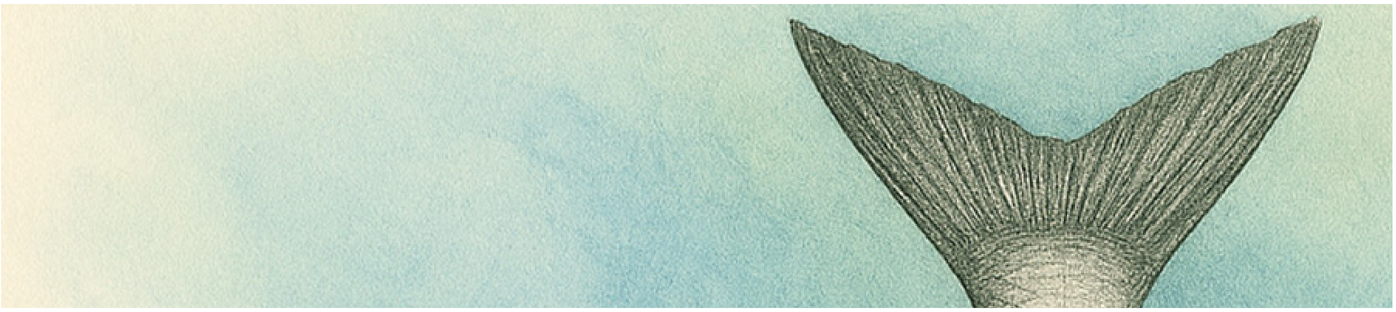

Life History, Population Status, and Restoration of American Shad and River Herring in the Delaware River Basin

2025

Partnership for the DELAWARE ESTUARY

DELAWARE ESTUARY PROGRAM'S
SCIENCE & TECHNICAL ADVISORY COMMITTEE

WHITE PAPER

Life History, Population Status, and Restoration of American Shad and River Herring in the Delaware River Basin

Compiled for the Delaware Estuary Program's Science and Technical Advisory Committee

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Executive Summary

American Shad (*Alosa sapidissima*), Alewife (*A. pseudoharengus*), and Blueback Herring (*A. aestivalis*) are migratory fish species that were historically abundant throughout the Delaware River Basin; however, populations of all three have experienced significant declines. American Shad and river herring—a collective term encompassing both Alewife and Blueback Herring—are anadromous species that spawn in the freshwater but spend a majority of their lives in the ocean, undertaking seasonal migrations along the Atlantic Coast. These fish return to their natal rivers to spawn, with adults entering the Delaware Bay from the Atlantic Ocean in the late winter. While in the Delaware River Basin, American Shad and river herring contribute vital ecosystem services, facilitating nutrient exchange between marine and freshwater systems, functioning as both predators and prey, serving as a host fish to freshwater mussel species, and historically providing an essential food source for humans.

Spawning typically occurs in the main stem and tributaries from late March through mid-June. Alewife generally spawn two to three weeks earlier than Blueback Herring and American Shad, with the timing of spawning for all species closely regulated by water temperature. After spawning, adults can return to the ocean, though some die after spawning. Juveniles of all three species remain in freshwater through the summer and begin their migration to the ocean in late summer through fall. The historic spawning range for American Shad and river herring was from Gloucester, New Jersey to over 500km inland to the headwaters of the Delaware River.

American Shad and river herring populations are now depleted in the Delaware River Basin, but the Basin once supported the largest harvest of American Shad on the Atlantic Coast from 1896 to 1901, where more than 3 million fish were harvested annually. Abundance declined rapidly in the following decades, and by the 1970s, the entire spawning population was estimated to range from 100,000 to 500,000 fish. Since the 1980s, populations have remained low, and recent assessments have determined that the level of mortality currently occurring in the population is too high to sustain current population levels. Annual surveys of adult and juvenile abundance reveal considerable variability. While adult American Shad spawning indices are at all-time lows, juvenile production in the non-tidal river has reached some of the highest levels recorded over the past three decades in certain recent years. Commercial landings of American Shad have dropped steadily since 1990, with less than 1,000 pounds being landed each year since 2020. Less is known about river herring abundance in the Delaware River Basin, though populations are assumed to be at, or near, historic lows. There is no commercial fishing permitted in the Delaware River Basin for river herring.

The depletion of the American Shad and river herring populations are likely due to historic overfishing, habitat fragmentation and loss of access caused by damming of tributaries, and low dissolved oxygen levels in the estuary that precluded safe upstream and downstream migration of American Shad and river herring for part of the year over many decades. For the most part, the factors that once severely reduced populations have now been largely mitigated. Currently, the commercial and recreational fisheries for American Shad and river herring are closely managed by state agencies. Significant improvements to water quality have occurred in the estuary since the 1940s, to the point where American Shad are being observed in the estuary in higher abundance than they have in the past century. Dam removals and fish passage facilities in Delaware River tributaries are increasing access to historic spawning and nursery habitats.

Several factors continue to influence American Shad and river herring populations, including predation, particularly by non-native and invasive species. Water quality in the Delaware Estuary, particularly dissolved oxygen levels, continues to improve; however, water quality remains threatened by ongoing land development within the Basin and by emerging contaminants whose impacts on fish populations are not yet fully understood. The Delaware River estuary serves as a vital industrial port, supporting extensive in-water activities such as dredging and underwater construction to maintain navigation and transportation infrastructure. Additionally, substantial volumes of river water are withdrawn for use as cooling water by thermoelectric power plants. These water intake systems pose a significant risk to fish, which may become impinged or entrained, with survival rates typically low. Changes in seasonal water temperatures and ocean currents can also have an impact on fish energetics and reproductive success, with potential negative impacts to American Shad and river herring populations in the Delaware River. Moving forward, the impacts of these ongoing stressors on American Shad and river herring populations should be systematically assessed and, where feasible, mitigated to support the restoration of these ecologically and culturally significant species.

1. Life History and Migration Patterns

1.1 Overview

American Shad (*Alosa sapidissima*), Alewife (*A. pseudoharengus*), and Blueback Herring (*A. aestivalis*) are migratory fish of the family Clupeidae. River herring is a term that collectively refers to both Alewife and Blueback Herring. All three species are anadromous, meaning they spawn in freshwater but spend most of their life in salt water. All species are highly migratory but generally return to natal rivers to spawn. American Shad and river herring were historically abundant and are an important forage fish in the ecosystems they inhabit.

1.2 Geographic Range

The geographic range for American Shad extends on the Atlantic Coast from the St. Lawrence River in Canada to the St. Johns River, Florida (Limburg et al. 2003). American Shad have also been introduced to the north Pacific Coast where they are considered an invasive species. Historically, American Shad likely spawned in nearly 140 river systems on the Atlantic Coast, but currently only reproduce in 68 rivers, which is about half of their historic distribution (Limburg et al. 2003). American Shad typically spawned up to the first natural barrier, which could be hundreds of kilometers upstream (Limburg et al. 2003).

For river herring, Alewife have a more northerly distribution than Blueback Herring, though there is much geographic overlap between the species. Alewife range on the Atlantic Coast from the Gulf of St. Lawrence and northern Nova Scotia to North Carolina while Blueback Herring range from Nova Scotia to the St. Johns River, Florida (ASMFC 2024). There are many introduced, landlocked populations of both Alewife and Blueback Herring, though Alewife are more common and notably occur throughout the Great Lakes.

Specific geographic distribution of these species in the Delaware River Basin is described in Section 3.

1.3 Physical Characteristics

All three species possess silvery, elongated bodies that are distinctly laterally compressed and feature a deeply forked tail. They also have ventral scutes which form a sharp ridge on the belly. Alewives are sometimes referred to as sawbelly because of these scutes. Mature females are larger than the males in all species.

American Shad are larger than river herring. Adults can be up to 760 mm and weigh 5.5 kg with a maximum age of 13 years. Male shad are generally between 300 and 500 mm and seldom exceed 2 kg, while females are generally between 410 and 590 mm and rarely exceed 3.6 kg. Shad typically take 3-6 years to reach sexual maturity, and males mature at a younger age than females (Miller et al. 1982, Brown et al. 2024). Spawning American Shad in the Delaware River range from 3 to 9 years old with lengths ranging from 300 to 625 mm (DRBFWMC, unpublished data). American Shad typically exhibit a horizontal row of 4-6 black spots behind the operculum (MacKenzie et al. 1985). In the Delaware River during the 1960s to 1970s, male American Shad were predominantly 4 to 5 years old, while females were typically 4 to 6 years old, with few repeat spawners (Miller et al. 1982). The age range or level of repeat spawning of American Shad in the Delaware River has not changed in recent decades. An electrofishing survey conducted between 2009 and 2013, spanning from Port Jervis, New York to Hancock, New York found that most American Shad were between 4 and 6 years old, with repeat spawning observed in only 1% of the individuals examined (Mohler and Sweka 2013). Similarly, from 1996 to 2023, the mean age of spawning shad at Smithfield Beach, Pennsylvania was between 5 and 6 years old (Pennsylvania Fish and Boat Commission, unpublished data).

Alewife and Blueback Herring are more similar in size and appearance, and difficult to distinguish from one another without close examination. The primary methods to distinguish the two species are eye diameter, body depth, and peritoneum color. The Alewife eye is generally larger, the depth of the body deeper, and the peritoneum is pale colored compared to the dark color of the Blueback Herring peritoneum (Loesch 1987). Both species are silver with greenish (Alewife) or bluish (Blueback Herring) backs and a dark shoulder spot (Fay et al. 1983). Alewife and Blueback Herring are typically similar in size, but females of both species are typically slightly larger than males. For Alewife, females average 285 mm and males average 272 mm and Blueback Herring females average 289 mm and males 277 mm (Brown et al. 2024). In Delaware tributaries, the average length of Alewife varied by year from 2017-2023 and ranged from 239 to 292 mm for females and 208 to 274 mm for males (Conroy 2024). In the same survey, Blueback Herring females averaged 242 to 272 mm and males averaged 228 to 257 mm. Coast-wide, females are generally older than males in both species with males typically aged 3 to 5 years and females aged 4 to 8 years old (Fay et al. 1983, Loesch 1987).

Fecundity of all species is variable and related to both size and age (Loesch 1987). American Shad are batch spawners, spawning repeatedly during the season as they migrate upriver (ASMFC 2020). American Shad fecundity can range from 100,000 to 600,000 eggs, though most females average 250,000 eggs (Miller et al. 1982, Limburg et al. 2003). Fecundity is similar between river herring species, in which Alewife have 100,000 to 467,000 and Blueback Herring have 33,000 to 400,000 eggs per female (Loesch 1987).

1.4 Life Cycle

All three species spend most of their lives migrating in large schools in the coastal waters of North America. All species join mixed-stock, single or multiple species feeding schools that occupy different areas seasonally. American Shad may migrate 20,000 km in their lifetime and follow isotherms during their coastal movements. American Shad from the Delaware River Basin mix with other coastal river stocks that travel to the feeding grounds in the Bay of Fundy in the summer, later congregating off the Middle Atlantic Bight in winter (Dadswell et al. 1987, Limburg et al. 2003). River herring also form mixed-stock feeding schools that have seasonal offshore migration patterns similar to American Shad where they summer in the north and winter in the south (Brown et al. 2024).

Diets of American Shad and river herring in the ocean primarily consist of zooplankton. American Shad at sea mainly consume copepods and mysids as well as some small fish (Brown et al. 2024). River herring are generally filter feeders, feeding primarily on zooplankton, though larger fish may have a more diverse diet (Brown et al. 2024).

As American Shad mature and prepare for spawning, they travel closer to the coastline before they enter their natal freshwater tributaries for spawning after spending 3-6 years at sea (Dadswell et al. 1987, Limburg et al. 2003). American Shad generally return to their natal rivers, but a low level of straying does occur (Hendricks et al. 2002, Limburg et al. 2003, ASMFC 2020). River herring also return to their natal rivers, though straying to adjacent rivers is somewhat common (Fay et al. 1983, ASMFC 2024), allowing for recolonization of stocks in neighboring rivers (Spares et al. 2023, Brown et al. 2024).

Some American Shad from other river stocks on the coast enter the Delaware Bay in the late winter and early spring prior to the spawning season and may stay in the Bay for a period of time before leaving to spawn in their natal rivers. Genetics and tagging data suggest that about half of the American Shad encountered in the commercial gillnet fishery in the Delaware Bay are comprised of Delaware River spawning stock, and most of the non-Delaware stock fish are from the Hudson River spawning stock and a small proportion are from spawning stocks of other coastal rivers (Waldman et al. 2014, Bartron and Prasko 2021, DRBFWMC 2022).

The timing of spawning is temperature dependent for all three species, with spawning occurring earlier in the year in the south and later in the north. In the southern latitudes all species are primarily semelparous, but frequency of iteroparity increases along the coast with increasing latitude (Fay et al. 1983, Limburg et al 2023). For American Shad, spawning begins in January and February in the southern part of its range and into June in the northern part of its range (Limburg et al. 2003). Shad spawn in temperatures ranging from 8°C to 26°C, with peak spawning occurring from 12°C to 21°C (Limburg et al. 2003, Brown et al. 2024). River herring spawning can occur as early as February in the southern part of their range through June in the northern part of the range (Loesch 1987). Alewife tend to spawn two to three weeks earlier than Blueback Herring. Alewife initiate spawning between 5°C and 10°C and Blueback Herring initiate spawning between 10°C and 15°C, with spawning ending for both species at 27°C (Fay et al. 1983).

