Habitat Suitability Models for Diadromous Fish in the Northeastern United States

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Introduction

Diadromous fish species exhibit an atypical 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.

Chapter 3

Methods

We describe our methods in this chapter.

Chapter 4

Alewives

This chapter aims to explore the habitat preferences and life cycle of alewives (Alosa pseudoharengus) in the northeastern United States. Alewives have faced significant declines, leading to their classification as a "species of concern" by the U.S. National Marine Fisheries Service (**?**). A combination of factors that have contributed to this decline, including deteriorating water quality, habitat loss, offshore bycatch/overfishing, increased predation, and dam construction [**?**; **?**; **?**; *Waldman & Quinn, 2022*]. They have also been considered for inclusion in the U.S. Endangered Species List, as indicated in reports by the National Marine Fisheries Service in 2013 (**?**).

Recent stock assessment reports reveal diverse trends in documented alewife runs over the last ten years, with some populations showing signs of stabilization or even growth (**?**). Additionally, in 2019, the National Marine Fisheries Service concluded that listing the alewife as threatened or endangered under the Endangered Species Act (ESA) was not warranted (**?**).

Alewives are widely distributed throughout the northeastern United States, thriving in freshwater rivers and estuaries along the Atlantic coast (**?**). Historically, alewives have undertaken extensive migrations to spawn in freshwater tidal systems, but limited information is available about estuary and marine movements during the juvenile and adult phases for alewives (**?**).

This chapter explores the favorable habitat conditions for spawning alewife adults, non-migratory juveniles, and larvae, which are influenced by factors such as suitable spawning habitats, water quality conditions, and availability of appropriate food resources (**?**).

4.1 Life cycle overview

Alewives exhibit a complex life cycle characterized by distinct stages and behaviors. Spawning typically occurs in waves during the spring season, triggered by rising water temperatures and increasing day length (**???**). Adult alewives migrate upstream from marine environments to reach suitable brackish or freshwater spawning habitats (**??**). Recent observations show that alewife migration can also be correlated with the lunar phase (**?**).

Upon arrival at the spawning grounds, adult alewives engage in immense spawning runs, where large aggregations gather to deposit their adhesive eggs over a variety of substrates (**??**). After spawning, both males and females return to the marine environment(**??**).

In the spawning habitat, the incubation period for eggs typically lasts for 3-6 days [**?**; *(Munroe, 2000)*; **?**]. Once hatched, the larvae begin their rapid migration downstream, eventually making their way towards estuary habitats where they will reside as they grow (**?**). This estuary environment serves as a nursery for juvenile alewives until they eventually migrate to the sea (**??**). It is noteworthy that the survival rate for larvae is relatively low, with only a small percentage successfully reaching the sea for each female alewife that entered the spawning grounds. This percentage can be as low as 1% or even less, depending on the specific conditions of the ecosystem (**?**). Similarly, mortality rates for migratory adults during a spawning season can reach as high as 90% in southern regions (**?**).

4.2 Habitat Requirements

4.2.1 Spawning Adult Alewives

Spawning adult alewives exhibit specific preferences and requirements related to habitat characteristics. Their annual migration during spawning is energetically demanding and notable variations in behavior have been observed. Some studies report fasting during the day and extensive feeding at night, while others document refraining from eating until their return downstream to productive tidal habitats (**???**). The preferred habitats for spawning are lacustrine and fluvial environments rather than riverine (**??**).

Temperature preferences during spawning vary across studies, but there is a consensus that optimal temperatures for successful spawning fall within the range of 12 to 16 degrees Celsius (**?**). Suitable spawning temperatures broadly span from 12 to 22 degrees Celsius (**????**) and during the migration inland, alewives tend to favor offshore locations where bottom temperatures are between 7 and 11 degrees Celsius *(Munroe, 2000)*. Spawning activity significantly diminishes above 27 degrees Celsius (**???**). Deviations from the optimal temperature range can significantly impact spawning success and the timing of migration. Water temperature also plays a critical role in alewife abundance and movement patterns (**?**).

