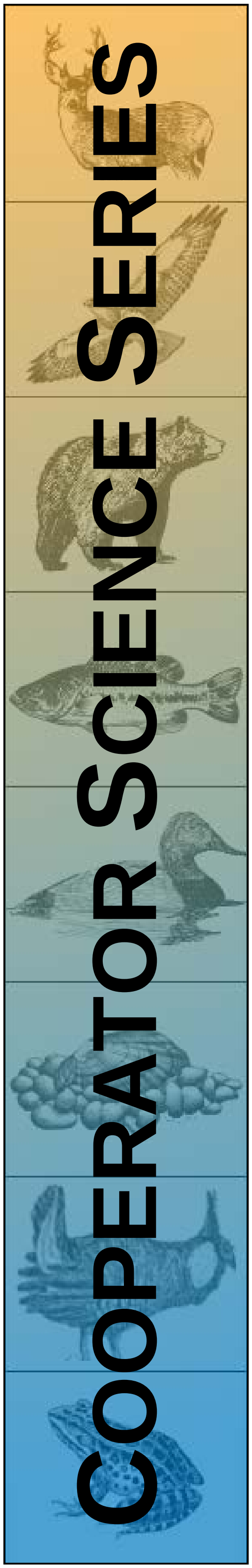

Impacts of Tidal Road-Stream Crossings on Aquatic Organism Passage

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EXECUTIVE SUMMARY

Rivers and streams are highly vulnerable to fragmentation from roads due to their prevalence in the landscape. Road-stream crossings are far more numerous than other anthropogenic barriers such as dams; these crossing structures (culverts, bridges, fords, and tide gates) have been demonstrated to impede the passage of aquatic organisms. However, road-stream crossings vary widely in the extent to which they serve as a barrier. It is important to identify barrier severity to facilitate prioritization of restoration activities, since proactively addressing all structures is not feasible.

In 2015 the North Atlantic Landscape Conservation Collaborative (LCC) funded a project managed by the North Atlantic Aquatic Connectivity Cooperative (NAACC) to develop a unified protocol for assessing aquatic road-stream crossings focusing on aquatic connectivity. The NAACC relied on rapid field-based assessments, which have been shown to be a useful tool for gathering information necessary for prioritization. However, the rapid assessment protocol developed from the NAACC initiative is not applicable to tidal crossings as it does not address two-directional flow, daily water depth fluctuations, or many of the species likely present in coastal habitats.

The goal of this report is to provide the background necessary to create guidelines and rapid assessment tools for assessing risk posed to aquatic organism passage at tidal crossings. To accomplish these goals, this report identifies species present in tidally influenced coastal wetlands, the unique traits they may display that puts them at risk for detrimental impact from impeded passage, and passage threats unique to tidal crossings that are not addressed by protocols designed for non-tidal systems. Species lists were compiled through literature reviews and discussions with regional researchers and managers familiar with coastal ecosystems or fish passage concerns. Life history traits, environmental sensitivities, and movement patterns for each species were compiled to build a database that can be queried to identify species that are highly vulnerable to impeded passage at tidal crossings (Available at: https://umass.box.com/s/w5mhokxjxshyxmr7si2v0gzcypcitu9d). These risk factors for species, combined with passage threats associated with specific crossing characteristics are discussed in this report. The species list is thorough enough to provide a baseline summary of the types of threats experienced by aquatic organisms at tidal road-stream crossings, but it is not exhaustive. Unique ecosystems, species assemblages, management goals, and prioritization models may require different approaches and solutions. Thus, care must be taken to ensure that assessment tools are appropriate to a project's target species, habitats, and scale.

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Table 18: Threat level for species listed as vulnerable, near threatened, or endangered on the International Union for Conservation of Nature (IUCN). U.S. Endangered Species Act (ESA) status also included. Mobile indicates that these species undergo known movements between habitat types as adults.

Table 19: Substrate preference for adults. Data from Fishbase.org.

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Project goals and scope

This report summarizes aquatic organism passage challenges unique to tidal road-stream crossings to provide guidance to the future development of a protocol for assessing tidal road-stream crossings. Connectivity between habitats is vital both for healthy ecosystems and healthy populations of aquatic organisms (Able 2005, Gillanders et al. 2003). Successful passage through and within tidal ecosystems is important both for resident marsh species and diadromous fish that must pass through the tidal portion of streams to reach vital habitat further upstream, as well as for freshwater and marine species that utilize the marsh for portions of their life cycle, or for foraging (Leaf 1986, Whitlatch 1982, MacKenzie and Dionne 2008). Road stream crossings, which are especially prevalent in coastal habitats due to high rates of development, can impede passage (Januchowski-Hartley et al. 2014). These crossings are highly variable in size, construction, maintenance, and position in the stream network and in relation to other barriers. Thus, crossings are highly variable in the degree of severity they present as barriers to aquatic organism passage (Anderson et al. 2012). To best understand the impact of road-stream crossings on connectivity and to effectively prioritize efforts to mitigate their impact, it is important to be able to rapidly assess and rank structures for detrimental impact (Kemp and O'Hanley 2010). Such assessments can incorporate field-based scores to inform a landscape scale prioritization model (Anderson et al. 2012).

This report focuses on determining the suite of species present in tidally influenced habitats and categorizing their risk level for impaired organism passage based on movement patterns, behaviors, and environmental requirements derived from the literature. The first step of this project was to generate a list of aquatic and semi-aquatic species that utilize tidally influenced coastal streams throughout tidally influenced coastal habitats on the U.S. East coast, ranging from Virginia to Maine (Table 1, Fig. 1).

We consulted primary literature and species databases (Fishbase.org) to compile relevant information for passage concerns, focusing on life history characteristics, movement patterns, environmental preferences, physical tolerances, and behaviors, all factors that have been identified as influential in predicting passage through a road-stream crossing (Kemp and O'Hanley 2010). These species traits were summarized to identify those at greatest risk for passage through tidal road-stream crossings. All species within the project scope were considered to identify passage concerns for a comprehensive species assemblage rather than a select few, large-bodied, highly migratory target species.

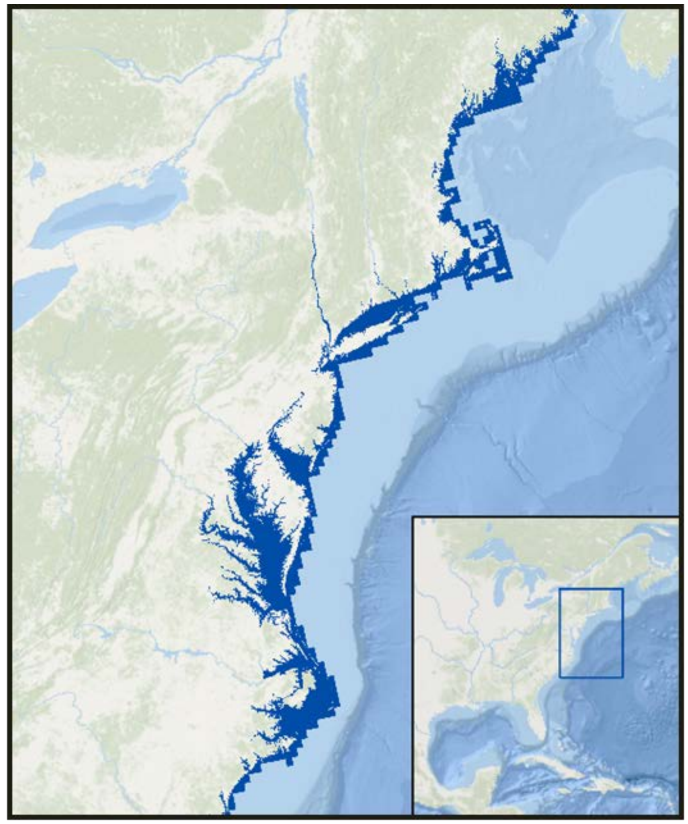

Figure 1: Tidally influenced coastal waters from Virginia to Maine. Data available from Conte Ecology 2016 (https://github.com/Conte-Ecology)

These species lists, along with consultation with fish passage literature and regional fish passage experts and managers were used to identify common traits that indicated passage threats. In addition to determining high risk traits for aquatic organisms, we also identified passage concerns present in tidal streams and crossing structures themselves, highlighting those that are unique to tidal systems. Species traits of high concern identified in this report include long migrations, movements that are necessary for survival or reproduction, short or specific movement windows, tidal movements, and sensitivities to abrupt changes in water quality. Crossing specific traits include the presence and severity of inlet or outlet drops, physical barriers within the crossing, excessive water velocities, insufficient water depths, high turbulence within the water column, the absence of bank edge for dry passage of terrestrial and semi-aquatic organisms, and discontinuity of channel substrate, which are present irrespective of tidal influence. Traits

identified as unique to tidal crossings include bidirectional flow, changing depths throughout the tidal cycle, and severe biochemical water quality transitions, all in relation to the timing of conditions and the movement cycles of aquatic organisms.

In addition to potentially disrupting stream connectivity, road-stream crossings may also destabilize natural hydrologic conditions, sediment flow, and vegetative communities (Buchsbaum et al. 2006), which can indirectly influence passage. Widespread habitat degradation that can occur compounds the threats to connectivity caused by passage barriers (Roman et al. 2002), and is important to consider to best manage ecosystem health in coastal habitats. However, for this report our treatment of habitat concerns are limited to the extent that they directly create conditions through which an organism cannot or will not pass.

TIDALLY INFLUENCED HABITATS

Focal habitats

Coastal habitats from Virginia to Maine include a wide variety of habitat types, such as estuaries, coastal rivers, salt marshes, mud flats, rocky coastlines, and sandy beaches (National Marine Fisheries Service 2015). Within these broad habitat types we have identified three unique categories: salt marsh and tidal creek complexes, tidal freshwater systems, and flow through coastal rivers and streams (Fig. 2). Each of these categories contains physical and ecological differences that present unique challenges in assessing passage at road-stream crossings.

Within these categories there is a large amount of variation in conditions within the Mid-Atlantic and Northeast geographic scope. Throughout the wide

Figure 2: Examples of tidally influenced habitat types. Clockwise from top left: salt marsh and tidal creek habitat, tidal freshwater marsh, large coastal river, small coastal stream. Photo credits: Beatriz Dias, Adrian Jordaan, Ashleigh Novak.

range of latitudes included in this study there are substantial differences in water temperature, which can drive community composition (Whitlatch 1982). Tidal range is also highly variable due to coastline topography and land configuration. Due to the temperate climate in this study area, there are also seasonal changes that impact these habitats (Leaf 1986). Seasonality affects conditions throughout the year, and those conditions vary in extremity with latitude and weather patterns. The following sections address general ecology and characteristics of these three habitat categories and the broad suite of species likely found within them, acknowledging the high degree of variability within these systems and across this region, and across seasons that impacts species distribution and movements.

Salt marsh and tidal creek complex

Salt marshes are characterized by the presence of tides, salinity, and anoxic sediments. They consist of flat, emergent vegetation interspersed with meandering tidal creeks and ponds (Leaf 1986). Depending on elevation, the marsh complex is divided into low marsh and high marsh sub-habitats. These systems are often interspersed with tidal mud flats and adjacent to large bays, all of which become intertwined in the exchange of nutrients and organisms (Leaf 1986, National Marine Fisheries Service 2015). Through these linkages the marsh complex contributes to estuarine and riverine food webs, sequesters nutrients from runoff that improves estuarine water quality, and provides important nursery, refuge, and forage habitat for many species (Leaf 1986).

Tidal salt marshes are among the most productive systems on earth, supporting a wide range of terrestrial, aquatic, and marine organisms for all or parts of their lives (Leaf 1986, Odum 1969, Steever et al. 1976). Odum (1969) first suggested this high productivity was due to tidal influx, an assumption later validated by Steever et al. (1976), who demonstrated a positive relationship between tidal influx and productivity (Leaf 1986). Due to their prevalence in the coastal landscape, the collective influence of tidal creeks on estuarine ecology may exceed that of large river systems (TNC 2016). Salt marshes are present throughout low energy coastal areas in the Mid-Atlantic and New England coast, often in areas shielded by barrier islands and estuaries (Leaf 1986). Marshes keep pace with sea level rise by accumulating sediment transported by rivers and coastal currents, which deposit the sediment in slow moving areas and build stability; however, barriers and development at the back end of marshes impede the salt marsh migration process inland (Leaf 1986) and freshwater impoundments created by dams can trap needed sediment.

Low marsh habitat is regularly flooded, and the vegetation community is dominated by *Spartina alterniflor*a, a perennial deciduous grass, while the high marsh is less frequently flooded, with a vegetation community dominated by *Spartina patens* (Leaf 1986). Sediments in the marsh community are typically comprised of silt and clay with sand-bottomed channels. They are sulfurous and low in oxygen (Leaf 1986). Rising and falling tidal flows are channeled primarily through creek beds that wind through marsh habitat until the tide rises high enough to inundate the marsh surface at peak high tides (Bertness 1991). There is a large variation in tidal range and inundation patterns depending on geography, wind, and sediments (Leaf 1986). Marsh waters are typically saline, or even hypersaline, but this is moderated inland by a varying degree of freshwater input from rivers, streams, and groundwater leading to a salinity gradient from headwater to river mouth which drives the vegetation and animal community composition (Leaf 1986).

