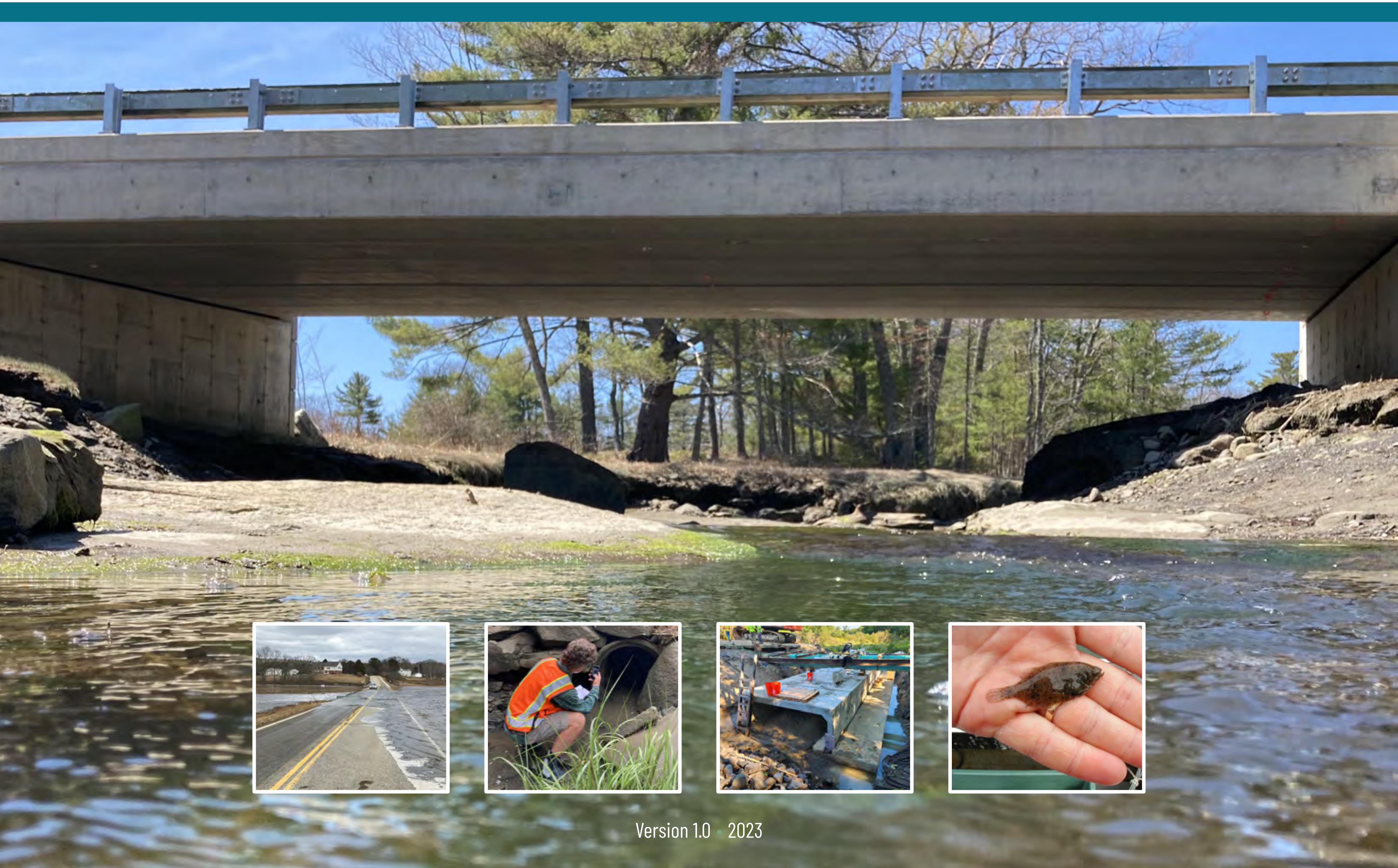
The CoastWise Approach

Achieving Ecological Resilience and Climate-Ready Road Crossings in Tidal Environments



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Welcome to the CoastWise Approach

BACKGROUND

Safe, dependable roads are crucial for supporting Maine's economy, access to critical services, and a way of life valued by citizens and visitors alike. The challenges of road management are multiplied at over 800 locations in Maine, where roads cross diverse tidal environments like salt marshes, mud and gravel flats, bedrock shore, and stream channels. Conditions in tidal environments are overwhelmingly influenced by water levels that rise and fall twice each day. Although the pattern repeats ceaselessly, its characteristics vary over time. Maximum and minimum tide elevations, the amount of flooded area, current speed, and other features continuously shift in step with the relative positions of the earth, sun, and moon over days, months, and even decades. Superimposed on these processes, sea level rise is accelerating at a rate unprecedented over the past few thousand years. These dynamic conditions make the design and management of tidal road crossings particularly challenging. It is a topic central to this document because it presents unique challenges for road owners and the well-being of coastal communities.

The extent to which road crossings allow unimpaired flow of tidal waters between upstream and downstream areas is another significant theme of this document. Recent assessments demonstrate that about ninety percent of Maine's tidal road crossings restrict tidal flow. When tidal flow is squeezed, accelerated, and misdirected through undersized culverts and bridges, premature structural wear or damage can result. Consequently, tidal restrictions can result in higher road maintenance costs, shortened service life of crossings, and unplanned road closures that put public well-being and safety at risk. The severity of today's tidal restrictions is likely to worsen as sea levels rise and the volume of water flows increases over the coming decades.

How well road crossings facilitate the movement of water is also critical to the future of tidal wetlands like marshes, mudflats, and rocky shores. These wetlands provide a range of benefits to local communities such as protection from coastal storms and flood damage, buffering the impact of land-derived pollutants on coastal waters, and support for commercial fisheries, subsistence harvesting, and recreation. Tidal wetlands also support diverse fish and wildlife species, some of which depend exclusively on the unique conditions in tidal wetlands to survive. Lastly, tidal environments supporting salt marshes and eelgrass meadows capture and store carbon at prodigious rates, and so have an important role in Maine's efforts to mitigate the impacts of climate change.

The sequence of best practices encouraged by the CoastWise Approach encourages the development of safe, climate resilient, cost-effective, and ecologically supportive crossings. Photo by Slade Moore.

For tidal wetlands to provide the benefits discussed above, they must remain healthy and resilient to rapidly changing conditions like accelerated sea level rise. Yet where tidal restrictions occur, the natural processes that create and sustain tidal wetlands are often impaired. For instance, salt marshes experiencing restricted tidal exchange do not experience plant growth, sedimentation, and soil stability sufficient to keep pace with sea level rise. Without prompt intervention, tidal wetlands compromised in this way face being overtaken by rising seas.

THE COASTWISE RESPONSE

The challenges of creating climate-resilient roads that serve communities best require us to more fully address the unique complexities, uncertainties, risks, and benefits associated with tidal environments. Even recent advances in crossing design, such as the successful Stream Smart program designed for improving freshwater road crossings, do not meet the full suite of design challenges presented by most tidal crossings. Recognizing the need for a crossing design method specifically developed for tidal environments, participants from over thirty organizations helped develop the CoastWise Approach.

CoastWise provides a voluntary set of science-based best practices, tools, and sequences to encourage the design of safe, cost-effective, ecologically supportive, and climate-resilient tidal crossings. With its prominent emphasis on sea level rise planning, tidal wetland resilience, and blue carbon potential, CoastWise was recommended by the Maine Climate Council's Scientific and Technical Subcommittee and Coastal and Marine Working Group as a tool for climate adaptation, providing benefits for road crossing longevity, carbon capture and storage, and the well-being of Maine's coastal communities.

USING THE COASTWISE MANUAL

The CoastWise Approach was developed for road owners, municipal staff, engineers, and other people interested in helping to replace tidal road culverts and bridges with safe, climate-resilient crossings. Section 1 of this manual establishes the foundation for CoastWise. Each subsequent section provides recommendations sequenced to mirror the chronology of a typical tidal crossing project. We expect readers will become familiar with parts of the manual most relevant to their role in a project, level of technical expertise, and interest in digging into the "finer details".

ADAPTABILITY AND VERSIONS OF COASTWISE

CoastWise attempts to provide a structured but adaptive framework for crossing design that is useful for most if not all tidal crossing sites. To the extent possible, CoastWise is meant to encourage the development of safe, climate-resilient, cost-effective, and ecologically supportive crossings. However, the design developed for each individual crossing will ultimately be influenced by site-specific conditions and road owner objectives, keeping within current regulatory requirements. Additionally, for some project sites, requirements for design methods are so specialized that they exceed the scope of recommendations in this manual.

Lastly, this version of the CoastWise manual reflects our effort to present best practices as they were understood at the time of publishing. Tidal crossing design methods and tools continue to evolve, and as that process unfolds we intend to revise CoastWise materials. Your input is important for keeping CoastWise up to date. Periodically checking with the CoastWise Technical Partners will ensure you are using the latest recommended practices. For more information about the CoastWise Approach or site-specific crossing questions, please refer to Section 2 of the Manual for a list of CoastWise contacts.

COASTWISE PRINCIPLES

Know Your Tidal Crossings

Use the Maine Coastal Program's Tidal Restriction Atlas or other available tools to learn which crossings are tidal or likely to become tidal in the coming decades.

Ask for Advice

CoastWise Technical Partners can help with project planning, connecting with the right resources, and providing other support to navigate the tidal crossing design process.

Engage Qualified Engineers

Crossings that effectively manage risk and provide the greatest resilience benefits require engineers skilled in tidal hydrodynamic modeling.

Encourage Local Participation

Crossing design involves value judgements having lasting impact. A transparent, participatory design process encourages outcomes that serve communities best.

Start with Sea Level Rise

Objective, risk-based selection of a sea level rise scenario early in the project process provides the necessary foundation for all subsequent work.

Identify Low-lying Features of Concern

Understanding the vulnerability of flooding to severely damaged wetlands, private property, the built environment, and resource uses is essential for managing risk.

Establish Clear Objectives

Early development of clear, measurable crossing performance objectives streamlines the design process and avoids costly design revisions.

Size Crossings for Resilience

Keeping pace with sea level rise requires tidal wetlands to experience the full ebb and flow of the highest tides throughout the life of the crossing. A central principle of the CoastWise Approach is to upsize crossings so they can achieve unrestricted tidal exchange and peak functionality of resilience processes to the extent practicable, under present and projected future conditions.

TABLE OF CONTENTS

1. TIDAL WETLANDS, ROADS, AND COASTWISE

Photo by Michael Burke

1.1 MAINE'S TIDAL WETLANDS AND THEIR VALUE

Introduction

In the narrow strip where land and sea meet, tidal wetlands develop as unique, adaptive expressions of dynamic and often harsh conditions. For the purposes of this document, "tidal wetlands" include the areas within the intertidal zone, which is the area between high and low tides. We also include the relatively shallow, but permanently flooded habitats associated with the lower elevations of tidal wetlands, such as creeks and shallow bays.

Mud and sand flats, salt marshes, and rocky shoreline are a few common types of tidal wetlands in Maine. The conditions that allow establishment of one tidal wetland type over another at a given location are diverse, but strongly influenced by physical and chemical factors, including: 1) underlying geology and local sediment sources, 2) wetland surface elevations relative to tide elevations, 3) degree of exposure to ocean winds, wave action, and currents, and 4) water salinities.

Development of wetlands as a response to these factors tends to follow a predictable pattern. Under some geological conditions, tidal wetlands in Maine with more exposure to wind, waves, and currents typically have more exposed bedrock or coarse sediment types, like large pebbles, cobbles, and boulders that resist being washed away (Figure 1.1). By contrast, lower-energy environments like mudflats and tidal marshes are settings where fine sediments and other materials delivered by the tides, surrounding land, or the wetland itself, have a chance to settle and accumulate (Davy 2022).

FIGURE 1.1 - High-energy conditions and the prevalence of bedrock at Pemaquid Point predispose rocky shore wetland types (left). The more sheltered environment and abundance of finer sediment classes near the mouth of the Sheepscot and Kennebec Rivers facilitated development of the Reid "Lagoon" salt marsh (right). Photos by Slade Moore.

Within the broad types of tidal wetlands, considerable variation occurs (Cowardin et al. 1979, CMECS 2012). Tidal wetlands are influenced by environmental shifts that can prompt short- and longer-term changes in plant and animal community structure and distribution (Connell 1961, Paine 1966, Dayton 1971). For instance, scour and sediment deposition caused by the movement of ice and/or storm surge can encourage or suppress the success of individual species (Ewanchuk and Bertness 2003). The frequency, duration, intensity, and extent of environmental shifts is central to how species diversity and abundance within individual wetlands evolves over time (Bertness and Ellison 1987).

The total acreages of distinct tidal wetland types in Maine varies considerably (Figure 1.2). Within each coastal region, the distribution and abundance of wetland types also differs according to prevailing conditions in one part of the coast to another (Jacobson et al. 1987).

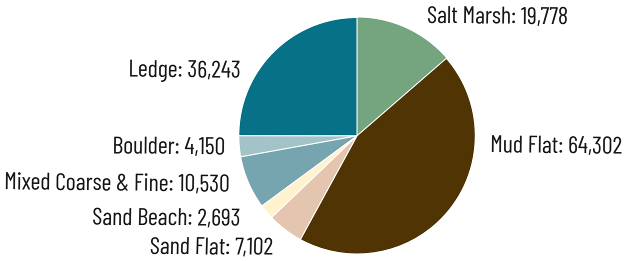


FIGURE 1.2 - Maine's intertidal wetland acreages by type, reported by Ward (1999) based on maps created by Barry S. Timson in the mid-1970s. In more recent analyses, the Maine Natural Areas Program estimated the area of salt marsh at 18,096 acres, and the National Wetland Inventory estimated it at 22,824 acres.

Tidal marshes, which are wetlands of heightened management interest, are most strongly associated with areas having sources of sediment that can be mobilized and deposited in sufficient quantities (Figure 1.3). They occupy a distinct elevation range within the intertidal zone and are dominated by grasses and other non-woody plants highly adapted to specific flooding regimes and salinity levels. Salt marshes are typically closer to marine waters, while brackish and freshwater tidal marshes are generally located farther

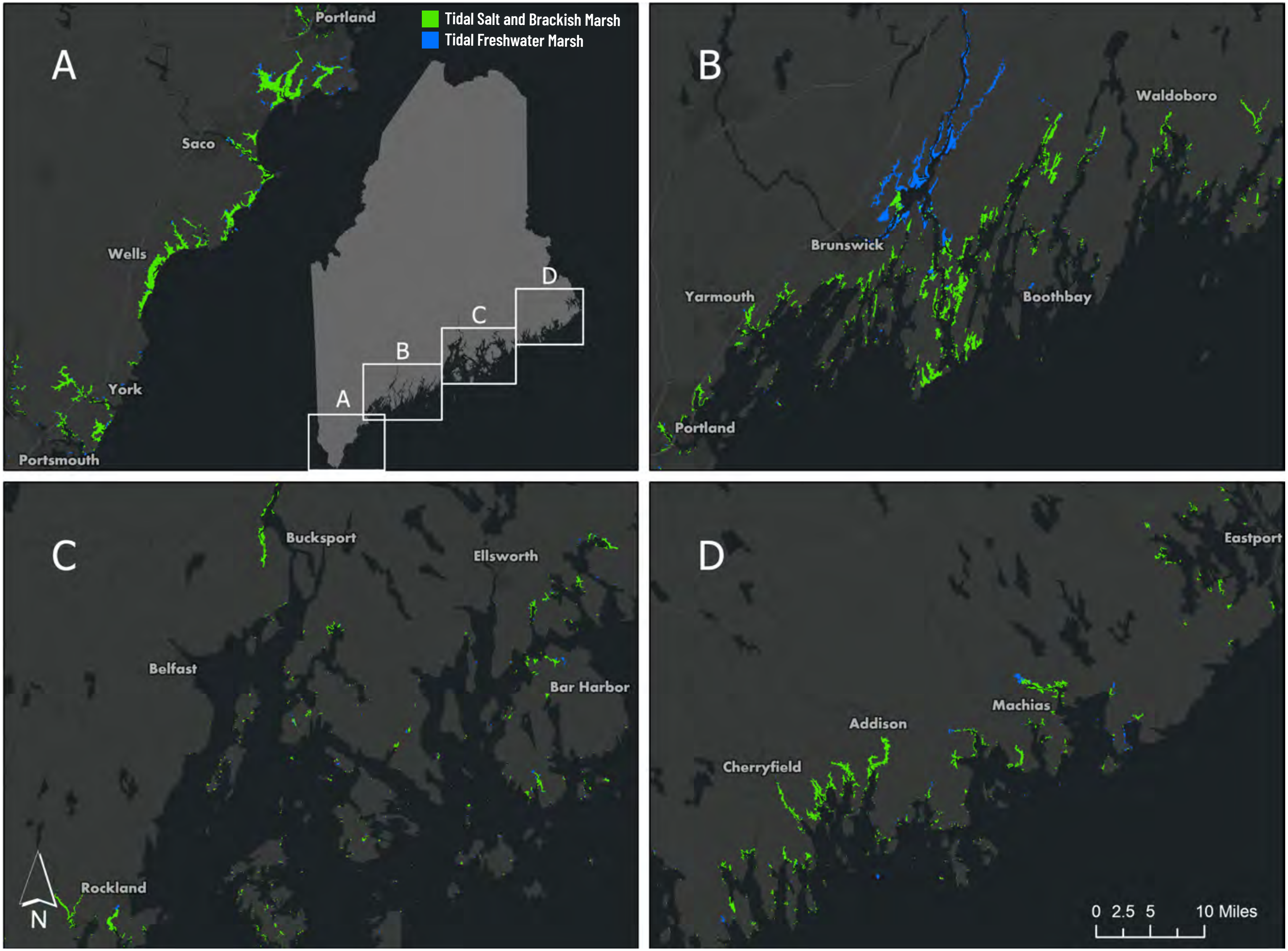


FIGURE 1.3 - The distribution and abundance of tidal marshes in Maine, as illustrated by National Wetland Inventory mapping. Map created by C. Enterline. Data sources: ESRI, ESRI Canada, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, NPS, NRCan, Parks Canada, and Province of New Brunswick.

upstream and along the landward edge of salt marshes where salinity declines. A key requirement of healthy salt marshes is the unimpaired ebb and flow of the tides, which deliver saline waters and materials necessary for salt marsh communities to persist over time.

Tides and Salt Marshes

Tides are waves or bulges in the ocean caused by the gravitational influence of the sun and moon. In Maine, there are usually two high and two low tides every day. The maximum and minimum daily tide heights are constantly changing, mostly because of changes in the relative distances and positions of the earth, sun, and moon. When they are closely aligned, such as during full and new moons, the largest tidal ranges occur, meaning higher high tides and lower low tides. These large tidal ranges are commonly referred to as astronomical tides or spring tides.

During the highest spring tides and storms, healthy salt marshes experience complete flooding of the high marsh plain. This flooding, which occurs a few days out of each month, supports processes that are critical for salt marshes to grow vertically and keep pace with sea level rise, such as sediment deposition, plant material accumulation, and maintenance of marsh soil stability (Cahoon et al. 2006).

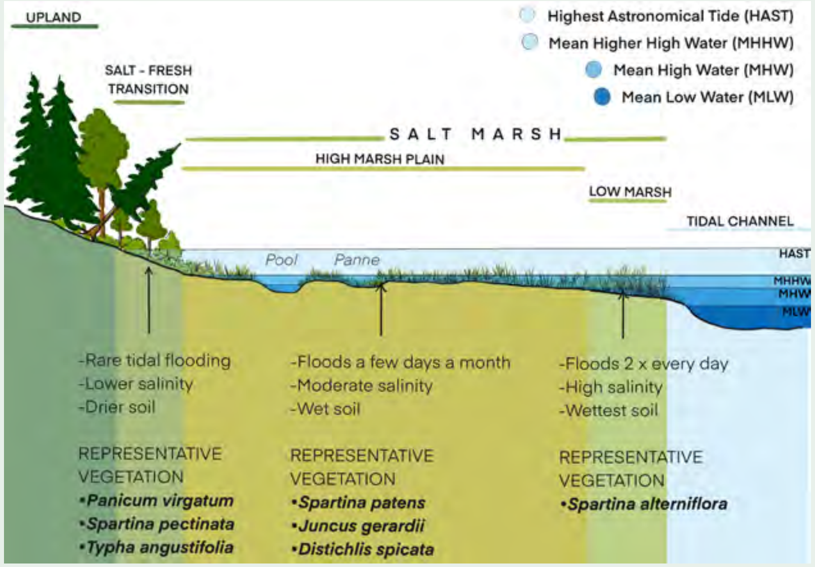


Figure adapted from E. Nadeau's drawing in Carlisle et al. 2002. Illustration by Maisie Richards.

Why Tidal Wetlands Matter

Healthy tidal wetlands provide a wide range of benefits to people. These are known as ecosystem services, and include flood and storm damage protection (Shepard et al. 2011), maintenance of fish and wildlife populations (Ayvazian et al. 1992, Shriver et al. 2004), support of commercially harvested species (Deegan et al. 2002), and storage of carbon that would otherwise contribute to accelerated sea level rise and other shifts caused by climate change (Chmura et al. 2003) (Table 1.1). Different types of tidal wetlands provide varying kinds and degrees of ecosystem services.

Some tidal wetlands have been assessed for their economic and market value. Even among the same wetland types, it is worth noting that values assessed at different locations can vary due to site conditions and differences in assessment methods. Recent examples from Massachusetts (MDER 2014) include:

- **Flood Protection:** Improved flood protection provided by the Town Creek Restoration Project in Salisbury is projected to reduce economic impacts to businesses and residents by an estimated $2.5 million over the next thirty years.
- **Water Quality:** Chatham and Harwich are projected to save $3.9 million over thirty years by reducing wastewater infrastructure construction and operating costs as a result of the Muddy Creek Estuary Restoration Project.
- **Carbon Sequestration:** By 2050, Hingham and Quincy salt marsh restoration projects are projected to prevent $224,000 in greenhouse gas damages. The carbon storage contribution from these projects is equivalent to avoiding the combustion of over 800,000 gallons of gasoline.
- **Aesthetics and Enhanced Real Estate Values:** The thousand-acre Herring River Restoration Project in Wellfleet and Truro was projected to enhance the combined values of over 1,400 properties by a total of $10.4 million.

While not exclusive to tidal wetlands, several assessments of Maine's estuarine nearshore habitats also indicate the value of services provided by tidal wetlands.

TABLE 1.1 - Potential ecosystem services provided by tidal wetlands of all types, but in the table below, framed within the context of salt marshes. Provision of services by individual marshes depends on a variety of factors, including location, size, and condition of the marsh.

SERVICES PROVIDED	DESCRIPTION OF SERVICE
Wave and storm surge attenuation	Shallow depths combined with friction caused by marsh vegetation reduce wave height and inland advance of storm surge.
Flood duration attenuation	Surface flood waters cause less damage when they can rapidly drain into adjacent tidal marshes.
Shoreline stabilization	Marsh vegetation helps protect erodible shorelines by stabilizing intertidal sediments and attenuating wave energy.
Water quality maintenance	Marsh vegetation increases sediment capture and retention, nutrient transformation, and breakdown of toxic pollutants, keeping coastal marine waters cleaner and safer.
Carbon capture and storage	Atmospheric carbon that would otherwise contribute to climate change is stored in salt marsh soils.
Maintenance of ecological diversity	Habitat for diverse assemblages of plants and animals, including species that live only in marshes
Commercial species habitat	Marine worms, clams, periwinkles, and other commercial species depend on habitats within marshes; nutrients and prey species from marshes enrich nearshore food webs supporting commercial species.
Recreation	Opportunities for fishing, hunting, shellfish harvesting, birding, paddling, photography, and other activities
Aesthetic value	Healthy marshes provide a source of inspiration that can add real estate value.
Education and research	Marshes are a natural laboratory for citizen science, understanding ecological processes, and monitoring responses to sea level rise and other coastal changes.

- **Commercial Fisheries:** The average 2015-2019 annual commercial landing value for species whose primary habitat includes intertidal wetlands was over $16 million, or a third of total landings after excluding the value of lobsters (https://www.maine.gov/dmr/commercial-fishing/landings/historical-data.html).
- **Recreation** (Pendleton 2009):
  - Beachgoing: Statewide beach usage in 2005 was estimated at $81-323 million.
  - Recreational Fishing: The estimated annual statewide value for coastal areas and estuaries in 2005 was $45-$297 million.
  - Marine Wildlife Viewing: The low range of the estimated value in 2005 was $200 million.

Where no readily identifiable markets correspond to these types of services, the intrinsic value of the species in question must also be considered.

1.2 IMPACTS TO MAINE'S TIDAL WETLANDS

Maine's tidal wetlands face a range of threats to their health and resilience. These include pollution from toxic compounds, establishment of invasive plant and animal populations, and impairments to natural patterns of flooding and drainage. This last category, which includes wetland filling, agricultural practices, and the construction of dams and transportation crossings, has inflicted profound damages to wetland health. Each activity has lasting effects, but an important distinction is that the replacement of old road crossings with new ones that impair tidal exchange remains an ongoing activity.

Wetland Filling

The construction of roads, railroads, and residential or commercial land required placement of materials such as rocks, soil, and debris in tidal wetlands to "make land". Restoration of tidal wetlands is often infeasible where extensive acreage was converted to upland (especially developed uplands) and communities have become accustomed to the prevailing uses of these highly altered coastal environments (Figure 1.4).

FIGURE 1.4 - Map showing the Portland peninsula's colonial-era shoreline. Built areas in the underlying 2001 satellite imagery illustrate the extent of tidal wetland acreage filled over time. Graphic created by Rosemary Mosher.

Agricultural Alterations

Many salt marshes in Maine have also been modified by dikes (usually low, earthen embankments) and ditches built to drain or "freshen" the high marsh. These activities allowed use of salt marsh vegetation for livestock fodder and creation of pastures on the marsh plain (Figure 1.5). Some marshes were also ditched to control mosquito populations. After many years, these alterations typically led to overly wet marsh conditions, which contributes substantially to marsh health decline and a lack of resilience to sea level rise (Adamowicz et al. 2020).

The extremely high prevalence of marshes that were altered in this way and the large amounts of affected acreage present unique challenges for statewide marsh conservation and restoration. There is growing recognition that correcting agricultural alterations in marshes is a necessary element of restoring marsh health, building resilience to sea level rise, and supporting the recovery of imperiled species, like the saltmarsh sparrow (*Ammospiza caudacuta*) (Adamowicz et al. 2020). Notably, correction of agricultural alterations at many of these sites may have to precede tidal flow restoration at transportation crossings if marshes are to respond favorably.

FIGURE 1.5 - Left: Ditches in Morse River Marsh impair sea level rise resilience processes. Photo source: Google Earth. Right: Remnant of a platform used to dry salt hay harvested in the Nonesuch River. Photo by Slade Moore.

Tidal Restrictions

More than a thousand built structures cross tidal streams and wetlands in Maine. These include dams, transportation crossings like roads, railroads, trails, earthen embankments, and others. Roads are the most common tidal crossing type, with over 700 (90%) restricting the ebb and flow of the tides in Maine (Bartow-Gillies et al. 2020). Undersized culverts and bridges and perched culverts are the primary cause of tidal restrictions associated with roads.

The first consequence of a tidal restriction is a change in the ways tidal waters interact with the upstream tidal environment. The tidal prism is the volume of water that flows into and out of the basin upstream of a location, excluding contributions from freshwater inflows. The degree of change to the tidal prism caused by a restriction depends on the restriction's severity and characteristics of the wetland. It is common for restrictions to alter how often and for how long large areas of wetland experience tidal flooding and drainage each day or month. These changes in hydrology can alter the physical, chemical, and biological features of tidal wetlands. Here are some typical examples of outcomes caused by tidal restrictions:

FIGURE 1.6 - This road dams a former tidal inlet of the Kennebec River estuary. Remnants of tide mill dams are in the adjacent mudflat and inlet to the east. Photo source: Google Earth.

FIGURE 1.7 - The hummocks surrounded by shallow flooded areas in this photo indicate a degrading marsh plain in this tidally restricted marsh. Photo by Slade Moore.

FIGURE 1.8 - This perched, undersized culvert blocks aquatic organism passage except during high tide. Photo by Slade Moore.

Rapid Loss/Conversion

When the most severe tidal restrictions block all or most tidal flow, upstream wetlands cannot drain sufficiently and convert to pond-like conditions (Figure 1.6). This conversion comes at the cost of losing many or all of the functions provided by the former wetland. Artificial ponds that replaced fully tidal wetlands were often created for purposes that are no longer relevant, such as ice production. Today their uses extend mainly to recreational or aesthetic value, but some are used for aquaculture and water supplies.

Progressive Wetland Resilience Decline

Most tidal restrictions are less severe than total blockages, but they can still impair processes necessary for the long-term health and resilience of upstream tidal wetlands. In mudflats and salt marshes, these processes include the accumulation of sediment. For salt marshes, accretion of plant material and the maintenance of soil stability are also highly relevant (Bartholdy 2012, Cahoon et al. 2006). Optimal performance of these processes depends on complete inundation of the marsh plain for sufficient durations during the few days each month when spring tides and storms occur (Stumpf 1983, Wood et al. 1989, Baranes et al. 2022, Reed et al. 1999, Fitzgerald et al. 2020, Moore et al. 2021, Portnoy and Giblin 1997, Fujii 2012). Even moderate tidal restrictions can alter these inundation patterns and undermine the requisite resilience processes. Tidal restrictions at some sites can also subject marsh soils to prolonged air exposure that leads to peat decomposition (Figure 1.7) (Roman et al. 1984). This causes the marsh plain to actively lose elevation, or subside, resulting in more frequent tidal flooding that eventually exceeds the tolerance of marsh plant communities. Without intervention, these conditions drive a progressive conversion to aquatic systems that are adapted to more frequent or permanent flooding and do not provide the same types of unique services as healthy salt marshes.

Impaired or Blocked Fish and Wildlife Passage

Dams and culverts perched high above the stream channel can totally block the movements of species requiring access between habitats necessary for their survival (Figure 1.8). Even moderately perched culverts can significantly reduce the window of time during which fish and wildlife can pass. For example, culverts that are perched only during low tide may nevertheless drastically reduce the spawning success of species like rainbow smelt whose upstream migrations can be influenced more by the time of day than tidal cycles (Enterline et al. 2019). Additionally, undersized road crossings unnaturally accelerate water velocity through the crossing. These pressurized conditions can result in water velocities that exceed the swimming abilities of fish, wildlife, and other aquatic organisms seeking passage to important habitats, while also causing erosion to the adjacent channel.

Impaired Carbon Capture and Storage

Salt marshes and eelgrass meadows can capture and store exceptionally large amounts of atmospheric carbon that would otherwise contribute to climate change effects such as accelerated sea level rise (Chmura et al. 2003, Röhr et al. 2018). Most carbon storage in forests occurs in the tissues of woody plants, but the majority of carbon in salt marshes is stored in soils. If marsh soils remain in a healthy condition, carbon storage can continue for thousands of years. However, when tidal restrictions cause sufficient declines in water salinity or cause marsh peat to deteriorate, stored carbon and other greenhouse gases are released into the atmosphere (Chmura et al. 2003, Kroeger et al. 2017, Gunn 2016). Worldwide, converted and degraded coastal wetlands annually release 450 million tons of carbon dioxide, which is equivalent to three to nineteen percent of releases from global deforestation and results in annual economic damages of $6 to $42 billion (Pendleton et al. 2012). Improving and protecting the carbon capture and storage potential of tidal wetlands is a prominent element of the 2020 Maine Climate Council's Blue Carbon Optimization strategy for climate change resilience. These actions contribute to resilience goals by reducing the impacts of storm events and sea level rise while also improving health and resilience of the tidal wetlands that contribute to Maine's coastal economy (Harvey et al. 2021).

Loss of Resilience to Sea Level Rise

Each of the impact types discussed so far impairs the resilience of tidal wetlands to sea level rise. Sea level rise (SLR) is influenced by several important factors, including the melting of land-based glaciers and ice sheets that add volume to the oceans, warming temperatures that expand ocean volume, changes in atmospheric and marine circulation patterns, and vertical movements of land masses (Harvey et al. 2021). Geological records demonstrate that sea levels in Maine have increased at dramatically different rates over the past 11,000 years, with the largest swings in the rate of SLR resulting from processes related to recent glaciation (Kelley et al. 1996).

Maine's average rate of SLR over the past few decades ranges between 3.27 and 5.71 mm/year across depending on the monitoring stations, which is the highest experienced in the past few thousand years (Maine Geological Survey 2021). At stations (Portland, Bar Harbor, and Eastport) where monitoring data are available to compare long-term and more recent trends, the rate of SLR since 1993 has been shown to increase between 1.4 and 1.8 times the long-term average (Figure 1.9) (Maine Geological Survey 2021, Sweet et al. 2017, Sweet et al. 2022). Future SLR scenarios (see Section 3) have been developed and are periodically updated to project potential magnitudes of SLR increase corresponding to different greenhouse gas emissions scenarios. These scenarios demonstrate that increases in the rate of SLR are inevitable (Hall et al. 2019).

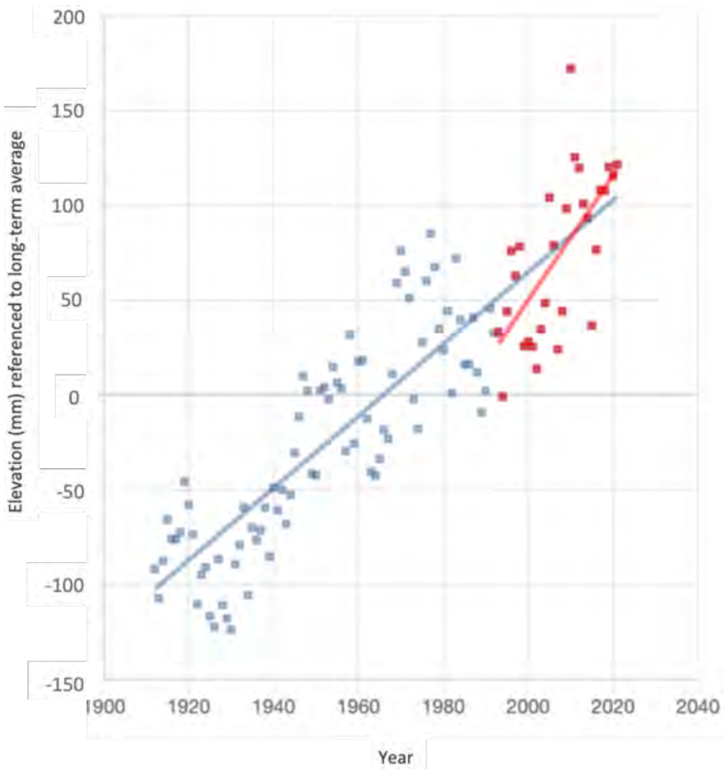


FIGURE 1.9 - Annual sea levels recorded at Portland. Blue squares represent 1912-2021 annual averages, and the blue line is the trend for that period. These data demonstrate that the Portland long-term average rate of sea level rise is 1.90 ± 0.09 mm per year or 0.62 ft (7.49 in) per century. Red squares indicate the more recent average (since 1993), which is 3.29±0.79 mm per year or 1.08 ft (12.94 in) per century. Source: Maine Geological Survey.

The extent to which tidal wetlands will adapt to accelerated SLR is uncertain, but it is expected that conditions corresponding to even the lowest SLR scenarios may exceed the ability of some wetlands to keep pace (Crosby et al. 2016). Individual wetland types have unique tolerances for flooding duration and/or exposure to saline conditions that correspond to narrow elevation ranges in the intertidal zone. As sea levels rise at an accelerated rate, tidal wetlands must occupy progressively higher elevations that provide the necessary combination of conditions. This requires lateral expansion into adjacent non-tidal wetlands and low elevation uplands (Fujii 2021). For that to occur, tidal wetlands must 1) build vertically at rates sufficient to keep pace with increasing surface water elevations, 2) maintain soil stability (for marshes), and 3) be allowed to progressively occupy higher upslope areas. Each of these processes requires unimpaired tidal exchange, now and in the future.

Lastly, recent research suggests an increased degree of urgency to re-establish tidal exchange at restricted wetlands. The moon's 18.6-year orbital cycle will shift in 2025 from dampening the rate of SLR acceleration to increasing it over and above already unnaturally high background levels (Baranes et al. 2020, Thompson et al. 2021). During this acceleration period, tidal wetlands like salt marshes that are already impacted by restrictions and other stressors may become more vulnerable to conversion to other wetland types and less responsive to the most common and affordable restoration actions.

1.3 ROADS IN THE TIDAL ENVIRONMENT

Challenges of Managing Tidal Crossings

A safe, dependable network of roads in Maine is necessary to support economic development and access to employment, healthcare, education, and emergency response services. Yet, like most public infrastructure, roads are often taken for granted. Maine is one of several states with over ninety percent of its economy generated in the coastal region (Colgan 2009). Not surprisingly, the average density of public roads is nearly three times greater in Maine's coastal counties than non-coastal counties.

A recent statewide assessment by the Maine Coastal Program documented over 800 tidal road crossings in Maine (Bartow-Gillies et al. 2020). In contrast to non-tidal crossings over streams, crossings in tidal environments require consideration of a larger, distinctive set of factors during the assessment and design process. Lack of adequate attention to these factors can impact public safety, the long-term cost effectiveness of the structure, and the health of associated tidal wetlands over the long-term.

About ninety percent of Maine's tidal road crossings restrict the ebb and flow of the tides under present conditions and many were not designed to meet the challenges associated with sea level rise projections throughout the service life of the crossing. Crossings are often undersized, leading to over-pressurized conditions within the structure. This can result in damage to the crossing structure and road embankment, more frequent maintenance, and—in extreme cases—the need to replace the crossing earlier than anticipated.

Crossings which restrict tidal flow to upstream marshes are of particular concern. In Maine there are at least 335 tidal road crossings that restrict upstream tidal exchange in salt and fresh marshes. Maine Coastal Program calculated upstream tidal marsh acreage for 305 of those restrictive road crossings. The results were distributed among five upstream acreage classes, skewed toward the smallest class (Figure 1.10), with approximately 70 percent in the 0.5- to 25-acre class. The median upstream acreage for restrictive road crossings with salt marsh and all tidal marsh types is 8 and 11 acres, respectively.

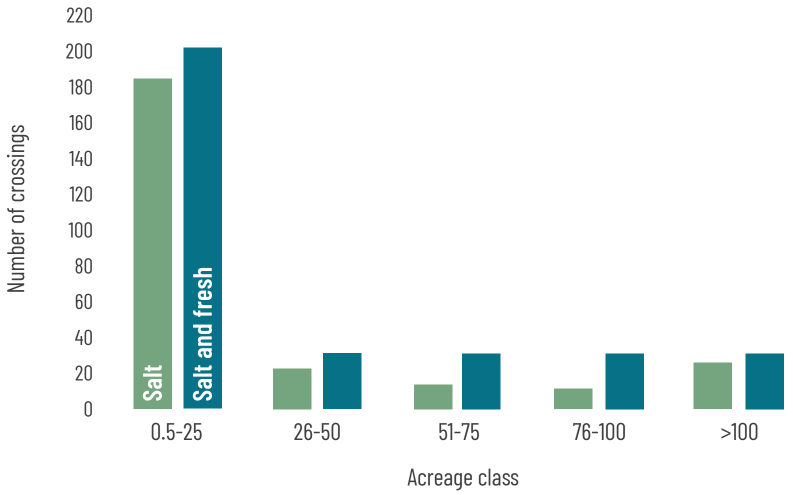


FIGURE 1.10 - Frequency distribution of road crossings presently restricting upstream tidal marshes, binned by acreage class.

FIGURE 1.11 - Roads flooded by tidal waters can block evacuation routes, cause slower response times by emergency medical services, and impair access to important services. Photo source: Town of Cape Elizabeth.

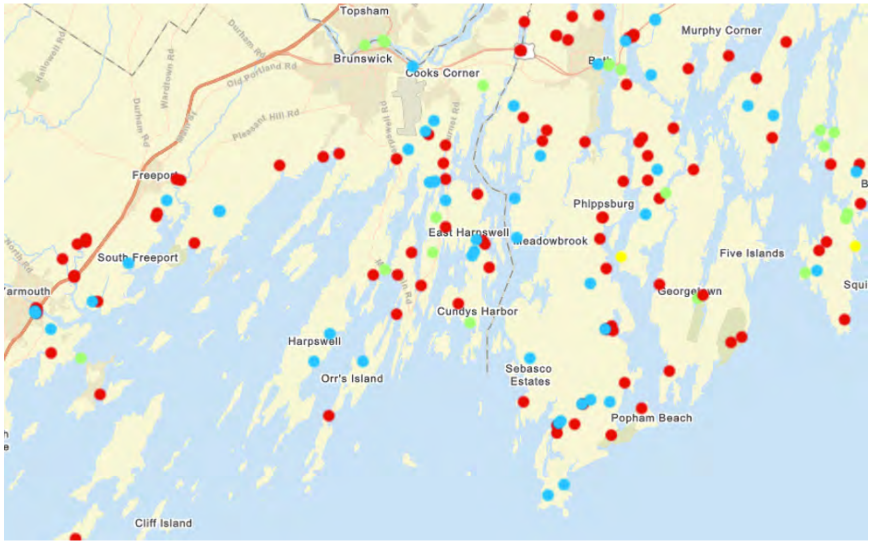


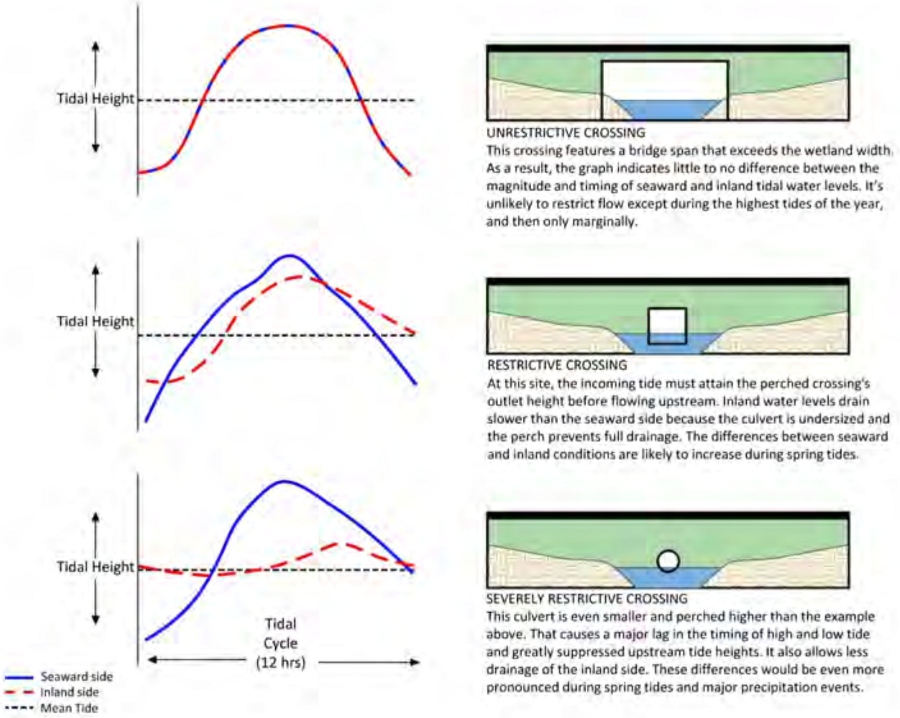
FIGURE 1.12 - Screenshot of the Maine Tidal Restriction Atlas showing the distribution of public road crossings that are tidal restrictions (red), non-restrictions (green), unknown status (yellow), and future tidal crossings (blue) in the Casco Bay-Kennebec River estuary area.

