Resilient Tidal Crossings

An Assessment and Prioritization to Address New Hampshire's Tidal Crossing Infrastructure for Coastal Resilience



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Prepared in partnership with:
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Cover photos (clockwise from upper left): (1) Atlantic Avenue's crossing of Fresh Creek in Dover, Crossing ID 85 (credit: NHDES Coastal Program); (2) Harbor Road's crossing of an unnamed tributary to Rye Harbor in Rye, Crossing ID 132 (credit: NHDES Coastal Program); (3) Route 1A crossing of an unnamed tributary to Rye Harbor before it was replaced, Crossing ID 45 (credit: NHDOT); (4) flooding at Bay Road's crossing of Lubberland Creek in Newmarket, Crossing ID 100 (credit: The Nature Conservancy).

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1. EXECUTIVE SUMMARY

One-hundred-eighteen tidal crossings were assessed across New Hampshire's coastal zone. Scoring criteria were applied to prioritize each crossing with a focus on enhancing coastal resilience for both human and natural communities. Infrastructure condition, inundation risk, tidal restriction, fish passage and salt marsh migration were among the scoring components.

Out of the 118 tidal crossings, the following are some of the significant findings from the Resilient Tidal Crossings project:

Infrastructure Results

- Thirty-three crossings have an immediate maintenance or replacement need. Just over half of crossings are in good or fair condition.
- Eleven crossings were recently inundated by flood waters; 24 additional crossings will be subject to inundation from high tides and storms with 1.7 feet of sea level rise.
- The overall infrastructure scores show that, when pairing structure condition and inundation risk to the roadway scores, the majority of crossings (58%) are at immediate or near-term risk, while less than 20% of crossings are currently adequate.

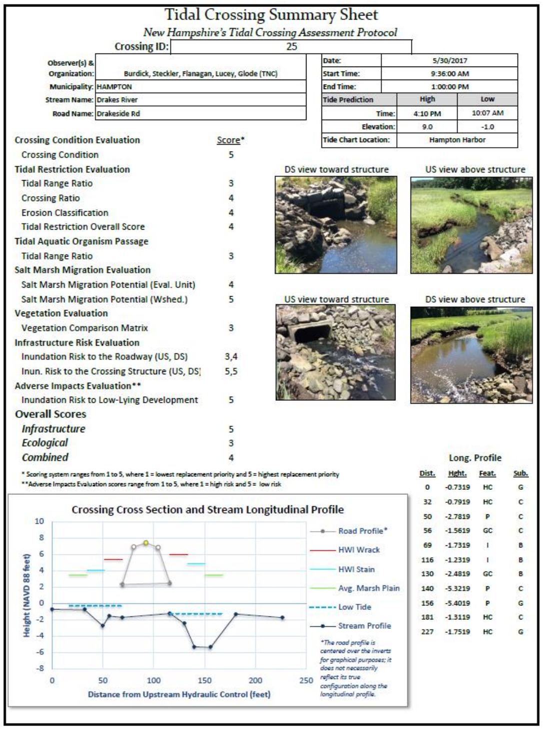
Ecological Results

- Greater than 80% of crossings are moderately to highly restrictive to tidal flows.
- Seven crossings are severe tidal restrictions and are permanent barriers to aquatic organism passage; many of these are perched at high tide or impounded.
- The majority of sites result in altered hydrology leading to severe channel erosion immediately upstream and downstream of the crossing.
- Sixty-two crossings (53%) were identified as having 5 acres or more of salt marsh migration potential.
- The overall ecological scores show that 39 crossings have high ecological priority scores, and 26 crossings have very high ecological priority. Only 17 crossings have low ecological priority.

Overall Results

- The overall combined score identifies 23 highest priority and 32 high priority crossings to be addressed or replaced.
- Seventeen crossings are currently adequate when pairing infrastructure and ecological scoring factors.

1.1 How to Access Data



Tidal Crossing Summary Sheet

New Hampshire's Tidal Crossing Assessment Protocol

Crossing ID: 25

Observer(s) & Organization:	Burdick, Steckler, Flanagan, Lucey, Glode (TNC)
Municipality:	HAMPTON
Stream Name:	Drakes River
Road Name:	Drakeside Rd

Date:	5/30/2017	
Start Time:	9:36:00 AM	
End Time:	1:00:00 PM	
Tide Prediction	High	Low
Time:	4:10 PM	10:07 AM
Elevation:	9.0	-1.0
Tide Chart Location:	Hampton Harbor	

	Score*
Crossing Condition Evaluation	
Crossing Condition	5
Tidal Restriction Evaluation	
Tidal Range Ratio	3
Crossing Ratio	4
Erosion Classification	4
Tidal Restriction Overall Score	4
Tidal Aquatic Organism Passage	
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Salt Marsh Migration Evaluation	
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Inundation Risk to Low-Lying Development	5
Overall Scores	
Infrastructure	5
Ecological	3
Combined	4

DS view toward structure | US view above structure | US view toward structure | DS view above structure

* Scoring system ranges from 1 to 5, where 1 = lowest replacement priority and 5 = highest replacement priority
**Adverse Impacts Evaluation scores range from 1 to 5, where 1 = high risk and 5 = low risk

Long. Profile

Dist.	Hght.	Feat.	Sub.
0	-0.7319	HC	G
32	-0.7919	HC	C
50	-2.7819	P	C
56	-1.5619	GC	C
69	-1.7319	I	B
116	-1.2319	I	B
130	-2.4819	GC	B
140	-5.3219	P	C
156	-5.4019	P	G
181	-1.3119	HC	C
227	-1.7519	HC	G

TIDAL CROSSING SUMMARY SHEET: Tidal Crossing Summary Sheets for each of the 118 assessed tidal crossings are available in **Appendix D.** Each of these two-page summary sheets contains crossing scores, photos, a map, and a "Crossing Cross Section and Stream Longitudinal Profile" graph. This graph illustrates the result of the elevation survey performed at each crossing, and displays key elevation data, including elevations of the road surface, stream channel, culvert and high water indicators. **Section 5.2** provides additional context for understanding the "Crossing Cross Section and Stream Longitudinal Profile." **Appendix F** contains an interpretation guide that explains the relevance of each evaluation criteria score and serves as a companion to the Tidal Crossing Summary Sheet

ONLINE DATA VIEWER: Tidal crossing results are available for viewing at:

https://www.nhcoastalviewer.org/.

This online viewer conveniently displays many of the tidal crossing scores. The scoring system of 1 (lowest replacement priority) to 5 (highest replacement priority) is color-coded to demonstrate lowest (green) to highest (red) priority scores. In addition to scoring data, five additional data layers are available in the online viewers that contain various crossing attributes, including structure condition, ecosystem attributes, local data, and past restoration and replacement information. The full project dataset can be downloaded by GIS users from ArcGIS Online as a file geodatabase (sign in is required for data download—new ArcGIS Online users can create a free account). The complete dataset can also be provided by NHDES, upon request.

2. INTRODUCTION

Tidal crossings are unique types of infrastructure that play an important role in the resilience of both the built and natural environment across the coastal zone. Significant investments have been made in New Hampshire over the last 10 years to inventory and assess freshwater road-stream crossings, but until recently, a gap has remained in the ability to assess the complexity and variability at tidal crossings. The Resilient Tidal Crossings Project (Project) set out to fill that gap with the following primary objectives:

1. Collect standardized data on each of New Hampshire's tidal crossings.
2. Prioritize each tidal crossing's attributes based on a set of management objectives.
3. Make project data and analysis results available to stakeholders.

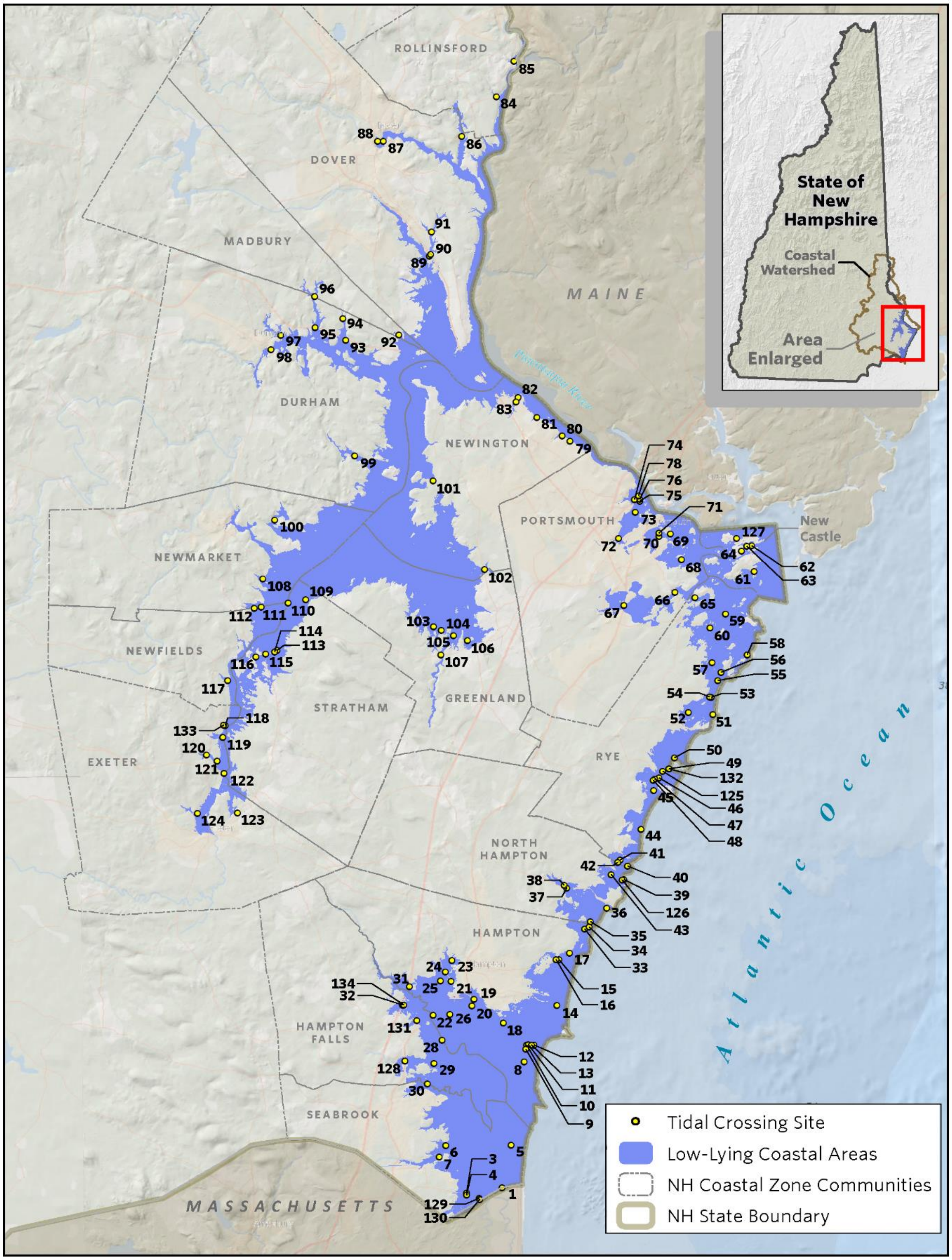
For the purpose of this Project, a tidal crossing is defined as a culvert or bridge that conveys bi-directional tidal flow, or that is predicted to become tidally influenced in the near future considering sea level rise (SLR) of 1.7 feet. Figure 1 shows the geographic distribution of New Hampshire's tidal crossings. Appendix A provides a tabular inventory of tidal crossings by town, road and stream names.

This report includes information on the Project's background, methods, a presentation of results, a discussion of results, and identification of next steps. **Section 2. Introduction** provides the broader context for why and how the Project was designed and implemented. Data collection and crossing prioritization efforts are detailed in **Section 3. Methods**. **Section 4. Results** presents distributions of scores across all prioritization categories for assessed tidal crossings. **Section 5. Discussion** considers the implications of Project results and data, including some examples of in-depth analyses that are enabled using Resilient Tidal Crossings data. **Section 6. Next Steps** identifies potential near and long-term actions to advance tidal crossing management for coastal resilience.

2.1 Project Team

The Project was performed by a team led by The Nature Conservancy (TNC) and New Hampshire Department of Environmental Services Coastal Program (NHCP) and included the University of New Hampshire (UNH) Jackson Estuarine Laboratory (JEL), UNH Technology Transfer Center (T^2), and UNH Geographically Referenced Analysis and Information Transfer System (GRANIT). Field data collection was coordinated and performed by NHCP. Desktop analysis, data quality control and data analysis were performed by TNC. JEL provided technical expertise regarding field assessments and crossing prioritization. The project's mobile data collection and management system was developed by T^2. T^2 hosts the Project's database and has made it available for public download. Primary project scoring results and select crossing attributes are displayed on GRANIT's NH Coastal Viewer.

Figure 1: Map of New Hampshire's Tidal Crossings. Each crossing is label with its unique identifier, or "Crossing ID." See Appendix A for additional crossing information details.



2.2 Funding

This Project was enabled by a $187,500 grant from the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (OCM) through the Projects of Special Merit (CFDA 11.419).

2.3 Context

Tidal crossings emerged as a priority for coastal zone management in 2015 when the need for asset management, coastal hazard mitigation and natural resource management converged. Sea level rise as a concept had been discussed and acknowledged for years, but newly available data products such as high-resolution topographic data, and sea level inundation and salt marsh migration mapping made detailed analyses of complex coastal management considerations possible. Similarly, the State of New Hampshire's investment in a transportation asset management system (the Statewide Asset Database Exchange System, or SADES) created an opportunity for tidal crossing asset management, while also highlighting tidal crossings as a gap in the asset management system.

As a result, TNC, NHCP and JEL developed a modern-day tool, New Hampshire's Tidal Crossing Assessment Protocol (Steckler et al. 2017) to assess and prioritize tidal crossings. The primary goal of the protocol was to assist transportation and coastal natural resource managers to maintain resilient tidal ecosystems and a safe and reliable transportation network. The protocol methodology collects a combination of field and GIS based data that feed into a prioritization process, which identifies tidal crossings in most need of attention with respect to infrastructure and ecological management. The highest priority tidal crossings are those that demonstrate the greatest potential to increase the resilience of our coastal infrastructure and tidal habitats.

Management Considerations

Tidal crossings require careful and deliberate management to maintain and protect the functions and values that estuarine habitats provide. These crossings are subject to high regulatory oversight by the NHDES Wetlands Bureau, Coastal Program and Shoreland Programs because of the unique and sensitive environments that they traverse, and the complexity of conditions that they are subject to. As with the rest of the transportation network, public safety is paramount, yet is especially challenging in these dynamic systems. Not only are tidal crossings subject to two high and two low tides most days, they are also subject to extreme precipitation events and coastal storm surges. On top of these design considerations and challenges is the need to plan for the anticipated effects of rising sea levels.

Tidal crossing replacement projects are undertaken for a variety of reasons. The driver for replacement in some cases is the failure or deterioration of existing infrastructure. Addressing a flooding problem might be a driver in other cases. And ecological restoration, such as addressing a tidal restriction that affects salt marsh health, salt marsh migration, or fish passage, is the focus of other tidal crossing replacements.

The design of a tidal crossing balances many considerations, including the drivers for replacement described above, costs, and managing risk. Cost can be considered in a number of ways, from the cost of no action, to construction, maintenance, and avoided costs depending on the scope and longevity of the engineered solution. Costs are not limited to the immediate transportation infrastructure alone; they extend to adjacent private property owners, ecosystem services and the intrinsic value of natural systems.

Managing risk is another consideration in the management of tidal crossings — but it's complicated in these low-lying coastal systems. Designing larger and taller tidal crossings to accommodate more frequent and intense storm events and higher tides will reduce the risk of road flooding and washouts. Generally speaking, these larger structures are more compatible with the ecosystems that they cross, creating a more resilient system for both people and nature. However, larger structures with greater hydraulic capacity may jeopardize upstream property and infrastructure through increased tidal flooding. On the other hand, undersized crossings risk upstream private property flooding because of limited seaward drainage capacity. This is all to say that each tidal crossing is unique and will have unique management and risk considerations when considered for replacement. The results of the Resilient Tidal Crossings Project highlights relevant management considerations at each of New Hampshire's tidal crossings.

The following sections provide additional details about management considerations at tidal crossings including sea level rise, transportation reliability, processes supporting salt marsh habitat and threats to salt marshes.

Sea Level Rise

There remains great uncertainty about the magnitude of sea level rise expected over the next 60 to 80 years as a result of our changing climate. Estimates range from 0.7 feet on the lower side (IPCC 2014) to 6.3 feet on the more extreme side (Wake et al. 2011). A 1.7-foot sea level rise (SLR) was used for this project as a near-term conservative projection in the assessment of tidal crossings. It captures the projected mean higher high water tide elevation at year 2050 under a high carbon emission scenario while also preparing for a lower SLR projection under a longer-term low emissions scenario (Wake et al., 2011). Approximately 35 additional crossings that are predicted to become tidal with 1.7 feet of SLR were included for assessment by the Project.

SLR will increase daily tidal flows at tidal crossings, adding additional pressure on crossing structures. Crossing structures already in poor condition may be more prone to failure from more intense physical exposure. High tide flooding, which is already documented at some crossings, will only become more frequent and severe, while additional crossings will become subject to regular or more regular high tide flooding. SLR will also exacerbate storm surge flooding and the negative effects of tidal restrictions on fish passage, salt marsh migration and salt marsh health. The planning need that this Project fills is even more important given the anticipated effects of SLR on tidal systems.

NH Coastal Risks and Hazards Commission

The New Hampshire Legislature created the NH Coastal Risks and Hazards Commission (CRHC) in 2013 to “recommend legislation, rules, and other actions to prepare for projected sea-level rise and other coastal and coastal watershed hazards such as storms, increased river flooding, and stormwater runoff, and the risks such hazards pose to municipalities and the state assets in New Hampshire” (CRHC 2016). The CRHC convened a Science and Technical Advisory Panel (STAP) to review available scientific information about coastal hazards and flood risks in New Hampshire. The STAP analyzed historic trends and projections out to years 2050 and 2100 for SLR, storm surge and extreme precipitation. The CRHC utilized the STAP report to make 35 recommendations to help New Hampshire Coastal Zone communities prepare for and respond to coastal risks and hazards.

For coastal infrastructure projects with a design life to 2050, CRHC recommends planning for at least 1.3 feet and as much as two feet of SLR (CRHC 2016). The Resilient Tidal Crossings Project is in service to the recommendations of the CRHC by assessing all tidal crossings and prioritizing replacements based on current and projected flood vulnerabilities.

Transportation Reliability

New Hampshire coastal communities rely on a functional, reliable and safe transportation network. Tidal crossings are a critical component of that network, which allow for the continuous flow of people, goods and services throughout the coastal zone. Across the 17 coastal communities there are over 1,300 miles of road used by nearly 150,000 residents (CRHC 2016). Tourism accounts for a considerable amount of both business revenue and roadway use across the seacoast. The views across our expansive tidal marshes from coastal roads are important to residents and visitors alike and provide a sense of place and quality of life.

Maintaining and upgrading our coastal transportation infrastructure is essential to the economic viability and vitality of the region — not to mention the safety of all public transportation system users. Many of New Hampshire’s tidal crossings fall along evacuation or emergency access routes that are essential for public safety. These critical routes are needed to manage emergency response, access and egress during natural and human caused disasters, such as severe weather events or an emergency at the Seabrook Nuclear Power Plant

A recent transportation vulnerability assessment project, From Tides to Storms, identified critical infrastructure at risk. Routes 1-A, 1, and Interstate 95 — the primary north-south roads, and Routes 101 and 286 — the primary east-west roads (and evacuation routes), are all identified as vulnerable to sea level rise. For example, almost eight of Route 1-A’s 18 miles will be inundated twice daily under a high SLR scenario of 6.6 feet at year 2100. Route 1-A runs adjacent to the Atlantic Coast and connects New Hampshire’s most popular beaches, tourist amenities and working waterfronts, transporting 18,000 vehicles per day during the peak summer season (Rockingham Planning Commission 2015). In March of 2018 Route 1-A sustained costly damages ($3.3 million) during a series of Nor’easters, which resulted in a Presidential Disaster Declaration and FEMA Public

Assistance. The 2018 Nor'easters are likely a harbinger of challenges that the region's transportation network will face in the years to come as a result of climate change.