Animal communities in salt marsh ecosystems have evolved to deal with highly variable and potentially stressful physical conditions. Marine meiofauana in salt marshes include nematodes, foraminiferans, harpacticoid copepods, soil mites, oligochaetes (abundant in marsh sediments), as well as planktonic meiofauna, which consist of the eggs and larvae of marsh inhabitants and adult benthic meiofauna that have become dislodged into the water column (Leaf 1986, Whitlatch 1982). All forms of meiofauna are food for filter-feeding invertebrates and plankton-feeding fish, which migrate to marshes on the flood tide to feed. Plankton washed out on the ebb tide also become food for organisms residing in channels, mudflats, and estuaries. Invertebrate macrofauna in salt marshes consist of crabs, snails, and mussels that are food sources for aquatic, avian, and terrestrial predators (Leaf 1986, Whitlatch 1982). Fish species may be resident in the marsh complex for their entire life, pass through on larger migrations, or use the marsh complex for key activities such as spawning, growing during larval/juvenile stages, or foraging (Leaf 1986, Whitlatch 1982). There is pronounced latitudinal, seasonal, and local variation in fish communities driven largely by water temperature (Whitlatch 1982). For example, north of Cape Cod, MA, salt marsh communities consist of more resident, cold water species, whereas communities south of Cape Cod are dominated by warmer water and

migratory species (Whitlatch 1982, Roman et al. 2000). Terrestrial predators such as insects, spiders, birds and mammals (otter, raccoon) also hunt in the marsh and tidal creek edges, leading to energy and nutrient subsidies across terrestrial-aquatic boundaries (Leaf 1986). This diversity of species and life history strategies make salt marshes important to populations and ecological functions far outside their geographic boundaries.

Coastal streams and rivers

Coastal streams and rivers can be loosely divided into groups based on size, connectivity to other habitats, tide, and salinity characteristics. Topography and geology also drive many important key characteristics of these habitats, which, depending on location, can range from slow moving, muddy, and brackish to high velocity, rocky, and freshwater, with important implications for species communities and relationships to adjacent habitats.

Small, coastal streams are primarily tidal creeks that are integrated into the salt marsh complex, as discussed in the previous section. Tidal creeks can depend predominantly on marine waters flowing in and out of the system, or can be flow through systems containing freshwater input from upland streams or groundwater. They usually contain salinities fluctuating between 0.5 and 30 ppt and often shift into freshwater system at their upper reaches (TNC 2016). They are often sinuous in shape and meander through salt marsh habitat, flowing into large estuaries or directly into the ocean. Intertidal habitat is often of greater prevalence in association with tidal creeks. The plant and animal communities associated with this stream type are the same as those previously identified as affiliated with salt marsh. The flow-through tidal creeks provide important nursery and foraging habitat for marine fish, foraging habitat for some opportunistic freshwater species, and migratory pathways for diadromous fish moving through coastal habitats into freshwater streams (TNC 2016).

Larger, coastal rivers such as the Hudson River in New York (USA) are distinct from tidal creeks in that they have enough consistent freshwater flow through to create vertical salinity gradients with fresh water on the surface and brackish water underneath. Salinity in these systems varies with tide, which forms a salt wedge that moves further up river with the rising tide and retreats downstream with the ebb tide (Geyer and Farmer 1988). Plant and animal communities are determined by depth and salinity (TNC 2016). Coastal riverine habitat is vital for diadromous species during migration, spawning, rearing, and juvenile development. In turn, these diadromous fish also support piscivorous marine fish populations that move upstream to feed on spawning adults or out-migrating juveniles (National Marine Fisheries Service 2015). Microhabitats within rivers (created by varying depth, substrate, velocity, large wood, and vegetation) provide habitat niches for diverse species with variable life history requirements (Moyle and Baltz 1985, Heggenes and Saltveit 1990). In addition to use by marsh residents, brackish portions of river are used as spawning, nursery, and foraging grounds for marine species; foraging for freshwater species; and migratory pathways for diadromous fish. Inland portions of tidal rivers provide resident habitat for freshwater species, as well as spawning and nursery habitat for diadromous species (TNC 2016).

Tidal freshwater

Above the head of tide where no saltwater intrusion occurs, water levels can still rise and fall with daily tides (TNC 2016). The tidal pulse forces water levels to rise and fall throughout the river system. Tidal freshwater habitats are usually associated with large river systems and estuaries with significant water displacement and large salt wedges (Odum 1988, TNC 2016). Tidal fluctuation can be present on the mainstem river, as well as in tributary streams and fringing marshes. Salt marshes can also transition directly to freshwater marsh impacted by similar tidal fluctuations (Odum 1988). Tidal range in these systems can still be noticeable, in some cases even larger than downstream ranges depending on the constriction of the water mass (Odum 1988).

Crossings located in tidal freshwater areas likely have unidirectional downstream water flow and are dominated by freshwater species, making them very similar to non-tidal systems in most regards besides daily water level flux. Even though the variability in conditions is less than in tidal systems where salt and fresh water mix and where flow direction changes with the tide, the daily rise and fall of the sea level can directly affect passage where physical barriers are created or exposed during ebb and flood tides.

Vascular plant and animal communities predominantly overlap with those found in freshwater systems. In freshwater marshes, invertebrate communities are dominated by oligochaetes, midge larvae, freshwater snails, and some crustaceans (mostly amphipods). Few bivalves are present in comparison to salt marshes, which overall have a greater diversity of

invertebrates (Odum 1988). Fish communities are also markedly different in freshwater tidal systems compared to estuarine habitat and are dominated by freshwater specialists, which make up 60% of species, followed by anadromous species (20%), estuarine species (13%) and marine species (7%) (Odum 1988). Reptiles and amphibians are also present in freshwater tidal in far greater numbers than in other tidal habitats (Odum 1988).

TIDAL ROAD-STREAM CROSSINGS

Overview

There has been a growing literature in recent years documenting the detrimental impacts of anthropogenic structures to fish and aquatic organism passage in river and stream ecosystems. As linear systems, rivers and streams are highly vulnerable to fragmentation (Bunn and Arthington 2002, Nilsson et al. 2016). At the same time, habitat connectivity is highly important to ecosystem function and to the life histories of many aquatic and marine species (Jager et al. 2000, Neraas and Spruell 2001, Gillanders et al. 2003, Able 2005, Sheer and Steel 2011). Animals may need to move between habitats on regular (daily or tidally) or infrequent (once in lifetime) temporal scales (Boesch and Turner 1984, Rountree and Able 1993, Becker et al. 2016), and on small (microhabitats within a stream) to large (ocean shelf to headwater streams) spatial scales (Gross 1987, Heggenes and Saltveit 1990, Nunn and Cowx 2012). Movements stem from biological needs such as foraging (Rick et al. 2011), seeking thermal refuge during hot or cold times of year (Conover and Murawski 1982) or refuge from predation exposure (Boesch and Turner 1984), breeding and spawning (Gross 1987), and ontogenetic shifts from nursery to adult habitat types (Gillanders et al. 2003). These movements may be obligatory for survival or may be facultative movements undertaken to increase fitness potential (Gross 1987, McDowall 1997). The degree to which an animal will be impacted by disrupted connectivity depends on the scale, frequency, and ecological need for movement (Gillanders et al. 2003, Able 2005, Nunn and Cowx 2012).

The extent to which a barrier disrupts connectivity depends on the type and characteristics of the barrier (McKay et al. 2013). Dams have been a primary focus of fish passage research, due both to their prevalence (e.g., >14,000 in New England, Magilligan et al. 2016) and to the severity of the barriers that they create (Bunn and Arthington 2002). However, dams are not the only anthropogenic impediments to connectivity throughout river systems. Road-stream crossings, which are far more numerous than dams, also present passage threats to aquatic organisms (Januchowski-Hartley et al. 2014) Road crossings can create partial or complete barriers to passage, depending on species of concern, construction type, and maintenance of a crossing structure (Kemp and O'Hanley 2010). Understanding the degree to which each crossing is a barrier is paramount in prioritizing replacement of structures with the aim of restoring connectivity amongst habitats (Kemp and O'Hanley 2010, Bourne et al. 2011, Anderson et al. 2012, Diebel et al. 2015).

Road-stream crossings are highly variable in the habitats they occur in, the species they impact, and the degree of passage they allow (Meixler et al, 2009, Anderson et al. 2012). Many crossings create partial barriers that may block movement for some species but not others, or that only create passage concerns under certain hydrologic conditions (Kemp and O'Hanley 2010, Anderson et al. 2012, Diebel et al. 2015). With dams, a realistic assumption is that without installing fish passage devices, passage is essentially zero. In contrast, road-stream crossings do not necessarily completely block passage and careful consideration must be taken to determine the severity of these barriers (Kemp and O'Hanley 2010, Anderson et al. 2012, King and O'Hanley 2016). Road-stream crossings are so numerous that prioritizing barrier severity is an important step in addressing passage concerns and working to restore connectivity (O'Hanley and Tomberlin 2005, Kemp and O'Hanley 2010, Bourne et al. 2011, Anderson et al. 2012, Nunn and Cowx 2012, Diebel et al. 2015, King and O'Hanley 2016). Prioritizing barriers for removal or replacement requires identifying target species and detrimental crossing characteristics, and understanding landscape scale variables such as proximity to other crossings and area of upstream habitat that determine the value of restoration or replacement (Anderson et al. 2012).

Crossing types

The eastern seaboard of the United States is highly developed and therefore road-stream crossings are very common (Januchowski-Hartley et al. 2014). Crossings were previously designed simply to divert water flow around or through a road with little or no thought to maintaining ecosystem connectivity, although newer structures may be designed with intention to maintain passage of organisms and hydrologic conditions, through either hydraulic or stream simulation

approaches (Larinier 2002, Bates 2003). In non-tidal systems, crossings include fords, bridges, and culverts (Barrett et al. 2006, Nedeau 2006). A ford is a shallow, open stream crossing in which water flows over sometimes raised and stabilized streambed. Bridges cross over the top of a stream or river and embankment rather than passing through a bank or hillside, leaving no fill on top of the structure. Bridges may include vertical side structures, reinforcing abutments to support the top deck, and fill or armoring within the streambed (Nedeau 2006). By comparison, culverts, which are tunnels through which a stream is routed underneath a road or other obstacle, contain a structure that is separated from the road surface by soil, gravel, or other materials (Barrett et al. 2006, Nedeau 2006). Culverts are highly variable in size and shape; they range from large box culverts made of concrete or stone, to open bottom arch culverts, to smaller round or elliptical pipe culverts with varying degrees of embeddedness within the streambed (Bates 2003, Nedeau 2006). A crossing may contain one of these types, or a combination (Fig. 3). Depending on crossing type, size and location in relation to the streambed, method of installation, and degree of maintenance, a crossing can cause minimal threat to organism passage, or alternately, act as a complete barrier (Anderson et al. 2012).

Tidal crossings also include tide gates, which are designed to intentionally block upstream tidal influence either consistently or during certain conditions (Bates 2003, Giaccico and Sounder 2005). Tide gates interrupt connectivity by design, blocking upstream flow of salt and brackish water during rising tides, while allowing drainage at lower tide stages. (Bates 2003, Giaccico and Sounder 2005). This engineering of coastal wetlands has

Figure 3: Examples of tidal road-stream crossing structures. Clockwise from top left: culvert; bridge; multiple separate gates, including old sluice gate (left) and flap gate (right); and combination flap and sluice gate. Photo credits: Beatriz Dias, Adrian Jordaan, and Ashleigh Novak.

allowed for the conversion of coastal land into agricultural, residential, and urban uses (Giaccico and Sounder 2005). This has come with repercussions for aquatic organism passage, although newer tide gate designs or management regimes aim to increase connectivity for fish (Bates 2003, Giaccico and Sounder 2005, Mouton et al. 2011, Franklin and Hodges 2015, Wright et al. 2016). Tide gates vary widely in appearance, ranging from a single culvert with a flap gate to a bridge-like structure with abutments, wing walls and multiple gates.

The impact of tide gates as a physical barrier depends on the length of time a gate is open, how far it opens, and many other ways in which a gate creates additional barriers, such as increasing velocity, increasing turbulence, and creating sharp transitions in pH, salinity, and temperature (Giaccico and Sounder 2005, Mouton et al. 2011, Green and Hall 2012, Wright et al. 2016). The weight of the gate and the materials used, as well as the hydraulic impact of the water moving through, will additionally influence the degree to which a gate opens and the amount of passage it allows (Giaccico and Sounder 2005, Franklin and Hodges 2015). Traditional designs of tide gates are either a) top-hinged, round, and cast iron or b) top-hinged, rectangular, and wooden. Both designs severely limit passage as they are open only for brief periods of time twice a day, may not open very far, and often create outflow with high turbulence (Bates 2003, Giaccico and Sauder 2005). Aluminum, PVC, and fiberglass top-hinged gates are lighter, allowing for larger openings at lower velocities during ebb tide, which increases organism passage, although they still close during flood tides, limiting connectivity for larger periods of the tidal cycle (Giaccico and Sauder 2005). Rubber duckbill designs allows lower velocity water to push open a piece of conical stiff rubber, allowing for potential downstream passage, but still impeding upstream migration. Pet doors allow for varying degrees of additional passage, with bottom hinged pet doors theoretically providing a larger passage window than top hinged pet doors. Permanent hole designs allow for some two-directional flow, increasing passage of aquatic organisms and restoring estuarine connectivity (Giaccico and Sauder 2005).