Crossings designed without adequate attention to sea level rise projections and tidal dynamics are also vulnerable to periodic overtopping by tidal waters with increasing frequency as sea level rise continues. Driving across a flooded roadway is never recommended, but local citizens' tolerance for these events appears influenced by the timing, frequency, depth, and duration of flooding as well as uses of the road (e.g., emergency services, residential access, commerce). The Maine Climate Council's Science and Technical Subcommittee concluded that one foot of sea level rise will cause a fifteen-fold increase in the frequency of nuisance flooding (Maine Climate Council Scientific and Technical Subcommittee 2020). At roads that are the only point of access to emergency services, residences, critical infrastructure, or other locations considered important by the road owner or community, the tolerance for flooding will be limited.

Common Features of Restrictive Tidal Crossing Conditions

As discussed in Section 1.2, road crossings that restrict the tides can undermine tidal wetland health in a variety of ways that diminish the types and level of services these wetlands provide to communities. Restrictions also jeopardize the existence of wetlands like tidal marshes by undermining self-maintenance processes like plant growth, soil stability, and sediment transport and deposition (Portnoy and Giblin 1997), and also by releasing stored carbon that contributes to accelerated sea level rise and other climate shifts that put wetlands and coastal roads at risk.

Tidal restrictions also cause hydraulic conditions that can damage crossings. The most common trait of tidal restrictions is a culvert or bridge span that is too small to adequately accommodate the full range of tides. Undersized crossings can limit the rate of tidal flooding into upstream wetlands, as well as drainage of fresh and tidal waters during outgoing tides. Crossings with culverts perched above the stream channel are another common cause of tidal restrictions (Figure 1.13). Perched crossings delay the onset of tidal waters flowing upstream and degree of drainage possible in the upstream wetland. Together these conditions can alter the frequency, duration, depth, and extent of upstream tidal flooding (Figure 1.13), and correspondingly, the distribution and amounts of salinity, sediment, nutrients, and organisms that contribute to wetland community health.



UNRESTRICTIVE CROSSING
This crossing features a bridge span that exceeds the wetland width. As a result, the graph indicates little to no difference between the magnitude and timing of seaward and inland tidal water levels. It's unlikely to restrict flow except during the highest tides of the year, and then only marginally.

RESTRICTIVE CROSSING
At this site, the incoming tide must attain the perched crossing's outlet height before flowing upstream. Inland water levels drain slower than the seaward side because the culvert is undersized and the perch prevents full drainage. The differences between seaward and inland conditions are likely to increase during spring tides.

SEVERELY RESTRICTIVE CROSSING
This culvert is even smaller and perched higher than the example above. That causes a major lag in the timing of high and low tide and greatly suppressed upstream tide heights. It also allows less drainage of the inland side. These differences would be even more pronounced during spring tides and major precipitation events.

FIGURE 1.13 - Conceptual hydrographs (left) corresponding to crossing configurations (right) demonstrating discontinuity between upstream and downstream conditions as a result of tidal restriction. Adapted from a figure by E. Nadeau in Carlisle et al. 2002. Graphic prepared by Michael Burke.

1.4 PLANNING FOR RESILIENCE

The CoastWise Approach

In the past few decades, our understanding of the impacts associated with tidal restrictions has improved considerably. There are examples of well-executed tidal road crossings in Maine. However, statewide road crossing assessments, research studies, and wetland restoration projects have demonstrated that, by and large, tidal road crossings in Maine: 1) often resulted in tidal restrictions, 2) undermined ecological processes of upstream wetlands, and 3) inconsistently provided community resilience benefits related to sea level rise or carbon storage value of salt marshes. As a result, tidal restrictions caused by roads contribute to impaired ecological health, well-being of local communities, and even worldwide climate conditions.

Fortunately, methods and expertise are available to design and build road crossings that correct the social and ecological liabilities associated with tidal restrictions under present conditions. These methods also integrate ways to make tidal crossings resilient throughout their service life by effectively planning for sea level rise and other climate factors. What is needed most is an efficient way to consolidate these practices into a framework that provides consistent results, and then apply it one crossing at a time. The CoastWise Approach described in this manual is meant to address that need.

CoastWise offers a process for road crossing design that specifically addresses the unique complexity and benefits of tidal environments. As a result, it differs from Maine's highly successful Stream Smart Program, which was developed based on the requirements of road crossings over non-tidal streams. CoastWise provides planning tools, recommended best practices, and a comprehensive design approach that reflects the needs of road owners and local communities, with the objectives of:

- Enhancing public safety and well-being
- Ensuring long-term cost effectiveness
- Accommodating sea level rise and other climate factors
- Improving the health of tidal wetlands and the degree of services they provide
- Identifying site-specific factors of concern and community preferences
- Consistently delivering good outcomes

FIGURE 1.14 - Like many aging crossings, this one was replaced well after its safe, useful service life concluded. Photo by Slade Moore.

CoastWise Principles

Tidal wetlands and streams are dynamic systems influenced by a wider range of interacting factors than most non-tidal streams. As a result, they require a specialized design approach that adequately addresses complexity and risk, now and in the future. Key principles of the CoastWise Approach include:

- **Know your Tidal Crossings:** Use the Maine Coastal Program's Tidal Restriction Atlas or other available tools to learn which crossings are tidal or likely to become tidal in the coming decades.
- **Ask for Advice:** CoastWise Technical Partners can help with project planning, connecting with the right resources, and providing other support to navigate the tidal crossing design process.
- **Engage Qualified Engineers:** Crossings that effectively manage risk and provide the greatest resilience benefits require engineers skilled in tidal hydrodynamic modeling.
- **Encourage Local Participation:** Crossing design involves value judgements having lasting impact. A transparent, participatory design process encourages outcomes that serve communities best.
- **Start with Sea Level Rise:** Objective, risk-based selection of a sea level rise scenario early in the project process provides the necessary foundation for all subsequent work.
- **Identify Low-lying Features of Concern:** Understanding the vulnerability of flooding to severely damaged wetlands, private property, the built environment, and resource uses is essential for managing risk.
- **Establish Clear Objectives:** Early development of clear, measurable crossing performance objectives streamlines the design process and avoids costly design revisions.
- **Size Crossings for Resilience:** Keeping pace with sea level rise requires tidal wetlands to experience the full ebb and flow of the highest tides throughout the life of the crossing. A central principle of the CoastWise Approach is to upsize crossings so they can achieve unrestricted tidal exchange and peak functionality of resilience processes to the extent practicable, under present and projected future conditions.

Stream Smart and CoastWise

Stream Smart is a successful program in Maine for presenting guidelines and training for non-tidal road crossing design. Stream Smart prominently features the use of stream bankfull width measurements during the process of sizing crossings. This can work very well for non-tidal streams.

Most tidal culverts and bridges restrict tidal exchange, which results in channel widths that are smaller than they would be under unrestricted conditions. Consequently, the current channel width in tidal environments is a poor guide for estimating effective tidal crossing size presently, or in the future. CoastWise encourages hydrodynamic modeling at most tidal sites to identify appropriate crossing sizes under present conditions and those associated with sea level rise.

The remainder of this manual provides a roadmap for applying the CoastWise Approach to tidal road crossings.

1.5 ADDITIONAL RESOURCES

Maine's Salt Marshes: Their Functions, Values, and Restoration
This illustrated resource booklet for Maine residents educates the reader about the properties and functions of salt marshes and contains resources to facilitate conservation by citizens.

Salt Marshes in the Gulf of Maine: Human Impacts, Habitat Restoration, and Long-term Change Analysis
This publication provides a user-friendly overview of salt marsh ecology in the Gulf of Maine, along with descriptions of typical impacts, and long-term monitoring of marsh health.

2 STARTING YOUR COASTWISE PROJECT

Photo by Slade Moore and John Sowles

2.1 PROJECT PHASING AND PARTICIPANT ROLES

There are a variety of reasons why road owners consider replacement of tidal road crossings, including unsafe structural conditions, increasing maintenance costs, roadway flooding, emergency management and sea level rise planning, and the need for habitat restoration. Regardless of the initial reasons, crossing replacement projects are often an opportunity to address multiple considerations having local benefit. Also clear is that the planning, design, and construction of tidal road crossings comes with levels of complexity, uncertainty, and risk uncommon to most non-tidal crossings.

The CoastWise Approach is a sequence of steps and recommended practices to navigate these challenges. CoastWise proceeds sequentially, with each new phase building on the last to inform decision-making leading to safe, climate-resilient road crossings. This sequence ensures that the most important factors are considered for each site and helps road owners avoid inefficiencies in the crossing design process that can result in lost time and money. A brief overview of project phasing is provided below (Table 2.1). Each of the phases is described in more detail in subsequent sections of the CoastWise Manual.

TABLE 2.1 - Typical project phases for the planning, design, and construction of a tidal road crossing project.

PHASE	DESCRIPTION	DURATION
Preliminary Site Assessment	Provides an initial orientation to the site and important considerations, and identifies provisional objectives	1-2 months
Detailed Field Investigation	Collects and analyzes the data used for subsequent phases	1-2 months
Establishment of Objectives and Design Criteria	Refines objectives and translates them to engineering criteria	1 month
Feasibility and Alternatives Evaluation	Uses tidal water modeling, sea level rise, constructability, and cost factors to develop and evaluate initial engineering design alternatives	2-5 months
Final Design and Permitting	Completes design and permitting so the project can be put out to construction bidding	3-12 months
Construction	Implements the tidal crossing replacement	1-6 months
Post-Construction Monitoring	Tracks performance against the objectives and identifies adaptive management needs	3-5 years

Know Your Tidal Crossings

Understanding which among your crossings are or will become tidal in the coming decades allows you to prioritize and sequence action for replacing crossings. Doing so provides the planning time necessary to allocate funding, acquire grant awards, and arrange for project support before a crossing's condition reaches a crisis point. Use the Maine Coastal Program's Tidal Restriction Atlas to start this process. CoastWise Technical Partners can assist with these steps.

Aside from the road owner and the consulting engineer, individual project phases benefit from having several people representing specific roles as part of a Project Team. For public crossings, these people typically include interested community members, a CoastWise Technical Partner, relevant non-government organizations, and Maine Department of Transportation (if applicable). Regulatory staff often appreciate early involvement in projects and can help projects avoid costly missteps. At sites with unique habitat vulnerabilities, early involvement of relevant natural resource agency species experts is recommended. The typical parties involved, their roles, and resources potentially available for projects are discussed in more detail in the following sections of this manual.

Engineers who are well-versed in CoastWise best practices for tidal road crossing design, or willing to apply these practices, are an important element of successful projects. Consequently, road owner requests for proposals from engineering consultants should emphasize that the project will apply recom-

Engineering Qualifications

Due to the specialized nature of tidal crossing study and design, hiring qualified engineering consultants with experience in estuary settings is crucial. Important areas of expertise include estuary hydrology and hydraulics, integration of sea level rise into project design, hydrodynamic modeling of estuary systems, crossing design and construction experience for estuary settings, and others. In addition, infusing projects with cross-disciplinary expertise is important, including a working knowledge of tidal wetland ecology and estuary geomorphology.

Fig 2.1 - The likelihood of a successful tidal road crossing replacement largely depends on the Project Team involved. Photo by Slade Moore.

mendations of the CoastWise Approach. To ensure that engineers provide a scope of work and budget corresponding to a project using CoastWise best practices, requests for proposals should include recommended steps and work products discussed in this CoastWise manual.

Road owners can access a range of resources for technical assistance, project management, and/or grant funding sources. CoastWise Technical Partners (listed below) are available to provide more information.

2.2 COASTWISE TECHNICAL PARTNERS

Early involvement of a CoastWise Technical Partner can help apply the CoastWise Approach most efficiently. Our Technical Partners can also assist with overall project planning, identification of funding options, execution of site assessments, and providing access to other technical resources and expertise. The CoastWise Technical Partners include representatives of state, federal, and non-governmental organizations, with a collective breadth of experience gained working on a wide range of tidal crossing projects. With time, we expect the list of CoastWise Technical Partners will grow. For more information, please refer to the list below.

Statewide

Bill Bennett, Fish and Wildlife Biologist
Gulf of Maine Coastal Program, U.S. Fish and Wildlife Service
william_bennett@fws.gov
207-781-8364 x15

Southern Maine

Jacob Aman, Stewardship Director
Wells National Estuarine Research Reserve
jaman@wellsnerr.org
207-646-1555 x112

Casco Bay

Matt Craig, Habitat Program Manager
Casco Bay Estuary Partnership
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207-228-8359

Downeast Maine

Jeremy Gabrielson, Senior Conservation Planner
Maine Coast Heritage Trust
jgabrielson@mcht.org
207-607-4587

3 PRELIMINARY SITE ASSESSMENT

Photo by Slade Moore

The planning, design, and construction of road crossings in tidal environments is often more complex than what js required at non-tidal sites. The standardized sequence of data collection and analyses encouraged by the CoastWise Approach helps manage this complexity. From the earliest project phases, collecting the right types of data correctly is essential to a cost-effective and efficient process.

The Preliminary Site Assessment starts with a Desktop Analysis that efficiently provides answers to some of the most fundamental questions relevant to tidal crossings and helps prepare for field activities. The next step, the Rapid Site Assessment, provides an initial field characterization of the site, with emphasis on the crossing's configuration, dimensions, and condition, as well as signs of wetland impairment. It also helps test assumptions and unanswered questions formed during Desktop Analysis.

3.1 DESKTOP ANALYSIS

It is important to learn some fundamental facts about a project site before starting more in-depth investigations. Below are some typical types of information that help put a project into the correct context from the start.

Tidal Hydrology Requires Specialized Assessment Methods

In a freshwater system, the size of the stream channel at the road crossing is determined by the upstream watershed, and water flows in only one direction: downstream. Higher and lower flows and water levels typically correspond to seasonal shifts. In a tidal system, water flows in both directions, and the size of the stream is determined by the volume of tidal waters that regularly pass through the crossing in both directions, plus flow that may come from upstream sources. High and low flows and water levels occur roughly twice each day. Flooding from storm surge is also distinctive from non-tidal flooding. The greater complexity of considerations and uncertainty at tidal crossings is most effectively managed when using assessment and data analysis methods specifically developed for tidal crossings.

Ownership and Maintenance Responsibilities

In Maine, the Department of Transportation (MaineDOT) manages and maintains all road crossings on state and federal roads. Even on town-owned roads, MaineDOT may have jurisdiction over the crossing. This is determined by the crossing span. Table 3.1 summarizes the criteria for determining MaineDOT jurisdiction (MaineDOT 2019) and the MaineDOT Public Map Viewer provides ownership information. If there is any question about who is responsible for ownership or maintenance, contact your local MaineDOT regional office.

TABLE 3.1 - Typical crossing ownership and responsibilities based on structure size.

CROSSING SPAN	CATEGORY	OWNERSHIP & RESPONSIBILITY
0 to 10 feet	Culvert	Town/private ownership maintained MaineDOT involvement not required
10 to 20 feet	Minor Span	Town/private ownership can be maintained on town/private way MaineDOT design review / comply with bridge manual MaineDOT inventory for bi-annual inspection
20 to 150 feet	Small to Large Bridges	Town/private ownership can be maintained on town/private way with special agreement MaineDOT ownership / maintenance more typical MaineDOT design review / comply with bridge manual MaineDOT design for state highway or state-aid roadway MaineDOT inventory for bi-annual inspection

Crossing Setting

An initial step is to verify whether the site is currently tidal or is expected to become tidally influenced during a replacement crossing's service life, which at present, could extend to 2100. A recommended first step is to check the Maine Tidal Restriction Atlas. The Atlas displays known tidal crossings in Maine, including those that may become tidal in the future, as suggested by sea level rise (SLR) mapping developed by Maine Geological Survey. Use the Atlas to find your crossing and select the highest astronomical tide (HAsT) layer to determine if it is likely to presently be within the influence of the highest tides. If the crossing is not within the presently mapped HAsT extent, select SLR scenario layers to determine if and under what scenario it is likely to become tidal.

Defining what kind of wetland or tidal system that the road crosses is key to understanding the crossing's potential impacts and opportunities to correct them. Mud and sand flats, marshes, gravel and rocky shores, deep-water areas, and others have unique characteristics that should be considered early in project planning. For instance, mud or sand flats upstream of a crossing may support shorebird habitats of statewide significance and/or be used for clam and marine worm harvesting. Knowing the types of wetlands present and their contributions to total wetland acreage in the surrounding area also helps anticipate ecological responses to a crossing replacement. The Tidal Restriction Atlas includes mapping created by the National Wetland Inventory and Maine Natural Areas Program (MNAP) that helps make these initial determinations. The Atlas also provides MNAP layers describing marsh migration potential.

The position of the crossing relative to the larger system is also important. For instance, does it cross a wide expanse of wetland, or is it closer to the head of tide where tidal influence is mostly confined to a stream channel (Figure 3.1). These differences can affect the site's tidal range, with more muted tide amplitudes farther inland as elevation increases. It is also helpful to think about other crossings and water control structures. Crossings upstream and downstream of the site could influence or be influenced by changes to the crossing under consideration for replacement.

FIGURE 3.1 - Red arrows indicate tidal restrictions in Machias caused by roads in the Middle River, near its outlet and farther upstream. The types of impacts caused by restrictions are strongly tied to their relative position in the system. Image source: Google Earth.

Public Welfare

Crossing Condition

The condition of the crossing is a critical factor for public safety and frequently the most important determinant of how soon the crossing is replaced. For some crossings in the Restriction Atlas, condition data are documented. Crossings in the Atlas that have site photos can also provide evidence of crossing condition. Visual evidence of scour or deterioration of the structure itself may also be visible in aerial photos. Damaged and deteriorating crossings should be evaluated promptly by a professional engineer to assess public safety risk.

Road Flooding

It is important to learn if any part of the road floods under present conditions or is likely to as sea levels rise. Local experts such as people involved in local road management can often provide information about flooding.

Facilities, Services, and Amenities Accessed by the Road

Another set of important questions involves the volume of traffic on the road and what the road provides access to. For instance, does it lead to critical infrastructure, like a hospital, wastewater treatment plant, or power substation? Does it provide access to other important community assets, like a working waterfront, schools, businesses, or residences? Is the crossing the only means of accessing these assets or others that are important to the community? Is the crossing part of a coastal evacuation route? If the answer to any of these questions is yes, the consequence of flooding can be high, resulting in a lower tolerance for flooding under present conditions and projected sea level rise. Town offices are often good sources of this type of information, and the MaineDOT Public Map Viewer provides classification and average daily traffic information for roadways.

Tidal Restriction Status

The Tidal Restriction Atlas provides assessments of restriction status for known tidal crossings. If a crossing of interest has not been assessed for its restriction status in the Atlas, satellite imagery can be used to observe indicators of restrictive conditions. Scour pools often cause the channel to bulge outward at one or both ends of the crossing structure. Channel "pinching," where the crossing embankment intrudes into the channel, is also typical. Restrictions also often lead to obvious differences in the width, depth, cross section, and color of water in the upstream versus downstream channel.

The most severe tidal restrictions impound water upstream of the road. In cases where severe restrictions are caused by natural bedrock features, the degree of tidal flow improvement attainable may be limited. Other abrupt shifts in wetland type or conditions upstream and downstream of the crossing are often observed. When restrictions limit upstream salinity, invasive plant species like common reed (*Phragmites australis*) and cattails (*Typha* spp.) can monopolize large areas of tidal marshes; the runoff from developed uplands can also be a contributing factor. More subtle signs of impaired upstream hydrology include the presence of both high and low marsh plant species on the marsh plain. These vegetation patterns are sometimes not identified until the initial site visit and it is worth considering that they can also occur at some marshes without tidal restrictions.

Anatomy of a Tidal Road Crossing

Tidal Crossing
The road embankment and crossing structure in the tidal environment.

Crossing Structure
Culvert or bridge that conveys tidal flow through the crossing.

Invert
Inside surface of the bottom of a fully enclosed culvert.

Road Embankment
Fill across tidal area to form the approach sections to a crossing structure.

Causeway
Long road embankment that may include semi-permeable or permeable construction. More common lower down in the estuary.

Approach
Roadway section across the tidal area that leads from the upland area to the open tidal crossing structure. Consists of road embankments or causeways.

3.2 CROSSING RISK CONSEQUENCES AND SEA LEVEL RISE

The potential financial, social, and ecological consequences of tidal road crossing design require these structures to perform optimally throughout their entire service life, which may last over 75 years. Selection of an appropriate SLR scenario (Figure 3.2) for the site is fundamental to crossing performance over that period. Crossings designed to accommodate lower magnitude SLR scenarios often result in smaller, less costly structures. As a result, it can be tempting to select a SLR scenario based primarily on short-term costs.

The long-term liabilities associated with selecting an insufficient SLR scenario can include road flooding, higher maintenance costs, premature replacement of the new crossing, impacts to public welfare, and loss of upstream wetland resilience to sea level rise. These circumstances may lead to replacing the crossing before the end of its service life, actually resulting in greater long-term costs. Selecting a SLR scenario early in the project process helps inform the identification of offsite property, infrastructure, and resource uses upstream of the crossing that may be subject to flooding risk as sea levels increase.

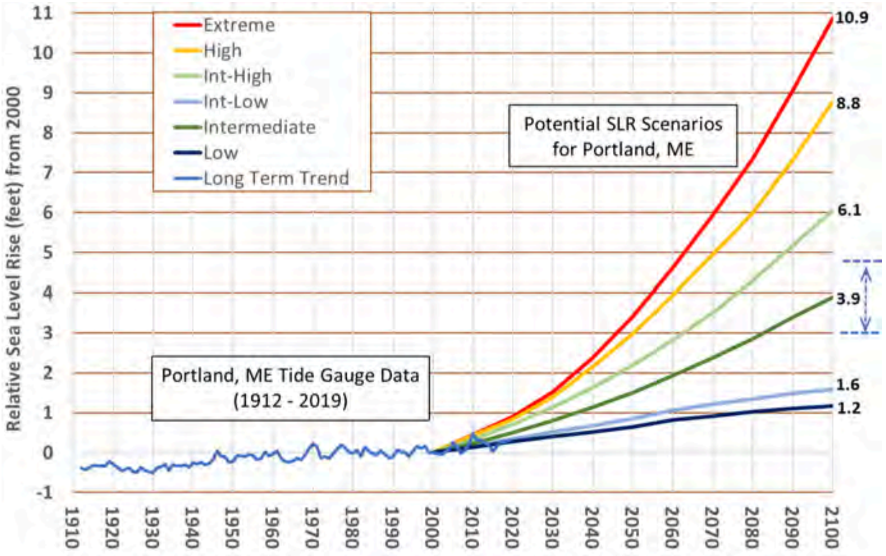


FIGURE 3.2 - Sea level rise trend and projections for Portland, Maine. Graph created by P. Slovinsky, Maine Geological Survey, in 2021. The brackets around the median estimate of 3.9 feet associated with the Intermediate scenario for year 2100 represent the 'likely range' for that scenario. These projections are based on SLR estimates by Sweet et al. (2017), which form the basis for Maine Climate Council recommendations. Updates to these estimates based on 2022 projections (Sweet et al. 2022) will eventually be reviewed for adoption by the Climate Council, and subsequently by CoastWise.

Maine Sea Level Rise Projections

The Maine Climate Council's release in 2020 of the Four-Year Plan for Climate Action recommended committing to manage for 1.5 feet of relative sea level rise by 2050, relative to the year 2000, and 3.9 feet by 2100, which corresponds to the Intermediate SLR scenario. The Climate Council also recommended preparing to manage for 3.0 feet of relative sea level rise by 2050, and 8.8 feet by the year 2100, which corresponds to the High scenario. Guidance for use of the High scenario was specifically aimed at infrastructure with long lifespans and facilities that are critical for public safety and local economies (Maine Climate Council 2020). The SLR scenarios are based on alternative global emissions projections, with corresponding SLR estimates specific to Maine developed by Sweet et al. (2017). Notably, the Climate Council did not recommend the Low or Intermediate-Low SLR scenarios, which depend on reductions in greenhouse gas emissions so large and swift that they are considered unlikely.

It is expected that as the State of Maine continues its efforts to increase coastal resilience, sea level rise projections will be integrated into state law, rulemaking, or agency policy. Recent examples include MaineDOT's announcement to adopt the Intermediate SLR scenario, and Maine Public Law 590, which provides the Maine Department of Environmental Protection and Land Use Planning Commission a basis for reviewing proposed projects in the context of the Intermediate scenario.

Risk-Based Sea Level Rise Scenario Selection

CoastWise adapts the Climate Council's SLR scenario recommendations to a criteria-driven, risk-based decision-making process informed by site characteristics, access needs, and local knowledge (Table 3.2). Essential to this approach is acknowledgement that sea level rise projections are updated periodically. In February 2022, the U.S. Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force released an update (Sweet et al. 2022) to sea level rise scenarios released in 2017 and on which the Climate Council's recommendations were based. As of October 2022, the 2022 update had not been adopted by the State of Maine, but users of the CoastWise Manual should always consider the latest recommendations of Maine climate experts and their federal partners.

The risk-based approach used by CoastWise is adapted from New Hampshire's coastal flood management framework. CoastWise assigns "risk consequence" categories according to unique conditions at each site. The four categories (Low, Medium, High, and Very High) correspond with flood design classes 1-4 defined in the American Society of Civil Engineers (ASCE) Flood Resistant Design and Construction Standard (American Society of Civil Engineers 2015). The ASCE standard provides guidance on the level of protection for varying types of structures and facilities (Federal Emergency Management Agency 2015).

TABLE 3.2 - Framework for determining risk and assigning corresponding sea level rise scenarios, adapted from New Hampshire coastal flood risk guidance (NH Coastal Flood Risk Science and Technical Advisory Panel 2020). Note that the Intermediate SLR scenario is assigned to both the Low and Medium risk consequence categories.

Crossing Risk Consequence:	LOW	MEDIUM	HIGH	VERY HIGH
CRITERIA:				
Value of assets to be accessed	Low	Medium	High	Very High
Ease or likelihood of adaptation	Easy or likely	Moderately easy or somewhat likely	Difficult or unlikely	Very difficult or very unlikely
Public function or safety implications	Few to none	Moderate	Substantial	Critical
Inundation/scour sensitivity	Low	Moderate	High	Very high
Examples of asset types served by the crossing	Residential area (variable risk consequence)			
	Conserved or working lands (agriculture, forestry, etc.), temporary or accessory structures, minor storage	Light commercial, or industrial	School, community center, public gathering facility, care facility, childcare, commercial hub, sensitive storage, or industrial	Hospital, public safety, power generating facility, emergency shelter, drinking water supply, essential communications facilities, hazmat storage
Corresponding Sea Level Rise Scenario:	INTERMEDIATE	INTERMEDIATE	INTERMEDIATE HIGH	HIGH

TABLE 3.3 - Relative sea level rise projections (in feet above 2000 levels) based on project timeframe and crossing risk consequence. Estimates for individual combinations are sourced from Intermediate, Intermediate High, and High scenarios from Sweet et al. 2017. Note that the Intermediate SLR scenario estimates are applied to both the Low and Medium risk consequence cases.

	LOW RISK CONSEQUENCE[1]	MEDIUM RISK CONSEQUENCE[2]	HIGH RISK CONSEQUENCE[3]	VERY HIGH RISK CONSEQUENCE[4]
	CORRESPONDING SEA LEVEL RISE SCENARIO ESTIMATES (FT) Compared to sea level in the year 2000			
TIMEFRAME	INTERMEDIATE	INTERMEDIATE	INTERMEDIATE-HIGH	HIGH
2050	1.5	1.5	2.2	3.0
2070	2.4	2.4	3.5	5.0
2100	3.9	3.9	6.1	8.8

[1] Corresponds with the Intermediate scenario, central estimate (50% probability of exceedance)
[2] Corresponds with the Intermediate scenario, central estimate (50% probability of exceedance)
[3] Corresponds with the Intermediate High scenario, central estimate (50% probability of exceedance)
[4] Corresponds with the High scenario, central estimate (50% probability of exceedance)

The crossing risk consequence categories in Table 3.2 correspond to the range of sea level rise scenarios recommended by the Maine Climate Council (Table 3.3) and will also apply to the selection of design flood elevations in Section 6. The degree of precaution applied in this process of selecting a sea level rise scenario is proportional to crossing risk consequences.

For instance, risk consequences are typically very high for crossings providing access to essential services and critical infrastructure like hospitals or power stations. Consequently, the "Very High" risk consequence would be applied for those crossings. At the other extreme, a crossing may lead to a private woodlot or conservation property where risk consequences are substantially lower. Roads leading exclusively to residences must be judged on a case-by-case basis and might align with any of the risk consequence categories.

In practice, users may find that criteria corresponding most similarly to their crossing may not occur in a single risk consequence column. In this and all cases, documenting why the crossing was assigned to a given risk consequence category is recommended to establish the basis for the selected SLR scenario.

TABLE 3.4 - Comparison of 2017 and 2022 relative sea level rise projections (in feet above 2000 levels) based on project timeframe and crossing risk consequence. **2017 NOAA estimates** (bold text) are based on Sweet et al. 2017. *2022 NOAA estimates* (italicized text in parentheses) are based on Sweet et al. 2022. Note that the Intermediate SLR scenario estimates are applied to both the Low and Medium risk consequence cases. CoastWise does not recommend one set of estimates over the other because the State of Maine has not yet rigorously compared the relative benefits of each.

	LOW RISK CONSEQUENCE[1]	MEDIUM RISK CONSEQUENCE[2]	HIGH RISK CONSEQUENCE[3]	VERY HIGH RISK CONSEQUENCE[4]
	CORRESPONDING SEA LEVEL RISE SCENARIO ESTIMATES (FT) Compared to sea level in the year 2000			
	INTERMEDIATE	INTERMEDIATE	INTERMEDIATE-HIGH	HIGH
TIMEFRAME	Source: **NOAA 2017** *(NOAA 2022)*	Source: **NOAA 2017** *(NOAA 2022)*	Source: **NOAA 2017** *(NOAA 2022)*	Source: **NOAA 2017** *(NOAA 2022)*
2050	**1.5** *(1.2)*	**1.5** *(1.2)*	**2.2** *(1.3)*	**3.0** *(1.4)*
2070	**2.4** *(1.9)*	**2.4** *(1.9)*	**3.5** *(2.4)*	**5.0** *(2.9)*
2100	**3.9** *(3.6)*	**3.9** *(3.6)*	**6.1** *(4.6)*	**8.8** *(5.9)*

[1] Corresponds with the Intermediate scenario, central estimate (50% probability of exceedance)
[2] Corresponds with the Intermediate scenario, central estimate (50% probability of exceedance)
[3] Corresponds with the Intermediate High scenario, central estimate (50% probability of exceedance)
[4] Corresponds with the High scenario, central estimate (50% probability of exceedance)

Once the risk consequence category and SLR scenario are assigned, CoastWise helps users project sea level rise increases in the coming decades (Table 3.3). As an example, for the Very High risk consequence cases discussed above, the corresponding SLR scenario is High, and the SLR estimate for the corresponding planning horizon would be selected using Table 3.3.

We again note here that projections in Table 3.3 are based on the 2017 SLR estimates, which align with the estimates adopted by the Climate Council, and represent the primary recommendation of CoastWise. The more recent 2022 NOAA SLR projections differ from the 2017 estimates for the Intermediate High and High scenarios, especially as the planning timeframe nears 2100 (Table 3.4). The Maine Climate Council is expected to review and consider the 2022 NOAA SLR projections for adoption, which may lead to adjustments to CoastWise recommendations. The final selection of SLR estimates for each individual project will be made based on the factors relevant to each crossing. Users of the CoastWise Manual should always attempt to keep abreast and consider the latest recommendations of Maine climate experts

Identify Risk Early

It is important to understand site conditions that can constrain the feasible range of improvements for a replacement crossing. For instance, buried utilities like water and sewer pipes can limit crossing upsizing and configuration. Wells, houses, roads, public facilities, commercial establishments, habitat for vulnerable species, and different types of resource uses near present or projected high tide elevations require thoughtful consideration when developing preliminary objectives for crossing design and performance.

and their federal partners when making project decisions regarding SLR projections.

Low-Lying Features of Concern

Low-lying features of concern are elements of the coastal landscape that warrant special attention because of their elevation relative to present and projected tides and concerns related to flooding risk. They include private property, resource uses, and built features, in addition to salt marshes and vulnerable species habitats that were degraded by tidal restrictions and other activities.

Low-lying features of concern are sometimes assumed to be inevitable constraints on the degree of crossing upgrades implemented to encourage upstream wetlands to keep pace with sea level rise. Given that the survival of wetlands is at stake, these assumptions should be rigorously tested before engineering design criteria are developed. With due diligence, project teams can often identify creative funding, technical, or landowner engagement solutions that mediate or remove flooding concerns. Regardless of the method chosen to address low-lying features of concern, strict attention to their vulnerability and condition is necessary throughout the project process.

Properties, Infrastructure, and Resource-Use Concerns

Houses, private wells, public facilities, utilities, commercial establishments, and other roads are just a few types of infrastructure that are sometimes situated at elevations close to those of the highest tides. These assets will experience increased flooding risk as sea levels rise, a process that can be hastened at some sites by re-establishing unimpaired tidal exchange. As a result, low-lying infrastructure can constrain the extent to which a restrictive road crossing can be improved. It is imperative to understand early in project evaluation the potential for increasing tidal inundation on private property or in relation to these other features of concern, either at typical or storm tides, at present or future sea levels. Early transparent communication with stakeholders regarding potential changes in inundation is essential for developing solutions that balance tidal restoration and risk considerations.

In contrast to the potential risks associated with tidal restoration, substantial benefits for property and infrastructure may also be realized. For example, poor drainage associated with tidal restrictions can result in prolonged upstream flooding events. Restrictions can also present hazards to downstream areas if storm surge or wave runup in a narrow tidal zone is blocked. In the latter case, the landward pressure of the stormwater piles up against the restriction, locally elevating water surface elevations.

FIGURE 3.3 - This residential development near typical high tide elevations is an example of low-lying infrastructure. Photo by Slade Moore.

Public utilities may be buried in the roadbed above or below the crossing structure, beside the crossing, or overhead. This information is often available from utility districts or the Town in online GIS databases and “as-built” construction plans. Onsite utilities can influence the design process if crossing upsizing requires them to be relocated and doing so is assumed too costly. As with all low-lying features of concern, the assumption that moving utilities is cost-prohibitive should be thoroughly tested before deciding that the new crossing design will need to limit the degree of crossing upsizing, tidal exchange re-established, and added resilience to upstream wetlands.

Understand Changes in Tidal Inundation

Early in project evaluation, it is imperative to understand the potential for increasing tidal inundation on private property or in relation to other features of concern as a result of tidal restoration. Changes in tidal inundation are likely to occur as a result of sea level rise, with or without tidal crossing replacement. Changes in tidal inundation may also occur specifically as a result of tidal crossing replacement. Increasing tidal inundation will be associated with alleviating tidal restriction in many, if not most cases. These changes may occur at typical tides or storm tides, at present or future sea levels.

Increasing tidal inundation should not be viewed as incompatible with crossing replacement. Rather, early transparent communication with stakeholders regarding potential changes in inundation is essential for developing solutions that balance tidal restoration and risk considerations. Where tidal inundation is projected to increase as a result of tidal restoration, property access agreements, property acquisitions, or other measures may be required to enable these projects to proceed.

Changes to tidal inundation can be evaluated to increasing levels of accuracy as project planning steps proceed. At the preliminary site assessment stage, online tools such as the Tidal Restriction Atlas, or project-specific GIS analyses can be used to understand the potential tidal inundation as a result of tidal restoration, at present and future sea levels. It is less practical to understand the current tidal inundation patterns at tidally-restricted sites with these tools. More accurate and precise assessment of tidal inundation for existing and proposed conditions results from hydrodynamic modeling completed during evaluation of project alternatives and project design phases.

Changes to tidal inundation patterns resulting from tidal restoration should be evaluated for typical (e.g., MHHW, HAsT) and storm tides (100-year return period storm, and more frequent storms, such as 5-year, 10-year and 25-year return period storms), at present and future sea levels. The figure below shows an example of assessed changes to typical tidal inundation as a result of tidal restoration at present sea levels.

FIGURE 3.4 - Example of simulated present sea-level HAsT inundation extent for existing site configuration (lighter blue) and proposed conditions (darker blue, barely visible at north margin).

Nearby resource uses that are incompatible with improved tidal exchange can also present challenges to improving tidal restrictions at road crossings. Crossings that create impoundment can be highly valued by communities if the artificially created fresh or “salt” ponds provide conditions supporting firefighting water supplies, freshwater swimming, aquaculture, or subtidal shellfish harvesting.

The Tidal Restriction Atlas can be used as described in previous sections to document potential conflicts among low-lying properties, infrastructure, and resource uses as a result of improved tidal exchange under present and future conditions. Other tools, such as The Nature Conservancy Coastal Risk Explorer can also be consulted. The Coastal Risk Explorer is particularly useful for flood risk screening, including a function to assess how many addresses in a town may be cut-off from emergency services under different sea level rise scenarios. Note that online road crossing viewers other than the Maine Tidal Restriction Atlas may use less complete tidal crossing databases than the Tidal Restriction Atlas. Local community members can often provide valuable information about resource uses.

Vulnerable Species

Managing risk to public welfare under present and future climate conditions is an essential element of the CoastWise Approach. CoastWise also emphasizes the need to support the health and resilience of tidal wetlands and the organisms that use them. CoastWise attempts to achieve this by encouraging the design of road crossings that restore unimpaired tidal exchange to restricted systems, provide full aquatic organism passage, and support fundamental ecosystem processes that keep tidal wetlands resilient to sea level rise.

Habitats for species that are extremely sensitive to changes in tidal hydrology warrant heightened attention when planning to correct tidal restrictions. Rainbow smelt and saltmarsh sparrow are examples of species for which tidal road crossing design can be an important influence on population recovery.

At sites where vulnerable species habitat is present, crossing design alternatives must be developed with an eye toward complementing recovery efforts. Early knowledge of these habitats presents better opportunities for species recovery and helps avoid the need for costly design and permitting changes later in the project process.

In addition to the Maine Tidal Restriction Atlas and Maine Stream Habitat Viewer, websites provided by the National Oceanic and Atmospheric Administration Fisheries Office (NOAA Fisheries), U.S. Fish and Wildlife Service (USFWS), and Maine Department of Inland Fisheries and Wildlife (MDIFW) provide online information about threatened, endangered, and otherwise vulnerable species in Maine. Maine Natural Areas Program can be consulted to identify the presence of rare plants.

Vulnerable Species in the Spotlight

The saltmarsh sparrow and the rainbow smelt are highly vulnerable species that rely on tidal areas with unimpaired hydrology. The saltmarsh sparrow is listed by the IUCN as Endangered. The rainbow smelt has been listed as a NOAA Species of Concern since 2004. Both are Priority 1 Species of Greatest Concern in Maine.

Saltmarsh sparrows and Nelson's sparrows nest a few inches above the salt marsh surface. This makes them extremely vulnerable to changes in marsh hydrology. Marshes with lower-than-normal surface elevations due to tidal restrictions and past agricultural practices often create wetter conditions than sparrow nestlings can withstand. Re-establishing healthy marsh conditions is an essential objective of recovery efforts for these species. Tidal restriction removal is considered an important tool, but it must be carefully planned to best complement other site-specific recovery actions and avoid flooding sparrow nests.

Sea-run rainbow smelt require unimpaired passage between the ocean and spawning areas in streams near the upper limits of tidal influence. Poorly configured road crossings, dams, and fishing nets set for other species can delay or block smelt passage to and from spawning habitat. Climate warming and polluted runoff also represent threats to this vulnerable species. Recovery requires a multifaceted approach, with re-establishment of unimpaired flow at tidal road crossings representing a critically important objective.

Top photo: Saltmarsh sparrow by Bri Benvenuti. Bottom photo: Rainbow smelt by Claire Enterline.

Internet resources are appropriate for quickly screening species of relevance at project sites, but there is no substitute for accessing information directly from species experts. State and federal agency staff are qualified to interpret the information provided on agency websites and can often provide the most recent data. Later in the process, consultations with these agencies are often necessary for acquiring regulatory permits and project funding applications. Early identification of vulnerable habitats and expert consultations also helps identify special data collection needs for field investigations.

Wetland Health Informs Project Objectives

Salt marshes upstream of restrictive crossings may have been impounded, starved of sediment and other materials for decades or centuries, or extensively modified by agricultural ditching and diking. This can result in unusually low wetland surface elevations that are prone to extended tidal inundation uncharacteristic of healthy systems. At some sites, correction of elevation deficits prior to full re-establishment of tidal exchange may be warranted.

