Habitat Suitability Models for Diadromous Fish in the Northeast United States

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# Technical Report: Habitat Suitability Models for Diadromous Fish in the Northeast United States

## Preface

## Abstract

## Introduction

Diadromous fish species exhibit a remarkable migratory behavior between marine and freshwater environments, playing a pivotal role in the ecological and socio-economic fabric of coastal communities. Their migration enables access to essential resources, identification of suitable spawning grounds, and maintenance of population connectivity, contributing to the overall health and resilience of aquatic ecosystems (Durbin et al., 1979)(Walters et al., 2009). These migratory patterns are categorized into anadromy, involving spawning in fresh or brackish inland water, and catadromy, where reproduction occurs at sea (Limburg & Waldman, 2009). The economic and cultural implications of these migratory movements are significant, as diadromous fish provide essential food resources, support recreational fisheries, and hold cultural importance for coastal and indigenous communities. Understanding and conserving these remarkable migratory species are crucial for sustaining livelihoods, traditions, and cultural heritage associated with coastal communities.

In the Northeastern United States, diadromous fish populations have faced a historic decline over the past century due to dam construction in rivers, overexploitation, and pollution (Brown et al., 2000; Helfman, 2007; Limburg & Waldman, 2009; Hare et al., 2021). Since the enactment of the Endangered Species Act (16 U.S.C. 1531-1544), a total of 47 anadromous fish species or populations have been federally listed as endangered or threatened, underscoring the urgency for conservation efforts (Federally Integrated Species Health (FISH) Act, 2017). However, no federally listed catadromous fish species currently exist. Christensen et al. (2003) revealed a significant decline in the biomass of high-trophic level fishes in the North Atlantic over the past century, highlighting the far-reaching consequences of these population declines on coastal communities.

Effective fisheries management and conservation efforts necessitate an understanding of the habitat requirements and distribution patterns of diadromous fish species (Helfman, 2007). By studying and monitoring the habitats used by these fish, key areas for protection and restoration can be identified, sustainable fishing practices can be implemented, and measures can be taken to mitigate pollution and habitat alteration. Preserving and restoring these habitats are critical steps toward ensuring the recovery and resilience of diadromous fish populations, which, in turn, supports the economic viability and cultural identity of coastal communities.

Although existing HSI models have significantly contributed to understanding habitat preferences and guiding conservation efforts, it is important to acknowledge their limitations. Many of these models, developed based on the best available data and observations at the time, are outdated and often fail to accurately capture the complexity of diadromous fish populations. They are often based on data and observations that group together similar species, such as Atlantic and Shortnose Sturgeon or alewives and blueback herring, thereby overlooking the distinct ecological requirements and behaviors of these species (i.e., Pardue, 1983, add more ). Additionally, models can rely on observation methods that may not be directly applicable to specific ecosystems, such as the U.S. Fish and Wildlife Service Habitat Evaluation Procedures Program, which primarily focuses on developing detailed models for assessing relatively small areas in terrestrial or freshwater environments, can introduce biases and hinder accurate assessments (USFWS 1980a, 1980b, 1981; Able et al., 2020).

Technological advancements such as acoustic telemetry, remote sensing, eDNA analysis, and high-resolution imaging have facilitated the increase in observations, studies, and data for diadromous fish behavior and movement. This wealth of new information has provided valuable insights into specific habitat requirements, migration patterns, and population dynamics of individual species within the diadromous fish community. To reflect these advancements more accurately, it is necessary to develop and refine additional HSI models.

Refined models incorporating these index approaches will exhibit direct sensitivity to alterations in physical characteristics, ensuring a more precise representation of habitat suitability for each diadromous fish species. This improved accuracy enhances the assessment of the impact of changing environmental conditions on the distribution and abundance of diadromous fish throughout the Northeast United States, facilitating targeted conservation efforts and effective fisheries management strategies. These updated models can also account for the unique ecological characteristics of each species, enabling more precise assessments of their distribution and the identification of critical areas for juvenile and spawning adults. The objectives of this paper are to synthesize the latest life cycle observations, studies, and data on diadromous fish species in the Northeastern United States and develop updated species-specific habitat suitability index (HSI) models for Atlantic Salmon, Atlantic Sturgeon, Alewives, American Eels, American Shad, Atlantic Tomcod, Blueback Herring, Rainbow Smelt, Shortnose Sturgeon, and Striped Bass, considering their unique habitat preferences and ecological needs during the juvenile and spawning adult life stages. By achieving these objectives, this study aims to contribute to a broader understanding of diadromous fish ecology, support effective fisheries management, and inform conservation strategies for the benefit of both the species and the coastal communities dependent on them.

