For example, a large rainfall event would have different impact when occurring at low tide versus high tide. Similarly, the ecological effects of crossings that create tidal restrictions are harder to identify as tidal stage has a substantial impact on whether these structures are barriers to animal movement. Due to these complexities, the vulnerability and ecological impact of individual tidal crossings is difficult to quantify as part of a rapid assessment protocol. For these tidal structures, we relied on results from the Draft Great Marsh Coastal Wetlands Restoration Plan (see below) as well as locations and information regarding tidal crossings obtained through the NAACC surveys, desktop GIS analysis, review of aerial imagery, site visits and local knowledge.

The Massachusetts Office of Coastal Zone Management's Wetlands Restoration Program (WRP), (now part of the MA Division of Ecological Restoration), together with numerous partners, completed the Draft Great Marsh Coastal Wetlands Restoration Plan (Draft GMP)[10] as a tool to help communities in the Great Marsh region identify and restore degraded and former coastal wetland habitats. The Draft GMP was initially developed in 2006 and is currently (2017) being updated and revised. It presents maps and descriptions of 121 potential and completed salt marsh restoration sites in the Great Marsh. The Draft GMP also included more detailed "rapid technical assessments" of a subset of the sites it considered. These reports include more detail on the degree of tidal restriction, including information such as measurements of tidal range over month-long periods, that may be of use if these sites are further explored.

Our analysis focused on tidal road crossings as well as some off-road structures (such as berms and water control structures) that may be acting as barriers to natural tidal exchange. We built our data set of tidal crossings by conducting a detailed review of the 121 records in the Draft GMP as well as 23 surveys from our NAACC field work that identified tidal conditions. Using these two data sets in conjunction with desktop GIS analysis of aerial photos and local knowledge, we identified a total of 89 tidal crossings within the study region.

[10] Developed by Massachusetts Office of Coastal Zone Management's Wetlands Restoration Program (WRP), (now part of the MA Division of Ecological Restoration) - 2006

These sites are all located within the seven coastal municipalities in the study (Essex, Gloucester, Ipswich, Newbury, Newburyport, Rowley and Salisbury).

We characterized each tidal crossing as to whether it was under a public way and whether it was associated with a marsh that was classified as tidally restricted in the Draft GMP. The Draft GMP prioritized tidally restricted marshes from low to high priority based on a subjective (best professional judgment) assessment of ecological restoration potential and feasibility at the site. Our analysis defined priority tidal crossings by combining the above criteria as shown in Table 6. Structures identified as high priority or problem areas for flooding by municipal staff or in the Great Marsh Regional Coastal Adaptation Plan were considered to be high priority tidal crossings if not already included through the above screening approach.

Table 6. Prioritization categories for tidal crossings in the Great Marsh Barriers Assessment.

<table>
<tr><th>On Public Way</th><th>Restoration Priority in 2006 Draft Great Marsh Plan (Draft GMP)</th><th>Tidal Crossing Priority</th></tr>
<tr><td rowspan="4">No</td><td>Not in Draft GMP</td><td rowspan="2">Low</td></tr>
<tr><td>Low</td></tr>
<tr><td>Med</td><td>Med</td></tr>
<tr><td>High</td><td>High</td></tr>
<tr><td rowspan="4">Yes</td><td>Not in Draft GMP</td><td>Low</td></tr>
<tr><td>Low</td><td>Med</td></tr>
<tr><td>Med</td><td rowspan="2">High</td></tr>
<tr><td>High</td></tr>
</table>

Coastal Stabilization Structures

To identify priority coastal stabilization structures, we relied on data from the Massachusetts Coastal Structure Inventory and Assessment Project[11] which inventoried both public and private shoreline stabilization structures throughout the Commonwealth. For this analysis, we considered hard, human-made structures including seawalls, revetments, bulkheads, groins, jetties, breakwaters, and dikes or levees. The available information on these structures allowed us to identify location, structure type, length of shoreline impacted and, in some cases physical condition of the structures. We were unable to assess ecological impacts of individual shoreline stabilization structures with the available data and screening tools.

Publicly Owned Structures

Publicly owned shoreline stabilization structures were inventoried and assessed in a report prepared for Massachusetts Departments of Coastal Zone Management (CZM) and Conservation and Recreation (DCR) from 2006 to 2009 (Bourne Consulting Engineering, 2009). The data and reports include condition ratings and estimated repair or reconstruction costs for publicly-owned coastal structures. These structures were characterized through on-site evaluation that focused primarily on shoreline stabilization structures and their ability to resist major coastal storms and prevent damage due to flooding and erosion.

[11] Massachusetts Coastal Structure Inventory and Assessment Project available at: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory/

The inventory rated structures based on a condition scoring system that ranged from excellent (A) to critical (F). For our analysis we used the condition structures from this assessment as a proxy for infrastructure risk under the assumption that structures in poorer condition are more likely to fail during storms. These publicly owned structures were separated into priority categories based on the condition scores as follows: low priority (A, B), moderate priority (C), high priority (D, F). This prioritization assumed that poor condition makes structures more vulnerable to failure during storms, increasing the risk of damage to both property and ecosystem services.

Privately Owned Structures

Privately owned coastal stabilization structures were inventoried and summarized in a 2013 report prepared for the Massachusetts Office of Coastal Zone Management (CZM) by Applied Science Associates, Inc. (Fontenault, Vinhateiro, & Knee, 2013). This 2013 effort identified location and type of coastal structures, such as seawalls and revetments, not included in previous phases of the Massachusetts Coastal Infrastructure Inventory and Assessment Project. These structures were identified using remote sensing techniques and are presumed to be privately owned. The data and report provide a comprehensive assessment of shoreline armoring coast-wide.

This inventory of privately owned coastal stabilization structures does not include an assessment of structure condition. For our analysis, we included information on number of structures, location and length of altered shoreline, but did not assess risk or prioritize the structures.

Crossing Replacement Designs

As the final component of this project, Meridian Associates, Inc. (MAI) was contracted to develop conceptual designs for the replacement of a subset of selected high priority crossings with structures designed to increase aquatic connectivity and resilience to flooding. These structures were identified as high priorities based on a combination of their numeric priority scores, municipal input, structural condition and proximity to other priority structures. This task was focused almost exclusively on non-tidal crossings, but tidal crossings could be designed where site-specific conditions allowed the engineering team to do so.

The designs were developed using available site data including measurements, photos and field notes collected by IRWA as well as results from the NAACC database[12] and the Trout Unlimited Hydraulic Conductivity screening tool. Modeling effort field measurements collected by IRWA for the NAACC and screening tools. The proposed designs focused on improving hydraulic capacity and ecological connectivity and were intended to conform to the Massachusetts Stream Crossing Standards where applicable (Jackson et al., 2011). The designs were developed using available site data including field measurements collected by IRWA during the screening analyses. The designs provide a visual representation of the size and scale of a potential replacement structure that would better convey storm flows and meet ecological stream crossing standards at each site. These designs can provide a starting point to more easily incorporate resilient and long-lived structures into maintenance and replacement schedules. These plans can help with scoping, budgeting and fundraising associated with crossing upgrades.

[12] NAACC Crossing database available at: www.streamcontinuity.org/cdb2

Results

A total of 1,026 potential barriers were assessed as part of this analysis. The following sections provide a broad summary of prioritization results for each barrier type for the whole study region. Those interested in results, discussion and complete data sets specific to individual municipalities should refer to the town specific packages in the appendices of this report.

Dams

There are 91 dam records in the Office of Dam Safety (ODS) Database that fall within the limits of the study region and were considered as part of our analysis. After review, we identified 84 records that represent existing dams and retained those for prioritization and analysis. The design purpose and active use of these dams is varied, however a considerable number (14) are currently used to impound water for municipal surface water supply reservoirs. No dams in the region produce hydroelectric power or are designed to provide flood control.

The geography, geology and hydrology of the Great Marsh region are generally not compatible with the construction of large dams. As a result, the study region is dominated by relatively small dams with small impoundments. Of the 81 dams in the region, 35 are not under the jurisdiction of the Office of Dam Safety (non-jurisdictional) because of relatively low risk of downstream damage based largely on height and impoundment size. While small dams generally present lower risk to life and property in the event of failure, non-jurisdictional dam owners are not required by ODS to conduct regular safety inspections of their structures. Due to the age of many of these structures as well as the absence of inspection requirements, many of these small structures are in considerable disrepair increasing the likelihood of eventual failure.