Highly Impaired Wetlands

Severe tidal restrictions, past agricultural activities, and other alterations of marsh hydrology can cause considerable wetland health impairment. Some of these wetlands appear to no longer keep pace with sea level rise and have become progressively wetter. One of the most strikingly obvious signs of severe wetland impairment observed using satellite or aerial imagery is the presence of extensive pondlike conditions. In salt marshes, expansive areas of shallow pooled water, vegetation loss, ditching/diking, and dominance of low marsh versus high marsh acreage are signs of impairment that can be readily observed using imagery.

Salt marshes with the worst impacts may have wetland surfaces that are lower upstream of the crossing than downstream. If available, high resolution lidar can be useful for initial screening for wetland elevation deficits where review of imagery indicates signs of severe impairment. Refer to the Rapid Site Assessment section “Review Available Elevation Data” for more information on lidar.

Depending on the degree of impairment, rapid re-establishment of tidal exchange at a road crossing can lead to excessively wet upstream conditions that cause further damage. Some sites may require re-establishment of upstream marsh plain elevations and conditions before fully restoring tidal exchange at the crossing site. Assessments to recognize wetlands in this range of the impairment spectrum are evolving, with expert advice available through the network of CoastWise participants.

Useful Links

Maine Department of Transportation Public Map Viewer

Maine Tidal Restriction Atlas
Maine Coastal Program, Maine Department of Marine Resources

Coastal Risk Explorer
Maine Chapter of the Nature Conservancy

Maine Stream Habitat Viewer
Maine Department of Inland Fisheries and Wildlife, Maine Department of Marine Resources

Beginning with Habitat
Maine Department of Inland Fisheries and Wildlife

USFWS Information for Planning and Consultation (IPAC)

NOAA Fisheries Section 7 Mapper for Listed Marine Species

NOAA Fisheries Essential Fish Habitat Mapper

Site History

A knowledge of site history provides important context for establishing objectives related to upstream wetland resilience. At some sites, crossings were built on dams installed to establish tide-driven mills or ice ponds. Ditch and dike networks were often constructed in salt marshes to support agricultural practices and to some extent mosquito control. Earthen dikes were also built across tidal wetlands to control tidal flow at railroad rights-of-way. In some cases, main channels were rerouted (Figure 3.5). These modifications to upstream wetland hydrology can create overly wet conditions and or considerable elevation deficits. To avoid irreparable impacts to marshes impaired in this way, special techniques to restore upstream wetland elevations and drainage patterns should be investigated and, if necessary, implemented before re-introduction of full tidal exchange at the crossing.

The first step in reconstructing site history involves assembling available information sources to systematically develop an understanding of changes at the site over time. Important observations include changes to the roadway, crossing structure, other built features, site drainage, channel alignments, and wetland characteristics. Historical topographic maps, nautical charts, satellite imagery, and aerial photographs can indicate the degree of change over time. Local knowledge of citizens, old site photographs, locally produced maps, and published town histories are often excellent sources of historical information. Good documentation of findings and data sources consulted is important to subsequent phases of the project (Table 3.5).

Free mapping tools such as Google Earth or Google Maps provide access to high-quality aerial and/or satellite photography over multiple periods. The NOAA Digital Coast data clearinghouse and the Maine GeoLibrary provide access to verified geospatial data including elevation, imagery, hydrography, land cover, and much more. Additional sources of historical mapping and aerial imagery include the U.S. Geological Survey (USGS) EarthExplorer, the USGS Historical Topographic Map Explorer, and the commercial Historic Aerials web-based service. The Maine Historical Society's Maine Memory Network website is also an excellent source of site photos, commissioned maps, and other items useful to constructing a historical context for project sites.

Useful Links

[Google Earth]

[Maine GeoLibrary]

[NOAA Digital Coast]

[USGS Earth Explorer]

[USGS Historical Topographic Explorer]

[Historical Aerials]

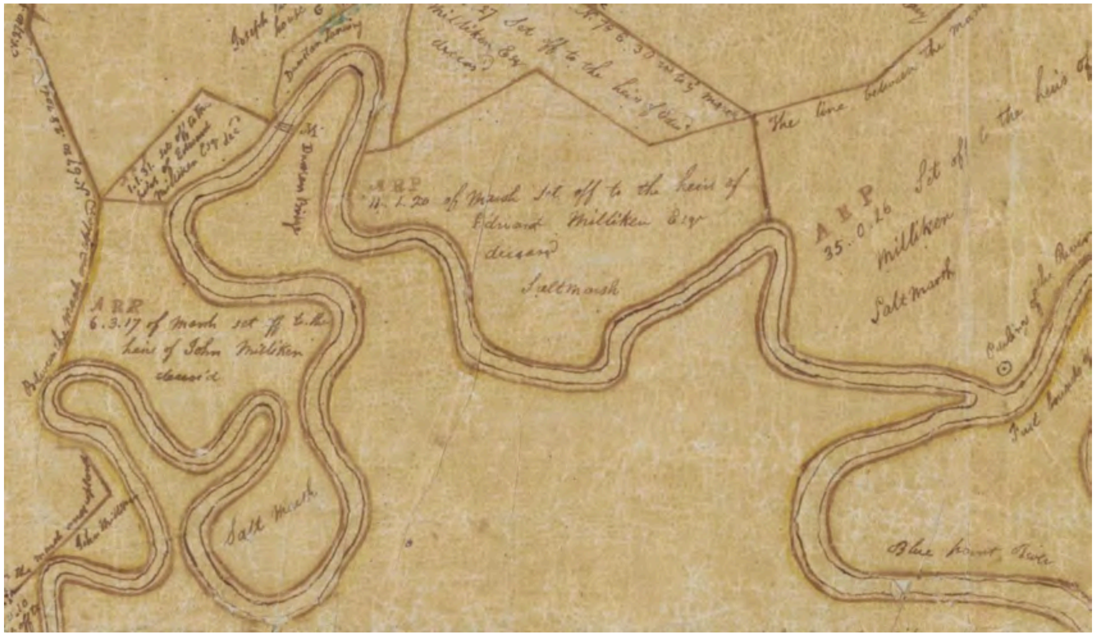


FIGURE 3.5 - Detail of a map documenting conditions before extensive channel modifications at Cascade Brook, Scarborough. The map was used extensively by diking companies to establish their rights to control water on the marsh.

TABLE 3.5 - Example of a site history summary table.

DATE	EVENT	ACTIVITY	DATA SOURCE
1860	Settlement	Single cabin noted at east margin of site	GLO Notes
1882	Railroad	Rail grade constructed at the south margins of the wetland	GLO Notes
1912-1914	Historic highway	Columbia River Highway constructed between the railroad and the valley slopes	National Scenic Area Interpretive History, 1930 aerial
1940s-1950s	Land clearing	Much of the site had been cleared	1948, 1956 aerials
1940s	Creek diversion	Lower Horsetail Creek and Eastern Slough diverted to new confluence with Oneonta Creek in preparation for interstate highway construction.	1948 aerial
1940s-1950s	I-84	Interstate Highway 84 construction along northern margin of site	1948, 1956 aerials
1950s-1960s	Gravel mining	Gravel excavated from Oneonta Creek and fan, and Lower Horsetail Creek for highway construction	1956, 1971 aerials

Ownership Patterns in the Crossing's Upstream Area of Influence

Understanding land ownership within the crossing's potential area of upstream influence is important for several reasons. First, access to property for data collection, construction, monitoring, and other project activities requires landowner consent. It is also necessary for identifying landowners who have an interest in the project's influence on upstream tidal exchange under present and future conditions. This includes the potential for increased tidal inundation through eliminating tidal restriction.

The potential area of upstream influence under present conditions starts at the crossing structure and extends upstream as far as the limit of the mapped or observed Highest Astronomical Tide (HAsT). The crossing's future potential area of influence can be estimated by observing the mapped SLR scenario selected by the Project Team. Both present and future areas of influence can be estimated using the Tidal Restriction Atlas. Note that tidal flooding conditions associated with coastal storm surges can periodically lead to even greater areas of inundation.

Provisional assessments of properties that could be subject to tidal flooding now and in the future can be executed using various sources of information. The most current information is usually available directly from the Town Office of the relevant municipality. Web resources, which are ever changing, can also be used. Some towns publish tax maps online. Maine property parcel mapping for organized and unorganized townships is available from ArcGIS online and can be loaded into the Tidal Restriction Atlas. These are then cross referenced with town ownership data using map and lot numbers to establish a means to contact landowners.

Climate Resilient Road Crossings

The concept of climate resilience as a goal for infrastructure design has gained considerable prominence. For tidal road crossings, climate resilience implies the ability to accommodate coastal storms, flooding, long-term sea level rise, and changes in uses, while providing optimal performance during its anticipated service life. This also includes the deliberate integration of design features that avoid damage to adjacent infrastructure and property resulting from normal use or a crossing failure. Lastly, climate resilient crossings also support the process of recovery for impaired natural systems like tidally restricted wetlands so they are healthy enough to adapt to future conditions.

3.3 RAPID SITE ASSESSMENT

The Rapid Site Assessment involves one or more site visits to answer important questions about the crossing and site conditions that the Desktop Analysis cannot. It also tests assumptions generated during the desktop investigations. The Rapid Site Assessment is performed by experienced personnel,

FIGURE 3.6 - Low-tide observations and photo documentation are essential elements of Rapid Site Assessments. Photo by Slade Moore.

TABLE 3.6 - Minimum recommended data types collected during the Rapid Site Assessment.

OBSERVATION	TIMING	MEASUREMENT OR OBSERVATION
Crossing type and condition	Low tide	Structure type, shape, material Presence of a tide gate, internal baffles, or other flow control Structural wear and damage, voids, piping, settling, blockage, or other deficiencies Geological characteristics, such as the presence of bedrock and bed materials Indications the crossing was built above an older structure
Crossing structure measurements	Low tide	Width Height Height of inside surface of inlet and outlet bottom (invert) above the streambed
Roadbed/ embankment	Low tide	Road surface width Height above wetland surface Location of obvious low points and flooding Cracks, holes, erosion, slumping, and possible causes Distance between wrack line and 1) road surface and 2) top of crossing structure Length, if not already measured using imagery
Scour pools	Low tide	Signs of substantial eddies, whirlpools, or flow jets Dimensions, if not already measured using imagery
Channel alignment	Low tide	Alignment upstream or downstream of the crossing Markedly different channel characteristics immediately upstream or downstream of the crossing, indicating structure influence
Channel dimensions	Low tide	If not already reported using imagery, calculate average upstream and downstream channel widths outside the area of crossing-related scour
Natural community condition	Low tide	Differences in upstream versus downstream wetland type, dominant plant community, or condition Relative coverage of species indicative of altered salinity, such as cattail (*Typha* spp.) and common reed (*Phragmites* spp.).
Inundation and drainage	Low and high tide	Differences in upstream versus downstream wetland flooding and drainage patterns Significant pooling or ponding Substantial eddies, whirlpools, or flow jets at the crossing
Infrastructure	Low tide	Signs of overhead, buried, or attached utilities Other low-lying infrastructure or current uses in the area, particularly upstream
Photographs	Low and high tide	Upstream and downstream views from the road Views of the roadway approaches from the crossing Views of the inlet and outlet from the wetland/stream Repeat photos of the inlet, outlet, and stream/wetland at mid and spring high tide

including CoastWise Technical Partners, consulting engineers, and other trained people.

Fieldwork Preparation

Assemble Site Mapping

Organizing relevant digital spatial data in a GIS database helps facilitate planning for field activities. As discussed above, this typically includes time series of topographic maps, satellite imagery, and aerial photography.

Understanding present and projected patterns of tidal inundation and drainage require distinct types of data. These include terrain data based on lidar and bathymetry, hydrography data including stream and waterway flowlines and watershed boundaries, sea level rise mapping, FEMA floodplain extents, and mapped highest astronomical or highest annual tide extents.

Ecological mapping should minimally include data describing natural communities, wetlands, and habitats of interest. Private and public property boundaries are also essential. If the staff capacity to work with GIS is not available, CoastWise Technical Partners, engineering consultants, or other trained professionals can help with this step.

Review Available Elevation Data

Elevation data are used to create a three-dimensional (3-D) digital representation of the landscape, including wetlands, stream channels, surrounding uplands, and other elements of interest in a project's area of influence. These are used to perform tidal hydrodynamic modeling and analyses relying on modeling, like those focused on crossing performance, sea level rise, and management of risk to public welfare, property, resources uses, and wetland resilience.

Elevation data used for these purposes are typically collected by airborne Light Detection and Ranging (lidar) systems and ground survey techniques. In some project areas, bathymetry data or merged lidar and bathymetry data (USACE 2019) may also be available from the NOAA Digital Coast website. The applicability of the bathymetry data may vary according to site characteristics and analysis needs.

Lidar data typically are used to supplement ground survey data. The rapid collection and dense coverage of data points made possible by lidar makes it an extremely efficient tool. Lidar data are collected by government agencies

Lidar Data Error Assessment and Correction

Not all lidar data are equally accurate. Lidar elevation error can be caused by the lidar system itself during data collection, environmental features, and a combination of both. Error can be higher in marshes due to dense vegetation, surface water, and the dark, saturated soil beneath. Impacts of these inaccuracies on the crossing design can be controlled by collecting ground survey data in strategic locations throughout the marsh system and using it to adjust the lidar data.

Vertical adjustments are sometimes performed using a single-value global offset, but a more robust solution can be generated by applying spatially stratified adjustments that correlate with the observed distribution of errors. Often, this stratification may be correlated with different vegetation or land cover types.

Adjustments to the data must be accomplished by an experienced spatial analyst using GIS or CAD data manipulation tools. See the case study example in Section 4.6 for additional detail.

and widely available in the coastal zone at no cost to users. Due to the scale of these efforts, the data have varying levels of accuracy. Lidar data collected for site-specific projects may require higher levels of accuracy. Users should review published estimated accuracies and the timing of collection before applying lidar data to a project.

Regardless of reported accuracy estimates, lidar data must undergo an error assessment and, if needed, calibration before use in a project. These procedures rely on comparisons of the lidar elevations with elevations from representative ground survey points in the project area (see Section 4.6.)

Field Parameters and Assessment Timing

A list of parameters to assess is provided in Table 3.6. It is best to perform the rapid assessment during spring tides, the time of month when the difference between high and low tides is greatest. This allows you to observe important features of the crossing, flooding and drainage patterns in adjacent wetlands, and how wetlands might have responded to the crossing.

Repeat observations of flooding and draining patterns at different points in the tide cycle can yield important insights. For example, low-tide observations can provide the most conclusive determinations of crossing configuration, condition, and perch. Observations closer to high tide can show the presence of highly pronounced upstream-downstream water level differences, the distance between high tide and the top of the crossing and road surface, and circulation patterns of interest, such as dangerous whirlpools. Use of trail cameras with a time lapse function is also helpful for documenting water level changes.

Field Safety

Above all, the safety of staff engaged in field activities is a paramount consideration and any off-road assessments should include two people if possible. Most sites have locations that are slippery, steep, unstable, rife with tripping hazards, and present a drowning risk. Conditions at tidal road crossings are extremely dynamic.

Water levels and current velocity can fluctuate rapidly. Entering the water near some crossings presents a heightened risk of drowning due to accelerated flow, vortices, and a lack of interior head space in the structure.

Field staff should not cross through an enclosed culvert, and it can be particularly dangerous to walk in some fine sediments which create a risk of entrapment. During warmer months, other factors to consider include heat injury, dehydration, and insect disease vectors.

The timing of high and low tide at crossings is often later than predicted for the nearest tide station, particularly if there are tidal restrictions downstream or if the crossing is located far upstream. Offsets of one to two hours are common for sites located in upper reaches of estuaries. Unless automated camera monitoring is employed at the site, a series of "drive-by" observations of conditions can help determine the tide offset between the nearest tide station and the site. Nearby tide prediction stations can be identified using NOAA's Tides and Currents website.

In addition to the data collection recommendations in Table 3.6, personnel are encouraged to review the Maine Tidal Crossing Rapid Survey Protocol. The New Hampshire Tidal Crossing Protocol (Steckler et al. 2017) and North Atlantic Aquatic Connectivity Collective protocol (Jackson 2019) provide more extensive methods that offer additional data collection options.

As in all fieldwork, the safety of personnel is paramount. Tidal systems are extremely dynamic. Field crew should work in teams, assess conditions each day, and adjust plans as needed to minimize risk.

3.4 PRELIMINARY SITE ASSESSMENT SUMMARY AND PROVISIONAL OBJECTIVES

Following the Desktop Analysis and Rapid Field Assessment, it is important to document and interpret in a dedicated report the information learned so far. This is useful for planning subsequent project phases and communicating to project partners, stakeholders, technical providers, and funders. The report can be broadly organized into topics such as site characteristics, low-lying features of concern, current crossing condition, and provisional objectives.

Projects vary considerably in location, size, setting, and risk to public welfare and ecological health. Yet they all share a common, overarching goal when CoastWise is applied:

> **Planning, design, and construction practices should result in safe, climate-resilient, ecologically supportive and cost-effective tidal crossings.**

The Project Team develops provisional crossing performance objectives that are appropriate for the site, based on what they learned from the Preliminary Site Assessment (Table 3.7). Achieving the highest-priority objectives at a particular site can sometimes limit the extent to which others are achieved.

TABLE 3.7 - Categories of crossing performance objectives relevant to most projects, adapted from the New Hampshire Tidal Crossing Protocol. Examples of provisional objectives presented here represent optimal levels of performance. They are framed within the context of present conditions and those expected throughout the service life of the proposed structure.

OBJECTIVE CATEGORY	PROVISIONAL OBJECTIVES The proposed crossing will:
Basic Crossing Expectations	Integrate safety, performance, and durability features consistent with established infrastructure practices and user's expectations.
Crossing Structure Resilience	Be climate-ready for the selected planning horizon and sea level rise scenario. This includes the ability to meet design criteria regarding future flow capacity, prevention of overtopping, structure stability, and other factors.
Low-lying infrastructure and resource uses	Not cause undesired tidal flooding or risk of erosion beyond what would be expected by the present crossing.
Wetland Health and Resilience	Re-establish unimpaired tidal exchange, enable marsh migration
Aquatic Organism Passage	Allow unhindered bidirectional movements of native species.
Vulnerable Species and Impaired Wetland Risk	Consider protection of severely impaired wetlands and vulnerable species while encouraging overall wetland resilience
Cost-Effectiveness	Provide the best performance of all objectives for cost and longevity during the established planning horizon.

Objectives Development Is a Participatory Process

Developing objectives for a tidal road crossing involves a series of decision-making points based on an understanding of the site. CoastWise encourages road owners to clearly address important topics like the proposed crossing's performance under selected sea level rise scenarios, local tolerance for road and property flooding, support for wetland and species resilience, and other factors that are relevant during the expected service life of the new structure. Tidal road crossings are usually expensive, long-lived types of infrastructure, so these discussions should include the participation of local people and other stakeholders who can best inform the process.

Planned Tidal Crossing Retirement as a Project Alternative

In some cases, projections of new or worsening roadway flooding caused by sea level rise signal that the costs of road repair, reconstruction, and intrusion into adjacent wetlands will mount progressively in the future. In these situations, removal of the road crossing, where conditions allow, may provide the best means to better allocate infrastructure investment and achieve upstream wetland resilience potential.

For instance, where an upstream residential area is situated near present high tide elevations, rapid re-establishment of full tidal exchange would seem to present unacceptably heightened risk to public well-being. However, even with apparent conflicts, creative solutions for risk management should always be explored before ecological objectives are abandoned. Regardless of the provisional objectives selected, they will be re-evaluated and refined as the Project Team's understanding of site conditions and feasibility improves. Ultimately, the Project Team uses refined objectives to directly inform the development of engineering design criteria.

3.5 TYPICAL ROLES AND TIMELINES

While many of the tasks for the Preliminary Site Assessment can be accomplished by trained town staff, technical assistance is likely necessary. CoastWise Technical Partners, consultants, and other trained staff can provide a variety of project planning and technical support. Typical timelines will vary with the size and complexity of the crossing and the time and resources available to complete the work. The Preliminary Site Assessment for a typical crossing on a town road could be completed over a one- to two-week period that would include one or more days each of Desktop Analysis (depending on the complexity of the site) and Rapid Site Assessment.

Timing of the Preliminary Site Assessment will vary. The Desktop Analysis can be conducted any time of the year. Field observations during the growing season are recommended. Late summer plant identification on tidal marshes maximizes species identification effectiveness and allows site observations with the least influence of freshwater inflow. This timing will also allow the sites to be observed with the least influence of freshwater inflow.

Timing of assessments is also influenced by the availability of technical support and funding. Early coordination with CoastWise Technical Partners and other resource providers helps ensure their contributions to your project make the most impact. The Preliminary Site Assessment should be completed as early in the project process as possible to take advantage of potential funding opportunities as they become available. It is also advisable to complete it two to three years before the desired start of construction. More complex projects may take longer.

At a minimum, preliminary objectives for the project must meet regulatory requirements and the objectives development phase is a good point to involve representatives from the regulatory community. The CoastWise Approach tends to exceed regulatory requirements, reinforced through objectives based on judgments having long-lasting impacts on the community and the environment. In doing so, the CoastWise Approach encourages a transparent, participatory stakeholder process. This process will vary from site to site, but many projects involve representation from diverse community members, especially where infrastructure, properties, resource uses, and ecological concerns overlap.

3.6 ADDITIONAL RESOURCES

Return the Tides: Tidal Hydrology Restoration Guidance Manual
Comprehensive resource on restoration of habitats affected by tidal restrictions, including typical considerations throughout the project, a toolkit, project examples, and other useful aids

Identification of Metrics to Monitor Salt Marsh Integrity on National Wildlife Refuges in Relation to Conservation and Management Objectives
Background, examples, and methods for using structured decision-making to inform how to approach a salt marsh restoration project, incorporate differing objectives from multiple partners, and complete and monitor a project using these objectives to guide the process

New Hampshire's Tidal Crossing Assessment Protocol
Field-based protocol for assessing tidal crossings for restriction status and prioritizing tidal crossing replacement

NAACC Aquatic Passage Protocol for Tidal Crossings
Field-based protocol for assessing aquatic organism passage at tidal crossings

NOAA Tides & Currents
Useful to identify current tidal elevations or data at tide recording stations in Maine (Wells,

Portland, Bar Harbor, Cutler and Eastport) and tide predictions in the vicinity of a tidal crossing. May also allow interpolation of preliminary estimates of tidal elevations at the site itself.

NOAA Storm Surge Hazard Maps
Storm surge hazard maps with indications of potential inundation and depth over land for various categories of hurricane along the eastern seaboard for current sea levels

USACE Sea-Level Curve Calculator and NOAA Sea Level Viewer
U. S. Army Corps of Engineers (USACE) tool can be used to calculate sea level rise in the future for long-term NOAA tidal gauges to provide an overview of predicted regional trends using a variety of sea level projections. NOAA sea level rise viewer estimates future inundation extents, high tide flooding, vulnerability, and other mapping. Supplemental information to the online viewers discussed in more detail elsewhere in the CoastWise guidelines.

FEMA Map Service Center
Current FEMA-mapped floodplains in the vicinity of the site

National Water Information System (NWIS) and StreamStats
USGS freshwater inflow data and estimates from existing stream gauges and for ungauged systems. Note that the use of the StreamStats system is limited to the freshwater, non-tidal systems with minimum watershed area of three square miles. These sources are helpful if the site has notable non-tidal inflow.

4 DETAILED FIELD INVESTIGATION

Photo by Slade Moore

THE DETAILED FIELD INVESTIGATION continues the theme of understanding characteristics of the project area but involves more detailed field measurements and interpretation of results. Data collected during this phase directly support the following aspects of the project:

- Management of risk to low-lying features of concern
- Refinement of crossing performance objectives
- Development of design criteria
- Tidal hydrodynamic modeling simulations needed to predict crossing design performance
- Development of detailed designs
- Post-construction monitoring

The Detailed Field Investigation is most often completed by consultants or other qualified technical providers, sometimes with the assistance of CoastWise Technical Partners. The following section provides an overview of the types of data needed to advance a project. Data needs are discussed in further detail in Appendix A.

Modeling to Reduce Risk

With accelerated sea level rise and associated risks, the best tidal crossing design investments address resilience needs of wetlands and the local community. Managing the risks effectively demands design methods that provide a higher level of certainty that crossing performance will meet project objectives. For most projects, tidal hydrodynamic modeling is necessary to provide that level of confidence but requires collection of precise and accurate water level and elevation survey data.

4.1 FIELD DATA COLLECTION PLANNING

Planning of the Detailed Field Investigation is informed by results and data gaps identified during the Preliminary Site Assessment. Activities during this project phase typically collect field data types falling into four essential categories: 1) natural community assessments and mapping, 2) elevation surveys, 3) tidal hydrology monitoring, and 4) geotechnical investigations. Investigations of risk to low-lying features of concern such as public and private property and infrastructure, wetlands with elevation deficiencies, and imperiled species habitats are nested within each of the first three categories.

At a minimum, the spatial scale of field data collection typically extends upslope of the crossing to the estimated or observed Highest Astronomical Tide (HAsT) level under present conditions. If there is concern with upstream flooding or heightened interest in habitat conversions related to sea level rise (SLR), data collection should extend to the future HAsT corresponding to the project's selected SLR scenario. The downstream limit of data collection extends at least some distance beyond obvious signs of channel or habitat alteration due to the (usually) restrictive crossing, or to downstream tidal restrictions, specific habitats, or other features of interest.

For more information about specific data collection protocols, please see the Appendices or contact CoastWise Technical Partners or other providers for assistance.

4.2 NATURAL COMMUNITY DATA NEEDS

With the need to encourage the resilience of tidal wetlands, CoastWise emphasizes understanding basic characteristics of adjacent natural communities, including signs of vulnerability. Among individual projects, objectives selected will vary to some extent, but at a minimum all projects should attempt to validate existing maps of natural community types or generate their own mapping. Characterizing the wetland's condition is the next important step for predicting natural community responses to different crossing design alternatives and avoiding further damage to severely compromised wetlands.

Consultations with experts on tidal habitats and species can help confirm the data collection needs and approach for each individual project. Natural community features assessed and monitored for tidal crossing projects include:

- major natural community/wetland type boundaries,
- wetland condition (see "Field Signs of Tidal Wetland Impairment" box), including specialized assessments to determine the need to correct elevation deficits and loss of marsh vegetation, and

- habitats for vulnerable species, such as sea-run fish like rainbow smelt or highly sensitive bird species, like saltmarsh sparrow or Nelson's sparrow.

Field Signs of Tidal Wetland Impairment

When present over relatively expansive areas, the conditions listed below indicate notable wetland impairment. Evaluation and interpretation of these conditions often requires experts.

All Wetland Types

- Permanently flooded conditions

Salt Marsh

- Overly soft and/or "soggy" upstream conditions compared to downstream areas
- Large pools relative to marsh acreage
- Pit and mound topography
- Unvegetated areas at high marsh elevations
- High marsh colonization by low marsh vegetation (i.e., *Spartina alterniflora*), or invasive species such as cattails or *Phragmites*
- Networks of ditches, embankments, and other marsh surface alterations

4.3 ELEVATION SURVEY DATA NEEDS

Elevation surveys allow an understanding of where features of interest reside in the present and projected tidal frame, relative to each other. Elevation data are collected for topography and bathymetry, the crossing and other structures that control tidal exchange, the roadway, and any features thought to be low-lying features of concern, such infrastructure and habitats of sensitive species.

These data are collected with land survey methods having high levels of precision and accuracy, which is required to confidently manage risk to private and public property and to address the sensitivity of tidal environments to small changes in water elevation. Additional guidance about survey data needs and data collection is found in Appendix A.

Survey Control

Plan for appropriate survey control benchmarks and reference datums as the basis of ground survey work. Both MaineDOT and the National Geodetic Survey (NGS) maintain online databases of established survey control points; these resources are included below. Large local landowners such as the U.S. Fish and Wildlife Service or the National Wildlife Refuge system, forest managers, municipalities, or preserve managers may also be sources of established survey control points that are not published.

In locations where established survey benchmarks are not available, new control benchmarks can be established by a land surveyor, engineer, or other provider experienced and knowledgeable in land surveying methods. As of 2021, the common vertical reference datum is the North American Vertical Datum of 1988 (NAVD 1988). This datum is scheduled to be replaced soon in the National Spatial Reference System.

Also plan for appropriate horizontal survey reference systems. Presently, the most common horizontal reference system in Maine is the Maine State Plane Coordinate System based on the North American Datum of 1983 (NAD83), which organizes the state into east and west zones. This system will also be replaced soon and will result in east, central, and west zones across the State. The Maine DOT has already adopted use of the three zone system, underscoring the need to confirm the appropriate coordinate system for each site prior to field data collection. The MaineDOT online viewer can be used to determine the zone in which a project site is located.

Land Survey Accuracy

A number of organizations have published surveying and mapping accuracy standards, such as the American Society for Photogrammetry and Remote Sensing (ASPRS), the American Society of Civil Engineers (ASCE), the American Congress on Surveying and Mapping (ACSM), and the American Land Title Association (ALTA). Typically, these guidelines assign accuracy standards to multiple classes of surveying and mapping tasks. Common expectations for closure of control points may be 0.03 feet or less, and for general topography, common accuracy expectations may range from 0.05 to 0.1 feet, or less.

Ground Survey

After local vertical control is established, the ground survey is executed. The following list provides typical minimum survey needs for a single road crossing. Ideally, the spatial extent of survey for features of interest extends as far upslope/upstream as projected tidal influence under the selected sea level rise scenario. This includes other crossings likely to influence or be influenced at the project site and low-lying features of concern identified earlier in the process. Surveys will collect elevations for the following features:

- Inside surface of crossing structure bottom (invert) and top (crown), low and high chords, and adjacent wrack lines if present
- Road surface shoulders, centerline, and low points
- Stream channel longitudinal profile
- Stream channel cross sections
- Upstream and downstream wetland surface cross sections from upland to upland through representative community types, if high resolution lidar data are unavailable or if a high degree of familiarity with wetland conditions is warranted, particularly at tidal marshes
- Wetland surface points for lidar data error evaluation and calibration
- Water level station vertical reference points, collected during installation and removal
- Low-lying features of concern, like infrastructure, resource uses, and vulnerable species habitats

The Gulf of Maine Council on the Marine Environment stream barrier removal monitoring guide and the New Hampshire tidal crossing assessment protocol provide guidance for survey of cross sections, longitudinal profiles, and crossing structures (Collins et al. 2007, Steckler et al. 2017).

Useful Links

[NGS datums replacement]

[NGS control database]

[MaineDOT control database]

FIGURE 4.1 - Real-time kinematic GPS receivers are one of several tools that are typical of elevation surveys. Photo by Slade Moore.

Elevation Survey Basics

Modeling used for road crossing engineering designs requires precise elevation data representing the crossing structure, tidal wetland, nearby uplands, and low-lying features of concern, if any. The first question is whether you can tie into existing elevation benchmarks or need to establish your own. Once that is decided, the choice of survey instruments is next.

Many field workers opt for use of real-time kinematic differential GPS (where satellite coverage and clear skies allow), total station surveying tools, or a combination of both for selected areas. Although the tools may vary, use as consistent an approach throughout the survey as possible. Collect elevations for the features that are most important to project objectives, but at a minimum those described in the CoastWise Manual.

4.4 TIDAL HYDROLOGY DATA NEEDS

Continuously recorded water level data is collected upstream and downstream of crossings to measure localized tidal patterns. These data are essential for characterizing present conditions and for developing hydrology projections corresponding to crossing design alternatives. For sites where adequate resources and expertise are available and project objectives warrant their inclusion, simultaneously collected salinity data, other water quality parameters, and sediment monitoring can also be useful.

Hydrology and hydraulics (H&H) data requirements must be clearly defined at this stage to avoid having to repeat the data collection effort, which is costly and time-consuming. Depending on the tidal environment, a range of conditions might need to be observed, such as spring/neap tides, storms (coastal and/or rainfall), and seasonal runoff.

FIGURE 4.2 - Water level monitoring instruments installed in a representative channel reach of a salt marsh. Photo by Slade Moore.

Effective data quality control and analysis are essential because field observations provide the foundation for subsequent modeling and other analyses. Section A-4 in Appendix A provides more specific guidance on field data considerations and requirements. Tidal hydrology monitoring protocols are provided by the National Park Service and the Casco Bay Estuary Partnership quality assurance plan (Curdts 2017, Craig and Bohlen 2018). Equipment and deployment methods vary, but most projects presently use pressure sensors for water levels. Typical tidal hydrology data requirements include the following:

Water Level Logger Planning

- Deploy loggers for at least a full spring tide and a full neap tide phase, typically equivalent to a minimum of a full 29.6-day lunar cycle.
- Configure loggers so they record data in sync with NOAA tide stations at six-minute intervals starting at the top of the hour.
- Data collected during the highest tides and high freshwater flow events help form a more complete understanding of site hydrology.
- Set water level and barometric pressure (if used) loggers to collect data at the same intervals (typically six minutes starting on the hour).
- At a minimum, survey logger elevations at the time of deployment and retrieval to determine if the logger shifted.
- Surveyed water level elevations at the logger site during deployment, retrieval, and in-between is used to post-process collected data and helps validate logger accuracy.

Water Level Logger Locations

- Install loggers on stable mounts where flow patterns, sediment movement, debris in the water, or other factors are unlikely to cause the loggers to move.
- Loggers are installed upstream and downstream of the crossing, but outside of scour pools, other disturbed areas, or features that could cause local anomalies in water level (Figure 4.2).
- Additional loggers placed farther upstream and/or downstream can improve model calibration, characterize the influence of nearby tidal crossings or other features, and refine flooding projections at low-lying features of concern.
- If used, install barometric pressure sensors at a shaded site above water, typically in an adjacent upland.

4.5 GEOTECHNICAL DATA NEEDS

Geotechnical investigations identify conditions beneath the roadbed and support the detailed design of crossing structure foundations and footings (see Section 7). They are important for assessing the feasibility of potential crossing configurations early in the design process, especially when shallow ledge or particularly weak soil conditions appear present. Geotechnical data are collected using test pit excavations, soil borings, or non-invasive techniques such as ground penetrating radar, where applicable.

4.6 DATA POST-PROCESSING

Tidal Hydrology

Engineers or other qualified individuals post-process water level data. Pressure measurements are converted to water depths using the collected atmospheric pressure data (if vented water level loggers were not used; see Appendix A) and water density. Water depths are converted to water surface elevations by using the surveyed reference elevations or the water level sensor elevations.

Continuously recorded water surface elevation data can be used to investigate specific characteristics of tidal restrictions like asymmetries between upstream and downstream tide elevations. Water level data also help provide an understanding of wetland hydroperiod, which is the frequency and duration that the wetland surface is inundated by the tides, and an important consideration for salt marsh health and resilience. Water level data are used to generate local tidal datums (e.g., Mean High Water, Mean Higher High Water) for the observation period and to establish time series of tide levels for modeling applications. Tidal datums can be calculated using the [NOAA Tidal Analysis Datum Calculator](#).

If tidal datums are calculated over a full lunar cycle, they should be reasonably representative of local tidal patterns. They will, however, differ from datums calculated based on the most recent nineteen-year national tidal datum epoch (NTDE), which is the basis for tidal datums published for each long-term NOAA recording station and currently spans the period 1983-2001 (National Ocean Service 2000). The difference between local and published datums is due to observation period length, but also seasonal and longer duration trends, and occurrences of isolated hydro-climatic events.

Tidal Datums

Tidal datums are elevation references that describe the expected tide water level at a certain phase of the tide cycle and are a useful frame of reference in project planning. For project applications, tidal datums can be calculated at a project site if tidal water level data has been collected for at least a full lunar month (29.6 days). NOAA recording stations publish their tidal datums based on a longer period of record, referred to as the National Tidal Datum Epoch (NTDE), defined below along with other commonly used tidal datums.

Mean Low Water (MLW)
The average of the low tide levels recorded over the observation period

Mean High Water (MHW)
The average of the high tide levels recorded over the observation period

Mean Tide Level (MTL)
The average of the MLW and MHW over the observation period

Mean Higher High Water (MHHW)
The average of the higher of the high tide levels of each tidal day recorded over the observation period

Mean Lower Low Water (MLLW)
The average of the lower of the low tide levels of each tidal day recorded over the observation period

Highest Annual Tide (HAT)
Highest tide predicted to occur on an annual basis, typically estimated by Maine DEP based on NOAA's published tide predictions

Highest Astronomical Tide (HAsT)
Highest astronomical tide predicted to occur over the NTDE

National Tidal Datum Epoch (NTDE)
The specific nineteen-year period adopted by the National Ocean Service as the official time segment over which tide observations are utilized to obtain official tidal datums at NOAA stations. This duration is used to account for periodic trends in sea level. The current NTDE spans the period 1983-2001.

To understand the relative difference between the tidal datums calculated for the observation period and tidal datums that would be calculated based on the long-term NTDE, these two sets of tidal datums can be first compared at the closest long-term NOAA recording station. To do so, the tidal datums for the observation period for the NOAA recording station would be calculated using the datum calculator, and then compared to the published datums for the station (which are based on NTDE).

To approximate the tidal datums for the long-term NTDE at the site itself, the relative differences calculated at the control station would be applied to tidal datums calculated at the site for the observation period. This assessment can be useful to compare recent and long-term tidal patterns at the site. If a suitable long-term gauge can be identified, this adjustment may be accomplished directly in the NOAA tidal datum calculator. See the datum calculator user manual for detail on selection of a relevant control recording station.

Lastly, the tidal datums calculated for the project site can also be compared to those established for the NOAA non-recording prediction stations located closest to the site. These sites may be accessed through the NOAA Tides and Currents website. Tidal datums published for these sites may provide a useful frame of reference for project planning, but they are not a substitute for localized tidal data. Datums are not published for every site, and care should be taken to understand that the datums and tide predictions at these stations are typically referenced only to the local MLLW datum.

Conversion to the vertical datum used for the project site (such as NAVD 88) is required for direct comparison to land elevations and is best accomplished using the surveyed elevations for the water level loggers. The conversion may be available on the home page for selected prediction stations. If not, the conversion would need to be analyzed using VDatum or a similar vertical datum conversion application. VDatum is a model that imparts additional uncertainty in the transformation between tidal and orthometric datums, so this approach must be used with caution and verified through a local survey.

Useful Links

Water Level Data Training

NOAA Tides & Currents

NOAA Tidal Analysis Datum Calculator

NOAA VDatum

Terrain Data

Lidar data often report elevations higher than actual ground level in tidal marsh systems (Figure 4.3) but can also have high levels of error for other reasons (Schmid et al. 2011, Hladik and Alber 2012). To evaluate potential lidar error, elevations of ground survey points are compared to the lidar elevations representing the same locations. Ground survey points for this purpose can be extracted from wetland surface cross sections. However, the most refined error assessments use data from multiple point locations within distinct plant communities. This allows the assessment to identify the degree of error corresponding to each community type.

Figure 4.3 provides a comparison between widely available lidar elevation data and ground survey elevations collected at a project site. The comparison can be described with mean error, root mean square error, and absolute error estimates. A recent evaluation report and guideline (Carter et al. 2017) by the NOAA Office for Coastal Management provides a useful guide for terrain data comparison field measurements and error analyses.

If the comparison reveals that all the lidar-derived terrain data points are systematically higher or lower than the collected elevation data, a global adjustment to the data may be justified. If the error values vary considerably among distinct community types, individual elevation adjustments corre-

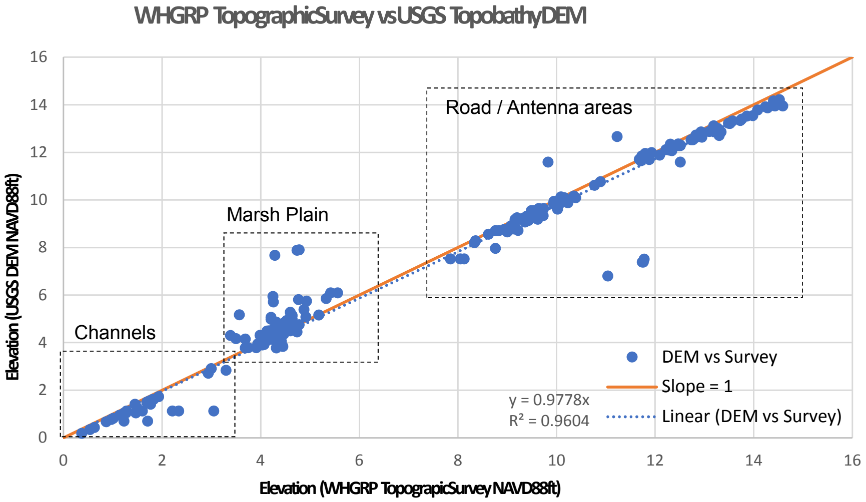
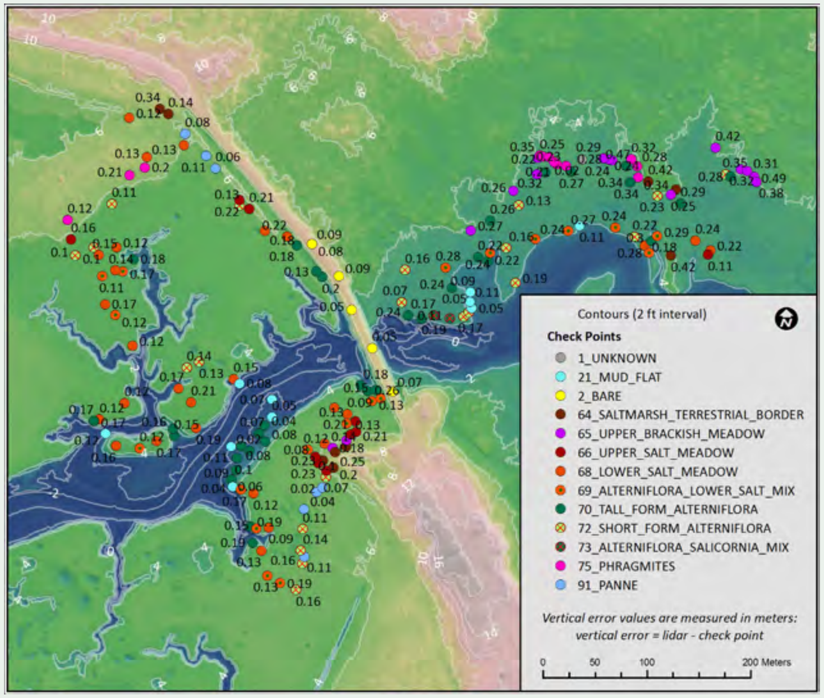


FIGURE 4.3 - Plot of surveyed ground elevations compared to topographic bathymetric elevation data classified by major cover class. Data from Namskatet Creek, Orleans, MA. Source: Woods Hole Group.

