River Herring Habitat in the Northeast United States

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2024-01-24

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Background and History

potential sources:

- However, overexploitation has reduced the population size of both species throughout their ranges (Gibson and Myers 2003; Schmidt et al. 2003).
- Widespread declines in these stocks and those of other alosine species have been attributed to overfishing, degraded water quality, and loss of habitat (Crecco and Savoy 1984; Kosa and Mather 2001).

Chapter 3

Methods

- methods in ecological modeling

We propose that there are temporal and spatial differences in the larval growth and mortality of river herring and that these differences are species specific. (Overton et al., 2012)

Due to their differences in biology, a single management plan will affect each species differently and exploitation within a river system may be biased towards one species (Schmidt et al 2003).

- how hsi breakpoints were derrived
- input data
- r functions?
- output format?

Chapter 4

Alewife (*Alosa pseudoharengus*)

This chapter is dedicated to the exploration of the habitat preferences and life cycle of alewives (*Alosa pseudoharengus*) in the northeastern United States. Despite their historical significance, alewife populations have encountered significant declines, leading to their classification as a "species of concern" by the U.S. National Marine Fisheries Service (National Marine Fisheries Service 2009). Various factors contribute to this decline, including deteriorating water quality, habitat loss, offshore bycatch/overfishing, increased predation, and dam construction (Kocovsky et al. 2008; National Marine Fisheries Service 2009; Bethoney, Stokesbury, and Cadrin 2014; Waldman and Quinn 2022). The consideration for inclusion in the U.S. Endangered Species List has also been raised, as indicated in reports by the National Marine Fisheries Service in 2013 (National Marine Fisheries Service 2013).

Recent stock assessments reveal diverse trends in documented alewife runs over the last ten years, with some populations showing signs of stabilization or even growth (ASMFC 2017). 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 (National Marine Fisheries Service 2019).

Alewives are widely distributed throughout the northeastern United States, thriving in freshwater rivers and estuaries along the Atlantic coast (ASMFC 1985). While historically known for extensive migrations to spawn in freshwater tidal systems, limited information is available about estuary and marine movements during the juvenile and adult phases for alewives (McCartin et al. 2019). This chapter aims to explore the favorable habitat conditions for spawning alewife adults, non-migratory juveniles, as well as eggs and larvae, considering factors such as suitable spawning habitats, water quality conditions, and availability of appropriate food resources.

4.1 Life cycle overview

Alewives have a complex life cycle with distinct stages and behaviors. Spawning occurs in waves during spring, triggered by rising water temperatures and increasing day length (ASMFC 2009; McCartin et al. 2019; Able et al. 2020). Adult alewives migrate upstream from marine environments to suitable brackish or freshwater spawning habitats (Pardue 1983; A. F. Bigelow et al. 2002). Recent observations also suggest a correlation between alewife migration and the lunar phase (Legett et al. 2021).

Alewife migration and spawning precedes blueback herring by 2-3 weeks (Fay, Neves, and Pardue 1983). Upon arrival at the spawning grounds, adult alewives engage in immense spawning runs, where large groups gather to deposit their adhesive eggs over a variety of substrates (O'Connell and Angermeier 1997; Able et al. 2020). After spawning, both males and females return to the marine environment.

In the spawning habitat, the incubation period for eggs lasts 3-6 days (Munroe 2000; A. F. Bigelow et al. 2002). The eggs hatch into yolk-sac larvae, representing an early developmental stage where larvae rely on an attached yolk sac for nutrients before transitioning to external feeding. For alewives, this stage typically lasts 2-5 days *(Bourne 1990).*

After this stage, larvae remain in the estuary to grow and migrate downstream towards more brackish areas, maturing into juvenile fish (Pardue 1983). These brackish areas serve as nurseries until the juvenile alewives migrate to the sea (Laney 1997; Kosa and Mather 2001). Alewife larvae can adapt to high salinities (35 psu) by 50 days post-hatch *(DiMaggio et al. 2015).* However, the survival rate for larvae is relatively low, with only a small percentage successfully reaching the sea, potentially as low as 1%, depending on ecosystem conditions (Kissil 1974). Similarly, mortality rates for migratory adults during a spawning season can reach as high as 90% (Brady et al. 2005).

4.2 Habitat Requirements

4.2.1 Spawning Adult Alewives

Spawning adult alewives exhibit specific habitat preferences and requirements. Their annual migration during spawning is energetically demanding, with notable variations in behavior. Some studies suggest fasting during the day and extensive feeding at night, while others report refraining from eating until their return downstream to productive tidal habitats (Janssen and Brandt 1980; A. F. Bigelow et al. 2002).

Preferred spawning habitats include lacustrine and fluvial environments rather than riverine ones (Reback et al. 2004; Frank et al. 2011). Alewives spawn and rear in lower salinity upper river pools *(Turner & Limburg 2016).*

4.2.1.1 Temperature

Spawning adult alewives exhibit distinct temperature preferences crucial to their reproductive success and migration patterns. The spawning process commences at temperatures around 10.5 °C, with upstream migration initiating within the range of 5°C to 10°C [(Cianci 1969); (Mullen et al., 1986); (Loesch 1987); Munroe (2000); (Reback et al., 2004)]. Notably, limited instream movement is observed below 8°C or over 18°C, emphasizing the species' preference for moderate temperature conditions [(Durbin et al., 1979); Collette and KleinMacPhee 2002]. Spawning ceases at temperatures exceeding 27°C, indicating an upper limit for optimal reproductive activity [(Kissil 1974);Pardue (1983); Brown et al. (2000); (Reback et al., 2004)]. The optimal temperature range for successful spawning is broadly identified as 10°C to 22°C, with consensus suggesting peak spawning occurring within the narrower range of 12 to 16 degrees Celsius [Tyus 1974; Pardue 1983; (O'Connell & Angermeier, 1997); Collette and Klein-MacPhee 2002]. While deviations from the optimal temperature range can impact spawning success and migration timing, the overall picture indicates that alewives thrive in moderate temperature conditions.