The results of our regional prioritization of dams based on DP score are summarized below in Table 7 (without water supply dams) and Table 8 (with water supply dams). Water supply dams occupy the top 4 priority spots and 8 of the top 12 (Table 8). This appears to largely be a function of the tendency for these to be larger structures and thus higher hazard. Many of the high-ranking water supply dams also represent parts of impoundments that are formed by multiple dams, so are somewhat redundant to consider separately. For example, three of the top four structures are components of the dam system that forms the Putnamville Reservoir.

When water supply dams are removed from the priority ranking, the list of high priority dams is dominated by structures that are old mill dams and, for the most part, no longer serve the purpose they were designed for. Some of these structures have active projects underway to remove or improve conditions at them and others have been identified as possible restoration sites pending owner interest and funding availability (Table 7). The locations of the 12 highest priority dams identified in this analysis are shown in Figure 6. Water supply dams that had high DP scores, but were removed from the final analysis, are also highlighted on the map.

A look at the infrastructure risk and ecological impact components of our screening approach can also provide some insight as to what is driving the DP score. The 46 dams that are regulated by the ODS are primarily classified as low risk (22) or significant risk (18) structures with only 6 dams classified as high risk. All 6 of the high risk dams are part of surface water supply reservoir systems. A map of the study region showing dams by ODS hazard class can be seen in Figure 7. Figure 5 shows a graphical representation of dams summarized by Restoration Potential Model (RPM) score and diadromous migration priority, the two sets of data that are used to determine the Ecological Impact Index (EI). There are 5 dams with RPM scores of >40 that are also along priority migration corridors. The region-wide results of the EI Index analsis are shown in Figure 8. The higher priority dams are concentrated lower down in the watersheds and along the mainstems of the major rivers, largely as a function of location relative to diadromous migration corridors.

Table 7. Top ranked dams in Great Marsh study region. List includes top 12 dams based on Dam Priority (DP) score and additional dams with active restoration projects or specific local priority. List excludes water supply dams. *Adjusted Priority Rank is the ranking with water supply dams excluded.

Adjusted Priority Rank*	Dam ID	Dam Name	Town	Risk Index (RI)	Eco Index (EI)	Dam Priority (DP)	Active Project or Local Priority
1	MA01137	Ipswich River Dam (South Middleton)	Middleton	1	1.5	2.5	Active
2	MA00159	Howe Pond Dam	Boxford	1	1	2.0	
2	MA00261	Pentucket Pond Outlet Dam	Georgetown	1	1	2.0	
2	MA01604	Jewel Mill Dam	Rowley	1	1	2.0	
5	MA01198	Baldpate Pond Dam	Boxford	0.5	1.5	2.0	
5	MA00231	Ipswich Mills Dam	Ipswich	0.5	1.5	2.0	Active
5	MA00241	Parker River Dam #1	Newbury	0.5	1.5	2.0	
8	MA01610	Howletts Brook Dam	Topsfield	0	2	2.0	
9	MA00181	Norwood Pond Dam	Beverly	1	0.5	1.5	
9	MA00158	Stiles Pond Outlet Dam	Boxford	1	0.5	1.5	
9	MA03006	Mill Pond Dam	Middleton	1	0.5	1.5	
9	MA01613	Bethune Pond Dam	Topsfield	1	0.5	1.5	
20	MA00276	Willowdale Dam	Ipswich	1.5	1.5	1.5	Active
45	MA00240	Parker River Dam #2 (Larkin Road)	Newbury	0	0.5	0.5	Priority

Table 8. Top 16 dams in Great Marsh study region ranked by Dam Priority (DP) score.

Priority Rank	Dam ID	Dam Name	Town	Water Supply
1	MA00745	Putnamville Reservoir Dam	Danvers	Yes
2	MA00744	Putnamville Reservoir West Dike	Danvers	Yes
2	MA00726	Winona Pond Dam	Peabody	Yes
2	MA01297	Putnamville Reservoir East Dike	Danvers	Yes
5	MA01137	Ipswich River Dam	Middleton	
6	MA01121	Mill Pond Dam	Burlington	Yes
6	MA01123	Mill Pond South Dike	Burlington	Yes
8	MA00182	Longham Reservoir Dam	Wenham	Yes
8	MA00165	Dow Brook Reservoir Dam	Ipswich	Yes
8	MA00159	Howe Pond Dam	Boxford	
8	MA00261	Pentucket Pond Outlet Dam	Georgetown	
8	MA01604	Jewel Mill Dam	Rowley	
13	MA01198	Baldpate Pond Dam	Boxford	
13	MA00231	Ipswich Mills Dam	Ipswich	
13	MA00241	Parker River Dam #1	Newbury	
16	MA01610	Howletts Brook Dam	Topsfield	

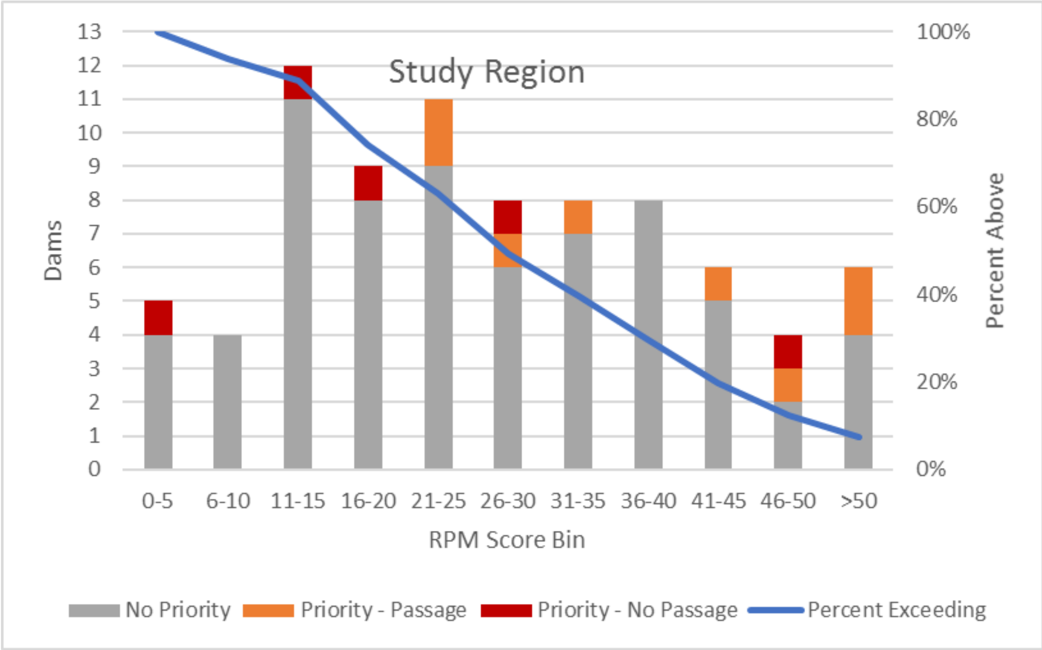

Figure 5. Summary of Dams in the Great Marsh study region summarized by RPM score and diadromous migration priority. The blue line shows the percentage of dams in the region that meet or exceed the RPM score.