Case Study: Lidar Data Evaluation

This 2017 evaluation (Carter et al. 2017) of lidar accuracy at Drake's Island Marsh in the Wells National Estuarine Research Reserve found a global root mean square error of nearly 0.7 feet (0.21 meters). The degree of error corresponding to individual plant communities in the marsh ranged from 0.26 feet (0.08 meters) to 1.1 feet (0.33 meters). This analysis provided the basis for making elevation adjustments to the lidar data based on delineated communities.



Classification	Count	RMSE of Z Error	Avg Of Z Error	St Dev of Z Error
MUD FLAT	11	0.08	0.08	0.03
BARE	10	0.08	0.08	0.03
PANNE	9	0.10	0.09	0.05
SHORT FORM ALTERNIFLORA	26	0.17	0.16	0.06
LOWER SALT MEADOW	34	0.17	0.17	0.05
UPPER SALT MEADOW	15	0.20	0.19	0.05
ALTERNIFLORA LOWER SALT MIX	27	0.21	0.20	0.07
TALL FORM ALTERNIFLORA	43	0.24	0.22	0.11
PHRAGMITES	12	0.23	0.23	0.05
SALTMARSH TERRESTRIAL BORDER	13	0.29	0.27	0.09
UPPER BRACKISH MEADOW	18	0.33	0.32	0.09

sponding to those types may be warranted. The decision to adjust the data should be informed by the sensitivity of analyses during the engineering Design phase to estimated error (Buffington et al. 2016). In many cases, it may not be possible to conclude this until starting that phase. Whether the decision is made to adjust the data or not, this potential source of uncertainty should continue to be considered in the interpretation of modeling results, project decision-making, and development of designs.

If the error trend appears less systematic, adjusting the data can be a more subjective, time-consuming process. In those cases, the best approach for addressing uncertainty might be to integrate precautionary accommodations to the design, such as specifying an incrementally larger structure. If the measured error introduces uncertainty to the project design solution, then it may be necessary to collect more detailed ground survey data for the area in question.

4.7 SUMMARY REPORT OF CURRENT CONDITIONS

At this point in the project, the Project Team will document information learned during the Preliminary Assessment and Detailed Field Investigation. A Summary of Conditions will include both narrative sections and data products such as maps, graphs, and tables to help users understand present and projected conditions. Data from water level monitoring, elevation surveys, high-resolution lidar (if available), and ecological assessments are used to describe the influence of the crossing and other features on inundation patterns in the channel and the adjacent wetland, and relative to known features of interest and concern.

Tidal Water Levels

Graphic representations of water level changes over one or more full lunar cycles help visualize if, when, and to what degree upstream versus downstream levels differ. Frequently, hydrographs of the full dataset are prepared in addition to one or more "zoomed-in" portions of the graph to better explore patterns of interest. Annotations help call attention to these patterns and features of interest. Typical annotations point to upstream versus downstream timing lags and elevation differences, which are indicative of tidal restrictions. Annotations also show elevations of local tide datums, the crossing structure and road surface, and low-lying features of concern. Hydrograph examples are provided in Appendix C.

Channel Longitudinal Profile

The longitudinal profile plots elevations of the stream channel up and downstream of the crossing. This is particularly useful for visualizing mechanisms of tidal restriction related to channel and crossing structure elevations. Annotations to the longitudinal profile include elevations of the crossing structure, road surface, and channel features like scour pools and existing or remnant structures. Marks indicating local tide datums and projected sea level rise elevations are also useful. Appendix C provides an example of a typical longitudinal profile.

Wetland Inundation Patterns

Tidal restrictions alter the frequency and duration that a wetland is flooded by tidal waters, which can influence the wetland's condition. For healthy, unrestricted salt marshes, it is expected that the high marsh plain will flood and drain during the highest tides of the month. Patterns of upstream high marsh inundation (e.g., frequency, duration) that differ notably from downstream can provide useful insights about the mechanisms influencing marsh condition. A graph or table can be used to compare upstream versus downstream high marsh elevations relative to monitored tidal water levels and local tidal datums.

Sea Level Rise and Low-lying Features of Concern

Elevation survey data collected during the Detailed Site Investigation provide a means to evaluate risk to low-lying features of concern that improves upon use of SLR mapping tools during the Desktop Assessment. Hydrodynamic modeling will not yet have been performed to estimate precise tidal water level elevations associated with a given crossing configuration. However, adding projected sea level rise values to local tidal datums based on monitored water elevations provides a useful understanding of risk to low-lying features if tidal exchange is fully re-established.

Properties, Built Features, and Resource Uses

Mapping is an effective tool to demonstrate the lateral distance between these surveyed features and the present and projected highest tides. Graphic elevation plots can also provide a way to visualize the separation between these features and tidal inundation extents now and in the future.

TABLE 4.1 - Useful information types for the Summary of Conditions. Useful products will usually include several types of information under present and projected conditions.

DATA TYPE	FORMAT	ADDITIONAL DETAILS, ANNOTATIONS
Historical vs. current: crossing	Photos, drawings	Dimensions, observed changes
Historical vs. current: wetland	Photos, maps	Observed changes
Stream profile	Plotted elevations	Thalweg, built, natural features, tidal datums
Tidal water levels	Hydrographs	Features of concern, marked and zoomed-in patterns of interest, tidal datums
Natural communities	Map, photos	Major wetland types, plant communities
Wetland inundation	Elevation plot, table	Upstream vs. downstream elevations, tidal datums, inundation frequency and duration
Vulnerable species	Map, plotted elevations	Locations, elevations/extents of tides
Sea level rise	Map/imagery	Extent of present highest tide and selected SLR scenarios, inundation frequency and duration for important elevation thresholds
Low-lying features	Map/photos/plotted elevations	Elevations, tidal extent and elevations

Severely Damaged Wetlands and Vulnerable Species Habitat

At many sites, tidal restrictions and other modifications to hydrology have severely damaged upstream wetland and habitat resilience processes. Re-establishing tidal exchange is considered the ultimate need for these sites to regain resilience to sea level rise. Before that can happen, it must be established that a rapid return to more natural tidal conditions would not cause further damage to already impaired ecological features. Maps, elevation profiles, and water level plots specifically associated with these features are recommended.

4.8 ONGOING MONITORING

The Project Team should begin discussing potential pre- and post-construction monitoring needs during this phase. A key consideration is how to maintain survey control benchmarks and other data collection points so pre-construction baseline monitoring can be carried through to the post-construction period.

Specific monitoring needs vary depending on each individual project's objectives. For most projects, basic post-construction monitoring is required to ensure the crossing achieves structural design objectives. Tracking the degree to which ecological resilience objectives are achieved requires additional monitoring parameters. These can be used to identify tidal inundation frequency, depth, and duration at given locations, in addition to re-establishment of healthy wetlands, habitats, and fish and wildlife species populations.

Monitoring Ecological Change

Re-establishing healthy and resilient conditions for tidal wetlands and specific habitats is a cornerstone of the CoastWise Approach. For projects that perform monitoring to confirm performance objectives are achieved, the choice of monitoring parameters and methods requires thoughtful consideration by experts during the project planning phase. The duration of monitoring must match the expected timescales corresponding to individual types of ecological response.

Local, relatively unaltered reference sites are useful for understanding how the wetland upstream of the crossing might function if not influenced by a tidal restriction. Reference sites are used in projects in which establishing and monitoring progress toward objectives for ecological restoration is required. Objectives often establish targets for specific physical, chemical, and biological characteristics of the wetland.

Reference sites should not be influenced by tidal restrictions. The presence of other alterations should also be minor, with similar tidal patterns, flow conditions, and sediment regimes as those at the crossing to be replaced. In many cases, wetlands downstream of the tidal restriction may provide the best option for projecting optimal conditions upstream of the crossing.

Project monitoring is discussed in more detail later in this manual. Two regional resources for monitoring were developed by the Global Program of Action Coalition for the Gulf of Maine (GPAC) (Neckles and Dionne 2000) and the Casco Bay Estuary Partnership (Craig and Bohlen 2018). Development of innovative monitoring tools and techniques is also an area of active research and development by state and federal agencies and updates to priorities and methods should be consulted.

4.9 TYPICAL ROLES AND TIMELINES

Contracted technical consultants most commonly perform the Detailed Field Investigation, but there are sometimes opportunities for additional support from CoastWise Technical Partners and others. Typical timelines vary with the size and complexity of the crossing and associated project area. A minimum timeframe for water level data collection is a full month-long lunar tidal cycle. Between field planning, data collection, and data post-processing and analysis, it can take three months to complete this project phase.

The ideal timing for the Detailed Field Investigation will vary, but could include spring, summer, or fall. Late summer plant identification on tidal marshes maximizes species identification effectiveness and allows site observations with the least influence of freshwater inflow. Final decisions about timing and frequency of field activities should be made after gaining an understanding of the landscape context and seasonal patterns at the site.

Timing is also influenced by the availability of potential technical and funding resources for the current and subsequent phases. Early coordination with professional engineering and consulting companies, CoastWise Technical Partners, and other resource providers helps ensure their contributions to your project make the most impact.

Funding for subsequent project phases may arise throughout the year. Prompt and early completion of the Detailed Field Investigation presents the potential for accessing more funding opportunities. For many sites, this project phase should be completed by autumn at least one year prior to the desired start of project construction, but more time is recommended.

4.10 ADDITIONAL RESOURCES

Stream Barrier Removal Monitoring Guide
Gulf of Maine Council on the Marine Environment

Quality Assurance Project Plan for Tidal Marsh Monitoring and Assessment
Casco Bay Estuary Partnership

Continuous Water Level Data Collection and Management Using Onset HOBO® Data Loggers: A Northeast Coastal and Barrier Network Methods Document
National Park Service

Regional Standards to Identify and Evaluate Tidal Wetland Restoration in the Gulf of Maine
United States Geological Survey

New Hampshire's Tidal Crossing Assessment Protocol
New Hampshire Chapter of the Nature Conservancy and NH Division of Environmental Services

Planning for Sea Level Rise in the Northeast : Considerations for the Implementation of Tidal Wetland Habitat Restoration Projects: Workshop Report
National Oceanic and Atmospheric Administration

5 CROSSING PERFORMANCE OBJECTIVES AND DESIGN CRITERIA

Photo credit: iStock

At this point in the process, the Project Team's understanding of present and projected conditions, as well as opportunities and potential constraints, allows them to refine provisional objectives to a higher degree of specificity. Consideration of the topics in this section helps teams begin the process of refining performance objectives, which in turn inform the development of corresponding engineering design criteria.

These criteria are used to design and evaluate competing design alternatives and inform the construction and monitoring project phases. In practice, design criteria may be refined iteratively as the process advances through tidal hydrodynamic modeling under present and projected conditions for each crossing alternative. This is typically referred to as the feasibility phase of a project. Examples of objectives and design criteria are summarized at the end of this section.

5.1 INITIAL CONSIDERATIONS

Sea Level Rise

In Section 3 of the CoastWise Manual, Project Teams are encouraged to select a risk-based sea level rise scenario using site characteristics and road access needs to guide decision-making. If information learned about the site since then suggests that the selected sea level rise scenario should be adjusted, now is the correct time to make that change. Likewise, if sea level rise scenario projections have been updated, the Project Team should make any necessary adjustments to previous analyses and the development of objectives and design criteria.

Typical Planning Horizons

As an initial step in the development of crossing objectives and design criteria, Project Teams are encouraged to determine the new crossing's planning horizon or service life, which is the timeframe during which the crossing is expected to remain in service. The importance of establishing the planning horizon extends to setting the context for sea level rise projections, construction methods, and materials, and other factors. Identifying a single planning horizon at this stage of the project can help streamline the project design process. However, some Project Teams may evaluate and compare conceptual design alternatives at different timescales before committing to a single planning horizon.

The MaineDOT bridge design guide (MaineDOT 2003) estimates life cycle intervals (analogous to service life) corresponding to various types of structures. More detail is provided in Appendix B:

- Bridge replacement – 75 to 100 years
- Deck replacement – 50 years
- Steel pipe – 30 to 50 years (service life less than 30 years for estuary and coastal use)
- Plastic pipe – 100 years
- Aluminum pipe – 75 years
- Concrete pipe, pipe arch or box culverts – 75 to 100 years.

A typical planning horizon for culverts and minor spans in tidal environments is 75 years, based on the durability of construction materials commonly used for these crossings. Regardless of the planning horizon selected, crossings should be designed to accommodate projected site conditions (e.g., sea level rise) throughout the structure's entire expected service life. This includes crossings that may not presently be tidal but are projected to become tidal under the selected sea level rise scenario.

Short-Phased Planning Horizons

Some projects may adopt planning horizons for the crossing structure, road embankment, or both that are shorter than 75 years. Short-phased planning horizons such as these are not well-documented in Maine but may experience increased use. Characteristics of projects that might use this approach include those in which the extent and location of projected tidal flooding in the next few decades argues against planning to accommodate long-term conditions. This includes sites where upland areas that the crossing facilitates access to are expected to experience extensive, unmitigated tidal flooding well before a 75-year planning horizon concludes. Other examples include sites where long road segments in the same network as the crossing are projected to flood, but plans to address that scale of road flooding have not yet been initiated or adopted. In these instances, road owners may ask whether the crossing should be upgraded to meet 2100 conditions if there is uncertainty whether the remainder of the road will meet those same criteria.

Where the types of tidal flooding issues discussed above are lacking, decisions about planning horizons are sometimes most influenced by fiscal considerations and uncertainty. Crossing designs based on projections of 2100 sea level rise conditions are assumed to require more height, opening size, and initial construction cost than designs meant to accommodate conditions in the next few decades. Sea level rise projections for 2100 are also attended by a greater degree of uncertainty than those corresponding to near- or mid-term planning horizons.

As a result, some Project Teams may adopt a short-phased planning horizon because they perceive that design and construction to meet 2100 conditions present excessive financial risk. In these cases, the potential added expense of redesign and construction thirty years or so after Phase I is built should be considered when comparing the advantages of short-phased or full-term planning horizons. Performing this type of comparison with confidence might require development of conceptual design alternatives (see Section 6) representing more than one planning horizon.

Regardless of why a short-phased approach is considered, Project Teams should ensure that the proposed Phase I crossing design fully meets infrastructure and ecological performance objectives and design criteria for the duration of its expected service life. Assessment of crossing performance and site conditions are performed to ensure that Phase II is designed and ready to implement prior to the obsolescence of Phase I. Project Teams may realize some cost savings by designing Phase I crossings that can be efficiently upgraded to Phase II.

Crossing Retirement

At some sites, crossing retirement is considered an appropriate option to support community adaptation and ecological resilience to sea level rise. Crossing retirement appears most feasible when tidal flooding at the road or the properties the road accesses occurs periodically or is predicted to do so in the near term. In these cases, retirement may be identified as the most cost-effective and ecologically supportive alternative. The presence of alternate access routes also makes crossing retirement a more viable solution. Feasibility planning for crossing retirement may include traffic studies and other assessments to consider social implications. If the Project Team considers crossing retirement a credible option, social and ecological performance objectives and engineering design criteria should be developed to meet stated goals. For instance, when traffic is redirected to another portion of the road network, upgrades to address safety and convenience needs may be necessary. Likewise, attainment of ecological goals would typically require removal of the crossing structure as part of the retirement process. How much is removed, and how best to stabilize the site, among other considerations, are questions that require the development of design criteria supportive of wetland resilience, among other factors.

5.2 CROSSING STRUCTURAL RESILIENCE

Planning for sufficient crossing capacity and road height under projected storm conditions is an essential step in the design process. The topics below are presented in a sequence to facilitate development of specific design criteria leading to a resilient structure.

Storm Surge and Storm Tides

Storm surge is the effect of coastal storms pushing water up against the coast. Storm surge adds to the tide level at the time of the storm, resulting in a storm tide. Maine Geological Survey (MGS) notes that the relative magnitude of extreme storm surge observations has generally been consistent at NOAA tide stations (Table 5.1). However, the local effects of storm surge can vary considerably along the Maine coast due to differences in coastal morphology, tidal range, aspect, wave and wind exposure, and other factors.

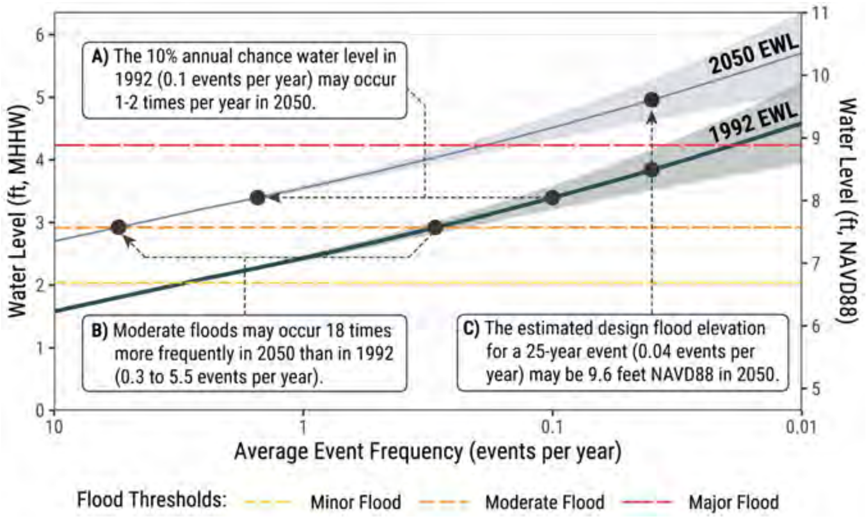
The storm surge magnitudes corresponding to recurrence intervals summarized in Table 5.1 are provided for information purposes only to illustrate the magnitudes of past storm surge patterns. Federal Emergency Management Agency (FEMA) Base Flood Elevations (BFEs; discussed in the next subsection of the guidelines) incorporate storm surge estimates for present sea levels in their calculation, thus design criteria for crossings that include adaptation of BFEs for future conditions integrate storm surge considerations.

Looking to the future, the Maine Climate Council Science and Technical Subcommittee (MCC STS) suggest that the potential superposition of high storm surges with rising sea levels will result in continually increasing coastal flooding elevations (Maine Climate Council Science and Technical Subcommittee 2020). The most recent NOAA SLR technical report (Sweet et al. 2022) integrates a detailed analysis of the combined effects of storm surge and sea level rise on “Extreme Water Levels” (EWLs), which are defined as coastal

TABLE 5.1 - Reprint from MCC-STS 2020. Calculated recurrence intervals in years for storm surges at Portland, Bar Harbor, and Eastport based on best-fit equations and annualized surge data. Data through December 31, 2019, from NOAA CO-OPs. These projections are provided for reference, not design purposes. Table by P. A. Slovinsky, MGS.

RECURRENCE INTERVAL[1]	% ANNUAL CHANCE	STORM SURGE (FEET)		
		PORTLAND	BAR HARBOR	EASTPORT
1	100%	2.0	1.8	2.0
5	20%	2.9	2.8	2.9
10	10%	3.3	3.3	3.3
25	4%	3.9	3.9	3.9
50	2%	4.3	4.3	4.3
100	1%	4.7	4.7	4.7

[1] Recurrence interval is often informally used in phrases such as 'hundred-year storm' to describe the frequency and magnitude of a particular storm. The recurrence interval describes the relative frequency of a particular size of storm, in years, on average, based on statistical analysis.



A) The 10% annual chance water level in 1992 (0.1 events per year) may occur 1-2 times per year in 2050.

B) Moderate floods may occur 18 times more frequently in 2050 than in 1992 (0.3 to 5.5 events per year).

C) The estimated design flood elevation for a 25-year event (0.04 events per year) may be 9.6 feet NAVD88 in 2050.

FIGURE 5.1 - Estimated extreme water levels (EWL) in Portland compared between 1992 and 2050. EWLs are defined as water levels associated with events occurring between 10 times per year and 0.01 times per year, or the 1% annual chance. The rise in occurrence from 1992 to 2050 is based on application of the Intermediate SLR scenario. Source: Collini et al. 2022. Graphic prepared by J. Carter.

flooding events with probable frequency ranging from ten events per year to 0.01 times per year, or the 1% annual chance. Figure 5.1 provides a sample of this analysis for informational purposes, highlighting the predicted increasing trends in EWL frequency and elevations.

Coastal Flood Levels and Base Flood Elevation

FEMA developed estimates of extreme flood elevations relative to present sea levels to inform flood insurance considerations for coastal areas. Base flood elevations (BFE; 1% annual chance flood) have recently been updated in some Maine communities and may be further revised in the coming years. FEMA base flood elevations combine the effects of tides, coastal storm surge, and wave runup after the storm surge reaches land.

Peak storm surge elevation combines the peak stillwater elevation (highest predicted tides) plus wave setup height, which is the result of water being pushed from the open ocean onto the coast (Figure 5.2). Wave runup height results from waves running overland after they break and is a more localized process. Since these flood analyses are based on statistical analyses of past coastal storm events, they do not represent future flood risk with sea level rise. The MCC STS estimated that an increase in sea level by just one foot would increase nuisance flooding by a factor of fifteen (MCC-STS 2020).

FIGURE 5.2 - Definition sketch of FEMA coastal base flood components. Base flood elevation is a combination of estimated peak storm surge elevation (stillwater elevation [SWEL] plus wave setup) plus wave runup (overland rush of water after waves break). Image reproduced from a FEMA graphic.

After FEMA updated BFEs, the North Atlantic Coast Comprehensive Study (NACCS) was completed by USACE to represent state-of-the-art high resolution coastal storm hazard analysis from Virginia to Maine (USACE 2015). Among the data generated by the NACCS are total water level estimates for coastal storms having annual recurrence intervals ranging from 1-year to 10,000 years. This data is available on the Northeast Ocean Data Portal. For selected projects, this data may provide improved localized estimates of coastal flood peak water levels.

In addition, it should be noted that MaineDOT commissioned development of a spatially explicit hydrodynamic coastal flood risk model (ME-CFRM) for the entire coast of Maine, which will further advance mapping of peak coastal storm elevations and patterns considering future sea level rise projections. It is anticipated that this model study will be completed by 2024.

Sea Level Rise-Adjusted Design Flood Elevation

The CoastWise Approach uses a risk-based strategy to estimate sea level rise-adjusted design flood elevations. Design flood elevation refers to maximum flood elevation that guides the tidal crossing design. In most instances, the tidal crossing is designed so that it does not overtop during the design flood.

Using mapped FEMA base flood elevation (Figure 5.2) as the baseline, the selected sea level rise and freeboard requirements are added to arrive at the estimated design flood elevation (NH Coastal Flood Risk Science and Technical Advisory Panel 2020). In this context, freeboard is defined as the height of the roadway above the design flood elevation. Incorporating freeboard into design criteria is a precautionary measure to address uncertainty in estimating the design flood elevation. Crossings having high risk consequence typically have higher freeboard requirements than those with low-risk consequence.

The base flood elevation and freeboard requirements are consistent with the recommendations of the ASCE Flood Resistant Design and Construction standard (24-14) (FEMA 2015), which vary by "flood design class". The risk-based strategy correlates risk consequence levels with the ASCE flood design classes (Table 5.2).

By default, this strategy integrates tidal and non-tidal contributions to coastal flooding because the FEMA base flood elevation includes the effect of both flooding sources. In some instances, it may be necessary or advisable to determine base flood elevations through alternate methods involving site-specific modeling of the combined effects of tidal and non-tidal flooding components. For instance, for crossings with substantial freshwater inputs, the Project Team should consider integration of predicted future precipitation trends into the estimated freshwater flooding component.

Designers should also keep abreast of new resources for coastal storm prediction (e.g., the MaineDOT coastal flood hydrodynamic model) so they can be applied to coastal flood elevation estimates for crossing project design. Based on site specific characteristics, it may also be necessary to follow alternate strategies than those described in the section to establish design flood elevations on a case-by-case basis.

For MaineDOT designs, the *MaineDOT Bridge Design Guide* (MDOT 2003) provides multiple combinations of freshwater, tidal, and tropical storm conditions that should be simulated and considered during the design process. These various combinations are specified for simulation of typical and extreme event conditions for the purposes of analyzing structure stability and scour. Minimum crossing resilience requirements are discussed below.

TABLE 5.2 - Relative sea level rise adjusted design flood elevations (DFE), based on risk consequence. Adapted from New Hampshire coastal flood risk guidance (NH Coastal Flood Risk Science and Technical Advisory Panel 2020).

IF PROJECT AREA IS LOCATED IN:	LOW RISK CONSEQUENCE	MEDIUM RISK CONSEQUENCE	HIGH RISK CONSEQUENCE	VERY HIGH RISK CONSEQUENCE
	Relative Sea Level-Adjusted Design Flood Elevation (DFE) =			
A, AO, or AE Zone Not Identified as Coastal A Zone	Base Flood Elevation + Relative Sea Level Rise	Base Flood Elevation + Freeboard > 1 foot + Relative Sea Level Rise	Base Flood Elevation + Freeboard > 1 foot + Relative Sea Level Rise	*Whichever is Greater:* Base Flood Elevation + Freeboard > 2 foot + Relative Sea Level Rise *OR* 0.2% Annual Chance Flood Elevation + Relative Sea Level Rise
VE Zone and Coastal A Zone			Base Flood Elevation + Freeboard > 2 foot + Relative Sea Level Rise	

Appendix A discusses several modeling scenarios that combine varying extreme event conditions.

Hydraulic Capacity Requirements

Sufficient hydraulic capacity for projected storm conditions is essential to designing a resilient structure, though in small coastal watersheds and tidal crossings roadway elevation is often an even more important factor in infrastructure resilience. Many designs will utilize large culverts and three-sided "open bottom" structures (Figure 5.3). The depth of water in the structure should be less than ninety percent of the interior height at the fifty-year storm peak water level, and the freeboard at the edge of pavement or road edge should meet the risk-based criteria for the base flood (hundred-year return period, Table 5.1).

This approach generally follows the *MaineDOT Bridge Design Guide* (MDOT 2003), with adaptations using the risk-based approach to incorporating sea-level rise as discussed earlier. Once these criteria are met, the preliminary structure sizing and design should be checked for critical factors such as scour and road embankment stability. The *MaineDOT Bridge Design Guide* and FHWA's HEC-18 guidelines provide methods for these analyses (Federal Highway Administration 2012).

FIGURE 5.3 - This MaineDOT crossing was designed to adequately accommodate storm flows, protect footings from scour, facilitate low-flow water depths sufficient for fish passage, and allow for semi-aquatic wildlife movements. Photo by Slade Moore.

Ice is an important design consideration at some tidal crossings where it may temporarily impair flow, especially where tide gates are involved. In these instances, and where the history of ice at the site suggests it may be a key design consideration, ice should be addressed explicitly by hydraulic analysis. However, ice-related considerations do not typically factor directly into hydraulic and hydrodynamic calculations.

Instead, the hydraulic effects of ice are typically addressed by hydraulic freeboard requirements. This is due to the intermittent pattern of ice formation and breakup in tidal systems over the winter season. The timing of peak ice conditions also does not typically coincide with peak upland or coastal flooding, though there may be exceptions.

The pressure or force applied to a crossing structure or embankment that results from ice accumulation (ice loading) is typically factored into structural stability calculations and design. The *MaineDOT Bridge Design Guide* includes requirements that should be considered in structural calculations. An extra factor of protection is applied for sites on one of the major rivers that are known to have severe ice conditions, such as the main stem of the Kennebec River. Provisions are also made to avoid damage to structures due to blunt ice impacts, or scour, such as adding protection plates to piers in locations that may see frequent ice impact or accumulation.

5.3 FLOODING AND LOW-LYING FEATURES OF CONCERN

Each phase of the CoastWise Approach emphasizes managing risk to low-lying properties, infrastructure, and resource uses. Following the Detailed Site Investigation, the Project Team should have enough data to determine how flood risks to low-lying feature of concern will influence hydraulic design. Integral to this step is a feasibility assessment to determine if the replacement structure can achieve unrestricted tidal exchange and facilitate wetland resilience.

It is often assumed that infrastructure and certain types of resource uses at or near present or future high tide elevations will constrain the degree to which the crossing design can improve tidal exchange and support upstream wetland resilience. That is often a correct conclusion where a return to natural tidal regimes and elevations would put high-density infrastructure and other important assets at risk of flooding and damage. Over the years, communities and road owners at some sites have deliberately restricted the tides by installing tide gates, undersized and perched culvert crossings, and other structures to address upstream tidal flooding concerns. To various degrees, these actions have provided at least a temporary solution to flooding concerns. This approach has important disadvantages. For example, it may cause degradation or total loss of upstream wetland services, it does not often provide a long-term solution to the inevitability of continued sea level rise, and tidal restrictions can interfere with drainage of floodwaters from areas where low-lying features of concern are located.

Test Assumptions About Constraints

Unimpaired tidal exchange for the life of the crossing is required so upstream wetlands can achieve and maintain resilience to sea level rise. The presence of upstream low-lying infrastructure and certain resource uses near high tide elevations are sometimes mistakenly perceived as "hard" constraints on re-establishing unimpaired tidal exchange. It is incumbent on Project Teams to explore creative solutions to apparent design constraints that can mediate upstream flooding concerns, with the aim of setting the stage for upstream wetland resilience.

At other sites, the influence of low-lying features of concern on the degree of possible tidal exchange improvements is less clear. In those instances, the Project Teams are encouraged to thoroughly review available data, perform relevant analyses, and explore options to mediate risk concerns rather than prematurely concluding that low-lying features of concern will in fact constrain the crossing design.

One option for mediating potential constraints is to acquire supplemental project funding to move low-lying utilities and other infrastructure or to develop purchase arrangements that potentially affected landowners find agreeable. At a subset of sites, the inevitability of sea level rise and associated costs of repair and re-construction to keep pace over the coming decades makes retirement of low-lying infrastructure an attractive choice to owners. Whatever the circumstances, Project Teams must acknowledge that without solutions like these to accommodate renewed tidal exchange and resilience to sea level rise, tidal wetlands like salt marshes are condemned to eventual drowning.

Site-specific design criteria to address low-lying features of concern including upstream properties should be evaluated through comparison of modeling simulation results for each crossing alternative. Key criteria can include the extent, depth, and duration of inundation for locations of interest at a selected tidal storm level under present and projected conditions. The peak base flood (hundred-year return period event) and typical high tide (e.g., HAsT) are often used, but site-specific considerations might warrant selection of other events.

5.4 ECOLOGICAL PERFORMANCE

The CoastWise Approach emphasizes ecological performance design criteria in addition to the infrastructure-focused considerations discussed in the previous sections. Ecological criteria are diverse, but they share a common goal of benefiting wetland resilience and species of interest.

Sea Level Rise Scenario Confirmation

Tidal flow restoration should anticipate the full planning horizon for the crossing, employing estimated sea level rise-adjusted tidal datums. In many cases, using the risk consequence-based sea level rise projections selected earlier in the process will be appropriate for ecological aspects of CoastWise crossing designs. However, the Project Team may wish to adopt a higher sea level rise scenario in some cases, such as where exceptionally high value wetlands or other ecological assets warrant a more precautionary approach.

Upstream Tidal Wetland Resilience

For tidally restricted wetlands to keep pace with sea level rise, they must experience recovery and maintenance of resilience processes. One of the most prominent of these processes for salt marshes and mudflats is wetland surface accretion as a result of sedimentation (Bartholdy 2012, Fujii 2012). Salt marshes also rely on plant material production and plant litter accumulation for accretion (Cahoon et al. 2006). Peak performance of each of these processes depends on unrestricted tidal inundation and drainage during the

A "Much Bigger" Crossing Isn't Necessarily "Big Enough"

Simply increasing the crossing structure size by leaps and bounds does not provide adequate assurance that the proposed crossing structure is large enough. The goal is not just to make the structure bigger, as big as the stream channel, or even 1.2 bankfull width as in Stream Smart. Instead, tidal exchange must be improved sufficiently to confidently predict that processes necessary for re-establishing wetland health and resilience to sea level rise are sufficiently encouraged, now and in the future. The magnitude of investment in these structures demands the use of procedures, like hydrodynamic modeling, that can provide the Project Team with the tools necessary to confidently evaluate the proposed crossing's performance.

highest and lowest tides, so the interior of wetlands can benefit along with areas adjacent to the channel (Stumpf 1983, Wood et al. 1989, Reed et al. 1999, FitzGerald et al. 2020, Moore et al. 2021).

A central principle of the CoastWise Approach is to upsize crossings so they can achieve unrestricted tidal exchange and peak functionality of resilience processes, under present and projected conditions. This often requires considerable increases in crossing structure size. However, size increases uninformed by tidal hydrodynamic modeling (unsteady state) in most cases cannot provide adequate assurance that tidal exchange will improve sufficiently to encourage present and future upstream wetland resilience.

Basic Criteria

Wetlands like salt marshes and tidal flats experience relatively gentle surface elevation changes within the relatively narrow portion of the tidal range they occupy. As a result, minor deviations between downstream and upstream tidal water level elevations and timing can cause considerable shifts in the amount of flooded area in these wetlands.

For sites with upstream wetlands that are smaller and less hydrologically complex, basic crossing design criteria for encouraging upstream wetland resilience presently focuses on the timing and elevation of simulated upstream and downstream water levels corresponding to the proposed crossing. These criteria are framed within the context of present conditions and also those corresponding to projected sea level rise conditions.

Maximum confidence that the proposed crossing design will fully achieve upstream wetland resilience requires modeling simulations. Under optimal conditions, these will demonstrate that upstream and downstream water levels match in terms of timing and elevation during the point of highest and lowest tides, and also during the in-between flood or ebb "running" tides, all corresponding to the selected design tide cycle, such as the highest astronomical tide (HAsT). When water levels match, there is no upstream-downstream hydraulic head differential (HHD) during hydrodynamic model simulations and the crossing is tidally "transparent". If the simulated upstream-downstream water level elevations deviate substantially, the design's potential wetland resilience performance is less certain. While zero or near-zero HHD is ideal and can serve as a useful reference objective on the spectrum of design alternatives, in many practical applications it may be difficult to attain due to a variety of physical and project constraints.

CoastWise partners are presently conducting a study to refine methods for establishing resilience criteria and evaluating crossing size alternatives.

Scheduled for completion in 2023, this work is expected to test the effectiveness and practicality of metrics and criteria use to evaluate the influence of crossing size and performance on wetland resilience. It will also compare the effectiveness of modeling approaches for wetlands having different characteristics.

Findings of the study will be used to inform updates to the CoastWise Approach.

There are two ways to calculate HHD. The maximum instantaneous difference (IHHD) is calculated as the largest difference between upstream-downstream water levels during the continuous time series including the high and low tides, and the intervening flood and ebb running tides. The peak-to-peak difference (PHHD) is calculated as the difference between upstream-downstream peak water levels on a tidal cycle. For a given HHD value (e.g., 0.25 foot difference), PHHD will result in a smaller structure (Figure 5.4).

The final choices of target HHD value and the instantaneous or peak-to-peak (IHHD or PHHD) basis for structure size selection will typically be determined on a project-by-project basis. In general, the selected structure size should be the most cost-effective solution to result in HHD value as near to zero as practicable. In addition, the structure vertical dimension should be great enough that the design tide does not touch the inside top of the structure. If the selection is based on PHHD, it will be necessary to verify that needed volumes of tidal exchange for upstream wetland resilience will be conveyed through the crossing for the design tide, and that other objectives such as aquatic organism passage will be met. If the selection is based on IHHD, this verification step is less essential.

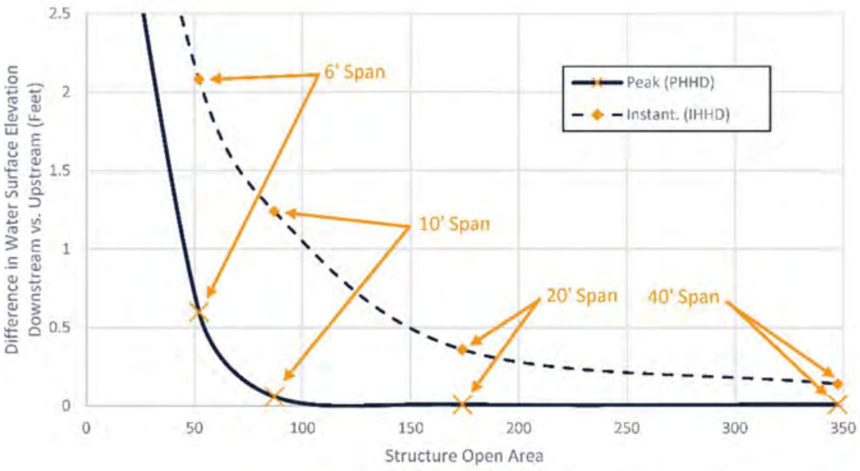


FIGURE 5.4 - Plot comparing HHD values calculated using PHHD and IHHD definitions, courtesy of Acadia Civil Works

Additional Considerations

On a site-specific basis, wetland resilience criteria can include thresholds corresponding to modeled tidal hydrology patterns, such as the simulated tidal prism, depth, and extent of tidal flooding upstream of the crossing. When these patterns are evaluated at different tidal datums, or over varying tidal cycles, they can be characterized in terms of frequency and duration. In some instances, objectives and design criteria for flow velocity or salinity concentration in the tidal wetland are also important to establish, which requires additional modeling capability.

Aquatic Organism and Wildlife Passage

Road crossings often impair movements of aquatic organisms and wildlife due to perched culvert inlets and outlets, accelerated flows through undersized structures, loss of natural substrate, and other factors. Ensuring that the crossing facilitates the unimpaired movement of aquatic organisms past a tidal road crossing is a standard ecological design criterion, but planning and implementation of passage requirements often requires the advice of experts who know most about species using the site (Figure 5.5).

Crossing designs that re-establish natural tidal exchange will typically improve aquatic habitat connectivity and conditions suitable for organisms to migrate through tidal road crossings, but passage performance should be confirmed using design criteria tailored to species needs. Overall, the potential benefits of improved habitat connectivity in tidal wetlands are difficult to fully anticipate. At regularly monitored tidal restoration sites, a wide variety of marine organisms have been observed to benefit from crossing improvements, including horseshoe crabs (*Limulus polyphemus*), dogfish (*Squalus* spp.), harbor seals (*Phoca vitulina*), and sturgeon (*Acipensar* spp.) (M. Craig, Casco Bay Estuary Partnership).

It has become standard practice when designing for aquatic organism passage through inland culverts to provide a nature-like substrate to facilitate species passage. However, in tidal crossings installation of substrate is not a standard practice and the need for substrate should be established on a project-by-project basis.

The simulated hydraulics of the crossing should be evaluated carefully for potential scour if a native channel bed is to be left in place, or to determine an appropriate design gradation if the bed will be constructed with new material.

FIGURE 5.5 - Species of the highest conservation interest at any given site can vary dramatically and are typically used to inform passage requirements for the crossing design. Another, more precautionary approach, is to use the weakest swimming species likely present at the site to establish passage requirements. Photo by Slade Moore.

With the improved hydraulic capacity and vertical alignment of a replacement tidal crossing structure, accumulated sediments in the upstream channel are likely to down-cut, and usually this is a predictable, but temporary, process potentially presenting a short-term impairment to passage if not managed proactively.

Predicted current velocity, turbulence, depth, and the potential for perched conditions over a range of tidal conditions should be compared to published passage requirements for species of interest. Managed fish species of interest often include rainbow smelt, river herring *(Alosa pseudoharengus, Alosa aestivalis)*, American eel *(Anguilla rostrata)*, Eastern brook trout *(Salvelinus fontinalis)*, Atlantic salmon *(Salmo salar)*, striped bass *(Morone saxatilis)*, and American shad *(Alosa sapidissima)*. The USFWS Northeast Region fish passage engineering design criteria document (USFWS 2019) provides guidance for individual species' swimming capabilities and general passage requirements, but it was not developed specifically for application to tidal environments. The MaineDOT waterway and wildlife crossing policy and design guide (MDOT 2008) provides another point of reference that reports sustained swimming speeds for some species. In addition, the Washington state stream crossing guidelines (Barnard et al. 2013) include general notes about passage considerations for estuary settings, though not specific to the species present in Maine.

Use of published passage requirements requires an understanding of what criteria are most relevant. For instance, burst speeds reported for individual fish species to traverse relatively short distances may not apply to flow velocities in road crossings. If necessary, applying a "safety" factor to published velocities should be considered.

It is also worth considering attention to passage requirements of small, weaker swimming fishes such as *Fundulus* species (e.g., mummichogs, killifish) and sticklebacks (*Gasterosteridae* spp.). These year-round residents serve as an important prey base for a variety of managed fish and wildlife (Deegan 1993). Recent research indicates that crossing velocities greater than 1.6 feet per second significantly decreased passage rates of mummichogs (Eberhardt et al. 2010).

Documentation of the timing of fish passage relative to tide levels is generally uncommon, but it is available in some cases. For example, rainbow smelt have been observed to swim to spawning grounds against the tide and at low tide (Enterline et al. 2019). Typical passage engineering criteria have included provision of volitional fish passage opportunity ninety percent of the time during the migration periods, although these criteria are generally developed for non-tidal systems.

Application of this type of standard is less straightforward for tidal systems given the likely nuances of fish movement relative to daily and monthly tide cycles. In evaluation of fish passage opportunity, it is recommended that hydraulic conditions in the tidal crossing structure be checked against species-specific passage criteria over the range of MLLW to MHHW at a minimum, and at least the central ninety percent of the tide range for conditions up to the highest astronomical tide.