In the Delaware River, American Shad enter the lower Bay in February to early March when water temperatures are above 4°C. In late March to early April, shad approach the freshwater interface near Wilmington, Delaware and are typically first found in the Trenton, New Jersey area in early April as waters warm to 10°C. Spawning occurs from mid-April to June with heaviest spawning from Easton, Pennsylvania (rkm 296) to the headwaters (Miller et al. 1982). The run peaks from 14°C to 24.5°C in mid-May to the last week of June (DRBFWMC 2022). Shad may spawn lower in the river if river temperatures warm up quickly and are more likely to be found in upriver areas if temperatures stay cooler longer (Miller et al. 1982). In the Schuylkill River, daily counts of shad passage are recorded at the Fairmount Fishway on the Fairmount Dam in Philadelphia, Pennsylvania. From 2004-2006, American Shad passed the fishway from mid-April to late June, and in 2011, the peak passage for upstream migrating adult American Shad occurred from late April to mid-May (Figure 1) (Perillo and Butler 2009, Philadelphia Water Department, unpublished data).

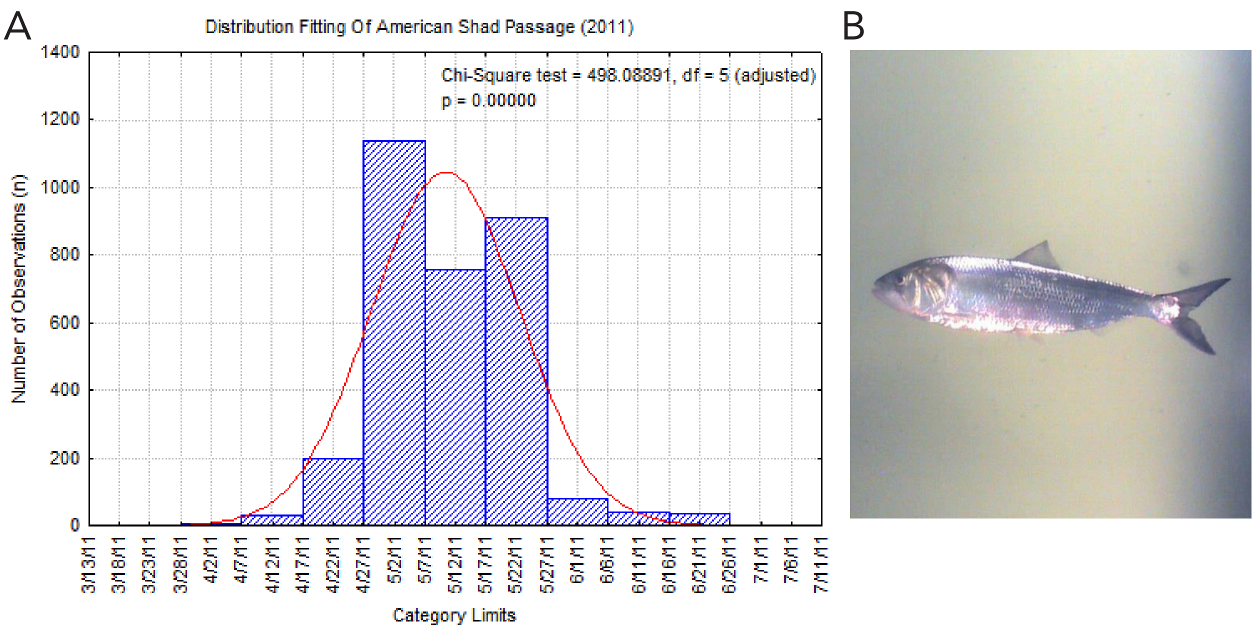

Figure 1. Weekly American Shad passage counts for the Fairmount Fishway in spring 2011 on the Schuylkill River (A), with a photograph of a Shad in the Fairmount Fishway (B). Data and photograph provided by the Philadelphia Water Department.

Alewife and Blueback Herring enter the Delaware River Basin in February and typically have peak spawning in April. Counts at fish ladders in tributaries to the Delaware River and Bay provide insight into the timing and duration of spawning activity in the lower Basin. Delaware Division of Fish and Wildlife annually monitors ten fishways on tributaries to the Delaware River and Bay in Delaware. Alewife pass the fishways from late March to late April and Blueback Herring pass the fishways from mid-April to mid-May. Alewives tend to arrive earlier than Blueback Herring, typically passing 3 to 16 days earlier than

Blueback Herring, which is likely due to the preferred temperature spawning difference between the species (Conroy 2024).

American Shad and river herring are broadcast spawners. Males typically arrive to the spawning area before the females, and females release eggs into the water column near the water surface where they are fertilized by one or more males (ASMFC 2020). American Shad spawning generally occurs after sunset at depths of 1 to 10 meters and over sand and/or gravel substrate (Limburg et al. 2003). In the Delaware River, American Shad show a preference for spawning in runs with current speeds up to 0.7 m/s and avoid spawning in deep slow water (Miller et al. 1982, Ross et al. 1993). Shad spawn at the tail end of runs, in schools with a female being paired up with one or two males on her side(s), and there is a brief splashing near the surface before the fish part (Miller et al. 1982, Ross et al 1993). Spawning typically begins in the evening around 7:00 pm to 8:00 pm with peak activity between 9:00 pm and 1:00 am (Miller et al. 1982, Ross et al. 1993). Spawning typically occurs over a rubble-boulder mixture, but substrate is likely not an important factor since eggs are released into the water column and are semi-buoyant, though if eggs do settle to the river bottom, sand and gravel may improve survival (Ross et al. 1993, ASMFC 2020). Water depth is also likely not an important factor in spawning success, but most spawning in the Delaware River occurs at less than 4m (Ross et al. 1993). American Shad require dissolved oxygen levels of 5 mg/l for reproduction. Dissolved oxygen levels less than 3 mg/L are hazardous and will block migration and levels below 2 mg/L are fatal (Miller et al. 1982).

Similar to American Shad, Blueback Herring prefer spawning in faster moving sections of streams, while Alewife prefer spawning in slower moving sections of streams or in lakes and ponds (Loesch 1987). Blueback Herring are more likely to spawn over sand and gravel while Alewife spawn over sand, gravel, organic detritus and submerged aquatic vegetation (ASMFC 2024).

Adult American Shad and river herring do not feed while in freshwater and become emaciated after spawning and adults generally return to sea shortly after spawning, sometimes feeding as they reach the estuary (Loesch 1987, Limburg et al. 2003). In the upper Delaware River, some post-spawn shad can remain in the river, rather than return to the ocean, and eventually die in the summer.

Eggs for American Shad and river herring are only temporarily adhesive until they water harden, which usually takes less than one day. Eggs may travel in river currents short distances downstream after spawning. Egg development is a function of temperature, with longer incubation times and lower survival at low temperatures (Limburg et al. 2003). For American Shad, optimal egg development temperature is 17°C, but hatching can take 12 days at 10°C compared to 3 days at 24°C, and eggs are not viable when temperatures reach 27°C (Miller et al. 1982). River herring eggs typically hatch within 3 to 4 days (ASMFC 2024).

In the Delaware River, Ross et al. (1993) found American Shad larvae at higher concentrations in riffle-pool habitat than other habitat types. Larvae were present from late April to early July, with water temperatures from 13°C up to 26.5°C. Larvae were found in all but the highest current velocities (>1m/s). Eggs were not found in waters with turbidity higher than 2.7 NTU, and larvae were found only when turbidity was less than 2.1 NTU. Eggs and larvae were found in all habitat types, but higher densities of larvae were found in riffle-pool habitat.

Generally, juveniles of all three species remain in freshwater through the summer and may migrate upstream during their freshwater residency to avoid encroachment of saline waters (ASMFC 2024). Large schools of juvenile American Shad are generally found in deep pools during the day and move into swift flowing waters at night (Miller et al. 1982). Juvenile shad are visual feeders, with food size increasing as fish grow. Younger juveniles feed mostly on zooplankton but switch to macroinvertebrates, insects, and crustaceans through their juvenile stages (Miller et al. 1982, Limburg et al. 2003). Juvenile river herring feed primarily during the day and their diet consists of zooplankton (Loesch 1987).

Juvenile shad begin their downstream migration from the Delaware River Basin in September and October and complete emigration from the river from October to December (Sykes and Lehman 1957, Friedersdorff 1976). The maximum size of remaining juveniles decreases as the summer progresses, suggesting that juveniles begin downstream movement once they reach a certain size, and later migrants are likely the result of later spawning events (Miller et al. 1982). Downstream migration appears to be temperature dependent with juveniles beginning migration at 15.5°C and avoiding waters less than 7°C (Miller et al. 1982). Juvenile shad are essentially gone from the upper river by November but start to show up in the Philadelphia area in late October and leave that area by early December (Miller et al. 1982). Similarly, decreasing water temperatures in the fall triggers river herring migration back to sea (Loesch 1987). Both American Shad and river herring may have pulses of downstream migration following high water and/or heavy rainfall events (Miller et al. 1982, Fay et al. 1983).

2. Ecosystem Services Provided

Ecosystem services—defined as the benefits people obtain from ecosystems—are typically categorized as supporting (e.g., nutrient cycling), provisioning (e.g., food, water), regulating (e.g., climate and water purification), and cultural services (e.g., recreation, spiritual value). These services collectively sustain human well-being by linking ecological processes with societal benefits (De Groot et al. 2002; Milcu et al. 2013). American Shad and river herring provide a range of ecosystem services that benefit both natural ecosystems and human communities (Limburg and Waldman 2009). Supporting ecosystem services include both nutrient cycling and habitat connectivity.

2.1 Nutrient Cycling

Both American Shad and river herring contribute to nutrient cycling by transporting nutrients to and from the ocean and freshwater ecosystems during migrations. While adults are migrating from the ocean to rivers during spawning, they are excreting marine-derived nutrients; additionally, gametes and carcasses of adults that may die after spawning are also a source of marine-derived nutrients in freshwater systems (Loesch 1987, Hare et al. 2021, Zydlewski et al. 2021, Brown et al. 2024). This influx of nutrients enriches rivers and streams, benefiting other aquatic and terrestrial organisms (Garman and Macko, 1998). Juveniles also contribute to nutrient transport as they amass freshwater-derived nutrients and return them to the ocean when they migrate downstream (Hare et al. 2021, Zydlewski et al. 2021). Both American Shad and river herring play a role in maintaining ecological connectivity between marine and freshwater habitats, supporting species that rely on these interconnected ecosystems, though the connection between habitats has been diminished with depleted populations of shad and herring (Zydlewski et al. 2021).

2.2 Cultural Importance

In addition to supporting services, American Shad and river herring directly provide resources to humans, primarily as food. Historically and currently, American Shad are harvested for their meat and roe, serving as a culturally significant food source for coastal communities. Historically, American Shad were celebrated with festivals and were considered staples in diets of indigenous peoples and early American settlers (Hall et al. 2011). The Lenape lived on the banks of the Delaware River and fish, including American Shad, were central to their culture[1]. Notably, an early migration of American Shad in the spring of 1778 was attributed to saving George Washington and his troops camped at Valley Forge after a difficult winter (Hardy 1999). In the 1800s, a substantial food-fishery was executed throughout the Delaware River and major tributaries and shad were considered the region's most important fishery (Hardy 1999). Shad fishing is also considered a popular recreational activity along the mid-Atlantic coast, fostering outdoor recreation, tourism, and community engagement (ASMFC 2020). American Shad and river herring are also used for bait in both recreational and commercial fisheries. The complex life cycle of American Shad and river herring has been extensively studied to understand migratory behaviors, ecosystem connectivity, and fisheries management, making them an important subject in education and scientific research.

2.3 Predator and Prey

American Shad and river herring also assist in the regulation of ecological processes such as predator-prey dynamics. Shad and herring are important forage species in both the freshwater and marine systems during all life stages, and serve as prey for a variety of

1. https://www.anspblog.org/river-of-people/ and https://delawaretribe.org/blog/2013/06/27/lenape-fishing/ accessed February 7, 2025.

predators, including Striped Bass, ospreys, eagles, and marine mammals (Hildebrand, 1963). Eggs and larval American Shad are preyed upon by a variety of riverine fish, including Smallmouth Bass (*Micropterus dolomieu)* and shiners (Johnson and Dropkin 1992). Juvenile American Shad and adult river herring are prey to many marine fish, including Striped Bass, Spiny Dogfish, Bluefish, Atlantic Cod, and Pollock (Bigelow and Schroeder 1953, Bowman et al. 2000). Adult American Shad may largely avoid predation due to their larger size, though marine mammals and other large predators can still consume shad (ASMFC 2020). Conversely, American Shad and river herring feed near the base of the food chain on zooplankton and organic particles (Haskell et al. 2013). As a result, American Shad and river herring may indirectly influence water quality in their localized habitats.

2.4 Freshwater Mussel Hosts

American Shad and river herring play a critical role as host fish for the reproduction of certain freshwater mussels. This ecological relationship is essential for the life cycle of many mussel species, particularly in river systems along the Atlantic coast. Regardless of species, juvenile freshwater mussel morphogenesis is contingent upon an obligate parasitic relationship between mussel larvae and an appropriate host fish (Haag and Stanton 2003). Fish host specificity varies considerably with some mussels reliant on one or a few closely related host fish (i.e., specialists), while other species can parasitize a wide range of fish (i.e., generalists) (Haag 2012). Mussel larvae, called glochidia, are released into the water by adult mussels and must attach to the gills or fins of a suitable host fish to develop further (Hastie et al. 2000). After parasitizing the fish for several weeks, the juvenile mussels detach and settle into the sediment to begin their independent lives.