In terms of depth preferences, spawning adult alewives are generally known to favor depths ranging from Mean Low Tide (MLT) to 10 meters (**?**), but recent field observations indicate that a significant proportion of alewives can be found in habitats as shallow as 2 meters (**?**). Offshore alewives migrating inland have been documented to favor deeper depths (depth $<$ 100m) [**?**; *(Munroe, 2000)*]. As such, alewives are capable of spawning in both shallow and deep water environments, highlighting their adaptability in selecting suitable spawning locations.

Further, documented behavior of alewives challenges the conventional belief that anadromous species exclusively depend on freshwater environments for spawning. Alewives have been observed spawning in freshwater habitats with minimal salinity concentrations, revealing a preference for environments with salinity levels below 0.5 psu. However, they can tolerate salinity levels as high as 5 psu for successful spawning, as documented in the study conducted by **?**. More recently, **?** emphasizes an additional heightened preference for habitats with salinity concentrations below 15 psu, while concentrations surpassing 20 psu are deemed unsuitable for spawning adults. Additionally, field studies have documented that adult alewives engage in spawning activities across a diverse array of estuarine habitats with varying salinity levels, including ponds within coastal systems, pond-like regions within coastal rivers and streams, oxbows, eddies, backwaters, stream pools, and flooded swamps (**????**).

Flow velocity is a crucial factor influencing the spawning of alewives (**?**). Alewives are thought to spawn in habitat that are slow moving with little or no current (**?**). **?** identifies velocities up to 0.3 m/s as suitable for spawning. However, **?** conducted laboratory experiments showing that migratory alewives can travel farther distances upstream when flow velocities are up to 1.5 m/s, compared to 3.5 m/s. Notably, these experiments indicate some suitability at these flow velocities and very little suitability for upstream migration when velocities reach 4.5 m/s (**?**). Understanding the preferred flow velocities is essential in managing and preserving the habitat conditions required for successful alewife spawning.

Previous studies have presented conflicting information regarding the substrate preferences of spawning adult alewives, often stemming from the generalization of alewives with blueback herring as river herring. While *(Janssen & Luebke, 2004);* suggests that alewives appear to prefer spawning over hard substrates such as cobble and rock, possibly due to the eggs' better adhesion to such surfaces, other documented observations provide evidence supporting a broader range of substrate utilization by spawning alewives (*Fay et al., 1983;* **????**). Notably, **?** documented observations of alewives spawning over sandy substrates, alongside the presence of eggs near hard substrates. Adult alewives spawn over a range of unconsolidated substrates, including small gravel, sand, vegetation, and other soft substrates (**???**). Aside from their demonstrated dependence on soft substrates, spawning adult alewives also exhibit a pronounced inclination toward habitats containing sub-aquatic vegetation [**?**; *Laney, 1997*]. Comprehending these substrate preferences is crucial to effectively manage and conserve the appropriate spawning habitats for alewives.

4.2.2 Premigratory Juvenile Alewives and Larvae

Premigratory juvenile alewives and larvae exhibit distinct habitat preferences and requirements, which play a crucial role in influencing their survival and growth. Several factors influence the abundance and successful development of these young alewives, including river flow, temperature, salinity, depth, and substrate (**???**). The preferred habitats for juveniles and alewife larvae are also lacustrine and fluvial environments (**?**).

Temperature significantly influences the distribution, behavior, and early development of premigratory juvenile alewives and larvae (**?**). Optimal temperatures for juvenile alewife development and larvae hatching fall within the range of 17°C to 22°C, with a broader suitability range for juvenile and larvae recruitment from 11°C to 28°C [**?**; **?**; **?**; **?**; *(Munroe, 2000)*; **?**]. Juvenile river herring do not survive temperatures of 3°C or less and hatching success ceases entirely above 29.7°C (**?**; *(Kellogg, 1982);* **?**). Maintaining water temperatures within these ranges is crucial for the successful development and overall health of premigratory juvenile alewives and larvae.