Severely Damaged Wetlands and Vulnerable Species Habitats

Tidal restrictions and other modifications such as those caused by past agricultural practices in marshes have severely damaged natural processes that would otherwise support upstream wetland resilience. Where these mechanisms cause notable wetland surface elevation deficits and or loss of native vegetation, a rapid return to unimpaired tidal inundation patterns can prove too much, too soon for damaged wetlands to respond well.

Another consideration is that at some of these sites, saltmarsh sparrows and other species vulnerable to rapid changes in hydrology maintain a tenuous existence under highly altered conditions. Rapid re-introduction of full tidal exchange could cause irreparable damage to local populations of these species.

Where wetlands show any of these characteristics, objectives for tidal exchange improvements must be developed and implemented with extreme care. Modeling simulation results for a given crossing size alternative would be used to evaluate the risk of harm based on specific design criteria that are identified. Application of restoration methods that prepare severely damaged marshes and habitats for re-introduction of unimpaired tidal exchange may be warranted at many of these sites (Adamowicz 2020).

Design Criteria Development and Documentation

At this point in the process, the Project Team meets to develop specific design criteria to support performance objectives for the crossing. Typical objectives and corresponding design criteria are summarized in Tables 5.3 and 5.4. Not all projects will adopt the same criteria target values, but the criteria categories presented are relevant to most projects.

The decisions made during this project phase will have long-lasting consequences for the local community, other road users, and adjacent ecological systems. An overemphasis on short-term cost savings can lead to undesirable impacts that cannot often be reversed without considerable expense, and greater long-term costs. A precautionary "no regrets" approach that features a long-term view of cost-effectiveness, community well-being, and ecological resilience is a valuable tool for managing future uncertainty and risk (Hallegatte 2009).

CoastWise Technical Partners are helpful assets during this step in the project process, particularly during discussions focused on tidal hydrology and ecologically focused criteria. The design engineer is pivotal in helping to objectively translate crossing performance objectives into criteria, in addition to determining the most appropriate hydraulic and structural design criteria for the crossing.

In practice, criteria may be refined iteratively during the feasibility and Design phases of the project, with the final design criteria documented in the final design report. However, the decisions made at this step in the process, and any subsequent changes, should be clearly documented in a brief memo or summary and distributed to avoid miscommunications leading to costly design revisions.

5.5 ADDITIONAL RESOURCES

Maine Climate Council Science and Technical Subcommittee Climate Change Synthesis
Observed and potential effects of climate change on Maine's ecosystems and infrastructure

State of Maine Water Crossing Guidelines
A guide to fish passage and wildlife passage engineering at road crossings in Maine

MaineDOT Bridge Design Guide
Procedures and criteria for design of bridges and road crossings under MaineDOT jurisdiction

New Hampshire Coastal Flood Risk Science Summary
Observed and potential effects of climate change in New Hampshire with emphasis on flooding and sea level rise

New Hampshire Coastal Flood Risk Guidance for Applying Scientific Projections
A streamlined strategy for applying climate change science projections to flood management

Northeast Ocean Data Portal
Provides maps and data on coastal storm and flood risk

USFWS Northeast Region Fish Passage Engineering Guidelines & Federal Inter-Agency Nature-Like Fishway Design Guidelines
Information about fish passage design, including nature-like fishways

FHWA Highways in the Coastal Environment Design Guidelines
Overview of coastal science and engineering, with specific application to roadway engineering and design

FHWA Highways in the Coastal Environment Guide for Assessing Extreme Events
Climate change and risk-based procedures for analyzing extreme events for coastal engineering applications

State of Washington Water Crossing Guidelines
A guide to fish passage engineering at road crossings, including an appendix that focuses on fish passage in estuary settings

TABLE 5.3 - Typical objectives and supporting design criteria for **crossing structural requirements** during the expected service life of the structure.

PERFORMANCE OBJECTIVE	DESIGN CRITERIA	TARGET VALUE
Crossing Longevity - The crossing provides the desired performance during its service life.	Planning Horizon/Service Life in years	75 years, or site specific
Crossing Structure Resilience - The crossing is climate ready for the selected planning horizon. This includes the ability to accommodate sea level rise, future flow capacity, inundation, structure stability, and other factors.	Projected Sea Level Rise Elevations (ft)	Scenario based on risk and planning horizon; at least the central or upper Intermediate projection
	Design Flooding Criteria (ft) *Base Flood (Current)* *Design Flood Elevation (Future)*	 FEMA Base Flood, or combination of tide/flow/storm Base Flood Elevation + sea level rise
	Design Freeboard (ft) *Road Embankment* *Crossing Structure*	 Site specific, risk-based Site specific, risk-based
	Maximum Upstream /Downstream Water Surface Elevation Difference at Design Flood (ft)	Site specific
	Maximum Scour Depth at Design Flood (ft)	Site specific
Low-Lying Features of Concern - The crossing does not cause undesired tidal flooding or damage of upstream infrastructure, properties, or resource uses	Maximum Water Elevation (ft)	Site specific
	Maximum Tidal Inundation Lateral Distance (ft)	Site specific
	Maximum Duration of Inundation Above Site-Specific Elevation	Site specific
	Maximum Water Velocity Adjacent to Site-Specific Infrastructure (ft/s)	Site specific

TABLE 5.4 - Typical objectives and supporting design criteria for **ecological resilience** during the expected service life of the structure.

PERFORMANCE OBJECTIVE	DESIGN CRITERIA	TARGET VALUE
Wetland Resilience - The crossing re-establishes fundamental processes that maintain tidal wetland health and resilience to sea level rise, like unimpaired tidal exchange. Listed design criteria target values often require comparing simulated upstream conditions associated with each crossing alternative with simulated unrestricted conditions, at present and future Highest Annual Tide or Highest Astronomical Tide (HAsT) conditions.	Projected Sea Level Rise Elevations (ft)	Based on risk/planning horizon; at least the central or upper Intermediate projection
	Up-Downstream Water Levels (ft) *Slack high and low tide* *Flood or ebb (running) tide*	 No elevation or time difference Minimal difference at any time[1]
	Upstream Tidal Inundation *Extent (ft)* *Residence Time/Duration*	 Match inundation extent under unrestricted conditions, subject to project constraints Match inundation duration under unrestricted conditions, subject to project constraints
	Upstream Salinity Concentration	Match salinity concentration under unrestricted conditions, subject to project constraints
	Wetland Community Criteria	Site-specific wetland community targets
Aquatic Organism Passage - The crossing maximizes organism passage for a list of selected species or the species with least relative swimming performance.	Time Duration	90% of the tide elevation range associated with the HAsT tide cycle, adapted subject to individual project constraints if necessary
	Allowable Hydraulic Drop Height (ft)	0" (no perch) other than natural bedrock features
	Maximum Allowable Velocity (ft/s)	Based on species and life stages utilizing the crossing
	Minimum Depth (ft)	Based on species and life stages utilizing the crossing
Vulnerable Species/Impaired Marshes - The crossing avoids adverse impacts to marshes with elevation deficits and vulnerable species.	Maximum Frequency, Depth (ft), and Duration of Tidal Inundation	Site specific; identify values that encourage tidal exchange to support marsh resilience processes without exceeding inundation tolerance of imperiled species and plant communities at impaired marshes

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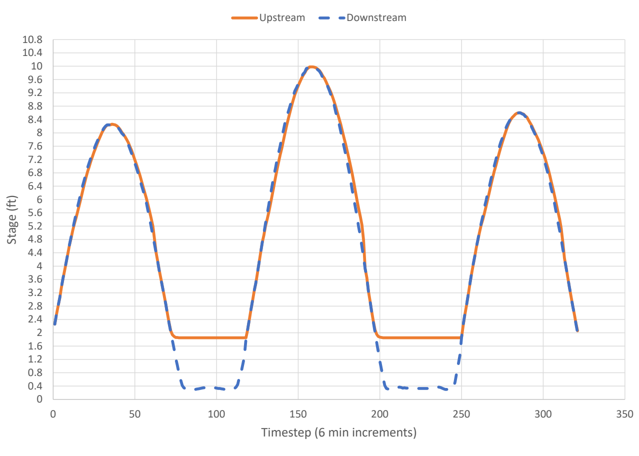
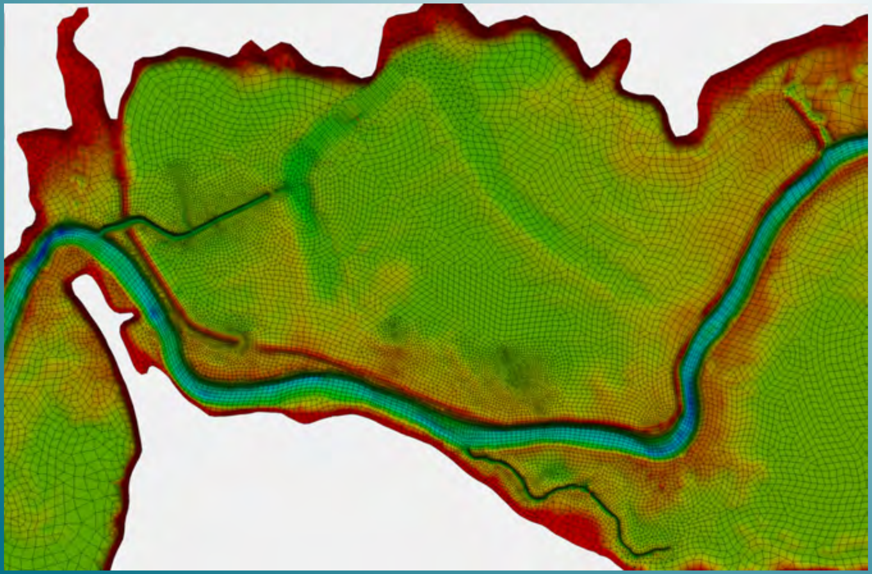
[1] CoastWise partners are presently conducting a study to identify metrics, criteria, and modeling methods well suited to cost-effective evaluation of wetland resilience potential associated with proposed crossing designs. The study is scheduled for completion in 2023.

6 DEVELOPMENT AND EVALUATION OF CONCEPTUAL DESIGN ALTERNATIVES





The previous section of this manual described the process of establishing design criteria for crossing performance. The design criteria are based on objectives identified by the Project Team and informed by what they learned about present and projected tidal conditions, opportunities to encourage structural and ecological resilience, risks to low-lying features of concern, and other site characteristics. Barring unforeseen factors that emerge during the design process, established crossing performance objectives and criteria provide the standard to which Project Teams should refer when developing the design.

Anatomy of a Tidal Road Crossing

Tidal Crossing
The road embankment and crossing structure in the tidal environment.

Crossing Structure
Culvert or bridge that conveys tidal flow through the crossing.

Invert
Inside surface of the bottom of a fully enclosed culvert.

Road Embankment
Fill across tidal area to form the approach sections to a crossing structure.

Causeway
Long road embankment that may include semi-permeable or permeable construction. More common lower down in the estuary.

Approach
Roadway section across the tidal area that leads from the upland area to the open tidal crossing structure. Consists of road embankments or causeways.

This section of the CoastWise Manual concerns the development and evaluation of conceptual design alternatives that best meet performance objectives and design criteria established by the Project Team. This critical step in the design process, often referred to as the feasibility phase, lays the foundation for more detailed design work. Initially, the Project Team will consider important factors influencing the range of likely alternatives for the replacement crossing's potential location, configuration, and planning horizon, among other considerations. They will then develop and evaluate several crossing structure size alternatives to identify which of the alternatives best meet performance objectives and design criteria. A "no action" alternative is also often used to predict crossing performance under future conditions if the structure is not replaced or if it is replaced with a similarly configured structure. Rather than present a comprehensive guide to the conceptual crossing design project phase, this section of the CoastWise manual covers key aspects of the process that distinguish tidal crossing design methods from methods used at non-tidal sites.

6.1 INITIAL CONCEPTUAL DESIGN CONSIDERATIONS

Prior to crossing sizing and other conceptual design activities, the Project Team should consider a few important topics central to identifying the range of crossing alternatives and configurations best suited to achieving established objectives and design criteria.

Tidal Geomorphology

Landscape Setting and Crossing Configuration

Tidal crossing configurations vary but often involve road embankments that intrude into the estuary basin and have a point where a bridge or culvert conveys tidal channel flow (Figure 6.1). Road embankments can extend across substantial distances in the tidal zone, with the bridge or culvert comprising only a very small proportion of that distance. The closer a tidal road crossing is to the sea, the greater the proportion of total wetland area potentially under its influence.

Regardless of a crossing's location within an estuary, crossing configurations that minimize contact with the wetland can usually be expected to provide the best ecological performance. In order of decreasing ecological preference, these include a) full span bridges, b) elevated, flow-through causeways, and c) embankments with adequately sized crossing structures and provisions for sheet flow across the tidal wetland. At tidal marshes where the community's tolerance for road flooding is high, a specially prepared roadbed can be constructed to nearly match the elevation of the marsh surface. These "fair weather" roads facilitate sheet flow by allowing spring tides to overtop the road surface. Appendix B provides more information on crossing structure configurations.

Early in the process of planning a crossing replacement, it is useful to consider whether there is an opportunity to relocate the crossing upstream to reduce the risk of flooding, damage, and ecological impairment. For instance, situat-

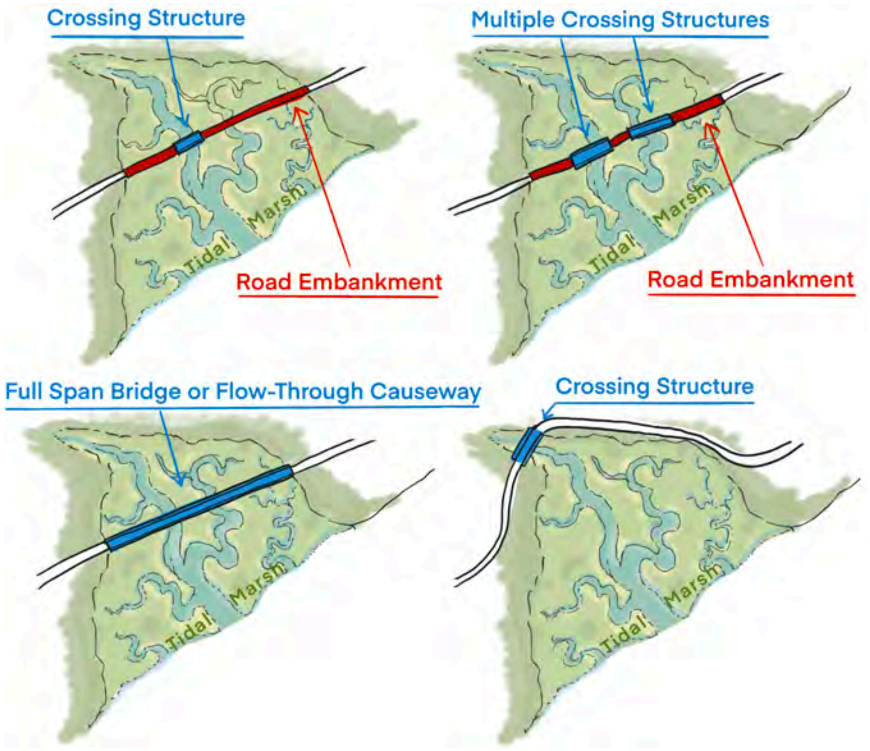


FIGURE 6.1 - Variations of tidal crossing locations and configurations in an estuary setting. In these examples, the top right configuration is preferable to the top left. The bottom two scenarios are preferable to the top two. Figure adapted from Barnard et al. 2013. Illustration by Maisie Richards.

ing the new crossing in a location better matched to the geomorphic context could involve moving the crossing structure within the present road alignment. In some cases, retiring and removing the existing embankment and establishing a new crossing elsewhere may provide the most cost-effective means to reduce risk to the road investment, public welfare, and upstream wetland resilience.

Localized Geomorphic Responses and Habitat Continuity

Geomorphic considerations include alignment with the natural configuration of the tidal channels and whether the crossing structure is at a location of active or potential future channel migration, which may lead to undesired erosion if not addressed. The current and most likely future trend in these factors can be evaluated using aerial photos and other data sources. Another consideration is re-alignment of the crossing's bottom at restored streambed elevations and the potential for the upstream channel to down-cut. The existing and design channel bed profiles should be evaluated carefully to anticipate the potential of downcutting impacts to the crossing.

Most tidal crossings in Maine require replacements with structures that are considerably larger to improve service life, wetland resilience, and other ecological attributes. Bridges, three-sided (open bottom) structures, and fully enclosed culverts may be considered for replacements, but care should be exercised with respect to likely geomorphic responses to proposed designs.

To install a fully enclosed culvert, the entire area within and immediately adjacent to the structure's footprint must be excavated. Once the culvert is in place, the empty area inside it may represent an abrupt shift in conditions compared to the adjacent channel and wetlands. Without placement of natural streambed materials or construction of channel banks inside the structure, the wetted area inside will widen to the span of the structure. In those instances where the new structure is notably wider than the existing channel, the water depth may become considerably shallower than the existing channel when the culvert is not backwatered by the tide or by the downstream channel. Left unaddressed, this condition could interfere with fish and wildlife passage and cause other unintended problems.

In cases where this circumstance applies, a proactive solution involves placing and retaining streambed substrate materials such as gravel and cobbles, and in some instances, boulders, within the structure. The composition of the substrate would be determined based on the individual characteristics of the site. Several road crossing design guidelines offer methods for designing the substrate material, including those published by U.S. Forest Service (2008) and the State of Washington (2013). One important distinction with tidal crossings is that the 'reference reach' method to substrate sizing will not apply. Rather, substrate sizing is based on the hydraulic conditions simulated by the hydraulic or hydrodynamic model.

Incorporation of substrate materials requires specification of a structure type and vertical rise dimension (typically eight feet or taller) to facilitate placement of the materials. Over time, the downstream and upstream channel size will adjust to the removal of the tidal restriction, and the bed and banks within the enclosed structure should be allowed to deform with similar rates to maintain continuity of channel conditions through the crossing. If the feasibility of placing materials within the structure is low or otherwise questionable, a bottomless structure should be considered.

Planning Horizons

Section 5 presented several considerations important to the overall fate of the crossing. These included discussions of the crossing's planning horizon. Carrying this topic forward, the Project Team will now decide if initial designs are intended to meet criteria within a typical (75-year) planning horizon, a short-phased planning horizon, or both, to evaluate which is most preferable.

Crossing Retirement

At this stage of the design process, the Project Team will also confirm whether crossing retirement is a credible option at the site and should be represented among competing design alternatives. If the Project Team decides to pursue a crossing retirement conceptual alternative after the design criteria development project phase, criteria will now have to be developed. At some sites, more than one alternative for crossing retirement may have to be developed to evaluate the relative merits of removing the entire crossing or just a portion.

Low-lying Features of Concern

Also discussed in Section 5, the inevitability of sea level rise and in some cases, unmitigated coastal flooding at sites with low-lying features of concern will influence some road owners to shorten planning horizons or even retire crossings. Built features, properties, and resource uses at or near present and projected high-tide elevations may also lead the Project Teams to develop performance objectives and design criteria that limit the degree of tidal exchange improvements. Other responses to these conditions can include changes to roadway alignments, creation of set-back levees that facilitate some degree of natural processes, and other water control methods. Each of these brings its own unique ecological and social cost-benefit impact to the project.

Vulnerabilities of upstream wetlands with elevation deficits (land subsidence) or other significant impairments and habitats for vulnerable species like saltmarsh and Nelson's sparrows will have been addressed during the development of crossing performance objectives and criteria. These habitats may respond negatively to rapid re-establishment of unimpaired tidal exchange, but they eventually need a full return to unimpaired tidal exchange to maximize their potential to keep pace with sea level rise.

The Project Team should seek expert advice on methods, resources, and likely timescales required to prepare damaged upstream areas (if required) for a return to unimpaired tidal patterns. A complementary element of these efforts may be the design and implementation of crossing configurations that incrementally advance marsh conditions toward a healthy condition, but at a pace that does not risk damage to vulnerable ecological assets.

Lastly, care is required when evaluating the potential influence of any given crossing design alternative on low-lying features of concern relative to the current configuration, so that an appropriate comparison can be made. For example, comparing a new crossing alternative under sea level rise conditions to the existing crossing configuration without sea level rise can overemphasize flooding risk associated with the new crossing. Instead, comparing the conceptual alternative to the existing crossing size and configuration under both present and future conditions provides a more informed assessment of potential impacts based on a valid comparison of conditions.

6.2 DEVELOPMENT OF CONCEPTUAL DESIGN ALTERNATIVES

Establishing the Range of Conceptual Design Alternatives

In the previous subsection, several topics important for setting the context for the conceptual design process were reviewed. With these in mind, the Project Team will decide whether design alternatives under consideration should include:

- Adjustments to the crossing's overall location in the tidal system
- Changes to the crossing structure's specific location and alignment at/near the present site
- Different types of crossing structures
- Integration of secondary flow structures to enhance sheet flow over wetland surfaces
- Phasing of crossing planning horizons/service life and crossing retirement

- Provisions for delayed or incremental tidal exchange improvements, which might be required to allow corrections of wetland elevation deficits or other wetland/habitat modifications before full tidal exchange is restored

Tidal Geomorphic Considerations for Crossing Sizing

Before starting the sizing process begins, it is worth considering some important distinctions between tidal and non-tidal channel formation and how those influence best practices for sizing. In an unrestricted tidal wetland system, the size or geometry of the primary tidal channel correlates with the regular, sustained volumetric tidal exchange, known as the “tidal prism”. Over the long term, this regular, bi-directional tidal exchange does most of the work in shaping the dimensions of the channel. When a tidal restriction reduces the volume of water allowed through the crossing with each tidal cycle, the channel upstream and downstream of the restriction will be smaller than an unrestricted channel in the same setting. In other words, the restrictive crossing directly controls the channel size. When the restriction is removed and tidal exchange is restored, the channel will increase in size.

A recent advancement in non-tidal crossing design in Maine is the Stream Smart method. Stream Smart encourages use of a crossing sizing rule of thumb, where the average bankfull width is multiplied by at least 1.2 to establish a minimum crossing span. For instance, if the average bankfull width is ten feet, a crossing structure span of at least twelve feet would be encouraged during initial sizing procedures. Designing the structure so it exceeds the bankfull width is intended to re-establish and maintain the connectivity of important non-tidal stream processes and aquatic organism passage. This rule of thumb is well regarded because it only requires a few rapidly obtained measurements and simple arithmetic.

Origins of Stream Smart Approach

The Stream Smart approach is Maine’s adaptation of the Stream Simulation design methodology that was developed nationally through decades of development, case study implementation, monitoring, and post-project appraisal. The bankfull width scaling factor adapted from Stream Simulation by different jurisdictions varies from 1 to 2 times bankfull, but most commonly it is within the 1.2 to 1.5 range.

The Stream Smart bankfull width rule of thumb works in non-tidal streams because channel size in those systems is determined solely by the characteristics of the watershed *upstream* of the crossing, including hydrology, sediment supply, and other factors. Except in the area immediately within its influence, the crossing itself does not influence the upstream channel size in non-tidal systems.

In contrast, tidal restrictions suppress channel size, preventing observations of channel dimensions representative of unimpaired conditions. This is one reason why in most cases, tidal crossing design must be approached differently than non-tidal sites. Another reason is the need to manage risks to property, public well-being, and ecological resilience under present and future tidal conditions. This requires a combination of empirical observations and projections based on tidal hydrodynamic modeling analyses that incorporate sea level rise over the service life of the structure.

Starting the Sizing Process

Identifying an adequate crossing structure size is frequently an iterative process. The eventual goal is to identify the most cost-effective size that meets the Project Team’s established design criteria for structural and ecological resilience, both presently and throughout the duration of the planning horizon. The project engineer typically generates an initial size based on one of the methods described below and then evaluates it and competing size alternatives using unsteady state/hydrodynamic modeling. Evaluating the conceptual crossing size and subsequent refinements to the crossing configuration uses these modeling methods to generate sufficient confidence that the preferred alternative adequately manages risk and uncertainty while maximizing social and ecological benefit.

Typical Empirical Approach

Most existing road crossings across present-day tidal wetlands in Maine restrict the tides (Bartow-Gillies 2020). As a result, project sites will often require crossing structures larger than existing ones to accommodate present and projected conditions. Additionally, channel dimensions at tidal restrictions are smaller than they would be under unrestricted conditions. As a result, a recommended initial sizing method is to select a size larger than the existing crossing structure and the existing channel dimensions. Observations of reference sites (discussed below) can inform this initial sizing perspective.

Sizing Constrained by Site Features and/or by Low-Lying Features of Concern

At some sites, low-lying features of concern like infrastructure, properties, and resource uses at or near present elevations of the highest tides are considered constraints on the full re-establishment of tidal exchange. The cost or feasibility to overcome some kinds of constraints can be a factor in constraining crossing size in some cases. As discussed in prior sections, the Project Team should explore all means available to mediate these constraints in ways that allow unimpaired tidal exchange necessary to encourage upstream wetland resilience.

To compare with estimates of structure size determined through modeling applications, some Project Teams may identify a maximum preliminary size based on constraints that clearly limit enlargement of the existing structure. This step includes basic layout, clearance, and orientation considerations. As stated previously, evaluation of sizes identified using this method warrants validation using the tidal hydrodynamic modeling procedures to confirm established performance objectives and design criteria are adequately met.

Preliminary Sizing Estimate Based on Hydraulic Geometry Relationships

Using a Local Reference Site – This preliminary sizing approach uses conditions at a naturally functioning system to estimate the appropriate size of the channel in the wetland slated for crossing replacement. Selection of reference sites requires the input of experienced professionals. Ideally, reference sites should be unimpaired by impacts described so far in this manual, including tidal restrictions. Reference sites should also be located near the project site, similar in basin size, and subject to the same tidal range, similar sedimentary regime, freshwater inflow, and coastal flooding patterns.

When assessments are completed at several locations within the reference site(s), a relationship between natural channel size and tidal prism can be developed using the hydraulic geometry relationship described below. This relationship is used to estimate the natural channel size at the crossing site, both under current conditions, and with increased tidal prism associated with future sea level rise. The initial approximation of crossing size will be larger than the existing and channel size. The initial estimate is refined through tidal hydrodynamic modeling simulations to meet the full design criteria.

Using Previously Established Relationships - In other regions, hydraulic geometry relationships based on data from unrestricted sites have been used to estimate a natural channel size at the project site (Williams et al. 2002). Presently, there are no known relationships derived specifically for northern New England or Maine. Williams *et al.* (2002) developed a set of relationships for the San Francisco Bay area, and others have developed similar relationships for the Columbia River estuary, areas of the Atlantic seaboard, and the United Kingdom. MacBroom and Schiff (2012) provided an overview of selected applications of hydraulic geometry relationships in southern New England and the mid-Atlantic and reported similarities in results to the relationships developed in California. Over time, it may be possible to develop these relationships for Maine using data from various ongoing monitoring efforts.

Advancing to Conceptual Crossing Sizing and Design Alternatives

Following preliminary sizing of the crossing structure, hydrology and hydraulics (H&H) analyses and other project considerations (e.g., crossing location, type, configuration) discussed earlier are used to identify several competing conceptual design alternatives.

Evaluating and comparing the performance of the existing crossing and new alternatives allows the Project Team to evaluate the degree to which each alternative meets established design criteria. H&H analyses also support the detailed Design phase when design refinements are needed. An important feature of the H&H analyses is tidal hydrodynamic modeling. A brief overview of modeling topics is discussed below, but note that tidal modeling is covered in far greater depth in Appendix A.

Tidal Model Selection and Data Requirements

In consultation with the Project Team, the engineer can match the appropriate tidal modeling analyses with the project's site characteristics and stated objectives and criteria. These analyses may typically include one-dimensional (1-D) and two-dimensional (2-D) model simulations. In some cases, simple zero-dimensional (0-D) calculations ("lumped" models) are used, often followed by 1-D or 2-D modeling in the detailed Design phase.

1-D and 2-D hydrodynamic model simulations use computer models to simulate the tidal flow explicitly over the detailed upstream and downstream bathymetry and terrain. The model types "1-D" and "2-D" refer to assumptions in computer programs that simplify the complex tidal systems for the purpose of computational efficiency. Hydrodynamic or unsteady models integrate time-varying tidal water levels that control the bi-directional flow in tidal environments.

In Maine, crossings near the head of tide in large marsh systems, or smaller marsh systems of the fluvial type common in many areas, often can be simulated with the 1-D approach. The underlying assumption with a 1-D model is that the flow direction in the tidal system is predominantly aligned with the direction of the channel. This is often applicable to crossings with a relatively narrow tidal wetland and limited lateral flow patterns. An example is a tidal system that consists primarily of a channel with relatively narrow adjacent overbank or marsh areas, without notable branching channel networks. It is likely that many of Maine's tidally restricted wetlands fall into this category, where the length of the tidal reach is multiple times greater than its width. This would not apply to crossings over narrow tidal areas that connect larger estuarine systems, such as tidal "guts".

Two-dimensional models are required for more complex systems with notable lateral flow patterns and branching channel networks, such as larger marshes and tidal flats. This includes larger tidal systems where the wetland's width is comparable to its length. Two-dimensional models would also be required for marsh systems with multiple primary tidal channels and tidal crossings with multiple hydraulic structures. Within Maine, examples of tidal systems that often will require 2-D models include back-barrier marshes such as those found in southern Maine.

0-D calculations are typically performed using spreadsheet tools or other applications that treat the upstream tidal area as a simplified volumetric basin described by the relationship of area inundated and associated storage volume to specific water levels. These calculations then relate the time-varying water surface elevation and associated storage volume to the volumetric flow rate through the tidal crossing structure itself. The flow hydraulics through the crossing structure are governed by downstream and upstream water levels and the structure geometry. One example of this type of modeling approach is provided by Boumans et al. (2002). These techniques are reserved for smaller sites with simple upstream tidal basins, such as small confined tidal areas near the head of tide, or very small back-barrier tidal wetlands.

The applicability of the various modeling approaches will need to be reviewed for each individual project. To evaluate whether proposed design alternatives meet established crossing performance objectives, it is expected that most projects will use at least 1-D hydrodynamic modeling. One example modeling package of this type is the U.S. Army Corps of Engineers' HEC-RAS (presently, version 6.3), but others are also available and are listed in Appendix A.

Tidal modeling procedures rely on tidal time series based on water level monitoring upstream and downstream of the crossing, elevation surveys, and terrain/bathymetry data to develop and calibrate the existing conditions model. Where applicable, freshwater inflow to the system is included in simulations by means of observed data if available or estimated by means of standard freshwater hydrology analytical methods. Proposed conditions simulations entail adjusting the existing conditions model terrain and structure definition to represent each design alternative.

Tidal Time Series for Modeling

In addition to typical tidal time series patterns based on the project's water level monitoring, design tide time series are required. These are developed for the design alternative simulations and comprise a range of tidal conditions, including the Highest Astronomical Tide (HAsT) (or the typically similar 99% annual exceedance probability (AEP) tide) and coastal flood events of varying annual recurrence interval. The HAsT and/or 99% AEP tide are often used for sizing of crossing structures to ensure upstream wetland resiliency objectives will be met, whereas coastal flood events may be utilized to determine the design elevation for the crossing embankment and roadway, for evaluating scour within the crossing structure, or other resiliency considerations.

Development of these design tides often involves correlation of the tidal water level data collected at the site to that of a nearby long-term recording station. Based on this correlation, tide time series are extrapolated for these infrequent conditions, which may not have occurred during the water level data collection period.

Correlating the collected local tide data to an applicable recording station to support extrapolation of longer periods of tidal time series requires care. The correlation should be accomplished based on the time period common to both the local site data and the long-term station. The strength of the correlation will increase with increased length of common record. Following extrapolation of the long-term time series to the project site, the error in the correlated time series should always be assessed and reviewed to determine the acceptability of the extrapolated time series for project use. In addition, differing correlations may be required for differing portions of the tide range. For example, isolating and correlating the peak tides, or a subset of peak tides, may be most applicable to developing an estimate of infrequent peak tides such as the HAsT.

The design tide time series are prepared for present conditions and for conditions projected at the conclusion of the structure's expected service life, which includes integration of sea level rise. Design flood time series of applicable storm recurrence intervals are added to the simulations for design criteria related to roadway height, crossing stability under flood conditions, low-lying features of concern, and certain ecological considerations. As with existing conditions simulations, freshwater inflow is added to the simulations if applicable and estimated based on standard freshwater hydrologic methods.

Wetland Surface Accretion Considerations

Some intertidal systems, like salt marshes and relatively fine textured flats (e.g., mud, sand), rely on accretion of materials to the wetland surface to keep pace with sea level rise (Bartholdy 2012, Fujii 2012). Conditions for optimal accretion include unimpaired tidal exchange at the highest projected tides during the proposed crossing structure's service life. During modeling procedures to identify a structure size facilitating unimpaired tidal exchange, the degree of assumed future accretion influences the simulated upstream tidal volume, and the frequency, duration, and depth of upstream inundation of the marsh surface.

The diverse factors influencing accretion at site-specific locations complicates projections of accretion rates that individual marshes will experience. Given the uncertainties, one method for considering accretion in structure sizing is to assume the present wetland surface elevation represents the future elevation (i.e., accretion is minimal). In this approach, the simulated volume of tidal exchange that must be accommodated by the new crossing is likely to exceed actual future tidal exchange requirements, which is akin to applying a "safety" factor.

In some cases, this approach may lead to conservatively large structure sizing results, which is favorable for ecological resilience, but in other cases may present challenges for project funding. Based on the specifics of each project, it may be important to assign potential future wetland surface accretion rates to model simulations. These accretion values may be based on existing data (if available) or hypothetical rates, such as estimating that accretion will match sea level rise, or that accretion will occur at half of the rate of sea level rise. The number of accretion scenarios simulated and compared depends on the conservation value of the upstream wetland, tolerance for ecological risk, or other site-specific factors. Incorporation of wetland surface accretion into modeling simulations requires specialized expertise.

Qualifications of Technical Providers

Due to the specialized nature of tidal crossing study and design, hiring qualified technical providers with substantial experience in estuary settings is crucial. Important areas of expertise include estuary hydrology and hydraulics, integration of sea level rise into project design, unsteady state hydrodynamic modeling of estuary systems, crossing design and construction experience for estuary settings, and other considerations. In addition, cross-disciplinary experience is important, including working knowledge of tidal wetland ecology and estuary geomorphology.

6.3 EVALUATION AND SELECTION OF CONCEPTUAL DESIGN ALTERNATIVES

Evaluating and selecting design alternatives is largely a matter of comparing the extent to which each alternative meets design criteria for structural and ecological resilience. Key considerations during this process are potential or demonstrated constraints on upsizing the crossing as a result of low-lying features of interest like infrastructure, resource uses, and highly impaired wetlands and vulnerable species habitats. The alternatives analysis can also include other factors such as real-time impacts to traffic patterns and whether a particular structure type is feasible given the soil conditions at the site. Generally, the overall goal is to identify the most cost-effective design alternative that best meets all established objectives and design criteria.

Recommended Modeling Products to Evaluate Design Alternatives

Objective, transparent decisions and clear documentation of decision-making are extremely important to the evaluation of design alternatives. Consequently, it is necessary that data products supporting comparisons of each alternative's performance are readily available.

For detailed structural and scour elements of crossing designs, sea level rise-adjusted tidal flood hydrographs (time-varying flood levels) should be simulated in addition to the static maximum flood inundation elevations described earlier. The critical design threshold or greatest scour potential may develop on the flood or ebb as the upstream tidal basin fills or drains, with an associated difference in water level across the crossing structure. Flood hydrographs are supplied by actual historical storm events, or in their absence through generation of synthetic tidal flood event hydrographs. Sea level rise based on the Project Team's selection of a scenario is added to these hydrographs to represent the future project conditions. More details on simulation approaches are included in Appendix A.

In support of ecological crossing performance objectives, modeling is used to identify crossing structure sizes and configurations most able to cost-effectively encourage upstream wetland resilience for the service life of the structure. For the crossing to adequately encourage wetland resilience, the upstream wetland should experience unrestricted tidal inundation and drainage at the highest tides of the year, such as the HAsT and/or 99% exceedence peak tide. This allows peak performance of resilience processes like marsh surface accretion, which are necessary for the wetland to keep pace with sea level rise. Synchrony in the timing and elevation of modeled tide water levels (high and low tides, and along flood and ebb running tides) upstream and downstream of the crossing is presently the most cost-effective indicator of unrestricted tidal exchange available.

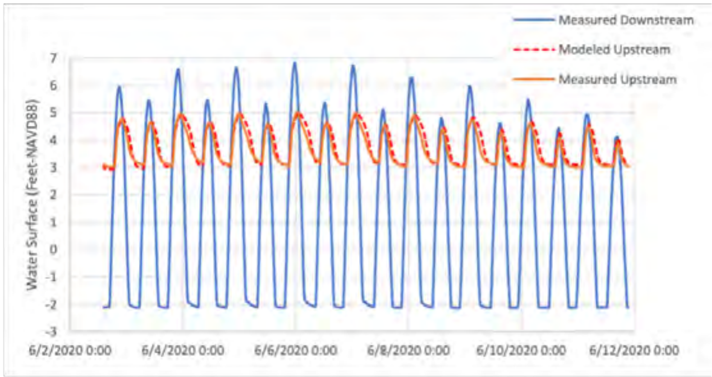


FIGURE 6.2 - Model calibration hydrograph, courtesy of Acadia Civil Works.

In analyses leading to products recommended below, a comparison is conducted between modeling simulations of 1) upstream tides with the proposed structure in place and 2) unrestricted tides represented by either downstream conditions or the conditions associated with no structure in place. Simulations are run under present conditions plus those projected for the conclusion of the structure's expected service life, and they may sometimes include an intermediate timestep.

Recommended products of modeling for evaluating design alternatives are provided below and included in the alternatives analysis report:

1. Model Calibration - Provide superimposed hydrographs of observed and modeled conditions under present conditions (Figure 6.2), an error analysis if applicable, and brief discussion to describe model fit.
2. Alternatives Evaluation/Analysis - Each analysis below should consider at least two sizing alternatives, but preferably more. These consist of the present crossing configuration and at least three larger alternatives. Each alternative is evaluated in the context of specified design tides, typically:
    - Present HAsT (or 99% annual exceedance probability (AEP) tide, if available), plus upstream storm event inflow
    - Future (typical year is 2100) HAsT (or 99% annual exceedance probability tide, if available), plus upstream storm event inflow.

CoastWise partners are presently conducting a study to refine methods for establishing resilience criteria and evaluating crossing size alternatives.

Scheduled for completion in 2023, this work is expected to test the effectiveness and practicality of metrics and criteria use to evaluate the influence of crossing size and performance on wetland resilience. It will also compare the effectiveness of modeling approaches for wetlands having different characteristics.

Findings of the study will be used to inform updates to the CoastWise Approach.

Tide elevations are informed by the CoastWise risk-based sea level rise scenario selection process.

a. Crossing Resilience - These considerations influence height of the embankment and capacity of the structure, to ensure crossing objectives are met. To best meet Project Team evaluation needs, conceptual design exhibits/drawings and mapping should project the degree to which the present crossing configuration and proposed crossing alternatives will perform under conditions now and in the future. Specific annotations to drawings include elevations representing:
    i. Local tidal datums
    ii. Design Flood Elevation, and other relevant/applicable coastal storm flood elevations
    iii. Existing channel cross section and tidal wetland elevation

b. Low-Lying Features of Interest - Provide elevation plots and mapping that clearly identify changes in tidal inundation, especially on private property, at current and future sea levels, for typical (e.g., MHHW, HAsT) and storm tides (100-year return period storm, and more frequent storms, such as 5-year, 10-year and 25-year return period storms). Mapping should also include the locations and elevations of infra- structure, resource uses, and habitats at risk of undesired flooding. Projections should estimate the degree to which the present crossing configuration and proposed crossing alternatives will mediate risk under conditions now and in the future.

c. Ecological Resilience - Where site conditions allow, at least one of the design alternatives should meet optimal wetland resilience performance criteria. For optimal performance, simulated upstream and downstream water levels during the highest and lowest points of the design tide match (e.g., hydraulic head differential = 0 feet) and occur at the same time, with differential as near to zero as possible along the intervening flood and ebb running tides. This indicates that the crossing structure does not impair tidal exchange and is therefore tidally "transparent". Other ecological criteria may include aquatic organism passage (AOP) for identified target species. All analyses below are conducted under present and projected conditions during the crossing's service life.
    i. Crossing Size Optimization - Modeled water level simulations are used to create crossing size optimization graphs (see Figure 5.4 for an example) that illustrate the relationship between structure size (e.g., open end area, width for rectangular openings or diameter for round openings) and upstream-downstream hydraulic head differential (HHD). The two ways to calculate HHD (IHHD and PHHD) are defined in Section 5.4. For a given HHD value (e.g., 3-inch difference), PHHD will result in a smaller structure as indicated in Figure 5.4 The range of sizes under consideration and shown in the graphs should include the existing structure size, plus enough additional sizes to establish smooth HHD-vs-size curves that extend to include HHD values as near to zero as practicable. Each optimization graph should be clearly labeled with the design tide (HAsT/99% AEP plus storm event), sea level rise scenario, and timing (e.g., 2050, 2100, other).
    ii. Hydrograph Plots and Data - Provide superimposed upstream and downstream hydrographs and supporting data corresponding to the crossing size likely to represent the preferred alternative. Hydrographs should include the elevations of local tidal datums (e.g., MLW, MHW, MHHW, and HAsT/99% AEP). For the present conditions hydrograph, the range and average of representative wetland surface elevations outside of the channel both up and downstream of the crossing should also be indicated.
    iii. Tidal Transparency Summary and Evaluation - For the preferred size alternative(s) under consideration, provide a table or graphic that compares high tide and low tide elevations and timing (at HAsT/99% AEP) associated with 1) the proposed structure in place and 2) either no structure in place or the downstream condition. These are provided to represent the design tide under present and future conditions.
    iv. Hydraulic Head Differential - For PHHD, identify the timing and single maximum difference between corresponding peak water levels. For IHHD, identify the timing and amount of the largest difference between upstream-downstream water levels during the continuous time series including the high and low tides, and the intervening flood and ebb running tides.
    v. Aquatic Organism Passage - Provide estimates of in-structure current velocities and other site-specific metrics relevant to the assessment of AOP objectives.