4.2.1.2 Depth

Spawning adult alewives exhibit specific depth preferences during their reproductive activities. Notably, adult alewives migrating inland show an overall preference for depths below 100 meters (Pardue 1983; Munroe 2000). Species of herring from the same clupeid family have been known to spawn at depths ranging from 0.5 to 15 meters (Haegele & Schweigert 1985). Alewives generally favor depths from Mean Low Tide (MLT) to 10 meters (Brown et al. 2000). Other studies report that alewives favor more shallow spawning habitats ranging from 0.15 to 3 meters (Pardue 1983), with significant spawning recorded around 0.5 meters (Kosa & Mather 2001). Additional field observations, reveal a significant proportion of alewives occupying habitats as shallow as 2 meters (Mather et al. 2012). This variability in depth preferences reflects the adaptability of alewives to different environmental conditions during their spawning and migration phases.

4.2.1.3 Salinity

The documented behavior of alewives challenges conventional beliefs about anadromous species exclusively relying on freshwater environments for spawning. Observations reveal that alewives engage in spawning activities in freshwater tidal habitats with minimal salinity concentrations, demonstrating adaptability to environments with salinity levels below 0.5 psu (Pardue 1983; Brown et al. 2000). This adaptability extends to tolerating higher salinity levels, with successful spawning observed in concentraions of 8 psu (Able et al. 2020). Other research by Brown et al. (2000) emphasizes a heightened preference for habitats with salinity concentrations below 15 psu, deeming concentrations exceeding 20 psu unsuitable for spawning adults.

Field studies further document that adult alewives exhibit spawning activities across diverse estuary habitats with varying salinity levels, including coastal ponds, pond-like regions in coastal rivers and streams, oxbows, eddies, backwaters, stream pools, and flooded swamps (Pardue 1983; Mullen, Fay, and Moring 1986; Collette and Klein-MacPhee 2003; Walsh, Settle, and Peters 2005). Remarkably, species of herring from the same clupeid family have been known to spawn in a wide range of salinities, from freshwater to levels exceeding 35 psu (Haegele & Schweigert 1985). This adaptability underscores the versatility of alewives in utilizing estuarine habitats with varying salinity conditions for their spawning activities.

4.2.1.4 Flow Velocity

The flow velocity preferences for adult alewives are crucial for understanding spawning habitat (Tommasi et al. 2015). Haro et al. (2004) highlighted the challenges faced by smaller species, including alewives, when subjected to high velocities above 3.5 m/s, leading to impingement issues and poor performance. In contrast, lower velocities, particularly below 1.7 m/s, as observed by Walsh, Settle, and Peters (2005), are favored by alewives. Mather et al. (2012) found that tagged alewives spent minimal time in riffle–run habitats but preferred pools, with varying locations of pool occupancy.

While conventional wisdom suggests that alewives spawn in slow-moving habitats with little to no current, Haro et al. (2004) swimming experiments also revealed that migratory alewives can travel farther distances upstream when flow velocities are increased to 1.5 m/s, compared to 3.5 m/s. However, these experiments indicated very little suitability for upstream migration when velocities reach above 3.5 m/s, suggesting no suitability if tested at 4.5 m/s (Haro et al. 2004). Older findings identify velocities up to 0.3 m/s as suitable for spawning (Pardue 1983). Understanding the influence of flow velocity is key for effective management and preservation of the habitat conditions required for successful alewife spawning.

4.2.1.5 Substrate

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. Despite Brown et al. (2000) arguing that substrate composition holds no significance in alewife models, contrasting observations from various sources, including studies by Fay, Neves, and Pardue (1983), Killgore, Morgan, and Hurley (1988), O'Connell and Angermeier (1997), and Able et al. (2020), present compelling evidence of a more defined range of substrate preferences. These preferences span a variety of unconsolidated substrates, such as small gravel, sand, detritus, and other soft substrates, as documented by Pardue (1983), *bourne 1990*, O'Connell and Angermeier (1997), and Brown et al. (2000). Moreover, there is an indication that spawning adult alewives may avoid habitats containing sub-aquatic vegetation (SAV), according to findings by Killgore, Morgan, and Hurley (1988) and Laney (1997). Comprehending and defining these substrate preferences is crucial for effectively managing and conserving the appropriate spawning habitats for alewives.

4.2.2 Non-Migratory Juveniles

Non-migratory juvenile alewives 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 (Pardue 1983; Walsh, Settle, and Peters 2005; Tommasi et al. 2015). The preferred habitats for juvenile alewife are lacustrine and fluvial environments (Overton, Jones, and Rulifson 2012).

4.2.2.1 Temperature

Temperature significantly influences the distribution, behavior, and early development of non-migratory juvenile alewives (Tommasi et al. 2015). Optimal temperatures for juvenile alewife development fall within the range of

- 12°C to 22°C Brown et al. (2000)
- most juvenile recruitment in Delaware River at 22°C Potomac River at 22.3°C Nanticoke River 21.8°C (tommasi 2015)
- The optimal nursery rearing temperature was 20–23 °C (tommasi 2015)
- The optimal temperature for river herring juveniles during the nursery phase varied across systems and species, but ranged between 20 and 22 °C (tommasi)

- final preference of young alewives was estimated to be 26.3 C (Kellogg, 1982).
- exposure to temperature extremes during development in nursery habitats may constrain juvenile growth and decrease performance (Pörtner and Farrell 2008; Kellogg 1982; Henderson and Brown 1985; Overton et al. 2012).
- broader suitability range for juvenile recruitment from 11°C to 28°C (Pardue 1983; Fay, Neves, and Pardue 1983; Klauda, Fischer, and Sullivan 1991; Brown et al. 2000; Munroe 2000; Tommasi et al. 2015).