American Shad and river herring were historically abundant in coastal rivers, providing critical support for mussel populations. The migratory nature of these fish allowed certain species of mussels to spread their larvae over large distances, maintaining healthy and diverse populations. In particular, mussel species such as the Alewife Floater (*Utterbackiana implicata*) are known to use Blueback Herring, Alewife, and American Shad as host fish (Strayer and Jirka 1997, Nedeau et al. 2000). Similarly, studies conducted by the Philadelphia Water Department between 2018-2022 have demonstrated high yields of juvenile Alewife Floaters (i.e., 80-90 juveniles/host) from inoculated Alewife (Philadelphia Water Department, unpublished data). Additionally, it has been purported that American Shad and Alewife are potential host fish for the coastal Tidewater Mucket (*Atlanticoncha ochracea*); however, there is no definitive evidence confirming this relationship (https://extapps.dec.ny.gov/docs).

The intricate relationship between American Shad and river herring and freshwater mussels may also play a vital role in water quality and stabilizing habitats within the Delaware River Basin. Freshwater mussels, through their biofiltration abilities, can process large volumes of water, effectively removing suspended particles, pollutants, and excess nutrients. This filtration improves water clarity, creating ideal conditions for submerged and emergent vegetation to thrive, while also enriching benthic habitats and fostering microbial activity within sediment layers (Black et al. 2017, Gagnon et al. 2020, Vaughn & Hoellein 2018). Consequently, robust mussel populations, supported by shad and herring, hold significant potential for revitalizing degraded aquatic ecosystems.

3. Distribution in the Delaware River Basin

3.1 American Shad

Historically, the spawning area for American Shad was thought to begin at Gloucester, New Jersey (rkm 154) and extend to the headwaters of the East and West Branches of the Delaware River (Miller et al. 1982). On the East Branch, shad traveled as far as Shavertown, New York, and on the West Branch, a short distance upstream Deposit, New York (Sykes and Lehman 1957). From 1823 through the late 1800s, the migration of shad was impeded by the Lackawaxen Dam, built by the Delaware and Hudson Canal Company in Lackawaxen, Pennsylvania (Miller et al. 1982). It is likely that the majority of spawning in the late 1800s and early 1900s occurred in the Delaware River downstream of Lackawaxen, Pennsylvania. This assumption was made because the addition of fish passage at the Lackawaxen Dam, and shortly after, the loss of the dam completely, did not result in significant increases in shad landings in subsequent years (Chittenden 1976). Excessive pollution in. the first half of the 20th century precluded spawning in the tidal River (Sykes and Lehman 1957, Miller et al. 1982), which may have also shifted primary spawning areas upstream of historic areas.

More recently, spawning takes place primarily in the middle to upper Delaware River from Easton, Pennsylvania (rkm 296) to Hancock, New York (rkm 532), though spawning also occurs in the lower non-tidal river (Figure 2) (ASMFC 2020, DeSalvo et al. 2022). Spawning occurs in the West Branch up to at least Hale Eddy, New York (14 km upstream of confluence) and on the East Branch up to Harvard, New York (30 km upstream of the confluence) (Miller et al. 1982). The West Branch currently has less production, potentially due to cold water releases from the Cannonsville Reservoir and production in the East Branch may be impacted by the water releases from the Pepacton Reservoir (Chittenden 1976, Miller et al. 1982, ASMFC 2020). The most significant nursery areas currently are from Belvedere, New Jersey (rkm 317) to Hancock, New York and up into the East Branch, but centered near Tusten, New York (rkm 459) and Lordville, New York (rkm 518) (Miller et al. 1982).

Historically American Shad also spawned in a number of tributaries to the Delaware River in Pennsylvania, New Jersey, and Delaware. In Pennsylvania, shad migrated upstream in the Schuylkill River, but the construction of dams in 1818 for the Schuylkill Navigation Company and 1820 for the City of Philadelphia at Fairmont reduced the fish returns to the river (Miller et al. 1982, Sykes and Lehman 1957). Installation of fishways on the lower four dams in the Schuylkill River began with the Fairmount Dam Fishway in 1979 (Perillo and Butler 2009). The Lehigh River was also an important American Shad river (Chittenden 1976). However, shad entry into the Lehigh was completely precluded in the 1820s by the construction of a series of canal dams, including the Easton Dam at the confluence of the Lehigh and Delaware Rivers. Fishways on the lower three of the five remaining dams on the Lehigh provided access to spawning shad to the first 39 km of the river in 1994. Fishways on the Schuylkill and Lehigh rivers have demonstrated variable success in facilitating the passage of shad and river herring. Several structures suffer from design deficiencies and inadequate maintenance (USFWS 2017), which have significantly reduced their overall effectiveness. While dam construction has been widely recognized as the primary driver of habitat loss in the Schuylkill and Lehigh Rivers, degraded water quality also played a significant contributory role (ASMFC 2020).

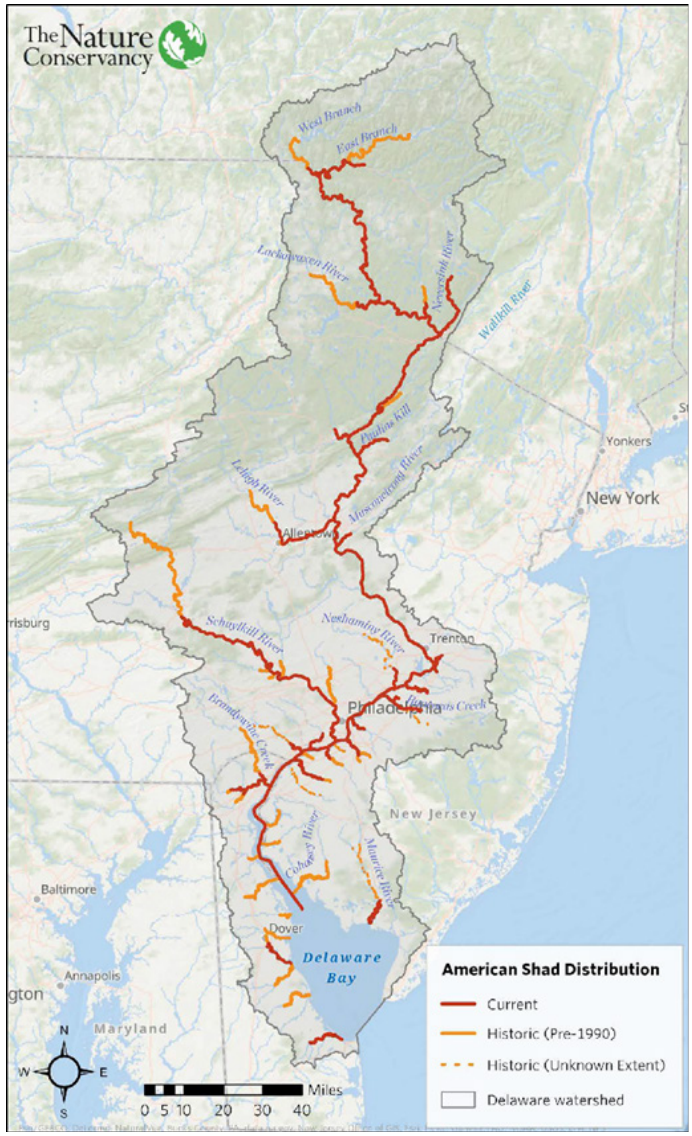

Figure 2. Distribution of historic and current American Shad habitat in the Delaware River Basin (taken from DeSalvo et al. 2022).

Spawning also occurs in other tidal tributaries including the Cohansey River, Salem River, Cooper River, Maurice River, Rancocas Creek, Raccoon Creek, Mantua Creek, and Big Timber Creek in New Jersey, and in the Broadkill and Christina Rivers in Delaware (Miller et al. 1982, NJDEP 2005). The combined impacts of dam construction and pollution led to the extirpation of shad from many of these tributaries. In New Jersey, the Cohansey River was the largest shad producing tributary before dam construction and water quality issues. The Musconetcong and Paulins Kill Rivers are seeing a return of American Shad after dams have been removed (ASMFC 2020). The Christina River historically supported a spawning run of shad before the construction of dams and decline of water quality (Miller et al. 1982). The Brandywine River, tributary to the Christina River, has many dams, but American Shad were documented using the Brandywine River up to Dam 2, after removal of Dam 1 in 2019 (Roday et al. 2024). American Shad are infrequent in the White Clay Creek tributary (Stangl 2023).

3.2 River Herring

Less information is known about historic Alewife and Blueback Herring spawning habitat in the Delaware River Basin, though they were thought to use both the mainstem of the Delaware River and many tributaries (Figure 3 and 4; NJDEP 2005, DeSalvo et al. 2022). A larger number of tributaries may support river herring runs compared to American Shad (NJDEP 2005). Notable tributaries with river herring runs included the Schuylkill and Lehigh Rivers in Pennsylvania, the Cohansey River, Salem River, Maurice River, Rancocas Creek, Raccoon Creek, Mantua Creek, and Cooper River in New Jersey, and in the Broadkill and Christina Rivers in Delaware (NJDEP 2005, Park 2021, Conroy 2024).

Though the Schuylkill and Lehigh are the largest tributaries to the Delaware River, river herring abundance through the fishways on those rivers remains low (Fairmount Dam: Philadelphia Water Department, unpublished data; Easton Dam: Pennsylvania Fish and Boat Commission, unpublished data). The Cooper River has seen a return of river herring runs since the 1970s following water quality improvements and moderately successful fish passage (Keller et al. 2024).

The Christina River has several tributaries with numerous dams that have influenced the distribution of river herring in that system. The Brandywine River is the largest tributary that had the first dam removed in 2019. Since dam removal, Blueback Herring have been noted to reproduce upstream of the removal site of Dam 1 (Park 2021). In White Clay Creek, river herring occupy the tidal portion of the river and the removal of the first dam on White Clay creek has provided additional access to spawning habitat for river herring (Stangl 2023).

4. Abundance

4.1 American Shad

Compared to historic conditions, the stock of American Shad in the Delaware River Basin is depleted (ASMFC 2020). Landings of the commercial fishery were 12-14 million pounds in the Delaware from 1896-1901 and were the largest of any river on the East Coast (Miller et al. 1982). At an average of three to four pounds per fish, that equated to over three

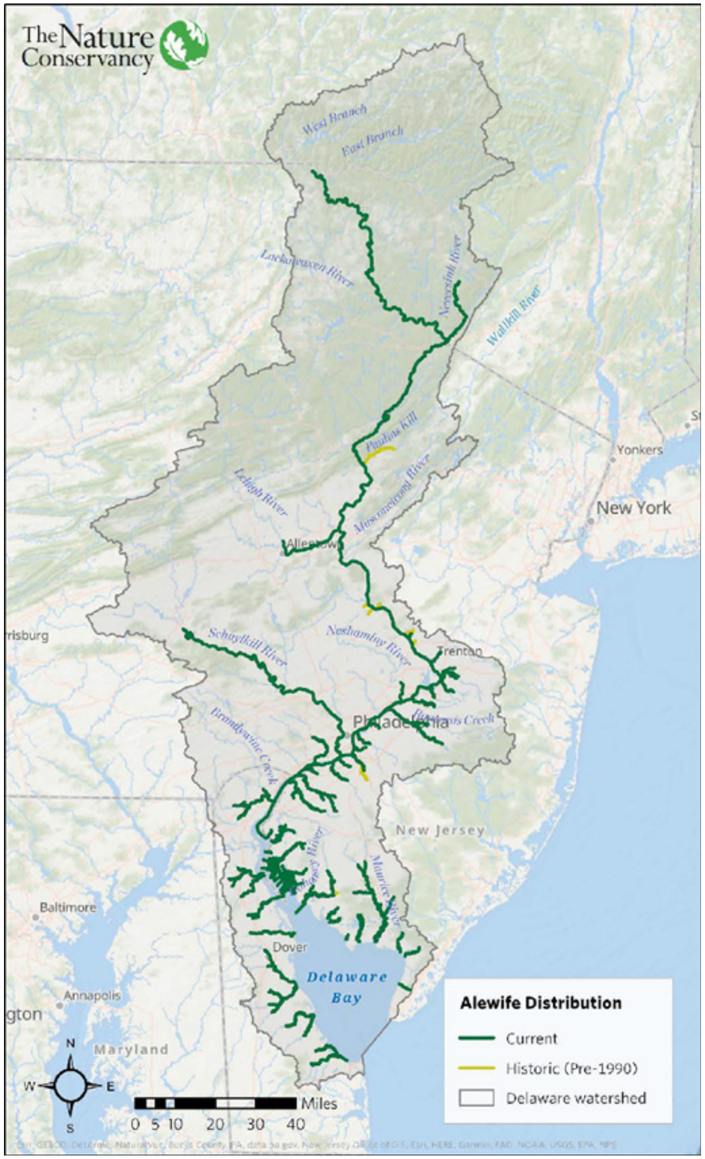

Figure 3. Distribution of historic and current Alewife habitat in the Delaware River Basin (taken from DeSalvo et al. 2022).