TABLE 6.1 - Example of a simplified design alternatives quick reference table.

	RELATIVE PERFORMANCE (Ratings Include: Y/N, Good/Better/Best, Low/Med/High)										
ALTERNATIVE	Flood Capacity	Scour Potential	Property Impacts	Species Impacts	Wetland Impacts	Wetland Benefits	Improves Tidal Exchange	Marsh Migration	Aquatic Organism Passage	Construction Complexity	Cost
Alternative 1											
Alternative 2											
Alternative 3											

d. Other Topics - This can include topics such as potential for head-cutting or other concerns.

Table 6.1 provides an example of a simplified summary table where relative qualitative performance rankings for each alternative are documented after a more detailed analysis based on each specific design criterion.

Following the detailed Feasibility and Alternatives Analysis phase tasks, the Project Team selects an alternative to advance toward final design.

6.4 TYPICAL ROLES AND TIMELINES

The development and evaluation of conceptual design alternatives is accomplished integrating the input of Town staff, other Project Team members, and local stakeholders, with technical and assessment tasks often completed by engineering consultants. CoastWise Technical Partners may be available to help advise stakeholders through the evaluation process, and to assist the Town in selection of a preferred design based on the completed analyses.

Timelines will vary with the complexity of the crossing site and stated project objectives. Between confirmation of objectives, development of concept alternatives, and completion of the Feasibility and Alternatives Analysis phase, allocation of approximately two to four months is suggested to complete this phase of a CoastWise project. Depending on the complexity of the project setting and potential constraints, selection of a preferred alternative can require considerable deliberation and stakeholder outreach. It is important to allocate a generous amount of time to allow a participatory and transparent decision-making process.

The ideal timing for developing and evaluating conceptual designs varies but should be considered in light of available of technical resources and funding for this and subsequent project phases. Many state, federal, and regional resource agencies and NGO restoration experts tend to have very busy summer field seasons. Road managers should plan for early coordination with these resources to find strategic opportunities to tap into their experience. Funding opportunities for subsequent project phases may arise throughout the year. Prompt and early completion of this project phase is recommended, at least one year before the desired start of project construction, and longer if fundraising for project construction is required.

6.5 ADDITIONAL RESOURCES

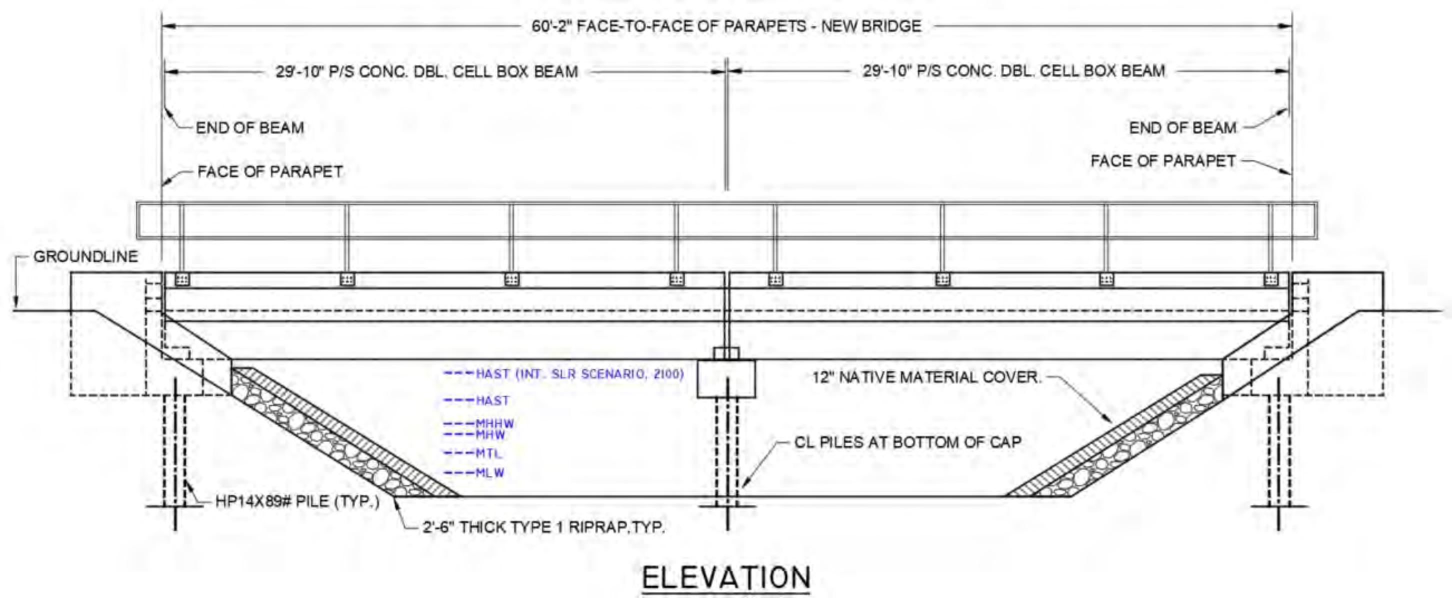
The following resources can be used as supplements to Appendix B of the CoastWise guidelines.

Overview of Hydrologic Analysis of Tidal Wetland Restoration

Tidal Hydrology, Hydraulics and Scour at Bridges (2004)
Overview of hydrologic analysis, in particular tidal analysis, for application to highway planning in the coastal environment

Highways in the Coastal Environment (2008)
Highways in the Coastal Environment (2020)
Newer editions of the 2004 document listed above, introducing sea-level rise and climate change concepts but with less tide analysis information

7 DESIGN AND PERMITTING



After the analyses and evaluation of conceptual design alternatives is completed, the preferred alternative is selected and advanced through the more detailed design and permitting phase of the project. This section focuses on elements of the process that distinguish tidal from non-tidal crossings.

7.1 PRELIMINARY ENGINEERING DESIGN

The Preliminary Design phase transitions the project from conceptual to detailed design procedures and development of construction plans and specifications. Project plans advance from schematics and sketches to engineering design and construction drawing format, typically resulting in 30%-complete drawings, a basis of design report, and the engineer's initial opinion of probable cost (EOPC). Refinements to the selected alternative are developed if needed, finalizing the overall scope for the project. Meetings with regulatory agencies such as the U. S. Army Corps of Engineers and Maine DEP are also resumed at this stage to confirm requirements for project permitting. The Preliminary Design phase concludes with a meeting to update the Project Team on progress and next steps.

Hydrology and Hydraulic Design

Supplemental hydrology and hydraulic (H&H) work is often required during this stage of the design process to confirm that structural and ecological design criteria (Table 7.1) are met, but this depends on the level of detail in conceptual alternative(s) and degree of refinements made to the design as it advances. Design refinements can include adjustments made as a result of the environmental permitting process. Sections A-6 and A-7 of Appendix A provide more details on H&H analysis to support the design process.

Geotechnical Design

Geotechnical design for the crossing is also advanced in the Preliminary Design phase to supplement earlier work during the Feasibility and Alternatives Analysis phase phase. In some instances, this may include supplemental field exploration. Soil or rock properties are reviewed to determine the most viable foundation types and to facilitate the foundation and slope stability design. Lastly, subsurface conditions, including presence of ledge, are evaluated to inform potential construction means and methods for temporary facilities such as coffer dams.

Structural Design

Construction materials are selected at this stage, based on the planning horizon, environmental conditions, and hydraulic and stability design. The engineering team determines whether materials such as aluminum are viable and/or whether to upgrade to more durable concrete and corrosion-proof reinforcing steel (e.g., stainless). This upgrade can add five to ten percent to the total project cost, or more, depending on project size and characteristics.

As discussed in Section 6, project planning will sometimes result in a phased approach for crossing replacement. In these cases, the structural design will consider design adaptations to accommodate future expansion. Additional detail on crossing structure options can be found in Appendix B.

Supplemental Restoration Design

Lastly, planning for implementation of supplemental restoration actions in the wetland will continue at this stage of the process on a site-by-site basis. These actions may include mediation of wetland surface elevation deficits caused by tidal restrictions, agricultural ditching and diking, or impoundments. They may also involve shaping or grading tidal channels, enhancements to habitats of vulnerable species, or mitigation of potential impacts associated with release of accumulated sediments.

7.2 DETAILED ENGINEERING DESIGN

This phase continues through the final design, permitting, and development of construction documents, leading to bidding and construction. The Project Team reviews progress of the developing design two or three times during this process through updates to the plans, design report, and EOPC. Each update provides an opportunity for Project Team consultation.

The 60% progress plans are most often used as the basis of project permitting, and include draft erosion, sediment and pollution control, water management, and sequencing details, along with depiction of potential regulatory impacts. Specific traffic control and detour details (if required) are also included.

Development of structural design elements continues during this step, including structural sizing to carry design loads, materials considerations relative to environmental factors (particularly salt or brackish water), and detail-ing to support project bidding. Initial project specifications are developed for the 60% complete design package and will continue development for the final package. In addition to regulatory and Project Team reviews, MaineDOT reviews (if required) will commence and/or continue through this phase. A near final (85%-90% complete) progress plan set may precede the final (100% complete) version.

7.3 TYPICALLY REQUIRED PERMITS & CONSULTATIONS

Permitting includes a combination of federal, state, and local permits, along with attendant agency consultations required by some permits. An overview of the permit authorizations potentially required are summarized in Table 7.1. It is best to contact relevant authorities early in project planning stages to confirm current regulatory requirements. To facilitate a more efficient project design, early coordination with natural resource agency habitat and species experts is also recommended.

Permitting Pre-Application Review

Coordination with regulatory officials during preliminary stages of the engineering design process allows them to inform the project before major engineering investments have already been expended. It also helps projects advance through the permitting process without avoidable delays.

As stated earlier in this manual, early determination of whether federal or State of Maine listed species of heightened conservation need are potentially present can help avoid permitting delays. If federally listed species are potentially present, an Endangered Species Act Section 7 consultation may be required. Likewise, the presence of habitats subject to heightened management interest can also trigger project delays if not identified and addressed early in the project process. Table 7.1 provides links to online resources to identify state and federal listed species and essential habitats potentially relevant to each project. Protected species and habitats change over time, and federal and state resource agencies should be directly consulted to confirm their presence.

7.4 TYPICAL ROLES AND TIMELINES

The Design phase of a CoastWise project may be managed by a town engineer, contracted consulting engineer, or other person qualified in project management. Regardless of who leads this project phase, the lead engineer is responsible for the technical design and often the permitting activities. CoastWise Technical Partners are also available to provide guidance during each of these activities.

Required design timelines can vary greatly depending on the size and complexity of the project. For very small tidal culvert crossings (spanning less than ten feet) with reduced complexity, design iterations may be limited to a single progress submittal and a final design submittal. This could be completed within two to three months. For minor span and bridge crossings where MaineDOT review will be required, and where permitting is more complex, multiple design submittals (e.g., 30%, 60%, 90% and 100% complete progress plans) will likely be required. This more involved design process may take six to twelve months.

Permitting timelines similarly vary with structure size and complexity. For less complex sites outside of designated critical habitat for species listed by the Endangered Species Act, permitting may be completed within six months. For larger sites within designated critical habitat, the time required for permitting may be up to one year from start to finish, including assembly of materials, review by the agencies, and issuance of permits. As noted previously, pre-application meetings should be held with regulatory and resource agencies early in the project and during Design phase initiation. Regulatory agencies (Corps and Maine DEP) often encourage intra-agency site visits.

Ideally, the Design phase is completed at least six months before construction is planned to allow for a deliberate project bidding phase that provides the most cost-effective quotes. Permitting activities should commence six months to one year before project bidding, depending on project complexity, to secure permits by the time the project is advertised for bidding. See discussion of construction timing in the next section of this manual.

TABLE 7.1 - Overview of permits or consultations potentially needed for typical tidal road crossing projects.

	PERMIT	REGULATORY AUTHORITY	NOTES AND LINKS
PRIMARY	**Natural Resources Protection Act (NRPA)**	Maine DEP	Under current regulations, any change in dimensions of a tidal crossing requires an individual NRPA permit. Requires mapping of wetlands and ordinary high water or HAT/HAST elevation near the site, and other project design information. May require compensation if fill of the protected resource is required, especially if the project has little restoration benefit. NRPA also satisfies Section 401 of the federal Clean Water Act Plan for six months duration to secure project permit. https://www.maine.gov/dep/land/nrpa/index.html https://www.maine.gov/dep/water/wd/wqc/ https://www.maine.gov/ifw/fish-wildlife/wildlife/endangered-threatened-species/essential-wildlife-habitat/index.html
	Section 404 Clean Water Act (CWA 404) and Section 10 Rivers and Harbors Act	U.S. Army Corps of Engineers	Required for any temporary/permanent discharge (dredge/fill) below the high tide line/in adjacent wetlands, and for work below the mean high water mark. Projects using CoastWise practices likely eligible under the Maine General Permits. Decision generally within sixty days of complete application. https://www.nae.usace.army.mil/Missions/Regulatory/State-General-Permits/Maine-General-Permit/ Permit applications shall include scaled and dimensioned plans. See permit application for specific requirements. Resource impacts exceeding Maine General Permits Self-Verification thresholds may be subject to compensatory mitigation (e.g., salt marsh, eelgrass, mudflat). Potential effect to federally listed species will require consultation under the Endangered Species Act. Adverse effect to Essential Fish Habitat will require consultation under the Magnuson-Stevens Act. Consultation under these acts will extend the permitting timeframe. Plan for six months to one year from start to finish, depending on consultation requirements. CWA Section 401 requirements covered by NRPA.
	Floodplain (FEMA) or Shoreland Zoning (SZO)	Individual Municipality	May require land use or planning board review. May require shoreland zone or floodplain permit. May require hydraulic evaluation for potential impacts to FEMA base flood elevation (BFE). See individual municipality for requirements. Plan for three to six months duration. https://www.maine.gov/dep/land/slz/
SECONDARY	**National Historic Preservation Act (NHPA)**	Maine Historic Preservation Commission (MHPC), Tribal Historic Preservation Officers (THPOs) In Maine, SHPO is the Maine Historic Preservation Commission. There are five THPOs; see USACE Maine General Permit for contact information.	Federal action (e.g., U.S. Army Corps of Engineers permit, federal funding) must comply with the NHPA. Applicants MUST notify MHPC and all five THPOs of Maine about their project for the identification of historic properties. Architectural, archeological, and/or cultural surveys may be required if there is potential to affect a historic property. Request for a survey should be coordinated with the federal action agency prior to scheduling. Any work that has an adverse effect on a historic property will require consultation under the NHPA. Information regarding historic properties under the Corps may be found at: https://www.nae.usace.army.mil/Missions/Regulatory/State-General-Permits/Maine-General-Permit/. The Maine Historic Preservation Commission can be found at: https://www.maine.gov/mhpc/programs/project-review
	Maine Construction General Permit	Maine DEP	Provides coverage under the National Pollution Discharge Elimination System for ground-disturbing activity in excess of one acre. Construction contractor to file Notice of Intent with Maine DEP. https://www.maine.gov/dep/land/stormwater/construction.html
	Traffic Analysis Movement Evaluation	MaineDOT	May be required for detours or other traffic management on busier roads. https://www.maine.gov/mdot/traffic/
FEDERAL CONSULTATIONS	**Federal Endangered Species Act (ESA)**	NOAA Fisheries (NMFS), U.S. Fish and Wildlife Service	Federal action (e.g., Corps permit, federal funding) must comply with the ESA. Potentially relevant listed species along Maine's coast include piping plover, roseate tern, red knot, Atlantic salmon, Atlantic sturgeon, shortnose sturgeon, and marine turtles. Work that may affect a federally listed species/designated critical habitat requires ESA consultation, which may be informal or elevated to formal if an adverse effect is expected. Where there is federal funding, consultation initiated by the Corps. Consultation is responsibility of the federal action agency. Applicants may be asked to provide support materials for consultation. Consultation typically through USFWS or NOAA, depending on which agency has a more prominent role in the project. Identify listed species that may be present in the project's action area: https://ecos.fws.gov/ipac/; https://noaa.maps.arcgis.com/apps/webappviewer/index.html Plan for six months to one-year duration for coordination and consultation (if required).
	General Bridge Act of 1946 **Rivers and Harbors Safety Act, Section 9** **Coast Guard Authorization Act of 1982**	United States Coast Guard	Bridge construction or modification across navigable waters as defined by 33 CFR 2.36 requires Coast Guard authorization. If the navigability of a waterway is in question, consult the Coast Guard's District Bridge Office to determine if a permit is required. The Bridge Project Questionnaire should be submitted with all navigability determination requests. Plan for thirty days to receive a navigability determination or permit exemption notification. If a bridge permit is required, consult the Bridge Permit Application Process website: https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Prevention-Policy-CG-5P/Marine-Transportation-Systems-CG-5PW/Office-of-Bridge-Programs/Bridge-Permit-Application-Process/ This guide explains the permitting process and details the list of plans, documents, and support materials required to obtain a Coast Guard Bridge Permit. Plan for 180 days for a Bridge Permit to be issued once a complete permit application has been submitted.
	Magnuson-Stevens Fishery Conservation and Management Act (Essential Fish Habitat)	NOAA Fisheries (NMFS)	Federal action (e.g., COE permit, federal funding) must comply with the Magnuson-Stevens Act. Essential Fish Habitat (EFH) includes salt marsh, mudflat, eelgrass, intertidal habitat, hard bottom habitat, and areas containing shellfish. Adverse effect to EFH will require consultation under the Magnuson-Stevens Act. Consultation is responsibility of the federal action agency. Applicants may be asked to provide support materials for consultation. The following link can help identify EFH at the project site: https://www.habitat.noaa.gov/application/efhmapper/index.html Plan for six months to one-year duration for coordination and consultation (if required).

8 CONSTRUCTION

Photo by Jacob Aman

THE CONSTRUCTION PHASE INVOLVES THE PROJECT BIDDING, contracting, and crossing installation. The following section focuses on identifying some key elements of this project phase, with special attention to those that differ from non-tidal crossings. Key topics include:

- Project contracting and management
- Construction time of year considerations
- Managing tidal waters at the site during construction
- Practices to avoid or lessen ecological impacts during construction
- Onsite construction observation and administration

8.1 CONSTRUCTION CONTRACTOR SELECTION AND CONTRACTING

Contractor Qualifications

Just like when building a home, a bridge, or a fish ladder, hiring a firm with the right kind of expertise for the job is essential to tidal crossing project success. Many facets of tidal crossing projects are similar to other types of culvert or bridge construction, such as the materials and methods of structure construction, and the interaction with roadways and utilities. There are, however, several unique and important attributes of tidal crossing replacements where the selected project contractor should demonstrate expertise. These include project sequencing to accommodate tides, storms, time of year restrictions for fish and wildlife, and limiting disruptions to emergency response, community asset access, and traffic flow, all within a tidal context.

Demonstrated experience using effective best management practices to limit construction impacts on the environment is another important qualification. Additionally, if the tidal crossing project incorporates restoration actions to reverse damages in adjacent tidal wetlands, experience and capacity for working effectively in these challenging environments is essential. Potential contractors should provide recent references from these types of projects.

Project Bidding

Depending on the road owner's resources and procurement requirements, smaller culvert replacements may be contracted directly with qualified contractors without requiring project bidding. These projects still require strict adherence to construction best management practices, water management, and diligent attention to the range of challenges encountered in the tidal environment. Where projects warrant a public bid process, selecting the appropriate method of bidding and contracting for the project helps ensure successful implementation. The best approach varies according to road ownership, project size, and complexity. Table 8.1 provides an overview of procurement options.

TABLE 8.1 - Overview of approaches to project construction.

METHOD	TYPICAL PROJECT SIZE	FEATURES
Time and Materials (T&M)	Small culvert spans	Informal approach for small projects Contractor hired directly and paid for labor and materials costs as they are encumbered
Design-Bid-Build (DBB)	Small to large culvert spans, minor spans, bridges	Common method of project completion 100% complete design released for public or pre-qualified invitation bidding
Request for Proposals (RFP)	Small to moderate culvert spans, minor spans, small bridges	Similar to Design-Bid-Build, but bidding process may be less formal May involve sole source selection Often the approach for private projects
Design-Build (DB)	Small to large culvert spans, minor spans, bridges	Designer and contractor collaborate on project delivery with contractor lead or engineer lead Typically used to enhance project schedule In some instances, may result in cost savings from streamlined design May provide design/construction flexibility to adapt to site conditions May still require completion of final design documents
Construction Manager General Contractor (CMGC)	Major projects bridges	Contractor lead Partnership between the municipality, engineer, and contractor May require separate design packages for separate project phases Contractor leads solicitation of specialty subcontractors

8.2 PROJECT SEQUENCING

Close attention to project sequencing is important due to the challenges of tidal crossing construction, which integrates time of year restrictions associated with seasonal fish and wildlife habitat use and ever-changing tide elevations. Traffic considerations are also a key element of project planning.

Time-of-Year Restrictions

Construction in estuary settings may be limited to certain times of the year to avoid conflicts between fish and wildlife habitat use and construction activities potentially incompatible with that use. The available timing may vary with project site, and final requirements are determined by the permitting process through consultation with Maine Department of Marine Resources, Maine Department of Inland Fisheries and Wildlife, National Marine Fisheries Service, and United States Fish and Wildlife Service.

In estuary environments where Atlantic salmon and river herring may be present, in-water construction may be required between early November and early April. If rainbow smelt are present, the available window may close earlier at the beginning of March, depending on location along the coast. However, if it can be demonstrated that impacts on these species can be avoided, resource agencies may consider allowing summer construction that is more forgiving to construction activities, on a case-by-case basis.

The late fall, winter, and early spring periods for construction present challenges to construction work. Worksite productivity often dips through these months due to colder temperatures, inclement weather, and reduced daylight. Construction materials may have limited availability during the winter, including asphalt. The potential also exists for increased freshwater inflows at some project locations, especially during the fall and spring rainy seasons. If summer construction is not permitted, these factors should be integrated in project planning and expected durations of construction. Early coordination with resource agency species experts is recommended to explore options for avoiding unnecessary project delays related to time of year restrictions.

Sequencing Construction with Tide Cycles

Planning for tidal cycles is one of the most critical elements in the construction of tidal crossing projects. Water levels fluctuate between high and low tides twice daily, with the timing of the tides shifting approximately fifty minutes later each day. The range in tides in lower portions of estuaries varies along the coast, from nine to eleven feet along the southern Maine coast, to nearly twenty feet along the Down East coast near Canada. In naturally restricted embayments (e.g., Merrymeeting Bay, Taunton Bay), average tidal range can be considerably less and tidal range in estuaries typically decreases with proximity to the natural head of tide.

Tidal crossing projects typically involve excavations and construction at elevations at or well below the low-tide elevation. Generally, this combination of factors requires coffer dams to isolate work areas from tidal action over the full range of anticipated tides. Some methods of construction call for dry work areas during key stages and require special sequencing. At many sites, this will require installation of sheet pile coffer dams. In these cases, it may be also necessary to provide a bypass culvert to provide water to upstream wetlands to prevent temporary impacts.

Depending on the size and complexity of the site, control of water facilities may need to be managed and adapted frequently during construction. Plans for dewatering and sediment control require careful consideration by the contractor and scrutiny by the Project Team and permitting agencies.

Along some areas of the coast however, it may be extremely difficult or prohibitively expensive to install coffer dams that are effective over the full tide range, including in part due to subsurface ground conditions and the presence of ledge. If this is the case, it will be necessary to stage construction in a way that work completed at low tides is not damaged by flooding during higher tide levels.

For project sites where it is not feasible to isolate the work area from tidal flow, construction activities need to maximize efficiency during low tide periods and shift operations to higher elevations or plan for temporary work stoppage during the high tides. In this case, spring tide cycles can be helpful for earthwork and grading at or below MLLW, to take advantage of the lower low tides.

For project sites that are isolated from flow, or work performed at higher tidal elevations, the neap tide phase will minimize the potential for higher high tides that create added water management challenges. However, project durations typically last longer than a single spring or neap tide phase, underscoring the need for strategic sequencing of construction activities.

Traffic Management

The goal for traffic management should be to limit traffic disruption to the minimum duration necessary to construct the project. Early coordination with the relevant municipalities and MaineDOT is essential. This starts during the Design phase by reviewing the DOT work plan and consulting other sources to learn about relevant road construction scheduled to occur at the same time. Coordination with other planned construction projects may be necessary.

FIGURE 8.1 - When tidal crossings are replaced in primary traffic corridors, temporary traffic bypasses may be required. This temporary bypass along Route 1 in Woolwich, Maine, was used during bridge replacement and construction to restore tidal flow to Back River Creek Marsh. Photo by Michael Burke.

It may be possible to sequence construction to minimize road closure with partial bypass road alignments or single lane closures, along with dedicated flagging operations. Some tidal structure crossing types may lend themselves to this approach better than others, such as reinforced concrete box culverts or similar modular construction that does not require continuous cast-in-place foundations or footers. Some traffic bypass arrangements may result in temporary, incremental impacts to adjacent wetlands or habitat. These potential impacts need to be considered in project planning and permitting, and also weighed against the inconvenience or feasibility of a full road closure.

Full road closures with detours may be required in some instances. Requirements for traffic control, and in particular detour requirements, need approval during the design and permitting phase. Traffic control performance specifications must be defined in the construction documents, with the selected contractor submitting a formal traffic control plan to the engineer and the town road commissioner, and in some instances to MaineDOT, for review and approval. Traffic control provisions during construction need to comply with the Manual of Uniform Traffic Control Devices published by the U.S. Department of Transportation (2009).

Useful Links

Manual of Uniform Traffic Control Devices

MaineDOT Work Plan

8.3 PROJECT-SPECIFIC BEST MANAGEMENT PRACTICES

Project-specific best management practices (BMPs) help ensure that collateral impacts to the environment are avoided or limited during tidal crossing construction. Important areas of consideration include erosion, sediment, and pollution control, water management, and protection of fish and wildlife.

Erosion, Sediment and Pollution Control

Erosion, sediment, and pollution control involves techniques to prevent the discharge of nuisance sediment or harmful pollution to sensitive environments that surround the tidal crossing project. Minimum requirements are established by the project permits, which will include an erosion, sediment, and pollution control plan that details the means and methods to be implemented during construction. Often, a draft plan is included in the design documents, with a final plan submitted by the contractor once engaged to complete the construction.

In Maine, erosion, pollution, and sediment control activities on the construction site are overseen by staff that have successfully completed training and certification in erosion and sediment control practices. For project sites that involve disturbance of one acre or more, the contractor will also be required to comply with the Maine Construction General Permit, including filing of a Notice of Intent and the erosion control plan prior to the start of construction activity. The project plans and specifications should detail any project specific requirements. Several BMP guides are available that detail common recommended practices.

Useful Links

Maine Construction General Permit

ME DEP Erosion and Sediment Control Best Management Practices Manual for Engineers and Designers

ME DEP Erosion and Sediment Control Practices Field Guide for Contractors

ME DOT BMP Manual

Water Management

Water management at tidal construction sites is complex due to the twice daily low and high tides, and the need for construction at or below the elevations of the lowest tides. Water management requires thorough planning and good communication between the construction crew and rest of the Project Team before and during construction. However, successful water management starts in the Design phase, with definition of performance expectations for water control in the project specifications. This includes providing necessary information to the contractor for effective planning, including characterization of the range of tides, freshwater inflows, and flood elevations expected if the construction occurs during a period of potential runoff events.

The performance specifications should also define the degree to which construction will be required to be completed in a dry or semi-dry condition. Commonly, water control will incorporate a combination of cofferdams and local dewatering pumps specifically selected to accommodate seepage that accumulates in the dewatered work zone. Discharge from these pumps needs to be well planned and managed to avoid erosion and sedimentation impacts. It may be also necessary to provide a bypass culvert to provide water to upstream wetlands to prevent temporary impacts. Depending on the size and complexity of the site, control of water facilities may need to be managed and adapted frequently during construction.

FIGURE 8.2 - A sheetpile coffer dam was utilized to isolate the work area from tidal flows during the replacement of the Long Reach Lane tidal crossing in Harpswell. Photo by Charlie Hebson.

Once the performance expectations are established in the project specifications, the detailed design for cofferdams and pumping capacities typically becomes the responsibility of the construction contractor. This allows the contractor to use equipment and approaches they find to be most effective. In estuary settings, cofferdams may use sheet pile walls, or modular installations with large sand or gravel-filled bulk bags.

As discussed above, in some instances it may be extremely difficult or expensive to install coffer dams that are effective over the full tide range. In these instances, the contractor will need to demonstrate the sequencing steps required to successfully complete the project. The contractor's proposed approach for water management, including cofferdam design and designs for appurtenant features like bypass pipelines, is typically submitted in a water control plan to the engineer and Project Team for review and approval.

Protection of Fish and Wildlife

Adequate planning is necessary to avoid and minimize impacts to fish and wildlife during construction. Practices include:

- Incorporate necessary provisions in construction specifications to define performance expectations for construction contractors, including coordination between the contractor and the resource agencies or other professionals to complete tasks such as fish relocation.

Lessons Learned: Water Management

A stream supporting sea-run brook trout was the target of a nearly million-dollar alewife recovery effort. During construction of the new crossing, coffer dam and pumping effectiveness proved insufficient, leading to a large, ongoing discharge of sediment into the stream. The construction crew made an attempt to correct the situation, with little success. Work continued, and the stream and a downstream cove with a lobster storage facility was allowed to run brown with silt-laden water for nearly 24 hours. Two days later juvenile alewives migrated through the worksite, narrowly avoiding the poor water quality conditions. After the water cleared, the streambed remained caked with sediment for months. What's the lesson? Effective planning can avoid most problems, but unintended consequences happen. If a problem occurs, stopping work until it is adequately addressed is often the best response. Minor project delays are much easier to accommodate than environmental damage.

- Dewatering pump hose inlets should be screened with a mesh size that will not allow small estuarine fish like sticklebacks and mummichogs to enter.
- Plan for isolation of work areas and relocation of fish and other aquatic life from work zones.
- Continue to monitor for fish and aquatic life after work zones are isolated. Be ready to transport fish stranded during dewatering and construction to suitable habitat.

Construction Observation

Onsite observation by the design engineer is strongly recommended to ensure that the crossing is installed according to the requirements of the plans and specifications, and fully meets the design intent. Construction observation typically involves periodic checks of the installation process, clarifying discussions with the contractor, measurements of key dimensions or elevations, and photo observations.

In addition, there may also be the need to adapt or troubleshoot newly discovered site conditions that complicate construction. In these instances, the contractor and engineer work cooperatively to assess and devise the best solution so the crossing design criteria continue to be met. Ideally, this is accomplished without impacting the construction budget and schedule.

Construction Observation

The discovery of unexpected conditions at the crossing site can stop a construction project in its tracks until qualified personnel make appropriate modifications to the design without sacrificing design criteria. Budgeting for the design engineer to be onsite at regular intervals and available for on-call consultation allows design adjustments to be made quickly and collaboratively with the construction contractor. Planning ahead for such situations can save significant amounts of money by shortening project delays and applying well-conceived solutions by those closest to the project and its objectives.

Lessons Learned: Fish Rescue and Relocation

Tidal wetlands are often populated by large numbers of small fish that provide much of the food relied on by larger predators such as harvested fish species and water birds. At one dewatered tidal road crossing site in Rockland, an alert crew observed many fish trapped in the muddy channel. Three hours later, they had relocated about 50,000 small fish to safety with a single bucket and dip net. In this instance, the ending was happy. But it demonstrated that monitoring for fish stranding and establishing a relocation plan provides cheap insurance against avoidable impacts. Photo by Slade Moore.

8.4 TYPICAL ROLES AND TIMELINES

The construction phase of a CoastWise project may be managed by experienced town staff, a contracted consulting engineer, or other qualified professional. The time required for construction will vary. Small projects may be able to be completed within two weeks, barring work stoppage due to inclement weather. More complex projects may have construction periods that extend over months.

8.5 ADDITIONAL RESOURCES

The following documents provide an overview of erosion control concepts, and typical designs and practices for control of erosion and sediment pollution resulting from construction activities. Maine DEP has tailored their guidelines towards both designers and contractors with focused documents.

Maine DEP Erosion and Sediment Control Best Management Practices Manual for Engineers and Designers

Maine DEP Erosion and Sediment Control Practices Field Guide for Contractors

MaineDOT Best Management Practices for Erosion and Sedimentation Control

9 MONITORING FOR SUCCESS

Photo by Slade Moore

Once construction concludes, pre-project monitoring that began during the assessment phase is supplemented with post-project monitoring to measure project success. This project phase focuses on determining whether the built crossing meets design criteria and performance objectives.

9.1 MONITORING APPROACHES

Monitoring for tidal crossing projects typically includes implementation and performance or effectiveness monitoring. Each of these activities is discussed briefly below, with notes on the strategies that are most applicable to the CoastWise Approach.

Implementation Monitoring

Implementation monitoring is important because it determines whether the constructed crossing matches design specifications. It is most typically performed by the design engineer, although in some instances could be accomplished by other trained personnel. This type of monitoring is often an extension of construction observation and may include an as-built survey and preparation of record drawings. These document the actual constructed condition, including changes which may have occurred during installation.

Implementation monitoring may extend for a period of several months after the crossing has been placed in service to check that no project details have been missed in project closeout, or whether minor adjustments may be required. Examples could include adjustments to surface drainage patterns, BMPS, or other project elements. This monitoring also assesses minor stability or erosion issues that can arise in the period of adjustment immediately following construction.

Performance/Effectiveness Monitoring

Performance or effectiveness monitoring determines whether the objectives and design criteria established for the site are met. The duration of performance monitoring corresponds to the timescales necessary to observe responses or changes influenced by the new crossing. This differs depending on the types of crossing performance objectives and design criteria under consideration.

Most, if not all, projects should monitor tidal water levels at the same locations upstream and downstream of the crossing as where these data were collected during the Detailed Site Investigation. If low-lying properties, infrastructure, resources uses, and/or damaged/vulnerable habitats are a concern for the project, additional water level monitoring is necessary to confirm that they will not experience undesired tidal flooding. Typically measured parameters corresponding to ecological performance include pore and surface water salinity, plant community characteristics, wetland and channel elevations, and fish and wildlife species usage. Monitoring focused on inundation patterns near low-lying features of concern or efforts to track responses in plant and animal communities might require long-term or even ongoing monitoring to ensure objectives are achieved.

FIGURE 9.1 - Monitoring for ecological performance may extend to specialized techniques necessary for capturing bird species such as this mist netted semipalmated plover (*Charadrius semipalmatus*). Photo by Slade Moore.

Performance monitoring may not be a requirement of all tidal crossing projects but is always encouraged. Monitoring recommendations and protocols developed by the Global Program of Action Coalition for the Gulf of Maine (GPAC) (Neckles and Dionne 2000) are a useful resource to inform development of the monitoring strategy. Some monitoring activities can be performed in collaboration with CoastWise Technical Partners, state and federal agencies, and NGOs, with the support of outside funding.

Case Study: Performance Monitoring of Long Reach Lane Project

Completed in 2014, the Long Reach Lane project in Harpswell was constructed by MaineDOT as compensatory mitigation for the Martin's Point Bridge between Falmouth and Portland. The project entailed the replacement of an existing 36-inch diameter culvert with a twelve-foot-wide by six-foot-high reinforced concrete box culvert. Project monitoring was performed by the Casco Bay Estuary Partnership (Craig 2019). The program included one year of pre-construction and five years of post-construction monitoring, implementing protocols set forth in CBEP's Quality Assurance Project Plan for Tidal Marsh Monitoring & Assessment (Craig and Bohlen 2018). Parameters studied at ten fixed monitoring stations included water levels, pore and surface water salinity, plant communities, channel morphology, and species of concern. The monitoring program was crucial to verify that the replacement crossing met all performance criteria.

9.2 LONG-TERM OPERATION, MANAGEMENT AND MAINTENANCE

Following the monitoring period, long-term management of the crossing will transfer to a regular operation and maintenance approach. As assets in transportation networks, tidal crossings are likely to continue to be inspected periodically by the responsible entity, with corrective actions taken as needed. These inspections and corrective actions typically focus on the structure itself. Specific measures should be determined on a project-by-project basis at the time of development of project performance monitoring measures.

9.3 ADAPTIVE MANAGEMENT FOR TYPICAL AND PHASED CROSSING DESIGNS

Adaptive management is a structured approach to long-term resource management that follows a cyclical pattern of assessment, design, implementation, monitoring, evaluation, and adjustment. This approach is useful where a natural resource is faced with major sources of uncertainty in ecosystem processes, and in the response to management actions as well as future environmental conditions.

Applied to the scale of a typical tidal crossing project, adaptive management is most likely to occur at two junctures. The first is the period shortly after construction, where adjustments to the project may be required to address minor construction or design issues. Adaptive management at this point could also include response to issues that arise from extraordinary events shortly after construction. For example, if a major storm occurs before vegetation has established, leading to erosion, a response may be necessary.

Adaptive management actions are also typically scheduled towards the end of the monitoring period unless more prompt action is warranted. For instance, if measured performance during the monitoring period falls short of objectives or seems unlikely to meet objectives during the intended life of the crossing, follow-up actions to make necessary adjustments may be warranted. Hypothetical examples of corrective actions could include adding to flow capacity with relief culverts, management of invasive vegetation, and management of the tidal channel geometry. Crossing performance under conditions of significant sea level rise will likely require decades to evaluate, which exceeds the typical duration of adaptive management regimes. This underscores the need for thorough project planning and may justify an added degree of engineering precaution by accommodating an extra degree of sea level rise in the final design.

Monitoring and adaptive management is applied throughout the service life. These crossings are designed with the understanding that at some point increasing sea levels may exceed the crossing's ability to achieve infrastructure and ecological resilience objectives. Should that happen, appropriate responses include implementation of necessary upgrades to achieve performance objectives or retirement of the crossing.

9.4 TYPICAL ROLES AND TIMELINES

Implementation and long-term infrastructure monitoring is typically conducted by qualified engineering resources. Ecological monitoring of any duration is usually accomplished by NGOs, natural resource agencies, or consulting firms, depending on the skills required. CoastWise Technical Partners may be available to help facilitate development of monitoring programs.

9.5 ADDITIONAL RESOURCES

Casco Bay Estuary Partnership Monitoring Protocol

Regional Standards to Identify and Evaluate Tidal Wetland Restoration in the Gulf of Maine

APPENDIX A: HYDROLOGY AND HYDRAULICS OF TIDAL CROSSINGS

Appendix A was prepared by Woods Hole Group, with assistance from Inter-Fluve

The primary purpose of this appendix is to provide guidance on hydrology and hydraulics tools and related data needs to support analysis and design of tidal crossing replacements. The emphasis is on identifying the range of tools available (including computer models) and selecting proper tools depending on project-specific characteristics and requirements. The influence of climate change is a prevailing theme, including suggested scenarios to simulate, because infrastructure built today is expected to operate on a time scale through which sea level rise, coastal storms, precipitation, and other parameters are expected to change.

Appropriately selected models and data sources support planning of road infrastructure needs. Additional applications include identification of potential impacts to adjacent resources areas and low-lying infrastructure, and habitat restoration opportunities. The following sections provide an overview of analysis tools and data needs, and then review selected case studies that highlight model outputs.

A-1 H&H APPLICABILITY TO PROJECT PHASES

Preliminary Site Assessment

The applicability of hydrology and hydraulics (H&H) analysis at this stage of project planning should focus on gathering and making the most use of existing information. This leads to the identification of data gaps, which will help define the scope of work needed for later project phases. Initial field observations of flow conditions provide additional insights that will help guide the eventual technical analyses.

Detailed Field Investigation

Rigorously obtained field data describing a range of environmental factors are essential for H&H studies that inform the design of safe, climate resilient, ecologically supportive, and cost-effective crossings. Clear identification of data requirements before the field investigation helps avoid having to repeat data collection activities, which are costly and time-consuming. Depending on the project specifics, data types to support H&H activities may include water surface elevation, tides, salinity, bathymetry and topography, freshwater inflow, natural community classification, channel bed sediment characteristics, vegetation distribution, structural parameters, and geotechnical data.

Crossing Performance Objectives and Design Criteria

When deciding on preferred alternative(s) for tidal crossings, the H&H analysis is a critical step in the process. Before conducting the analysis, the planning team needs to confirm and translate the project objectives into quantitative design criteria. These are discussed in detail earlier in the guidelines and include factors such as sea level rise, flood capacity, tidal flow and habitat restoration, and aquatic organism and wildlife passage.

Development and Evaluation of Conceptual Design Alternatives

Careful examination of potential alternatives, including comparisons to baseline conditions, is required to quantify potential impacts/benefits using meaningful metrics and outputs. The focus should not only be on the structure, but also on waterway modifications or wetland refinements. H&H analyses have a key role in the selection of the preferred alternative through the feasibility stage.

In consultation with the Project Team, the engineer can match the appropriate analyses with stated objectives and criteria. For CoastWise projects, these may range from simple analytical (0-D) calculations, through 1-D and 2-D model simulations. Simple 0-D calculations may be spreadsheet calculations, whereas 1-D and 2-D models simulations use computer models to simulate the tidal flow, discussed in more detail below.

Design and Permitting

Typically, final H&H analysis refinements are completed in the design and permitting processes. Depending upon how detailed the preferred alternative was developed in the prior project phase, supplemental H&H work may be required to simulate refinements that may evolve during the final engineering design. The environmental permitting process may also result in design refinements to minimize potential impacts or maximize potential restoration benefits. At a minimum, H&H analyses include final model simulations to confirm the final design continues to meet the established design criteria. Often, final H&H analysis may also be needed to confirm specific structural dimensions, elevations of the inside surface of the culvert bottom (invert), and scour pads/wing walls. To support environmental permit applications, H&H outputs may be required to quantify areas of impact or benefits.

Construction

By the time construction commences, H&H work is typically completed. Supplemental H&H work may be required if there are unexpected circumstances revealed during construction. One example may be if bedrock is encountered that limits the bottom elevation of the tidal crossing, and the higher bed elevation must be assessed against key design criteria.