The depth preferences of premigratory juvenile alewives differ from their adult counterparts, as juveniles exhibit a preference for depths ranging from 0 to 10 meters, with no habitat suitability observed beyond 20 meters (**??**). Research by **?** further supports this finding, indicating that juveniles prefer depths between 0.5 to 5 meters. Lake Ontario research by **?** found that early post-hatch larvae are abundant in depths less than 3 meters, while larger larvae occupy progressively deeper habitats. Similarly, observations in Nova Scotia's Margaree River indicate that alewife larvae predominantly reside in depths shallower than 2 meters, while juvenile abundance increases around five meters deep (**?**). Overall, these field observations indicate that optimal depth for juvenile alewives and larvae is <5 meters. These shallow-water habitats provide protection from predators and access to food sources, facilitating growth before downstream migration.

Juvenile alewives exhibit a distinct salinity preference, favoring concentrations exceeding 10 psu and even tolerating levels up to 30 psu (**??**). Research by **?** notes their presence in areas with salinity below 12 psu, indicating adaptability to lower salinity environments. **?** along with **?** emphasize the preference of juveniles for estuarine habitats with salinity concentrations spanning 0.5 to 25 psu, promoting an ideal balance between freshwater and marine conditions for growth. While salinities exceeding 20 psu might impede suitability by affecting feeding and physiological processes (?), higher salinities up to 30 psu show minimal adverse effects on the health and survival of juvenile alewives, with a 100% survival rate observed at 15 psu (?). In summary, juvenile alewives exhibit a versatile salinity preference that ranges from thriving in concentrations exceeding 10 psu up to tolerating levels as high as 30 psu, highlighting their adaptability to diverse environments for optimal growth and survival.

Flow velocity is a crucial determinant of the development and survival of premigratory juvenile alewives (?). Previous optimal velocities for larvae and egg development were observed from 0 to 0.3 m/s (?). Other studies document juvenile alewife preference for habitats with flow velocities ranging from 0.05 to 0.17 m/s (??). Larval alewives are consistently found in water velocities up to approximately 0.12 m/s, but they are absent in faster currents (?). Slower flow rates offer suitable conditions for juveniles and larvae to conserve energy while effectively foraging for food (?). Conversely, higher flow velocities may hinder their ability to access critical food resources, maintain their position in the water column, and displace recently spawned eggs from their initial location (??). Understanding the flow velocity preferences and effects on premigratory juvenile alewives and larvae is crucial for effective habitat management and successful transition from egg to adulthood.

Premigratory juvenile alewives exhibit diverse substrate preferences that reflect their adaptability to various environments. While previous studies suggest a preference for sandy substrates ?, more recent observations indicate a potential preference for rocky substrates [?; *Boscarino et al., 2020*]. Seagrass coverage also plays a vital role in the habitat of these juveniles. Despite some studies suggesting avoidance of areas with aquatic vegetation ?, research by ? and ? demonstrates that seagrass beds provide essential nursery habitat, offering refuge from predators and abundant food sources. Seagrass beds enhance water quality by stabilizing sediments and promoting nutrient cycling, creating a favorable environment for juvenile alewives to thrive. These vegetated areas are also crucial for overwintering habitat (?). Understanding these diverse substrate preferences and the importance of seagrass coverage is essential for effective habitat management and the successful development of premigratory juvenile alewives.

4.3 Habitat suitability models

The Alewives Habitat Suitability models, originally developed by ? and ?, with reliance on similar sources such as ?, possess several limitations that make them inadequate for current applications. Primarily, these models are constructed solely on observations of alewives' daytime behavior, neglecting their significant nocturnal activity patterns. Recent studies have revealed that alewives are primarily active at night, engaging in feeding and exhibiting substantial downstream movement during these nocturnal periods (???). ? even notes that groups of alewives spawn in the evening. Consequently, the exclusive focus on daytime behavior in the existing models fails to capture the true habitat preferences and requirements of alewives, particularly in estuary and brackish environments.

Furthermore, the current models predominantly consider variables such as temperature, depth, and substrate, while disregarding other crucial factors that significantly influence alewives' habitat selection, including flow velocity, subaquatic vegetation, and life stage differences. This limited scope results in incomplete assessments of habitat suitability. Moreover, the existing models fall short of encompassing the comprehensive spectrum of knowledge available for alewives, as inconsistencies and potential inaccuracies emerge from conflicting information concerning substrate, salinity, and depth preferences. These limitations undermine the models' effectiveness in predicting habitat suitability for alewives, and since the release of these models, updated observations and stock assessments have been published that offer more detailed information on the habitat for alewives.