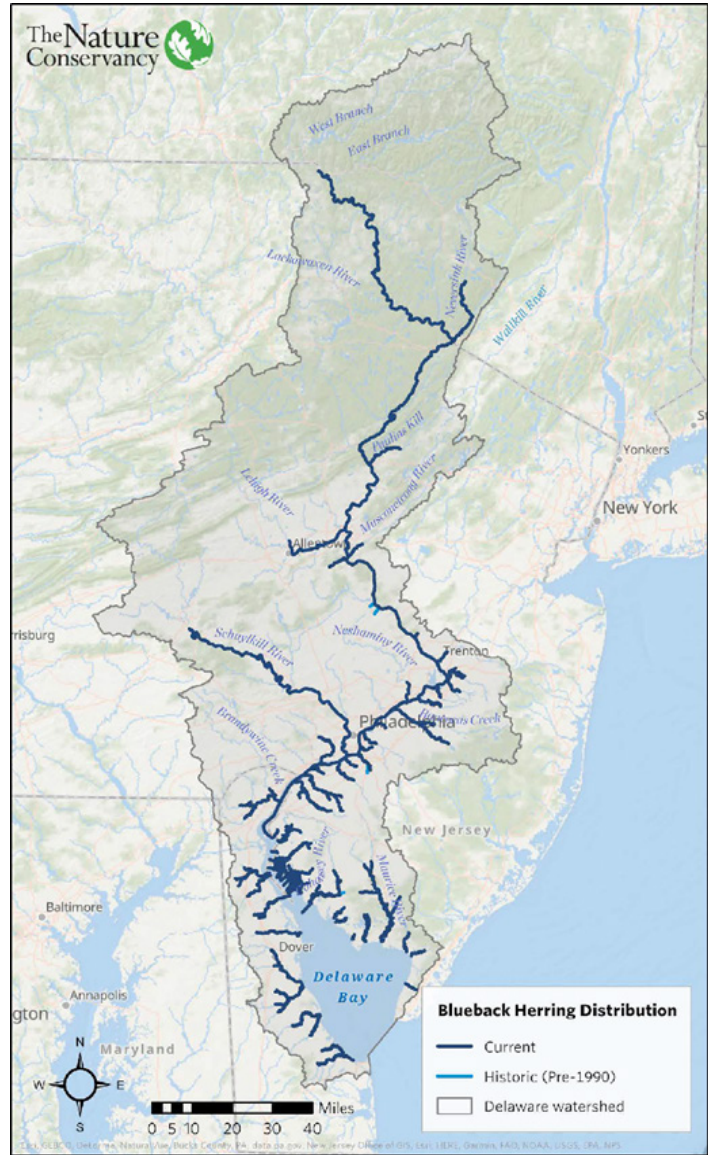

Figure 4. Distribution of historic and current Blueback Herring habitat in the Delaware River Basin (taken from DeSalvo et al. 2022).

million American Shad being landed annually in those years. Abundance declined in the subsequent years and spawning population estimates in the mid-1970s to the mid-1980s ranged from just over 100,000 to 550,000 fish and an increase in the spawning population was observed in the late 1980s to 830,000 fish (Lupine 1989).

Although population estimates are no longer routinely generated, available evidence suggests that the population has remained relatively stable in recent years, albeit at levels lower than those observed in the 1980s. According to a relatively recent stock assessment completed by the Atlantic States Marine Fisheries Commission, American Shad abundance is unknown. Between 2005 and 2017, no clear trends were observed in juvenile abundance. Adult abundance data were conflicting, with one survey indicating no discernible trend during this period, while another reported an upward trend (ASMFC 2020).

The Delaware River Basin Fish and Wildlife Management Cooperative (Co-op) comprised of fisheries agencies of the four basin states, as well as the U.S. Fish and Wildlife Service and National Marine Fisheries Service, work collectively to manage American Shad and river herring in the Delaware River Basin. The Co-op uses six indices to track the abundance of American Shad in the Basin (DRBFWMC 2022). One index tracks total mortality of female American Shad and that is updated every five years. The remaining indices are updated annually and include abundance indices for young-of-year American Shad in the tidal and non-tidal portions of the mainstem Delaware River, adult female American Shad abundance spawning at Smithfield Beach, and two indices that track the commercial fishery and harvest of the Delaware River Stock and the Mixed Coastal Stock. Data from the Lewis Haul Seine is also available, but not used by the Co-op as the basis for management decisions at this time.

The following abundance indices for American Shad are taken from the Co-op's 2022 Sustainable Fishing Plan (DRBFWMC 2022) and updated with more recent unpublished data from the contributing agencies of the Co-op. Exceeding any of the benchmarks may initiate management action by the basin state agencies to institute more protective regulations for American Shad management.

4.1.1 Total Mortality

The female total mortality Z_{40} benchmark developed for the Delaware River in the 2020 stock assessment is 1.07 (ASMFC 2020). The three-year average female Z estimate from otoliths in 2017 (1.3) was above the benchmark (1.07), therefore; mortality was determined to be unsustainable (Figure 5). Due to the unstainable finding, the members of the Co-op instituted increased fishing regulations in their respective jurisdictions in 2023 to reduce mortality on American Shad, including putting quotas and gear restrictions on the commercial fishery and reducing the recreational creel limit from three to two fish per day (DRBFWMC 2022).

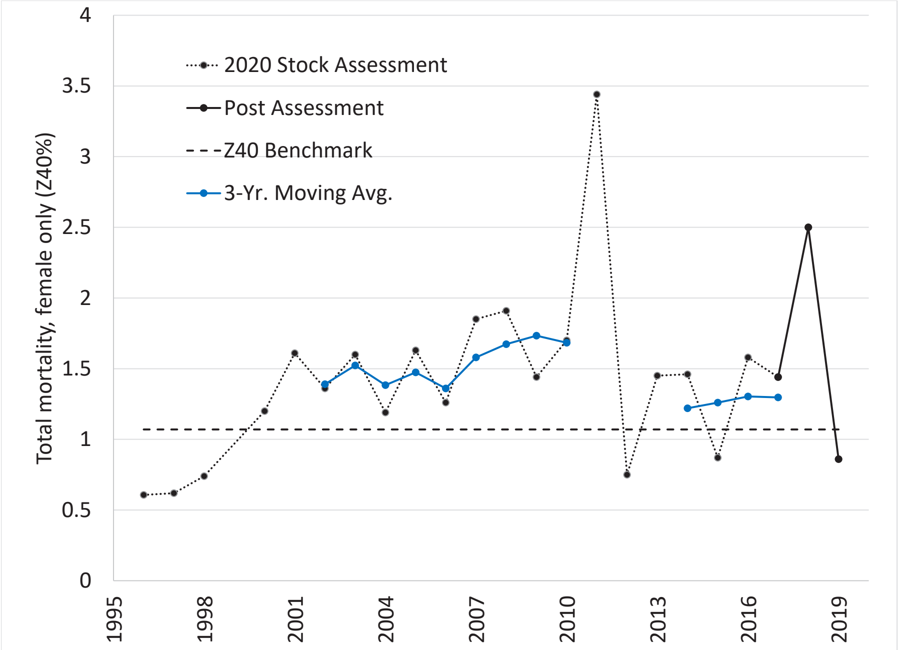

Figure 5. Female American Shad total mortality for the Delaware River population.

4.1.2 Non-Tidal Juvenile Abundance Index

This index is based on annual catch of juvenile American Shad in haul seining from three locations in the non-tidal Delaware River; Phillipsburg, Delaware Water Gap, and Milford Beach (Figure 6). Sampling is led by the Pennsylvania Fish and Boat Commission with assistance from other resource agency staff. Data are standardized by environmental covariates using the generalized linear model (GLM) methodology. Failure is defined as the occurrence of three out of five years where values fall below the 50th percentile from the reference period. No sampling occurred at any non-tidal station between 2008 and 2011 or in 2018 or 2020. The survey fell below the benchmark most recently in 2021 and 2023. In 2024, the juvenile abundance was near record high level, despite low adult abundance in the same year (see Smithfield Beach Adult Female Abundance).

4.1.3 Tidal Juvenile Abundance Index

This index is based on annual geometric means of seining catch data from tidal stretches of the mainstem Delaware River from Trenton, New Jersey to the Delaware Memorial Bridge (Figure 7). Sampling is conducted by the New Jersey Division of Fish and Wildlife. Failure is defined as the occurrence of three out of five years where index values are below the 50th percentile. The tidal index fell below the benchmark most recently in 2023.

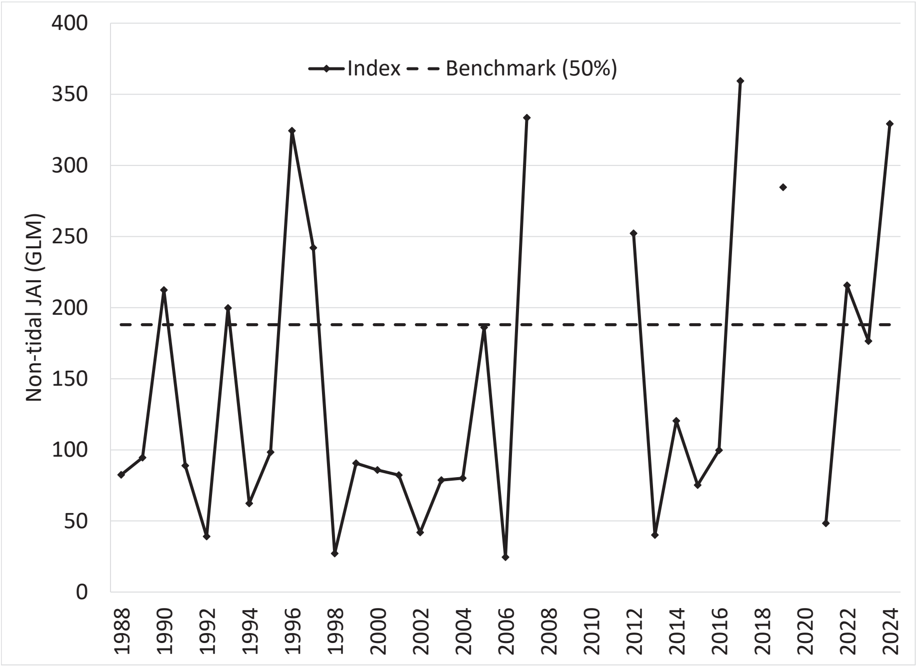

Figure 6. The Delaware River non-tidal juvenile American Shad abundance (GLM) with a 50th percentile benchmark.

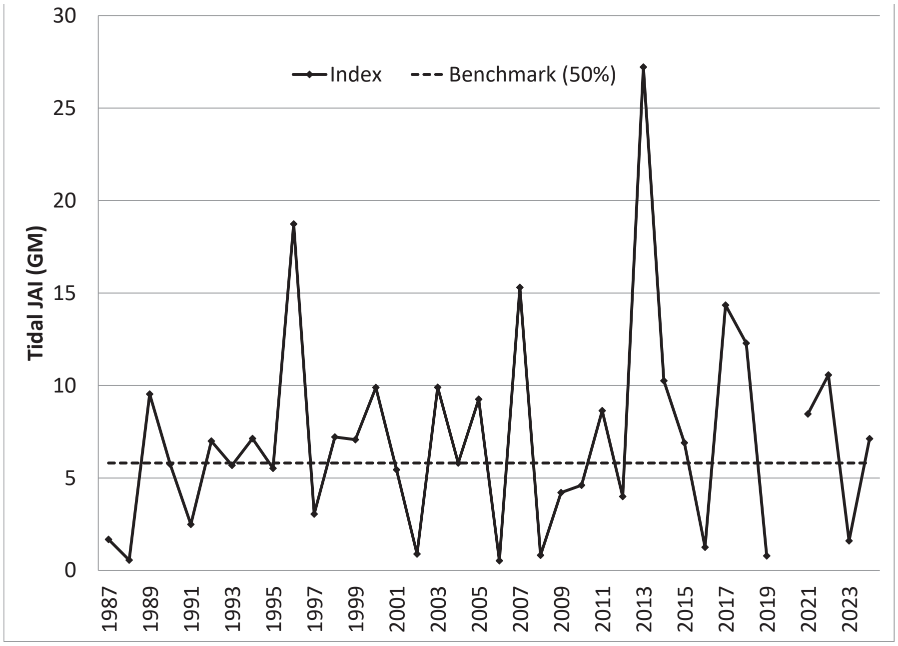

Figure 7. The Delaware River tidal American Shad juvenile American Shad abundance (geometric mean - GM) with a 50th percentile benchmark.

4.1.4 Smithfield Beach Adult Female Abundance

This index is based on the annual geometric mean (GM) of the catch-per-unit-effort (shad/net-ft-hr) of female shad in the Pennsylvania Fish and Boat Commission egg-collection effort at Smithfield Beach (Figure 8). This index represents a fishery-independent measure of the spawning run success as survivors after the fishery. Failure is defined as the occurrence of three out of five years where geometric mean values are below the 50th percentile. The index fell below the benchmark in four of the past five years.

4.1.5 Ratio of Commercial Harvest to Smithfield Beach Abundance

This index is defined as the ratio of the total Delaware River stock landed by commercial fishers as reported to the States of New Jersey and Delaware divided by the survivors after the fishery as indexed by the Smithfield Beach gill net female shad catch-per-unit-effort (Figure 9). Failure is defined as the occurrence of three out of five years where ratio values are higher than the 50th percentile. The ratio estimate exceeded the benchmark most recently in 2014.