Monitoring for Success

Post-project monitoring may involve H&H observations to confirm expected project performance. For instance, post-construction tidal water level measurements are often used to monitor the actual change in tidal flow patterns. Other hydrologic monitoring requirements or compliance criteria may be set forth in environmental permit conditions.

A-2 OVERVIEW OF HYDROLOGY AND HYDRAULIC CONSIDERATIONS FOR TIDAL CROSSINGS

Tidal road crossings have the potential to significantly modify water flow in the system. Whether a bridge, culvert, or other structure is installed to convey water, the extent to which that structure can allow natural flow to occur is critical to understand. This understanding has meaningful influence on the design of the structure, as well as the evolution of adjacent habitats and wildlife. Often, aged or failing infrastructure substantially limits flow, which exacerbates structure loading and scour, and compromises habitat condition, particularly upstream.

For successful repair, replacement, or installation of new tidal crossing structures, the design purpose and expectations must be clearly identified, which often includes restoration objectives for adjacent habitats.

With design and restoration objectives clearly defined, the next steps are to ensure there is adequate baseline data about physical processes, vegetation, and wildlife, and then apply appropriate tools to evaluate the existing conditions and possible project alternatives. Often there is a need to apply numerical computer models to support this evaluation.

Models of various levels of rigor and sophistication can be applied to more fully understand the existing conditions of a system. The models can then be used to evaluate various “what if” scenarios related to different structural designs (e.g., different size culverts) and environmental conditions (e.g., rain events, coastal storm surge, a range of high and low tides, sea level rise). Once a preferred alternative is selected, appropriate H&H tools are used to support engineering design.

Unique considerations for tidal hydrodynamics

Tidal crossings involve complex hydrodynamics considerations. They have reversing flows on flood and ebb tides as the tide rises and falls, which creates analysis and design challenges. Tides also change throughout the course of the month and year, based on the relative position of the moon and sun. Spring and neap tides occur on a monthly cycle and result in periods of variable tide range between consecutive low and high tides.

Tidal systems are also exposed to the coast, along with the influence of coastal storms and storm surge, which can raise water levels by several feet or more. Tidal systems can also be affected by precipitation and runoff, which adds water to the system as it interacts with the tidal and storm currents. These highly variable natural fluctuations and dynamics must be understood when designing a tidal crossing.

Tidal flow is also important for distributing sediment, nutrients, organisms, and waters having unique salinity properties to tidal wetlands. Consequently, H&H conditions govern tidal wetland health and influence the ability of unique tidal wetland types to self-regulate and keep pace with sea level rise. The ability for fish and wildlife species to access tidal wetlands and streams is also influenced by H&H conditions.

Computer model applicability

To help understand the complexities of tidal crossing H&H dynamics, computer models are often applied. The models provide outputs to guide engineering design and facilitate evaluation of other factors.

What is a computer model?

A numerical model is a program that runs on a computer that can be used to calculate estimates of water elevation, current speed and direction, sediment transport, salinity levels, and areas flooded and/or exposed in a tidal system. There are numerous types of models available depending on the required application. They vary in complexity and data requirements, level of information that can be output, and the cost to apply the model. Selection of the proper tool for the job at hand is critical.

Why use computer models? When are they needed?

The primary reasons to use a computer model include the following:

- To learn more about a waterway than can be feasibly measured: Measurements are difficult and can be costly to collect. Field measurements are essential for any model application to ensure what the model predicts matches what is observed in nature. However, a strength of a numerical model is the ability to provide outputs at many more places over a much broader range of conditions than could be measured.
- To evaluate the "What If" scenarios:
  - Evaluation of different design alternatives: What happens if a small culvert is replaced with an open span bridge? A model can be applied to help answer this question, to select and to optimize the proper size and position of the structure. Without such analysis, a new structure that is too small may inhibit upstream flow and affect habitat. Conversely, if there is upstream flooding vulnerability, an oversized crossing could exacerbate this trend. Model scenarios can also facilitate cost optimization.
  - Evaluation of different natural conditions, including normal, extreme, and future conditions: What happens if a hundred-year storm impacts my site? What happens when sea level rises? Tidal crossing infrastructure is expensive and often needs to last for fifty or more years. Designing a structure that will last helps support responsible infrastructure investments.

What are expected outcomes from computer models for tidal crossing projects?

When applying computer models to a tidal crossing project, the approach should be designed specifically to produce the outcomes required to support project planning. Depending upon complexity of the system and project objectives, outcomes may include the following:

- Information needed to evaluate and select a preferred conceptual alternative: This usually involves a detailed analysis from simulations of the existing system, simulations for a range of possible project design alternatives, and side-by-side comparisons, or key project metrics needed to select the preferred alternative.
- Design criteria needed by the engineering team for developing specifications for the selected preferred alternative: Depending upon the type of infrastructure preferred, these outputs may include water levels (tidal datums or storm surge elevations corresponding to specific return period storms like hundred-year storms), current velocities adjacent to and within the crossing, and analysis of scour and sediment transport. These parameters should be produced for existing conditions, coastal storm events, runoff/flow from precipitation, sea level rise, and other scenarios.
- Habitat restoration parameters expected from the project: These may include areas of inundation at specific tidal datums (e.g., area inundated at MHHW, MHW, MTL, MLW, and MLLW), net areas between certain tidal datums (e.g., if salt marsh restoration is intended), salinity levels at restoration locations, and time duration and frequency of expected inundation.
- Areas of impact needed for risk assessment and/or regulatory approvals and compliance: Upfront discussions with regulatory agencies and stakeholders are invaluable to identify habitats at risk of impact and opportunities for improvement. This influences the types of analysis needed to quantify potential impacts. With this information, the H&H analysis scope can be designed to produce needed information to expedite environmental review. For instance, if nesting saltmarsh sparrow habitat is a concern, the H&H modeling

must produce the desired outputs to determine if the project has potential to flood identified nesting areas.

A-3 SELECTION OF APPROPRIATE COMPUTER MODELS

What types of computer models are there?

There are several different of types of computer models used for hydrology and hydraulic analysis of tidal crossings. They can generally be described in the following categories:

Box/analytical

This category of models uses analytical equations to solve basic problems of hydrology or hydraulics. The analytical equations are typically based on relationships established through the collection of empirical data. Example models in this category include user-created spreadsheets, or simple single structure analysis models developed by FHWA or others. These are most often steady-state models that can be applied to get an initial estimate of tidal crossing structure size or vegetation change within a marsh system.

Advantages of these types of models are that they are useful for initial habitat and structure estimates and they are an easy-to-use planning tool for prioritizing sites. Disadvantages include: 1) they lack significant processes (e.g., wetting/drying, velocities, salinity, freshwater input,), 2) the user must determine the system dynamics, 3) they are not recommended for design or simulating engineering alternatives, and 4) they can only be used for the simplest estuarine systems.

Watershed hydrology

This category of models is applied to simulate a watershed using established rainfall runoff relationships. While not applied to directly simulate estuarine systems or marsh restoration, these models determine the discharge to surface water systems from a watershed. Examples of models in this category include HEC-HMS (USACE), SWMM (EPA), TR-20, and HSPF.

Advantages of these types of models are that they can simulate precipitation drainage from a watershed and provide watershed input discharge conditions to a surface water model. Disadvantages are that they are not developed for wetland modeling or for simulating dynamic, tidally forced estuaries. Also, the accuracy of these models can vary substantially from project to project due to the large number of assumptions and parameters that must be estimated. This is particularly the case when there is insufficient data to calibrate the flow predictions. The complexity of the chosen model should not exceed the ability to calibrate it.

In most of Maine's coastal watersheds, freshwater flow estimates derived from USGS regression equations are often sufficient for development of project designs. More complex rainfall-runoff models (as listed above) are typically not needed for design of crossings in undeveloped watersheds. However, in urban watersheds or watersheds likely to undergo significant land use change, more complex models may be needed to inform project alternatives.

River hydraulics (steady-state)

This category of models is applied to simulate riverine hydraulics assuming steady-state flow. The assumption of steady-state flow can be applied in river systems with minimal tidal influence. These models typically allow for the incorporation of hydraulic structures and can be used to determine design parameters. Examples of models in this category include HEC-RAS (USACE), XPSWMM (Innovyze), and PondPack (Bentley Systems). These are typically 1-D models.

Advantages of these types of models are that they: 1) can be applied for assessment of hydraulic structures, 2) can provide velocity information, and 3) can be applied for scour analysis. Disadvantages are they can be used only for unidirectional flow and they lack significant processes (e.g., wetting and drying), so they are not recommended for estuaries.

What is a steady-state model?

Steady-state flow refers to the condition where the fluid properties at any single point in the system do not change over time. These fluid properties include temperature, pressure, and velocity. One of the most significant properties that is constant in a steady-state flow system is the system mass flow rate. This means that the flow through the model is constant at all points in the model over the simulation and that the downstream boundary condition (such as a tide level) is also constant over the simulation.

Hydrodynamic models (zero-, one-, two-, and three-dimensional models)

This category of models is most used for the assessment of tidal crossings in estuarine systems. These models allow for dynamic (time-varying) bi-directional flow found in tidally driven systems. The different options for model dimensions (0-D, 1-D, 2-D, 3-D) can be selected based on the tidal system that is being assessed and the importance of capturing different types of flow conditions. These models also typically allow for the incorporation of hydraulic structures for establishing design parameters. The following table (Table A.1) provides examples of these models together with their advantages and disadvantages.

What is a hydrodynamic model?

Hydrodynamic flow refers to the condition where the fluid properties at any single point in the system change over time. These fluid properties include temperature, pressure, and velocity. This means that the flow through the model varies over time and space in the model over the simulation. For an estuary model, the downstream boundary condition (such as a tide level) varies with time, the non-tidal inflow may also vary with time, and bi-directional flow is simulated.

TABLE A.1 - Examples of hydrodynamic model types and capabilities.

MODEL TYPE	EXAMPLE MODELS	ADVANTAGES	DISADVANTAGES
0-D	User-developed spreadsheet	Simplicity Used to estimate structure size based on upstream tidal volume and tide cycle Planning tool for prioritization	Limited to very simple estuaries Does not incorporate freshwater input/other significant processes Not intended for detailed design applications
1-D	DYNLET (USACE) HEC-RAS (USACE) MIKE 11 (DHI) UNET (USACE)	Bi-directional flow Scour analyses and velocity estimation Can be applied to estuaries with tides and freshwater input	Limited in capturing complex estuary channel network Unable to assess wide expanses, overbank/overland flooding/uplands Typically unable to include water quality and salinity
2-D	HEC-RAS(USACE) MIKE 21 (DHI) EFDC (USEPA) SRH-2D (Bureau of Reclamation) TUFLOW	Dynamic and multi-directional flow Developed for estuaries with detailed circulation ability Assess flooding across wide floodplains Full wetting and drying Couple with sediment transport and water quality modules	Lack ability to capture stratification and vertical mixing processes (i.e., salinity and temperature driven currents)
3-D	MIKE 3 (DHI) EFDC (USEPA) DELFT3D (Deltares) TUFLOW	All dynamic processes included	Complexity Computation Time Cost

How do you select an appropriate model for a specific project or site?

When considering a model for application at a tidal crossing, there are a number of key questions and considerations to take into account. Some of the key questions relate to what the project encompasses and the criticality of the roadway crossing:

- Are you looking to engineer and design a new or replacement hydraulic structure?
- Is this a critical road crossing (e.g., high traffic volume, sole emergency access route)?
- Is there surrounding infrastructure or development that may be at risk for inundation?

These types of questions, and the type of infrastructure investment that will be made, will help dictate where a simpler model may be sufficient or if a more comprehensive modeling assessment should be made. For example, for a road crossing that does not provide critical access and does not have significant overland flooding or sheetflow near surrounding development, a 1-D model may be sufficient. In situations with more extensive lateral flow patterns, a 2-D model will likely be required. CoastWise projects are unlikely to require a 3-D model.

Other considerations relate to the estuarine system itself and the type of flow conditions that are expected to occur. These considerations can help identify the model capabilities that are needed for the project site:

- Will there be wetting and drying?

- Will there be significant overland sheet flow (wide floodplain)?
- Are there multiple inlets to the system?
- Is overtopping/overflow of the roadway expected?
- Does the system have intricate channel complexity?
- Are salinity levels and other water quality parameters important to quantify?
- Does the system exhibit stratification (not well mixed vertically)?
- What types of hydraulic structures exist?
- What are the flow conditions that exist (e.g., subcritical, supercritical)?
- Are there historical modifications to the upstream marsh system that could cause unintended impacts to habitat after restoration occurs?

The following graphic (Figure A.1) from the Federal Highway Administration HEC-25 Manual (FHA 2004) illustrates some of the parameters to consider when selecting a model for a project site, also summarized in Table A.2. The parameters are listed in the center of the figure. If a parameter is less significant at the project site, the model approach would fall on the left side of the arrow. As the parameter increases in significance, the model approach moves to the right along the arrow to the point where a 2-D dynamic, or unsteady, model is recommended.

FIGURE A.1 - Factors influencing the selection of a tidal modeling approach. Source: FHWA 2004.

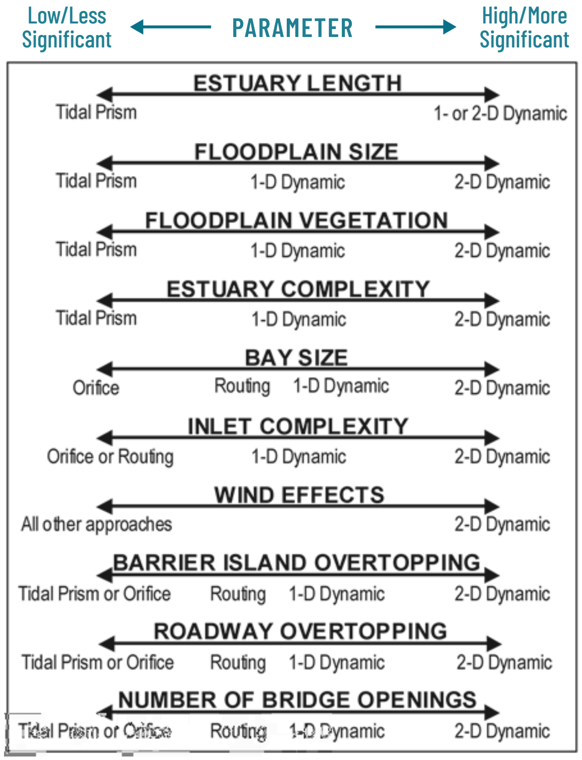


TABLE A.2 - Estuary parameters and model selection.

1-D MODEL	2-D MODEL	3-D MODEL
Estuary System Parameters and Appropriate Model Type:		
Simple one-inlet/estuary Relatively small system Limited width of overbank inundation and overland flooding Length of tidal reach is multiple times greater than width Fluvial marsh type, or smaller marsh area near head of tide	Wide floodplain/large marsh system Intricate channels Multiple inlets Variable topography/ground cover Overtopping/overflow Salinity Back barrier marsh types, tidal flats, and most other tidal wetland types	Stratification Density-driven currents Proposed construction activity at bottom
Circumstances Where Model Type Is Not Applicable:		
Broad wetland areas where width of wetland is comparable to or greater than length of tidal reach Multiple primary tidal channels with multiple hydraulic structures Substantial lateral overbank flow or multiple branching channels	Tidal areas with substantial vertical mixing or stratification	

A-4 DATA NEEDS AND SOURCES

This section is intended to identify the data needs for H&H studies, including for modeling applications.

System geometry

Shoreline configuration

The basic shoreline configuration for a system is often available from aerial photographs and/or existing GIS layers. When more details are required, the shoreline can be extracted from lidar data, or it can be delineated with site-specific surveys.

Topography

In most instances, lidar data will be available at CoastWise project locations; see NOAA's Digital Coast for data availability. Lidar should be verified because of the dynamic nature of estuaries and the errors caused by standing water or vegetation debris in marshes that may create the appearance of land surface, particularly in lidar data. Topographic measurements can be made using a variety of survey methods, but most typically total station or real-time kinematic DGPS (RTK GPS) methods. Data should always be referenced a geodetic vertical datum (e.g., NAVD88) and horizontal projects (e.g., Maine State Plain Coordinates). If lidar are not available, survey transects should be identified that can be used to characterize the general area geometry. For example, a transect might cross a marsh plain and continue over a mud flat down to a subtidal elevation in a channel. See Section 4 for additional detail.

Bathymetry

Bathymetric data availability is often limited at nearshore and estuarine locations. An exception to this is the merged topobathy data available for most of southern Maine. These data are required to complete the characterization of the subtidal basin geometry necessary to model hydraulics and hydrodynamics. Bathymetric data can be collected using traditional survey methods if the areas are wadable. For larger areas or greater water depths, sonar methods may be most applicable, assessed on a case-by-case basis.

Infrastructure (road, bridge, culvert, etc.) geometry

All critical infrastructure items, especially those affecting or controlling the hydraulics and hydrodynamics of the system, must be identified and defined with the present dimensions (e.g., length, width, diameter, height, inside surface of the culvert bottom [invert] elevation). Field measurements are made using survey techniques. If as-built information is available, differences may exist compared to the existing condition (due to failure, settling, etc.). Therefore, each infrastructure component should be inspected and measured. With culverts, noting any obvious or suspected blockage of flow is critical since this will affect the flow rate to be addressed in the model design.

Land cover characteristics

Land cover at the project site is important for H&H analyses to help define frictional resistance, watershed storage and infiltration. Development type, vegetation type, and density are needed to specify the appropriate friction coefficients in a model. Land cover type is also a basic parameter for calculating runoff and infiltration for watershed models. Remotely sensed land cover datasets are typically available through the Maine GeoLibrary, or through NOAA and USGS data portals (links below). Ground-truthing the remotely sensed data through observations and selected site survey is often necessary.

Soils and sediments

Soil, sediment, and substrate composition is important to the stability of the system and should be considered when evaluating changes to hydrodynamics and sediment transport. Sediment grain size is the most important parameter to characterize in order to specify bottom roughness in hydrodynamic models and to calculate sediment transport potential. Sediment transport calculations are likely to be integrated into CoastWise project primarily on a case-by-case basis.

Hydrodynamics and hydrology

Water levels and tides

- Water levels and tides can be measured using in-situ pressure sensors or non-contact ultrasonic, radar, or laser sensors. Pressure sensors are typical for CoastWise projects and must remain under the water surface to collect a complete record. Site selection should be carefully considered. Apart from the spatial aspect of site selection, the deployment location should always remain wet and deep enough that the sensor always remains underwater.

- Pressure sensors should be securely mounted to ensure they do not move or settle for the duration of the deployment. Mounting methods include weighted bottom platforms, pipe anchors, and post or piling mounts. Consideration should also be given to the potential for theft, vandalism, and curiosity disturbance.

- Pressure sensors are made in two configurations: absolute and vented. Absolute sensors measure the total pressure applied by the atmosphere and the water column. If absolute sensors are used, a barometric (atmosphere) pressure record must be collected and subtracted from the absolute record to calculate the pressure caused by the water column only. Vented pressure sensors compensate for atmospheric pressure in real-time by using a cable with a small tube (vent) that is connected to the pressure sensor and mounted above the water surface; they are less common for CoastWise projects.

- The elevation of all water level sensors should be surveyed at time of deployment, and at time of retrieval, to the same vertical datum as the project site (e.g., NAVD88). This allows the water level data to be compared to site features and infrastructure. The method that will be used to survey the sensor should be considered when choosing a deployment location. For example, deep channels or sites with heavy canopy can make accurate measurements with an RTK GPS challenging, and for remote sites it can be very time consuming to complete a survey traverse from a known benchmark location. In these instances, a hybrid approach works well, combining the use of RTK-GPS and total station surveys.

- In tidal situations, good temporal resolution of water levels can be attained with measurements logged at intervals of six-minutes (or less), which is the time interval used by NOAA. Matching the logging interval and start time to the time interval of a NOAA tide station is critical when planning to conduct comparisons with NOAA tide data. Be sure to check that the clock on the computer used to launch the sensor(s) is correct when preparing a deployment.

- Manual measurements of water level should be made during deployment and recovery of instrumentation for quality control.

Water density and salinity

- Water density and salinity are not among the minimum data requirements for most typical CoastWise projects, but they may be required on a case-by-case basis. One example is to understand how the tidal crossing may influence an upstream vegetative community in more detail than required for a typical CoastWise project.

- When required, conductivity and temperature measurements are collected to calculate water density.

- These measurements can be made using a variety of multiparameter water quality instruments (e.g., CTD, Sonde, TROLL).

Current velocity and flow

- Current velocity and flow measurements are not typical minimum data needs for CoastWise projects. The need for these measurements is determined on a case-by-case basis. Examples may include required calibration of current velocity related to a very specific project objective, or a requirement to supplement existing freshwater inflow data with field measurements.

- The most common techniques for measurement of current velocity in a non-wadable channel utilize acoustic doppler current profilers (ADCP) or acoustic AV sensors (ADV).

- The most common techniques for measurement of current velocity in a wadable channel utilize conventional current meters deployed on a top-setting rod.

Tributary inflow

- Tributary inflow measurements are not a typical minimum data need for CoastWise projects, but they may be required on a case-by-case basis.

- These measurements may be targeted for a specific set of environmental conditions, accomplished by one or more streamflow measurements

- In other instances, it may be necessary to collect a longer-term time series of flow discharge, which would involve a combination of periodic flow discharge measurements to develop a discharge rating curve and continuous water level logging so that a time series could be extrapolated over the period of observation.

Groundwater recharge

- Groundwater measurements are not a typical minimum data need for CoastWise projects, but they may be required on an infrequent case-by-case basis.

- Local and regional groundwater levels may be obtained from USGS Groundwater Watch and the National Groundwater Monitoring Network (NGWMN). These data together with precipitation data can be used to establish relationships between groundwater recharge, rainfall runoff, and contributions to tidal estuaries.

- In-situ measurements of water level can also help to determine the expected lag time between precipitation events and groundwater flows to the system, in relation to tidal patterns.

Useful Links

Maine GeoLibrary

NOAA Digital Coast

USGS Earth Explorer

USGS Groundwater Watch

National Groundwater Monitoring Network

A-5 MODEL DEVELOPMENT PROCESS

Hydrodynamic model development follows a systematic process that leads to a calibrated existing conditions model, which can then be modified to simulated future conditions or proposed project configurations. The overall sequence of steps is similar whether the modeling work uses a 0-D, 1-D or 2-D model, but the specifics of each step vary with the variable data and computational requirements across these modeling approaches.

With respect to the model development process, 0-D models are most typically custom built by the user using spreadsheet or other automatic calculation platforms, including development of simple codes or scripts to iteratively complete the calculations. Given this specialized nature, development of 0-D models is not discussed further in this document.

There are multiple robust modeling platforms to complete 1-D hydrodynamic modeling simulations, including public source (e.g., HEC-RAS) and proprietary (e.g., Mike 11, TuFlow) options. The steps to develop 1-D models are reasonably standard, and there are several resources available that lead the modelers through a step-by-step process to develop these models. These resources include well-prepared model software user manuals and many online resources. For these reasons, develop of 1-D models is also not discussed further in this document.

Utilization of 2-D models is less standard in general engineering practice, but they are commonly used in coastal applications. Depending on system characteristics, and project risks, requirements and constraints, 2-D models may be recommended over 1-D models. The 2-D model development process typically includes the steps summarized below.

Establish the model area (domain), resolution, and grid

The first step in the process is to establish the area to be modeled, or model domain. The model domain should include the full extent of the estuarine system that would have an influence on the road crossing, including under future conditions. Additionally, the model domain should cover all areas that are expected to be inundated for the most extreme storm scenario that will be simulated. For example, if the hundred-year storm elevation is the highest level anticipated in the modeling and is established at twelve feet relative to the NAVD88 vertical datum, all areas that are hydraulically connected and fall below this elevation should be included in the model domain.

For CoastWise, additional consideration should be given for the water level elevations and the associated lateral extent associated with future sea level rise and storm surge conditions. The online mapping resources identified in Phase I (Section 3) such as the Maine Tidal Restriction Atlas and the Maine Geological Survey Mapper can be helpful in determining these extents. Overall, providing some extra buffer past the expected maximum extent of inundation is advisable to provide a margin of error in the estimated model domain. The size of the model domain is easier to reduce at a later point in time, as opposed to needing to increase the size of the model domain after several simulations have already been completed.

Once the model domain is established, the model grid is developed. The target number of grid points (points where calculations are made within the model) will vary depending on the specifics of the site, and particular areas of interest. Constraints on grid specialization vary from model platform to model platform, but most provide some means of variation between grid elements. Model documentation will provide guidance on these aspects of the model platform

It should be noted that model runtime is directly tied to the number of grid points in the model, so a model developer must balance the complexity of the grid and the number of features to resolve in the model, so that the model is relatively efficient for simulation of the desired model scenarios. Specific to tidal channels, the required resolution of grid points will depend on the width of the estuary channels that are included in the model. A good rule of thumb is that three grid points in the model mesh are required across the channel width to accurately represent the channel in the model (specific resolution requirements are typically provided in model documentation).

Assign model inputs and boundary conditions

Once the model grid is established, model parameters are then assigned to the grid points which would typically include:

- Elevations based on the compiled ground surface and underwater survey information (topography and bathymetry)
- Bottom friction based on different sediment and land use types (e.g., vegetation, development)
- Structure parameters (e.g., dimensions, entrance and exit loss coefficients)

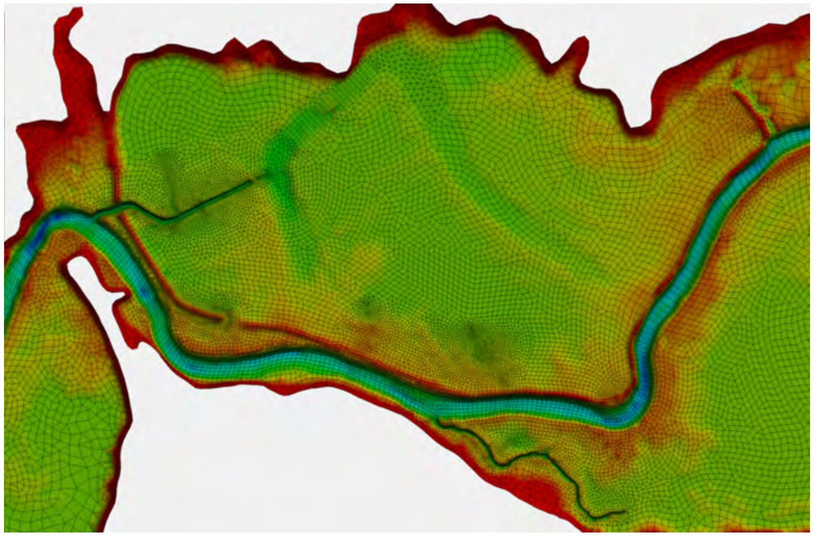


FIGURE A.2 - Example of a two-dimensional model grid overlain on an integrated bathymetric-topographic surface.

The establishment of boundary conditions is required to represent the different environmental conditions that drive circulation within the estuarine system. They are defined at the edges of the model domain. Detailed in Table A.3, the types of boundary conditions that are typically applied in 2-D hydrodynamic surface water models include the following:

- Ocean/tidal conditions – basic requirement
- Upstream freshwater inflow – basic requirement
- Atmospheric conditions – case-by-case basis only
- Other, including salinity, temperature – case-by-case only

Sensitivity simulations

This step in the model development process occurs once the model grid, parameters, and boundary conditions have been established. Test model simulations are conducted to assess:

- Model sensitivity to specified parameters
- Whether the model produces velocities and water levels that are reasonable and expected
- Model instability

TABLE A.3 - Types of model boundary conditions and key considerations.

	BOUNDARY CONDITION	KEY ELEMENTS
Basic Requirement	Ocean / estuary boundary (water level) Typical tides Typical tides with sea level rise (SLR) Coastal storm event with and/or without sea level rise	Limited to very simple estuaries Does not incorporate freshwater input/other significant processes Not intended for detailed design applications
	Upstream freshwater inflow (discharge)	Limited in capturing complex estuary channel network Unable to assess wide expanses, overbank/overland flooding/uplands Typically unable to include water quality and salinity
Case-by-Case Only	Atmospheric (i.e., wind, rainfall)	Lack ability to capture stratification and vertical mixing processes (i.e., salinity and temperature driven currents)
	Salinity, temperature, other	Complexity Computation Time Cost

What's a model timestep?

A model timestep is the time interval at which calculations are made in the model. High velocity flows that occur during storm events may require a small timestep so that the model can capture the flow variations. The model timestep is also dependent on the spatial resolution of the model. Increasing the model grid resolution may require a reduction in the timestep. Ultimately, the timestep controls the model runtime.

- Hydraulic connectivity
- Appropriate time step to use in the model

If a model proves to be very sensitive to specified parameters, the model developer will focus on these parameters during model calibration. If model instabilities occur, the model grid and time step may be adjusted so that the model can more accurately represent the flow conditions that occur within the estuarine system.

Calibration

Model calibration is the process by which adjustments are made to the model parameters to ensure the model appropriately simulates measured water surface elevation, salinity, and other observed parameters, as applicable. Calibration is performed on existing conditions simulations because the simulation results can be compared to measured data. After the existing conditions model has been calibrated, it can then be modified to simulate proposed project scenarios, or future environmental conditions. The calibration process provides assurance that the simulations will continue to reflect actual conditions outside the area of influence for project changes.

Key Elements of Model Calibration

- Use of available measurements
- Sufficient duration (spring and neap tidal cycles)
- Iterative process
- Quantify model performance through visual comparison and with error statistics

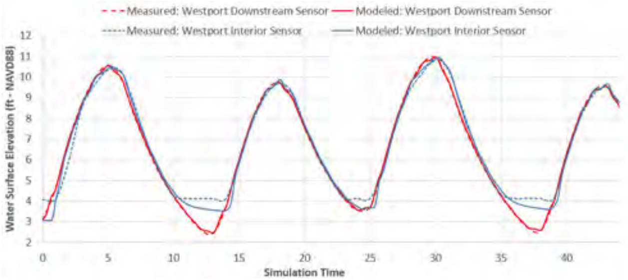


FIGURE A.3 - Example calibration plot comparing simulated water levels (solid lines) to measured water levels (dashed lines).

Calibration requires conducting a series of iterative model simulations to ensure the model is stable and that the results compare favorably with measured data. Calibration can be a lengthy process involving hundreds of model simulations. Specifically, the model coefficients are adjusted (within acceptable ranges) until the modeled water surface elevation, salinity, and other model parameters closely approximate the measured field observations.

The model performance is evaluated through visual comparisons with measured data and through computing error statistics such as the mean error (ME, also known as bias), root-mean-square error (RMSE), and relative mean absolute error (RMAE). U. S. Environmental Protection Agency recommends less than thirty percent error for hydrodynamics (water levels and currents) and less than 25 percent error for salinity (USEPA 1990).

Validation

Once the model has been calibrated, a second time period with a different set of environmental conditions is simulated to validate the model configuration. The model validation period could have different tidal conditions than the calibration period (spring versus neap) or it could be a time when there was a different rate of freshwater discharge into the system, or when a storm event occurred. Again, comparisons are made with measured data to evaluate the model's performance. If the defined error criteria are met, the model is considered calibrated and validated. If the model's performance during the validation period is not satisfactory, adjustments to the model may be required. This would then require the model to be recalibrated.

A-6 MODELING SCENARIOS

Project stakeholders will sometimes dictate which scenarios are required to simulate in the model. For example, Maine Department of Transportation requires specific storm conditions to be simulated for the evaluation of hydraulic structure design and evaluation of potential scour (MDOT 2003). In other cases, stakeholders and regulatory agencies may require there be no adverse flooding impacts to adjacent properties in a specific return-period storm event.

For CoastWise projects, scenarios are generally selected from many possible combinations of site conditions and environmental boundary conditions, represented schematically in Table A.4. The subsections that follow detail the scenarios that may be beneficial to simulate for tidal crossing projects.

TABLE A.4 - Possible combinations of project alternatives, boundary conditions, and sea level combinations from which model simulations may be selected.

SITE CONDITION	BOUNDARY CONDITION (S)	SEA LEVEL	TYPICAL APPLICATION
Existing Condition	Typical Tides Typical Inflow	Current	Calibration / verification Baseline for comparison for habitat improvement resulting from restoration Demonstration of tidal restriction
	Extreme Tides Extreme Coastal Storm Peak Flood	Current	Calibration / verification Baseline for comparison of effects on flooding
Project Alternatives Structure and roadway modifications With or without sediment accretion and/or thin layer placement Other enhancements	Typical Tides	Current	Near-term habitat impacts Aquatic organism passage
	Extreme Tides Extreme Coastal Storm Peak Flood	Current	Flooding and resilience Structure design Risk evaluation
	Typical Tides	Future	Marsh migration Long-term habitat impacts Aquatic organism passage
	Extreme Tides Extreme Coastal Storm Peak Flood	Future	Flooding and resilience Structure design Risk evaluation

Baseline present-day environmental scenarios

The baseline simulations are for existing conditions during typical tides and during storm events. Since in most cases the decision to replace the crossing structure is clear, existing conditions simulations are typically limited to the minimum necessary to enable model calibration and validation, and to develop a baseline of results against which the effects of crossing replacement can be assessed. The existing conditions simulations are typically selected from the following scenarios:

Typical tides

- Including spring and neap tidal cycles with mean freshwater discharge

Coastal storm conditions (i.e., storm surge combined with tides)

- Most often the dominant extreme event in coastal systems
- Typically simulate three or four different return-period events (i.e., 10-year to hundred-year)
- Storm of record may also be important to simulate

Riverine storm conditions (i.e., extreme freshwater discharge)

- Typically simulate one or two events to assess whether riverine will be dominant extreme event
- Simulate with range of tidal cycles (spring and neap)

Combinations of coastal and riverine storm conditions

- Determine correlation or joint probability between both types of events occurring using historical data
- Select appropriate combination of events based on correlation analysis (e.g., 10-year coastal storm surge with 1-year rainfall)

Future climate change environmental scenarios

Future climate change scenarios are important to assess how a particular road crossing will be impacted by these changes. The selected future climate change scenarios are simulated for both the existing road crossing and any proposed project to assess differences with and without the project. Future climate change scenarios include:

Sea level rise

- Typically consider one or two sea level rise scenarios. The Project Team will need to assess the crossing risk consequence, habitat risk, planning horizon, future need for the road, and other factors when determining which sea level rise scenarios should be incorporated in the modeling and design. See Section 3 of the CoastWise manual for further guidance on selection of the most appropriate sea level rise scenario for a specific project.
- Evaluate effects with both typical tides and select coastal storm events.

Increased precipitation intensity

- Follow guidance of Maine Climate Council related to projected changes in precipitation and runoff.
- Typically consider one or two cases related to projected future precipitation shifts.

Structural design alternatives

Once roadway and hydraulic structure alternatives are identified, each alternative is simulated under the same set of environmental scenarios evaluated for existing conditions. The structural design alternatives may include culvert and bridge alternatives. Each design alternative may include one structure or a combination of structures. Each alternative is implemented in the model by updating the grid elevations and/or specification of new structure parameters. A separate model grid is developed for each alternative for conducting the simulations. This allows for comparisons to be made between existing conditions and the alternatives. The comparisons will demonstrate the benefits with the proposed alternative along with any adverse impacts, so that a preferred alternative can be identified.

Alternative waterway and wetland scenarios

In addition to structural alternatives, there may be other alterations within the estuarine system to consider and simulate in the model. These other alterations may include:

- Proposed excavation and channel reconfiguration scenarios
- Future erosion/accretion scenarios, which may be based on regional observed trends or hypothetical accretion intervals
- Proposed vegetation and wetland restoration scenarios

These alterations can be combined with the structural alternatives, to holistically evaluate the proposed and expected changes within the system. Similar to the structural alternatives, each alternative is implemented in a separate model grid and simulated under the same set of environmental scenarios evaluated for existing conditions.

A-7 H&H OUTPUTS

The types of information produced from H&H analysis to support tidal crossing projects varies widely. Some products are derived directly from data and field measurements, while other products are produced by computer models. A key application of the outputs is to facilitate review and decision-making by the road owner and stakeholders. The outputs need to efficiently support project planning, such as selection of preferred alternatives, engineering design development, assessment of habitat restoration and/or habitat impacts, completion of environmental permitting and compliance, developing climate change resilience strategies.

Understanding the options for the types of outputs that are possible is essential, along with specifying the outputs and deliverables to serve project needs. Graphics and animation products can be quite helpful and instructive; however, basic numerical parameters and statistics are important as well. This section provides examples of outputs as a guideline to help the reader understand options and purposes of outputs.

Overall purpose and utility of H&H outputs

The outputs from hydrology and hydraulics analyses, including modeling, serve a variety of applications. These include the following:

- Providing insight into system dynamics
- Providing engineering design parameters
  - Sizing culvert / bridge openings (e.g., cross-section, invert elevation, height)
  - Scour protection measures (e.g., wing walls, scour aprons, armor unit sizes)
  - Assessing habitat conditions and potential
    - Potential for salt marsh restoration
    - Impacts to freshwater wetlands / upland forest
    - Suitability for fish passage
- Addressing environmental regulatory criteria

There are range of potential H&H outputs, which include the following:

- Time series plots (may include a combination of measured data and simulated results)
  - Water surface elevation
  - Current speed
  - Salinity
  - Water quality
- Model animations
- Statistics and derived parameters (may include a combination of measured data and simulated results)
  - Water level datums: MLLW, MLW, MSL, MTL, MHW, MHHW, HTL
  - Max / mean/ min salinity
  - Peak flood and ebb tide currents
- Mapping products
  - Snapshots in time (e.g., at high tide or low tide)
  - Time averages
  - Depth-averages
  - Outputs at different depths (3-D)

All of these types of outputs can be generated for a variety of environmental conditions (discussed above), including:

- Typical average tide and runoff conditions
- Range of spring and neap tides
- Coastal storm surge
- Variable precipitation (drought, high flow)
- Climate change (sea level rise scenarios, future storm frequency & intensity for surge and precipitation)

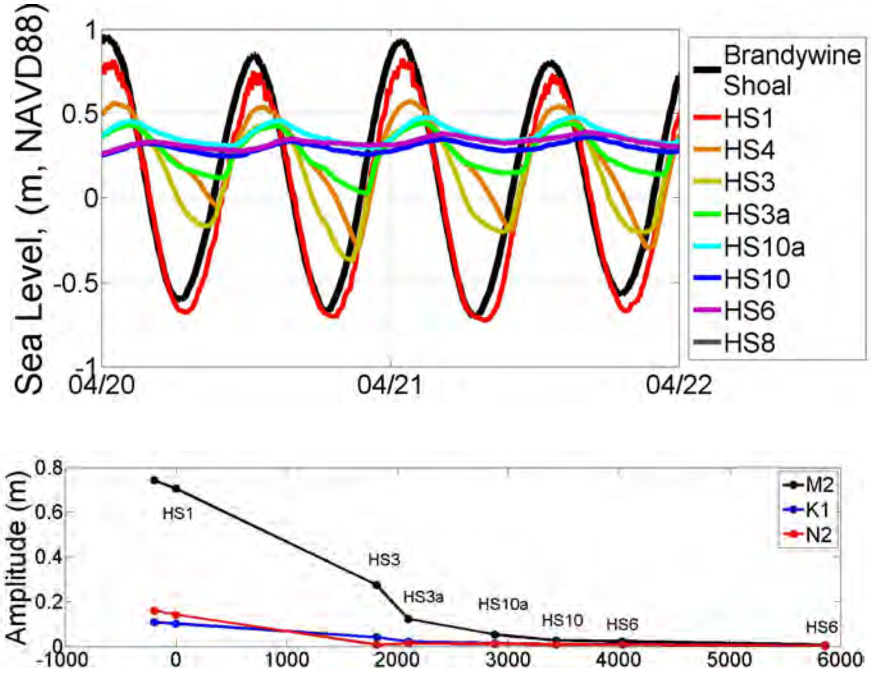
Furthermore, all of these types of H&H outputs can be generated for a range of project alternatives, such as:

- Existing conditions and structural configurations
- Proposed structural design alternatives
- Proposed system configurations (e.g., dredging, channel realignment, thin layer deposition)
- Possible future natural system changes (e.g., shoaling, barrier beach erosion)

The number of possible outputs can become overwhelming. Map out the outputs in a matrix which integrates the combinations of sea level rise and other varied inputs for each project alternative. This helps tailor the outputs to the project requirements. The subsections below provide several example outputs to provide a sampling of the range of possibilities.

Example: Water Level

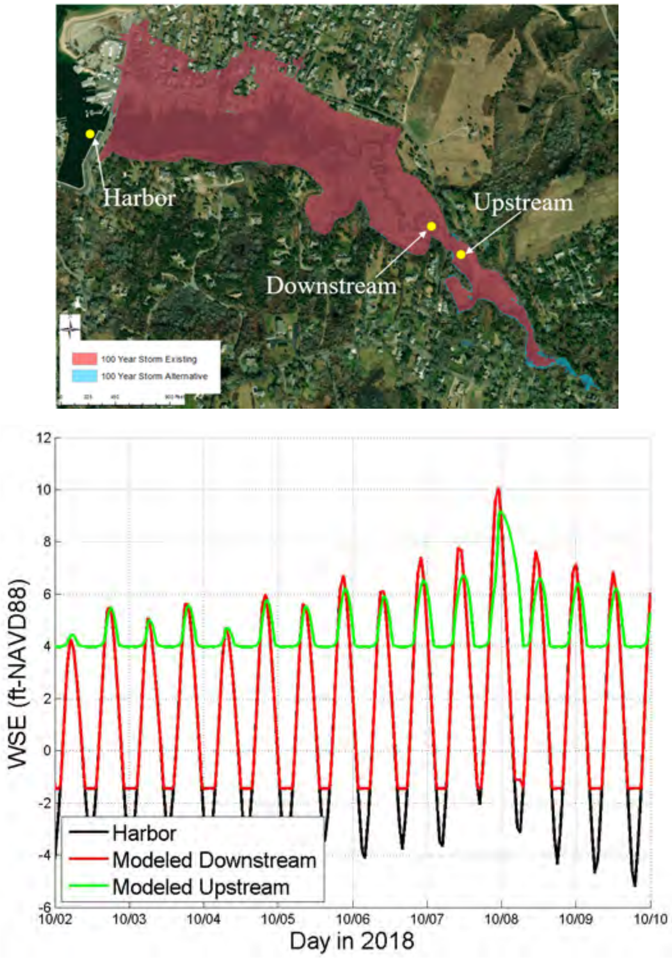
These figures show locations of tide gauges in the Milford Neck, Delaware, system, along with a time series plot and a tidal constituent plot indicating how the water changes substantially within the system. This type of presentation is useful to understand where within a system most of the tidal dampening occurs. Is it at a tidal crossing where something can be done locally to mitigate, or is the tidal dampening a result of meandering shallow channels where larger scale dredging would be required? Here the tidal constituent amplitude plot shows the majority of the M2 tidal signal (from the moon) is lost between HS1 and HS3, before the wooden crossing, but a significant amount is also lost between HS3 and HS3a, just after the wooden crossing, which can be mitigated locally.