## Methods

To develop the habitat suitability model for each diadromous fish species, a comprehensive and rigorous scientific process was followed. The first step involved synthesizing current relevant literature to gather a comprehensive understanding of the species’ habitat requirements, and previously published habitat models. This involved conducting an extensive review of scientific articles, reports, and studies that documented the ecological characteristics, migratory behaviors, and habitat associations of the 10 diadromous fish species under study. By assimilating this wealth of information, this study aims to ensure that the models capture the most up-to-date knowledge and insights into the specific needs and preferences of each species.

Building upon this literature synthesis, we developed a comprehensive habitat index that incorporated the key environmental variables known to influence the survival, growth, and reproduction of diadromous fish. For diadromous species in the northeast, environmental variables like water temperature, depth, salinity, flow velocity, and substrate type are important for defining estuarine habitat (Brown et al 2000). The calculation used for the models was an unweighted geometric mean. The geometric mean was chosen over an arithmetic mean due to its multiplicative calculation, which ensures that if any term in the model is zero, the overall suitability will also be zero. This approach emphasizes the importance of each environmental variable within the model, effectively identifying unsuitable habitats where any single characteristic falls outside the species’ range of preference.

In some cases, certain habitat variables were excluded from the final models based on a comprehensive analysis of the literature and expert judgment. “For example, the distribution of Atlantic tomcod juvenile was found to be independent of substrate type, leading to the exclusion of this variable from the final model.” This reduction in variables allowed for a more streamlined and focused model that captured the most influential factors driving habitat suitability for each diadromous fish species.

A systematic approach based on the available literature and previously published models was used to assign suitability index (SI) values to the ranges of each environmental variable. This involved determining the specific ranges of each variable that corresponded to different levels of suitability, ranging from 0 to 1. For instance, the most favorable conditions were assigned an SI of 1.0, representing highly suitable habitat for the species. An SI of 0.5 was assigned to ranges of environmental conditions approximately representing average suitability, indicating habitat about half as suitable as the most favorable conditions. In cases where species or life stages could occur but were rare, an SI of 0.1 was assigned, representing habitat approximately 1/10 as suitable as the most favorable conditions. Finally, an SI of 0 was assigned to environmental parameters outside the naturally used range for the particular species or life stage.

By following this systematic approach, we generated habitat suitability models for each of the 10 diadromous fish species, producing an average suitability index using the unweighted geometric mean. This allowed for a comprehensive evaluation of the habitat suitability across all environmental variables, with equal weighting assigned to each factor. The resulting models provide a quantitative assessment of the species’ habitat preferences and allow for the identification of critical areas of interest for survival, reproduction, and migration. The development of these updated habitat suitability models represents a significant improvement over previous approaches, as they incorporate the latest research, knowledge, and understanding of the diadromous fish species’ ecology and habitat requirements.

## Alewives

Alewives are widely distributed throughout the northeastern United States, inhabiting coastal areas from the Gulf of St. Lawrence in Canada to the mid-Atlantic region of the United States (citation needed). They are particularly abundant in freshwater rivers and estuaries along the Atlantic coast. Figure x shows the range of alewife habitat throughout the Northeast. Alewife populations can be found in various states, including Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Delaware, among others. They have historically undertaken extensive spawning migrations, ascending rivers and streams from their marine habitat to reach their preferred spawning grounds in freshwater tidal systems (citation needed). The distribution of alewife populations is influenced by several factors, including the availability of suitable spawning habitats, water quality conditions, and the presence of appropriate food resources (citation needed).

### Life cycle overview

The alewife, exhibits a complex life cycle characterized by distinct stages and behaviors. The spawning of alewives typically occurs in waves during the spring season, triggered by rising water temperatures and increasing day length (Able et al., 2020). Adult alewives migrate upstream from their marine environment to reach suitable spawning habitats (Bigelow & Schroeder, 1953). Upon arrival, they engage in impressive spawning runs, where large aggregations of individuals gather at spawning grounds.