Juvenile river herring do not survive temperatures of 3°C or less (Otto, Kitchel, and Rice 1976; Kellogg 1982; Pardue 1983:(Mullen et al., 1986)). Maintaining water temperatures within these ranges is crucial for the successful development and overall health of non-migratory juvenile alewives and larvae.

- supported in observations where Eel River had a mean temperature of 23.1°C, while the Herring River (Bourne) had temperatures with a mean of 25.1°C (Ames & Lichter, 2013).
- feeding behavior disrupted at 6.7 C, 4.5 C schooling behavior is disrupted, 2.8 fish are completely disoriented (Mullen et al., 1986)

4.2.2.2 Depth

- MLT - 10 m Brown et al. (2000)
- other juvenile cluepids found abundant in 4.6 m(Mullen et al., 1986)

The depth preferences of non-migratory 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 (Brown et al. 2000; Höök et al. 2008). Research by Pardue (1983) further supports this finding, indicating that juveniles prefer depths between 0.5 to 5 meters, and that juvenile abundance increases around five meter depths (Pardue 1983). Overall, these field observations indicate that optimal depth for juvenile alewives <= 5 meters.

4.2.2.3 Salinity

- The findings in the study suggest that alewives, during their juvenile development, exhibit adaptations in response to different levels of salinity (salt in the water). When exposed to seawater, the alewives showed increased activity in specific proteins and structures in their gills, indicating a capacity for osmoregulation, or the ability to regulate salt and water balance.

This adaptation suggests that alewives are capable of maintaining a stable internal environment in seawater. While the study doesn't explicitly state a salinity preference, the observed physiological adjustments imply that alewives have the ability to thrive in environments with varying salinity, making them adaptable to both freshwater and saltwater habitats during different stages of their life cycle (Christensen et al., 2012).

- found up to 32 psu Pardue (1983)
- prefer > 10 psu Brown et al. (2000)
- Alewives demonstrate complete survival when maintained in control conditions (0‰ to 0‰ salinity). However, when transferred from higher salinities (15‰ and 30‰) to 0‰ salinity, Alewives show significantly lower survival rates. The lower survival rates under sudden shifts to lower salinities suggest that Alewives may be less tolerant to rapid decreases in salinity, emphasizing a potential preference for higher salinity environments. This information implies that Alewives might be better adapted to or have a preference for estuarine areas with higher salinities.(DiMaggio et al., 2015)

Juvenile alewives exhibit a distinct salinity preference, favoring concentrations exceeding 10 psu and even tolerating levels up to 30 psu (Brown et al. 2000). Research by Fay, Neves, and Pardue (1983) notes their presence in areas with salinity below 12 psu, indicating adaptability to lower salinity environments. Turner and Limburg (2016) along with Able et al. (2020) 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 (Fabrizio et al. 2021), 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 (DiMaggio et al. 2015). 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.

4.2.2.4 Flow Velocity

- Numbers of recruits were maximized at a flow of 672 $m3 \cdot s{-}1$ and flow of6m3 $\cdot$ s−1 (tommasi 2015)
- Both species spawn primarily in habitats with little or no current Walsh 2005

Flow velocity is a crucial determinant of the development and survival of non-migratory juvenile alewives (Tommasi et al. 2015). Other studies document juvenile alewife preference for habitats with flow velocities ranging from 0.05 to 0.17 m/s (Richkus 1975; O'Connell and Angermeier 1999). Slower flow rates offer suitable conditions for juveniles to conserve energy while effectively foraging for food (Haro et al. 2004). 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 (Haro et al. 2004; Able et al. 2020). Understanding the flow velocity preferences and effects on non-migratory juvenile alewives is crucial for effective habitat management and successful transition from egg to adulthood.

4.2.2.5 Substrate

Non-migratory juvenile alewives exhibit diverse substrate preferences that reflect their adaptability to various environments. While previous studies suggest a preference for sandy substrates Fay, Neves, and Pardue (1983), more recent observations indicate a potential preference for rocky substrates (Janssen and Luebke 2004; 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 Ingel (2013), research by Laney (1997) and Smith and Rulifson (2015) demonstrates that seagrass beds provide essential nursery habitat for juveniles, 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 (Killgore, Morgan, and Hurley 1988). Understanding these diverse substrate preferences and the importance of seagrass coverage is essential for effective habitat management and the successful development of non-migratory juvenile alewives.

- Alewife catches at rocky sites were about four times those for sandy sites Janssen and Luebke (2004)
- could be because Wells (1980) rocky habitat was more profitable in feeding on zooplankton.

4.2.3 Eggs & Larvae

- Alewife planktonic larval phases are vulnerable to passive transport dispersal (Schmidt et al 1988

4.2.3.1 Temperature

- most larvae growth at 26.4 with optimal estimated at 26.3 Pardue (1983)

- 12 - 30 egg survival broad range (Kellogg, 1982).

- hatching success ceases entirely above 29.7°C Kellogg (1982); Pardue (1983)

- Moreover, temperature can reduce the suitability of nursery areas by influencing predation rates (Tommasi 2015).