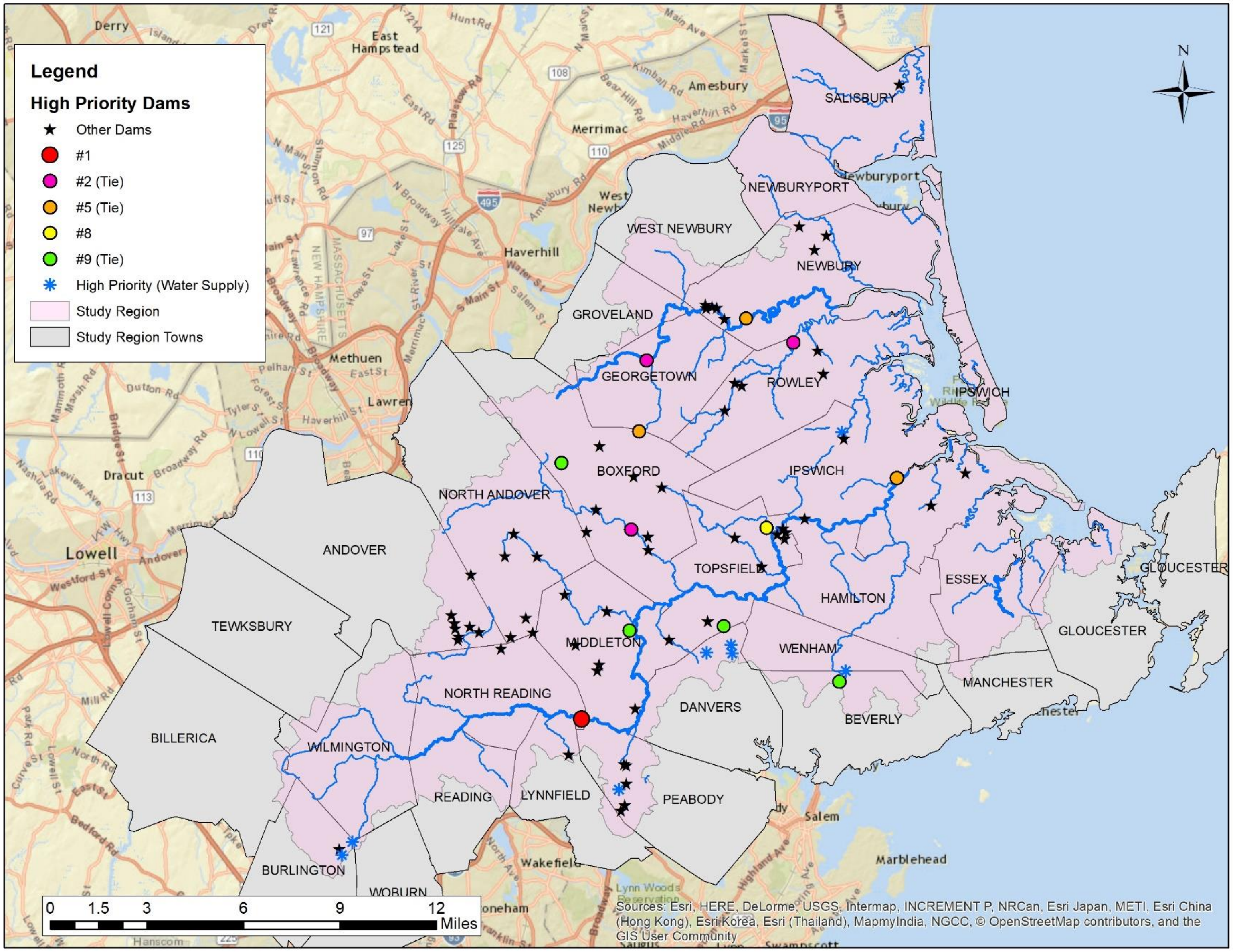

Figure 6. Map of Great Marsh study region showing highest priority dams based on DP Score analysis. Water supply dams were removed from the final ranking.

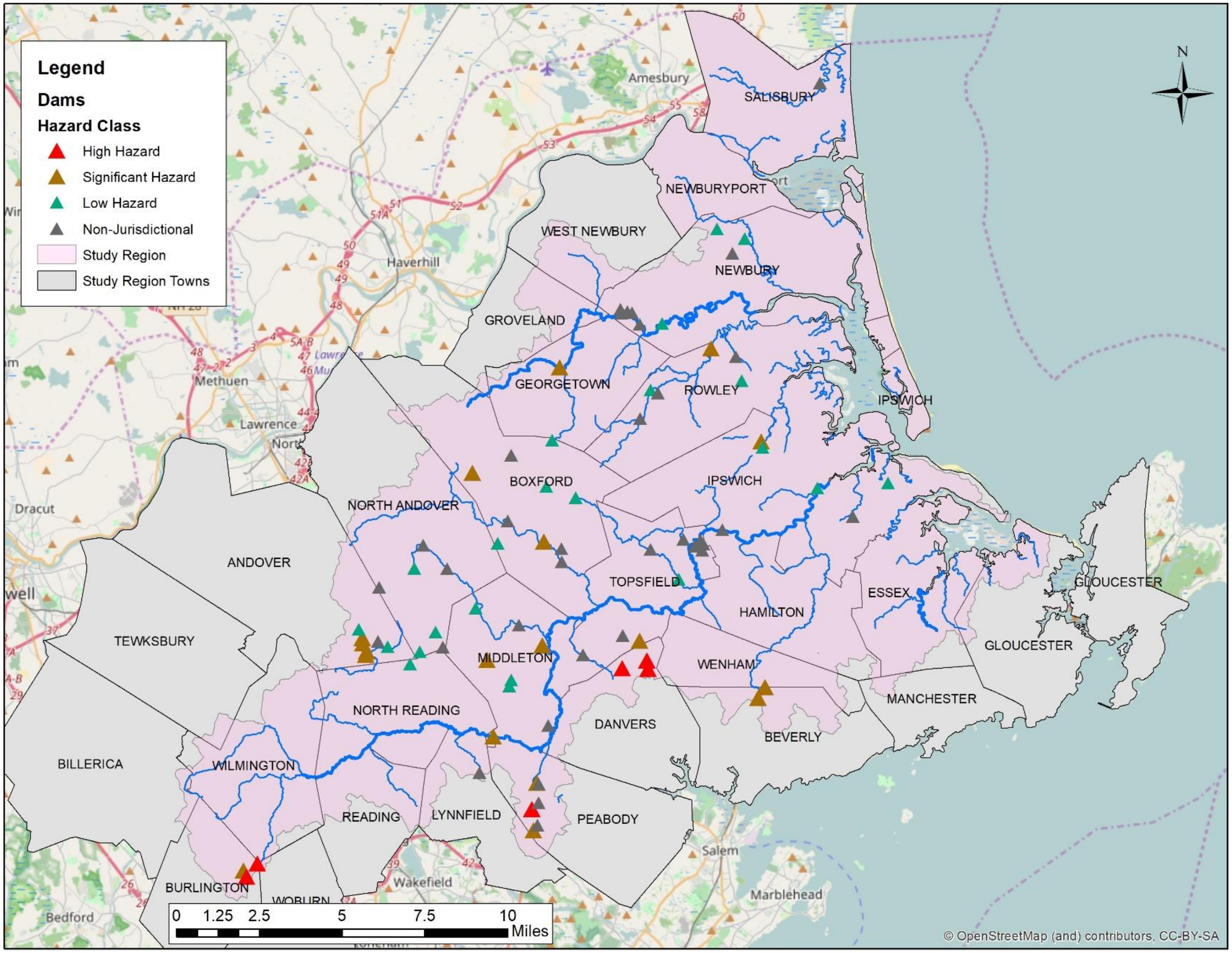

Figure 7. Map of the Great Marsh study region showing dams classified by MA Office of Dam Safety hazard class.