During the spawning process, male alewives release sperm into the water, while females deposit their adhesive eggs over gravel or other hard-substrate types (Pardue, 1983; Janssen & Luebke, 2004). Both males and females return to the marine environment after spawning (Bigelow & Schroeder, 1953). The adhesive nature of the eggs helps them attach to the substrate, protecting them from being washed away by the current (Brown et al., 2000).

Following spawning, the eggs undergo a period of incubation, which typically lasts for several days (Bigelow & Schroeder, 1953). Once the eggs hatch, the larvae emerge and slowly begin their migration upstream where they will use the estuary habitat as a nursery until migrating out to sea (Pardue, 1983). Alewife larvae exhibit high rates of survival early on in higher concentrations of salinity (diMaggio 2015)(Bigelow & Schroeder, 1953). This characteristic enhances the fitness of alewife larvae in estuary environments where salinity concentrations can change rapidly.

### Habitat requirements

Spawning adult alewives exhibit specific preferences and requirements related to various habitat factors. Their annual migration during spawning is energetically demanding, with notable variations in behavior observed. Bigelow & Schroeder (1953) report that adult alewives migrate upstream and refrain from eating until their return downstream to productive tidal habitats. In contrast, Janssen & Brandt (1980) document fasting during the day and extensive feeding at night.

Temperature plays a critical role in alewife spawning behavior. Optimal temperatures for successful spawning generally fall within the range of 12 to 16 degrees Celsius (Brown et al., 2000). Above 29.7 degrees Celsius, spawning success becomes limited (Pardue). Alewives typically migrate into freshwater streams when temperatures range from 8 to 18 degrees Celsius (Mather et al., 2012). Spawning ceases when temperatures exceed 27 degrees Celsius (Kissil, 1974), and suitable spawning temperatures broadly range from 10 to 22 degrees Celsius (Tyus, 1974; Pardue, 1983; Collette and Klein-MacPhee, 2002). Alewife eggs can develop within a temperature range of 11 to 28 degrees Celsius (Klauda et al., 1991).

In terms of depth preferences, spawning adult alewives are generally known to favor depths ranging from MLT-10 meters (Brown et al., 2000). However, recent field observations conducted by Mather et al. (2012) have indicated that a significant proportion of alewives can be found in habitats shallower than 2 meters. These findings suggest that alewives are capable of spawning in both shallow and deep water environments, highlighting their adaptability in selecting suitable spawning locations (O’Connell & Angermeier, 1997).

The current understanding of adult alewife spawning behavior indicates a deviance from the traditional assumption that anadromous species exclusively rely on freshwater environments for reproduction. Notably, Brown et al. (2000) emphasizes a heightened preference for habitats with salinity concentrations below 15 psu, while concentrations surpassing 20 psu are deemed unsuitable for spawning adults. This observed variability in spawning behavior suggests that alewives possess the ability to tolerate moderate levels of salinity during the reproductive process. Field studies have documented adult alewives engaging in spawning activities across a diverse array of estuarine habitats, including ponds within coastal systems and pond-like regions within coastal rivers and streams (Pardue 1983; Mullen et al. 1986; Collette and Klein-MacPhee 2002; Walsh et al. 2005). These habitats encompass various environments, such as ponds, oxbows, eddies, backwaters, stream pools, and flooded swamps, and are characterized by their typical attributes of deep and slow water flow (Pardue 1983; Mullen et al. 1986; Collette and Klein-MacPhee 2002; O’Connell and Angermeier 1997; Walsh et al. 2005). Consequently, this revised understanding challenges the longstanding notion that river herring are exclusively obligated to freshwater for spawning purposes, as highlighted by laboratory experiments conducted by DiMaggio et al. (2016) that demonstrate the notable survival rates of alewife embryos at salinities ranging up to and including 10‰.