To address these shortcomings, updated models should encompass a more comprehensive understanding of alewives' behavior, specifically acknowledging their use of estuarine and brackish habitats. These habitats serve as critical areas for alewives, exhibiting relatively high levels of habitat use [**?**; *(Stevens et al., 2021)*]. Incorporating these estuarine and brackish areas into management strategies is of paramount importance to ensure the conservation and successful management of the species. Notably, utilizing estuaries and brackish habitats for spawning may offer energetically favorable conditions for alewives, as it eliminates the need for them to acclimate to complete freshwater environments (**?**). This recognition highlights the significance of incorporating these habitats into conservation efforts and management plans to safeguard the species and support their reproductive success.

4.3.1 Spawning Adult Alewives

The updated HSI model for spawning adult alewives introduces several noteworthy breakpoints that distinguish it from previous models. These breakpoints provide a more refined understanding of alewife habitat preferences and suitability.

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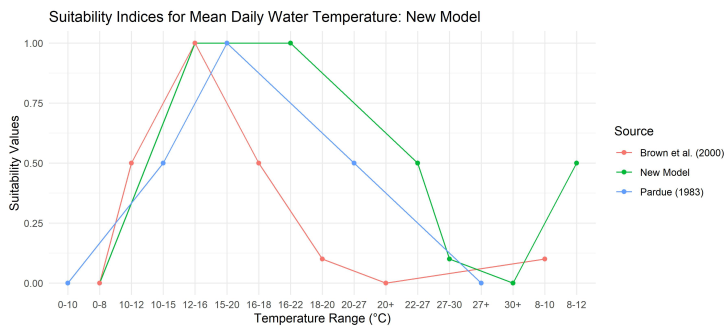

Figure 4.1: Spawning Adult Alewife Temperature Suitability Indices

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## The following objects are masked from 'package:stats':
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##     filter, lag
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## The following objects are masked from 'package:base':
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##     intersect, setdiff, setequal, union
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Table 4.1: Suitability Indices for Mean Daily Water Temperature: Spawning Adult Alewives

	Temperature Range (C)	Suitability Values
New Model	0-8	0
	8-12	0.5
	12-16	1
	16-22	1
	22-27	0.5
	27-30	0.1
	30+	0
Pardue (1983)	0-10	0
	10-15	0.5
	15-20	1
	20-27	0.5
	27+	0
Brown et al. (2000)	0-8	0
	8-10	0.1
	10-12	0.5
	12-16	1
	16-18	0.5
	18-20	0.1
	20+	0

In contrast to earlier models, the new HSI model delineates mean daily temperature preferences with greater accuracy. While previous models often employed broader temperature categories, the current model introduces finer distinctions. For instance, the new model identifies a specific range (12 to 16 degrees Celsius) where alewives exhibit peak suitability, providing a more accurate depiction of their thermal requirements for successful spawning. Moreover, the model highlights an upper mean daily temperature limit (27 degrees Celsius) where suitability drastically decreases, emphasizing the importance of maintaining suitable thermal conditions in spawning habitats.

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Table 4.2: Suitability Indices for Average Depth: Spawning Adult Alewives

	Depth Range (meters)	Suitability Values
New Model	0-2	0
	2-10	0.5
	10-20	1
	20-50	0.5
	50-100	0.5
	100+	0
Pardue (1983)	NA	NA
Brown et al. (2000)	0-MLT	0.5
	MLT-3	1
	3-10	1
	10-20	0.1
	20-50	0
	50-100	0

The updated model also offers more detailed depth preferences. Previous models might have employed generalized depth categories, but the new model introduces distinct depth ranges. This allows for a more refined assessment of habitat suitability. For instance, the new model specifies a peak suitability range (2 to 10 meters), reflecting the depth preferences of spawning adult alewives more accurately. Additionally, it identifies a depth threshold (100 meters) beyond which habitats are unsuitable for spawning.