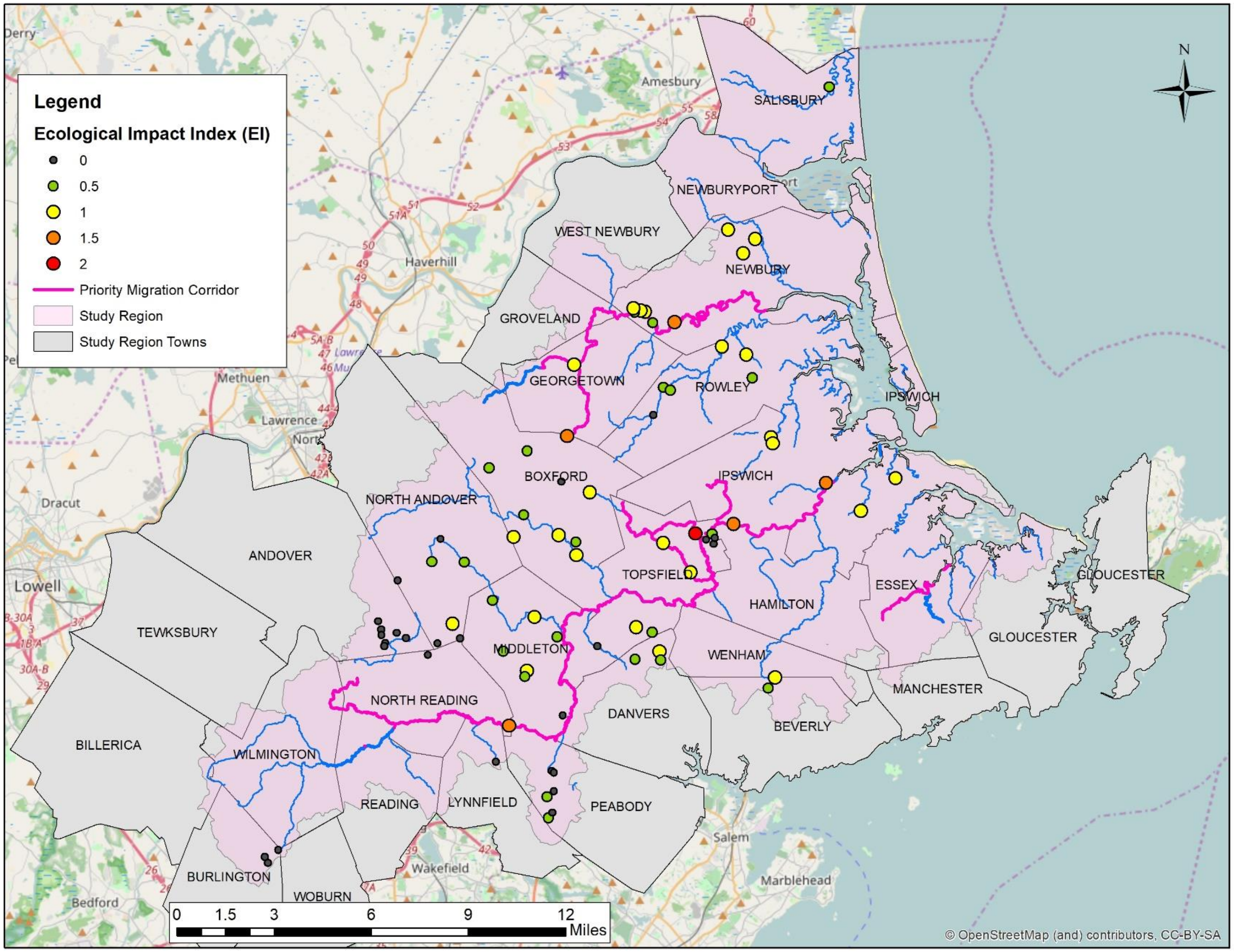

Figure 8. Map of Great Marsh study region showing dams prioritized by Ecological Impact Index scores.

Non-Tidal Road Stream Crossings

The North Atlantic Aquatic Connectivity Collaborative (NAACC) database predicted a total of 1,176 road-stream crossings within the 280 square mile study region. Over the course of this project, a total of 704 (60%) of the predicted structures were inventoried by IRWA-trained survey teams. Within the higher priority portions of the region, percent coverage was higher with 76% (292) of the crossings along rivers/major tributaries and 79% (92) of the crossings along priority migration corridors inventoried. These numbers are an underrepresentation of the number of sites that crews visited since a considerable number of sites were deemed inaccessible by crews in the field. Ninety three of the 704 inventoried sites either had no crossing or the crossing had been removed prior to the survey; this left 611 sites where we were able to collect survey data to run screening analyses. We assigned Crossing Priority (CP) index scores and ranked each of these 611 crossings[13].

The CP scores calculated ranged from 0 to 9.94 on the 10-point scale. Most of the crossings scored in the lower part of the range with a median CP score for all scored crossings of 2. A histogram displays two separate peaks in score frequency with high numbers of crossings scoring either around 1 or around 6.5 (Figure 9). These distinct frequency peaks of CP scores helps distinguish between groups of structures with relatively low combined priority and those that are more problematic from both infrastructure and ecological perspectives.

The 35 highest priority structures had CP scores greater than 7 (Table 9). Thirty-two of these structures were single culvert crossings and the remaining three were multiple culvert crossings, highlighting that bridges tend to be more effective at passing both flood waters and aquatic organisms. Figure 10 shows a map of crossings throughout the study region by CP score. We did not detect a strong distribution pattern for high CP scores; however it appears that the density of higher priority crossings is lower in the upper portions of the Ipswich, Parker, Essex and Miles River watersheds than in much of the rest of the Great Marsh study region.

Maps showing results for the infrastructure (CRI) and ecological (CEI) components of the CP score are included below in Figure 11 and Figure 12. Sites with the highest infrastructure risk are predicted to fail to pass flows associated with the 2-year return interval storm. Structures in this high risk CRI category appear to be slightly more highly concentrated in portions of the study region east of North Andover and Middleton and less common in the headwaters of the Ipswich River (Figure 11). Structures with higher ecological impact (CEI) scores appear to be somewhat more concentrated on small, low order tributaries where it is more likely that crossings structures are small culverts (Figure 12).

[13] Crossing Priority (CP) scores for 488 sites were calculated using both infrastructure risk (CRI) and ecological impact (CEI) values. For 123 crossings, we lacked usable results for the infrastructure risk (CRI) screening tool, mainly because the more detailed survey data need to run that model could not be collected for those sites. Sites lacking CRI scores were assigned CP scores and ranked using results from CEI scores only.

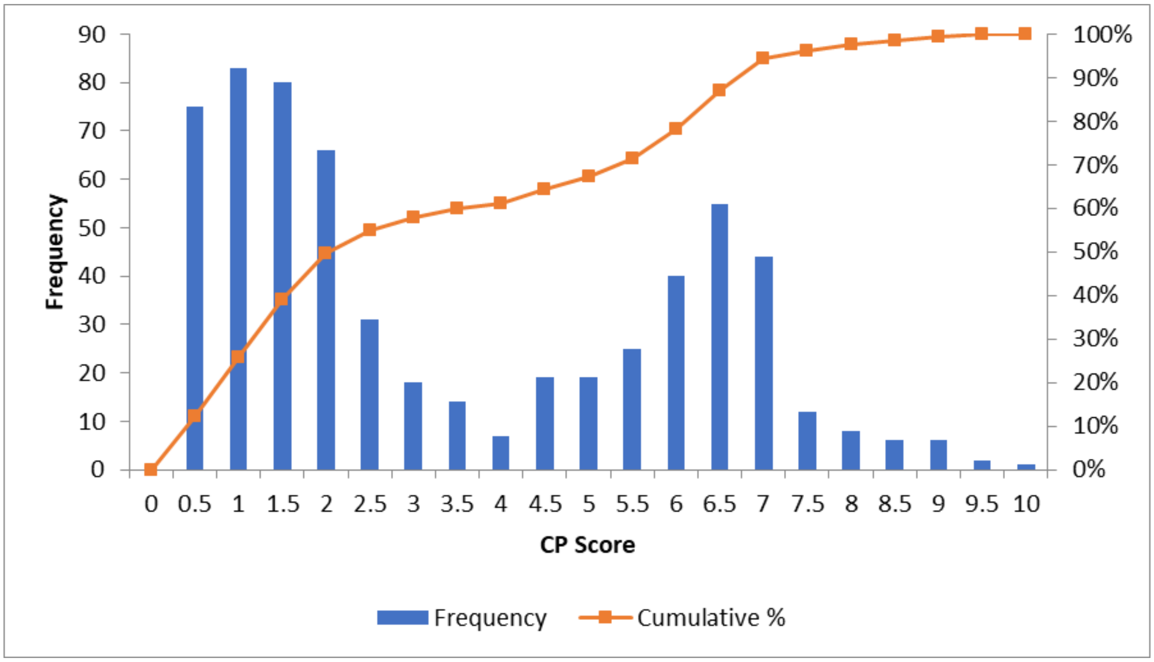

Figure 9. Frequency histogram showing Crossing Priority (CP) scores for non-tidal road-stream crossings in the Great Marsh study region.

Table 9. Non-tidal road-stream crossings with Crossing Priority (CP) scores of greater than 7 in the Great Marsh Barriers Assessment. This represents the 35 highest priority structures in the region based on screening model results.