Temperature preferences of alewives during spawning exhibit variations across different studies; however, there is a general consensus that optimal temperatures for successful spawning fall within the range of 12 to 16 degrees Celsius (Brown et al., 2000). Above 29.7 degrees Celsius, spawning success becomes limited (Pardue). Alewives typically migrate into freshwater streams when water temperatures range from 8 to 18 degrees Celsius (Mather et al., 2012). Spawning ceases when water temperatures exceed 27 degrees Celsius (Kissil, 1974), and suitable spawning temperatures broadly span from 10 to 22 degrees Celsius (Tyus, 1974; Pardue, 1983; Collette and Klein-MacPhee, 2002). Notably, alewife eggs can develop within a temperature range of 11 to 28 degrees Celsius (Klauda et al., 1991).

Flow velocity is a crucial factor influencing the spawning of alewives. O’Connell (1999) proposes that habitat patches with velocity values ranging from 0.06 m/s to 0.16 m/s have a 50% probability of alewife egg presence, while Pardue identifies velocities below 0.3 m/s as suitable habitat for spawning. It should be noted that higher flow velocities have the potential to displace recently spawned eggs from their initial spawning location, as indicated by Able et al.

Previous studies have presented conflicting information regarding the substrate preferences of spawning adult alewives. It has been suggested that alewives prefer to spawn over hard substrates such as gravel and rock (Pardue, Brown et al., 2000), potentially due to the eggs’ better adhesion to such substrates. However, Able et al. (2020) have documented observations of alewives spawning over sandy substrates, as well as the presence of eggs adhered to rocky substrate base types. In terms of sediment composition, alewives are known to spawn over a range of substrates, including gravel, sand, and other soft substrates (O’Connell & Angermeier, 1997). It is important to note that alewife spawning also displays high tolerance to suspended sediments (Pardue; Auld and Schubel, 1978).

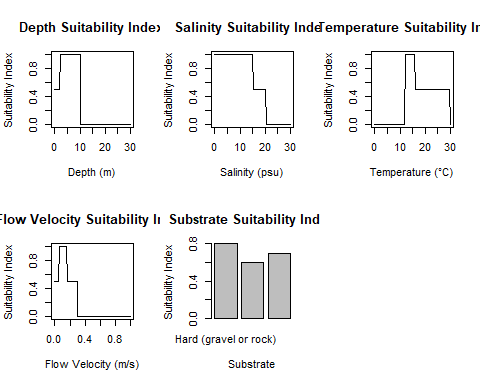
* juvenile Janssen & Luebke, 2004 describes a significant observations of juvenile herring over rocky substrates.

### Habitat suitability models

The Alewives Habitat Suitability models developed by Brown et al. (2000) and Pardue (1983), which relied on similar sources like Bigelow and Schroeder (1953), suffer from several limitations that render them inappropriate for current use. Firstly, these models are based solely on observations of Alewives’ daytime behavior, neglecting their nocturnal activity patterns. However, studies have revealed that Alewives are primarily active at night, feeding and potentially spawning during these nocturnal periods (Janssen & Brandt, 1980; Aquinnah source?). Therefore, the exclusive reliance on daytime behavior in the models fails to capture the true habitat preferences and requirements of Alewives. Additionally, the existing models mainly incorporate variables such as temperature and depth, while disregarding other critical factors that influence Alewives’ habitat selection, such as water flow, and life stage. Moreover, there is conflicting information within the models regarding the substrate, and depth preferences of Alewives, leading to inconsistencies and potential inaccuracies in predicting their habitat suitability. To overcome these limitations, updated models should incorporate a comprehensive understanding of Alewives’ behavior, including their predominantly nocturnal activity, and consider a broader range of habitat variables to provide more reliable and precise assessments of their habitat suitability.

#### Spawning Adult Alewives

par(mfrow=c(2, 3))  
  
# Depth Suitability Index  
depth\_values <- seq(0, 30, length.out = 100)  
depth\_suitability <- ifelse(depth\_values <= 2, 0.5, ifelse(depth\_values <= 10, 1, 0))  
plot(depth\_values, depth\_suitability, type = "l", xlab = "Depth (m)", ylab = "Suitability Index")  
title("Depth Suitability Index")  
  
# Salinity Suitability Index  
salinity\_values <- seq(0, 30, length.out = 100)  
salinity\_suitability <- ifelse(salinity\_values < 15, 1, ifelse(salinity\_values <= 20, 0.5, 0))  
plot(salinity\_values, salinity\_suitability, type = "l", xlab = "Salinity (psu)", ylab = "Suitability Index")  
title("Salinity Suitability Index")  
  