Salt Marsh Habitat Background

In New Hampshire, salt marshes occur along the 18-mile Atlantic coast; along the Piscataqua, Salmon Falls, and Cocheco Rivers; and around the Great Bay Estuary and its tributaries. Total salt marsh in New Hampshire as inventoried by NWIPlus (NHDES 2017) is 5,975 acres. These wetlands are subject to daily tides where the dominant vegetation is salt tolerant perennial grasses. Salt marsh formation and development, described by Redfield (1972), begins where smooth cordgrass (*Spartina alterniflora*) colonizes un-vegetated intertidal habitat. Plants grow and interact with floodwaters by capturing sediments and producing belowground biomass that forms peat. Over centuries the marsh builds to an elevation that approximates mean high tide.

Salt marsh plant communities are primarily an expression of site salinity and tidal inundation. Smooth cordgrass grows at low marsh elevations subject to twice daily flooding. High marsh habitats are dominated by salt meadow cordgrass (*Spartina patens*) and other plants, which occur above the low marsh. Salt marshes transition to either upland or to brackish and then freshwater marshes as salinity inputs decrease and hydrology is driven more by land than by sea.

Salt marsh abundance and extent depends upon the physical exposure and slope of the shoreline. Extensive marshes typically form in shallow embayments, especially landward of barrier beach systems. Examples of barrier beach estuaries in New Hampshire are the Hampton Seabrook Estuary, Little River, Bass Beach and Parsons Creek. Narrow fringe marshes typically occur along steep shorelines (Mitsch and Gosselink 2000; Morgan et al. 2009). Fringe marshes are found along the Piscataqua and Cocheco rivers, and the Great and Little Bay shorelines. New Hampshire also has several examples of brackish tidal river bank marshes that occur along the Salmon Falls, Bellamy, Lamprey and Squamscott rivers.

Salt marshes possess a variety of ecological functions that are important to humans as ecosystem services, as detailed in Table 1. These range from support of coastal food webs and biodiversity to storm protection and carbon storage (Short et al. 2000, Barbier et al. 2012). They support a suite of plants and animals that have adapted to these dynamic biophysical systems. However, without daily tidal flooding, the processes that sustain salt marshes are interrupted, leading to salt marsh degradation and a loss of functions and values.

Table 1: Ecosystem functions and values of salt marshes, adapted from Short et al. 2000.

Number	Functions	Values
1	Primary Production	Support of food webs, fisheries and wildlife
2	Canopy Structure	Habitat, refuge, nursery, and settlement; support of fisheries
3	Organic matter accumulation	Support of food webs, counter sea level rise
4	Seed production/vegetative expansion	Maintenance of plant communities and biodiversity

5	Sediment filtration and trapping	Counter sea level rise, improve water quality, and support of fisheries
6	Epibenthic and benthic production	Support of food web, fisheries and wildlife
7	Nutrient and containment filtration	Improve water quality and support of fisheries
8	Nutrient regeneration and recycling	Support of primary production and fisheries
9	Organic export	Support of estuarine, offshore food webs, and fisheries
10	Wave and current energy dampening	Protect upland from erosion and reduce flood-related damage
11	Self-sustaining ecosystem	Recreation, aesthetics, open space, education, landscape level biodiversity, and historical value.

Threats to Salt Marshes

Regional studies have shown that about 37% of tidal marsh area was lost in New England due to development (Bromberg Gedan et al. 2009). Much of the marsh that currently exists is affected by direct impacts like ditching and pollution and indirect impacts from a variety of stressors, including excess nitrogen (Deegan et al. 2013), invasive species (Hazelton et al. 2014) and climate change (Smith 2009).

Tidal crossing structures that limit tidal flows are called tidal restrictions, which are known to result in a range of negative impacts to the wetland systems that they cross. These impacts include:

- Alteration of the composition of salt marsh flora and fauna.
- Reduced inundation by spring tides that periodically flood the marsh surface. This directly interferes with marsh maintenance processes (sedimentation, marsh peat development), which have allowed New Hampshire’s tidal marshes to maintain their position relative to sea level for thousands of years.
- Impounding freshwater upstream of the restriction, which creates opportunities for colonization by invasive plants such as *Phragmites australis,* and increases flooding of nearby low lying properties.
- Increased oxidation of organic matter; causing degradation of salt marsh peat and subsidence of the salt marsh plain.
- Reduced ability of the salt marsh to migrate upstream by limiting high tide inundation.

Of the 11 functions listed by Short et al. (2000) in Table 1, all are lost or reduced by tidal restrictions except for Number 10: Wave and current energy dampening. In New Hampshire, as in the rest of New England, about 20% of salt marshes are currently impacted by tidal restrictions (USDA, NRCS 1994, Bromberg and Bertness 2005). Removal of tidal restrictions has resulted in restored tidal systems by re-establishing more natural hydraulic and hydrologic conditions. Monitoring shows that the removal of tidal restrictions restores plant communities, processes that rebuild marsh surface elevation, and fish passage fairly quickly (Burdick and Roman 2012, Dibble and Meyerson 2012, Hazelton et al. 2014).

The cumulative impacts of tidal restrictions and SLR is especially concerning. It is unknown whether SLR alone will exceed the pace of salt marshes' ability to build in elevation at a commensurate rate (Kirwan et al. 2010, Raposa et al. 2015). Tidal restrictions put upstream salt marshes at a severe disadvantage in keeping up. Sea levels around the world are rising at a faster pace in the past 20 years than the previous century and global SLR has increased from 1.7 to 3.3 mm/year (Nichols and Cazenave 2010). As coastal managers work toward building resilience in anticipation of climate change impacts, it is critical to allow adequate flows through tidal crossings to upstream salt marshes so they can build in elevation and migrate inland.

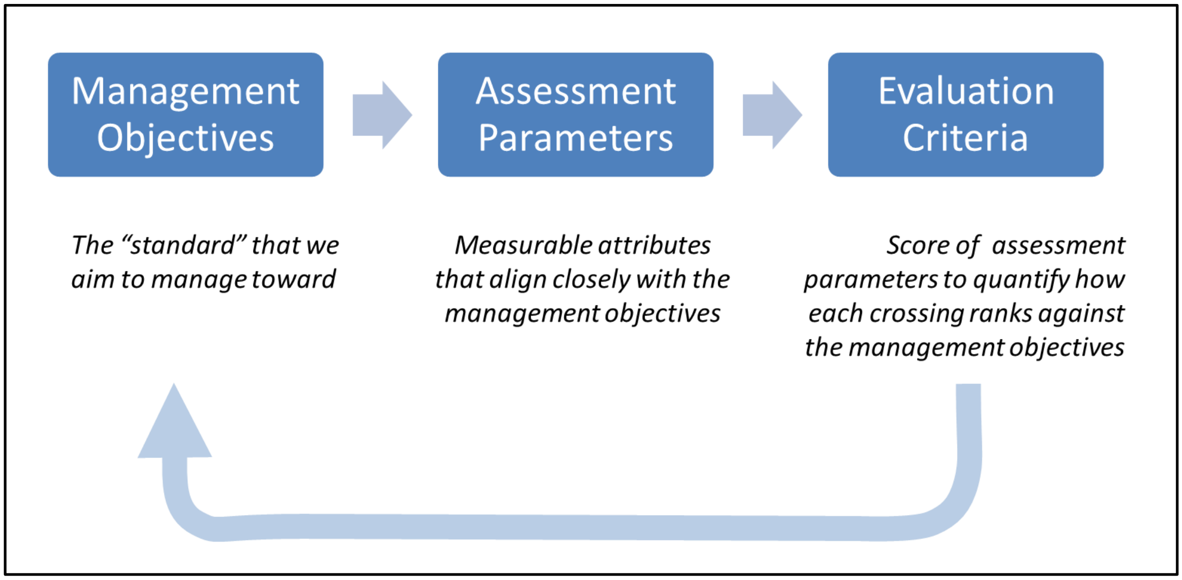
Over the previous 25 years, New Hampshire has demonstrated that the impacts of tidal restrictions are reversible. Between 1994 and 2015, salt marsh restoration was the primary design consideration for tidal crossing replacements in New Hampshire, resulting in the pro-active removal of fifteen tidal restrictions and replacement with larger structures. These restoration initiatives restored tidal flow to an estimated 635 acres of salt marsh

2.4 Tidal Protocol Background and Framework

New Hampshire's Tidal Crossing Assessment Protocol (Tidal Protocol) is a methodology to assess tidal crossings and prioritize their replacement based on a range of management objectives. Development of the Tidal Protocol began in early 2015 and was a collaborative effort led by TNC in close partnership with NHCP and UNH JEL. Broad input was solicited and received from transportation and coastal natural resource managers to inform the protocol. In addition to the formation of a Local Advisory Committee, a "Tidal Crossings Assessments Workshop" was convened in September of 2015 with nearly 50 regional, national and international professionals who provided invaluable feedback on an early draft of the protocol. After nearly two-and-a-half years of development, testing and refinement, the Tidal Protocol was completed in the summer of 2017.

The Framework (Figure 2) served as a primary guide in the Tidal Protocol's development, which includes management objectives, assessment parameters and evaluation criteria. These components of the framework are detailed in the following sections.

Figure 2: The framework that drove the development of New Hampshire's Tidal Crossing Assessment Protocol.



Management Objectives

The Tidal Protocol uses management objectives to determine how tidal crossings measure toward various performance standards. Seven management objectives are described in Table 2, which were chosen as essential drivers for the assessment and successful management of tidal crossings in New Hampshire.

Table 2: A list of the management objectives that the Tidal Protocol addresses, including an explanation of each objective's relevance.

Management Objective	Relevance of Management Objective
Crossing Condition	Understand the condition of tidal crossings to address safety and transportation infrastructure management
Tidal Restriction	Understand hydraulic compatibility of crossing structures with their tidal system
Tidal Aquatic Organism Passage	Understand the compatibility of crossing structures for fish and other aquatic organism passage
Salt Marsh Migration	Understand the upstream opportunity for salt marsh habitat to migrate inland with rising sea levels
Vegetation	Understand the influence of crossing structures on the up and downstream plant community, which can indicate effects on hydrology, salinity, and sedimentation
Infrastructure Risk	Understand the degree of risk at crossings, considering inundation risk and headwater buildup conditions
Adverse Impacts	Understand the likelihood of restoring full tidal range at a crossing given upstream low-lying infrastructure

Assessment Parameters

Assessment parameters are measurable, crossing-specific characteristics that are collected in the field and through a Geographic Information System (GIS) at each tidal crossing. Table 3 offers examples of different assessment parameters and whether they are assessed in the field or using GIS. For GIS-based assessments, a variety of data layers are used including innovative mapping products such as SLR mapping and the Sea Level Affecting Marshes Model (SLAMM).

Table 3: A summary of the Assessment Parameters.

Example Assessment Parameters	Field Assessment	GIS Assessment
Structure type and dimensions	✓	
Structure condition	✓	
Longitudinal profile	✓	✓
Roadway cross section	✓	✓
Channel characterization	✓	✓
Fish and wildlife observations	✓	
Vegetation characterization	✓	✓
Sea level rise inundation		✓
Salt marsh migration potential		✓

Evaluation Criteria

Twelve evaluation criteria are applied to select assessment parameters to score tidal crossings based on the seven management objectives. The evaluation criteria use a scoring system of 1 through 5, where a score of 1 indicates a low replacement priority or opportunity and a score of 5 indicates a high replacement priority or opportunity. In addition, three overall crossing scores are used to synthesize tidal crossing replacement priorities across many of the 12 evaluation criteria. Overall scores are tailored toward (1) infrastructure management, (2) ecological management, and (3) a combination of the two — one overall score that prioritizes based on a combination of infrastructure and ecological management considerations. Table 4 details the relationship between scores, generalized evaluation criteria, and replacement priorities from the Tidal Protocol.

Table 4: Evaluation Criteria Scoring System.

Score	Generalized Evaluation Criteria	Replacement Priority
1	**Ideal conditions:** → good structure condition → no tidal restriction → full aquatic organism passage → low salt marsh migration potential → vegetation unaffected by crossing → low flood risk	Lowest
2	Acceptable conditions	Low
3	Conditions flagged as concern	Moderate
4	Conditions flagged as high concern	High
5	**Conditions flagged as highest concern:** → poor structure condition → severe tidal restriction → reduced organism passage → high salt marsh migration potential → vegetation affected by crossing → high flood risk	Highest

3. METHODS

This section details Project methodologies for data management, field data collection, desktop analyses, quality assurance and quality control, and prioritization. The methods described in the Tidal Protocol (Steckler et al. 2017) were largely followed to conduct the field data collection, desktop analyses, and in applying the evaluation criteria. Corrections and clarifications of the tidal protocol were identified and documented during field training and follow-up quality assurance and quality control activities. Scoring criteria, as anticipated and expected in the Tidal Protocol, were adjusted to stratify scoring results in the prioritization process. An updated version of the Tidal Protocol will be released in the near future.

3.1 Data Management

A data management plan was developed to guide data collection and management, to assure data quality, and enable data quality control processes. Key components of the implemented data management plan are described in the following section; see the Quality Assurance/Quality Control (QA/QC) section for methods specifically associated with data QA/QC.

Database Development, Data Storage Structure, and Backups

A file geodatabase was created in ArcMap by UNH T^2 using parameters identified in the data dictionary (see Data Dictionary section below). The file geodatabase was loaded to an Esri Server where it was hosted as a feature service on ArcGIS Online and managed by UNH T^2. Data was shared to a private web mapping service for viewing and collection. The web mapping service interfaces with ArcMap (desktop application), Collector for ArcGIS (mobile application), and ArcGIS Online (online application).

The Esri Server stores all tidal crossing data collected. Editing access to the Esri Server was limited to stakeholders and users trained and certified in the use of the Tidal Protocol and the data collection system. UNH T2 created regular backups of the feature service during the collection period for data safety and security.

Data Dictionary

T^2 built a file geodatabase to the structure and specifications set in the project's data dictionary to store all tidal crossing data. A data dictionary details the assessment parameters to be collected at each tidal crossing based on the Tidal Protocol. The data dictionary details attribute names, data collection requirements, data type (e.g. date, integer, text), default values, and descriptions of each attribute. Appendix B includes tables from the data dictionary. Additional information about each data field is detailed in the Tidal Protocol (Steckler et al. 2017).

Table 5 details the nine discrete tables that were built into a relational database as defined by the data dictionary.

Table 5: A summary of the nine tables from the data dictionary.

Table Name	Description of Table Contents
Site Information	Basic site location attributes for each tidal crossing, such as stream name, road name, and crossing assessment status
Site Assessment	Field collected attributes relating to the crossing cross section, habitat and natural community classifications, etc.
Structure Condition	Field collected attributes pertaining to the crossing type and condition
Longitudinal Profile	Field collected attributes associated with the collection of the longitudinal profile
Desktop Assessment	GIS calculated and QAQC related attributes
Tide Gate	Field collected attributes relative to tide gate structures, if present
Replacement History	Attributes related to repair and/or replacement history
Scores	Includes the 15 score attributes based on the evaluation criteria
Tidal Crossing Photos	Photos and field collected attributes associated with crossing photos

3.2 Field Assessment Methods

Field data collection was performed by a trained field team based on the assessment guidelines laid out in the Tidal Protocol. Data collected in the field was entered electronically, using Collector for ArcGIS, Esri's mobile mapping application. An iPad protected by a water and shatterproof case was used by the field team to collect and store field data. These data were synced to ArcGIS Online via the web mapping service at the end of each field day. See Appendix C for the mobile data collection user guide that provides additional details about mobile data collection methods.

Field assessments were performed by a two-person field team. Field team availability limited the field assessment period to June through September 2018. Detailed scheduling was required to ensure that all identified tidal crossings would be assessed during low tide conditions over the field season. Tide charts for New Hampshire's semi-diurnal tide regime were reviewed and a field schedule was prepared. Given the geography of New Hampshire's coastal zone, with an outer coast and an inland estuary, the field team was generally able to conduct two crossing assessments a day because of the inland tidal delay of two or more hours.

Midday high tides periodically limited the field crew's ability to conduct two assessments in a day. On these occasions NHCP recruited volunteer assistance from partner organizations including: NH Department of Transportation, Great Bay National Estuarine Research Reserve, Piscataqua Region Estuaries Partnership, NHDES Wetlands Bureau, NHDES Watershed Assistance Section and the Maine Coastal Program. These professional volunteers enabled NHCP field staff to operate two crews on days with constrained low tide windows and maintain progress with two assessments per day. In addition to helping stay on track with the project schedule, partner involvement increased awareness and understanding about the Resilient Tidal Crossings Project and its utility to coastal resource managers.

Tidal crossings with limited or difficult access were often accessed by boat. At sites where boat access was necessary, three NHCP personnel utilized a combination of kayaks and/or canoe to transport equipment and personnel as well as for use in performing the survey. For example, kayaks were necessary for completion of longitudinal profiles with pool depths greater than 4 feet.

The primary instruments for relative elevation surveys included a laser or optical level, a 25-foot survey rod and a 300-foot measuring tape. A range finder was useful for determining the length of a culvert, the width of a bridge, or distances between longitudinal profile features. Refer to the Tidal Protocol for a full list of necessary equipment to collect field-based assessment parameters.

3.3 Desktop Assessment Methods

As with field data collection, desktop data collection was performed according to the Tidal Protocol. Desktop data was loaded directly to the project geodatabase hosted on ArcGIS Online. ArcMap 10.3 and ArcGIS Pro were used for desktop data analysis to determine or calculate assessment parameters. The sections below provide additional details about desktop assessment methods.

Watershed Delineation

Watershed delineations are required to calculate desktop assessment parameters. To maximize desktop analysis efficiency, tidal crossing watersheds were auto-delineated using a two-meter hydro corrected LiDAR-based digital elevation model (2011). Stream flow lines were burned into the digital elevation model (DEM) to guarantee appropriate drainage directions and sinks were removed, followed by flow direction and flow accumulation processes. The snap pour point tool was used to snap tidal crossing points to the nearest area of high flow accumulation. This output was used as the pour points to delineate the upstream watersheds for each tidal crossing. All pour points were verified to ensure correct placement with stream flow lines. Batch watersheds were delineated using a custom model builder tool using each tidal crossing's point location as the watershed pour point and flow direction raster as inputs. Each watershed was reviewed for accuracy and corrected as deemed appropriate.

Upstream evaluation units were delineated for all crossings. Evaluation units include the catchment or drainage area up to the next upstream tidal crossing. The watershed tool in ArcGIS 10.3 was used to auto-delineate upstream evaluation units based on the pour points used in the upstream watershed delineation process. Each evaluation unit was reviewed for accuracy and corrected as deemed appropriate.

Landscape Position

Assessments of each tidal crossing in relation to its position on the landscape were completed. Tallies of upstream and downstream tidal crossings were determined using recent high-resolution aerial imagery. Upstream and downstream tidal restrictions were tallied based on up and downstream crossings with a Tidal Restriction Overall Score of three or more. Crossings with upstream impoundments were identified using high resolution aerial imagery and NWIPlus

Wetlands data (2017). Upstream watershed land use percentages were calculated using 2011 National Land Cover Data and the delineated upstream watersheds for each tidal crossing. Watershed land use categories used included wetland, forest, impervious and developed.

Channel and Pool Widths

High resolution aerial photos were used in ArcMap 10.3 to measure upstream and downstream channel and scour pool widths. Different source imagery was used at different crossings depending on which imagery depicted low tide conditions. Channel widths were measured to be used for comparison with structure widths. Three individual channel widths were taken on the upstream and downstream sides of each tidal crossing, respectively, and then averaged independently. Scour pool widths were measured for comparison with channel widths. Pool widths were measured at the widest scour feature perpendicular to stream flow.

Salt Marsh Migration Potential

Salt marsh migration potential was calculated for each tidal crossing based on a 1.7-foot sea level rise scenario using the Sea Level Affecting Salt Marshes Model (SLAMM) tool (NHFG 2014), crossing watersheds, NWIPlus wetlands (2017), and high resolution impervious surfaces (2010). A custom model builder tool was developed in ArcMap 10.3 to batch process marsh migration potential calculations, which (1) clipped the SLAMM output to a crossing's watershed, (2) erased existing NWI salt marsh habitat, (3) erased impervious surfaces, and (4) calculated the remaining area as the salt marsh migration potential. These calculations were performed for both the entire upstream watershed and the upstream evaluation unit.