Regional CP Rank	Crossing ID	Town	Road	Structure Type	CRI Score	CEI Score	CP Score
1	188	Wenham	Dodges Row	Single Culvert	5.0	4.9	9.9
2	9011	Topsfield	Meetinghouse Lane	Single Culvert	5.0	4.3	9.3
3	472	North Andover	Liberty Street	Single Culvert	4.6	4.4	9.0
4	670	Topsfield	Pond Street	Single Culvert	5.0	3.9	8.9
5	1054	Newbury	Coleman Road	Single Culvert	5.0	3.9	8.9
6	151	Wilmington	Ainsworth Road	Single Culvert	5.0	3.7	8.7
7	879	Boxford	Washington Street	Single Culvert	5.0	3.7	8.7
8	421	Andover	Gray Road	Single Culvert	4.0	4.6	8.6
9	408	Andover	Salem Street	Single Culvert	4.0	4.6	8.6
10	862	Georgetown	Nelson Street	Single Culvert	5.0	3.5	8.5
11	435	Topsfield	River Rd	Single Culvert	4.6	3.7	8.3
12	84	North Reading	Concord Street	Single Culvert	5.0	3.3	8.3
13	859	Boxford	Main Street	Multiple Culvert	5.0	3.3	8.3
14	990	Rowley	Main Street	Single Culvert	3.6	4.7	8.3
15	517	Hamilton	Winthrop Sreet	Single Culvert	3.6	4.4	8.0
16	753	Ipswich	Pine Swamp Road	Single Culvert	5.0	2.9	7.9
17	681	Boxford	Main Street	Single Culvert	3.0	4.8	7.8
18	755	Boxford	Kelsey Road	Single Culvert	5.0	2.7	7.7
19	439	Essex	Story Street	Single Culvert	4.0	3.7	7.7
20	413	Hamilton	Moulton Street	Single Culvert	5.0	2.7	7.7
21	1162	Newbury	Off Middle Road	Single Culvert	4.6	3.0	7.6
22	1094	Newbury	Orchard Street	Single Culvert	2.6	5.0	7.6
23	765	Boxford	Off Styles Pond Road	Single Culvert	2.6	5.0	7.6
24	898	Rowley	Daniels Road	Single Culvert	5.0	2.5	7.5
25	860	Georgetown	Central Street	Single Culvert	5.0	2.5	7.5
26	639	Ipswich	Essex Road	Single Culvert	5.0	2.4	7.4
27	587	North Andover	Carlton Lane	Single Culvert	3.6	3.6	7.2
28	462	Topsfield	Summer Street	Single Culvert	5.0	2.1	7.1
29	878	Rowley	Haverhill Street	Single Culvert	5.0	2.1	7.1
30	1231	Newburyport	Pheasant Run Drive	Multiple Culvert	5.0	2.1	7.1
31	788	Rowley	Boxford Road	Single Culvert	5.0	2.1	7.1
32	9017	Newbury	Off Middle Road	Single Culvert	5.0	2.0	7.0
33	1155	West Newbury	Georgetown Road	Multiple Culvert	5.0	2.0	7.0
34	292	Hamilton	Alan Road	Single Culvert	5.0	2.0	7.0
35	484	Boxford	Middleton Road	Single Culvert	4.0	3.0	7.0

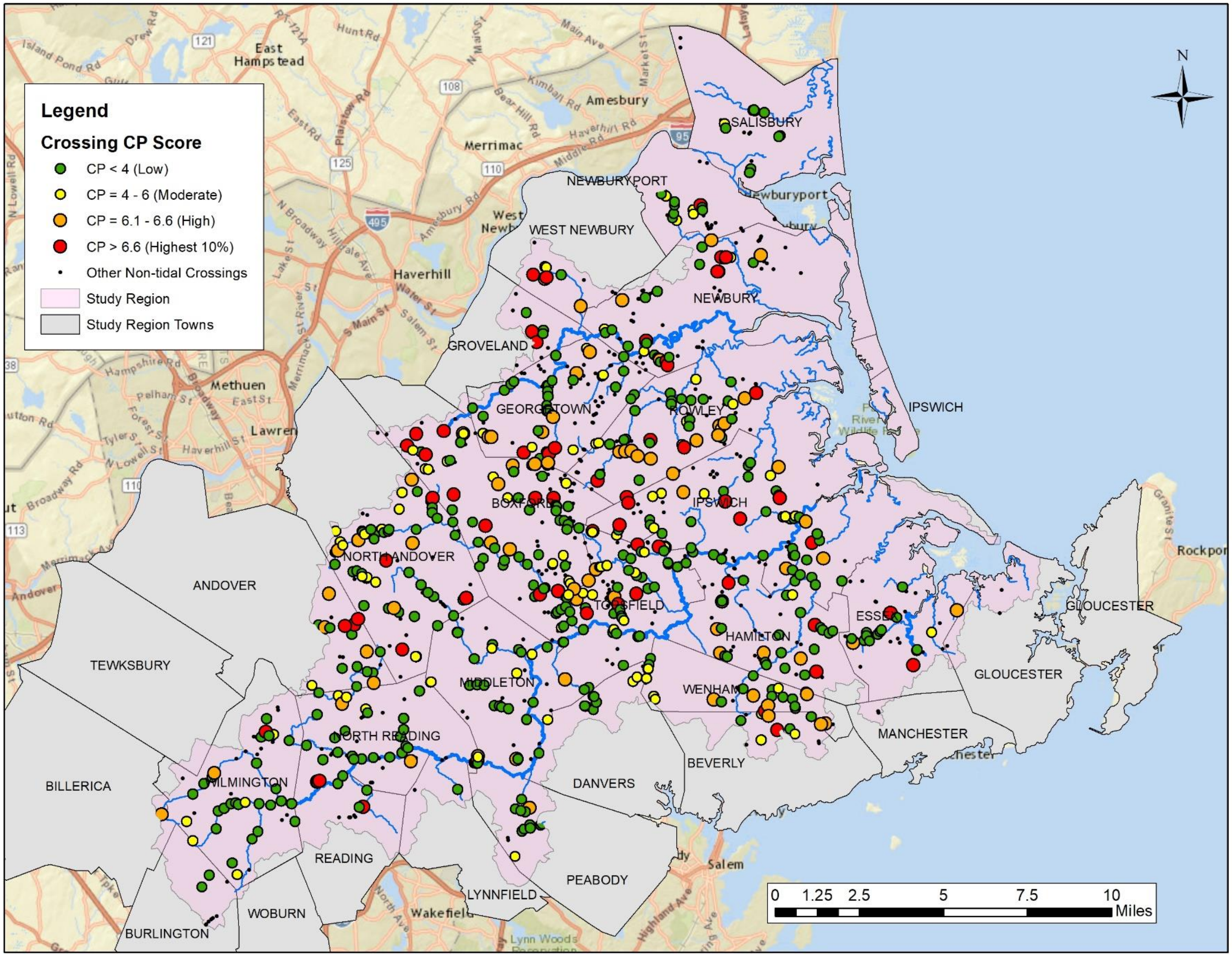

Figure 10. Map of the Great Marsh study region showing non-tidal road-stream crossings prioritized by Crossing Priority (CP) score.