- Chowan River was the only system in which June maximum air temperature reached values above both the temperature of maximum alewife larval growth rate (29.1 °C) and their upper thermal tolerance (31 °C) (Kellogg 1982)

- peak densities were positively associated with peaks in water temperature (within the range of 4-19 C) (O'Connell & Angermeier, 1999).

- lower temperatures and peaks in river flow negatively impacted early life stages (O'Connell & Angermeier, 1999)

- The two highest peaks of alewife egg 'b' densities occurred at temperatures within optimal and suitable ranges (O'Connell & Angermeier, 1999) (16-21°C and 11-28"C, respectively, Klauda et al. 1991)

- A metric of the optimal hatching temperature for alewife larvae was defined as 16°C, as used by Edsall (1970).

- maximum hatching success occurred at 12.7 and 15.0, 20.8 C, fell significantly 26.7-26.8 C, and no hatch occurred at 29.7 C (Kellogg, 1982).

- 31 degrees larvae mortality (Kellogg, 1982).

- Edsall (1970) Eggs hatched at test temperatures between 7 and 29.5 *C.

- larval health decreases at 26.5 C (Mullen et al., 1986)

- 11.48C to 23.08C, 10.98C to 20.88C (walsh 2005)

- Larvae were not found in the canal oroxbow until late April and were never abundantat water temperatures below 14 C (walsh 2005).

4.2.3.2 Depth

- In general, alewife larvae were uniformly distributed in the nearshore at Chaumont and Irondequoit in 1998 out to the 15-m contour captured in waters < 5 m deep (Klumb et al., 2003)

Lake Ontario research by Ingel (2013) 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. These shallow-water habitats provide protection from predators and access to food sources, eventually facilitating growth and development into a juvenile.

- < 2 m Pardue (1983)
- very few larvae were found at sampling locations shallower than 0.5 m (Ingel, 2013).
- In Lake Ontario, early post-hatch larvae were most abundant in shallow areas less than 3m in depth, with larger larvae progressively occupying deeper habitat (Dunstall 1984).
- Larval Alosa in Nova Scotian fmgs rivers inhabite-i-waters that were relatively shallow (<2 m) (Mullen et al., 1986)

4.2.3.3 Salinity

- < 12 ppt Pardue (1983)
- After hatching, the larvae and small juveniles use freshwater streams (Kosa and Mather 2001; tommasi 2015)
- highly tolerant of salinity changes (Mullen et al., 1986)
- Alewives:

The highest mean survival rate for Alewives is observed at 15‰ salinity (76.0%). As salinity increases to 20‰ and 30‰, the mean survival rates for Alewives decrease (69.3% and 64.7%, respectively). This pattern suggests that Alewives may exhibit a preference for lower salinity conditions, as indicated by their higher survival rates at 15‰ compared to higher salinities. (DiMaggio et al., 2015)

- Pacific herring eggs are tolerant to salinities in the range of 3-33% (Haegele & Schweigert, 1985).
- Alewife embryo survival following acute transfer to low salinities (2, 5, and 10 g/L) was significantly greater (> 97%) than at 15–30 g/L ($P < 0.0001$, Fig. 2a). Alewife embryo survival at 2, 5, 10, 15, 20, 25, and 30 g/L was 97.6 ± 1.2%, 98.0 ± 0.4%, 98.1 ± 0.4%, 6.2 ± 2.7%, 3.7 ± 0.3%, 2.9 ± 0.6, and 0.7 ± 0.3%, respectively (DiMaggio 2016)
- herring eggs and larvae developing in abundance in sea-water with healthy and active larvae (Ford, 1929)

4.2.3.4 Flow Velocity

- Occurrences of alewife early egg stages were positively related velocity (3-20 cm/s) (O'Connell & Angermeier, 1999)
- Rapid decline in larvae associated with high flows (O'Connell & Angermeier, 1999)
- Data from the Delaware River show that too high flows may also be detrimental to juvenile recruitment. High flow increases water velocity and may create high velocity barriers that reduce the swimming performance of anadromous fish (Haro et al. 2004).
- Larval alewives were consistently found in water velocities up to 12 cm/sec, but not in faster currents (Ingel, 2013).
- alewife distribution is not primarily influenced by overall tidal fluctuations or the highest speeds of water flow but rather by more localized and instantaneous changes in velocity, Larvae are not solely distributed in pockets of constant low-velocity habitat (Ingel, 2013).
- Previous optimal velocities for larvae and egg development were observed from 0 to 0.3 m/s (Pardue 1983).

4.2.3.5 Substrate

- thought to provide spawning and nursery habitat for anadromous and resident fishes (Miller et al 2006); however, in the case of alewives, larval catch was inversely related to vegetation density. larvae were most frequently found in areas with less than 10 percent vegetation density and were never found in areas where vegetation density exceeded 30 percent (Ingel, 2013).
- Anderson and Schmidt (1989) found that alewife larvae were a dominant fish species prior to the development of dense water-chestnut cover, but no longer inhabited these areas after the establishment of this invasive plant, while larval minnows and killifish persisted in the dense beds. Schmidt and Kiviat (1988) caught small numbers of larval alewife in water-chestnut and water celery beds compared to minnows and killifish larvae.

4.3 Habitat suitability models

The Alewives Habitat Suitability models, originally developed by Brown et al. (2000) and Pardue (1983), with reliance on similar sources such as H. B. Bigelow and Schroeder (1953), 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 (Janssen 1978; Janssen and Brandt 1980; McCartin et al. 2019). Collette and Klein-MacPhee (2003) 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 (McCartin et al. 2019; Stevens, Saunders, and Duffy 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 (DiMaggio et al. 2015). 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.