A limitation of the SLAMM data was encountered pertaining to some areas designated as inland open water, which are not addressed in the model. It appears that the NWI input for these areas include a dam modifier (or similar). These areas were originally left out of our salt marsh migration calculations, in some places resulting in donut holes of inland open water surrounded by projected salt marsh habitat. To resolve this issue, acres of inland open water surrounded by projected salt marsh habitat were added back into the salt marsh migration area. This was completed for both the upstream watershed and the evaluation unit calculations.

Inundation Risk to the Roadway

Inundation risk to the roadway was assessed through GIS using (1) the 1.7-foot SLR at mean higher high water (MHHW) and (2) the 1.7-foot SLR with 1% annual flood. Inundation risk was determined if the SLR layers inundates the roadway associated with each crossing. Comments on inundation risk were recorded.

Inundation Risk to Low-Lying Development (Non-Transportation)

Inundation risk to low-lying development was assessed through GIS using (1) the 1.7-foot SLR at mean higher high water (MHHW). Additional GIS data layers used included the latest high resolution aerial imagery, each crossing's upstream watershed, and parcel data for Strafford and Rockingham counties. Parcels upstream of each crossing with SLR impacts to low lying development were enumerated. Low-lying development included structures, driveways and lawns.

Crossing Cross Section and Stream Longitudinal Profile Completion

To complete the crossing cross section and stream longitudinal profile for each tidal crossing, additional measurements were collected using ArcMap 10.3. A LiDAR elevation was captured at the road centerline of the crossing and the road width was measured using the latest high-resolution aerial imagery. At crossings where the LiDAR was hydro-corrected, such as for larger bridge structures where the elevation at the crossing represents the water elevation and not the road surface, the road centerline elevation was extrapolated from the edges of the hydro-corrected areas.

3.4 Quality Assurance/Quality Control

Initial field trainings and follow-up trainings were conducted for overall project QA/QC. At the start of the field data collection effort, members of the project team accompanied the field team to three tidal crossings to complete field assessments and to test and correct mobile data collection procedures. Two weeks into the field data collection effort, team members accompanied field staff at three additional crossing assessments to assure consistent field data collection methodologies and to review and resolve questions arising from data collection efforts in the field. Four weeks later, team members accompanied field staff to review four crossings to address the most common QA/QC issues arising from the QA/QC process (described below). An additional crossing was assessed at that time to further assure consistent field data collection and to address other questions from the field staff. In addition to trainings and follow-up visits with field staff, clear lines of communication were maintained between team members and field staff at all times to address questions and challenges as they arose.

A QA/QC process was developed and implemented to ensure the consistent, thorough and accurate collection of field and desktop data. A Microsoft Excel-based file was used to process and summarize field and desktop data for each crossing using crossing data from the ArcGIS Online-hosted file geodatabase. QA/QC of field data provided the field team with crossing-specific feedback of any data issues or questions arising from field assessments. Steps in the QA/QC process included the following for each tidal crossing:

1. Download the latest Tidal Crossing file geodatabase from ArcGIS Online.
2. Initiate QA/QC process once the crossing's "Status" attribute was marked as "Complete."
3. Import field-based crossing data into the Microsoft Excel processing and summarization file.

4. Export site photos from ArcGIS Online and import into Microsoft Excel processing and summarization file.
5. Verify that all relevant assessment parameters were completed using aerial imagery and site photos.
6. Review "Crossing Cross Section and Stream Longitudinal Profile" graph generated in the processing and summarization file in conjunction with the crossing photos. Specifically, determine if elevations for features such as low tide water, marsh plain, HWI stain, HWI wrack and perches were accurately collected.
7. Send crossing-specific data requests or clarifications to the field team. Track QA/QC issues and communications with the field team in a QA/QC tracking spreadsheet.
8. Update the QA/QC tracking spreadsheet as data issues were resolved either through clarifications from the field team or follow-up field visits to collect additional data.
9. All data updates resulting from the QA/QC process were entered into the ArcGIS Online-hosted file geodatabase.

3.5 Prioritization

Evaluation criteria were applied to the assessment parameters to score and prioritize tidal crossings based on the set of management objectives listed in Table 2. The evaluation criteria support our understanding of how each tidal crossing performs against each management objective.

In some cases, evaluation criteria were adjusted from the Tidal Protocol to further stratify or spread scoring results. This was especially helpful for some evaluation criteria where the majority of crossings ended up scoring in a single category, which was not helpful for identifying priorities. The following sections detail the evaluation criteria and how they were applied; **Section 4. Results** presents the prioritization scores based on the evaluation criteria.

Crossing Condition Evaluation

Crossing condition was evaluated using the following nine assessment parameters:

- Structure Condition – Overall
- Headwall Condition (upstream and downstream)
- Wingwall Condition (upstream and downstream)
- Scour Severity at Structure (upstream and downstream)
- Scour Severity in Structure
- Tide Gate Device Condition

Table 6 details the crossing condition evaluation scores that were applied to their respective evaluation criteria.

Table 6: Crossing condition evaluation scores and criteria.

Evaluation Score	Evaluation Criteria
0	Crossing condition not evaluated
1	Condition mostly good (3 or more condition scores are good and no poor's or high scours, or more goods than fairs and no poor's or high scours)
2	Condition mostly fair (3 or more condition scores are fair and no poor's, or more fairs than goods and no poor's or high scours)
3	One poor condition score, or one high scour severity score, and not meeting criteria for "4" or "5"
4	Two poor condition scores or two high scour severity scores, or one of each, or overall structure condition is poor
5	Three or more poor condition scores or three high scour severity scores, or a total of three when combined (e.g. two poor's and one high), or overall structure condition is the only structure condition assessment and is poor (US and DS headwalls and wingwalls are not present)

Scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's condition score is as follows:

CONDTION SCORE =IF(A="", 0, IF(OR(B>=3,AND(A="Poor", C="N/A", D="N/A", E="N/A", F="N/A")),5, IF(OR(B=2,A="Poor"),4, IF(OR(G=1,H=1),3, IF(AND(G=0, H=0, I<1), 2, IF(AND(G=0, H=0, I>0), 1, 999)))))), where

A is Overall Structure Condition
B is a sum of the tallied number of "poor" and "high" condition and scour values, respectively
C is the upstream headwall condition
D is the upstream wingwall condition
E is the downstream headwall condition
F is the downstream wingwall condition
G is a tally of the number of poor condition values
H is a tally of the number of high scour values
I is the difference between the tallied number of good and fair condition scores

Tidal Restriction Evaluation

Three tidal restriction evaluation components were scored independently. These components include tidal range ratio, crossing ratio and erosion classification. The component scores were combined into a tidal restriction overall score. The methodology for scoring component scores and the tidal restriction overall score is detailed below.

Tidal Range Ratio

Tidal range ratio compares the tidal range (elevation difference between high tide and low tide) at the upstream side of the crossing to the downstream side.

The tidal range ratio is determined from assessment parameters collected in the Site Assessment table. The Quality Control/Quality Assurance section above describes the process of importing crossing data into the Microsoft Excel processing and summarization file. Through this process, all elevation data collected are adjusted relative to the elevation of the established control point. Once adjusted, the evaluation criteria are applied as described in Table 7.

Table 7: Tidal range ratio evaluation scores and criteria.

Evaluation Score	Evaluation Criteria
1	No downstream invert perch at low tide; stream grade through the crossing matches that of the natural system (upstream tidal range is >90% of downstream tidal range), or crossings with limited tidal influence (downstream natural community is brackish or fresher) have no downstream perch and low tide water depth at crossing inverts are six inches or greater.
2	Tidal range upstream is between 80% and 90% of downstream range.
3	Tidal range upstream is between 70% and 80% of downstream range, or crossings with limited tidal influence (downstream natural community is brackish or fresher) have no downstream perch and low tide water depth at one or both crossing inverts is less than six inches.
4	Tidal range upstream is between 50% and 70% of downstream range.
5	Downstream invert is perched at high tide, or tidal range upstream is less than 50% of downstream range, or crossings with limited tidal influence (downstream natural community is brackish or fresher) have a downstream perch.

Tidal range ratio scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's tidal range ratio is as follows:

<u>Microsoft Excel Based Algorithm:</u>
TIDAL RANGE RATIO SCORE=IF(AND(A=0, B=0), 0, IF(AND(C=1, D>0), 5, IF(AND(C=1, D=0, E>=0.5), 1, IF(AND(C=1, D=0, E<0.5), 3, IF(OR((F<50), (G>0)), 5, IF(AND(F>=90, D=0), 1, IF(F>=80, 2, IF(F>=70, 3, IF(F>=50, 4,))))))))), where

A is the US dimension B^{CB} (this indicates if the US side of the crossing was assessed or not)
B is the DS dimension B^{CB} (this indicates if the DS side of the crossing was assessed or not)
C indicates if the site has limited tidal influence (1=yes (DS natural community is brackish or fresher), 0=no)
D is the height of the DS low tide perch
E is the shallowest water depth at either the US or DS invert
F is the tidal range ratio ((US HWI stain elevation minus US low tide water elevation) divided by (DS HWI stain elevation minus DS low tide water elevation) multiplied by 100)
G is DS high tide perch elevation

Crossing Ratio

Crossing ratio compares the width of the upstream and downstream channels to the width of the upstream and downstream crossing structure, respectively. Crossing ratio is determined at each crossing using channel widths (see 3.3 Desktop Assessment Methods, Channel and Pool Widths) and the structure widths collected in the field. Crossing ratio scores are generated for both the upstream and downstream sides of the crossing by applying the evaluation criteria as described in Table 8.

Table 8: Upstream and downstream crossing ratio evaluation scores and criteria.

Evaluation Score		**Evaluation Criteria**
Upstream	*Downstream*	
	0	Crossing outlets to subtidal conditions (i.e. no measurable downstream channel)
1	**1**	Channel Width < Opening Width
2	**2**	Channel Width ≥ 1 and < 1.2 times opening width
3	**3**	Channel Width ≥ 1.2 and <2.5 times Opening Width
4	**4**	Channel Width ≥2.5 and <5 times Opening Width
5	**5**	Channel Width ≥5 times Opening Width, or for the upstream side only, crossing structure permanently impounds water and no channel feature is present.

Tidal range ratio scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's crossing ratio score for the upstream side is as follows (crossing ratio was similarly calculated on the downstream side using the respective downstream crossing attributes):

<u>Microsoft Excel Based Algorithm:</u>
UPSTREAM CROSSING RATIO SCORE=IF(OR(A="Bridge with Side Slopes and Abutments", A="Bridge with Side Slopes"), IF(B/((C+D)/2)=0, 0, IF(B/((C+D)/2)<1, 1, IF(AND(B/((C+D)/2)>=1, B/((C+D)/2)<1.2), 2, IF(AND(B/((C+D)/2)>=1.2, B/((C+D)/2)<2.5), 3, IF(AND(B/((C+D)/2)>=2.5, B/((C+D)/2)<5), 4, IF(B/((C+D)/2)>=5, 5)))))), IF(B/C=0, 0, IF(B/C<1, 1, IF(AND(B/C>=1, B/C<1.2), 2, IF(AND(B/C>=1.2, B/C<2.5), 3, IF(AND(B/C>=2.5, B/C<5), 4, IF(B/C>=5, 5))))))), where

A is the crossing structure type
B is the upstream channel width
C is the upstream structure dimension A
D is the upstream structure dimension C

Erosion Classification

Erosion classification compares the width of the scour pool to the channel width (see 3.3 Desktop Assessment Methods, Channel and Pool Widths). Erosion classification scores are generated for both the upstream and downstream sides of the crossing by applying the evaluation criteria as described in Table 9.

Table 9: Upstream and downstream erosion classification evaluation scores and criteria.

Evaluation Score		**Evaluation Criteria**
Upstream	*Downstream*	

0	**0**	For upstream only: if the crossing serves as an impoundment resulting in no detectable scour pool For downstream only: if the crossing outlets directly to subtidal conditions resulting in no detectable scour pool
1	**1**	Unrestricted/ No Pooling (erosion classification <=1)
2	**2**	Flow Detained/ Slight Erosion (>1, <=1.2, pool width is up to 20% wider than channel)
3	**3**	Minor Pooling/ Erosion Present (>1.2, <=2, pool width is between 20% and 100% wider than channel)
4	**4**	Significant Pooling/Erosion Present (>2, <=3, pool width is two to three times wider than channel)
5	**5**	Major Pooling/ Major Erosion Present (>3, pool width is more than three times as wide as channel)

Erosion classification scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's erosion classification score for the upstream side is as follows (erosion classification was similarly calculated on the downstream side using the respective downstream crossing attributes):

<u>Microsoft Excel Based Algorithm:</u>
UPSTREAM EROSION CLASSIFICATION SCORE =IF(A/B <=1, 1, (IF(AND(A/B>1, A/B<=1.2), 2, IF(AND(A/B>1.2, A/B<=2), 3, IF(AND(A/B>2, A/B<=3), 4, IF(A/B>3, 5)))))), where

A is the upstream scour pool width
B is the upstream channel width

Tidal Restriction Overall Score

The Tidal Restriction Overall score is an average of the scores resulting from tidal range ratio, crossing ratio, and erosion classification. The higher of the two scores (i.e. upstream or downstream) for crossing ratio and erosion classification were used. At crossings where both upstream and downstream erosion classification scores are 0, erosion classification was removed from the average altogether.

Tidal Aquatic Organism Passage

Scores for tidal aquatic organism passage were calculated using the methodology for Tidal Range Ratio, which is detailed under the Tidal Restriction Evaluation section above.

Salt Marsh Migration Evaluation

The salt marsh migration evaluation ranks crossings based on their upstream or inland salt marsh migration potential. Salt marsh migration potential was calculated two different ways: (1) considering the entire upstream watershed for each crossing and (2) considering just the upstream evaluation unit (or catchment) at crossings where additional upstream tidal crossings occur. Methods for calculating these attributes are detailed in section 3.3 Desktop Assessment Methods under Salt Marsh Migration Potential. Both salt marsh migration potential evaluations use the same evaluation scores and criteria, which is provided in Table 10.

Table 10: Salt marsh migration evaluation scores and criteria for both the entire upstream watershed and the upstream evaluation unit.

Evaluation Score	Evaluation Criteria
1	0-1 acre potential salt marsh increase
2	1-2 acre potential salt marsh increase
3	2-5 acre potential salt marsh increase
4	5-10 acre potential salt marsh increase
5	>10 acre potential salt marsh increase

Salt marsh migration evaluation scores were applied in a Microsoft Excel worksheet for both the entire upstream watershed and the upstream evaluation unit. Areas of salt marsh increase at each site were sorted by size and scores were applied to their respective size class based on Table 10.

Vegetation Comparison Evaluation

Vegetation comparison evaluations, which compared upstream and downstream plant communities at each crossing, were performed in the field. The vegetation comparison matrix shown in Table 11 was used to translate the vegetation comparison matrix code (e.g. 1A, 1B, 1C, etc.) collected in the field into a vegetation evaluation score. Scores were applied directly in the file geodatabase structure through a one-to-one relational scoring approach.

Table 11: Vegetation comparison matrix used to determine a vegetation comparison evaluation score.

Vegetation Comparison Matrix*	The plant community appears to be the same on both sides of the crossing; both sides are occupied by tidal marsh of similar species and structure	The up and downstream plant communities appear different (i.e. two different expressions of tidal marsh are on either side of the crossing)	The up and downstream plant communities are different. One side is tidal marsh, while the other side is unvegetated, open water, un-naturally modified (i.e. armored, channeled), or is occupied by a completely different structure or suite of plants
Native plant species only	**1A (Score: 1)**	**1B (Score: 3)**	**1C (Score: 5)**
Invasive plants prevalent over a wide area of the marsh plain on both sides of the crossing**	**2A (Score: 0)**	**2B (Score: 0)**	**2C (Score: 0)**
Invasive plants present within the marsh plain near one side of the crossing, and absent (or present in a constricted area close to the crossing) on the other side	**3A (Score: 3)**	**3B (Score: 4)**	**3C (Score: 5)**

* Crossings that outlet directly to the Atlantic Ocean receive a score of 1
**If invasive species are prevalent in the plant community on both sides of the crossing, there is likely another issue beyond the crossing that is affecting the vegetation. A vegetation comparison is unlikely to help understand inundation and salinity conditions at a site with these conditions.

Infrastructure Risk Evaluation

The infrastructure risk evaluation includes two evaluations: inundation risk to the roadway and inundation risk to the crossing structure. Methods for evaluating and scoring both are detailed in the following sections.

Inundation Risk to the Roadway

Inundation risk to the roadway considers and scores the upstream and downstream vertical distance between the highest water indicator (wrack) and the road surface. Upstream and downstream inundation risk to the roadway is determined from assessment parameters collected in the Site Assessment table. The Quality Control/Quality Assurance section above describes the process of importing crossing data into the Microsoft Excel processing and summarization file. Through this process, all elevation data collected are adjusted relative to the elevation of the established control point. Once adjusted, the evaluation criteria are applied as described in Table 12.

Table 12: Upstream and downstream inundation risk to the roadway scores and criteria.

Evaluation Score		**Evaluation Criteria**
Upstream	*Downstream*	
1	**1**	High water indicator is greater than 6' from road surface
2	**2**	High water indicator is between 3 and 6' from road surface
3	**3**	High water indicator is between 1.5 and 3' from road surface
4	**4**	High water indicator is less than 1.5' from road surface
5	**5**	High water indicator suggests road is occasionally inundated

Inundation risk to the roadway scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's score is as follows:

> <u>Microsoft Excel Based Algorithm:</u>
> INUNDATION RISK TO ROADWAY SCORE =IF(A<=0, 5, IF(A<1.5, 4, IF(AND(A<3, A>=1.5), 3, IF(AND(A<=6, A>=3), 2, IF(A>6, 1))))), where
>
> A is the lesser of the upstream or downstream distances between the low road surface elevation and the high water wrack indicator, respectively.

Inundation Risk to the Crossing Structure

Inundation risk to the crossing structure considers and scores the upstream and downstream vertical distance between the high water indicator (stain) and ceiling of the structure. Upstream and downstream inundation risk to the structure is determined from assessment parameters collected in the Site Assessment table. The Quality Control/Quality Assurance section above describes the process of importing crossing data into the Microsoft Excel processing and summarization file. Through this process, all elevation data collected are adjusted relative to the elevation of the established control point. Once adjusted, the evaluation criteria are applied as described in Table 13.

Table 13: Upstream and downstream inundation risk to the crossing structure scores and criteria.

Evaluation Score		**Evaluation Criteria**
Upstream	*Downstream*	
1	**1**	High water indicator is greater than 3' from ceiling of structure
2	**2**	High water indicator is between 2 and 3' from ceiling of structure
3	**3**	High water indicator is between 1 and 2' from ceiling of structure
4	**4**	High water indicator is less than 1' from ceiling of structure
5	**5**	High water indicator is above ceiling of structure

Inundation risk to the crossing structure scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's score for the upstream side is as follows (scores were similarly calculated on the downstream side using the respective downstream crossing attributes):

<u>Microsoft Excel Based Algorithm:</u>

> UPSTREAM INUNDATION RISK TO STRUCTURE SCORE =IF(A>3, 1, IF(A<=0, 5, IF(AND(A <=3, A >2), 2, IF(AND(A <=2, A >1), 3, IF(AND(A <=1, A >0), 4))))), where
>
> A is the distance between the US ceiling of structure and US high water stain indicator

Adverse Impacts Evaluation

The adverse impacts evaluation considered the inundation risk to low-lying development (non-transportation) attribute detailed in the 3.3 Desktop Assessment Methods section. Inundation risk to low lying development (non-transportation) scores were applied in a Microsoft Excel worksheet. The number of potential upstream impacts at each site were sorted and scores were applied to their respective criteria class based on Table 14.

Table 14: Inundation risk to low-lying development evaluation scores and criteria.

Evaluation Score	Evaluation Criteria
1	> 5 impacts identified
2	3-5 impacts identified
3	2 impacts identified
4	1 impact identified
5	No impacts identified

Overall Crossing Evaluations

In addition to the seven evaluations detailed above, three overall crossing evaluation scores were developed targeting a rolled-up prioritization for infrastructure management, ecological management, and a combination of the two — one overall score that prioritizes based on a combination of infrastructure and ecological management considerations. The prioritization methods for overall crossing evaluation scores are detailed below.

Overall Infrastructure Score

The overall infrastructure score considers the crossing condition score and the inundation risk to the roadway score, as detailed in Table 15.

Table 15: Overall infrastructure evaluation scores and criteria. The overall infrastructure score uses a combination of the crossing condition and the inundation risk to the roadway scores.