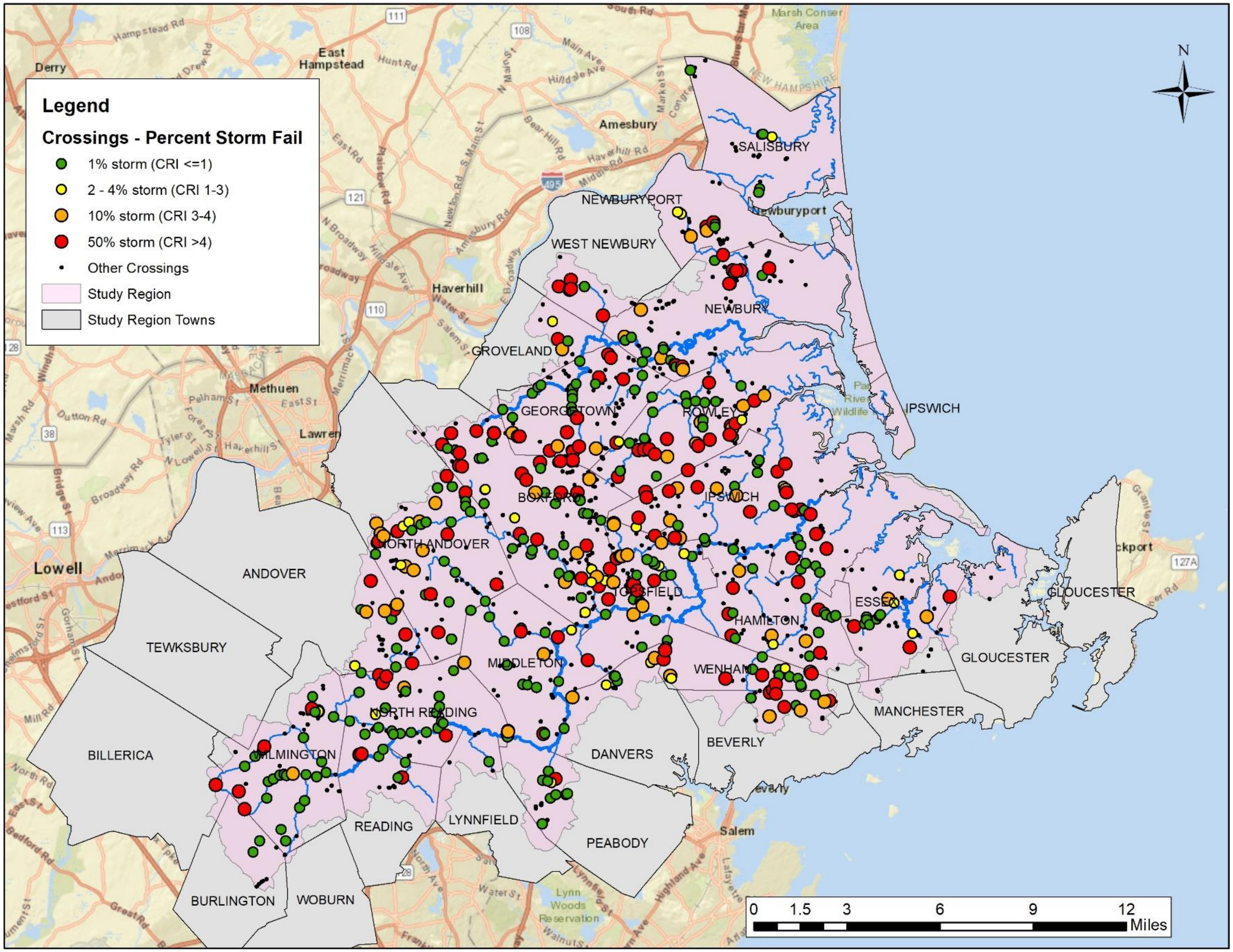

Figure 11. Map of the Great Marsh study region showing non-tidal road-stream prioritized by Crossing Infrastructure Risk Index (CRI) and the percent storm at which it is expected to fail to adequately pass flows.

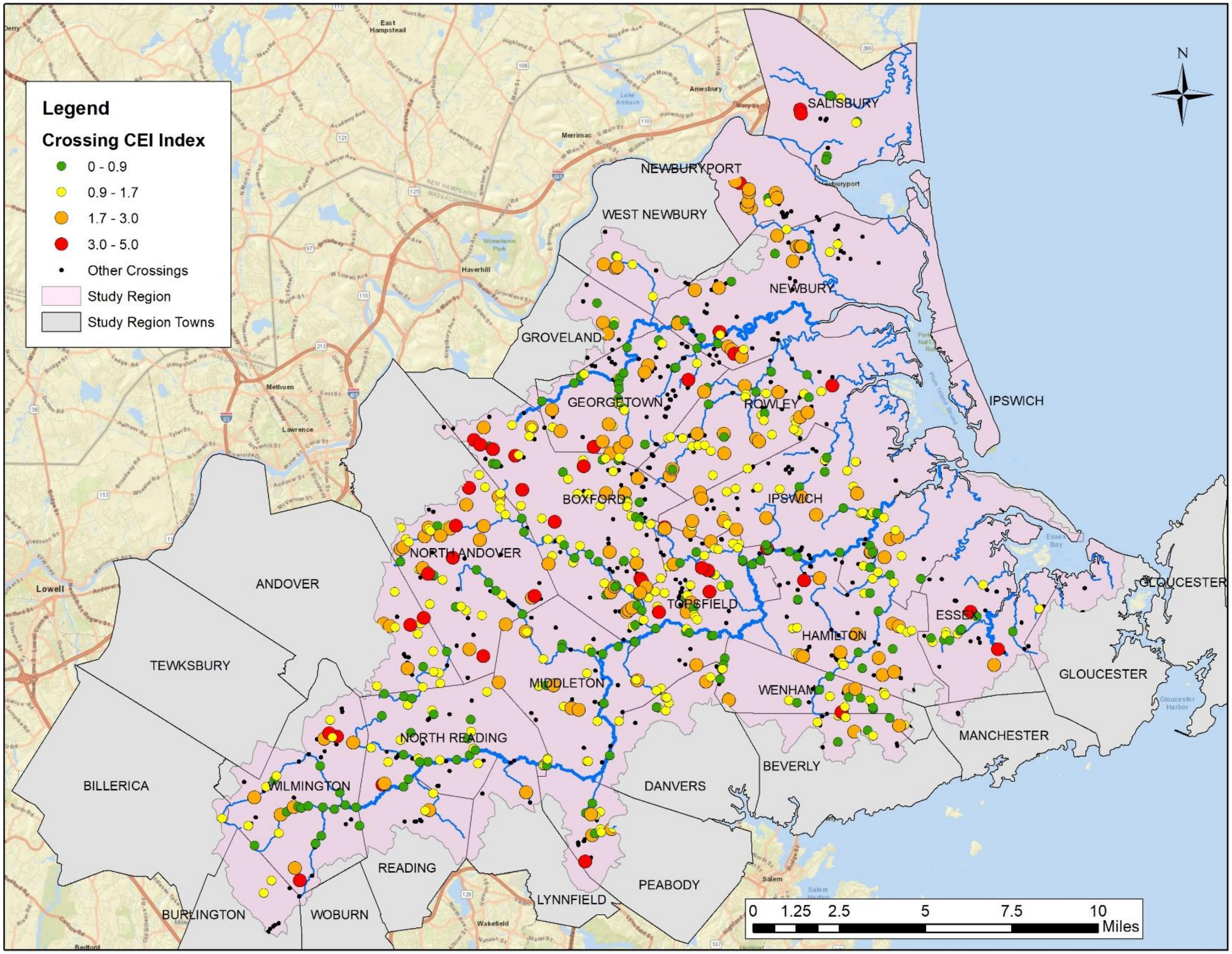

Figure 12. Map of the Great Marsh study region showing non-tidal road-stream crossings prioritized by Crossing Ecological Impact Index (CEI).

Tidal Crossings

Based on a detailed review of 23 tidal crossings encountered during our field surveys and 121 site records in the Draft Great Marsh Plan, we identified a total of 89 tidal crossings in the study region. Seventy-one (80%) of those 89 crossings were located under a public way and nearly half (44) were associated with a tidally restricted salt marsh identified in the Draft GMP. As noted in the methods section, prioritizing tidal crossings with rapid screening techniques is a challenge. A group of partners led by UMass Amherst is currently developing and testing a rapid assessment technique for ecological connectivity at tidal crossings which we tested in our study region in the summer of 2017. Once the protocol is finalized and available for use, these sites can be assessed using the new protocol which will be adopted as a formal module in the NAACC assessment framework.

Based on our tidal crossing screening criteria 31% (27) are high, 15% (13) medium and 55% (48) low priority for further investigation. The spatial distribution of the prioritized tidal crossings is mapped in Figure 13. Salisbury has the most (12) high priority tidal crossings in the study region followed by Ipswich (7) as shown in Table 10. The cities of Gloucester and Newburyport don't have any high priority tidal crossings that were part of this study.

Table 10. High priority tidal crossings in the Great Marsh study region.