Parameter	Range	**Habitat Suitability Value**
A. Temperature (°C)	$0 < t < 8$	0.0
	$8 <= t < 12$	0.5
	$12 <= t < 16$	1.0
	$16 <= t < 22$	1.0
	$22 <= t < 27$	0.5
	$27 <= t < 30$	0.1
	$t > 30$	0.0
B. Depth (*meters*)	$MLT < d < 2$	0.0
	$2 <= d < 10$	0.5
	$10 <= d < 20$	1.0
	$20 <= d < 50$	0.5
	$50 <= d < 100$	0.5
	$d > 100$	0.5
C. Salinity (*psu*)	$0 < s < 0.5$	1.0
	$0.5 <= s < 5.0$	1.0
	$5.0 <= s < 15.0$	1.0
	$15.0 <= s < 20.0$	0.5
	$s > 20$	0.0
D. Flow Velocity (m/s)	$0 < v < 0.3$	1.0
	$0.3 <= v < 1.5$	1.0
	$1.5 <= v < 3.5$	0.5
	$3.5 <= v < 4.5$	0.3
	$4.5 <= v < 5$	0.1
	$v > 5$	0.0
E. Substrate	Hard Substrate	0.5
	Soft Substrate	1.0
	Present SAV	1.0
	Absent SAV	0.5

Table 1. Model Parameters and Habitat Suitability Values for Spawning Adult Alewives

4.3.1.1 Temperature

- Alewives begin spawning at temperatures of 10.5 °C (Cianci 1969).
- Upstream migration is reported to begin at temperatures between $5 \circ C$ and $10 \circ C$ (Loesch 1987), little instream movement occurs below $8 \circ C$ or over $18 \circ C$ (Collette and KleinMacPhee 2002), and spawning ceases at water temperatures exceeding $27 \circ C$ (Kissil 1974).
- Appropriate spawning temperatures broadly fall between $10 \circ C$ and $22 \circ C$ (Tyus 1974; Pardue 1983; Collette and Klein-MacPhee 2002)

- fish tagged when temperatures were 10.29–22.31 $\circ$ C (O'Connell & Angermeier, 1997)
- temps measured before the spawning run around 6 C and temps measured during the spawning run 12.8 C-14 C (Durbin et al., 1979).
- spawning begins at 10.5 C (Mullen et al., 1986)
- Alewives begin spawning when water temperatures reach 10.56 C (Reback et al., 2004).
- Both species cease spawning when the water warms to 26.11 C (Reback et al., 2004).

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 (Brown et al. 2000). Suitable spawning temperatures broadly span from 12 to 22 degrees Celsius (Tyus 1974; Pardue 1983; Collette and Klein-MacPhee 2003; Mather et al. 2012) 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 (Kissil 1974; Pardue 1983; Brown et al. 2000). 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 (Legett et al. 2021).

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.

4.3.1.2 Depth

- 0.15–3 m Pardue (1983)
- spawning habitat were all 0.5m or less (Kosa & Mather, 2001)
- Species of herring from the same cluepid family have been known to spawn majority 0.5-5m and up to 15 m (Haegele & Schweigert, 1985).

In terms of depth preferences, spawning adult alewives are generally known to favor depths ranging from Mean Low Tide (MLT) to 10 meters (Brown et al. 2000), but recent field observations indicate that a significant proportion of alewives can be found in habitats as shallow as 2 meters (Mather et al. 2012). Offshore alewives migrating inland have been documented to favor deeper depths (depth $<$ 100m) (Pardue 1983; Munroe 2000).

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.

4.3.1.3 Salinity

Further, documented behavior of alewives challenges the conventional belief that anadromous species exclusively depend on freshwater environments for spawning. Alewives have been widely observed spawning in freshwater tidal habitats with minimal salinity concentrations, revealing a habitat use in environments with salinity levels below 0.5 psu (Pardue 1983). However, they can tolerate salinity levels as high as 8 psu for successful spawning, as documented in the study conducted by Able et al. (2020). More recently, Brown et al. (2000) 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 estuary 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 (Pardue 1983; Mullen, Fay, and Moring 1986; Collette and Klein-MacPhee 2003; Walsh, Settle, and Peters 2005). Species of herring from the same cluepid family have been known to spawn in a range of salinities from freshwater to 35+ psus (Haegele & Schweigert, 1985).

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 (20 psu) where suitability declines significantly, indicating the importance of maintaining lower salinity levels in suitable habitats.

4.3.1.4 Flow Velocity

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.

4.3.1.5 Substrate

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 Non-Migratory Juveniles

Table 4.2: **Table 2.** Model Parameters and Habitat Suitability Values for Non-Migratory Juvenile Alewives

Parameter	Range	**Habitat Suitability Value**
A. Temperature (°C)	$0 < t < 8$	0.0
	$8 <= t < 12$	0.5
	$12 <= t < 16$	1.0
	$16 <= t < 22$	1.0
	$22 <= t < 27$	0.5
	$27 <= t < 30$	0.1
	$t > 30$	0.0
B. Depth (*meters*)	$MLT < d < 2$	0.0
	$2 <= d < 10$	0.5
	$10 <= d < 20$	1.0
	$20 <= d < 50$	0.5
	$50 <= d < 100$	0.5
	$d > 100$	0.5
C. Salinity (*psu*)	$0 < s < 0.5$	1.0
	$0.5 <= s < 5.0$	1.0
	$5.0 <= s < 15.0$	1.0
	$15.0 <= s < 20.0$	0.5
	$s > 20$	0.0
D. Flow Velocity (*m/s*)	$0 < v < 0.3$	1.0
	$0.3 <= v < 1.5$	1.0
	$1.5 <= v < 3.5$	0.5
	$3.5 <= v < 4.5$	0.3
	$v > 5$	0.0