Evaluation Score	Evaluation Criteria
1	**Good Crossing Condition, Low Inundation Risk** Crossing Condition = 1, AND Inundation Risk to the Roadway ≤ 2
2	**Fair Crossing Condition, Low/Moderate Inundation Risk** Crossing Condition = 2, AND Inundation Risk to the Roadway ≤ 3
3	**Poor Crossing Condition OR Moderate Inundation Risk** Crossing Condition = 3, OR Inundation Risk to the Roadway = 3
4	**Very Poor Crossing Condition OR High Inundation Risk** Crossing Condition ≥ 4, OR Inundation Risk to the Roadway ≥ 4
5	**Failing Crossing Condition OR Very High Inundation Risk** Crossing Condition = 5, OR Inundation Risk to the Roadway = 5

Overall infrastructure scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's score is as follows:

Microsoft Excel Based Algorithm:
OVERALL INFRASTRUCTURE SCORE = IF(AND(A=1, B<=2), 1, IF(AND(A=2, B<=3), 2, IF(OR(A=5, B=5), 5, IF(OR(A>=4, B>=4), 4, IF(OR(A=3, B=3), 3))))), where

A is the crossing condition score
B is the inundation risk to the roadway score

Overall Ecological Score:

The overall ecological score considers the scores for tidal restriction overall, tidal aquatic organism passage, salt marsh migration (using the entire upstream watershed score), and vegetation comparison evaluation, as detailed in Table 16.

Table 16: Overall ecological evaluation scores and criteria. The overall ecological score uses a combination of scores from tidal restriction overall, tidal aquatic organism passage, salt marsh migration potential, and vegetation comparison evaluation.

Evaluation Score	Evaluation Criteria
1	**Limited Tidal Restriction** Tidal Restriction < 3, AND Vegetation = 1 Aquatic Organism Passage (not included because of limited tidal restriction) Salt Marsh Migration (not included because of limited tidal restriction)

3	**Moderate Tidal Restriction, TAOP Reduced, <u>OR</u> Moderate Salt Marsh Migration Potential** Tidal Restriction is < 4 AND ≥ 3), OR Aquatic Organism Passage = 3, OR Salt Marsh Migration = 3, OR Vegetation = 3
4	**Severe Tidal Restriction, TAOP Very Reduced, High Salt Marsh Migration Potential if Tidally Restricted, <u>OR</u> Vegetation Different or Invasive Dominant** Tidal Restriction ≥ 4, OR Aquatic Organism Passage ≥ 4, OR Salt Marsh Migration ≥ 4 AND Tidal Restriction ≥ 4, OR Vegetation ≥ 4, OR Vegetation = 0
5	**Very Severe Tidal Restriction, TAOP Barrier, Very High Salt Marsh Migration Potential if Tidally Restricted, OR Vegetation Very Different if Tidally Restricted** Tidal Restriction = 5, OR Aquatic Organism Passage = 5, OR Salt Marsh Migration = 5 AND Tidal Restriction ≥ 4, OR Vegetation = 5 AND Tidal Restriction ≥ 4

Overall ecological scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's score is as follows:

<u>Microsoft Excel Based Algorithm:</u>
OVERALL ECOLOGICAL SCORE =IF(OR(A=5, B=5), 5, IF(AND(C=5, A>=4), 5, IF(AND(D=5, A>=4), 5, IF(OR(AND(C>=4, A>=4), A>4, B>=4, D>=4, D=0), 4, IF(OR(AND(A<4, A>=3), B=3, C=3, D=3), 3,IF(AND(A<3, D=1), 1)))))), where

A is the tidal restriction overall score
B is the tidal aquatic organism passage score
C is salt marsh migration score for the entire upstream watershed
D is the vegetation evaluation score

Overall Combined Crossing Score

The overall combined crossing score considers the scores for salt marsh migration (using the entire upstream watershed score), tidal restriction overall, vegetation comparison evaluation, crossing condition, inundation risk to the roadway, and tidal aquatic organism passage, as detailed in Table 17.

Table 17: Overall combined crossing evaluation scores and criteria. The overall combined crossing score uses a combination of scores from crossing condition, inundation risk to the roadway, tidal restriction overall, tidal aquatic organism passage, salt marsh migration potential and vegetation comparison evaluation.

Evaluation Score	Evaluation Criteria
1	**Good Crossing Condition <u>AND</u> Limited Tidal Restriction, <u>AND</u> Vegetation similar <u>AND</u> Inundation Risk to Road is low**

	Crossing Condition ≤ 2, AND Tidal Restriction ≤ 2, AND Vegetation = 1, AND Inundation Risk to the Roadway ≤ 2 Aquatic Organism Passage (not included because of limited tidal restriction) Salt Marsh Migration (not included because of limited tidal restriction)
2	**Fair Crossing Condition, Limited Tidal Restriction OR Low/Moderate Infrastructure Risk** Crossing Condition ≤ 2, OR Tidal Restriction < 3, OR Vegetation = 1, OR Inundation Risk to the Roadway ≤ 3 Aquatic Organism Passage (not included because of limited tidal restriction) Salt Marsh Migration (not included because of limited tidal restriction)
3	**Poor Crossing Condition, Tidal Aquatic Organism Passage reduced, OR moderate Salt Marsh Migration Potential AND moderate Tidal Restriction, OR Vegetation different AND moderate Tidal Restriction, OR moderate Infrastructure Risk** Crossing Condition ≥ 3, OR Tidal Aquatic Organism Passage ≥ 3, OR Salt Marsh Migration (upstream watershed) ≥ 3 AND Tidal Restriction > 3, OR Vegetation ≥ 3 AND Tidal Restriction > 3, OR Inundation Risk to the Roadway ≥ 3
4	**Failing Crossing Condition, OR very poor Crossing Condition AND high Inundation Risk to Road, OR Tidal Aquatic Organism Passage reduced AND severe Tidal Restriction AND Vegetation different, OR high Salt Marsh Migration Potential AND severe Tidal Restriction** Crossing Condition = 5, OR Crossing Condition ≥ 4 AND Inundation Risk to the Roadway ≥ 4, OR Aquatic Organism Passage ≥ 4 AND Tidal Restriction ≥ 4 AND Vegetation ≥ 4, OR Salt Marsh Migration (upstream watershed) ≥ 4 AND Tidal Restriction ≥ 4
5	**Failing Crossing Condition AND very high Inundation Risk to Road, OR Tidal Aquatic Organism barrier AND very severe Tidal Restriction, OR very high Salt Marsh Migration Potential AND severe Tidal Restriction, OR Vegetation very different AND severe Tidal Restriction** Crossing Condition = 5 AND Inundation Risk to the Roadway = 5, OR Aquatic Organism Passage = 5 AND Tidal Restriction = 5, OR Salt Marsh Migration = 5 AND Tidal Restriction ≥ 4, OR Vegetation = 5 AND Tidal Restriction ≥ 4

Overall combined crossing scores were applied in a Microsoft Excel worksheet. The algorithm used to determine each crossing's score is as follows:

Microsoft Excel Based Algorithm:
OVERALL COMBINED CROSSING SCORE =IF(OR(AND(A=5, B>=4), AND(C=5, B>=4), AND(D=5, E=5), AND(B=5, F=5)), 5, IF(OR(AND(A>=4, B>=4), AND(B>=4, F>=4, C>=4), AND(D>=4, E>=4), D=5), 4, IF(OR(AND(A>=3, B>3), AND(C>=3, B>3),D>=3, F>=3, E>=3), 3, IF(OR(D<=2, B<3, C=1, E<=3), 2, IF(AND(D<=2, B<=2, C=1, E<=2), 1))))), where

A is the salt marsh migration score for the entire upstream watershed
B is the tidal restriction overall score

C is the vegetation evaluation score
D is the crossing condition score
E is the inundation risk to the roadway score
F is the tidal aquatic organism passage score

4. RESULTS

Data were collected, analyzed and prioritized at 118 tidal crossings to identify replacement and/or restoration priorities based on individual and collective management objectives. Fifteen scores were generated for each assessed crossing. Table 18 details the distribution of crossing scores across each score category.

Table 18: Distribution of crossing scores across each score category.

Score Category*	Number of Crossings by Score					
	0	**1**	**2**	**3**	**4**	**5**
Crossing Condition	12	35	29	6	15	33
Tidal Restriction Overall	12	4	18	52	37	7
Tidal Range Ratio	*12*	*53*	*12*	*25*	*6*	*22*
Crossing Ratio	*12*	*12*	*8*	*29*	*32*	*37*
Erosion Classification	*18*	*7*	*5*	*34*	*40*	*26*
Tidal Aquatic Organism Passage	12	53	12	25	6	22
Salt Marsh Migration Potential: US Watershed	12	34	10	12	14	48
Salt Marsh Migration Potential: Evaluation Unit	12	41	9	13	18	37
Vegetation Comparison	33	48	0	22	11	16
Inundation Risk to Roadway	13	30	26	26	24	11
Inundation Risk to Crossing Structure	12	25	11	21	22	39
Inundation Risk to Low-Lying Development**	13	21	8	5	10	73
Overall Infrastructure Score	12	17	18	15	27	41
Overall Ecological Score	12	18	0	37	37	26
Overall Combined Score	12	0	17	46	32	23

* Scoring system ranges from 1 to 5, where 1 = lowest replacement priority and 5 = highest replacement priority

** Inundation Risk to Low-Lying Development scores range from 1 to 5, where 1 = high risk and 5 = low risk

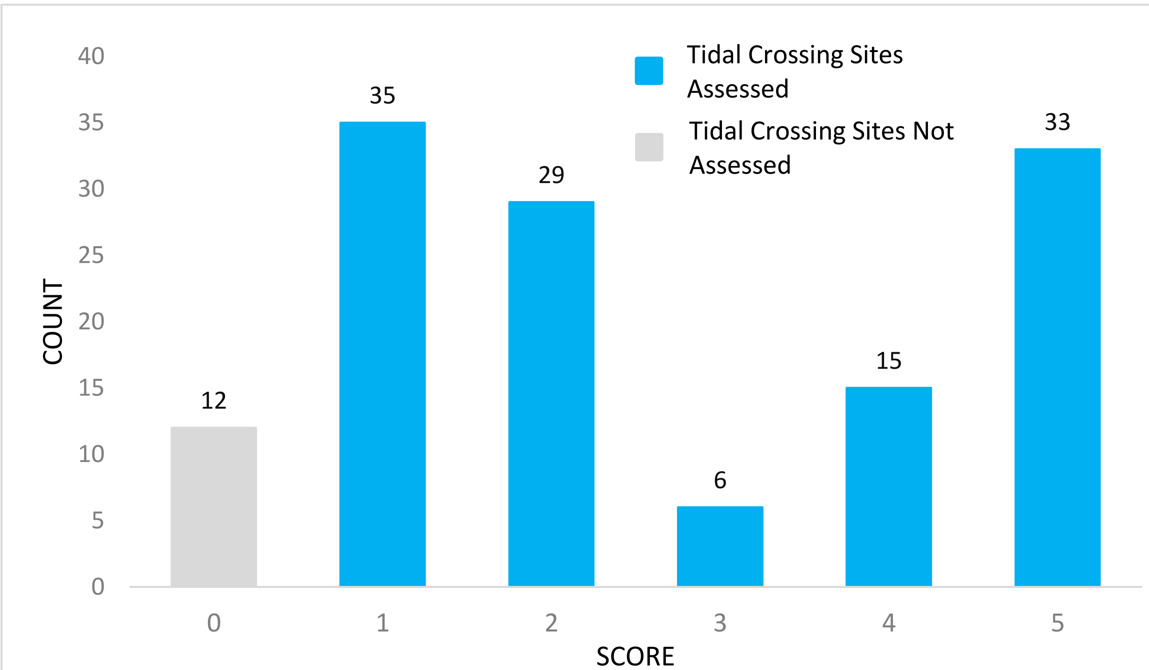
The scoring system from the Tidal Protocol was designed to meet the decision making and management needs of a broad group of coastal stakeholders. Road managers are likely drawn to condition and inundation scores; natural resource managers to tidal restriction, fish passage, marsh migration and vegetation comparison, while municipal decision makers might be particularly interested in inundation risk to low-lying development. No matter the category of interest, stakeholders can access results in various forms and levels of resolution; see section **1.1 How to Access Data** for details. Each of the scoring categories from Table 18, including a closer look at score distributions, are detailed in the following sections.

4.1 Crossing Condition Score

New Hampshire coastal communities depend on a functional, reliable, and safe transportation network. Tidal crossings are a critical component of that network, which allow for the continuous flow of people, goods and services across the coastal zone. Reliable tidal crossings are especially important when we need them most, which also corresponds to when they may be most susceptible to failure during major storm events.

Figure 3 illustrates the distribution of crossing condition scores, where a score of one indicates a "good" crossing structure condition and a score of five indicates a structure with an exceedingly poor condition, such as having an immediate maintenance and/or replacement need.

Figure 3: Distribution of crossing condition scores.



The distribution of crossing condition scores shows that just over 50% of crossings are in good or fair condition (scores one and two, respectively). Scores three, four and five indicate increasing levels of poor condition. Twelve crossings were not assessed and are represented by a score of zero. From an infrastructure management standpoint, the 33 crossings with a score of five present an immediate need to be addressed.

4.2 Tidal Restriction Evaluation

Tidal habitats are special systems with complex hydraulic and hydrologic processes. Tidal crossings often affect these processes by restricting the tidal range upstream of the crossing. Three scores are used to characterize the degree that each crossing is a tidal restriction, from a score of one (limited restriction) to five (severe restriction). Each of these scores, tidal range ratio, crossing ratio and erosion classification, consider different measurable indicators or expressions of a tidal restriction. For example, the tidal range ratio score considers the crossing structure's ability to pass the full vertical extent of the tide to the tidal system beyond the structure; whereas, the crossing ratio considers the cross-sectional width compatibility of the crossing structure to the tidal system; and the erosion classification determines how eroded the channel is at both the upstream and downstream outlet due to the accelerated water velocity through an undersized structure. Once independently scored, the three component scores are combined into the tidal restriction overall score. Each of these scores are detailed in their respective sections below.

For simplicity of data display and usability, the NH Coastal Viewer only offers the tidal restriction overall score for viewing. Users can access crossing-specific component scores for the tidal restriction evaluation on the Tidal Crossing Summary Sheets (Appendix D), and in the Crossing Scores Table (Appendix E), and are available for download from ArcGIS Online. The tidal aquatic organism passage score (detailed later) is based on the tidal range ratio scoring criteria. NH Coastal Viewer users can view tidal range ratio scores using the tidal aquatic organism passage data layer.

Tidal Range Ratio Score

Tidal range ratio compares the tidal range (elevation difference between high tide and low tide) at the upstream side of the crossing to the downstream side. A crossing where the tidal range is similar on both sides indicates no tidal restriction from a tidal range standpoint (i.e. tidal range ratio score is low). Increasing differences in tidal range between the upstream and downstream sides of the crossing indicate increasing severity of a tidal restriction, and therefore a higher tidal range ratio score. Figure 4 illustrates the distribution of tidal range ratio scores.

Figure 4: Distribution of tidal range ratio scores.

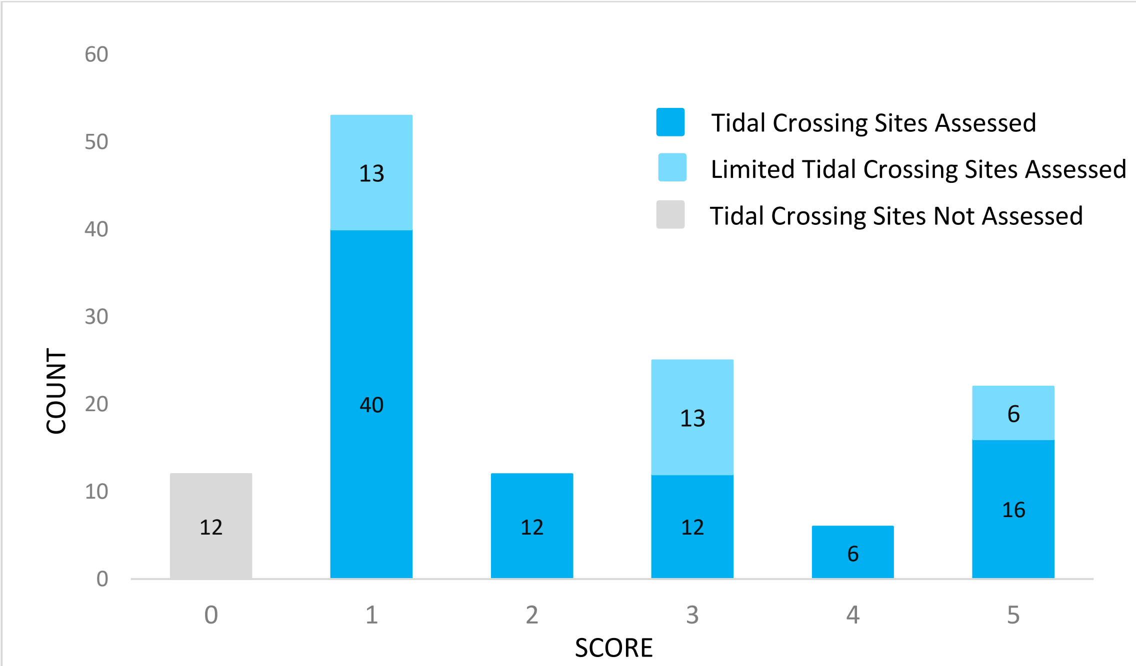


Figure 4 differentiates the results for crossings that are subject to “full tidal” (darker blue) and “limited tidal” (lighter blue) influence, as well as crossings not assessed (score of zero). This differentiation between full and limited tidal sites was necessary to adequately characterize the variability of tidal range found at tidal crossing sites. For instance, a 6-inch tidal range restriction is more significant at a site with a 1-foot tidal range than for a site with a 10-foot tidal range. Therefore, limited tidal sites were scored differently, as described in Section 3.5 Prioritization.

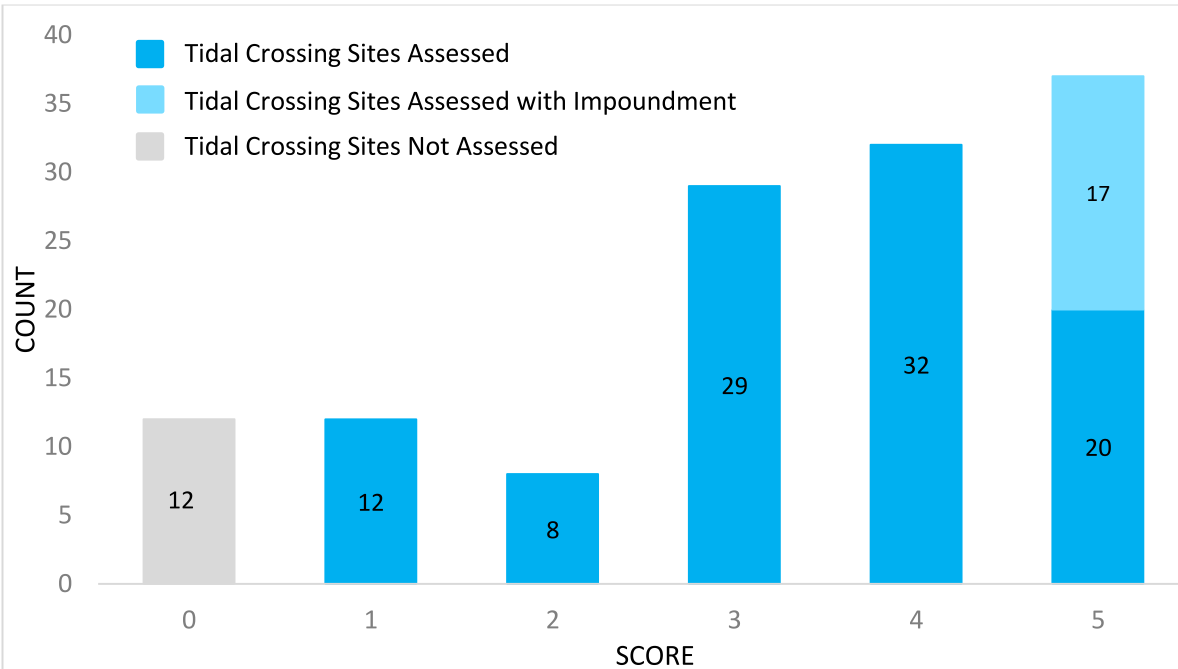
Out of the full tidal crossing sites, just over 60% of crossings assessed are not significant tidal restrictions (scores one and two). The remaining 34 full tidal crossings indicate restricted tidal ranges that prevent tidal flooding and interfere with aquatic organism passage. Tidal flooding is necessary to build marsh elevation and enable inland migration.