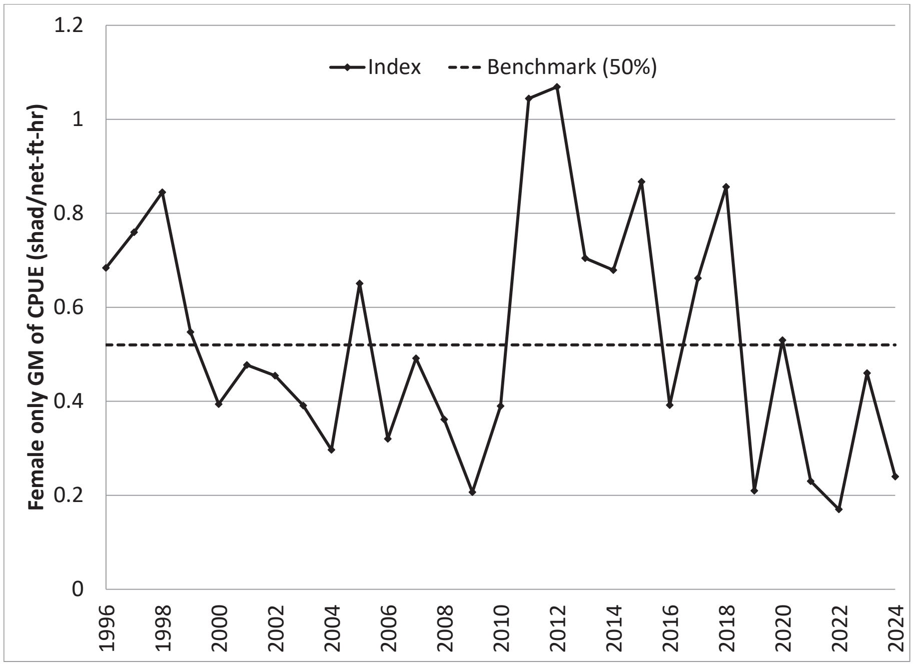

Figure 8. The Delaware River spawning adult female American Shad index at Smithfield Beach (RM 218) with a 50th percentile benchmark.

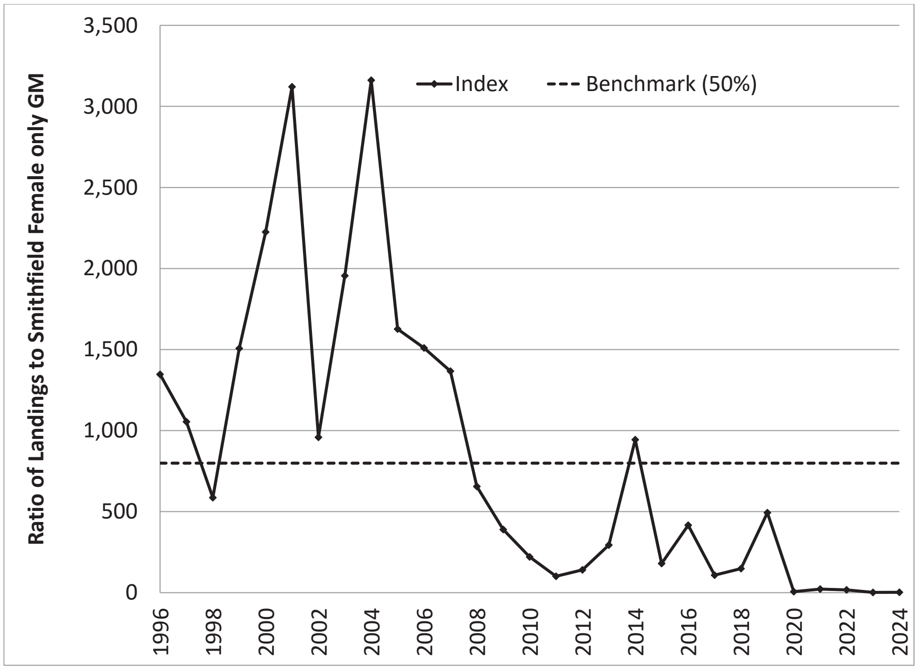

Figure 9. Ratio of Delaware River stock landings divided by Smithfield Beach female shad geometric mean (GM) (divided by 100) with a 50th percentile benchmark.

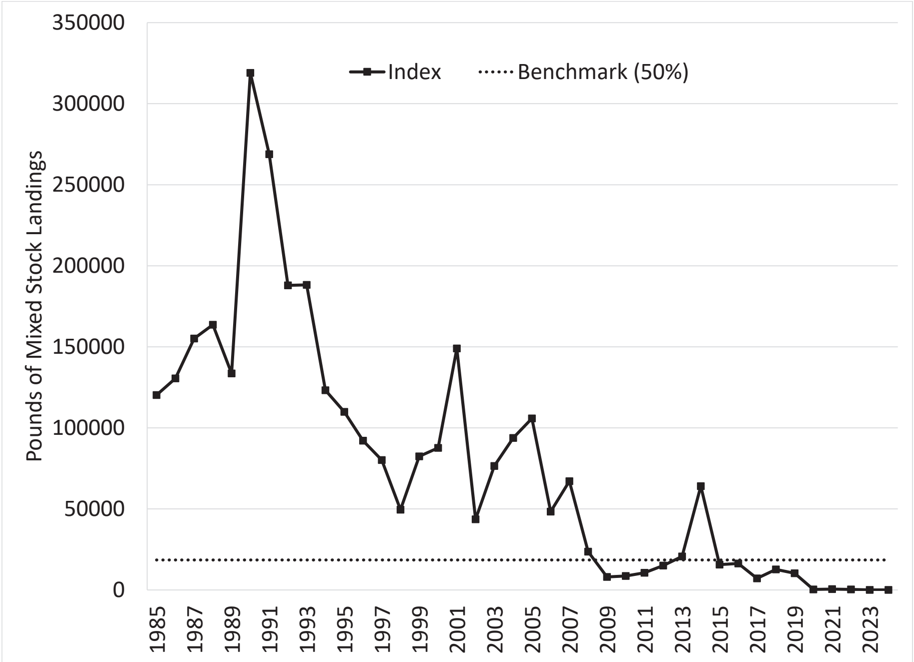

Figure 10. American Shad landings in the Delaware Bay from the mixed stock fishery with a 25th percentile benchmark.

4.1.6 Mixed-Stock Landings

This index is defined as the total pounds landed from the mixed stock, which consists of 50% of combined commercial landings from Delaware and New Jersey (Figure 10). The benchmark is defined as the 25th percentile of the time-series where 75% of values are higher. Failure is defined as the occurrence of 2 consecutive years above the benchmark. This index provides additional harvest protections for American Shad stocks with origins outside of the Delaware River, some of which have closed commercial fisheries. The pounds landed on the mixed stock exceeded the benchmark most recently in 2013 and 2014.

In addition to the indices that are being tracked as part of the Sustainable Fishing Plan, a long-term haul-seine fishery at Lambertville, New Jersey (Lewis haul seine) also can be used to track abundance of adult American Shad in the Delaware River Basin. Information on the fishery can be found in the American Shad stock assessment (ASMFC 2020) with updated, unpublished data from the Co-op. The Atlantic States Marine Fisheries Commission standardized the Lewis haul seine data and found that the index was low and variable from 1925-1947 with a period of slightly higher values in the 1930s and early 1940s (Figure 11). The index fell to the lowest values from 1948-1957 with a large peak

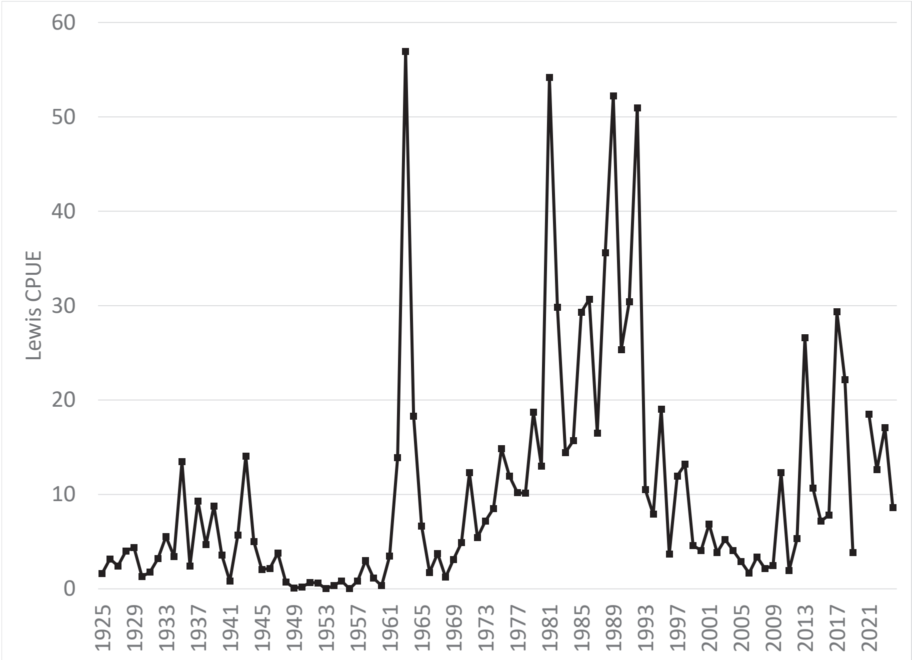

Figure 11. American Shad catch-per-unit-effort from the Lewis haul seine survey in Lambertville, New Jersey.

in 1963 before falling again in 1965-1967. An increase was observed from 1968 through 1992 before the index fell again in the 1990s and 2000s. Since 2009, the index has been increasing again though not to levels as high as were observed in the 1980s.

Both landings and catch-per-unit-effort of the commercial American Shad fishery have been declining since the 1980s, with less than 1,000 pounds landed annually in recent years (Figure 12 and 13, DRBFWMC, unpublished data).

American Shad use of the Schuylkill River for spawning has also provided a means of tracking abundance over time. The Philadelphia Water Department monitors populations in the Schuylkill River below the Fairmount Dam in an electrofishing survey and at the Fairmount Dam fish ladder. Electrofishing catch-per-unit-effort and fishway counts have been variable over the past decade (Figure 14).

American Shad electrofishing catch-per-unit-effort in the Lehigh River, near the mouth and downstream of the Easton Dam, shows variable but generally low abundance in the past decades in a survey conducted by the Pennsylvania Fish and Boat Commission (Figure 15).

In an effort to bolster American Shad populations, hatchery stocking efforts have been attempted in the Delaware, Lehigh, and Schuylkill Rivers by the Pennsylvania Fish and Boat Commission. Since 1999, over 16 million American Shad larvae have been stocked into the Lehigh and Schuylkill Rivers, and just over 400,000 in the Delaware River mainstem (Figure 16; DRBFWMC 2022). Adult returns of hatchery origin fish in the Delaware River mainstem have been less than 5% in the past two decades, suggesting the more recent limited stocking in the mainstem is not contributing substantially to the adult population. In the Lehigh River, stocking has resulted in a high proportion of hatchery returns, with greater than 50% of the adults captured being of hatchery origin in most years (Figure 16). In the Schuylkill River, stocking resulted in a very high proportion of hatchery returns, with generally greater than 75% of adults being of hatchery origin in most years (Figure 16). The sustained high proportion of hatchery-reared adults in the Lehigh and Schuylkill Rivers suggests that the decades-long stocking has not materialized into self-sustaining populations in those tributaries, and that improved fish passage or dam removal should be conducted to address habitat access before restoration can be realized in those tributaries (DRBFWMC 2022).

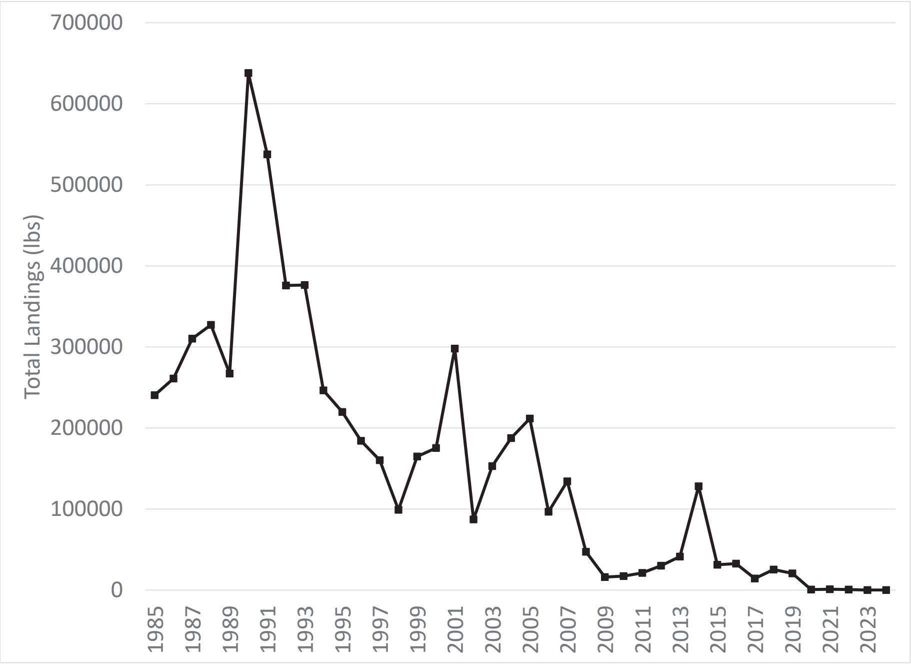

Figure 12. Landings of American Shad in commercial fisheries from Delaware and New Jersey operating in the Delaware River Basin.