More complex tide gates are specifically designed to increase fish passage and habitat connectivity, while at the same time still function as flood and tide control structures. Self-regulating tide (SRT) gates use a buoyant lid in a variation of a traditional top-hinged door. This design allows for upstream flow of tide, with the gate only closing when water levels reach a pre-designated point that will cause undesirable upstream flooding. The floats that control this system can be adjusted so that gates close at every flood tide, or only during peak monthly tides or storm events (Giaccico and Sauder 2005). The mitigator fish passage (MFP) device uses a float operated locking system that locks open the gate for a portion of the flood tide. The muted tide regulator (MTR) is a newer design that maintains passage during flood time similarly to the SRT and MFP designs, but with openness regulated by the upstream inlet pool rather than by tide elevation. Tide gates can also be manually operated, propped open or raised on a sluice gate during certain times of the year and lowered when flooding is more of a concern. To determine the passage threat caused by a tide gate, it is important to know the implication of tide gate design, material, and management regimen (Green and Hall 2012, Franklin and Hodges 2015). Altering management strategies through adjusting the duration or angle of gate opening has been shown to improve passage for certain species (Mouton et al. 2011, Green and Hall 2012, Franklin and Hodges 2015, Wright et al. 2016).

Comparing non-tidal and tidal crossings

In non-tidal crossings flow is unidirectional and variability of flow conditions is primarily linked to season and precipitation (Dettinger and Diaz 2000). Upstream and downstream passage must both be considered, but historically there has been greater emphasis in primary passage mitigation efforts on upstream passage against velocity barriers or outlet drops, with an emphasis on the swimming and leaping ability of large-bodied fish (Katopodis and Williams 2012, Anderson et al. 2012). Despite this, downstream passage can still be impeded by road-stream crossings and therefore appropriate access into a crossing inlet, depth, and sufficient flow must still be considered (Bates 2003, Nedeau 2006). Crossing characteristics that may be problematic for aquatic organism passage through non-tidal culverts include: the presence and severity of inlet or outlet drops, physical barriers within the crossing (including debris accumulation), excessive water velocities, insufficient water depths, high turbulence within the water column, the absence of bank edge for dry passage of terrestrial and semi-aquatic organisms, and discontinuity of channel substrate (Bates 2003, Nedeau 2006).

Tidal road-stream crossings come with their own suite of challenges, both to aquatic organism passage and to evaluating passage for prioritization. While fluctuation in water level and velocity exists at crossings

in non-tidal streams, based on season, weather, and precipitation, tidal crossings overall are more variable than non-tidal crossings (Childers et al. 1993, Voulgaris and Meyers 2004, Chen et al. 2008). Water depth and velocity can change continuously throughout a day, and flow direction canchange up to four times a day with the tide. These conditions can also vary across the monthly tidal cycle when spring or neap tides may create more or less drastic conditions (Childers et al. 1993). Depending on the tidal range and location of the crossing within a tidal system, these three factors (depth, velocity, and flow direction) can also interact in complex ways that may be hard to predict based on the complex hydrology of a modified system. Downstream structures can impact the tidal regime of upstream structures, either dampening tides or increasing them due to streambed constriction, as well as delaying when peak tide may arrive at a given site (Giaccico and Sauder 2005, Eberhardt et al. 2011, Bowron et al. 2011, Green and Hall 2012). Local streambed modifications can add to the variability at a given site (Bunn and Arthington 2002, Bates 2003).

Depending on how close a crossing exists to the head of tide, there may also be drastic variations in salinity as the tide cycle changes (Giaccico and Sauder 2005). Tidal restrictions, caused by tide gates or constricted crossings, block the incoming water from entering upstream habitat and slow the process of draining ebb tides downstream, potentially leading to dramatic salinity, dissolved oxygen, temperature, and pH gradients at crossings, which can act as both physical and behavioral barriers for fish (Giaccico and Sauder 2005, Eberhardt et al. 2011). In addition, many tidal crossings fall within salt marsh habitat, which is inherently less linear and more hydrologically complex than a non-tidal stream (Leaf 1986). Tidal creeks are linear and channel much of the water that passes through the marsh in the rising and falling tide, but water also moves through the high marsh during flood tides (LEAF 1986, Whitlatch 1982). The high marsh can be altered by crossings that restrict tides, removing access into this habitat for marsh animals, and potentially changing basic functions of marsh ecology (Raposa and Roman 2001, Roman et al. 2002, Eberhardt et al. 2011).

Characteristics potentially limiting passage at tidal crossings also vary spatially and seasonally. Tidal influence varies among different areas of the Northeast and Mid-Atlantic due to the variable topography of coastal areas and the difference in tidal ranges. Similar variation in tide depths occur between coastal and inland areas, with some inland areas having a greater tidal depth range than further downstream in the same watershed due to constrictions in the stream bed (Giaccico and Sauder 2005). As tidal influence fades further inland in rivers, the influence may be just a rise and fall in water level, whereas further downstream direction of flow may change at every tide (Giaccico and Sauder 2005). Impact of seasonal change creates further variability in crossing conditions, both temporally over the course of the year, as well as spatially with the change in latitude (Leaf 1986, Whitlatch 1982).

AQUATIC ORGANISM PASSAGE

Tidal crossing threats to passage

The high level of temporal variability in conditions found in tidal systems could either create passage concerns unique to tidal environments or allow for passage at certain times, thus mitigating passage concerns. Constantly changing water levels, velocities, and directions of flow mean that barriers will vary temporally in severity, and passage threats depend heavily on timing of movements (Shaw et al. 2016). The importance of movement timing in assessing barrier severity has been noted in non-tidal barrier assessments, but it is even more applicable in tidal crossings given the increased variability in conditions (Anderson et al. 2012). Evolved behaviors and responses to environmental movement cues also influence whether an aquatic organism may pass a barrier successfully (Haro et al. 2004, Castro-Santos 2004, Lemasson et al. 2008). For example, if a fish encountered an impassable velocity barrier during ebb tide, it could theoretically wait until slack or flood tide and move through a crossing once the velocity decreased or the direction of flow shifted. However, if a fish requires attraction flow to pass through a barrier (Castro-Santos 2004), or only moves at a certain stage in the tidal cycle (Teo and Able 2005, Jones et al. 2014, Becker et al. 2016), the barrier could completely prevent passage. Timing of movements relative to the timing of detrimental conditions, therefore, becomes very important in understanding the ability of an organism to successfully pass through a tidal crossing.

While aquatic organism passage at non-tidal crossings has focused on the swimming ability of target species in influencing passage (Weaver 1963, Haro et al. 2004, Castro-Santos 2004, Castro-Santos 2013), this report aims to identify passage concerns focused more on timing of movements and environmental and physical requirements of species rather than athleticism

(swimming and leaping ability), although where available those data are also considered. Our synthesis includes a variety of taxonomic groups (fish, herpetofauna, invertebrates) and numerous species that, while not exhaustive, is comprehensive and representative of the entire species assemblage. Tables highlighting species that demonstrate life history traits, sensitivities, or behaviors that increase risk of passage failure have been included at the end of this report and are referenced in text where relevant.

Threats to individual animals

Movements by aquatic organisms

Animals undergo movements between habitats to fulfill varied life needs. Common reasons to move include foraging, seeking refuge, ontogenetic shifts, and spawning (Conover and Murawski 1982, Boesch and Turner 1984, Gross 1987, Gillanders et al. 2003, Rick et al. 2011). Foraging movements (Table 2) can be occasional or sporadic ventures into neighboring habitats to optimize foraging (Rick et al. 2011) or can be a diel or seasonal shift into a different habitat type used specifically as foraging grounds (Aagaard et al. 1995). While foraging movements may in some cases be facultative– meaning that the movement is voluntarily undertaken– some foraging movements may also be more obligatory in nature, with instinct driving animals to migrate to a certain habitat at a certain time of year when an important food source is abundant (Brodersen et al. 2014).

Refugia-seeking movements (Table 3) can be initiated to avoid predation or detrimental conditions (Conover and Murawski 1982, Boesch and Turner 1984, Gillanders et al. 2003). In areas with high seasonal variation in temperature, such as the US Northeast and Mid-Atlantic, it is common for aquatic organisms to seek thermal refuge daily or seasonally to avoid temperature extremes. This can be as minimal as seeking microhabitats such as vegetation or cobbles or can be a larger scale shift in habitat use during a specific season or life history phase (Boesch and Turner 1984). Moving into deeper or offshore waters in the winter and into shallower inshore waters in the summer is common for coastal fish in the Northeast, such as the Atlantic silverside, *Menidia menidia* (Conover and Murawski 1982).

Many species undergo obligatory spawning migrations (Table 4), often over very large distances (Gross 1987). There are several defined life history strategies that are strong predictors of whether an organism has life history needs that depend on habitat connectivity (Table 5). Diadromous species migrate between salt and fresh water, with anadromous species living in salt water but breeding in fresh water, and catadromous species living in fresh water but breeding in salt water. Some diadromous species such as Atlantic salmon undergo very large, regional spawning runs from open ocean into the headwaters of streams (Fleming 1996) Others, such as striped bass, may undergo smaller migrations, for example from coastal marine habitats into large rivers (Carmichael et al. 1998). Amphidromous species migrate between fresh and salt water for purposes other than spawning, such as for winter refuge, foraging, or nursery grounds. Other migration categories include oceanadromous species, which migrate only within salt water. Oceanadromous species include pelagic species that are found primarily in the open ocean but may migrate to salt marshes or estuaries, and also salt marsh and estuary fish, which could be regularly impacted by tidal road-stream crossings. Potamodromous species are the freshwater equivalent: organisms that undergo migrations but only within freshwater habitats. Species that fall into this category may inhabit tidal freshwater habitats or, depending on degree of salt tolerance, may occasionally venture into brackish waters to forage (Gross 1987, McDowall 1997).

Spawning habitats are often critical for providing refuge for juveniles. More sheltered areas (often meaning more vegetation or bottom rugosity) create spaces for small juveniles to hide from predators during this vulnerable life stage (Boesch and Turner 1984). Once juveniles reach a certain size or level of maturity (which is highly variable depending on species) they will out migrate from nursery habitats into the primary habitat used by adults of their species in an ontogenetic habitat shift (Gillanders et al. 2003).

Consequences of impaired movements

Passage threats can impact individual animals' survival, fitness, or reproduction, and can also have implications for local population viability (Januchowski-Hartley et al. 2014). Threats to individuals include preventing an animal from reaching a specific habitat vital to it for spawning, foraging, ontogenetic habitat shifts, overwintering, or seeking other thermal refuge, among other life history needs (Conover and Murawski 1982, Boesch and Turner 1984, Gross 1987, Gillanders et al. 2003, Rick et al. 2011). The consequences of lost access to habitats include failure to reproduce (Gross 1987), a decrease in fitness due to spending time in less

preferential habitats (Rick et al. 2011), and mortality (Boesch and Turner 1984). Lost access may detrimentally impact that individual (in the case of decreased fitness or mortality) or populations, if many individuals are impacted such as in the example of failed spawning runs (Gross 1987). The likelihood of a tidal road-stream crossing creating a threat is tied to the scale, timing, and necessity of the movement that is prevented (Anderson et al. 2012). The longer the linear distance that an organism must travel, the greater the chance that a road-stream crossing (or several) will be encountered (Table 6).

Difficulty in passage due to low athleticism (Weaver 1963), repeated attempts at passage caused by delays (Kemp and O'Hanley 2010), and navigating barriers in suboptimal environmental or water quality conditions can all lead to exhaustion (Yetsko and Sancho 2015, Brennan et al. 2016). Exhaustion can decrease fitness as increased predation and stress increase population mortality rates (Leonard and McCormick 1999). Increased predation is very site-specific with some crossings providing habitat for predators to ambush migrating fish., At other crossings increased vulnerability occurs after passage due to exhaustion (Schilt 2007).

Fish that have low athleticism (Table 7) or are small in size (Table 8) will be quicker to exhaust than more athletic and larger fish if swimming against the tide when trying to pass. In addition, less athletic and smaller fish would be more likely to need to wait for tidal conditions to change, delaying passage and increasing the risk of predation (Weaver 1963, Anderson et al. 2012). The influence of athleticism on barrier passage has been covered in other road-stream crossing studies and reports (Castro-Santos and Haro 2006, Coffman 2005, Nedeau 2006). Since flow at many tidal road-stream crossing sites is not unidirectional and thus passage conditions have high temporal variability, the timing of movements becomes very important in determining passability of a barrier, as discussed in the next section.

Role of movement timing

Timing of movements in relation to tidal variability in velocity, depth, and direction of flow is important in identifying barrier severity of tidal crossings. Some species make diel movements (Table 9) or tidal movements (Table 10) for spawning or foraging. Movements also vary by season, and include adult movements for spawning, foraging, and refugia, and ontogenetic movements for juvenile fishes.