Out of the 32 limited tidal crossings, 13 sites are unrestricted (score of one) with water depths of six inches or more through the crossing structure at low tide. Six inches of water depth is a fish passage design criteria used based on spawning habitat for alewife (Pardue 1983). An additional 13 sites have less than six inches of water depth at low tide and no downstream perch, which receive a score of three. Six limited tidal crossings received a score of five, meaning they are perched on the downstream side under low tide conditions. Given the limited tidal ranges at these sites, a low tide perch is generally much more restrictive than a low tide perch at crossings with greater tidal range.

Crossing Ratio Score

Crossing ratio is an evaluation developed by Purinton and Mountain (1996) that compares the width of the upstream and downstream channels to the width of the crossing structure. A crossing structure that spans the stream channel should be adequately sized in terms of the width dimension. Narrowing structure widths, when compared to the stream channel, are indicative of increasingly severe tidal restrictions and will receive higher scores. A relatively narrow structure will act like a funnel and result in greater water velocities through the structure with headwater buildup from the direction of flow (depending on tide direction). This can result in a reduced upstream tidal range and the desynchronization of tidal flows from the normal tide cycle. Figure 5 illustrates the distribution of crossing ratio scores.

Figure 5: Distribution of crossing ratio scores.

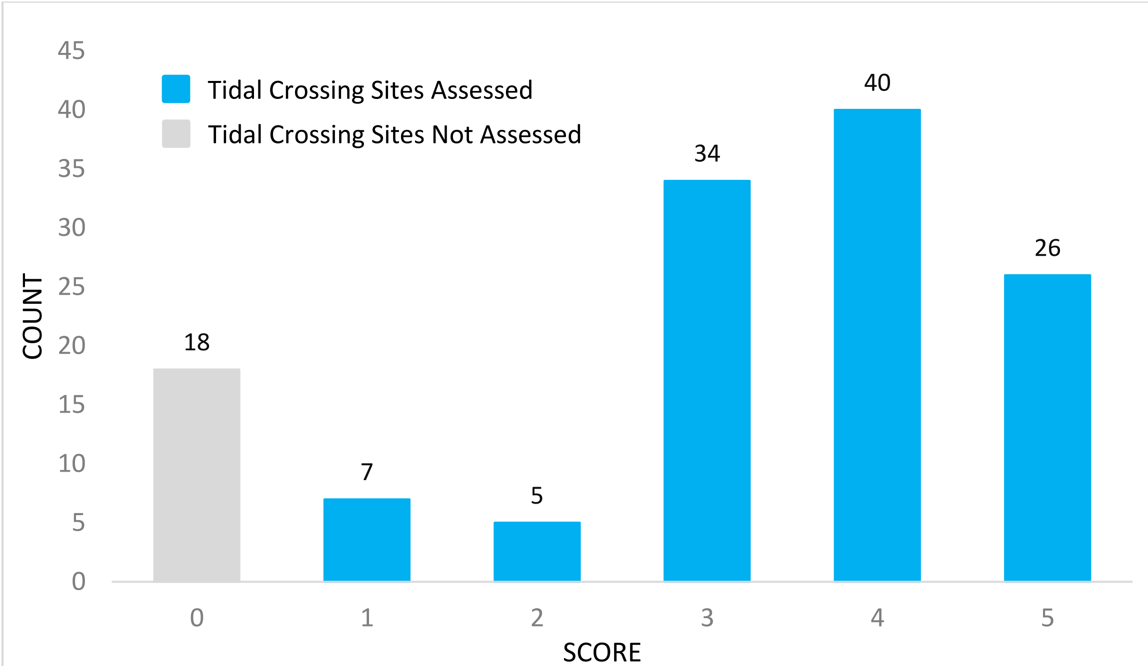


The distribution of crossing ratio scores shows that the majority of crossings (98) are undersized (scores three, four, or five) when compared to the cross-sectional width of their stream channel. Seventeen crossings restrict flows to such an extent that they create an upstream impoundment; some of these impoundments are by design whereas others are the result of an undersized structure.

Erosion Classification Score

Erosion classification is another evaluation developed by Purinton and Mountain (1996). It scores the degree that the tidal crossing causes erosion immediately upstream and/or downstream of the crossing. Erosion or scour pools are indicators that the crossing structure is undersized or incompatible with the stream system; the width of the scour pool relative to the channel width is used to characterize the degree of incompatibility. Low scores indicate the presence of limited scour, whereas high scores are the result of sites with high scour. Figure 6 illustrates the distribution of erosion classification scores.

Figure 6: Distribution of erosion classification scores.

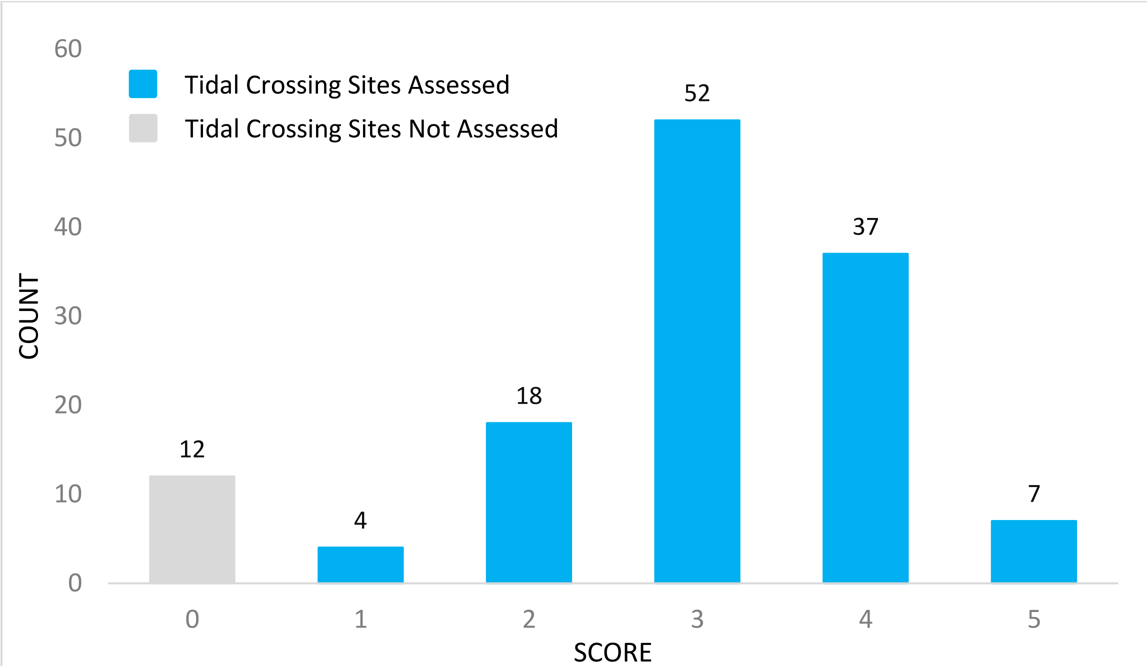


The distribution of erosion classification scores shows that the majority of crossing structures (100) are incompatible with their tidal system from an erosion standpoint (scores three, four, or five).

Tidal Restriction Overall Score

The tidal restriction overall score rolls up the three tidal restriction component scores detailed above into a single score, combining both indicators and expressions of tidal restrictions. Figure 7 illustrates the distribution of tidal restriction overall scores.

Figure 7: Distribution of tidal restriction overall scores.



The distribution of tidal restriction overall scores indicates that the majority of crossings (89) are moderately or highly restrictive to tidal flows (scores three or four, respectively). Seven sites are severe tidal restrictions (score five); many of these crossings are perched at high tide or are impounded.

4.3 Tidal Aquatic Organism Passage Score

Tidal crossings can serve as either gateways or barriers to upstream habitats for fish and other aquatic organisms. Anadromous species' complex life cycles and habitat needs rely on passage through tidal systems to access spawning and nursery habitat, as do resident estuarine fish. Fish passage, or lack thereof, at tidal crossings have much broader ecosystem implications than at a specific crossing site. Successful passage supports higher trophic levels across the land and ocean-scape, from headwaters, through estuaries, and out to the Atlantic Ocean.

Tidal aquatic organism passage is affected by multiple factors at a tidal crossing, including invert perches, flow velocities, water depth and desynchronized tidal flows—meaning that high and low tide water elevations will be delayed or out of sync. The tidal range ratio evaluation criteria consider these factors, and is therefore used to score tidal aquatic organism passage. Figure 8 illustrates the distribution of tidal aquatic organism passage scores.

Figure 8: Distribution of tidal aquatic organism passage scores.

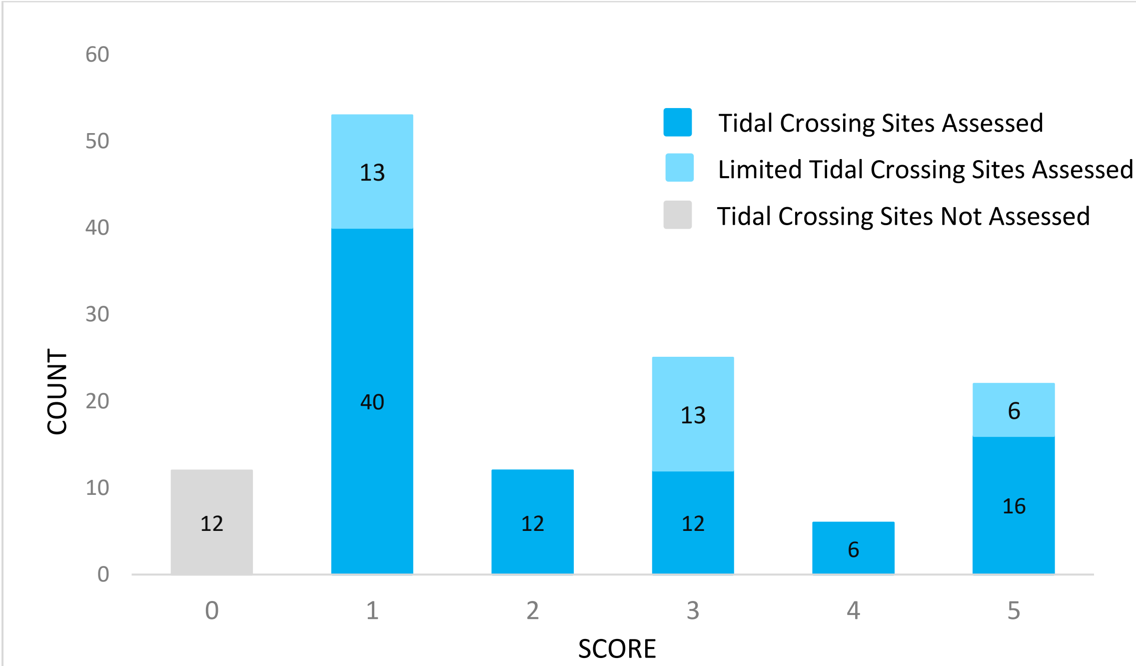


Figure 8 differentiates the results for crossings that are subject to "full tidal" (darker blue) and "limited tidal" (lighter blue) influence, as well as crossings not assessed (score of zero). Tidal aquatic organism passage scores are based on the tidal range ratio evaluation, so small differences in upstream versus downstream tidal range can score quite high using the tidal range ratio evaluation criteria in limited tidal situations. Therefore, limited tidal sites were scored differently, as described in Section 3.5 Prioritization.

Out of the full tidal crossing sites, just over 60% of crossings assessed are not significant barriers to tidal aquatic organism passage. The remaining 34 full tidal crossings indicate moderate or greater barriers. Nearly half of those are severe barriers to tidal aquatic organism passage.

Out of the 32 limited tidal crossings, 13 sites are passable (score of one) with water depths of six inches or more through the crossing structure at low tide. Six inches of water depth is a fish passage design criteria used based on spawning habitat for alewife (Pardue 1983). An additional 13 sites have less than six inches of water depth at low tide and no downstream perch. These crossings receive a score of three for not meeting the alewife design criteria. Six limited tidal crossings received a score of five, meaning they are perched on the downstream side under low tide conditions and may be impassable most of the time at these limited tidal sites.

4.4 Salt Marsh Migration Potential Score

Rising sea levels are a major threat to existing salt marshes, which are home to critically important and imperiled habitats and species that are adapted to life in these dynamic places. A significant concern is that sea level rise will outpace the rate that existing salt marshes can build in elevation.

Migration of salt marshes inland is necessary for ecologically significant assemblages of salt marsh habitats to persist under projected sea level rise scenarios. Tidally restrictive crossings reduce the ability of a salt marsh system to meet its upstream migration potential by limiting high tide inundation of salt water. This process is necessary for the conversion of upstream low-lying areas to salt-tolerant marsh habitat.

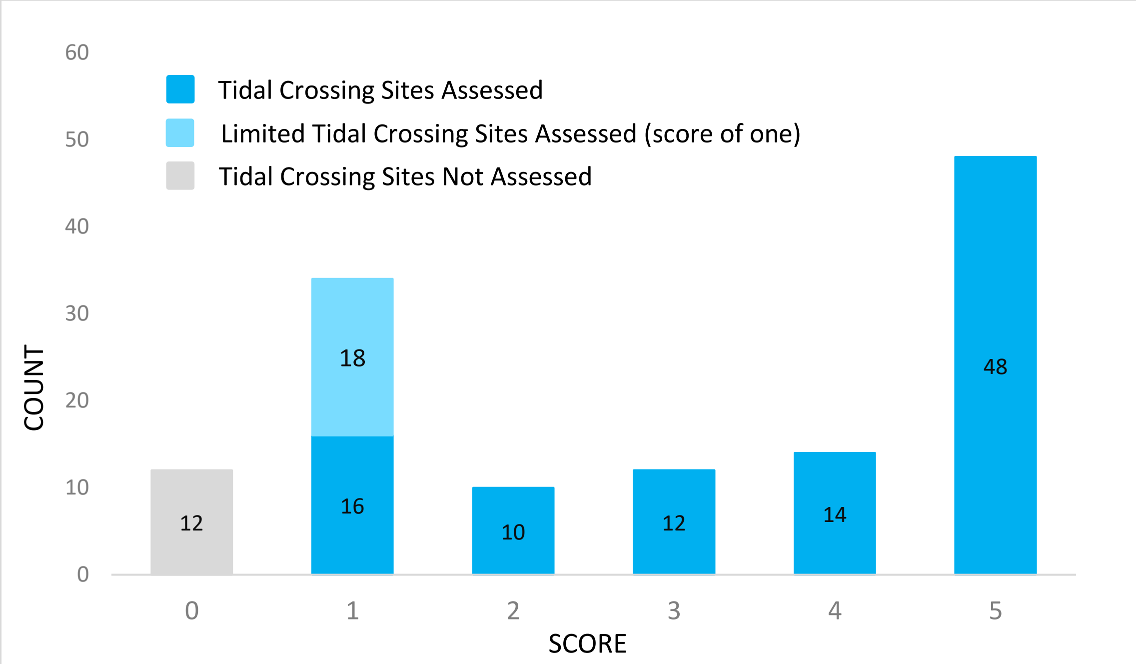
Salt marsh migration potential is scored in two different ways: (1) based on the entire upstream watershed, and (2) based on the upstream salt marsh evaluation unit or catchment — that is, the upstream watershed area before the next upstream tidal crossing, if present. The results for these two scoring approaches are described below.

To minimize confusion between the upstream watershed and upstream evaluation unit scores, only the upstream watershed score is presented on the NH Coastal Viewer. However, both scores are presented on the Tidal Crossing Summary Sheets (Appendix D), in the Crossing Scores Table (Appendix E), and are available for download from ArcGIS Online.

Upstream Watershed Score

The salt marsh migration potential — upstream watershed score, considers the marsh migration potential of the entire upstream watershed above a tidal crossing, despite upstream crossings or restrictions. Figure 9 illustrates the distribution of the upstream watershed scores for salt marsh migration potential.

Figure 9: Distribution of salt marsh migration potential scores for the upstream watershed.



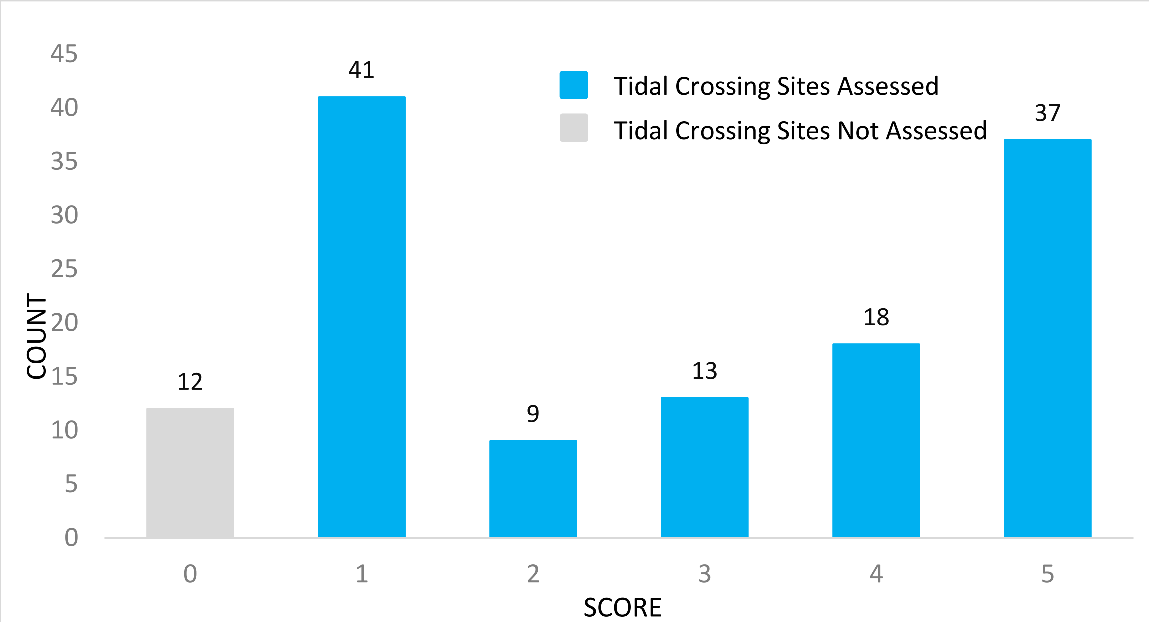
The distribution of salt marsh migration potential — upstream watershed scores shows that the majority of crossings (62) are situated in a marsh system with high or very high potential for inland migration (scores of four or five, respectively). A score of five indicates salt marsh migration potential of greater than 10 acres; a score of four indicates five to 10 acres of migration potential. Not surprisingly, 18 "limited tidal" crossings offer little salt marsh migration opportunity because they are relatively high in the tidal system.

It is especially informative to evaluate a crossing's salt marsh migration potential in combination with its overall tidal restriction score. A crossing with high salt marsh migration potential that is unrestricted will likely enable salt marsh migration as-is in the near-term. A crossing that is both highly restrictive and offers high salt marsh migration potential is a much higher priority to enable upstream salt marsh expansion.

Upstream Evaluation Unit Score

The salt marsh migration potential — upstream evaluation unit score, considers the marsh migration potential of the upstream evaluation unit or catchment — that is, the upstream watershed area before the next upstream tidal crossing, if present. If no upstream tidal crossings are present, then the scores for the upstream watershed and upstream evaluation unit are the same. The upstream evaluation unit score is a more nuanced analysis that allows resource managers and restoration planners to consider crossing specific marsh migration potential relative to upstream and downstream crossings. This information is useful to understand the marsh migration potential from a watershed approach (e.g. addressing a series of in-line tidally restrictive crossings) and to understand the upstream potential enabled by addressing a single tidal restriction. Figure 10 illustrates the distribution of the upstream evaluation unit scores for salt marsh migration potential.

Figure 10: Distribution of salt marsh migration potential scores for the evaluation unit.