# Temperature Suitability Index  
temperature\_values <- seq(0, 30, length.out = 100)  
temperature\_suitability <- ifelse(temperature\_values >= 12 & temperature\_values <= 16, 1, ifelse(temperature\_values > 16 & temperature\_values <= 29.7, 0.5, 0))  
plot(temperature\_values, temperature\_suitability, type = "l", xlab = "Temperature (°C)", ylab = "Suitability Index")  
title("Temperature Suitability Index")  
  
# Flow Velocity Suitability Index  
velocity\_values <- seq(0, 1, length.out = 100)  
velocity\_suitability <- ifelse(velocity\_values >= 0.06 & velocity\_values <= 0.16, 1, ifelse(velocity\_values < 0.3, 0.5, 0))  
plot(velocity\_values, velocity\_suitability, type = "l", xlab = "Flow Velocity (m/s)", ylab = "Suitability Index")  
title("Flow Velocity Suitability Index")  
  
# Substrate Suitability Index  
substrate <- c("Hard (gravel or rock)", "Sandy", "Soft (other substrates)")  
substrate\_suitability <- c(0.8, 0.6, 0.7)  
barplot(substrate\_suitability, names.arg = substrate, xlab = "Substrate", ylab = "Suitability Index")  
title("Substrate Suitability Index")



library(knitr)

## Warning: package 'knitr' was built under R version 4.1.3

# Create the data for the table  
index <- c("Depth", "Salinity", "Temperature", "Flow Velocity", "Substrate")  
breakpoints <- c("Depth ≤ 2 m: 0.5\nDepth > 2 m: 1",  
 "Salinity < 15 psu: 1\nSalinity ≤ 20 psu: 0.5",  
 "Temperature 12-16°C: 1\nTemperature > 16°C & ≤ 29.7°C: 0.5",  
 "Velocity 0.06-0.16 m/s: 1\nVelocity < 0.3 m/s: 0.5",  
 "Hard (gravel or rock): 0.8\nSandy: 0.6\nSoft (other substrates): 0.7\nSuspended sediments: 0.9")  
  
# Create a data frame  
df <- data.frame(Index = index, Breakpoints = breakpoints)  
  
# Print the table using kable  
kable(df, format = "markdown")

| Index | Breakpoints |
| --- | --- |
| Depth | Depth = 2 m: 0.5 |
| Depth > 2 m: 1 |  |
| Salinity | Salinity < 15 psu: 1 |
| Salinity = 20 psu: 0.5 |  |
| Temperature | Temperature 12-16°C: 1 |
| Temperature > 16°C & = 29.7°C: 0.5 |  |
| Flow Velocity | Velocity 0.06-0.16 m/s: 1 |
| Velocity < 0.3 m/s: 0.5 |  |
| Substrate | Hard (gravel or rock): 0.8 |

Sandy: 0.6 Soft (other substrates): 0.7 Suspended sediments: 0.9 |

# Required packages  
#library(ggplot2)  
#library(sf)  
  
# Read the alewife habitat data (replace "alewife\_habitat.shp" with the actual file name and path)  
#alewife\_habitat <- st\_read("alewife\_habitat.shp")  
  
# Plot the map  
#ggplot() +  
# geom\_sf(data = alewife\_habitat, fill = "lightblue", color = "black") +  
# coord\_sf() +  
# labs(title = "Alewife Habitat Distribution",  
# subtitle = "Northeastern United States",  
# x = "Longitude", y = "Latitude")

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## American Eels

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## American Shad

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Atlantic Salmon

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Atlantic Sturgeon

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Atlantic Tomcod

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Blueback Herring

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Rainbow Smelt

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Shortnose Sturgeon

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Striped Bass

* description of species
* map of geographic range
* description of northeast distribution

### Life cycle overview

### Habitat requirements

* spawning
* juvenile

### Habitat suitability models

#### Spawning

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

#### Juvenile

##### Depth

##### Salinity

##### Temperature

##### Flow Velocity

##### Sediment Composition

## Synthesis and Discussion

* Comparison of habitat suitability models across species
* Implications for fisheries management and conservation
* Future directions and potential improvements for habitat suitability models

## Conclusion

* Summary of key findings
* Importance of habitat suitability models for diadromous fish management
* Final remarks and call to action

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