To determine the extent to which a crossing is a barrier for different organisms, the crossing must be assessed for threats throughout the tidal cycle in relation to tidal stage, time of day, and time of year in which a species may be attempting to cross. The likelihood of an animal being able to wait for a change in the tide to create the appropriate depth (Table 12), direction of flow, and velocity (Table 13) for passage must be weighed against risks it might occur by delaying crossing, such as predation (Giaccico and Sauder 2005) or missing the appropriate movement window (Kemp and O'Hanley 2010). For example, if an animal needs to access a certain habitat to feed but is only active for feeding at night (Jessop 2010), then it will not be successful if passage is only available during the day. Similarly, if a fish reaches its spawning location after the spawning event is complete, which is a risk if the spawning window is short and an organism incurs significant delays at multiple crossings, it will not successfully reproduce. Additionally, some species require specific environmental cues such as light, attraction water flow, or tidal stage to initiate migration (Castro-Santos 2004, Teo and Able 2005, Jones et al. 2014, Becker et al. 2016). In this case, even if crossing conditions become theoretically passable at some stage in the tidal cycle, a mismatch may exist between the migratory cues needed by the animal and the timing of passable conditions.

The severity of the consequences of exclusion from choice habitats depends on whether the movement is facultative or obligatory. A freshwater fish such as largemouth bass that occasionally forages in brackish tidal creeks (Rick et al. 2011) will likely be less impacted than a marsh fish such as a mummichog, which lives in tidal creeks but forages mainly on the high marsh accessible during high tide (Teo and Able 2005). The species' flexibility to adapt its diet is also critical to determine consequences. As a general trend, species with more specific habitat needs will likely face greater impacts if access to those habitats is prevented. Similarly, failure to access a spawning site is often flagged as a high concern impact due to the importance of successful spawning to the viability of a population.

Biochemical barriers

All tidal systems have fluctuating biochemical conditions, such as salinity, dissolved oxygen, temperature, or pH. However, barriers that cause tidal restrictions, whereby the crossing restricts, delays, or prevents passage of the flood or ebb tides, impact the natural gradual transitioning between varying water

chemistry that occurs when natural hydrology is intact (Raposa and Roman 2003, Ritter et al. 2008). Restrictions can create rapid gradients in salinity, temperature, pH, and dissolved oxygen by creating abrupt transitions between upstream and downstream conditions. These transitions can act as a biochemical barrier or can create conditions at the crossing or near it that are intolerable to certain species (Dibble et al. 2015). Changes in water chemistry upstream of crossings can also alter vegetation communities (Konisky et al. 2006, Bowron et al. 2011), which can. have implications for aquatic organism passage.

Identifying species' tolerances to critical biochemical characteristics such as pH (Table 14), turbidity (Table 15), salinity (Table 16), and temperature (Table 17) is a first step in evaluating biochemical barriers as a threat. Even species such as diadromous fish that use waters of widely variable conditions throughout their life history may be sensitive to abrupt biochemical transitions, which can result in negative physiological changes in fish (e.g., Martínez-Álvarez et al. 2002) or mortality. Normal migration patterns allow for a slow transition between salinity levels, temperatures, and other conditions to allow time for physiological shifts to take place without causing shock. Even if an animal can withstand rapid transitions, tolerance does not equate to peak function. Many fish have different metabolic rates and swimming abilities in different salinities and temperatures (Yetsko and Sancho 2015, Brennan et al. 2016). Rapid transitions are likely to reduce fitness and swimming ability even if they do not cause mortality.

Threats to populations

Overview

Threats to individual passage scale up to impact species at the population level. These threats include population decline and fragmentation, which can lead to a loss in genetic diversity, local extirpation, and extinction (Bunn and Arthington 2002, Nilsson et al. 2016). Other risks to aquatic organisms can be caused by crossings that do not directly pertain to passage itself. For example, habitat degradation through altered hydrology and geomorphology is a significant threat associated with tidal crossings, as evidenced by ecosystem recovery following culvert replacement and associated habitat restoration (Konisky et al. 2006, Bowron et al. 2011).

Reduced reproduction and recruitment

Populations are at risk of shrinking due to the combination of increased mortality and decreased reproductive success that can be caused by impaired passage at crossings. Lack of reproductive success can eventually lead to population declines, even if adults do not experience mortality at crossings. This can be caused by individuals failing to reach spawning grounds, or being delayed enough at crossings (or, especially at a series of crossings in a long migration) that they miss the spawning window (Schilt 2007). When adults are denied access to spawning grounds, or juveniles are impeded from out-migrating from nursery grounds, the result can be reduced overall recruitment and diminished population sizes (Hall et al. 2011; Tommasi et al. 2015). Impediments to successful reproduction and recruitment may be more problematic at the population level than individual mortality, although the combination of individual and population level impacts can be disastrous for a species.

The extreme scenario resulting from decreasing populations is extinction of a species. There are a number of species dependent on connectivity through coastal and tidal systems that are listed as vulnerable, threatened, or endangered (Table 18). Even if a species is not close to overall extinction, localized extirpations can occur where strain is highest on a population (O'Hanley and Tomberlin 2005, Louca et al. 2014). If localized extinctions occur, barriers can impede recolonization (Bunn and Arthington 2002, Nilsson et al. 2016). The impact this has on the global population of a species relates to its overall abundance, geographic distribution, and life history strategies. For anadromous species that migrate to natal grounds to spawn, local extirpations may mean the permanent loss of species from that region, shrinking of the gene pool, and reduced resiliency of the overall population to recover from other stressors (Waldman et al. 2016), such as harvest for human use (Jager et al. 2000) and climate change (Hare et al. 2016).

Population fragmentation

While non-migratory animals may live out their full life cycle on one side of a road-stream crossing, the inability of individuals to pass through a crossing leads to a greater risk of population fragmentation (Neraas and Spruell 2001). The creation of isolated populations on either side of a crossing could lead to loss of genetic variation and increased inbreeding (Shaw et al. 2016). Inbreeding and lack of genetic variability within isolated populations increases vulnerability to extirpation and a

loss in ability to recover from high mortality events (Shaw et al. 2016). Fragmented habitats are at much higher risk for experiencing the localized extinctions described above and are less likely to recover from them (Jager et al. 2000, Bunn and Arthington 2002, Nilsson et al. 2016, Shaw et al. 2016).

Habitat degradation

Crossings that constrict the channel can alter the natural hydrology of a stream both upstream and downstream of a crossing, leading to altered habitat extending sometimes far beyond the crossing structure itself. Crossings can also alter natural sediment regimes, changing the amount, movement, and distribution of fine sediments (Bowron et al. 2011). This can be problematic for species with specific substrate preferences (Table 19). Tidal restrictions in salt marshes can lead to sharp transitions in salinity, which is one of the main drivers in upstream habitat degradation (Giaccico and Sauder 2005, Green and Hall 2012). Salt marsh plants are adapted to inundation with salt water from the tides. When salt water is blocked the marsh undergoes a vegetative shift, with salt tolerant species replaced with freshwater species (Roman et al. 2002, Buchsbaum et al. 2006). The resulting marsh is more susceptible to invasive species, such as the grass *Phragmites australis*. In addition, blocking of tidal influx prevents the passage of larval organisms whose main mode of movement is drifting with the current (Jager 1999, Wilber et al. 2013).

Salt water is different from fresh water not only in salinity, but also potentially in temperature, dissolved oxygen, and other chemical properties. The biochemical gradients created between salt water and fresh water can be directly detrimental to aquatic organism health and create sub-optimal habitats (Dibble et al. 2015). Even if an animal is able to pass through a crossing, the crossing may have altered the hydrology of the marsh enough that the upstream habitat may be less than ideal or completely inhospitable. An example is when the diurnal cycling of dissolved oxygen produces anoxic periods above a crossing at greater frequency under certain conditions. While not necessarily a consideration in passage issues within a crossing itself, overall habitat degradation is an important consideration when prioritizing crossings for restoration and replacement.

Animal movements in many different ecosystems transport nutrient subsidies across habitat boundaries (Sabo and Power 2002). In the Pacific Northwest, salmon runs have been shown to contribute to the productivity of coastal forests (Gende et al. 2002) and on the East Coast alewives have been shown to contribute substantial amounts of nutrients into coastal stream food webs (Walters et al. 2009). Disruption of movements between habitats may therefore disrupt local and regional food webs by blocking contributions of marine-derived nutrients, with consequences to overall ecosystem function and habitat degradation that may be difficult to predict.

PRIORITIZING CROSSINGS BY PASSAGE THREAT

Summary of detrimental crossing characteristics

Many categories of passage threats at tidal road-stream crossings are the same as those at non-tidal crossings. These include velocity, turbulence, depth of water, lack of bank edge, inlet and outlet perch, physical barriers, and substrate discontinuity. Tidal road-stream crossings add additional temporal considerations of tidal cycle, direction of flow, and biochemical barriers. The non-linear nature of marsh habitat is an additional confounding factor unique to that tidal habitat, which may require additional or special consideration when considering restoration to mitigate passage threats.

Specific types of crossings are likely to contain multiple detrimental characteristics. Constriction of the natural stream channel can lead to many problems due to disrupted hydrology. These include increased velocity, turbulence, and scour that can remove sediment from the structure and cause erosion upstream and downstream, which could lead to an outlet perch. Constriction can also make it less likely that there will be adequate bank habitat for overland passage by semi-aquatic and terrestrial species. Thus, for many organisms that use streams as movement corridors, the blocking of passage can lead to increased mortalities via car-strikes (Gibbs 1998, Crawford et al. 2014). While not covered in this work, secondary effects on terrestrial wildlife can also be improved through effective passage.

Interactions between crossing characteristics

The temporal variability of tidal crossings means that detrimental characteristics may appear in numerous combinations and at different times over each tide cycle. These combinations can have cumulative detrimental effects. For example, velocity, habitat, and biogeochemical barriers during flood tides may completely prevent passage if they occur at critical times for species that have narrow movement windows. Biochemical gradients may be most severe when the tide water backs up downstream of the crossing. Assessing the barrier severity of a tidal crossing necessitates some

approximation of how these variables interact at a given barrier throughout the tidal cycle. This likely varies in specifics from crossing to crossing, but interaction categories are likely to be predictable due to correlations with other variables. Velocity, flow direction, water depth, salinity (and likely other water quality traits such as temperature and turbidity) will all vary with daily and monthly tidal stage in varying degrees at different sites. The degree of variation will be impacted by distance from the head of tide, stream morphology and hydrology, proximity to other barriers, location within a watershed, as well as seasonal variability in flow conditions and weather.

Identifying high-risk species

Based on life history traits, some species are at greater risk either for encountering or being unable to pass barriers are more likely to be negatively impacted by tidal road-stream crossings. Movements and migrations over long distances or across a variety of habitat types puts species at greater risk of encountering barriers. A higher frequency of movements also increases the likelihood of passage disruptions. Narrow movement windows (including those short in duration or only during a specific time of day, year, or tide) increase the likelihood that barriers to passage will result in failure to complete a biological requirement even if passage is eventually achieved. The impacts of failed or delayed passage depend on what type of movement is disrupted, how many barriers an animal may need to pass, and how frequently they need to achieve the movement. Increased exposure to barriers increases the likelihood of these barriers having an adverse impact on an individual or population.

The combination of movements between habitats along with sensitivities to certain water quality or environmental conditions, or in combination with small size or low athleticism, also increases the risk of detrimental impacts. Any combination of risk categories increases the chances that a tidal road-stream crossing will create a passage barrier. It is therefore not only important to know how many species are threatened by certain conditions, but also how many species are at risk in multiple ways, and how these various threats interact.

Mitigation approaches

The response of different aquatic organisms to barriers is so varied that it is important to simultaneously determine whether a crossing is a barrier and what species need to pass it. Many fish passage projects have very specific target species in mind and design engineered solutions to create passable conditions for the specific species' characteristics rather than the full suite of species. With an interest in entire species assemblages, designing a replacement crossing structure tailored to a narrow range of species is not sufficient.

Stream simulation has been used to create crossing structures that maintain stream conditions that are comparable to the stream reach within which they occur (Barnard et al. 2015). This more conservative approach aims to account for the many unknowns with species movement patterns and environmental requirements, based on the assumption that a structure that creates less disruption to the natural stream flow and morphology will be less of a disruption to aquatic organism movement.

Mimicking upstream and downstream channel size and conditions at all times of the tidal cycle may be challenging. Each jurisdiction's regulatory framework and property footprints can limit the degree of naturalization that is possible, particularly in salt mash habitats that are less linear than streams. Due to the crucial nature of timing in aquatic organism passage through tidal crossings, it is important to replicate conditions during all times, so as not to disrupt passage timing. Although many estuarine and diadromous species are adapted to dynamic tidal systems, barriers that disrupt natural inclinations of these species can be problematic. Thus, care must be taken to restore the channel to permit natural tidal fluctuations and timing. . Sites with tide gates require special consideration in planning appropriate management sequences to allow for passage in addition to considering options in updated tide gate technologies.