Parameter	Range	**Habitat Suitability Value**
E. Substrate	Hard Substrate	0.5
	Soft Substrate	1.0
	Present SAV	1.0
	Absent SAV	0.5

4.3.2.1 Temperature

4.3.2.2 Depth

4.3.2.3 Salinity

4.3.2.4 Flow Velocity

4.3.2.5 Substrate

4.3.3 Eggs & Larvae

Table 4.3: **Table 3.** Model Parameters and Habitat Suitability Values for Alewife Larvae and Egg Development Stages

Parameter	Range	**Habitat Suitability Value**
A. Temperature (°C)	$0 < t < 8$	0.0
	$8 <= t < 12$	0.5
	$12 <= t < 16$	1.0
	$16 <= t < 22$	1.0
	$22 <= t < 27$	0.5
	$27 <= t < 30$	0.1
	$t > 30$	0.0
B. Depth (*meters*)	$MLT < d < 2$	0.0
	$2 <= d < 10$	0.5
	$10 <= d < 20$	1.0
	$20 <= d < 50$	0.5
	$50 <= d < 100$	0.5
	$d > 100$	0.5
C. Salinity (*psu*)	$0 < s < 0.5$	1.0
	$0.5 <= s < 5.0$	1.0
	$5.0 <= s < 15.0$	1.0
	$15.0 <= s < 20.0$	0.5
	$s > 20$	0.0

Parameter	Range	**Habitat Suitability Value**
D. Flow Velocity (m/s)	$0 < v < 0.3$	1.0
	$0.3 <= v < 1.5$	1.0
	$1.5 <= v < 3.5$	0.5
	$3.5 <= v < 4.5$	0.3
	$v > 5$	0.0
E. Substrate	Hard Substrate	0.5
	Soft Substrate	1.0
	Present SAV	1.0
	Absent SAV	0.5

4.3.3.1 Temperature

4.3.3.2 Depth

4.3.3.3 Salinity

4.3.3.4 Flow Velocity

4.3.3.5 Substrate

Chapter 5

Blueback Herring (*Alosa aestivalis*)

This chapter aims to explore the habitat preferences and life cycle of blueback herring (*Alosa aestivalis*) in the northeastern United States. Blueback herring have faced significant declines,

This chapter explores the favorable habitat conditions for spawning blueback adults, non-migratory juveniles, as well as eggs and larvae, which are influenced by factors such as suitable spawning habitats, water quality conditions, and availability of appropriate food resources (Lynch et al. 2015).

blueback herring spawn in higher salinity, faster-moving waters in the lower river (Turner & Limburg, 2016)

5.1 Life cycle overview

- Alewives enter the river first, followed by blueback herring 2-3 weeks later (Jessop 2003).
- juveniles may take longer to move into brackish waters (Schmidt et al. 1988).
- Blueback larvae demonstrate the ability to adapt to marine environments by 58 days post-hatch (DiMaggio et al., 2015).

5.2 Habitat Requirements

5.2.1 Spawning Adults

5.2.1.1 Temperature

- move into estuary begins at 14 and ceases at 27 Pardue (1983)
- 16 - 16 klauda et al 1991
- Our results indicate that blueback herring adults require temperatures of at least 16.8”C to spawn. (O’Connell & Angermeier, 1999)
- range 17 - 26 and optimal 20 - 24 Pardue (1983)
- spawning stops at 27 Pardue (1983)
- Our results demonstrate that the spawning temperature that maximized juvenile blueback herring abundance in the Delaware River was 11 °C (tommasi 2015)
- spawning begins at 14 C (Mullen et al., 1986)
- Alewives begin spawning when water temperatures reach 51 and bluebacks 57 degrees F (Reback et al., 2004).
- Both species cease spawning when the water warms to 81°F (Reback et al., 2004).

5.2.1.2 Depth

- 0.15–3 m Pardue (1983)
- spawning habitat were all 0.5 m or less (Kosa & Mather, 2001)
- Species of herring from the same cluepid family have been known to spawn majority 0.5-5m and up to 15 m (Haegele & Schweigert, 1985).

5.2.1.3 Salinity

- spawning begins then or shortly thereafter. Although this species apparently spawns primarily in fresh water, spawning also occurs in brackish ponds at Woods Hole (Nichols and Breder, 1926; Hildebrand, 1963).
- I found that the chief spawning grounds in the Delaware River were in tidal water (Chittenden, 1972)
- Species of herring from the same cluepid family have been known to spawn in a range of salinities from freshwater to 35+ psus (Haegele & Schweigert, 1985).

- Alewives have been widely observed spawning in freshwater tidal habitats with minimal salinity concentrations, revealing a habitat use in environments with salinity levels below 0.5 psu (Pardue 1983).

- Blueback herring in Winnegance Lake and Patten Pond show a preference for high salinity environments for spawning, indicated by their limited residency time in freshwater. The immediate transition of fish from Winnegance Lake to the estuary after spawning suggests a preference for high salinity spawning, with the estuarine environment supporting early egg and larvae development (Payne Wynne et al., 2015).

5.2.1.4 Flow Velocity

- blueback herring show a preferance for higher velocities than alewives (haro 2004)
- Low velocities (0.0–1.7 m/s) (Walsh et al 2005)
- 0.11 m/s (O'Connell & Angermeier, 1997)
- blueback tend to favor running water and a fairly clean hard bottom, Bourne 1990
- Both species spawn primarily in habitats with little or no current Walsh 2005

5.2.1.5 Substrate

- Blueback herring do not usually spawn as far upstream as the alewife and selectively choose spawning sites in fast-flowing water over a hard substrate, particularly in shared spawning grounds (Loesch and Lund 1977; Jones et al. 1978; Scott and Scott 1988).