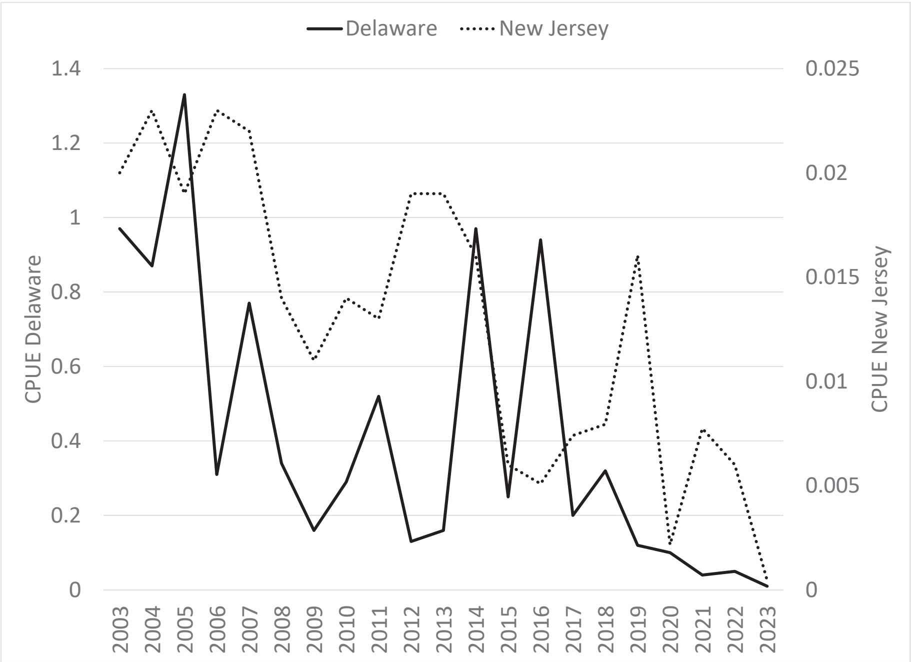

Figure 13. Catch-per-unit-effort of American Shad in commercial fisheries from Delaware and New Jersey operating in the Delaware River Basin.

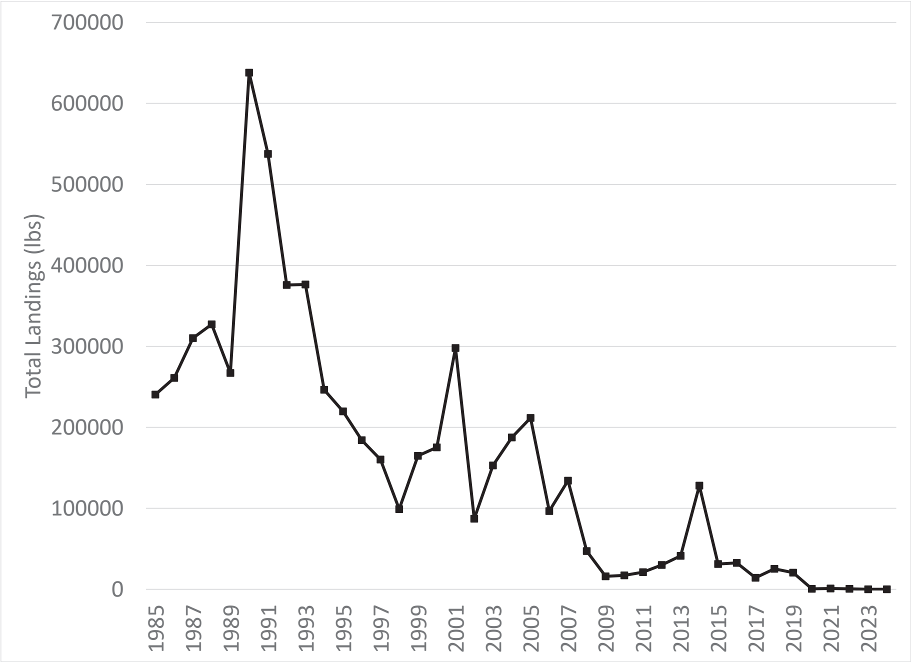

Figure 14. American Shad catch-per-unit-effort for electrofishing in the lower Schuylkill River and annual fishway counts at the Fairmount Fishway. Data courtesy of Philadelphia Water Department (Joe Perillo, Philadelphia Water Department, unpublished data).

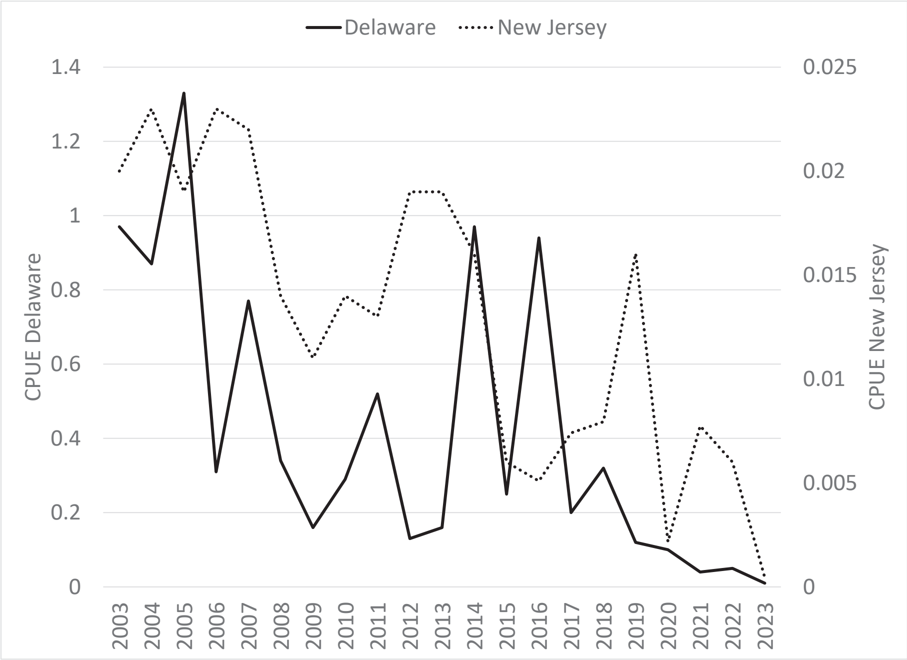

Figure 15. American Shad catch-per-unit-effort for electrofishing in the lower Lehigh River.

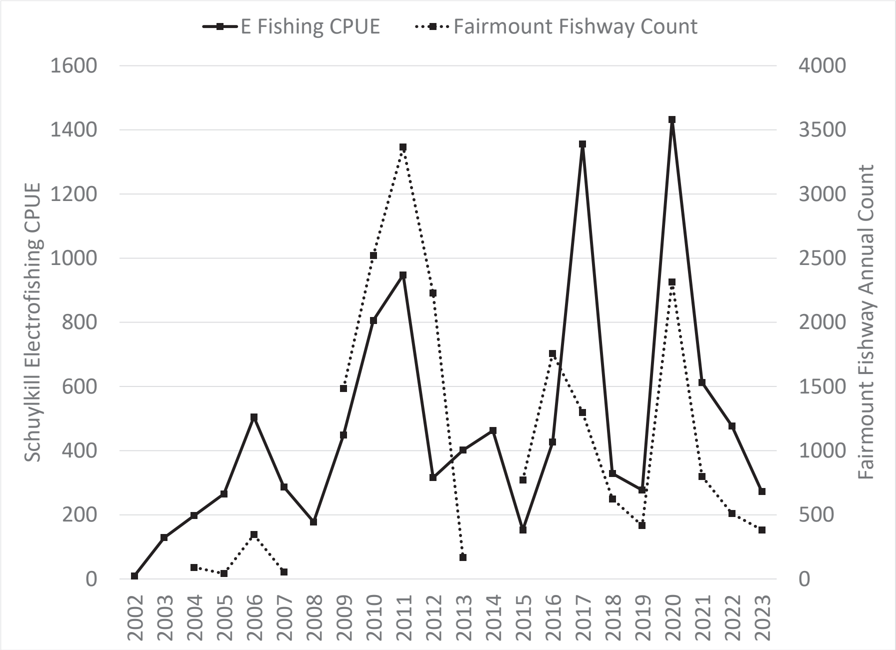

Figure 16. Number of hatchery-reared larval American Shad stocked by waterbody (bars) and percent of adult returns of hatchery origin (lines) caught in that waterbody.

4.2 River Herring

Similar to American Shad, river herring supported large harvests in historic commercial fisheries. Today, fishing is prohibited, and abundance of Alewife and Blueback Herring in the Delaware River Basin are less well known compared to American Shad. Several surveys have been conducted that encounter river herring in the Delaware River basin and tributaries. During the most recent Atlantic States Marine Fisheries Commission stock assessment for river herring (ASMFC 2024), only the abundance of juvenile river herring was able to be evaluated. Three surveys were considered in the stock assessment; the 16' Delaware Bay trawl survey (1991-2021), the 30' Delaware Bay trawl survey (1990-2021) and the New Jersey Striped Bass seine survey (1987-2021). The 16' Delaware Bay trawl was used only for Alewife and showed a significant declining trend in the time series. The New Jersey seine survey showed significant declining trends for both Alewife and Blueback Herring over the time series (Figure 17). The Delaware Bay 30' trawl found no significant trend for Alewife or Blueback Herring over the time series (Figure 18).

Data are available from other surveys that were not evaluated in the recent stock assessment that may provide more insight on river herring populations in the Bay and tributaries to the Delaware River including the Schuylkill River, Maurice River, and Delaware tributaries to the Bay.

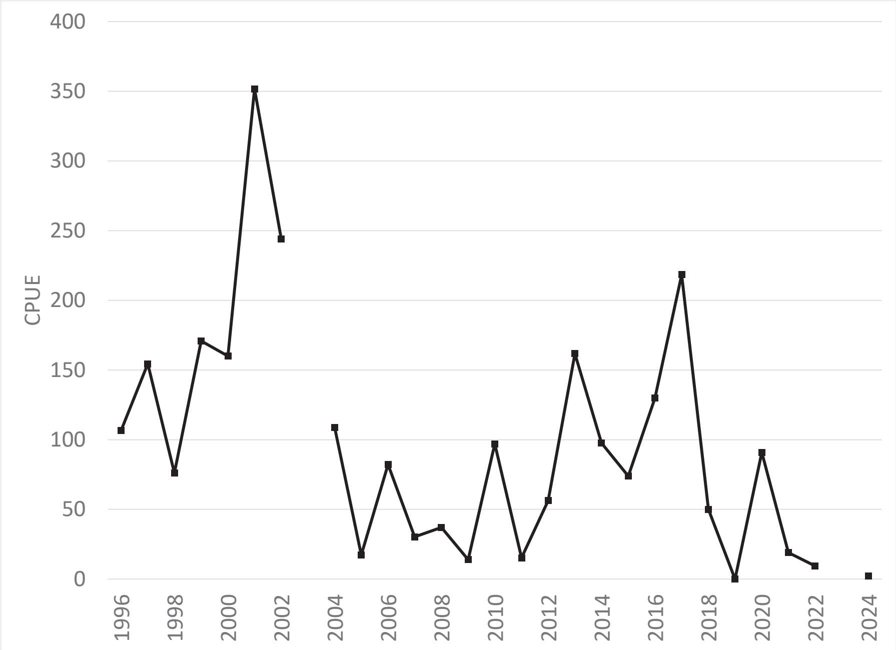

Figure 17. Young-of-year Alewife and Blueback Herring caught in the New Jersey juvenile Striped Bass seine survey conducted by New Jersey Fish and Wildlife.

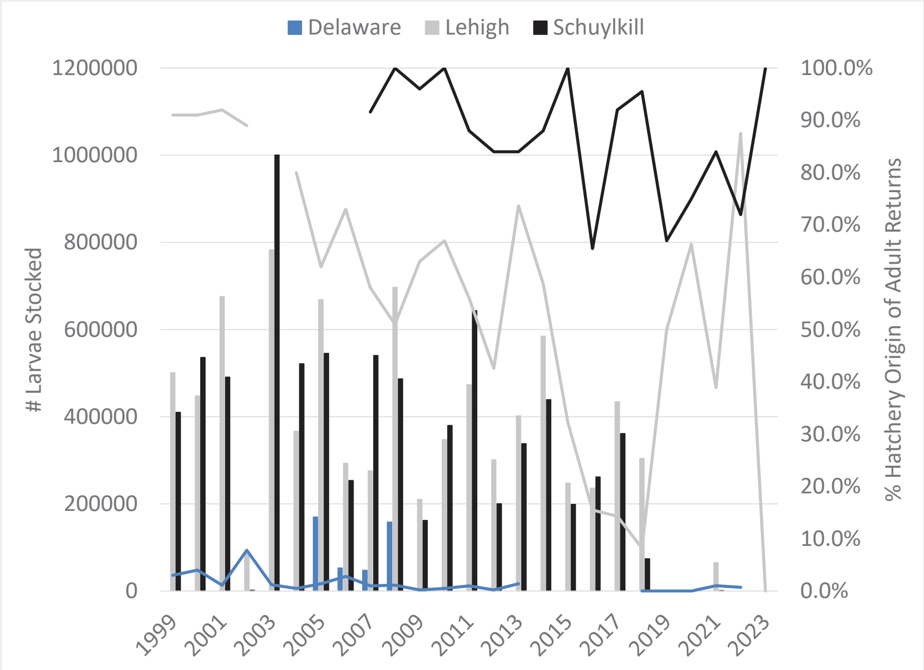

Figure 18. Young-of-year Alewife and Blueback Herring caught in the Delaware 30′ trawl survey conducted by the Delaware Division of Fish and Wildlife.