Water quality gradients are another threat to aquatic organism passage unique to tidal systems. Signs of tidal restriction could provide insight to how problematic these gradients might be. In salt marshes salinity gradients often create changes in vegetation community. Sites with drastic vegetation shifts can be assumed to have drastic salinity gradients and are therefore potential locations for crossing restoration.

Developing ranking and prioritization tools

The first step in mitigating detrimental impacts of disrupted passage at tidal crossings is identifying those that are problematic and prioritizing replacement or mitigation efforts. An assessment methodology for documenting problematic characteristics of road crossings on tidal streams will most likely require at least two visits. Assessing crossings at low tide will allow the

identification of many characteristics and potential problems (e.g. substrate type, dimensions, presence of physical barriers, severity of scour pools) that may not be observable at high tide, while observations of high tide indicators are critical to determine whether barriers persist throughout the tide cycle and if additional problems arise. For example, some potential problems at low tide (e.g. inlet drop, inlet or outlet perch, shallow water depth) may not be as problematic if they disappear at higher tides and organisms are flexible about migration timing relative to the tide cycle. Velocity and turbulence issues might be most evident during periods between low and high tide, but might not be an issue if organisms are able to pass at either low or high tide.

The following are problems that should be documented when assessing crossings for aquatic passability. Some problems might be documented directly (e.g. outlet drop at high tide, physical barriers). For others it might be necessary to infer what the conditions are using indirect indicators. For example, it may not be practical to collect water quality data necessary to evaluate steep salinity, temperature, dissolved oxygen or pH gradients that might be caused by a crossing. However, indicators of tidal restriction (constriction ratio, scour pools, changes in channel width and changes in vegetation) could be used as indirect indicators of potential biochemical problems. For each of the problems below, metrics or attributes of road-stream crossings are listed that could be used to evaluate them.

Velocity problems:

- Presence/absence of substrate within the structure
- Constriction ratio based on width of the structure relative to the width of the channel
- Scour pools at inlet and/or outlet
- Armoring at inlet or outlet
- Absence of edge vegetation or other physical complexity creating lower velocity zones for small organisms
- Lack of connection to marsh habitat
- Velocity in the structure relative to velocities in natural channel (mid-tide)

Turbulence problems:

- Constriction ratio based on width of the structure relative to the width of the channel
- Scour pools at inlet and/or outlet
- Armoring at inlet or outlet

Depth problems:

- Water depth in the structure relative to depths in natural channel at low tide
- Water depth in the structure relative to depths in natural channel at high tide

Jump barriers:

- Perched inlet or outlet at low tide
- Perched inlet or outlet at high tide
- Freefalls or cascades within or associated with the structure

Physical barriers:

- Tide gates
- Fencing
- Debris jams
- Damaged or unmaintained crossing structures
- Other barriers

Inappropriate substrate/cover:

- Substrate type (comparable, contrasting, inappropriate)
- Substrate coverage (continuous, partial, none)

Biochemical problems:

- Constriction ratio based on width of the structure relative to the width of the channel
- Scour pools at inlet and/or outlet
- Change in channel width above and below the crossing
- Change in vegetation above and below the crossing

Size/light/openness:

- Structure height
- Structure openness (cross sectional area divided by structure length from inlet to outlet)

These problems have all been considered and incorporated, where feasible, in the draft aquatic passability scoring system for tidal stream crossings (Jackson 2018). Based on the data collected in the field, coarse screens or numerical scoring algorithms can be developed for particular species, species groups, or aquatic communities as a whole. Varying ranking and prioritization schemes based on taxa may result in conflicting identifications of problematic crossings and care must be taken to identify appropriate benchmarks for assessing the severity of threat categories identified

in this report (Anderson et al. 2012). Given the wide variability in habitat types impacted by tidal influence, it may prove necessary to establish different standards for different types of crossing structures in different types of conditions. Salt marshes will likely have different signs of disrupted aquatic organism passage than a coastal river or a tidal freshwater river. Establishing a prioritization scheme that accounts for the severity of barriers to aquatic organism passage will be inherently more challenging in tidal systems given that many of the important factors vary widely throughout the tidal cycle. Timing of tidal cycles and distance from head of tide may provide some insights that can supplement data collected during site visits.

Coastal habitats contain a broad diversity of species with a wide variation in traits, life history strategies, and habitat use patterns (Leaf 1986, Whitlatch 1982). The species information included in this report aims to be representative of the types of threats tidal crossings may confer to different species groups. However, there are many data gaps in species range, habitat use, movement patterns, sensitivities, and swimming ability. Additionally, even if comprehensive data were available for each species, management strategies that aim to specifically address the needs of a full species assemblage in such a diverse system may prove prohibitively complex. Therefore, identifying specific passage goals and benchmarks that can be directly evaluated is critical for assessing threats to aquatic organism passage by tidal crossings. This report summarizes tidal crossing characteristics that create passage threats and species traits that indicate susceptibility to these threats to offer a starting point for identifying these goals and benchmarks.

APPENDIX 1: Tables

Table 1: Complete species list including common name, scientific name, and broad taxonomic category (fish, invertebrate, reptile, or amphibian) for taxa found in the literature review to be present in tidally influenced waters from Virginia to Maine. Taxa are listed at the lowest possible taxonomic level. Species without specific common names are labeled with (a-c) in order to differentiate between them.

Common name	**Scientific name**	**Category**
Alewife	Alosa pseudoharengus	Fish
American brook lamprey	Lethenteron appendix	Fish
American eel	Anguilla rostrata	Fish
American shad	Alosa sapidissima	Fish
Atlantic croaker	Micropogonias undulatus)	Fish
Atlantic herring	Clupea harengus	Fish
Atlantic menhaden	Brevoortia tyrannus	Fish
Atlantic needlefish	Strongylura marina	Fish
Atlantic salmon	Salmo salar	Fish
Atlantic silverside	Menidia menidia	Fish
Atlantic Spanish mackerel	Scomberomorus maculatus	Fish
Atlantic sturgeon	Acipenser oxyrinchus oxyrinchus	Fish
Atlantic tomcod	Microgadus tomcod	Fish
Banded killifish	Fundulus diaphanus	Fish
Banded sunfish	Enneacanthus obesus	Fish
Bay anchovy	Anchoa mitchilli	Fish
Black crappie	Pomoxis nigromaculatus	Fish
Black drum	Pogonias cromis	Fish
Black sea bass	Centropristis striata	Fish
Blackspotted stickleback	Gasterosteus wheatlandi	Fish
Blueback herring	Alosa aestivalis	Fish
Bluefish	Pomatomus saltatrix	Fish
Bluegill	Lepomis macrochirus	Fish
Bridle shiner	Notropis bifrenatus	Fish
Broad stripe anchovy	Anchoa hepsetus	Fish
Brown bullhead	Ictalurus nebulosus	Fish
Butterfish	Peprilus triacanthus	Fish
Chain pickerel	Esox niger	Fish
Channel catfish	Ictalurus punctatus	Fish
Clear muskellunge	Esox immaculatus	Fish
Common carp	Cyprinus carpio	Fish
Creek chubsucker	Erimyzon oblongus	Fish
Crevalle jack	Caranx hippos	Fish
Drum (family)	Sciaenids	Fish
Eastern mosquitofish	Gambusia holbrooki	Fish
Eastern mudminnow	Umbra pygmaea	Fish
Eastern silvery minnow	Hybognathus regius	Fish

Common name	Scientific name	Category
Fallfish	Semotilus corporalis	Fish
Flathead grey mullet	Mugil cephalus	Fish
Fourspine stickleback	Apeltes quadracus	Fish
Gizzard shad	Dorosoma cepedianum	Fish
Glassy darter	Etheostoma vitreum	Fish
Golden shiner	Notemigonus crysoleucas	Fish
Goldfish	Carassius auratus	Fish
Greater amberjack	Seriola dumerili	Fish
Green sunfish	Lepomis cyanellus	Fish
Grubby	Myoxocephalus aenaeus	Fish
Hickory shad	Alosa mediocris	Fish
Hogchoker	Trinectes maculatus	Fish
Inland silverside	Menidia beryllina	Fish
Inshore lizardfish	Synodus foetens	Fish
Ironcolor shiner	Notropis chalybaeus	Fish
Largemouth bass	Micropterus salmoides	Fish
Longear sunfish	Lepomis megalotis	Fish
Mullet	Mugil halus	Fish
Mummichog	Fundulus heteroclitus	Fish
Muskellunge	Esox masquinongy	Fish
Naked goby	Gobiosoma bosci	Fish
Ninespine stickleback	Pungitius pungitius	Fish
Northern kingfish	Menticirrhus saxatilis	Fish
Northern pipefish	Syngnathus fuscus	Fish
Pumpkinseed	Lepomis gibbosus	Fish
Rainbow smelt	Osmerus mordax	Fish
Rainwater killifish	Lucania parva	Fish
Red drum	Sciaenops ocellatus	Fish
Redbreast sunfish	Lepomis auritus	Fish
Redfin pickerel	Esox americanus americanus	Fish
Rock bass	Ambloplites rupestris	Fish
Rough silverside	Membras martinica	Fish
Sand lance	Ammodytes americanus	Fish
Sandbar shark	Carcharhinus plumbeus	Fish
Satinfish shiner	Cyprinella analostana	Fish
Scup	Stenotomus chrysops	Fish
Sea lamprey	Petromyzon marinus	Fish
Sea-run brown trout	Salmo trutta	Fish
Seaboard goby	Gobiosoma ginsburgi	Fish
Sheepshead minnow	Cyprinodon variegatus	Fish
Shorthead redhorse	Moxostoma macrolepidotum	Fish

Common name	Scientific name	Category
Shortnose sturgeon	Acipenser brevirostrum	Fish
Smallmouth bass	Micropterus dolomieui	Fish
Spot	Leiostomus xanthurus	Fish
Spotfin killifish	Fundulus luciae	Fish
Spottail shiner	Notropis hudsonius	Fish
Star butterfish	Peprilus alepidotus	Fish
Striped bass	Morone saxatilis	Fish
Striped killifish	Fundulus majalis	Fish
Summer flounder	Paralichthys dentatus	Fish
Swallowtail shiner	Notropis procne	Fish
Tautog	Tautoga onitis	Fish
Tesselated darter	Etheostoma olmstedi	Fish
Threespine stickleback	Gasterosteus aculeatus	Fish
Walleye	Stizostedion vitreum	Fish
Weakfish	Cynoscion regalis	Fish
White catfish	Ictalurus catus	Fish
White crappie	Pomoxis annularis	Fish
White hake	Urophycis tenuis	Fish
White mullet	Mugil curema	Fish
White perch	Morone americana	Fish
White sucker	Catostomus commersonii	Fish
Windowpane	Scophthalmus aquosus	Fish
Winter flounder	Pseudopleuronectes americanus	Fish
Yellow perch	Perca flavescens	Fish
American lobster	Homarus americanus	Invertebrate
Amphipod (family)	Gammaridae	Invertebrate
Bay scallop	Argopecten irradians	Invertebrate
Blue crab	Callinectes sapidus	Invertebrate
Blue mussel	Mytilus edulis	Invertebrate
Common periwinkle	Littorina littorea	Invertebrate
Crayfish	Cambarus robustus	Invertebrate
Daggerblade grass shrimp	Palaeomonetes pugio	Invertebrate
Eastern pondmussel	Ligumia nasuta	Invertebrate
Fiddler crab (a.)	Uca pugilator	Invertebrate
Fiddler crab (b.)	Uca pugnax	Invertebrate
Fiddler crab (c.)	Uca minax	Invertebrate
Grass shrimp	Palaeomonetes vulgaris	Invertebrate
Green crab	Carcinus maenas	Invertebrate
Gulf periwinkle	Littorina irrorata	Invertebrate
Atlantic horseshoe crab	Limulus polyphemus	Invertebrate
Long-clawed hermite crab	Pagurus longicarpus	Invertebrate

Common name	Scientific name	Category
Marsh clam	Polymesoda caroliniana	Invertebrate
Marsh crab	Sesarma reticulatum	Invertebrate
Mud crab (family)	Panopeus	Invertebrate
Mud dog whelk	Nassarius obsoletus	Invertebrate
Mud snail	Ilyanassa obsoletus	Invertebrate
New England slitsnail (subclass)	Prosobranchia	Invertebrate
Periwinkle (a.)	Littorina obtusata	Invertebrate
Polychaete (a.)	Nereis succinea	Invertebrate
Salt marsh snail	Melampus bidentatus	Invertebrate
Sand shrimp	Crangon septemspinosa	Invertebrate
Snail (a.)	Hydrobia totteni	Invertebrate
Snapping shrimp	Alpheus heterochaelis	Invertebrate
Tidewater mucket	Leptodea ochracea	Invertebrate
Wharf crab	Sesarma cinereum	Invertebrate
White fingered mud-crab	Rhithropanopeus harrisi	Invertebrate
White shrimp	Penaeus setiferus	Invertebrate
Diamondback terrapin	Malaclemys terrapin	Reptile
Northern water snake	Nerodia sipedon	Reptile
Spotted turtle	Clemmys guttata	Reptile
Green frog	Rana clamitans	Amphibian
Common shiner	Luxilus cornutus	Fish
Asian shore crab	Hemigrapsus sanguineus	Invertebrate
Brown shrimp	Penaeus aztecus	Invertebrate

Table 2: Movement characteristics for species that undergo foraging movements as adults.*

Species	Scale	Start habitat	End habitat	Direction	Season	Time	Tide	Cue	Frequency
White sucker	One habitat	Coastal stream	Coastal stream	Shallower		Dusk			Daily
Threespine stickleback	Adj. habitats	Tidal creek	High marsh			Day	Flood		Daily
Mummichog	Adj. habitats	Tidal creek	High marsh				Flood	Tidal	Daily
Weakfish	Adj. habitats	Tidal creek	Marsh pond		Summer	Night			
Fourspine stickleback	Adj. habitats	Tidal creek	Marsh pond				Flood	Tidal	Daily
White perch	Adj. habitats	Tidal creek	High marsh	Upstream		Night	Flood	Tidal	Daily
Brown shrimp	Adj. habitats	Tidal creek	High marsh			Night			
Chain Pickerel	Adj. habitats	Large river	Brackish stream	Downstream					Daily
Largemouth bass	Adj. habitats	FW stream	Tidal creek						
Redbreast sunfish	Adj. habitats	FW stream	Tidal creek						
Swallowtail shiner	Adj. habitats	FW stream	Tidal creek						
Bluegill	Adj. habitats	FW stream	Brackish stream	Downstream					
White catfish	Adj. habitats	FW stream	Brackish stream	Downstream					
Channel catfish	Adj. habitats	FW stream	Brackish stream	Downstream					
Bluefish	Adj. habitats	Coastal marine	Tidal creek	Inshore					
Striped bass	Adj. habitats	Coastal marine	Tidal creek	Inshore	Summer				Annual
Spot	Adj. habitats	Coastal marine	Estuary	Inshore	Fall				

* Blank cells indicate a lack of data. Adj. = adjacent. FW = freshwater.