- blueback tend to favor running water and a fairly clean hard bottom, bourne 1990

- prefer hard substrate (Loesch and Lund 1977)

5.2.2 Non-Migratory Juveniles

5.2.2.1 Temperature

- supported in observations where Eel River had a mean temperature of 23.1°C, while the Herring River (Bourne) had temperatures with a mean of 25.1°C (Ames & Lichter, 2013).

5.2.2.2 Depth

- Juvenile Blueback herring in Potomac River, Virginia abundant in 4.6 m(Mullen et al., 1986)

5.2.2.3 Salinity

Bluebacks:

Bluebacks exhibit high survival rates when transferred between certain salinities, particularly from 3‰, 15‰, and 30‰ into 3‰ salinity. The high survival rates indicate that Bluebacks are well-adapted and can thrive under a range of salinity conditions within the specified experimental scenarios. While the information does not explicitly state a preference for specific salinities, the high survival rates suggest that Bluebacks may have a relatively broad salinity tolerance in the studied range.(DiMaggio et al., 2015)

- blueback herring is highly salinity tolerant early in life (28 psu) (Chittenden, 1972)
- herring eggs and larvae developing in abundance in sea-water with healthy and active larvae (Ford, 1929)

5.2.2.4 Flow Velocity

- Previous optimal velocities for larvae and egg development were observed from 0 to 0.3 m/s (Pardue 1983).

5.2.2.5 Substrate

- blueback tend to favor running water and a fairly clean hard bottom, bourne 1990

5.2.3 Eggs and Larvae

5.2.3.1 Temperature

- blueback herring early egg stages were positively related to water temperature (14-22°C). (O'Connell & Angermeier, 1999)
- Blueback herring eggs have been found in water temperatures ranging from 7 to 14°C in the upper Chesapeake Bay, with most being collected at 14°C (Dove1 1971).

- Temperatures observed in our study were always below those known to impair hatching success (32.9 to 36.1°C) or cause larval deformities (34°C). (O'Connell & Angermeier, 1999)
- eggs recorded at 20-24 C (Mullen et al., 1986)
- 19 C 0-5% deformities, 20 0-24% deformities, Complete larval deformities in eggs exposed to 34 C (Koo and Johnston 1978)
- 11.48C to 23.08C, 10.98C to 20.88C walsh 2005
- Larvae were not found in the canal oroxbow until late April and were never abundantat water temperatures below 148C (walsh 2005).
- peak densities were positively associated with peaks in water temperature (within the range of 4-19 C) (O'Connell & Angermeier, 1999).

5.2.3.2 Depth

- In Lake Ontario, early post-hatch larvae were most abundant in shallow areas less than 3m in depth, with larger larvae progressively occupying deeper habitat (Dunstall 1984).
- Larval Alosa in Nova Scotian fmgs rivers inhabite-i-waters that were relatively shallow (<2 m) (Mullen et al., 1986)

5.2.3.3 Salinity

- Bluebacks:

The mean survival rates for Bluebacks consistently increase with higher salinities. The highest mean survival rate for Bluebacks is observed at 30‰ salinity (95.3%). This pattern indicates that Bluebacks may exhibit a preference for higher salinity conditions, as indicated by their higher survival rates at 30‰ compared to lower salinities. (DiMaggio et al., 2015)

- highly tolerant of salinity changes (Mullen et al., 1986)
- Pacific herring eggs are tolerant to salinities in the range of 3-33% (Haegele & Schweigert, 1985).
- blueback herring embryos displayed a wide salinity tolerance throughout the range. Embryos of both species exhibited high survival in tidal salinity exposures. Survival of acutely-transferred alewife and blueback herring larvae decreased with increasing salinity (>20 g/L)(DiMaggio et al., 2016).

5.2.3.4 Flow Velocity

- lower temperatures and peaks in river flow negatively impacted early life stages (O'Connell & Angermeier, 1999)

5.2.3.5 Substrate

- thought to provide spawning and nursery habitat for anadromous and resident fishes (Miller et al 2006); however, in the case of alewives, larval catch was inversely related to vegetation density. larvae were most frequently found in areas with less than 10 percent vegetation density and were never found in areas where vegetation density exceeded 30 percent (Ingel, 2013).

5.3 Habitat suitability models

5.3.1 Spawning Adults

Table 5.1: **Table 1.** Model Parameters and Habitat Suitability Values for Spawning Adult Blueback Herring.

Parameter	Range	**Habitat Suitability Value**
A. Temperature (°C)	$0 < t < 8$	0.0
	$8 <= t < 12$	0.5
	$12 <= t < 16$	1.0
	$16 <= t < 22$	1.0
	$22 <= t < 27$	0.5
	$27 <= t < 30$	0.1
	$t > 30$	0.0
B. Depth (*meters*)	$MLT < d < 2$	0.0
	$2 <= d < 10$	0.5
	$10 <= d < 20$	1.0
	$20 <= d < 50$	0.5
	$50 <= d < 100$	0.5
	$d > 100$	0.5
C. Salinity (*psu*)	$0 < s < 0.5$	1.0
	$0.5 <= s < 5.0$	1.0
	$5.0 <= s < 15.0$	1.0
	$15.0 <= s < 20.0$	0.5
	$s > 20$	0.0
D. Flow Velocity (*m/s*)	$0 < v < 0.3$	1.0
	$0.3 <= v < 1.5$	1.0
	$1.5 <= v < 3.5$	0.5
	$3.5 <= v < 4.5$	0.3
	$v > 5$	0.0

Parameter	Range	**Habitat Suitability Value**
E. Substrate	Hard Substrate	0.5
	Soft Substrate	1.0
	Present SAV	1.0
	Absent SAV	0.5

5.3.1.1 Temperature

5.3.1.2 Depth

5.3.1.3 Salinity

5.3.1.4 Flow Velocity

5.3.1.5 Substrate

5.3.2 Non-Migratory Juveniles

Table 5.2: **Table 2.** Model Parameters and Habitat Suitability Values for Non-Migratory Juvenile Blueback Herring.