Town	Crossing ID	Road/Site	Public Way	GMP Priority Marsh	Local Priority
Essex	17107	Route 133	Yes	Medium	
	17108	Old Essex Road	Yes	Medium	
	17109	Behind Town Hall	No	High	
	436	Eastern Ave	Yes	Low	Yes
	406	Landing Road	Yes	NIP	Yes
Ipswich	660	Argilla Road (Labor in Vain Creek)	Yes	Medium	
	6864	Labor in Vain Road (Labor in Vain Creek)	Yes	Medium	
	17240	MBTA Marsh West of Rowley River (N)	Yes	Medium	
	17241	MBTA Marsh West of Rowley River (S)	Yes	Medium	
	17242	Town Farm Road North	Yes	Medium	
	17243	Town Farm Road South	Yes	Medium	
	17246	Trustees East side of Castle Hill	No	High	
Newbury	17329	Route 1A - 500 ft N of Rowley Line	Yes	High	
	17330	Route 1A - Rowley Town Line	Yes	High	
	17343	Newman Road East of Little River	Yes	High	
	17331	River Front	Yes	Medium	
	17344	Kents Island Road	No	Medium	Yes
Rowley	17462	Red Gate Road	Yes	Medium	
Salisbury	10104	Ferry Road	Yes	High	
	10107	Route 1 (Town Creek)	Yes	High	
	10108	State Reservation Road	Yes	Medium	
	10117	State Reservation Road	Yes	Medium	
	10118	State Reservation Road	Yes	Medium	
	17471	Rail Trail	No	High	
	17472	Rail Trail	No	High	
	17473	Route 1	Yes	High	
	17474	Old County Road	Yes	Medium	
	17475	Old County Road	Yes	Medium	
	17477	March Road	Yes	High	
	17478	1st Street	Yes	High	

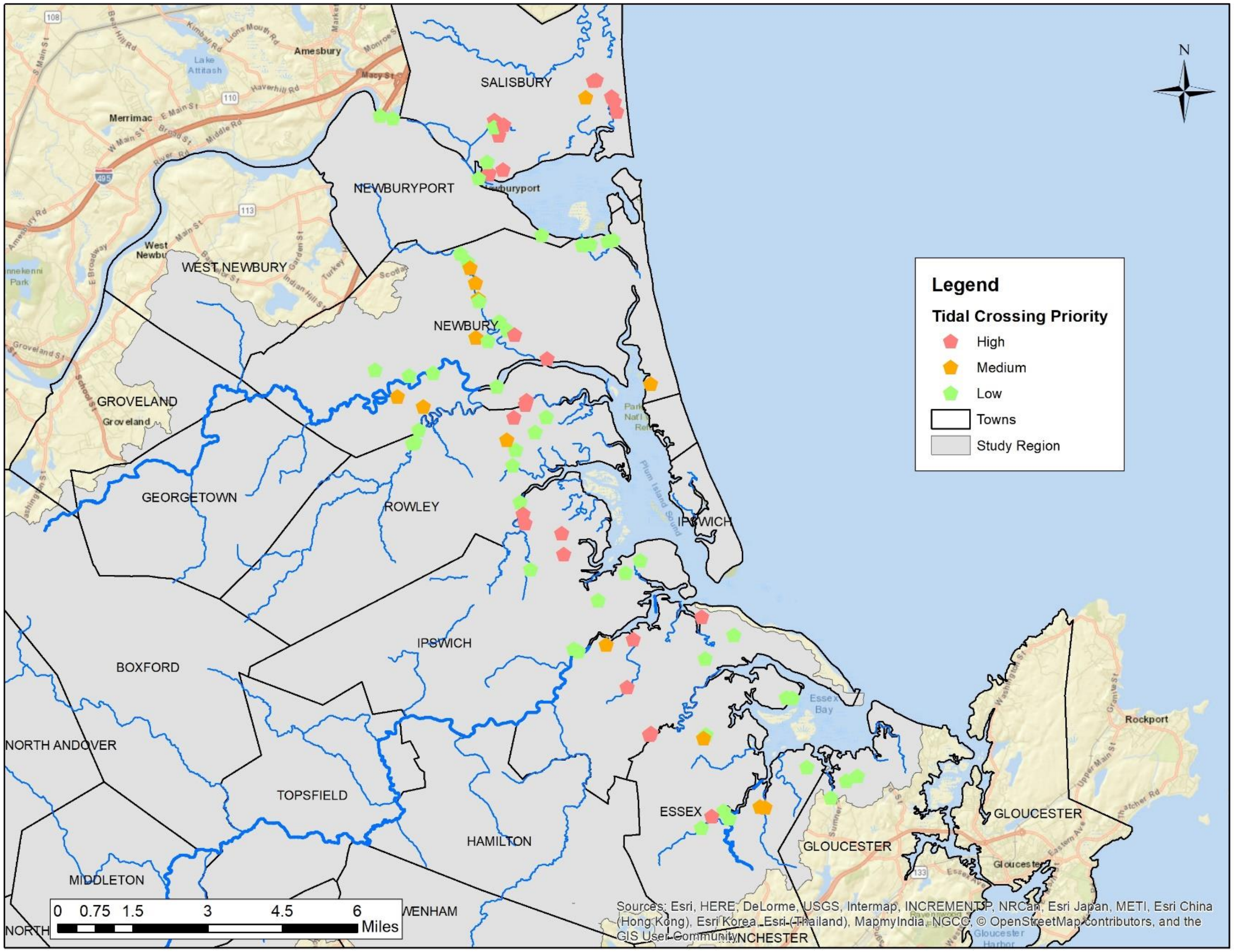

Figure 13. Map of the Great Marsh study region showing prioritized tidal crossings.

Coastal Stabilization Structures

We evaluated a total of 87 coastal stabilization structures as part of this study using the existing data sets from MA Office of Coastal Zone Management (CZM) on public and private shoreline stabilization structures. Within the study region there are 27 public structures and 60 private structures covering almost 6,000 linear meters (3.7 miles) of shoreline (Table 11). Since the CZM inventory of private stabilization structures was conducted by remote sensing methods, the condition of the private structures was not available.

Of the 27 public structures, 1 was identified as high priority and 9 were moderate priority with the remaining 17 (63%) in good condition and therefore low priority (Table 11). Ninety five percent (57) of the private shoreline stabilization structures are located in the municipalities of Ipswich, Newbury and Newburyport. Newburyport (17 structures) and Salisbury (7 structures) together have more than half (63%) of the public structures. Across the region, the vast majority of stabilization structures are located around the mouths of the Merrimack and Ipswich rivers (Figure 14). The areas associated with Salisbury Beach, the Parker River National Wildlife Refuge, Crane Beach and Essex Bay show few signs of hardened shorelines within these data sets.

Table 11. Summary of coastal stabilization structures in the Great Marsh study region. Structure totals include structure count and cumulative length.

Structure Category	Structure Priority	Count	Length (meters)
Public	High	1	32
	Moderate	9	458
	Low	17	2223
Private	NA	60	3259
Total		**87**	**5972**