Top: Water level measurement stations. *Middle*: Time series of water level. *Bottom*: Primary tidal constituent amplitudes (M2, K1, N2) in Milford Neck, Delaware. M2: Principal lunar semidiurnal constituent. K1: Lunar diurnal constituent. N2: Larger lunar elliptic semidiurnal constituent.

Example: Flooding Considerations

Locations of tide gauge deployments for Maraspin Creek system in Barnstable, Massachusetts, are shown in the figure below. Data show that there is tidal dampening upstream caused by a culvert under a road crossing that significantly inhibits low tide, as well as high tide for storm events. Inundation mapping model output shows there is potential to modestly exacerbate flooding upstream for a hundred-year storm if the road crossing is improved (e.g., extra blue area at lower right that is flooded compared to the red area). The key question is whether this newly flooded area is of concern for property flooding and whether it is a benefit for habitat.

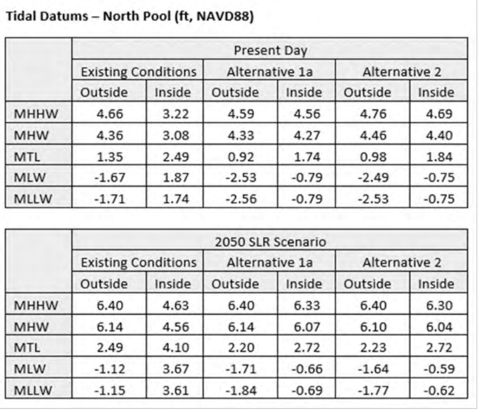


Top: Inundation map for hundred-year event for existing conditions (red) and with proposed culvert alternative (blue) in Maraspin Creek in Barnstable, Massachusetts. *Bottom*: Water levels during a hundred-year storm in Maraspin Creek system.

Example: Wetting and Drying Considerations

This example focuses on a freshwater impoundment, called North Pool, connected to Great Marsh in Newbury, Massachusetts. There is consideration to open the tidal crossing to relieve the freshwater impoundment and restore it to a natural salt marsh system. The tidal datums are critical in making this decision, as they compare to the existing and potential future system bathymetry, considering potential for future shoaling and sea level rise.

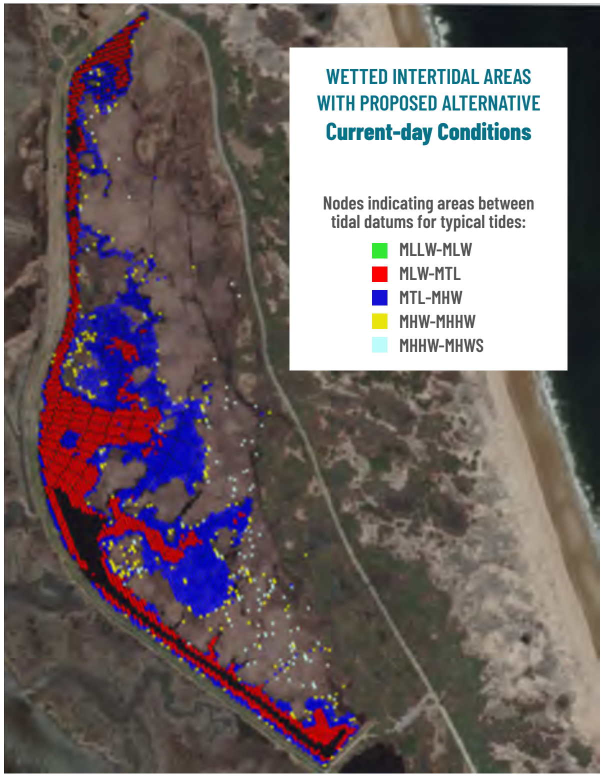
The three consecutive graphics below indicate the potential areas for intertidal mud flat (red area between MLW and MTL), low marsh (blue area between MTL and MHW), and high marsh (yellow area between MHW and MHHW). Results show that with an improved tidal crossing there is opportunity to restore habitat and that the potential low marsh area expands significantly with sea level rise (SLR). If accretion is included, then there is potential for additional high marsh as well. This type of output can be used to answer key questions such as whether it is worthwhile to invest in a tidal crossing improvement, understanding how rising sea levels and sediment accretion and marsh migration will potentially influence the system in the future.



Tidal Datums – North Pool (ft, NAVD88)

	Present Day					
	Existing Conditions		Alternative 1a		Alternative 2	
	Outside	Inside	Outside	Inside	Outside	Inside
MHHW	4.66	3.22	4.59	4.56	4.76	4.69
MHW	4.36	3.08	4.33	4.27	4.46	4.40
MTL	1.35	2.49	0.92	1.74	0.98	1.84
MLW	-1.67	1.87	-2.53	-0.79	-2.49	-0.75
MLLW	-1.71	1.74	-2.56	-0.79	-2.53	-0.75

	2050 SLR Scenario					
	Existing Conditions		Alternative 1a		Alternative 2	
	Outside	Inside	Outside	Inside	Outside	Inside
MHHW	6.40	4.63	6.40	6.33	6.40	6.30
MHW	6.14	4.56	6.14	6.07	6.10	6.04
MTL	2.49	4.10	2.20	2.72	2.23	2.72
MLW	-1.12	3.67	-1.71	-0.66	-1.64	-0.59
MLLW	-1.15	3.61	-1.84	-0.69	-1.77	-0.62

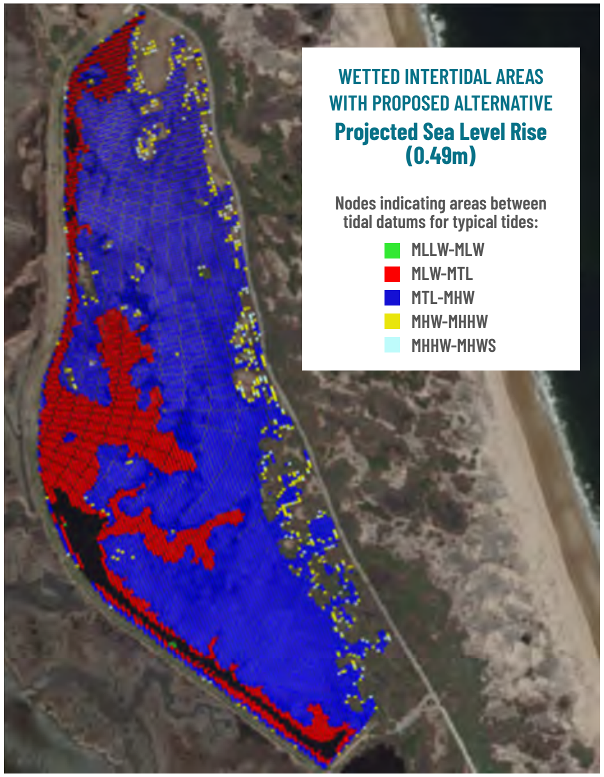


WETTED INTERTIDAL AREAS WITH PROPOSED ALTERNATIVE

Current-day Conditions

Nodes indicating areas between tidal datums for typical tides:

- 🟩 MLLW-MLW
- 🟥 MLW-MTL
- 🟦 MTL-MHW
- 🟨 MHW-MHHW
- ⬜ MHHW-MHWS

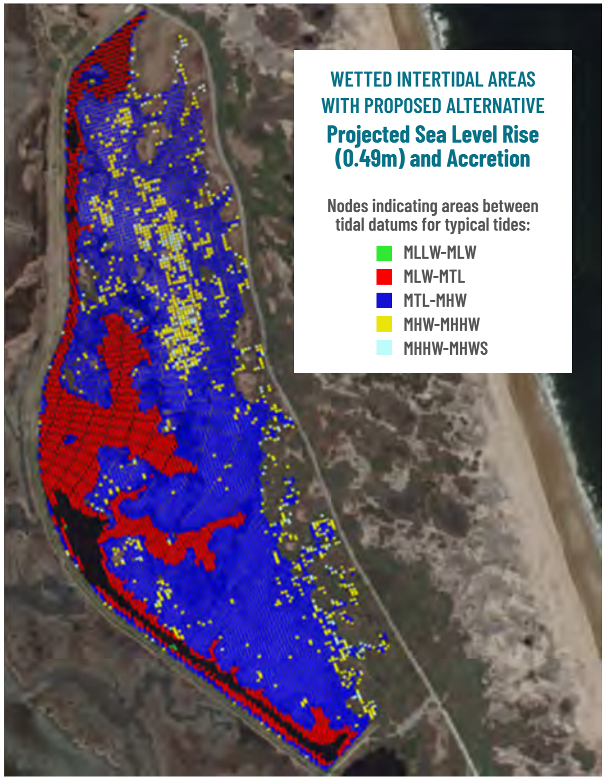


WETTED INTERTIDAL AREAS WITH PROPOSED ALTERNATIVE

Projected Sea Level Rise (0.49m)

Nodes indicating areas between tidal datums for typical tides:

- 🟩 MLLW-MLW
- 🟥 MLW-MTL
- 🟦 MTL-MHW
- 🟨 MHW-MHHW
- ⬜ MHHW-MHWS



WETTED INTERTIDAL AREAS WITH PROPOSED ALTERNATIVE

Projected Sea Level Rise (0.49m) and Accretion

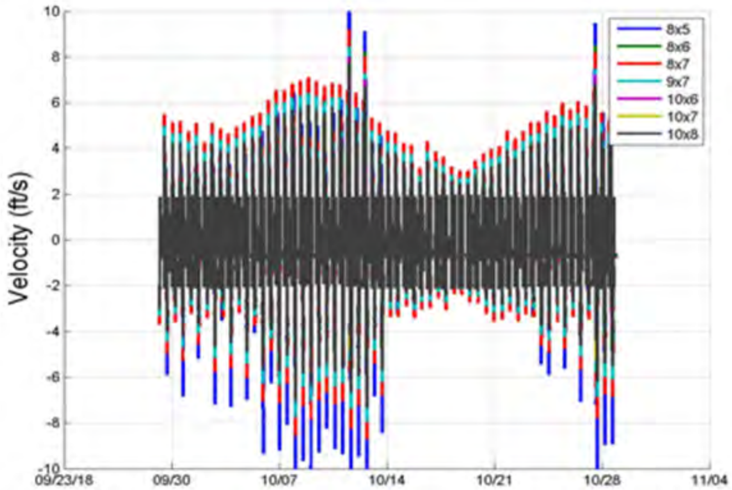
Nodes indicating areas between tidal datums for typical tides:

- 🟩 MLLW-MLW
- 🟥 MLW-MTL
- 🟦 MTL-MHW
- 🟨 MHW-MHHW
- ⬜ MHHW-MHWS

Example: Current Velocity Considerations

The graph below shows the changing current velocity at a tidal constriction for a range of potential box culvert sizes (shown in legend as width x height), including the reversing current velocity (upstream + and downstream -). A structure needs to be designed to withstand the reversing current speeds for a variety of magnitudes. For selection of a preferred alternative, the table of velocities is helpful both for current design and for helping to select a structure with a suitable current velocity, including to provide full passage for diadromous fish.

The most commonly managed fish species will include rainbow smelt, river herring, American eel, eastern brook trout, Atlantic salmon, striped bass, and American shad. Species-specific passage criteria can be found in the Northeast Region fish passage engineering design criteria document (USFWS 2019). This document is predominantly focused on non-tidal passage conditions, but species-specific hydraulic criteria are provided. The MaineDOT waterway and wildlife crossing policy and design guide (MaineDOT 2008) provides another point of reference. The Washington stream crossings guidelines (Barnard et al. 2013) includes additional notes about passage criteria for estuary settings. Key questions may include whether there are anadromous fish needing passage and whether the structure needs to be designed with a certain maximum velocity and/or minimum depth.



Velocities (fps) for Typical Tides

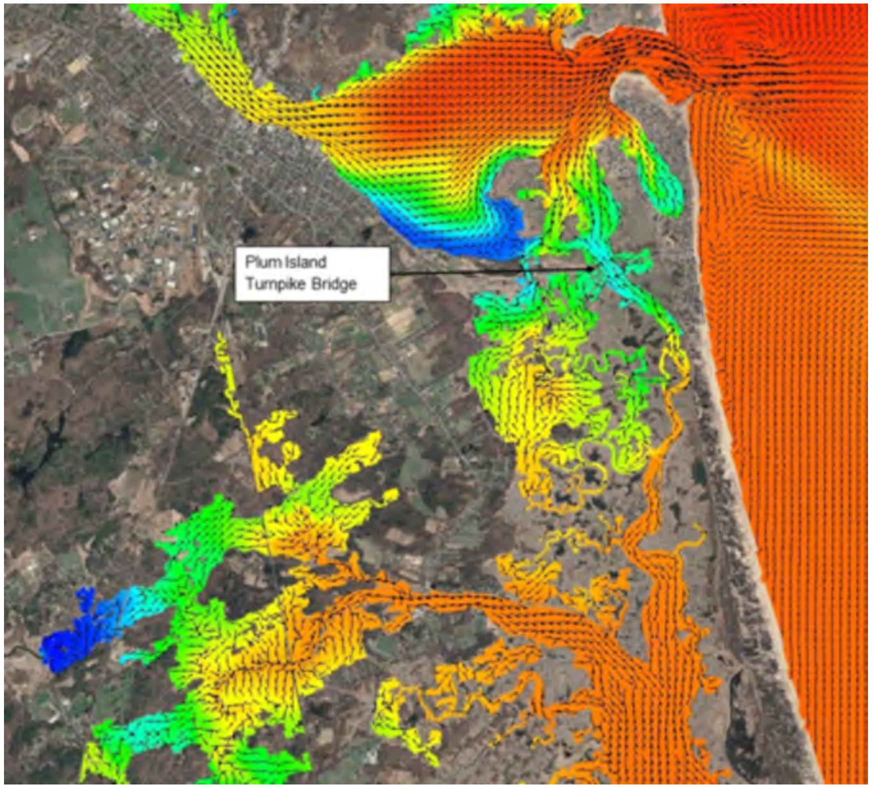
Max & Mean Velocity	Box Culvert Opening Size (w x h)						
	8x5	8x6	8x7	9x7	10x6	10x7	10x8
max Flood	10.2	9.2	9.2	8.4	8.0	7.7	7.7
max Ebb	-11.2	-8.7	-8.7	-7.9	-7.3	-7.3	-7.3
mean Flood	3.0	2.9	2.8	2.5	2.3	2.3	2.3
mean Ebb	-1.5	-1.5	-1.5	-1.3	-1.2	-1.2	-1.2

Water level measurement stations (top), time series of water level (middle), and primary tidal constituent amplitudes (M2, K1, and N2; bottom) in Milford Neck, DE. M2-principal lunar semidiurnal constituent, K1-lunar diurnal constituent, N2-larger lunar elliptic semidiurnal constituent.

Example: Salinity Considerations

The figure below illustrates a snapshot in time of the modeled salinity distribution in the Great Marsh system in Massachusetts. There is a major tidal crossing on the Plum Island Turnpike bridge that was being considered for expansion to promote tidal flushing for purposes of possible wetland restoration, and with consideration of potential influences of future sea level rise (e.g., allow more flow to help minimize flooding of adjacent infrastructure and property). The Merrimack River to the north is a major source of freshwater inflow, whereas the ocean to the east provides the salt water.

Simulations showed that opening the bridge would enhance flow, but it would also serve as an improved pathway for freshwater flow from the Merrimack to be transported into the Great Marsh to the south. Great efforts have been made to combat the invasion of Phragmites in the Great Marsh system; thus, it was concluded that opening the Turnpike Bridge was not a current high priority. A key question for a project like this is whether and when to make the substantial investment of raising the road to minimize potential for episodic future flooding during coastal storms with sea level rise.



Flood simulation results showing color contours of salinity overlaid with current velocity vectors for a proposed widened Plum Island turnpike bridge opening in Great Marsh, Massachusetts. Blue tones represent low salinity, and red tones represent higher salinity.

APPENDIX B: CATALOG OF TIDAL CROSSING DESIGN ALTERNATIVES

Under present and projected sea level conditions, crossings with minimal intrusion into the tidal environment such as elevated spans would encourage the greatest degree of ecological resilience. However, many tidal crossings will include a conveyance structure or structures, along with approach sections installed on the wetland surface. The approach sections are typically referred to as road embankments. Long tidal crossings that include long approaches and one or more conveyance structures (often resulting in major crossings) are typically referred to as causeways. In addition to the conveyance structure or structures, the configuration of the approach sections plays a crucial role in crossing safety and resilience, flood capacity, and ecological processes.

CoastWise tidal crossing structures are sized and designed using appropriate tidal hydraulic modeling and analysis and typically result in structures substantially wider than the adjacent tidal stream channel (Figure B.1). This promotes structure stability and resilience given flooding and sea level rise concerns, and also allows for tidal and ecological connectivity, including sediment continuity. Section 5 provides more detail on sizing of tidal crossings.

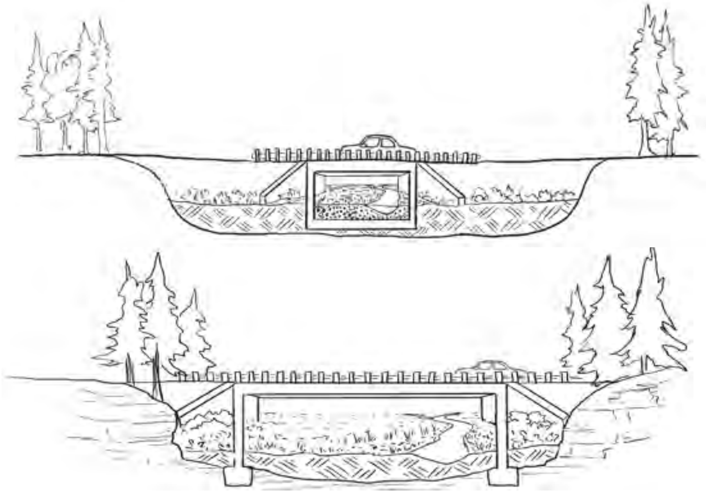


FIGURE B.1 - Conceptual tidal crossing configurations. Upper: Approach sections cross the tidal zone to an embedded concrete box culvert conveyance structure that is wider than the tidal channel and allows flood flow, habitat and overbank tidal flow connectivity. Lower: A wider span concrete rigid frame or bridge is used to span nearly the entire tidal zone. The span is substantially wider than the tidal channel, allowing for increased flood flow as well as improved habitat and overbank tidal flow connectivity. Illustration by Maisie Richards.

FIGURE B.2 - Single-lane bridge on piers in Chilmark, Massachusetts, that spans an area projected to flood more frequently with sea level rise. Photo by Slade Moore.

FIGURE B.3 - Example of a “fair-weather” road that overtops with a similar frequency as the adjacent marsh in Phippsburg. Photo by Erno Bonebakker.

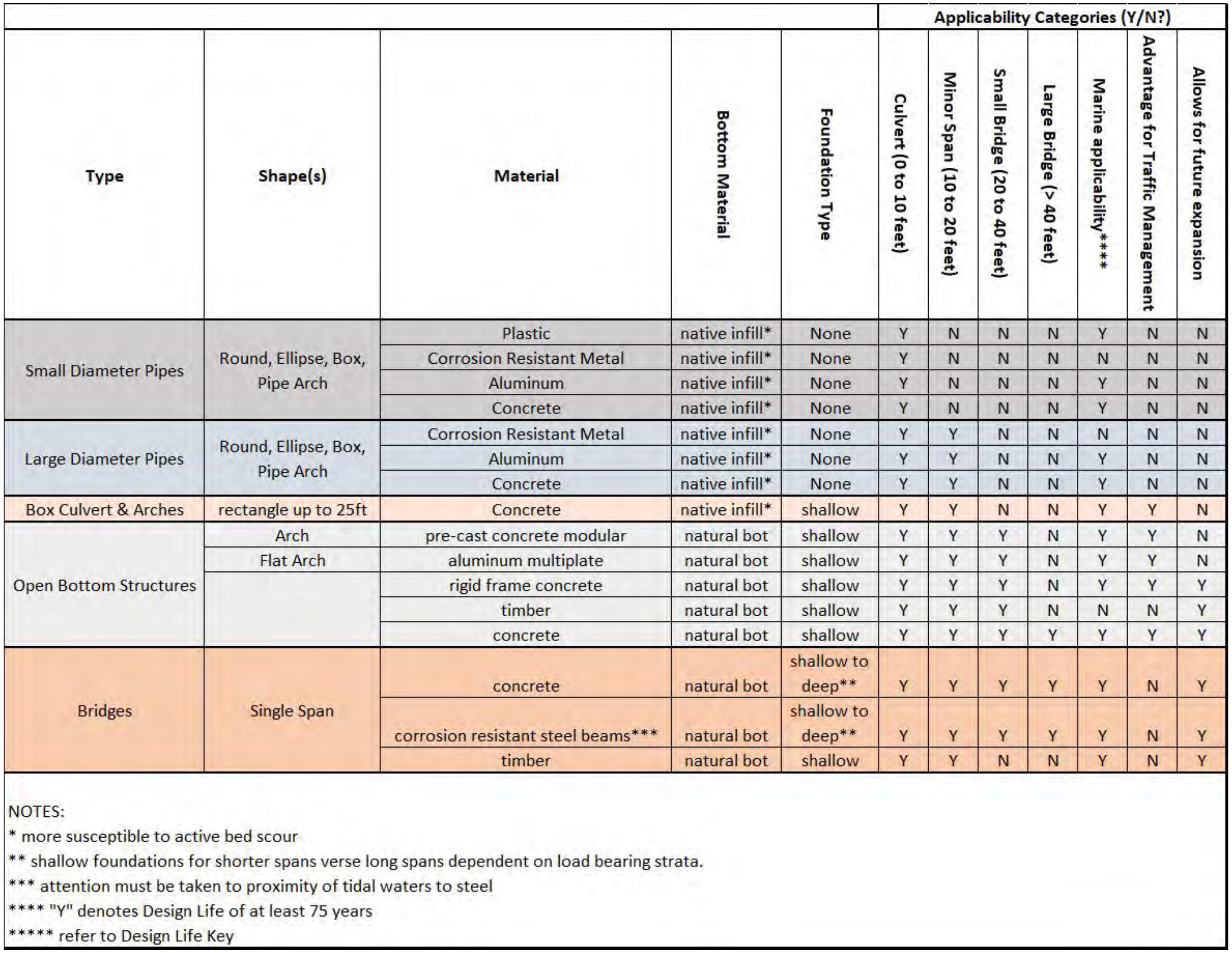
A range of shapes and materials, pre-cast or cast-in-place configurations, and other options are available for crossing structures. Table B.1 and Table B.2 summarize the range of structure options, where the various combinations of shapes and materials are organized in comparison to common MaineDOT span categories and other factors. Of these categories, Marine Applicability refers to the material's degree of durability in estuary settings. While aluminum is generally regarded as corrosion resistant, some case studies have suggested that its durability is substantially less in estuary settings than in freshwater.

The category Advantage for Traffic Management in Table B.1 indicates structures that are modular in nature that may allow a lane of traffic to be routed over an installed portion (e.g., the first half) while the remaining portion is installed. This may reduce the duration of complete road closure and traffic detour.

The category Allows for Future Expansion suggests a configuration that may allow the abutments and foundation elements to be reused in the future, if it were determined it was necessary to raise the superstructure or deck. This might be relevant for a phased installation approach where the future increase in road embankment height and/or crossing deck are planned in response to sea level rise.

Photos of crossing structure types are included after Tables B.1 and B.2 for reference.

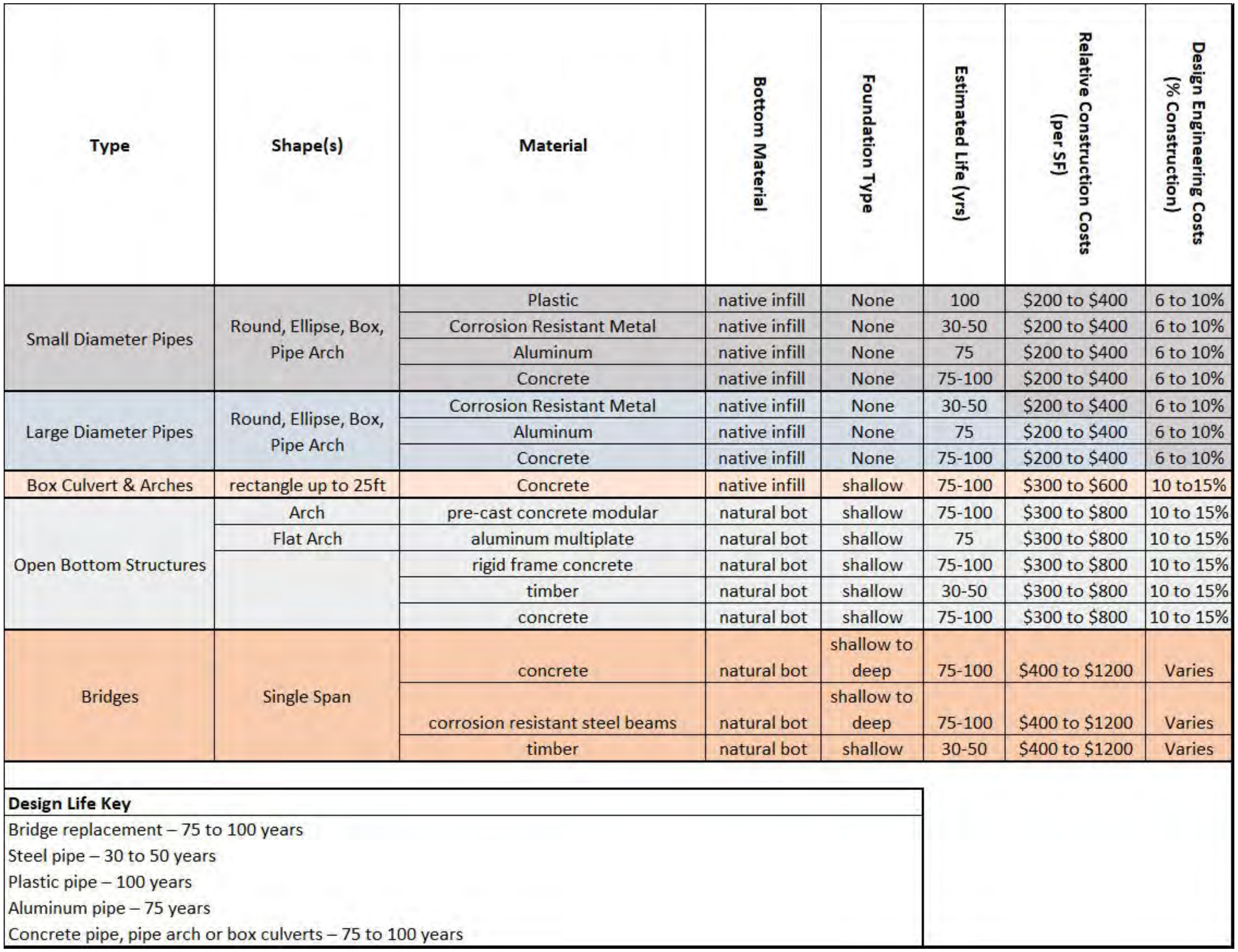
TABLE B.1 - Overview of tidal crossing structure types and applicability to span categories and other factors.



					Applicability Categories (Y/N?)						
Type	**Shape(s)**	**Material**	**Bottom Material**	**Foundation Type**	**Culvert (0 to 10 feet)**	**Minor Span (10 to 20 feet)**	**Small Bridge (20 to 40 feet)**	**Large Bridge (> 40 feet)**	**Marine applicability******	**Advantage for Traffic Management**	**Allows for future expansion**
Small Diameter Pipes	Round, Ellipse, Box, Pipe Arch	Plastic	native infill*	None	Y	N	N	N	Y	N	N
		Corrosion Resistant Metal	native infill*	None	Y	N	N	N	N	N	N
		Aluminum	native infill*	None	Y	N	N	N	Y	N	N
		Concrete	native infill*	None	Y	N	N	N	Y	N	N
Large Diameter Pipes	Round, Ellipse, Box, Pipe Arch	Corrosion Resistant Metal	native infill*	None	Y	Y	N	N	N	N	N
		Aluminum	native infill*	None	Y	Y	N	N	Y	N	N
		Concrete	native infill*	None	Y	Y	N	N	Y	N	N
Box Culvert & Arches	rectangle up to 25ft	Concrete	native infill*	shallow	Y	Y	N	N	Y	Y	N
Open Bottom Structures	Arch	pre-cast concrete modular	natural bot	shallow	Y	Y	Y	N	Y	Y	N
	Flat Arch	aluminum multiplate	natural bot	shallow	Y	Y	Y	N	Y	Y	N
		rigid frame concrete	natural bot	shallow	Y	Y	Y	N	Y	Y	Y
		timber	natural bot	shallow	Y	Y	Y	N	N	N	Y
		concrete	natural bot	shallow	Y	Y	Y	Y	Y	Y	Y
Bridges	Single Span	concrete	natural bot	shallow to deep**	Y	Y	Y	Y	Y	N	Y
		corrosion resistant steel beams***	natural bot	shallow to deep**	Y	Y	Y	Y	Y	N	Y
		timber	natural bot	shallow	Y	Y	N	N	Y	N	Y

NOTES:
* more susceptible to active bed scour
** shallow foundations for shorter spans verse long spans dependent on load bearing strata.
*** attention must be taken to proximity of tidal waters to steel
**** "Y" denotes Design Life of at least 75 years
***** refer to Design Life Key

TABLE B.2 - Overview of tidal crossing structure types, estimated life spans, and relative cost ranges.



Type	**Shape(s)**	**Material**	**Bottom Material**	**Foundation Type**	**Estimated Life (yrs)**	**Relative Construction Costs (per SF)**	**Design Engineering Costs (% Construction)**
Small Diameter Pipes	Round, Ellipse, Box, Pipe Arch	Plastic	native infill	None	100	$200 to $400	6 to 10%
		Corrosion Resistant Metal	native infill	None	30-50	$200 to $400	6 to 10%
		Aluminum	native infill	None	75	$200 to $400	6 to 10%
		Concrete	native infill	None	75-100	$200 to $400	6 to 10%
Large Diameter Pipes	Round, Ellipse, Box, Pipe Arch	Corrosion Resistant Metal	native infill	None	30-50	$200 to $400	6 to 10%
		Aluminum	native infill	None	75	$200 to $400	6 to 10%
		Concrete	native infill	None	75-100	$200 to $400	6 to 10%
Box Culvert & Arches	rectangle up to 25ft	Concrete	native infill	shallow	75-100	$300 to $600	10 to15%
Open Bottom Structures	Arch	pre-cast concrete modular	natural bot	shallow	75-100	$300 to $800	10 to 15%
	Flat Arch	aluminum multiplate	natural bot	shallow	75	$300 to $800	10 to 15%
		rigid frame concrete	natural bot	shallow	75-100	$300 to $800	10 to 15%
		timber	natural bot	shallow	30-50	$300 to $800	10 to 15%
		concrete	natural bot	shallow	75-100	$300 to $800	10 to 15%
Bridges	Single Span	concrete	natural bot	shallow to deep	75-100	$400 to $1200	Varies
		corrosion resistant steel beams	natural bot	shallow to deep	75-100	$400 to $1200	Varies
		timber	natural bot	shallow	30-50	$400 to $1200	Varies

Design Life Key

Bridge replacement – 75 to 100 years
Steel pipe – 30 to 50 years
Plastic pipe – 100 years
Aluminum pipe – 75 years
Concrete pipe, pipe arch or box culverts – 75 to 100 years

FIGURE B.4 - A reinforced concrete box structure with prefabricated wingwalls and an installed channel bed. Structure size in this example was five feet rise by ten feet span. Eel River, Plymouth, MA. Image source: Inter-Fluve.

FIGURE B.6- A three-sided concrete rigid frame structure, installed on pre-cast footings. Clear span of 24 feet. Structure includes a pre-cast modular design with six-foot-long sections. Due to cover limitations within the road prism, an insulated water line was attached to side of headwall. Coonamessett River, Falmouth, MA. Image source: Inter-Fluve.

FIGURE B.5 - An embedded pre-cast concrete box culvert, with 16-foot span by 8.5-foot rise. Lubberland Creek, Newmarket, NH. Image source: Peter Steckler.

FIGURE B.7 - A three-sided concrete rigid frame structure, installed on Wallace Shore Road (private) in Harpswell, ME. Image source: Matt Craig.

FIGURE B.8 - Maine DOT installation of precast concrete box culvert with twelve-foot span and six-foot rise. Long Reach Lane, Long Marsh, Harpswell, ME. Image source: Casco Bay Estuary Partnership.

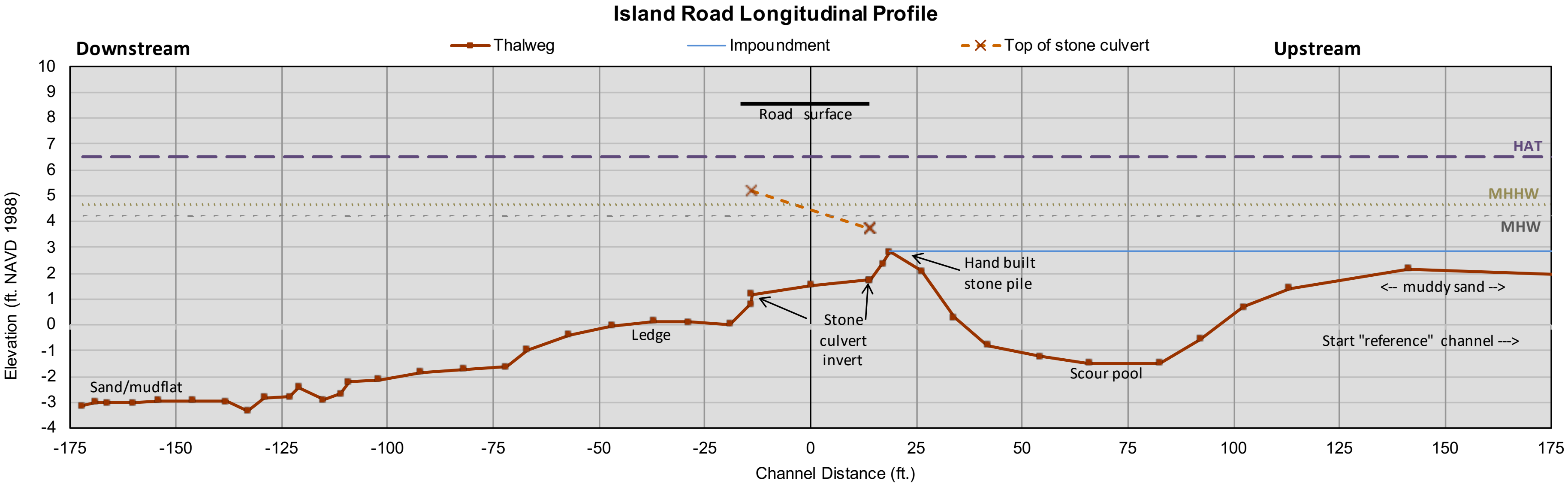
FIGURE B.10 - A three-sided rigid frame section being installed on pre-cast footings. Coonamessett River, Falmouth, MA. Image source: Betsy Gladfelter.

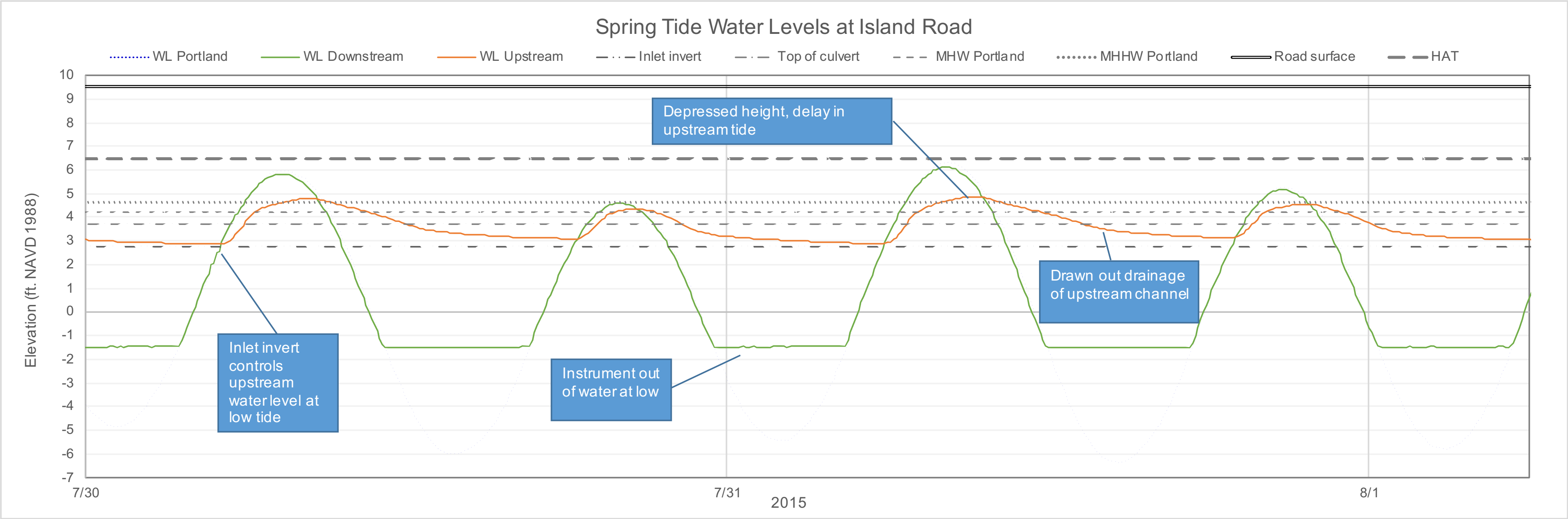
FIGURE B.9 - A three-sided rigid frame section. Image source: Precast Solutions.

FIGURE B.11 - A pre-cast wingwall installation for a three-sided rigid frame with pre-cast footings. Coonamessett River, Falmouth, MA. Image source: Chris Bennett.

APPENDIX C: FIELD DATA EXAMPLES

The following plots are examples of post-processed and interpreted data from a Detailed Site Investigation. The plots are a longitudinal channel profile and tidal water level monitoring data for spring and neap tide conditions.



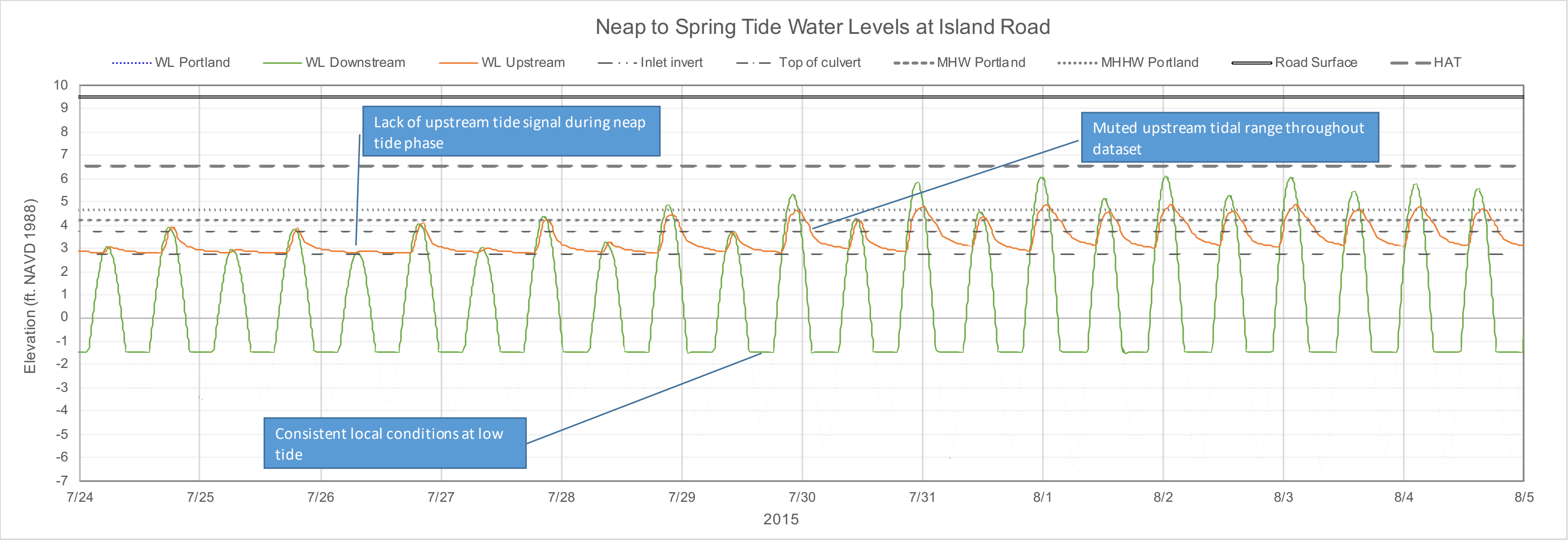


Depressed height, delay in upstream tide

Inlet invert controls upstream water level at low tide

Instrument out of water at low

Drawn out drainage of upstream channel



Lack of upstream tide signal during neap tide phase

Muted upstream tidal range throughout dataset

Consistent local conditions at low tide

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CoastWise

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