Parameter	Range	**Habitat Suitability Value**
A. Temperature (°C)	$0 < t < 8$	0.0
	$8 <= t < 12$	0.5
	$12 <= t < 16$	1.0
	$16 <= t < 22$	1.0
	$22 <= t < 27$	0.5
	$27 <= t < 30$	0.1
	$t > 30$	0.0
B. Depth (*meters*)	$MLT < d < 2$	0.0
	$2 <= d < 10$	0.5
	$10 <= d < 20$	1.0
	$20 <= d < 50$	0.5
	$50 <= d < 100$	0.5
	$d > 100$	0.5
C. Salinity (*psu*)	$0 < s < 0.5$	1.0
	$0.5 <= s < 5.0$	1.0
	$5.0 <= s < 15.0$	1.0
	$15.0 <= s < 20.0$	0.5
	$s > 20$	0.0

Parameter	Range	**Habitat Suitability Value**
D. Flow Velocity (m/s)	$0 < v < 0.3$	1.0
	$0.3 <= v < 1.5$	1.0
	$1.5 <= v < 3.5$	0.5
	$3.5 <= v < 4.5$	0.3
	$v > 5$	0.0
E. Substrate	Hard Substrate	0.5
	Soft Substrate	1.0
	Present SAV	1.0
	Absent SAV	0.5

5.3.2.1 Temperature

5.3.2.2 Depth

5.3.2.3 Salinity

5.3.2.4 Flow Velocity

5.3.2.5 Substrate

Previous studies have presented conflicting information regarding the substrate preferences of spawning adult blueback herring, likely stemming from the generalization of alewives with blueback herring as river herring. Adult blueback herring spawn over both soft and hard substrates (Pardue 1983; O'Connell and Angermeier 1997; Brown et al. 2000).

Aside from their demonstrated dependence on soft substrates, spawning adult alewives also exhibit a pronounced inclination toward habitats containing subaquatic vegetation (Killgore, Morgan, and Hurley 1988; Laney 1997). Comprehending and defining these substrate preferences is crucial to effectively manage and conserve the appropriate spawning habitats for alewives.

5.3.3 Larvae

Table 5.3: **Table 3.** Model Parameters and Habitat Suitability Values for Blueback Herring Larvae Stage.

Parameter	Range	**Habitat Suitability Value**
A. Temperature (°C)	$0 < t < 8$	0.0
	$8 <= t < 12$	0.5
	$12 <= t < 16$	1.0
	$16 <= t < 22$	1.0
	$22 <= t < 27$	0.5
	$27 <= t < 30$	0.1
	$t > 30$	0.0
B. Depth ($meters$)	$MLT < d < 2$	0.0
	$2 <= d < 10$	0.5
	$10 <= d < 20$	1.0
	$20 <= d < 50$	0.5
	$50 <= d < 100$	0.5
	$d > 100$	0.5
C. Salinity (psu)	$0 < s < 0.5$	1.0
	$0.5 <= s < 5.0$	1.0
	$5.0 <= s < 15.0$	1.0
	$15.0 <= s < 20.0$	0.5
	$s > 20$	0.0
D. Flow Velocity (m/s)	$0 < v < 0.3$	1.0
	$0.3 <= v < 1.5$	1.0
	$1.5 <= v < 3.5$	0.5
	$3.5 <= v < 4.5$	0.3
	$v > 5$	0.0
E. Substrate	Hard Substrate	0.5
	Soft Substrate	1.0
	Present SAV	1.0
	Absent SAV	0.5

5.3.3.1 Temperature

5.3.3.2 Depth

5.3.3.3 Salinity

5.3.3.4 Flow Velocity

5.3.3.5 Substrate

Chapter 6

Application

example of application to martha's vineyard

6.1 Study Area

We do not know right now the precise places where the herring spawn within Squibnocket and its tributary brooks and pond and salinity conditions where spawning occurs. spawn successfully in the slightly brackish water at the west end of the Pond (or elsewhere within it), or whether they manage to work their way up little tributaries. Bourne 1990.

6.2 Input Data

6.3 Pre-Processing

6.4 Post-Processing

6.5 Results

6.5.1 Spawning Adults

- Alewives
- Blueback Herring

6.5.2 Non-Migratory Juveniles

- Alewives
- Blueback Herring

6.5.3 Eggs and Larvae

- Alewives
- Blueback Herring

Chapter 7

Validation

Future tagging data??

Chapter 8

Discussion

- Utility
  - management
  - what do the results tell us
- Limitations
  - regional
  - accuracy based on current knowledge
  - prediction power
- Compare to similar models (Pardue & Brown)

other factors impacting habitat health - nitrogen - dissolved oxygen - PH levels "Blueback eggs and larvae to pulses of acidified water (pH 5.5 to 5.6) was reported to increase their mortality rate substantially (Klauda, 1987; see also Byrne, 1988). The pH of many Cape and Island soils is roughly in tnis range, and the ability of these soils to neutralize additional acidic inputs is limited. Bourne 1990)

Chapter 9

Summary

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Appendices

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