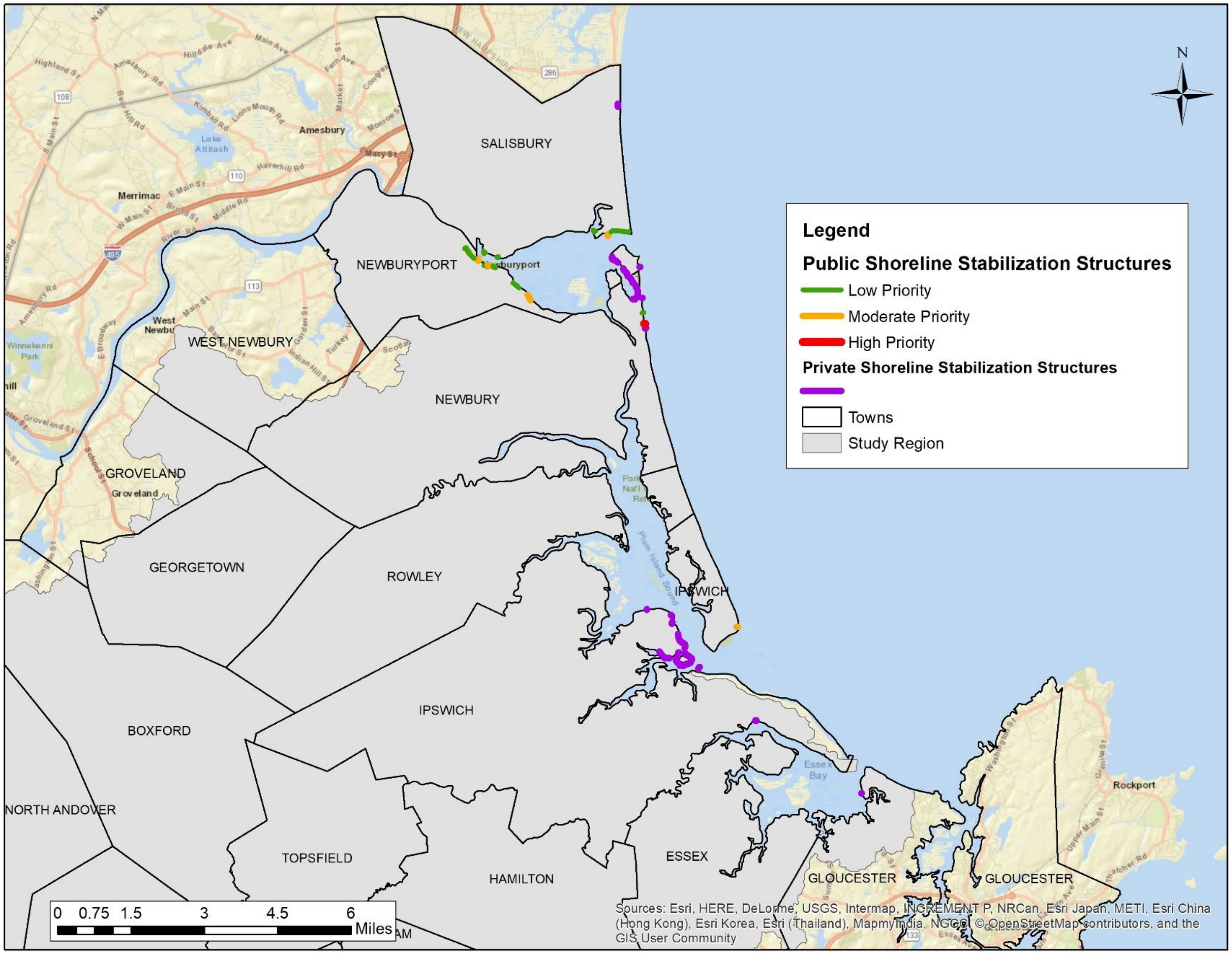

Figure 14. Map of the Great Marsh study region showing prioritized coastal stabilization structures.

Crossing Replacement Designs

Meridian Associates, Inc. (MAI) developed conceptual designs for 103 high priority crossings in the region. The structures designed were almost exclusively non-tidal crossings (101), but two sites were tidal crossings for which the engineering team felt comfortable proposing conceptual designs. These designs can provide a starting point for municipalities and other crossing owners to more easily incorporate more resilient and long-lived structures into their bridge and culvert maintenance schedules. We hope the plans are useful tools to help with scoping, budgeting and fundraising associated with crossing upgrades. A summary of the number of crossings designed by municipality is shown below (Table 12). Figure 15 shows the distribution of designed crossings throughout the Great Marsh study region. Please refer to Appendix 3 for the full package of designs and recommendations prepared by MAI and IRWA.

Table 12. Summary of conceptual designs for crossing replacement by municipality.

Municipality	Number of Crossings Designed
Andover	5
Boxford	15
Essex	3
Georgetown	4
Hamilton	3
Ipswich	4
Middleton	3
Newbury	12
Newburyport	2
North Andover	10
Reading	1
Rowley	6
Salisbury	5
Topsfield	14
Wenham	3
West Newbury	2
Wilmington	11
Total	**103**

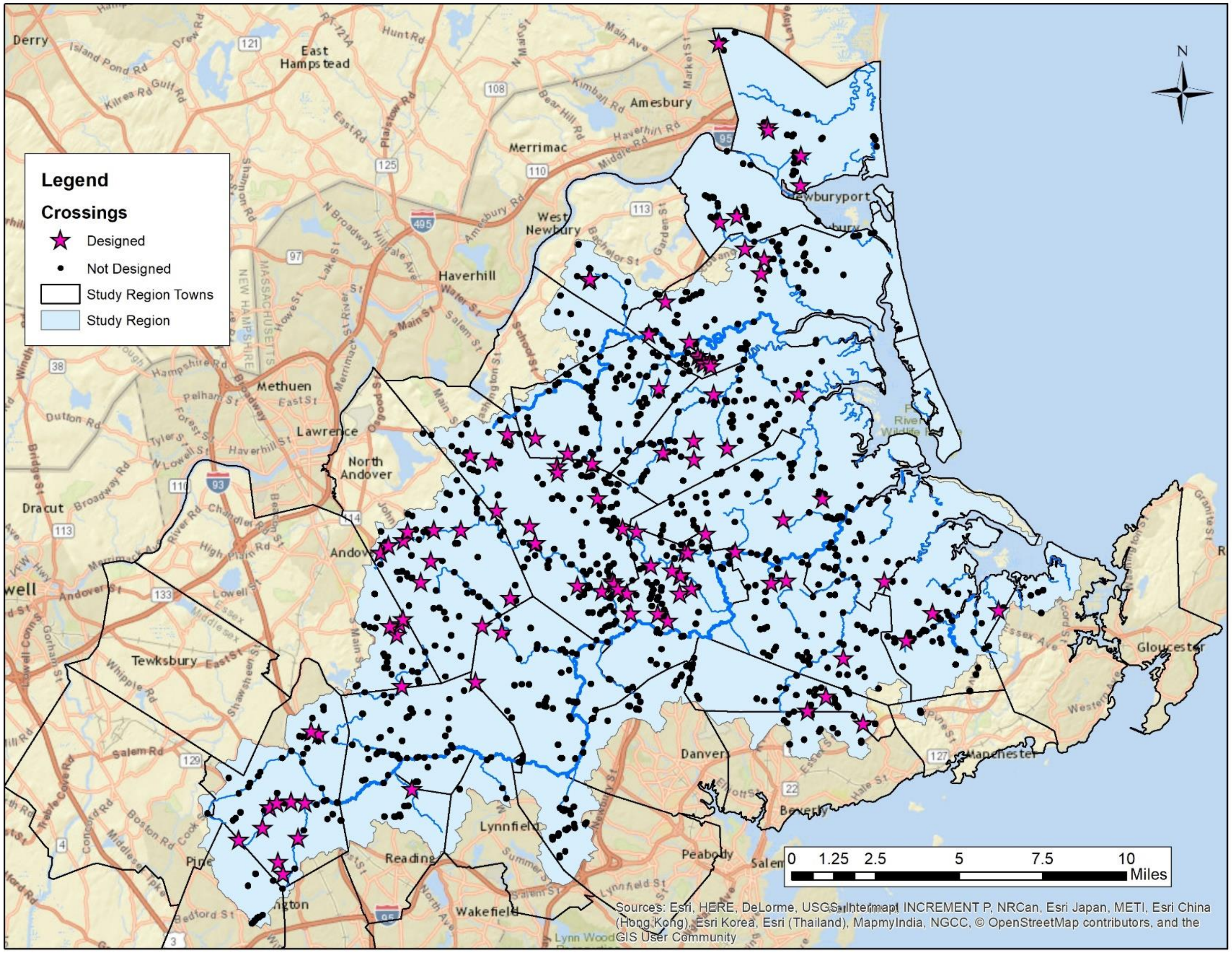

Figure 15. Map of the Great Marsh study region showing crossing sites for which conceptual designs were developed as part of the project.

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Appendix 1 – Coastal Municipality Barrier Reports

This appendix contains town-specific summary reports for the coastal municipalities in the Great Marsh study region. These seven municipalities contain areas within the tidally influenced portion of the study region and therefore may have all four barrier types considered in our analysis. The municipalities are listed in Table 13 and the summary reports follow in alphabetical order. No report was produced for the City of Gloucester because only a very small portion of the city and few barriers fell within the study region.

Table 13. Alphabetical list of coastal towns in the Great Marsh study region showing the total number of each barrier type assessed within the surveyed portions of each municipality. The area column represents the land area of the municipality that falls within the study region. **No report was produced for the City of Gloucester because only a very small portion of the city and few barriers fell within the study region.*

Town	Area (square miles)	Dams	Non-Tidal Stream Crossings	Tidal Crossings	Shoreline Stabilization Structures	Structures Designed
Essex	13.0		38	12		3
*Gloucester	2.9		3	3	1	
Ipswich	32.4	6	87	17	25	4
Newbury	23.4	9	80	27	21	12
Newburyport	8.8	4	34	4	31	2
Rowley	18.6	6	76	9		6
Salisbury	16.0		20	15	9	5

IN SEPARATE DOCUMENT FOR NOW

Appendix 2 – Inland Municipality Barrier Reports

IN SEPARATE DOCUMENT FOR NOW

Appendix 3 – Road-Stream Crossing Designs

IN SEPARATE DOCUMENT FOR NOW

Appendix 4 – Full Result Tables

IN SEPARATE DOCUMENT FOR NOW

Appendix 5 – Trout Unlimited Modeling

The Final TU assessment will be appended or linked here (53 pages)

Linked here: https://drive.google.com/file/d/0B5dK-db48bBjTzRTMEFQNFdPdWc/view?usp=sharing