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Table 4.3: Suitability Indices for Average Salinity: Spawning Adult Alewives

	Salinity Range (psu)	Suitability Values
New Model	0-0.5	1
	0.5-5	1
	5-15	1
	15-20	0.5
	20+	0
Pardue (1983)	0-6	0.86
	6-14	0
	14-20	0
	20+	0
Brown et al. (2000)	0-0.5	1
	0.5-5	1
	5-10	1
	10-15	1
	15-20	0.5
	20-25	0.1
	25-30	0

The new HSI model also refines the depiction of alewife salinity preferences. Unlike earlier models, which may have had narrow salinity categories, the updated model provides a more nuanced view. It pinpoints a specific range (0 to 5 psu) where alewives exhibit the highest suitability, aligning closely with empirical data. Moreover, it designates a clear upper limit (15 psu) where suitability declines significantly, indicating the importance of maintaining lower salinity levels in suitable habitats.

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Table 4.4: Suitability Indices for Flow Velocity: Spawning Adult Alewives

	Flow Velocity Range (m/s)	Suitability Values
New Model	0-0.3	1
	0.3-1.5	1
	1.5-3.5	0.5
	3.5-4.5	0.3
	4.5+	0
Pardue (1983)	NA	NA
Brown et al. (2000)	NA	NA

The new model enhances our understanding of alewife flow velocity preferences. While previous models might have used less specific flow velocity categories, the updated model introduces distinct ranges. For example, it highlights a range (0 to 0.3 meters per second) where alewives demonstrate the highest suitability and extends moderate suitability to a broader range (0.3 to 1.5 meters per second), offering a more defined view of their flow velocity requirements. Additionally, it designates an upper threshold (4.5 meters per second) beyond which habitat would be considered unsuitable, in line with observed behaviors.

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Table 4.5: Suitability Indices for Predominant Substrate Type: Spawning Adult Alewives

	Predominant Substrate Type	Suitability Values
New Model	soft substrate	1
	hard substrate	0.5
	present SAV	1
	absent SAV	0.5
Pardue (1983)	NA	NA

	Predominant Substrate Type	Suitability Values
Brown et al. (2000)	NA	NA

Substrate preferences remain a crucial aspect of spawning habitat for alewives. Previous models have employed general substrate categories, while the new model emphasizes the significance of diverse substrate types, including soft (e.g. small gravel, sand, silt, detritus) and hard substrates (e.g. cobble, rock, boulders, clam beds), as well as sub-aquatic vegetation (i.e. absence/presence).

4.3.2 Juvenile Alewives

4.3.3 Figures & Tables

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Table 4.6: Habitat Suitability Indices for Spawning Adult Alewives

	Variable	Parameter	Range	HSI	Formulas
Spawning Adults	A	Temperature	$temp_C = 0 - 8$	0	$0 + (0.0625 * temp_C)$
			$temp_C = 8 - 12$	0.5	$-0.5 + (0.125 * temp_C)$
			$temp_C = 12 - 16$	1	$1 + (0 * temp_C)$
			$temp_C = 16 - 22$	1	$2.33 + (-0.0833 * temp_C)$
			$temp_C = 22 - 27$	0.5	$2.26 + (-0.0800 * temp_C)$
			$temp_C = 27 - 30$	0.1	$1.00 + (-0.0333 * temp_C)$
			$temp_C = 30+$	0	$0 + (0 * temp_C)$

	Variable	Parameter	Range	HSI	Formulas
	B	Depth	$depth_m = 0-2$	0	$0+(0.005*depth_m)$
			$depth_m = 2-10$	0.5	$0.38+(0.0625*depth_m)$
			$depth_m = 10-20$	1	$1.5+(-0.05*depth_m)$
			$depth_m = 20-50$	0.5	$0.5+(0.0*depth_m)$
			$depth_m = 50-100$	0.5	$1+(-0.01*depth_m)$
			$depth_m = 100+$	0.5	$0.0+(0.0*depth_m)$
	C	Salinity	$sal_{psu} = 0-0.5$	1	$1+(0*sal_{psu})$
			$sal_{psu} = 0.5-5$	1	$1+(0*sal_{psu})$
			$sal_{psu} = 5-15$	1	$1.25+(-0.05*sal_{psu})$
			$sal_{psu} = 15-20$	0.5	$2.0+(-0.1*sal_{psu})$
			$sal_{psu} = 20+$	0	$0+(0*sal_{psu})$
	D	Flow Velocity	$vel_(m/s) = 0-0.3$	1	$1+(0*vel_{m/s})$
			$vel_(m/s) = 0.3-1.5$	1	$1.13+(-0.4167*vel_{m/s})$
			$vel_(m/s) = 1.5-3.5$	0.5	$0.65+(-0.1*vel_{m/s})$
			$vel_(m/s) = 3.5-4.5$	0.3	$1.35+(-0.3*vel_{m/s})$
			$vel_(m/s) = 4.5+$	0	$0+(0*vel_{m/s})$
	E	Substrate	$soft$	1	
			$hard$	0.5	
	F	SAV	$present$	1	
			$absent$	0.5	