Table 3: Movement characteristics for species that undergo movements as adults in order to seek refuge from predators or adverse environmental conditions.*

Species	Scale	Start habitat	End habitat	Direction	Season	Cue	Frequency
Chain pickerel	One habitat	Large river	Large river	Deeper	Winter	Temperature	
Redfin pickerel	One habitat	FW stream	FW stream	Shallower			Annual
Bluefish	One habitat	Coastal marine	Coastal marine	South	Winter	Temperature	
Butterfish	One habitat	Coastal marine	Coastal marine	Deeper	Winter		
Mummichog	Adj. habitats	Tidal creek	Marsh pond		Winter	Temperature	Annual
Scup	Adj. habitats	Estuary	Coastal marine	Offshore	Winter	Temperature	Annual
Atlantic silverside	Adj. habitats	Estuary	Coastal marine	Deeper	Winter		Annual
Northern pipefish	Many habitats	Tidal creek	Coastal marine	Offshore	Winter	Temperature	Annual
Winter flounder	Many habitats	Estuary	Coastal marine	Offshore	Summer		Annual
Brook trout	Many habitats	Coastal stream	Coastal marine	Downstream	Summer		Annual
Weakfish	Many habitats	Coastal marine	Estuary	Upstream	Summer		
Atlantic menhaden	Many habitats	Coastal marine	Coastal marine	North	Summer		

* Blank cells indicate a lack of data. Adj. = adjacent. FW = freshwater.

Table 4: Movement characteristics for species that undergo spawning movements as adults. Migration types include amphiadromous (Amph), anadromous (Anad), catadromous (Catad), oceanadromous (Ocean), and resident (Res).*

Species	Scale	Start habitat	End habitat	Direction	Season	Time	Tide	Cue	Migration type
Fourspine stickleback	One habitat	Tidal creek	Coastal stream	Upstream	Spring				Amph
Threespine stickleback	One habitat	Tidal creek	Tidal creek		Spring				Anad
Chain pickerel	One habitat	Large river	Large river	Shallower	Spring			Temp	Res
Hogchoker	One habitat	Coastal stream	Coastal stream	Downstream					Amph
White sucker	One habitat	Coastal stream	Coastal stream						Res
White perch	Adj. habitats	Tidal creek	Coastal stream	Upstream					Anad
Mummichog	Adj. habitats	Tidal creek	Marsh pond		Spring		Spring		Res
Greater amberjack	Adj. habitats	Ocean shelf	Coastal marine	Inshore	Summer				Ocean
Gizzard shad	Adj. habitats	Large river	FW stream	Upstream	Winter				Anad
Redfin pickerel	Adj. habitats	FW stream	Marsh pond	Shallower					Res
Summer flounder	Adj. habitats	Estuary	Tidal creek						Ocean
Yellow perch	Adj. habitats	Estuary	Coastal stream	Upstream	Spring			Temp	Res
Tautog	Adj. habitats	Coastal marine	Tidal creek	Upstream	Summer	Night			Ocean
Spot	Adj. habitats	Coastal marine	Estuary	Upstream	Summer				Ocean
Black sea bass	Adj. habitats	Coastal marine	Tidal creek	Upstream	Summer				Ocean
Sea-run brown trout	Adj. habitats	Coastal marine	FW stream	Upstream				Tidal	Anad
Atlantic sturgeon	Many habitats	Ocean shelf	Large river	Upstream	Spring			Age	Anad
Shortnose sturgeon	Many habitats	Ocean shelf	Large river	Upstream					Anad
Mullet	Many habitats	Large river	Ocean shelf	Downstream					Catad
American eel	Many habitats	Coastal stream	Ocean shelf	Downstream	Fall				Catand
Atlantic salmon	Many habitats	Coastal marine	FW stream	Upstream	Summer				Anad
Sea lamprey	Many habitats	Coastal marine	Large river	Upstream	Spring				Anad
Alewife	Many habitats	Coastal marine	Lake	Upstream	Spring	Night			Anad
Blueback herring	Many habitats	Coastal marine	FW stream	Upstream	Spring	Night		Temp	Anad
American shad	Many habitats	Coastal marine	FW stream	Upstream				Temp	Anad
Atlantic tomcod	Many habitats	Coastal marine	FW stream	Upstream					Anad
Ninespine stickleback	Many habitats	Coastal marine	Brack. stream	Inshore	Spring				Anad
Inland silverside	Many habitats	Coastal marine	FW stream	Upstream					Anad

Species	Scale	Start habitat	End habitat	Direction	Season	Time	Tide	Cue	Migration type
Striped bass	Many habitats	Coastal marine	Coastal stream	Upstream	Spring				Anad
Hickory shad	Many habitats	Coastal marine	FW stream	Upstream	Spring				Anad
Striped bass	Many habitats	Coastal marine	Coastal stream	Upstream	Spring				Anad
Winter flounder	Many habitats	Coastal marine	Estuary	Inshore	Winter				Ocean
Ninespine stickleback	Many habitats	Coastal marine	Brack stream	Inshore	Spring				Anad
Blueback herring	Many habitats	Coastal marine	FW stream	Upstream	Spring	Night		Temp	Anad
Winter flounder	Many habitats	Coastal marine	Estuary	Inshore	Winter				Ocean
Rainbow smelt	Many habitats	Coastal marine	FW stream	Upstream	Spring	Night			Anad
Flathead grey mullet	Many habitats	Estuary	Coastal marine	Downstream				Tidal	Catad
Brook trout	Many habitats	Coastal stream	FW stream	Upstream	Spring				Anad
White mullet	Many habitats	FW stream	Coastal marine	Downstream					Catad

* Blank cells indicate a lack of data. Adj. = adjacent. FW = freshwater. Brack = brackish. Temp = temperature.

Table 5. Habitat and migration types for species that move between habitats. Rows are separate species and lifestages (adult, juvenile, and larval). Migration types include amphiadromous (Amph), anadromous (Anad), catadromous (Catad), oceanadromous (Ocean), potanodromous (Potam), and resident (Res). Blank cells indicate a lack of data. FW = freshwater.

Species	Lifestage	Migration type	Primary	Spawning	Nursery	Foraging	Refugia
Bay anchovy	Adult	Amph	Tidal creek				
Fourspine stickleback	Adult	Amph	Coastal marine	Coastal stream		High marsh	
Fourspine stickleback	Juvenile	Amph					
Grubby	Adult	Amph	Estuary				
Hogchoker	Adult	Amph	Coastal stream	Coastal stream			
Hogchoker	Juvenile	Amph					
Largemouth bass	Adult	Amph	FW stream	Tidal creek		Tidal creek	
Northern pipefish	Adult	Amph	Tidal creek				Coastal marine
Rainwater killifish	Adult	Amph	Tidal creek				
Seaboard goby	Adult	Amph	Coastal marine				
Alewife	Adult	Anad	Coastal marine	Lake			
Alewife	Juvenile	Anad			Lake		
American shad	Adult	Anad	Coastal marine	FW stream			
American shad	Juvenile	Anad			Large river		
Atlantic needlefish	Adult	Anad	Coastal stream				
Atlantic salmon	Adult	Anad	Coastal marine	FW stream			
Atlantic salmon	Juvenile	Anad			FW stream		
Atlantic sturgeon	Adult	Anad	Ocean shelf	Large river			
Atlantic sturgeon	Juvenile	Anad					
Atlantic tomcod	Adult	Anad	Coastal marine	Coastal stream			
Atlantic tomcod	Juvenile	Anad					
Blueback herring	Adult	Anad	Coastal marine	Coastal stream			
Blueback herring	Juvenile	Anad			Coastal stream		
Brook trout	Adult	Anad	Coastal stream	FW stream			Coastal marine
Brook trout	Juvenile	Anad			FW stream		
Gizzard shad	Adult	Anad	FW stream	FW stream			

Species	Lifestage	Migration type	Primary	Spawning	Nursery	Foraging	Refugia
Gizzard shad	Juvenile	Anad			FW stream		
Hickory shad	Adult	Anad	Coastal marine	FW stream			
Hickory shad	Juvenile	Anad					
Inland silverside	Adult	Anad	Coastal marine	FW stream			
Inland silverside	Juvenile	Anad					
Ninespine stickleback	Adult	Anad	Brackish stream	Coastal stream	Coastal stream		Coastal marine
Rainbow smelt	Adult	Anad	Coastal marine	FW stream			
Rainbow smelt	Juvenile	Anad					
Sea lamprey	Adult	Anad	Coastal marine	Large river			
Sea lamprey	Juvenile	Anad			Large river		
Sea-run brown trout	Adult	Anad	Coastal marine	FW stream			
Sea-run brown trout	Juvenile	Anad					
Shortnose sturgeon	Adult	Anad	Ocean shelf	Large river			
Shortnose sturgeon	Juvenile	Anad					
Striped bass	Adult	Anad	Coastal marine	Large river		Tidal creek	
Striped bass	Juvenile	Anad			High marsh		
Threespine stickleback	Adult	Anad	Tidal creek	Tidal creek		High marsh	
White perch	Adult	Anad	Tidal creek	Coastal stream		High marsh	
White perch	Juvenile	Anad					
American eel	Juvenile	Catad			Coastal marine		
Flathead grey mullet	Adult	Catad	Estuary	Coastal marine			
Flathead grey mullet	Juvenile	Catad			Coastal marine		
Mullet	Adult	Catad	Coastal marine	Coastal marine			
Mullet	Juvenile	Catad			Tidal creek		
American eel	Adult	Catad	Coastal stream	Ocean shelf			
White mullet	Adult	Catad	Estuary				
Atlantic croaker	Adult	Ocean	Coastal marine			Estuary	
Atlantic menhaden	Adult	Ocean	Coastal marine	Estuary			

Species	Lifestage	Migration type	Primary	Spawning	Nursery	Foraging	Refugia
Atlantic silverside	Adult	Ocean	Estuary				Coastal marine
Atlantic spanish mackerel	Adult	Ocean	Coastal marine				
Black drum	Juvenile	Ocean			Estuary		
Black sea bass	Adult	Ocean	Coastal marine	Tidal creek			
Black sea bass	Juvenile	Ocean					
Bluefish	Adult	Ocean	Coastal marine			Tidal creek	
Butterfish	Adult	Ocean	Coastal marine				Coastal marine
Greater amberjack	Adult	Ocean	Ocean shelf	Coastal marine			
Greater amberjack	Juvenile	Ocean			Coastal marine		
Scup	Adult	Ocean	Coastal marine				
Spot	Adult	Ocean	Coastal marine	Estuary		Estuary	
Spot	Juvenile	Ocean			Estuary		
Star butterfish	Juvenile	Ocean			Estuary		
Summer flounder	Adult	Ocean	Estuary	Tidal creek			
Summer flounder	Juvenile	Ocean					
Tautog	Adult	Ocean	Coastal marine	Tidal creek			
Tautog	Juvenile	Ocean					
Weakfish	Adult	Ocean	Coastal marine			Estuary	
Weakfish	Juvenile	Ocean			Estuary		
Winter flounder	Adult	Ocean	Coastal marine	Estuary	Estuary		
Winter flounder	Adult	Ocean	Coastal marine	Estuary			
Eastern mosquitofish	Adult	Potam	Coastal stream				
Pumpkinseed	Adult	Potam	FW stream				
Walleye	Adult	Potam	Large river				
Bluegill	Adult	Res	FW stream			Brackish stream	
Chain pickerel	Adult	Res	Large river	Large river		Brackish stream	Large river
Channel catfish	Adult	Res	FW stream				
Mummichog	Adult	Res	Tidal creek	Marsh pond		High marsh	Tidal creek

Species	Lifestage	Migration type	Primary	Spawning	Nursery	Foraging	Refugia
Mummichog	Juvenile	Res					
Northern kingfish	Adult	Res	Coastal marine				
Northern kingfish	Juvenile	Res			Tidal creek		
Redbreast sunfish	Adult	Res	FW stream			Tidal creek	
Redfin pickerel	Adult	Res	FW stream	Marsh pond			Marsh pond
Redfin pickerel	Juvenile	Res			Marsh pond		
Swallowtail shiner	Adult	Res	FW stream			Tidal creek	
White catfish	Adult	Res	FW stream				
White sucker	Adult	Res	Coastal stream	Coastal stream		Coastal stream	
White sucker	Juvenile	Res					
Yellow perch	Adult	Res	Estuary	Coastal stream			
Yellow perch	Juvenile	Res					
Pumpkinseed	Juvenile	Potam					

Table 6: Movement scales for spawning, foraging, ontogenetic, and refuge-seeking movements are given here for species indicated in the literature review to move between habitat types. Lifestage categories (adult, juvenile, and larval) are listed on separate rows.