In the Schuylkill River, sampling for river herring is done concurrently with American Shad in the electrofishing surveys and fishway counts at Fairmount Dam conducted by the Philadelphia Water Department. Generally, fishway counts are relatively low at Fairmount Dam, with most years passing less than 20 river herring (Figure 19). Catch-per-unit-effort in the electrofishing survey has also been relatively low, but consistent for the past eight years (Figure 20).

New Jersey Fish and Wildlife has surveyed river herring in the Maurice River since 2013. In the adult gillnetting survey (Figure 21) as well as the young-of-year seine survey (Figure 22), catch has been variable during the time series.

The Delaware Division of Fish and Wildlife has monitored river herring passage at ten different fishways on tributaries to the Delaware River and Bay from 2017-2023 (Figure 23). Although total annual passage counts range from 3 to 1,617 for Alewife and 1,084 to 8,103 for Blueback Herring, there is no trend in passage numbers over time for either species (Conroy 2024).

The Delaware Division of Fish and Wildlife also conducts a haul seine survey that collects young-of-year herring. This survey has also been variable over the time series (Figure 24).

5. Factors Influencing Abundance and Distribution

American Shad and river herring populations have declined from historic levels coast wide. Key factors contributing to population declines include the loss of spawning habitat caused by dam construction, the formation of hypoxic zones due to pollution, and intensive overfishing during the late 19th century (Limburg et al. 2003). In addition to historical impacts, several of these factors along with more recent stressors continue to influence the current population status of American Shad and river herring in the Delaware River Basin.

5.1 Fishing

5.1.1 Commercial Harvest

Historically, the Delaware River Basin supported one of the largest American Shad fisheries on the U.S. Atlantic Coast, with commercial landings totaling 12 to 14 million pounds between 1896 and 1901—valued at approximately $0.4 million during that period (Miller et al. 1982). At that time, most landings were from New Jersey (77%), followed by Pennsylvania (14%) and Delaware (9%). Two-thirds of the fish caught during the peak of harvest of 14.5 million pounds in 1896 originated from the tidal river, one-quarter from the bay, and the remaining from the non-tidal river (Sykes and Lehman 1957, Miller et al.

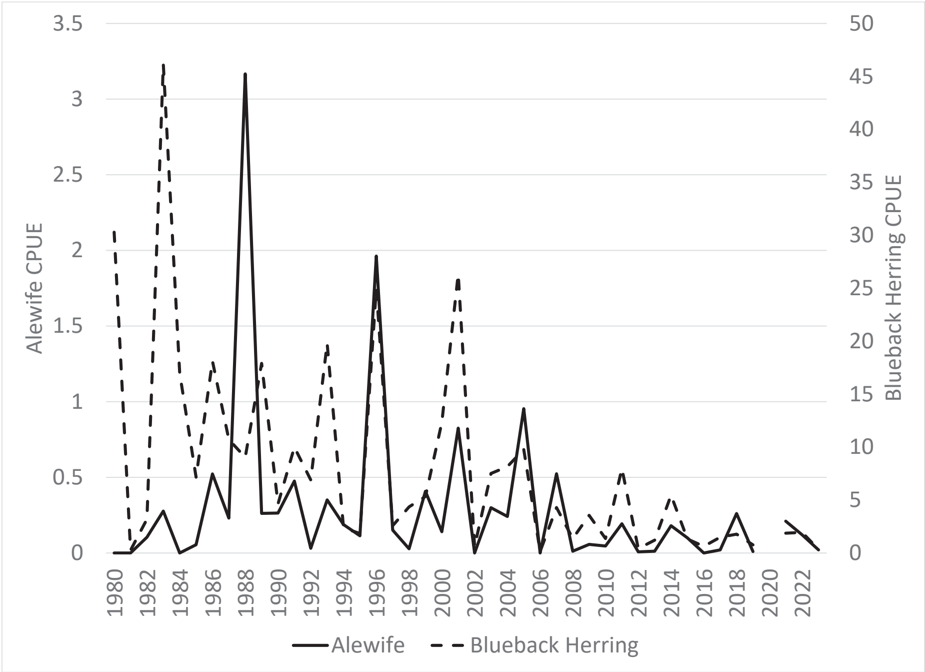

Figure 19. Fairmount Dam fish ladder river herring annual counts.

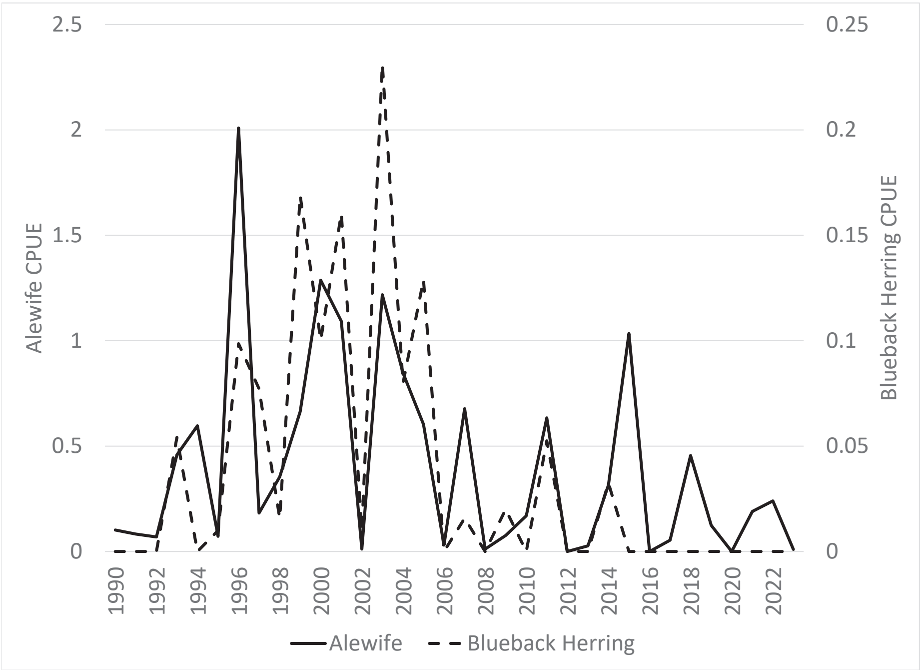

Figure 20. Electrofishing catch-per-unit-effort for river herring the lower Schuylkill River.

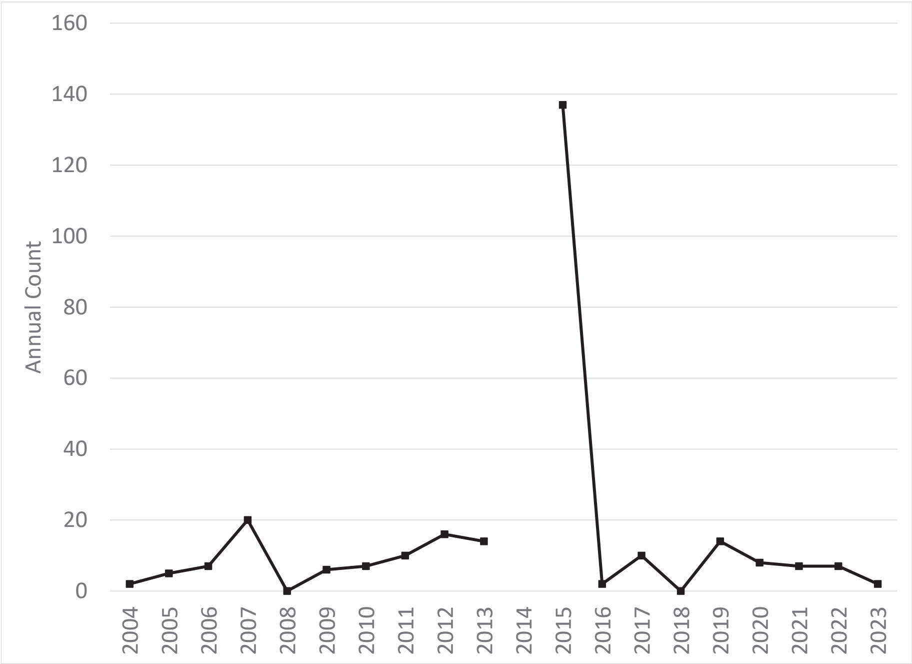

Figure 21. Adult river herring catch-per-unit-effort in the Maurice River gillnetting survey conducted by New Jersey Fish and Wildlife.

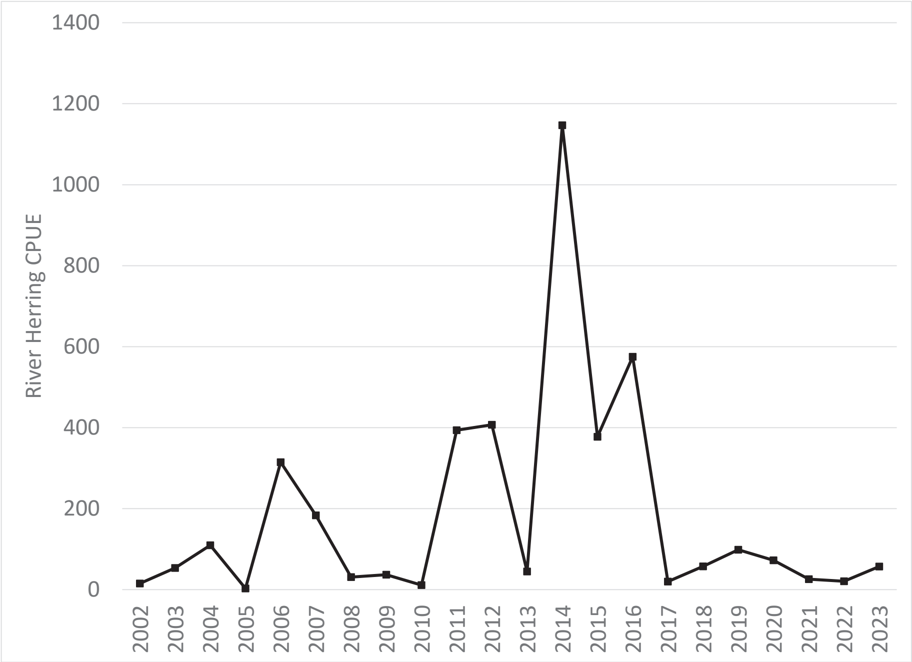

Figure 22. Young-of-year river herring captured in a seine in the Maurice River by New Jersey Fish and Wildlife.

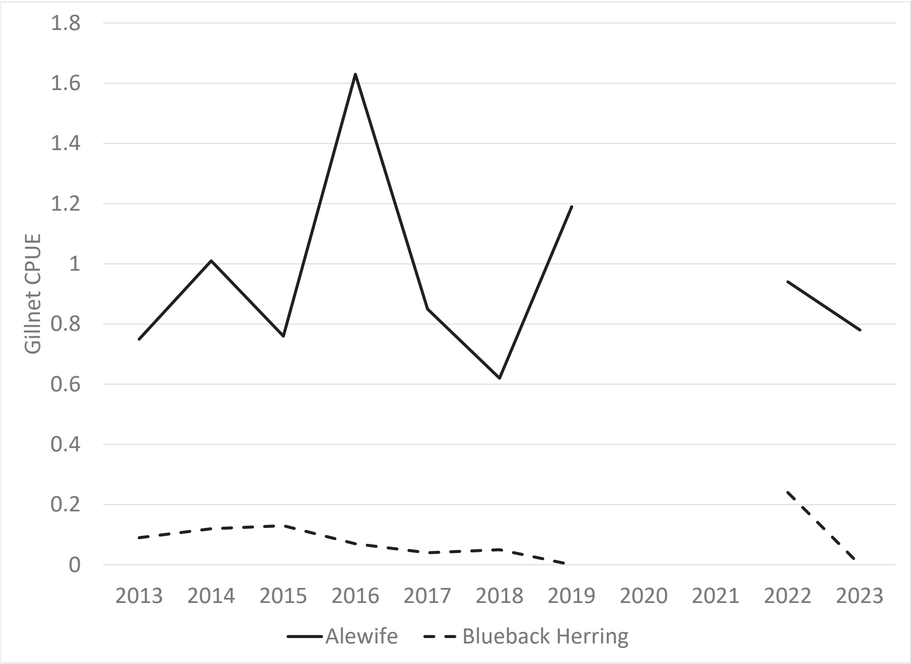

Figure 23. Annual Counts of Alewife and Blueback Herring at ten different fishways in Delaware tributaries to the Delaware River Basin (from Conroy 2024).