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## kableExtra can customize either HTML or LaTeX outputs. See
## https://haozhu233.github.io/kableExtra/ for details.

## Warning in column_spec(., 4, width_min = "20em"): Please specify format in
## kable. kableExtra can customize either HTML or LaTeX outputs. See
## https://haozhu233.github.io/kableExtra/ for details.
```

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## Warning in column_spec(., 5, width_min = "20em"): Please specify format in
## kable. kableExtra can customize either HTML or LaTeX outputs. See
## https://haozhu233.github.io/kableExtra/ for details.
```

Table 4.7: Habitat Suitability Indices for Non-migratory Juvenile Alewife and Larvae

	Variable	Parameter	HSI	Formulas
Non-migratory Juvenile and Larvae	A	Temperature	$temp_C = 3 - 6$	$-0.2 + (0.0667 * temp_C)$
			$temp_C = 6 - 12$	$-0.4 + (0.1 * temp_C)$
			$temp_C = 12 - 20$	$0.5 + (0.025 * temp_C)$
			$temp_C = 20 - 22$	$1 + (0 * temp_C)$
			$temp_C = 22 - 26$	$3.2 + (-0.1 * temp_C)$
			$temp_C = 26 - 30$	$4.5 + (-0.15 * temp_C)$
	B	Depth		
	C	Salinity		
	D	Flow Velocity		
	E	Substrate		
	F	SAV		

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American Eels

5.1 Life cycle overview

5.2 Habitat Requirements

5.2.1 Spawning Adult American Eels

5.2.2 Juvenile American Eels

5.3 Habitat suitability models

5.3.1 Spawning Adult American Eels

5.3.2 Juvenile American Eels

5.4 Figures & Tables

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American Shad

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6.2 Habitat Requirements

6.2.1 Spawning Adult American Shad

6.2.2 Juvenile American Shad

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6.3.1 Spawning Adult American Shad

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Atlantic Salmon

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7.2.1 Spawning Adult Atlantic Salmon

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7.3 Habitat suitability models

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8.2.2 Juvenile Atlantic Sturgeon

8.3 Habitat suitability models

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9.2.2 Juvenile Atlantic Tomcod

9.3 Habitat suitability models

9.3.1 Spawning Adult Atlantic Tomcod

9.3.2 Juvenile Atlantic Tomcod

9.4 Figures & Tables

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Blueback Herring

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10.3 Habitat suitability models

10.3.1 Spawning Adult Blueback Herring

10.3.2 Juvenile Blueback Herring

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Rainbow Smelt

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11.2.2 Juvenile Rainbow Smelt

11.3 Habitat suitability models

11.3.1 Spawning Adult Rainbow Smelt

11.3.2 Juvenile Rainbow Smelt

11.4 Figures & Tables

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Shortnose Sturgeon

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12.2 Habitat Requirements

12.2.1 Spawning Adult Shortnose Sturgeon

12.2.2 Juvenile Shortnose Sturgeon

12.3 Habitat suitability models

12.3.1 Spawning Adult Shortnose Sturgeon

12.3.2 Juvenile Shortnose Sturgeon

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Striped Bass

13.1 Life cycle overview

13.2 Habitat Requirements

13.2.1 Spawning Adult Striped Bass

13.2.2 Juvenile Striped Bass

13.3 Habitat suitability models

13.3.1 Spawning Adult Striped Bass

13.3.2 Juvenile Striped Bass

13.4 Figures & Tables

Chapter 14

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

Chapter 15

Conclusion

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