Species	Lifestage	Spawning	Foraging	Ontogenetic	Refugia
Alewife	Adult	Many habitats			
Alewife	Juvenile			Many habitats	
American eel	Adult	Many habitats			
American eel	Adult	Many habitats			
American eel	Juvenile			Many habitats	
American shad	Adult	Many habitats			
American shad	Juvenile			Many habitats	
Atlantic menhaden	Adult				Many habitats
Atlantic menhaden	Adult				Many habitats
Atlantic salmon	Adult	Many habitats			
Atlantic salmon	Juvenile			Many habitats	
Atlantic silverside	Adult				Adjacent habitats
Atlantic silverside	Adult				Adjacent habitats
Atlantic sturgeon	Adult	Many habitats			
Atlantic sturgeon	Juvenile			Many habitats	
Atlantic tomcod	Adult	Many habitats			
Atlantic tomcod	Juvenile			Many habitats	
Black drum	Juvenile			Adjacent habitats	
Black sea bass	Adult	Adjacent habitats			
Black sea bass	Juvenile			Many habitats	
Blueback herring	Adult	Many habitats			
Blueback herring	Juvenile			Many habitats	
Bluefish	Adult		Adjacent habitats		One habitat
Bluefish	Adult		Adjacent habitats		One habitat
Bluegill	Adult		Adjacent habitats		
Brook trout	Adult	Many habitats			Many habitats

Species	Lifestage	Spawning	Foraging	Ontogenetic	Refugia
Brook trout	Juvenile			Many habitats	
Butterfish	Adult				One habitat
Butterfish	Adult				One habitat
Chain pickerel	Adult	One habitat	Adjacent habitats		One habitat
Channel catfish	Adult		Adjacent habitats		
Flathead grey mullet	Adult	Many habitats			
Flathead grey mullet	Juvenile			Many habitats	
Fourspine stickleback	Adult	One habitat	Adjacent habitats		
Fourspine stickleback	Juvenile			Many habitats	
Gizzard shad	Adult	Adjacent habitats			
Gizzard shad	Juvenile			Adjacent habitats	
Greater amberjack	Adult	Adjacent habitats			
Greater amberjack	Juvenile			Adjacent habitats	
Hickory shad	Adult	Many habitats			
Hickory shad	Juvenile			Many habitats	
Hogchoker	Adult	One habitat			
Inland silverside	Adult	Many habitats			
Inland silverside	Juvenile			Many habitats	
Largemouth bass	Adult		Adjacent habitats		
Mullet	Adult	Many habitats			
Mullet	Juvenile			Many habitats	
Mummichog	Adult	Adjacent habitats	One habitat		Adjacent habitats
Mummichog	Larval			Adjacent habitats	
Mummichog	Juvenile			Adjacent habitats	
Ninespine stickleback	Adult	Many habitats			
Ninespine stickleback	Adult	Many habitats			
Northern pipefish	Adult				Many habitats
Rainbow smelt	Adult	Many habitats			

Species	Lifestage	Spawning	Foraging	Ontogenetic	Refugia
Rainbow smelt	Juvenile			Many habitats	
Redbreast sunfish	Adult		Adjacent habitats		
Redfin pickerel	Adult	Adjacent habitats			One habitat
Redfin pickerel	Juvenile			Adjacent habitats	
Scup	Adult				Adjacent habitats
Sea lamprey	Adult	Many habitats			
Sea lamprey	Juvenile			Many habitats	
Sea-run brown trout	Adult	Adjacent habitats			
Sea-run brown trout	Juvenile			Many habitats	
Shortnose sturgeon	Adult	Many habitats			
Shortnose sturgeon	Juvenile			Many habitats	
Spot	Adult	Adjacent habitats	Adjacent habitats		
Spot	Juvenile			Many habitats	
Star butterfish	Juvenile			Adjacent habitats	
Striped bass	Adult	Many habitats	Adjacent habitats		
Striped bass	Adult	Many habitats	Adjacent habitats		
Striped bass	Juvenile			Many habitats	
Summer flounder	Adult	Adjacent habitats			
Summer flounder	Juvenile			Adjacent habitats	
Swallowtail shiner	Adult		Adjacent habitats		
Tautog	Adult	Adjacent habitats			
Tautog	Juvenile			Many habitats	
Threespine stickleback	Adult	One habitat	One habitat		
Threespine stickleback	Adult	One habitat	One habitat		
Weakfish	Adult		Adjacent habitats		Many habitats
Weakfish	Juvenile			Many habitats	
White catfish	Adult		Adjacent habitats		
White catfish	Adult	Adjacent habitats	Adjacent habitats		

Species	Lifestage	Spawning	Foraging	Ontogenetic	Refugia
White perch	Juvenile			Adjacent habitats	
White sucker	Adult	One habitat	One habitat		
White sucker	Juvenile			One habitat	
Winter flounder	Adult	Many habitats			Many habitats
Winter flounder	Adult	Many habitats			Many habitats
Yellow perch	Adult	Adjacent habitats			
Yellow perch	Juvenile			Many habitats	

Table 7: Leaping height (m), sustained swimming speeds (m/s), and burst speed (m/s) for adult migratory fish species. Data from Meixler et al. (2009).

Species	**Leap**	**Sust.**	**Burst**
Atlantic salmon	1.94		6.17
Sea-run brown trout	1.10	4.64	
White sucker	0.68		3.66
Shorthead redhorse	0.57		3.36
Alewife	0.39		2.77
Brook trout	0.37		2.70
Gizzard shad	0.34		2.59
Yellow perch	0.22		2.06
White perch	0.09		1.36
Spottail shiner	0.04		0.85

Table 8: Maximum and mean total body length (cm) for species for which size data were available on Fishbase.org.

Species	Max TL	Mean TL	Species	Max TL	Mean TL
Atlantic sturgeon	403	250	Atlantic menhaden	50	
Striped bass	200	120	White perch	49.5	13.5
Greater amberjack	190	100	Black crappie	49	27.5
Black drum	170	50	Inshore lizardfish	48.3	30
Red drum	155	100	Northern kingfish	46	30
American eel	152	50	Scup	46	25
Atlantic salmon	150	38	Alewife	40	30
Shortnose sturgeon	143	50	Blueback herring	40	27.5
Sea-run brown trout	140	72	Pumpkinseed	40	9.9
Bluefish	130	60	Redfin pickerel	39.4	
Sea lamprey	120	60	Atlantic tomcod	38.1	
Atlantic needlefish	111	60	Spot	36	25
Walleye	107	54	Rainbow smelt	35.6	
Flathead grey mullet	100	50	American brook lamprey	35	15.6
Mullet	100	50	Northern pipefish	33	0
Chain pickerel	99	41.9	Golden shiner	32	14.4
Weakfish	98	50	Redbreast sunfish	30.5	10.8
Summer flounder	94		Butterfish	30	20
Tautog	91		Star butterfish	30	18
Atlantic Spanish mackerel	91		Longear sunfish	24	11.5
White mullet	90	30	Sand lance	23.5	
Largemouth bass	87	40	Hogchoker	20	11
Brook trout	86	26.4	Common shiner	18	8.3
American shad	76	61.7	Striped killifish	18	
Shorthead redhorse	75	40.8	Grubby	18	
Smallmouth bass	69	8	Striped killifish	18	
Black sea bass	66	30	Fallfish	17	15
White sucker	65	40.7	Spottail shiner	15	90
Winter flounder	64		Atlantic silverside	15	11.5
Hickory shad	60	34	Mummichog	15	8.9
Gizzard shad	57	35	Eastern silvery minnow	15	8.8
Atlantic croaker	55	30	Eastern mudminnow	13.7	
White crappie	53	25	Banded killifish	13	6.3
Yellow perch	50	19.1	Satinfish shiner	13	
Rough silverside	12.5		Ironcolor shiner	6.5	5
Tesselated darter	11	5.1	Bridle shiner	6.5	

Species	Max TL	Mean TL	Species	Max TL	Mean TL
Threespine stickleback	11	5	Fourspine stickleback	6.4	4.1
Bay anchovy	10	5.9	Rainwater killifish	6.2	3.7
Banned sunfish	9.5	6.1	Naked goby	6	4.1
Ninespine stickleback	9	6.5	Seaboard goby	6	
Sheepshead minnow	9	3	Spotfin killifish	5	2.8
Eastern mosquitofish	8		Glassy darter	5	2.8
Inland silverside	7.8		Windowpane	4.5	
Swallowtail shiner	7.2	4.2			

Table 9: Time of day for species (separated into lifestage categories where relevant) that display diel patterns for spawning, foraging, or ontogenetic movements.

Species	Lifestage	Spawning	Foraging	Ontogenetic
Alewife	Adult	Night		
Blueback herring	Adult	Night		
Rainbow smelt	Adult	Night		
Tautog	Adult	Night		
Tautog	Juvenile			Night
Threespine stickleback	Adult		Day	
Weakfish	Adult		Night	
White perch	Adult		Night	
White sucker	Adult		Dusk	
White sucker	Juvenile			Night

Table 10: Tidal stage for adults of species that display tidal movements for spawning or foraging.

Species	Spawning	Foraging
Mummichog	Spring	Flood
Threespine stickleback		Flood
White perch		Flood
Fourspine stickleback		Flood

Table 11: Seasonal movements for species (separated into lifestage categories where relevant) that display seasonal patterns for spawning, foraging, ontogenetic, or refuge-seeking movements.

Species	Lifestage	Spawning	Foraging	Ontogenetic	Refugia
Alewife	Adult	Spring			
Alewife	Juvenile			Fall	
American eel	Adult	Fall			
American eel	Juvenile			Spring	
American shad	Juvenile			Fall	
Atlantic menhaden	Adult				Summer
Atlantic salmon	Adult	Summer			
Atlantic silverside	Adult				Winter
Atlantic sturgeon	Adult	Spring			
Black sea bass	Adult	Summer			
Blueback herring	Adult	Spring			
Bluefish	Adult				Winter
Brook trout	Adult	Spring			Summer
Butterfish	Adult				Winter
Chain pickerel	Adult	Spring			Winter
Fourspine stickleback	Adult	Spring			
Gizzard shad	Adult	Winter			
Greater amberjack	Adult	Summer			
Hickory shad	Adult	Spring			
Mummichog	Adult	Spring			Winter
Ninespine stickleback	Adult	Spring			
Northern pipefish	Adult				Winter
Rainbow smelt	Adult	Spring			
Scup	Adult				Winter
Sea lamprey	Adult	Spring			
Spot	Adult	Summer	Fall		
Striped bass	Adult	Spring	Summer		
Tautog	Adult	Summer			
Threespine stickleback	Adult	Spring			
Weakfish	Adult		Summer		Summer
Winter flounder	Adult	Winter			Summer
Yellow perch	Adult	Spring			

Table 12: Minimum (min.) and maximum (max.) depth (m) preferences for adults. Data from Fishbase.org.

Species	Min.	Max.	Species	Min.	Max.
Alewife	5	145	Northern pipefish	5	366
American eel	0	464	Rainbow smelt	0	425
American shad	0	250	Rainwater killifish	0	2
Atlantic croaker		100	Red drum	10	
Atlantic menhaden	0	50	Rough silverside	3	15
Atlantic silverside	0	3	Sand lance	0	73
Atlantic Spanish mackerel	10	35	Sandbar shark	0	500
Atlantic sturgeon	1	46	Scup	15	
Atlantic tomcod	0	69	Sea lamprey	1	4099
Banded killifish	10		Sea-run brown trout	0	28
Bay anchovy	1	70	Seaboard goby		50
Black drum	10		Shortnose sturgeon	6	53
Black sea bass	1		Spot		60
Blueback herring	5	55	Star butterfish	15	136
Bluefish	0	200	Striped bass	30	
Brook trout	15	27	Striped killifish	0	1
Butterfish	15	420	Summer flounder	10	183
Flathead grey mullet	0	120	Tautog	1	75
Fourspine stickleback	0	3	Threespine stickleback	0	100
Gizzard Shad		33	Walleye		27
Greater amberjack	1	360	Weakfish	10	26
Grubby	1	357	White mullet	1	30
Hogchoker	0	74	White perch	10	
Inland silverside	0	30	White sucker		30
Inshore lizardfish	0	210	Windowpane	55	73
Longear sunfish	0	10	Winter flounder	5	143
Mullet	0	120	Yellow perch	1	56
Northern kingfish	10				

Table 13: Velocity speed preference for adult taxa. Data from Fishbase.org.