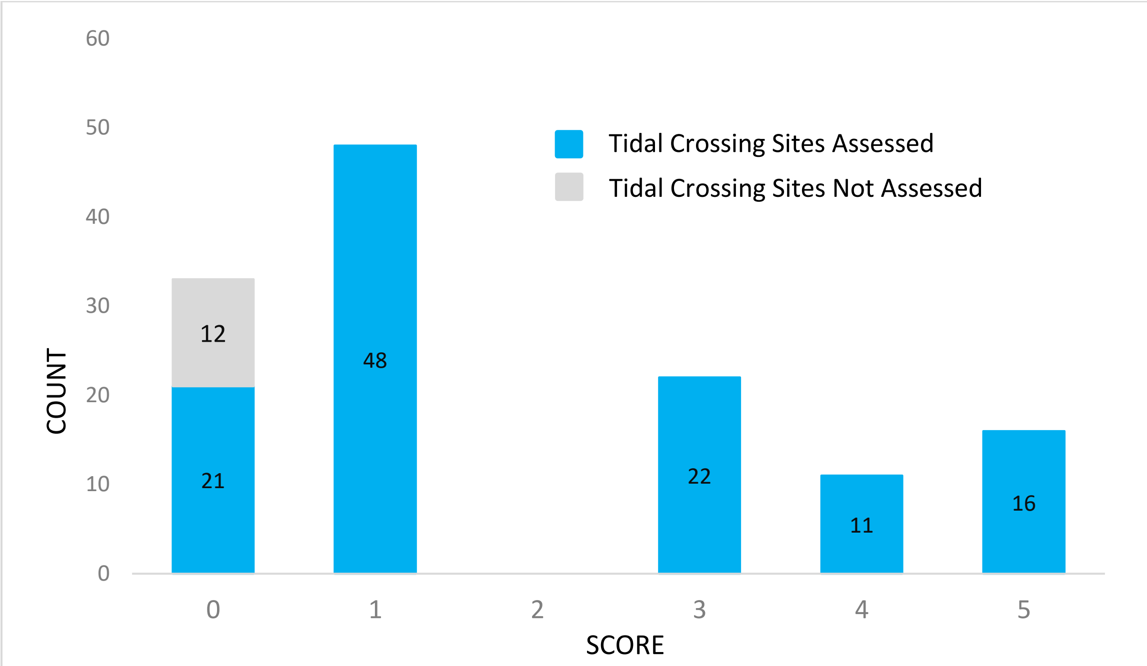


In comparing upstream watershed scores to upstream evaluation unit scores, results show a shift from higher scores to lower scores. This is because, for crossings with an upstream tidal crossing, the evaluation unit area is a smaller portion of the entire upstream watershed area, and therefore only offers that portion for marsh migration. Comparing the distribution of upstream watershed scores to upstream evaluation unit scores isn't all that informative; the upstream evaluation unit scores are developed for site-specific planning of crossings that may be considered for replacement in-series.

4.5 Vegetation Comparison Score

Wetland plants in the tidal zone have specialized adaptations to inhabit and compete in areas subject to flooding and changes in salinity. Wetland plant communities at tidal crossings are an expression of site conditions, both in terms of flooding frequency/duration and salinity. The vegetation comparison score compares the dominant upstream and downstream plant communities at each tidal crossing to understand the crossing's influence on upstream tidal flooding and salinity. Crossings with a low score indicate similar vegetation communities on both sides, whereas high scores indicate increasing divergence in the up and downstream vegetation communities. Figure 11 illustrates the distribution of the vegetation comparison scores.

Figure 11: Distribution of vegetation comparison scores.



The vegetation comparison score considers crossings with prevalent invasive species on both sides as an issue that is likely not limited to the crossing itself. There are 33 crossings that score a zero; 21 are due to invasive species while the remaining twelve were not assessed. Nearly half of the remaining assessed crossings have a score of one, meaning the crossing has a limited effect on up and downstream vegetation communities. The remaining crossings influence vegetation to varying degrees, from having moderate to severe affects (scores three through five, respectively). Note that the evaluation criteria for vegetation comparison does not assign a score of two.

4.6 Infrastructure Risk Evaluation

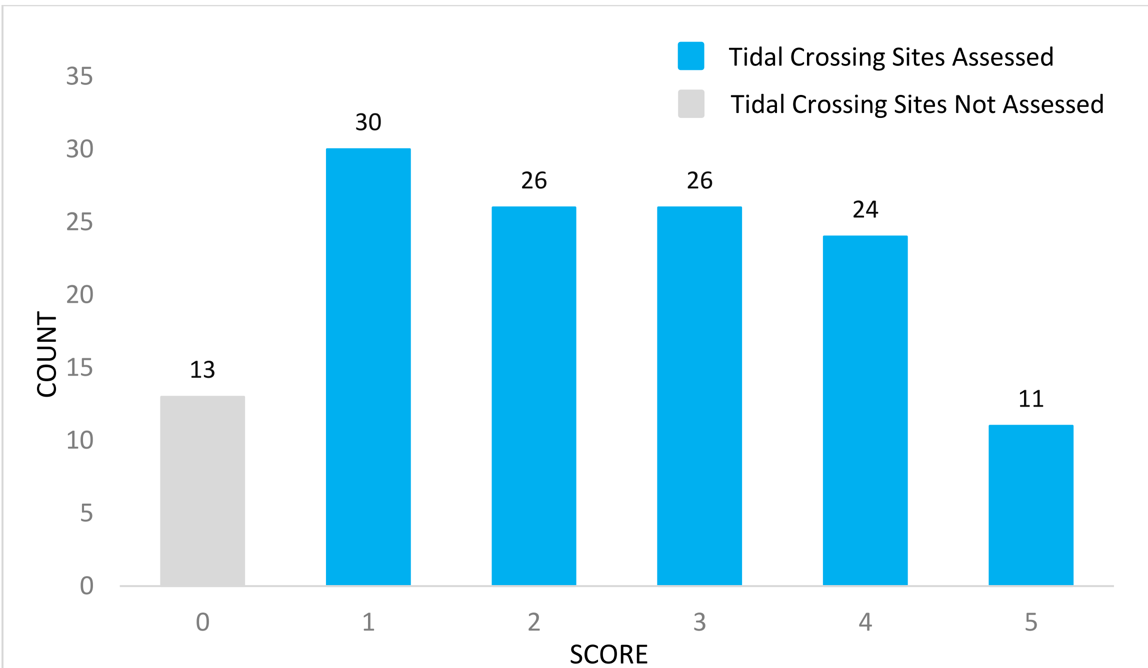
Tidal crossing infrastructure is at the front lines of coastal challenges associated with climate change, including sea level rise and more frequent and intense storm events. Our transportation infrastructure is critical to meet the needs of coastal communities, but that infrastructure is at serious risk. Much of our transportation infrastructure was not designed or constructed with sea level rise in mind. Therefore, it is important to identify tidal crossings that are at more immediate risk to prioritize their replacement, which will support a network of climate-ready transportation infrastructure.

The infrastructure risk evaluation includes two distinct scores: (1) inundation risk to the roadway and (2) inundation risk to the crossing structure. The results for each of these scores are detailed below.

Inundation Risk to the Roadway Score

The inundation risk to the roadway score evaluates the vertical distance between the highest water indicator (wrack) and the road surface. This indicates how susceptible the road is to flooding during high water events such as spring tides, king tides, or storm surges, as well as an indicator of future susceptibility with sea level rise. Figure 12 illustrates the distribution of inundation risk to the roadway score across all crossings. The Tidal Crossing Summary Sheets in Appendix D provide a score for both upstream and downstream inundation risk to the roadway, whereas Figure 12 represents only the highest of the two scores for each site.

Figure 12: Distribution of inundation risk to the roadway scores.

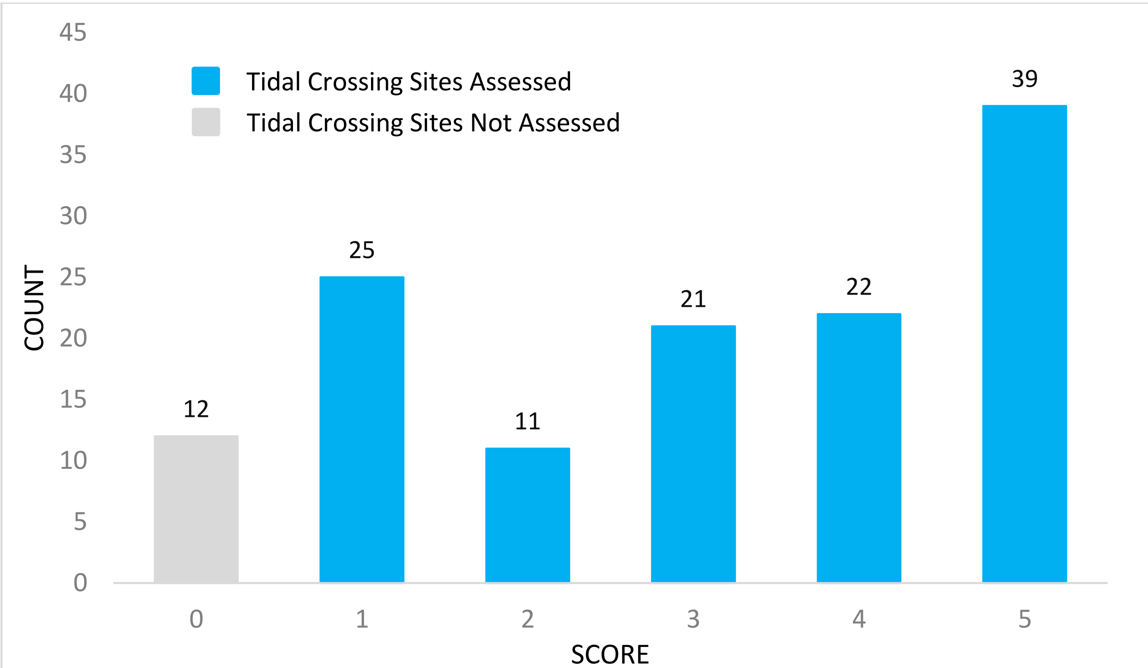


The inundation risk to the roadway scores show that only eleven crossings show signs of occasional or recent inundation (score of five). Twenty-four crossings have flood indicators within 1.5 feet of the roads surface (score of four), while an additional 26 crossings have flood indicators within three feet of the road surface. The remainder of the crossings are not likely at risk of flooding in the near future from regular high tides or high tides coincident with small storm surges (scores one and two). The inundation risk to the roadway scores will increase over time with sea level rise.

Inundation Risk to the Crossing Structure

The inundation risk to the crossing structure score evaluates headwater buildup conditions to determine the distance between the high water indicator (stain) and the ceiling of the crossing structure. A structure that is not tall enough will become completely inundated at high tide. In addition to restricting hydraulic capacity, this condition introduces high pressure on crossings that can result in vulnerabilities from scour and erosion, especially if not designed for headwater buildup. Figure 13 illustrates the distribution of inundation risk to the crossing structure score across all crossings. The Tidal Crossing Summary Sheets in Appendix D provide a score for both upstream and downstream inundation risk to the structure, whereas Figure 13 represents only the highest of the two scores for each site.

Figure 13: Distribution of inundation risk to the crossing structure scores.



The inundation risk to the crossing structure score shows that 39 crossings are inundated by high tides on a regular basis (score of five). Twenty-two crossings have high water stain indicators within one foot of the ceiling of the crossing structure (score of four). These crossings have no or limited additional capacity to convey high water events from spring tides, king tides, extreme precipitation, or storm surge. Thirty-six crossings have two or more feet of freeboard between their high water stain indicator and the ceiling of the structure (scores one and two). The inundation risk to the crossing structure scores will increase over time with sea level rise.

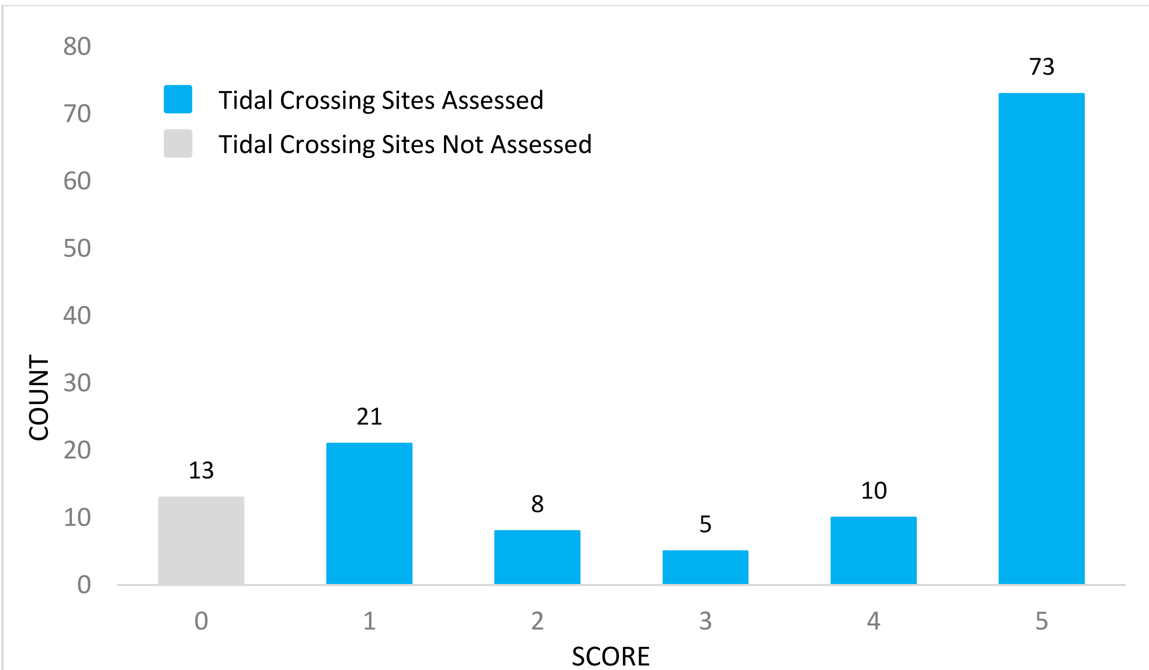
4.7 Adverse Impacts Evaluation

Careful consideration of upstream infrastructure and property susceptible to flooding is necessary in the assessment of tidal crossings — both under current conditions and accounting for rising sea levels. For example, some existing tidal crossings may serve to protect inland communities by restricting tidal flows, but may also cause more severe flooding inland because of poor drainage seaward. It is important to understand potential adverse impacts associated with replacing a tidal crossing, which informs the feasibility of restoring full or even partial upstream tidal range at some crossings.

Inundation Risk to Low-Lying Development (Non-Transportation) Score

The inundation risk to low-lying development score evaluates the number of upstream infrastructure impacts associated with 1.7 feet of SLR by 2050 (MHHW). It is important to note that the scoring scale for inundation risk to low lying development is structured to prioritize sites with high restoration opportunity. That is, crossings with low risk receive a high replacement priority/opportunity score because the feasibility of restoring full tidal range at those crossings is higher given the absence of (or limited) upstream low lying development. Figure 14 illustrates the distribution of the inundation risk to low lying development scores.

Figure 14: Inundation risk to low-lying development scores.



The inundation risk to low lying development scores show that the broad majority of tidal crossings (83) have no anticipated upstream infrastructure impacts or very limited impacts associated with a 1.7-foot SLR (scores five and four, respectively). Conversely, 21 sites have over five infrastructure impacts (score of one), which indicates low potential for restoring full tidal range.

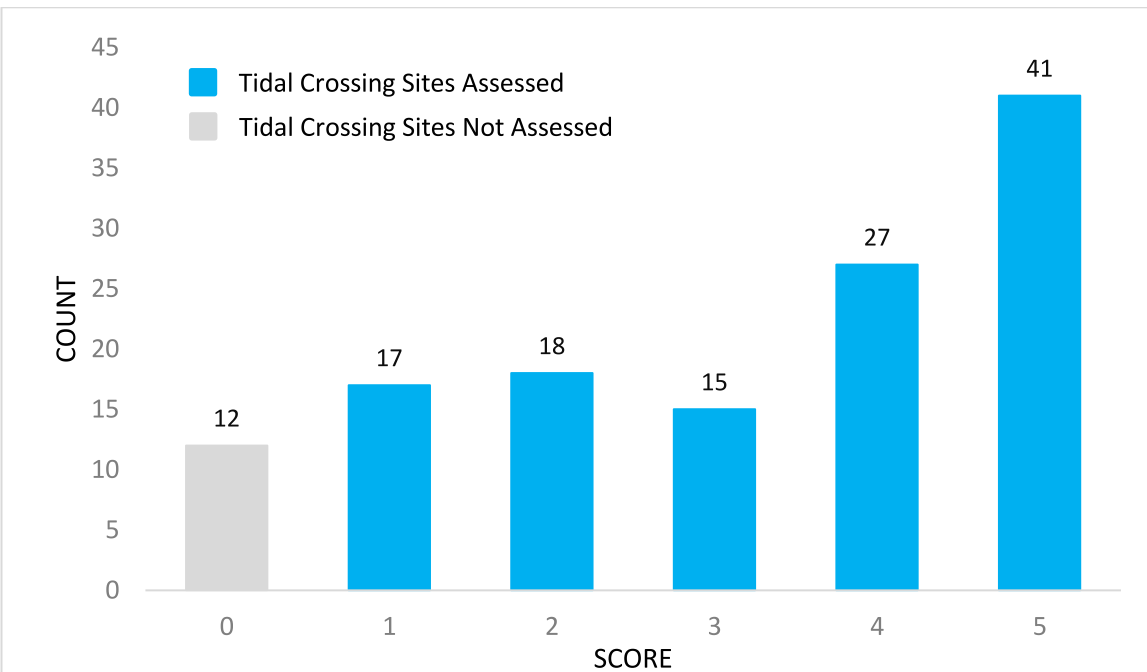
4.8 Overall Crossing Evaluations

Three overall crossing evaluation scores were developed to synthesize tidal crossing replacement priorities across many of the scores presented above. Rolled-up scores are tailored toward infrastructure management, ecological management and one overall score that prioritizes based on a combination of infrastructure and ecological management considerations. Inundation risk to low lying development is not incorporated into any of the three overall crossing evaluations — it can be used as a feasibility and management screen of the overall scores. The results of the three overall crossing scores are detailed below.

Overall Infrastructure Score

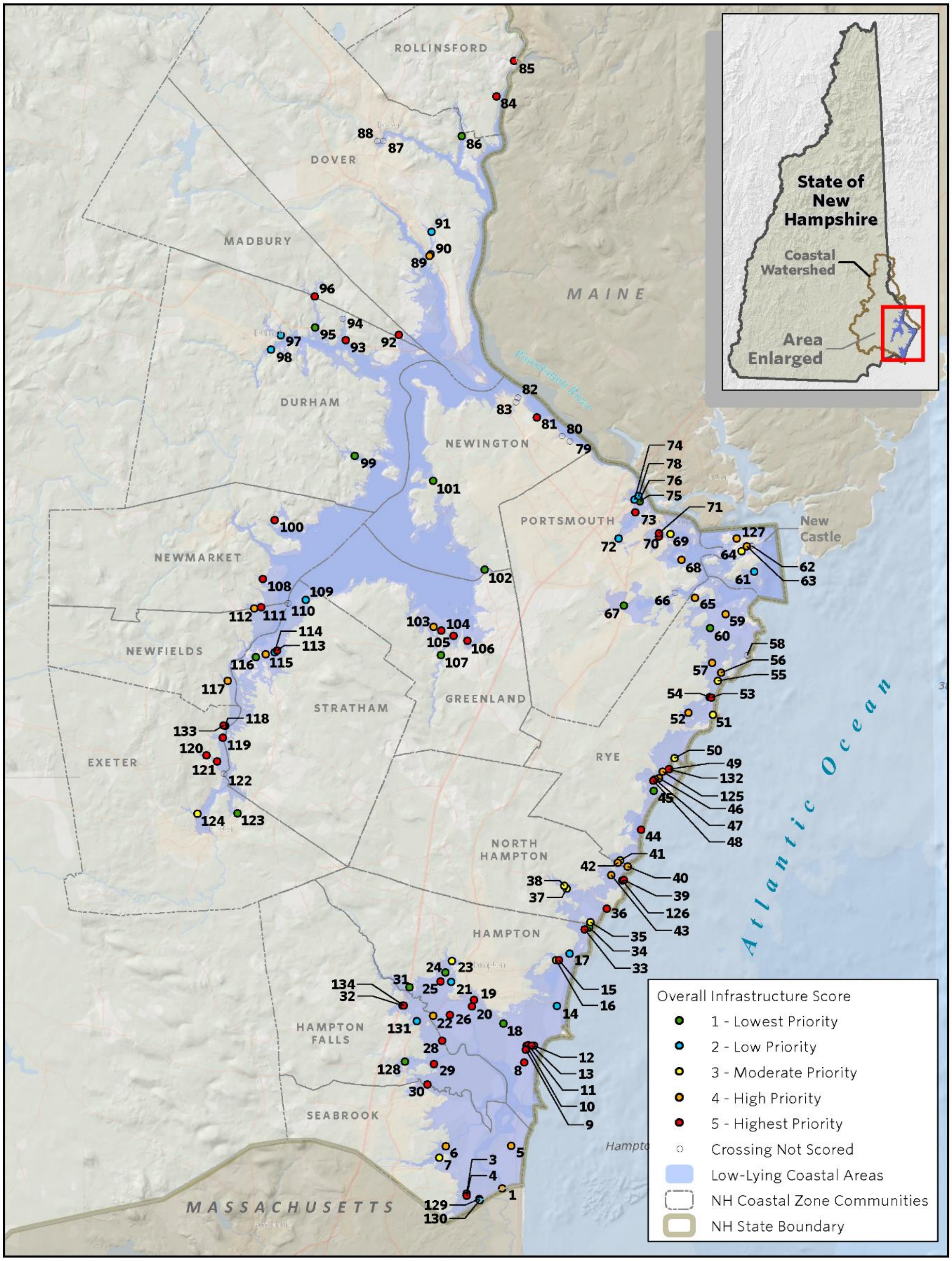
The overall infrastructure score prioritizes crossings based on increasingly poor crossing structure condition and increasing inundation risk to the roadway components. Figure 15 illustrates the distribution of the overall infrastructure risk scores.

Figure 15: Distribution of overall infrastructure scores.



The overall infrastructure scores show that when pairing structure condition and inundation risk to the roadway scores the majority of crossings (68) are at immediate or near-term risk (scores five and four, respectively). Less than 30%of crossings are currently adequate in terms of condition and inundation risk to the roadway (scores one and two). Figure 16 displays the geographic distribution of overall infrastructure scores.

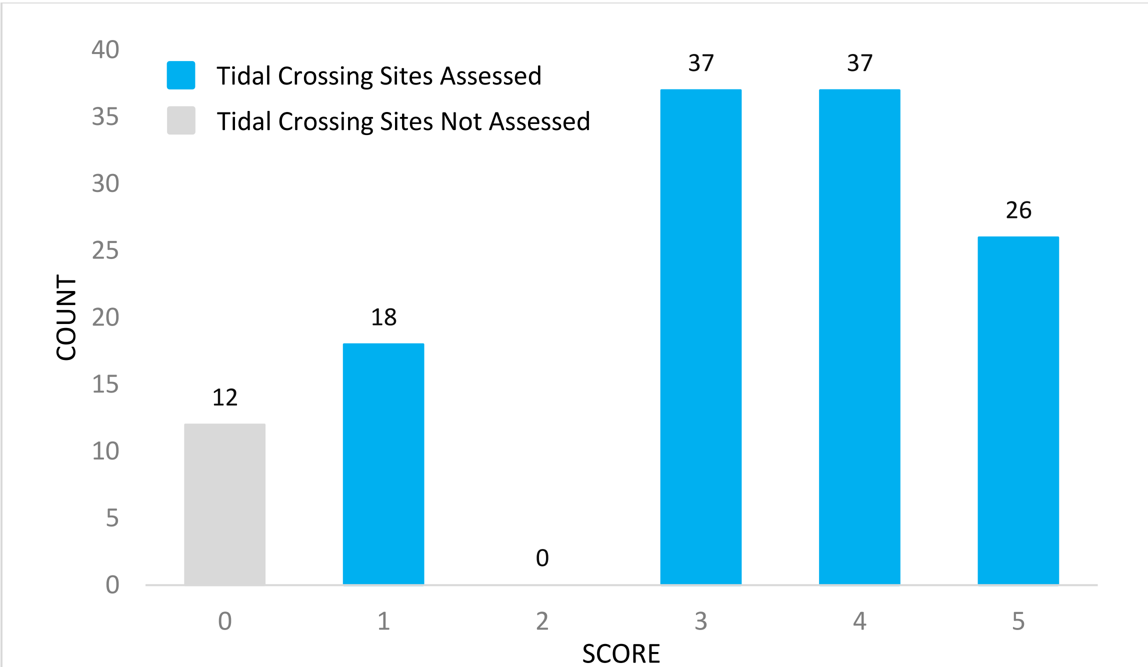
Figure 16: Geographic distribution of overall infrastructure scores.



Overall Ecological Score

The overall ecological score prioritizes crossings based on increasing ecological restoration potential for tidal restriction, tidal aquatic organism passage, salt marsh migration and vegetation. Figure 17 illustrates the distribution of the overall ecological scores.

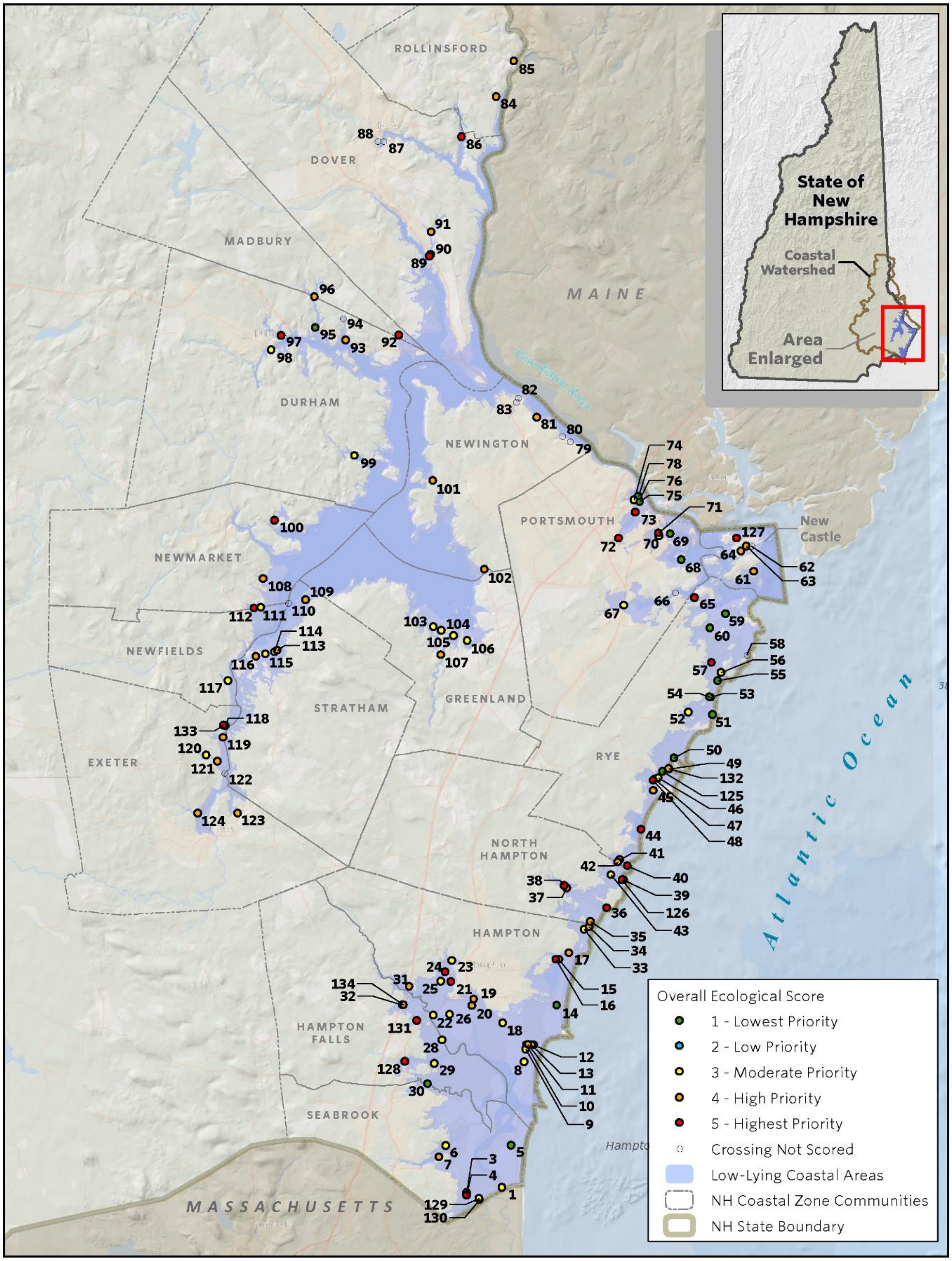
Figure 17: Distribution of overall ecological scores.



The overall ecological scores show that 37 crossings have high ecological restoration potential, and 26 crossings have very high ecological restoration potential (scores four and five, respectively). Just 18 crossing are in no need of restoration from an ecological perspective. Note that the evaluation criteria for the overall ecological score does not include a scoring category for "2." Figure 18 displays the geographic distribution of overall ecological scores.

Vegetation comparison scores of zero due to prevalent invasive species in the marsh plain on both sides of a crossing result in a minimum overall ecological score of four. Prevalent invasive species on both sides of a crossing is likely not the sole result of the crossing itself, but could be the result of numerous factors beyond the scope of this Project. However, these sites are flagged as high restoration priorities because they warrant further attention, whether independent or in conjunction with the crossing structure, to restore healthy native plant communities.

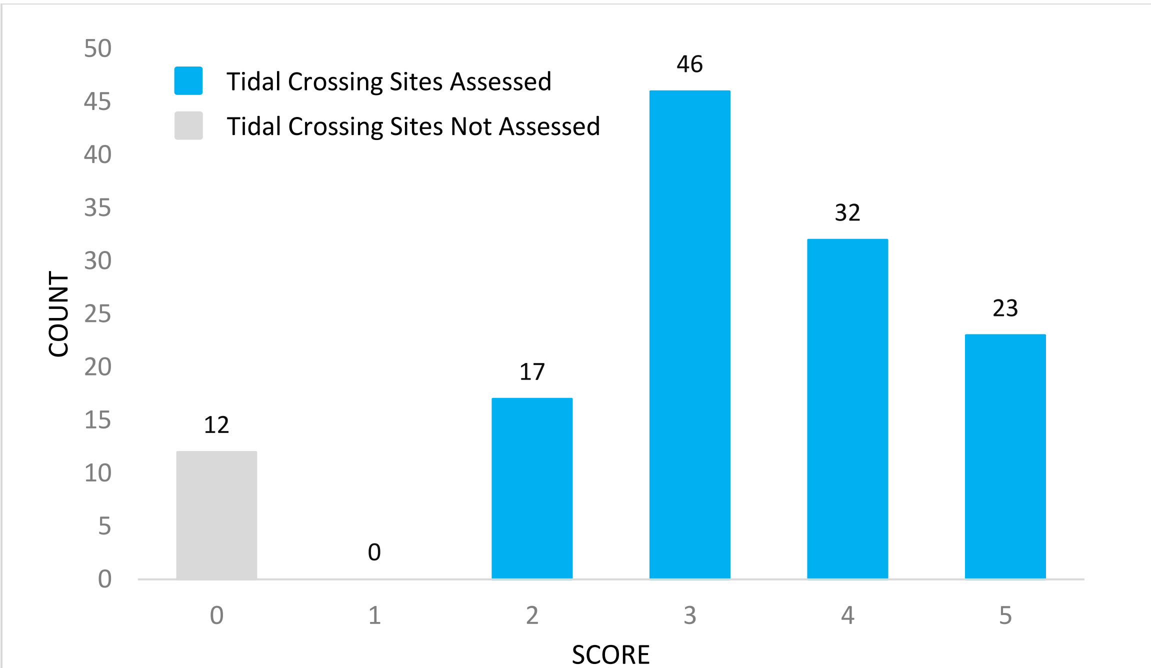
Figure 18: Geographic distribution of overall ecological scores.



Overall Combined Score

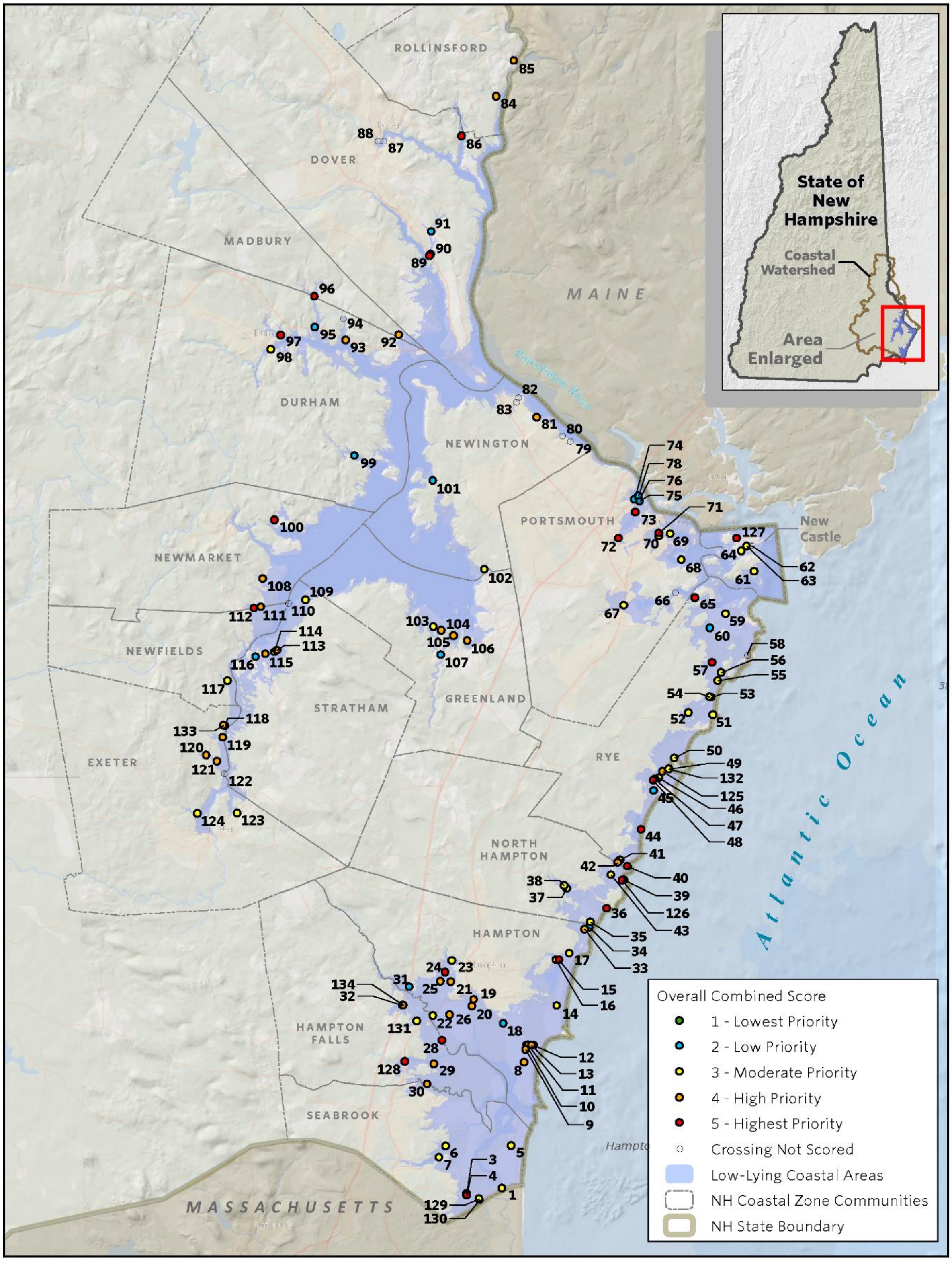
The overall combined score prioritizes crossings based on a combination of infrastructure and ecological component scores. Component scores that feed into the overall combined score includes salt marsh migration potential (upstream watershed), tidal restriction overall, vegetation evaluation, crossing condition, inundation risk to the roadway and tidal aquatic organism passage. Figure 19 illustrates the distribution of the overall combined scores.

Figure 19: Distribution of overall combined scores.



The overall combined score identifies 23 highest priority and 32 high priority crossings to be addressed (scores five and four, respectively). Seventeen crossings are currently adequate when pairing infrastructure and ecological scoring factors. Figure 20 displays the geographic distribution of overall combined scores.

Figure 20: Geographic distribution of overall combined scores.



5. DISCUSSION

Extensive data was collected and analyzed to inventory and prioritize New Hampshire's tidal crossings. Project data enables a wide range of additional analyses to further understand tidal crossings and context for their management. This section synthesizes Project results and includes examples of additional analyses that are enabled by Project data.

5.1 What is a Resilient Tidal Crossing?

The NHDES Coastal Program defines resiliency as the capacity of a community or system to proactively prepare for and promptly recover from hazardous events such as hurricanes, coastal storms and the effects of long-term SLR, rather than the ability to simply react and respond to events.

The Resilient Tidal Crossings Project was designed to understand the vulnerabilities of tidal crossing infrastructure and their effects on tidal systems. In addition to identifying tidal crossings in need of improvement or replacement, the Project also identifies tidal crossing sites that score well across the Project's multiple evaluation criteria. The most resilient tidal crossings in New Hampshire were identified through the overall combined score (see Figure 19), which identified 17 tidal crossing structures with low replacement priority scores (scores ≤ 2) and thus a high degree of resiliency.

The most resilient tidal crossings in New Hampshire share similar attributes; most notably structure type and condition. Nearly all of these sites are either bridges or box culverts and are in very good condition. In addition, the most resilient tidal crossings in New Hampshire have low inundation risk and are generally unrestrictive to tidal flows.

Figure 21. Crossing #95 at Johnson Creek on Route 4 (L), Crossing #60 at Berry's Brook on Brackett Road in Rye (R). Both crossings received low priority replacement scores for Overall Combined, demonstrating a high degree of resiliency.

Despite having sufficient vertical capacity, the majority of the most resilient crossings still have insufficient horizontal capacity. As indicated in **Section 4.2 Tidal Restriction Evaluation**, 98 assessed tidal crossings have insufficient structure opening width, which has likely resulted in severe channel scour conditions at 100 crossings. Project results also show that a site can have a tidal restriction in the form of insufficient structure width and still be resilient, especially if tidal range is not significantly affected and scour isn't compromising the structure's condition.

Restoring tidal range was the primary goal for 15 tidal crossing replacement projects proactively undertaken in New Hampshire between 1994 and 2015. Despite indicators of good tidal range and similar upstream and downstream native plant communities at restoration sites, Project results show that only one restoration site fully meets optimal infrastructure and ecological criteria (i.e. overall combined score ≤ 2). This suggests that the design considerations for restoration activities did not consider climate resiliency factors and the threats and implications of accelerated sea level rise that are considered today. Instead, restoration management objectives focused on improving tidal range, enhancing fish passage and were often constrained by balancing potential adverse impacts of restoring tidal flow. As depicted in Parsons Creek example in Figure 22, many restored crossings occur in low-lying areas near the coast where low road elevations limit tidal crossing design options. Enhancing coastal resilience at these crossings is achieved only by the costly process of raising roadway elevations to reduce inundation risks. Achieving resilience through the raising of roads is not without environmental impact; as higher road elevations will require wider road causeways that will result in a loss of tidal wetlands caused by road fill.

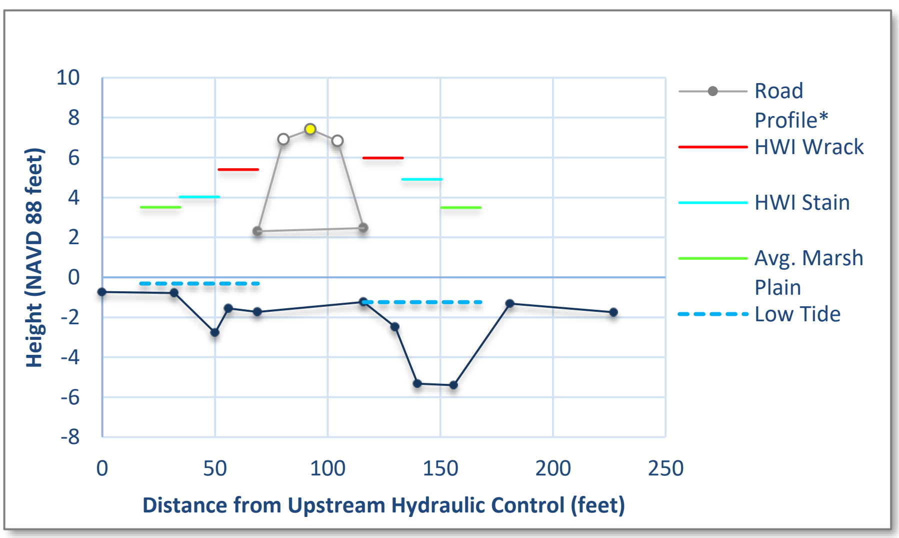
Figure 22. Crossing 54 at Parsons Creek and Wallis Road is a restoration site that received good scores for tidal range, vegetation, salt marsh migration; however, the road is very low in elevation and subject to periodic inundation and thus received high inundation risk scores.