Species	Velocity
Sand lance	Still
Ninespine stickleback	Slow
Mummichog	Slow
Fourspine stickleback	Slow
Banded sunfish	Slow
Mummichog	Slow
Pumpkinseed	Slow
Inland silverside	Slow
Threespine stickleback	Slow
Longear sunfish	Slow
Banded killifish	Slow
Fallfish	Slow
Bridle shiner	Slow
Black crappie	Slow
Shorthead redhorse	Slow
Ironcolor shiner	Slow
Eastern silvery minnow	Slow
Threespine stickleback	Slow
Rainwater killifish	Slow
Chain pickerel	Slow
Ninespine stickleback	Slow
American brook lamprey	Moderate
American shad	Moderate
Smallmouth bass	Moderate
American shad	Moderate

Table 14: Maximum and minimum pH tolerance for adults. Data from Fishbase.org.

Species	Max.	Min.
Redfin pickerel	10.1	
Eastern mosquitofish	8.8	6
Redbreast sunfish	7.5	7
Pumpkinseed	7.5	7
Banded sunfish	7.5	7
American brook lamprey	7.5	6.8
Eastern mudminnow	6.5	6

Table 15: Turbidity preference for adults. Data from Fishbase.org.

Species	Turbidity
Golden shiner	Turbid
Sheepshead minnow	Turbid
White crappie	Turbid
Yellow perch	Clear
Inland silverside	Clear
Ironcolor shiner	Clear
Fallfish	Clear
Black crappie	Clear
Common shiner	Clear

Table 16: Salinity preference and breadth of tolerance range for species (separated into lifestage where applicable). Data from Fishbase.org

Species	Lifestage	Preference	Range
Alewife	Adult	Saline	Wide
American brook lamprey	Adult	Fresh	Moderate
American eel	Adult	Brackish	Wide
American lobster	Adult	Brackish	Moderate
American shad	Adult	Saline	Wide
Amphipod	Adult	Fresh	Moderate
Asian shore crab	Adult	Brackish	Moderate
Atlantic croaker	Adult	Saline	Narrow
Atlantic menhaden	Adult	Saline	Moderate
Atlantic needlefish	Adult	Brackish	Wide
Atlantic salmon	Adult	Saline	Wide
Atlantic Spanish mackerel	Adult	Saline	Narrow
Atlantic sturgeon	Adult	Saline	Wide
Atlantic tomcod	Adult	Saline	Wide
Banded killifish	Adult	Fresh	Wide
Banded sunfish	Adult	Fresh	Moderate
Bay anchovy	Adult	Brackish	Wide
Bay scallop	Adult	Brackish	Moderate
Black crappie	Adult	Fresh	Narrow
Black drum	Adult	Saline	Narrow
Black sea bass	Adult	Saline	Moderate
Blue crab	Adult	Brackish	Moderate
Blue mussel	Adult	Brackish	Moderate
Blueback herring	Juvenile	Fresh	Wide
Blueback herring	Adult	Saline	Wide
Bluefish	Adult	Saline	Moderate
Bluegill	Adult	Fresh	Moderate
Brook trout	Adult	Fresh	Wide
Bridle shiner	Adult	Fresh	Moderate
Brown shrimp	Adult	Brackish	Moderate
Butterfish	Adult	Saline	Moderate
Chain pickerel	Adult	Fresh	Moderate
Channel catfish	Adult	Fresh	Moderate
Common periwinkle	Adult	Brackish	Moderate
Common shiner	Adult	Fresh	Moderate
Crayfish	Adult	Fresh	Moderate

Species	Lifestage	Preference	Range
Daggerblade grass shrimp	Adult	Brackish	Moderate
Diamondback terrapin	Adult	Brackish	Moderate
Eastern mosquitofish	Adult	Fresh	Moderate
Eastern mudminnow	Adult	Fresh	Narrow
Eastern pondmussel	Adult	Brackish	Moderate
Eastern silvery minnow	Adult	Brackish	Moderate
Fallfish	Adult	Fresh	Moderate
Fiddler crab	Adult	Brackish	Moderate
Flathead grey mullet	Adult	Saline	Wide
Fourspine stickleback	Adult	Brackish	Moderate
Gizzard shad	Adult	Fresh	Moderate
Gizzard shad	Juvenile	Fresh	Narrow
Glassy darter	Adult	Fresh	Moderate
Greater amberjack	Adult	Saline	Narrow
Green crab	Adult	Brackish	Moderate
Grubby	Adult	Brackish	Moderate
Gulf periwinkle	Adult	Brackish	Moderate
Hickory shad	Adult	Saline	Wide
Hogchoker	Adult	Brackish	Moderate
Horseshoe crabs	Adult	Brackish	Moderate
Inland silverside	Adult	Brackish	Moderate
Inshore lizardfish	Adult	Brackish	Wide
Ironcolor shiner	Adult	Fresh	Moderate
Largemouth bass	Adult	Fresh	Moderate
Long-clawed hermit crab	Adult	Brackish	Moderate
Longear sunfish	Adult	Fresh	Narrow
Marsh clam	Adult	Brackish	Moderate
Marsh crab	Adult	Brackish	Moderate
Periwinkle	Adult	Brackish	Moderate
Mud crab	Adult	Brackish	Moderate
Mud dog whelk	Adult	Brackish	Moderate
Mud snail	Adult	Brackish	Moderate
Mullet	Adult	Brackish	Wide
Mummichog	Adult	Brackish	Wide
Naked goby	Adult	Brackish	Wide
Ninespine stickleback	Adult	Brackish	Moderate
Northern kingfish	Juvenile	Saline	Moderate
Northern kingfish	Adult	Saline	Moderate

Species	Lifestage	Preference	Range
Northern pipefish	Adult	Brackish	Moderate
Northern water snake	Adult	Fresh	Narrow
Pumpkinseed	Adult	Fresh	Narrow
Rainbow smelt	Adult	Saline	Wide
Rainwater killifish	Adult	Brackish	Moderate
Red drum	Adult	Saline	Narrow
Redbreast sunfish	Adult	Fresh	Moderate
Redfin pickerel	Adult	Fresh	Moderate
Rough silverside	Adult	Saline	Narrow
Salt marsh snail	Adult	Brackish	Moderate
Sand lance	Adult	Brackish	Moderate
Sand shrimp	Adult	Brackish	Moderate
Sandbar shark	Adult	Saline	Narrow
Satinfish shiner	Adult	Fresh	Moderate
Scup	Adult	Saline	Narrow
Sea lamprey	Adult	Saline	Wide
Sea-run brown trout	Adult	Saline	Wide
Seaboard goby	Adult	Brackish	Moderate
Sheepshead minnow	Adult	Brackish	Wide
Shorthead redhorse	Adult	Fresh	Moderate
Shortnose sturgeon	Adult	Saline	Wide
Smallmouth bass	Adult	Fresh	Narrow
Snapping shrimp	Adult	Brackish	Moderate
Spot	Adult	Saline	Moderate
Spotfin killifish	Adult	Saline	Moderate
Spottail shiner	Adult	Brackish	Moderate
Spotted turtle	Adult	Fresh	Narrow
Star butterfish	Adult	Saline	Moderate
Striped bass	Adult	Saline	Wide
Striped killifish	Adult	Brackish	Moderate
Summer flounder	Adult	Saline	Narrow
Swallowtail shiner	Adult	Fresh	Moderate
Tautog	Adult	Saline	Moderate
Tesselated darter	Adult	Fresh	Narrow
Tidewater mucket	Adult	Brackish	Moderate
Walleye	Adult	Fresh	Narrow
Weakfish	Juvenile	Saline	Moderate
Weakfish	Adult	Brackish	Wide

Species	Lifestage	Preference	Range
Wharf crab	Adult	Brackish	Moderate
White catfish	Adult	Fresh	Moderate
White crappie	Adult	Fresh	Narrow
White fingered mud-crab	Adult	Fresh	Moderate
White hake	Adult	Brackish	Moderate
White mullet	Adult	Saline	Moderate
White perch	Adult	Brackish	Moderate
White shrimp	Adult	Brackish	Moderate
White sucker	Adult	Fresh	Moderate
Winter flounder	Adult	Saline	Moderate
Yellow perch	Adult	Brackish	Moderate

Table 17: Maximum (max.), minimum, (min.) and preferred (pref.) temperature (°C) for adults. Data from Fishbase.org. Blank cells indicate lack of data.

Species	Max.	Min.	Pref.	Species	Max.	Min.	Pref.
Alewife			8	Naked goby	33	11	
American eel	25	4		Ninespine stickleback	20	10	
American shad			10	Northern kingfish			25
Atlantic menhaden	23	5	15	Northern pipefish	17	4	
Atlantic salmon	20	10		Pumpkinseed	22	4	
Atlantic silverside	33	1		Rainbow smelt	15.6	7.2	
Atlantic Spanish mackerel	30	20	24	Red drum	25		
Atlantic tomcod			7	Redbreast sunfish	22	4	
Banded killifish	35	10		Redfin pickerel	26		
Banded sunfish	22	10		Sand lance	25	10	
Bay anchovy			23	Sandbar shark	27	23	27
Black crappie	31			Scup			19
Black drum			23	Sea lamprey	20	1	8
Black sea bass			19	Sea-run brown trout	24	18	
Blueback herring			12	Sheepshead minnow	42	2	
Bluefish			26	Shortnose sturgeon	28		
Bridle shiner	20	6		Smallmouth bass	30	10	
Brook trout	25			Spot			22
Butterfish			20	Spotfin killifish	25	10	
Chain Pickerel	20	10		Spottail shiner	24	10	
Common shiner			31	Star butterfish			27
Eastern mosquitofish	35	15		Striped bass	25	8	20
Eastern mudminnow	23	4		Striped killifish	25	10	
Flathead grey mullet	28	8	26	Summer flounder			13
Fourspine stickleback	20	4		Tautog			12
Gizzard Shad	32		20	Tesselated darter	24	10	
Golden shiner	35			Threespine stickleback	20	4	7
Greater amberjack			27	Walleye	29		
Grubby	21	0		Weakfish	27	17	
Hickory shad			18	White crappie	31		
Hogchoker	22	5		White perch			11
Inshore lizardfish	35	25		White sucker	29		
Largemouth bass	32	10		Windowpane	45.7		11
Mullet	24	8		Winter flounder			9
Mummichog	24	10		Yellow perch			30

Table 18: Threat level for species listed as vulnerable, near threatened, or endangered on the International Union for Conservation of Nature (IUCN). U.S. Endangered Species Act (ESA) status also included. Mobile indicates that these species undergo known movements between habitat types as adults.

Species	IUCN Threat Level	ESA Status	Mobile?
Bluefish	Vulnerable	Not listed	Yes
Tautog	Vulnerable	Not listed	Yes
Sandbar sharks	Vulnerable	Not listed	
Blueback herring	Vulnerable	Not listed	Yes
Atlantic salmon	Vulnerable	Endangered (Northeast region)	Yes
Bridle shiner	Near threatened	Not listed	
Atlantic sturgeon	Near threatened	Endangered (several locations) & Threatened (Gulf of Maine)	Yes
Shortnose sturgeon	Endangered	Endangered (rangewide)	Yes
American eel	Endangered	Not listed	Yes

Table 19: Substrate preference for adults. Data from Fishbase.org.

Species	**Substrate**	**Species**	**Substrate**
American brook lamprey	Sand	Red drum	Sand
American eel	Mud	Redbreast sunfish	Rock
Atlantic croaker	Sand	Sand lance	Sand
Banded killifish	Mud	Sand shrimp	Sand
Banded sunfish	Mud	Sandbar shark	Sand
Bay anchovy	Mud	Satinfish shiner	Sand
Black crappie	Mud	Sheepshead minnow	Mud
Black drum	Mud	Shorthead redhorse	Rock
Blue mussel	Rock	Spottail shiner	Rock
Bridle shiner	Mud	Striped killifish	Sand
Common shiner	Rock	Summer flounder	Sand
Fallfish	Rock	Swallowtail shiner	Sand
Flathead grey mullet	Sand	Tautog	Sand
Glassy darter	Sand	Tesselated darter	Sand
Inland silverside	Sand	Weakfish	Sand
Ironcolor shiner	Sand	White crappie	Mud
Largemouth bass	Sand	White perch	Mud
Mullet	Sand	Winter flounder	Sand
Mummichog	Mud		

APPENDIX 2: Expert interviewees

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