5.2 Crossing Cross Section and Stream Longitudinal Profile

A Crossing Cross Section and Stream Longitudinal Profile was generated for each of the 118 assessed crossings based on a relative elevation survey performed at each site. A two-page Tidal Crossing Summary Sheet is provided for each crossing in Appendix D. These summary sheets include a graph that depicts the longitudinal profile of the stream through the crossing and the cross section of the road at the stream crossing as well as a table depicting raw elevation data, channel features and substrate.

The stream profile in Figure 23 represents relative elevations of the stream channel, as represented by the solid black line. The crossing cross section captures relative elevations of the crossing structure including the ceiling of the crossing structure, high water indicators, average marsh plain and road surface elevations (upstream and downstream low points and the road centerline). For the purpose of the crossing cross section, the road profile is centered over the upstream and downstream inverts for graphical purposes, and do not necessarily reflect the true configuration of the road fill slopes and roadway.

Figure 23: An example of a Crossing Cross Section and Stream Longitudinal Profile graph that depicts key elevation data collected using the New Hampshire Tidal Crossing Assessment Protocol. The table to the right of the graph corresponds to the stream longitudinal profile stations (black dots along the black line), providing information about the distance from the upstream hydraulic control, height of the feature, the feature type, and the channel substrate.



Long. Profile

Dist.	Hght.	Feat.	Sub.
0	-0.7319	HC	G
32	-0.7919	HC	C
50	-2.7819	P	C
56	-1.5619	GC	C
69	-1.7319	I	B
116	-1.2319	I	B
130	-2.4819	GC	B
140	-5.3219	P	C
156	-5.4019	P	G
181	-1.3119	HC	C
227	-1.7519	HC	G

Data from the Crossing Cross Section and Stream Longitudinal Profile are used for multiple scoring criteria (e.g. tidal range ratio, inundation risk to roadway, inundation risk to crossing structure, and tidal aquatic organism passage). Additionally, this information provides insightful context about the compatibility of a tidal crossing with the aquatic system that it conveys.

Scour Pools

Scour Pools are erosion features that indicate geomorphic incompatibilities when present immediately upstream or downstream of a tidal crossing. The erosion classification scoring criteria evaluates scour pool width (if present) relative to average channel width. Project results show that 100 of the 118 assessed sites are tidally restrictive based on this metric alone, which indicates widespread incompatibility of tidal crossings from an erosion standpoint. Scour pools generally result from increased water velocities flowing through undersized culverts or bridges. They are particularly damaging in the estuarine environment, especially to salt marsh peat, which is highly erodible and not easily restored.

Project scoring criteria do not prioritize based on scour pool depth. However, the stream longitudinal profile depicts upstream and downstream pool depths to understand the vertical dimension of channel scour. The Project team was surprised to learn that many tidal crossings exhibit deep scour pools on both sides. This suggests highly pressurized systems due to flow restrictions created by undersized crossings. At Crossing #1 in Seabrook, for example, upstream and downstream scour pool depths at low tide were greater than the field crew's 25' survey rod, demonstrating not only the effects of increased water velocities through undersized crossings but also indicating high erodibility of the unconsolidated channel substrates that are typically found in New Hampshire's tidal systems.

Channel Substrate

The data table to the right of the Crossing Cross Section and Stream Longitudinal Profile graph in Figure 23 and on the Tidal Crossing Summary Sheets provides elevation, channel feature and channel substrate information. Channel substrate (e.g. silt/clay, sand, gravel, cobble, boulder) observed in the field is not incorporated into the Project's evaluation criteria; however, it can be used to determine the compatibility of the crossing structure with the aquatic system. Undersized tidal crossings are expected to result in higher water velocities through the structure, resulting in increased channel erosion upstream and downstream of the crossing. Because smaller channel substrate particles such as, silt, sand and gravel are more susceptible to erosion, it is expected that channel substrate at tidal restrictions are dominated by larger and less mobile substrates such as cobbles and boulders. The stream profile in Figure 23 shows that the channel at the crossing inlet and outlet (feature "I") is boulder (B) dominated but the remainder of the channel is dominated by gravel (G) and cobble (C).

High Water Indicators

Another helpful aspect of the Crossing Cross Section and Stream Longitudinal Profile graphs are the high water indicators, which can inform the hydraulic performance of a tidal crossing structure. Assessed tidal crossing sites exhibit many configurations of high water indicators. Figure 23, for instance, shows that the high water indicators (wrack and stain) features are higher on the downstream side of the crossing, indicating slight buildup of water on the incoming tide. Other sites exhibit indicators of water build up on the upstream side of a crossing, indicating a restriction of seaward flows. The Tidal Crossing Site Summary Sheets (See Appendix D) present upstream and downstream scores for inundation risk to roadway and inundation risk to crossing structure, allowing data users to hone in on hydraulic compatibility with ebb and flow tides through each tidal crossing structure.

5.3 Marsh Subsidence relative to Vegetation Evaluation

One of the prominent features of salt marshes in New England is the flat plain of the high marsh (Nixon and Oviatt 1980). This plain can be impacted by hydrologic restrictions that over-drain marshes, allowing peat oxidation where carbon loss leads to subsidence (Burdick et al. 1997, Anisfeld 2012).

The Crossing Cross Section and Stream Longitudinal Profile also depicts the average marsh plain elevation on both sides of the crossing. These measurements independently average four upstream and four downstream elevations of the adjacent salt marsh plain. The purpose of collecting these marsh plain elevations is to determine if the crossing structure has a noticeable effect on marsh subsidence (i.e. loss of elevation due to oxidation of peat) or accretion (i.e. the ability of the marsh to build in elevation with sediment deposition from frequent flooding).

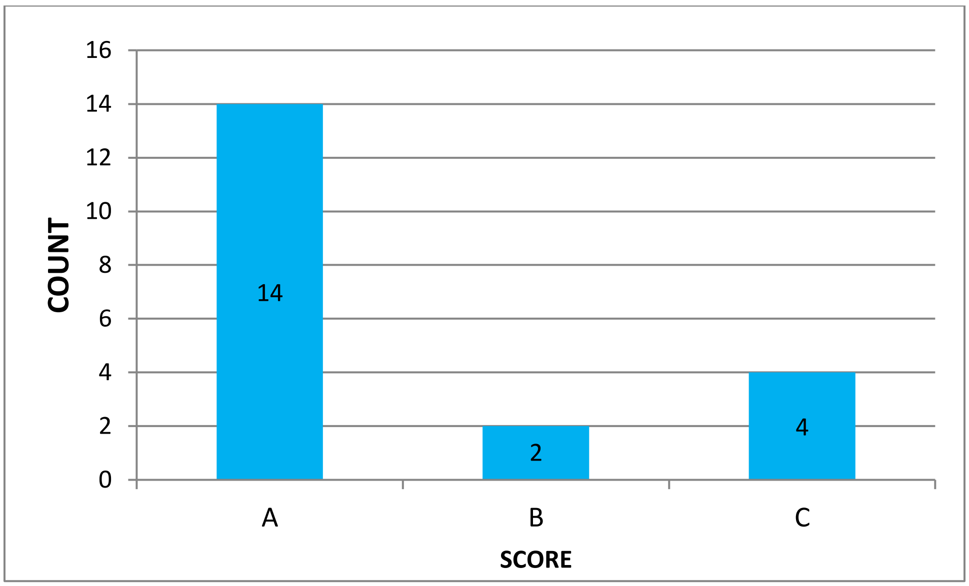
Of the 118 crossings assessed, 93 had marsh plains available to measure on both sides. Considering small amounts of elevation difference might be due to sampling variation, sites with 0.2 feet of elevation difference were removed from the analysis. A total of 20 crossings showed marsh plain elevations at least 0.2 feet lower upstream than downstream. The average amount of subsidence for these 20 crossings was only 0.39 feet. The analysis also showed that 43 tidal crossings had notably higher marsh plains upstream than downstream, 31 of which were associated with a crossing at the upper edge of the marsh or approaching the head of tide (where higher marsh plains would be expected given the topography of the land). The 20 crossings exhibiting subsidence were then analyzed, as described below, with several of our ecological assessment parameters to determine if subsidence correlates with impaired plant communities or tidal restriction.

The “Crossing ID site #” for the sites included in this subsidence analysis are: 4, 9, 10, 29, 32, 34, 35, 43, 47, 48, 54, 65, 71, 93, 99, 103, 105, 118, 121, 125.

Subsidence vs. Upstream/Downstream Plant Community

Tidal Crossing sites exhibiting upstream subsidence were compared to scores from the Project’s vegetation comparison evaluation, shown in Figure 24. Vegetation Comparison Category ‘A’ represents crossings where the plant community is the same on both sides, ‘B’ represents a slight difference in plant communities, and ‘C’ represents very different plant communities. Seventy percent of crossings with upstream subsidence have similar plant communities on both sides, while the remaining 30%of crossings express different plant communities. Subsidence sites were also compared to the presence of invasive species. Fifty percent of subsidence sites had no invasive species and the remaining half have varying degree of infestation by invasive species. Regardless of plant communities, average marsh plain elevations suggest that these 20 crossings are at greater risk of eventual collapse given that they are not maintaining elevation with their downstream marsh unit.

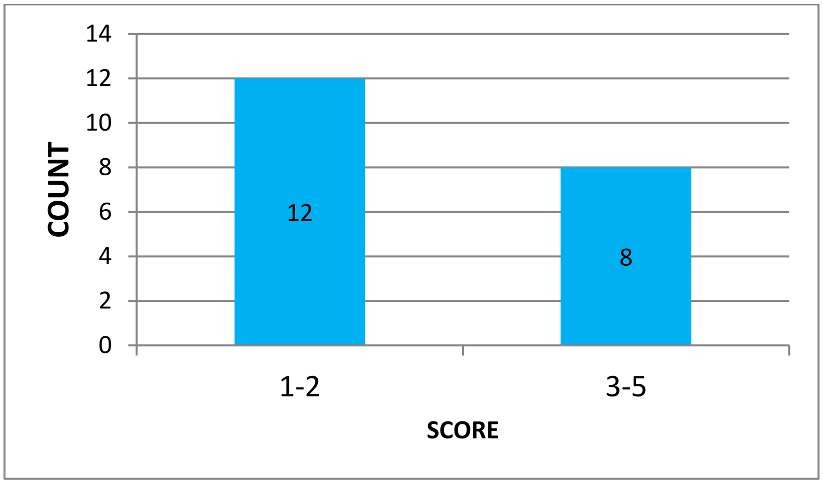
Figure 24: Comparison of crossings exhibiting subsidence to the results of the vegetation comparison evaluation. 'A' represents crossings where the plant community is the same on both sides, 'B' represents a slight difference in plant communities, and 'C' represents very different plant communities.



Subsidence vs. Tidal Range Ratio

Tidal Crossing sites exhibiting upstream subsidence were compared to the Tidal Range Ratio score, shown in Figure 25. Subsidence can be the direct result of a tidal restriction. Tidal Range Ratio Score Category "1-2" represents crossings with minimal or no tidal range difference between the up and downstream sides, category "3-5" represents moderate to severe tidal range differences. Figure 25 shows that 60% of subsidence sites have no/minimal tidal restriction and 40% of subsidence sites have moderate/severe tidal restriction.

Figure 25: Comparison of crossings exhibiting subsidence to Tidal Range Ratio score categories



Subsidence at tidal crossing sites does not appear to be strongly correlated with differences in vegetation community or a reduced tidal range ratio. Most sites with indicators of subsidence received low replacement priority scores, indicating that these sites have similar upstream /downstream plant communities and minimal tidal range issues despite exhibiting subsidence. This analysis did identify several high priority replacement sites that exhibit subsidence plus other indicators of incompatibility, including Crossing ID# 65, 99 and 118.

Project data demonstrate that measurable subsidence has occurred at 20 individual tidal crossing sites. Project data also demonstrate that subsidence of upstream marsh plain does not yet appear to be a significant natural resource management concern at tidal crossings; however, these results are based on only eight elevation readings measured adjacent to the tidal crossing. More in depth analysis of subsidence at these 20 sites would help inform possible management options at tidal crossings.

5.4 Hazard Mitigation Plans Compared to Inundation Risk to Roadway

In 2017, the New Hampshire Geological Survey compiled and digitized data from over 200 hazard mitigation plans from New Hampshire communities into an online database known as the New Hampshire Flood Hazards Geodatabase (NHFHG 2017). Tidal crossing sites identified in the NHFHG were inserted into the tidal crossing database and compared to inundation risk scores to understand alignment across both datasets. Of the 118 tidal crossings assessed, 56 are identified in a municipal hazard mitigation plan. An analysis was conducted to determine whether tidal crossings with high priority scores for inundation risk to the roadway are adequately represented in existing hazard mitigation planning documents. This analysis shows that 36 crossings in the moderate to high inundation risk categories (priority scores 3-5) are identified in a hazard mitigation plan, while 25 are not, demonstrating a potential opportunity to update hazard mitigation plans throughout out the Coastal Zone. This analysis also shows that an additional 20 crossings are identified in a hazard mitigation plan; however, received a low priority inundation risk to the roadway score. These low inundation risk sites may be in Hazard Mitigation Plans as a result of other factors beyond high tide flooding, such as flooding from the upstream watershed, flooding from an extreme storm event, or maintenance issues, among others. Road managers and planners should consider Project priority scoring for both inundation risk to roadway and inundation risk to crossing structure to inform future revisions to hazard mitigation planning documents.

6. NEXT STEPS

The Resilient Tidal Crossings Project collected, analyzed and prioritized attributes at 118 tidal crossings in New Hampshire. Priority scores allow stakeholders to evaluate crossings from a number of coastal resilience-focused management objectives to identify replacement, maintenance and/or restoration priorities and opportunities. The Project team identified the following next steps as important to leverage, implement and advance the findings of this project.

6.1 Data Sharing

A first next step is to inform stakeholders about the availability of Resilient Tidal Crossings data and priorities. Project data and results are available for public use on the NH Coastal Viewer, ArcGIS Online, and in this report. The NH Coastal Viewer is a widely used web mapping tool tailored to New Hampshire's Seacoast; access to Resilient Tidal Crossing data on the Coastal Viewer will facilitate the use of this new information by both general and technical stakeholders alike. Technical users, such as road managers, engineers and natural resource managers, can access all tidal crossing assessment parameter attributes by downloading the full Resilient Tidal Crossing database from ArcGIS Online (see section **1.1 How to Access Data**). The full tidal crossing dataset is also available upon request to the NHDES Coastal Program. Finally, all crossing scores are presented in this report in **Appendix D. Tidal Crossing Summary Sheets** and **Appendix E. Crossing Score Table**.

Conducting outreach about Project results is beyond the scope of the Resilient Tidal Crossings Project; however, the Project team identified the following recommended outreach actions to improve dissemination of Project information:

<u>Recommended Actions</u>

- Conduct direct outreach (e.g. workshops, presentations, etc.) to transportation managers and planners at the state and municipal level and among private sector engineering firms to increase understanding of Project data, particularly sites with high priority condition and inundation risk scores.

- Conduct direct outreach (e.g workshops, presentations, etc.) to conservation commissions and conservation organizations to increase understanding of Project data, particularly sites with high ecological priority scores.

- Prepare Coastal Viewer training materials to assist users navigate tidal crossing data.

6.2 Tidal Crossing Replacement

A longer term goal for the Resilient Tidal Crossings Project is to enhance coastal resilience for people and nature through the prioritized replacement of substandard tidal crossings. A key next step is to utilize Project results to queue the next set of tidal crossing replacements for coastal resilience. TNC and NHCP recently secured funding to complete full design and engineering at four to five high priority tidal crossings resulting from this assessment and prioritization effort. Identifying candidate crossings for this next phase, then working with state and/or municipal partners to start addressing management issues at those crossings is an immediate next step planned for 2019.

Recommended Actions

- Enable tidal crossing replacements by incorporating high priority tidal crossings into relevant planning documents, including but not limited to: Capital Improvement Plans, Hazard Mitigation Plans, Coastal Hazards and Adaptation Master Plans, NHDOT 10 Year Plan, NHDOT Long Range Plan.

- Link high priority sites with applicable grant funding sources for ecosystem restoration and or community resiliency.

- Work with partners to advance moderate and high priority tidal crossings through feasibility, engineering, permitting and construction.

6.3 Maintain Current Tidal Crossing Data

This Project has made a valuable investment in asset management of tidal crossings. The SADES program enabled the efficient collection and management of current tidal crossing conditions. Data from this Project enables the ability to shift from “reactive” to “proactive” management, thereby increasing the impact of infrastructure investments, as well as working toward readiness (design, engineering, permitting) for replacement of high priority tidal crossings. It is important to maintain the tidal crossing dataset going forward to take advantage of the valuable information it provides.

Recommended Action:

- Maintain and update the tidal crossing dataset for reliable long-term asset management and the ability to rapidly respond to unanticipated infrastructure needs, such as road washouts during major storms.

6.4 Tidal Crossing Design Standards

Just as there was no widely accepted assessment protocol for tidal crossings when the Project started, there are similarly no detailed and widely accepted design standards for tidal crossings. The New Hampshire Stream Crossing Guidelines (University of New Hampshire 2009) provide guidance and a regulatory framework for replacement of freshwater stream crossings, but do not address the needs and unique conditions encountered in tidal systems. Simple parameters for replacement of freshwater stream crossings such as watershed size and bankfull width are insufficient for defining the hydraulic complexity at tidal stream crossings, which must also consider site-specific tidal data, bi-directional flow, storm surge and projected SLR.

Recommended Actions

- Encourage the creation of a regional initiative to develop tidal crossing design standards with other state and federal partners across New England and the Northeast to harness professional expertize across the region and use coastal zone management planning resources efficiently.

6.5 Research

Research is necessary to enable science-based management of salt marsh. Research is more critical now than ever, as natural resource managers face significant uncertainty regarding salt marsh response to rapid SLR. Road managers and coastal engineers will also benefit from research of coastal flooding dynamics and techniques for achieving resilient coastal infrastructure. The Project database is available to researchers, natural resource professionals and engineers to advance a range of research topics to improve understanding and management at tidal crossings. The Project Team identified the following preliminary list of research topics that will improve management of tidal crossings:

Recommended Topics for Further Research:

- Investigate flooding dynamics at the tidal/freshwater interface.

- Investigate the effects of tidal crossings on salt marsh health, processes and functions and values, including but not limited to:

    - hydraulic dynamics at tidal crossings, particularly the tidal prism that is necessary to convey through each tidal crossing (under existing and potential future conditions) to achieve adequate inundation of the upstream salt marsh plain.

    - sediment dynamics, particularly the ability of salt marsh to maintain elevation relative to sea level rise.

    - native and invasive plant dynamics, particularly the effect of tidal crossings on upstream and downstream plant community.

- Monitor tidal crossing replacement projects to determine if they are achieving their specific management objectives.

6.6 Regional Transferability

The size and scale of New Hampshire's Coastal Zone is perfectly suited for a comprehensive inventory of tidal crossings, which inspired the Project Team to design and implement a field protocol that could be accomplished at 120 tidal crossings within a 4-month summer field season. While the Project was designed for specific use in New Hampshire, the Project Team was cognizant of its potential applicability elsewhere in the Gulf of Maine and perhaps throughout the US. To enable regional transferability, all Project reports, data, data management structures, scoring criteria, etc. are available through the NHDES and SADES websites.

<u>Recommended Action:</u>

- Revise New Hampshire Tidal Crossing Assessment Protocol to incorporate lessons learned from the 2018 implementation of the Protocol.

- Depending on interest/demand, use lessons learned to generate a streamlined assessment protocol that collects a limited number of assessment parameters to satisfy evaluation criteria requirements for scoring.

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Appendix A: Table of New Hampshire’s Tidal Crossings

Appendix B: Data Dictionary Tables

Appendix C: User Guide for ArcGIS Collector

Appendix D: Tidal Crossing Summary Sheets

Appendix E: Crossing Score Table

Appendix F: Interpretation Guide