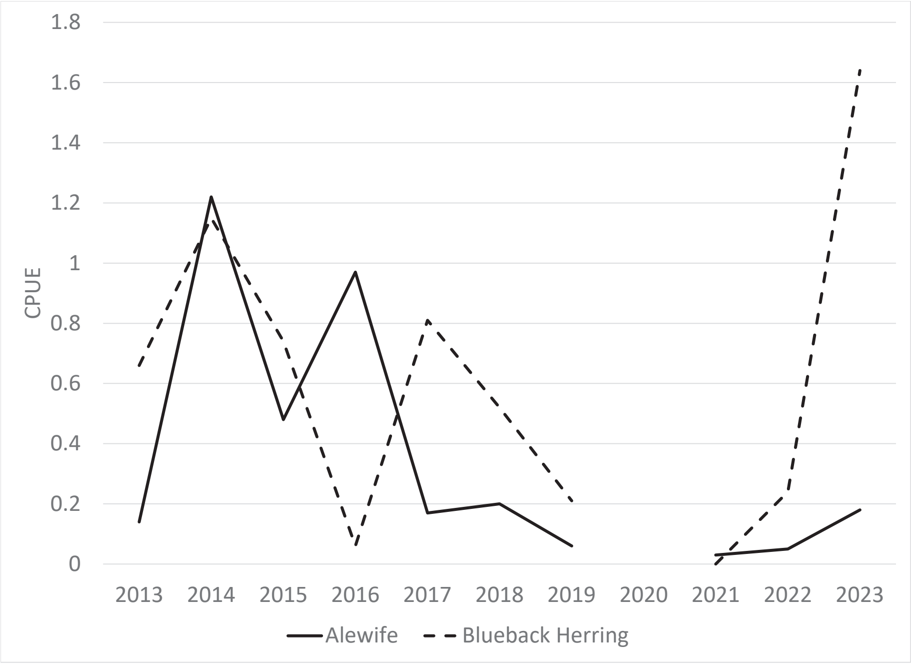

Figure 24. Young-of-year river herring collected in the Delaware haul seine.

1982). Of the bay and tidal river landings, about 500,000 pounds were harvested from Delaware and New Jersey tributaries. Catch declined rapidly after the peak years, likely due to high rates of harvest combined with declining water quality associated with the industrialization of the Delaware River estuary. By 1904, landings had dropped to just over 5.4 million pounds, and by the 1920s, they had fallen to less than 200,000 pounds. In subsequent years, the river continued to support a reduced commercial fishery and recreational fishery. From the 1920s to 1940s, commercial catch declined to below 150,000 shad annually and less than 100,000 pounds by the 1970s (Sykes and Lehman 1957, Miller et al. 1975). Shad harvest saw some modest increases through the 1980s and early 1990s but have since declined to less than 1,000 pounds harvested annually since 2020 (Figure 25).

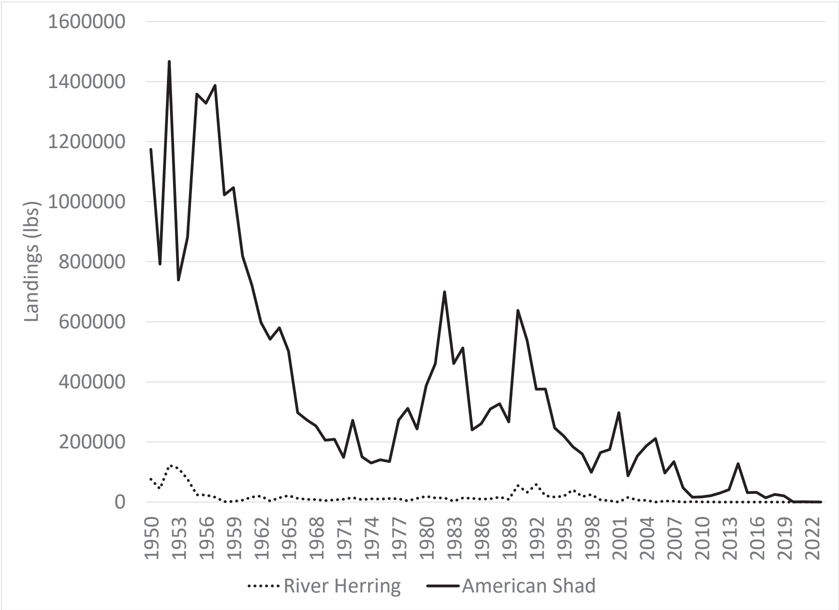

Figure 25. Landings of American Shad and river herring in Delaware and New Jersey. Data source Atlantic Coastal Cooperative Statistics Program (ACCSP, accsp.org).

The commercial fishery used a variety of traditional gear to catch fish including gill nets in the bay and tidal section of the river. Haul seines were used in the estuary and along the entire mainstem of the river into the West Branch at least as far as Deposit, New York. By 1950, essentially no shad were caught upstream of Trenton, with 25% of the catch in the estuarine section of the river (Port Penn, Delaware to Trenton, New Jersey) and 75% of the catch from the bay (Sykes and Lehman 1957). More recently the fishery is executed using gillnets in the Delaware Bay and estuary. No commercial harvest occurs in the non-tidal river or tributaries in the Delaware River Basin. The Lewis haul seine, partially funded by the Co-op, continues as a long-standing time-series of effort in Lambertville, New Jersey. This is the only haul seine currently in operation in the basin and a small number of shad are harvested from this fishery each year. Commercial harvest of river herring has been prohibited in the Delaware River Basin since 2012.

In addition to the directed fishery for American Shad within the Delaware River Basin, both American Shad and river herring have been subject to directed and bycatch fisheries targeting migrating coastal stocks in the Atlantic Ocean, occurring across both state and federal waters. In the late 1970s and 1980s, coastal ocean landings of American Shad tripled, and by 1989, ocean landings increased to 2.1 million pounds and remained high in 1996 with 1.1 million pounds landed. The ocean fishery represented 11% of the coast-wide landings in 1978, but that proportion increased to 67% by 1996 (ASMFC 2020). In the late 1960s, river herring landings peaked at 80 million pounds and dropped to 1.1 million pounds by the late 1970s (ASMFC 2024). In the 1980s, the directed fishery was regulated to limit the harvest of American Shad and river herring and catch caps were instituted in the Atlantic Mackerel and Atlantic Herring fisheries to reduce the bycatch. Directed fishing for American Shad in ocean waters was closed in 2005. In 2012-2013, the Atlantic Herring fishery landed, on average, 2.5 million river herring per year even though the river-based fisheries were generally closed by that point to protect declining stocks (Hasselman et al. 2016). In response to these high harvest rates, catch caps for shad and river herring were updated in the Atlantic Herring and Atlantic Mackerel fisheries in 2014 to reduce bycatch and now these fisheries can be modified or closed if the catch caps are reached. Between 2014 and 2022, average annual bycatch of American Shad and river herring in these fisheries was 287,000 pounds (ASMFC 2024). Although river of origin for the bycatch is not always known, genetic analysis has been able to assign bycatch to river of origin for American Shad and river herring. The Mid-Atlantic stock of Blueback Herring, which would include fish originating from the Delaware River Basin, comprised a high proportion of the bycatch of Blueback Herring in offshore fisheries (Hare et al. 2021).

5.1.2 Recreational Fishing

Recreational fishing for American Shad was, and continues to be, important in the non-tidal reaches of the Delaware River Basin. In the 1970s and 1980s, an estimated 60,000-70,000 recreational fishing trips targeting American Shad occurred in the Delaware River Basin, with effort primarily focused upstream of Trenton, New Jersey with the concentration in the free-flowing river between Yardley, Pennsylvania and the East Branch (Friedersdorff et al. 1976, Miller and Lupine 1987). In the late 1970s, the recreational fishery had an estimated value of $828,000 annually (Miller et al. 1982). In 2002, a creel survey was conducted of the shad fishery from the I-295 Delaware Memorial Bridge to Downsville, New York (Volstad et al. 2003). The survey was conducted from March through October and estimated over 120,000 angler trips on the Delaware River during that time period. An estimated 35,000 American Shad and 7,500 river herring were caught in 2002. The fishery was largely catch and release for American Shad (19% retained) but 65% of river herring were retained. This survey represented a reduction in fishing effort compared to the previous creel surveys in 1986 and 1995 (Volstad et al. 2003). Though no creel surveys have been conducted on the American Shad and river herring recreational fishery since 2002, it is assumed that fishery participation has continued to decline in more recent years. The current recreational harvest is not well quantified, but a majority of anglers engage in catch-and-release practices (Barshinger 2023).

Basin states with small recreational fisheries for river herring have recently restricted creel limits that were previously open year-round with no minimum length. Pennsylvania had a 35 fish/day creel limit for the recreational fishery from the mid-1980s until 2010 when it was reduced to 10 fish/day limit along with New Jersey upstream of the Commodore Barry Bridge, though the limited remained 35 fish/day downstream of the bridge (ASMFC 2024). In 2012, all recreational harvest of river herring in the Delaware River Basin was prohibited.

5.1.3 Management

In the Delaware River Basin, fishery management regulations have been in place for over 125 years and continue to evolve to protect American Shad and river herring populations. Early fishing regulations focused on increasing the survival and outmigration of juvenile American Shad from the Delaware River. Eel baskets, set up along rock walls that funneled fish into a fine mesh basket, indiscriminately captured all fish coming down river and ultimately caused high mortality of juvenile shad. Regulations were put in place to require eel weirs to have appropriate spacing between the racks to allow safe passage of juvenile shad migrating downstream (Sykes and Lehman 1957).

In more recent history (prior to 2012), commercial fishing for American Shad and river herring was permitted in New Jersey and Delaware, though the fishery had restrictions on participation including limited entry to the fishery, restrictions on the amount of gear and location where that gear could be fished (ASMFC 2020, ASMFC 2024).

The ocean fisheries are regulated by Fishery Management Councils, and both the Northeast and Mid-Atlantic Fishery Management Councils have taken management action in the past two decades to reduce harvest and bycatch of American Shad and river herring in ocean fisheries in response to declining river stocks. In 2005, the directed ocean fishery for American Shad was closed. No directed ocean fishery exists for Alewife or Blueback Herring, though, river herring are encountered as bycatch in the Atlantic Herring and Atlantic Mackerel fisheries. There are currently catch caps regulating the bycatch in both of these fisheries (ASMFC 2024).

In the Delaware River Basin, American Shad and river herring are currently managed by the Co-op and the Atlantic States Marine Fisheries Commission, with implementation of regulations by the Basin states. The Co-op, as required by the Atlantic States Marine Fisheries Commission, prohibited commercial and recreational harvest of river herring in

2012. A Sustainable Fishing Plan (SFP) for American Shad was initially produced in 2012 and was updated in 2017 and 2022 (DRBFWMC 2022). The SFP is required by Atlantic States Marine Fisheries Commission in order to allow a commercial and recreational fishery for American Shad. The SFP currently tracks six indices against benchmark values to determine the sustainable status of the stock. If one or more indices fall below their respective benchmark values, the Co-op can consider enacting management action to address the index whose values are not meeting desired levels. The SFP and any subsequent management actions are reviewed and approved by the Atlantic States Marine Fisheries Commission before being implemented by the respective Basin state agencies. Currently, commercial fishing for American Shad is only permitted in Delaware and New Jersey and is regulated by a quota restriction in New Jersey and by gear restrictions for the gillnet fishery in Delaware. For the recreational fishery, all Basin states implement a 2-fish daily creel limit (DRBFWMC 2022).

5.1.4 Impacts of Fishing

Fishing in freshwaters was a major contributor to population declines for American Shad and river herring in recent history (Brown et al. 2024). Besides the intense harvest depleting the population, consistent fishing pressure also alters the genetics and life history of fish stocks through time. These effects can include reducing the number of repeat spawners, reducing the maximum size and age of adults in fisheries that target larger individuals, and promoting early maturation of smaller fish (Kuparinen et al. 2016, Brown et al. 2024). Ultimately these life history modifications can destabilize a population, making restoration efforts less effective and more variable, and the impacts of sustained fishing pressure may remain even after the fisheries have ceased operation (Kuparinen et al. 2016). Although fishing regulations largely do not allow for significant harvest of American Shad and river herring populations from the Delaware River Basin, long-term impacts of historic fishing may still hinder restoration efforts.

5.2 Access to Habitat

Lack of access to spawning and nursery habitat in freshwater rivers is an important factor that has contributed to population declines for American Shad and river herring in many Atlantic Coast Rivers (ASMFC 2020, ASMFC 2024) and continues to be a threat to successful restoration (Hare et al. 2021). The Delaware River is unique in that it currently has no mainstem dams and is the longest undammed river east of the Mississippi River. The current unobstructed habitat area available in the Delaware River Basin represents 72% (93 of 130 square kilometers) of the historic habitat used by American Shad in the Basin (ASMFC 2020). The loss of available habitat is mostly attributed to the damming of the tributaries, including a number of dams on the Schuylkill and Lehigh Rivers, the largest tributaries to the Delaware River (Friedersdorff 1976).

The Nature Conservancy developed a restoration plan for American Shad and river herring in the Delaware River Basin which identifies high priority tributaries for restoration and high priority barriers for removal or improved fish passage (Figure 26, De Salvo et al. 2022). These identified high priority tributaries include the Schuylkill River, Brandywine River, White Clay Creek, Lehigh River, Pequest River, and Neshaminy Creek, and lower priority, but important tributaries include the Musconetcong River, Rancocas Creek, Cohansey River, and the East Branch of the Delaware River. Tributaries that are considered the highest priority for restoration have a suite of action items that, if implemented, could provide benefit to restoring and improving American Shad and river herring populations.

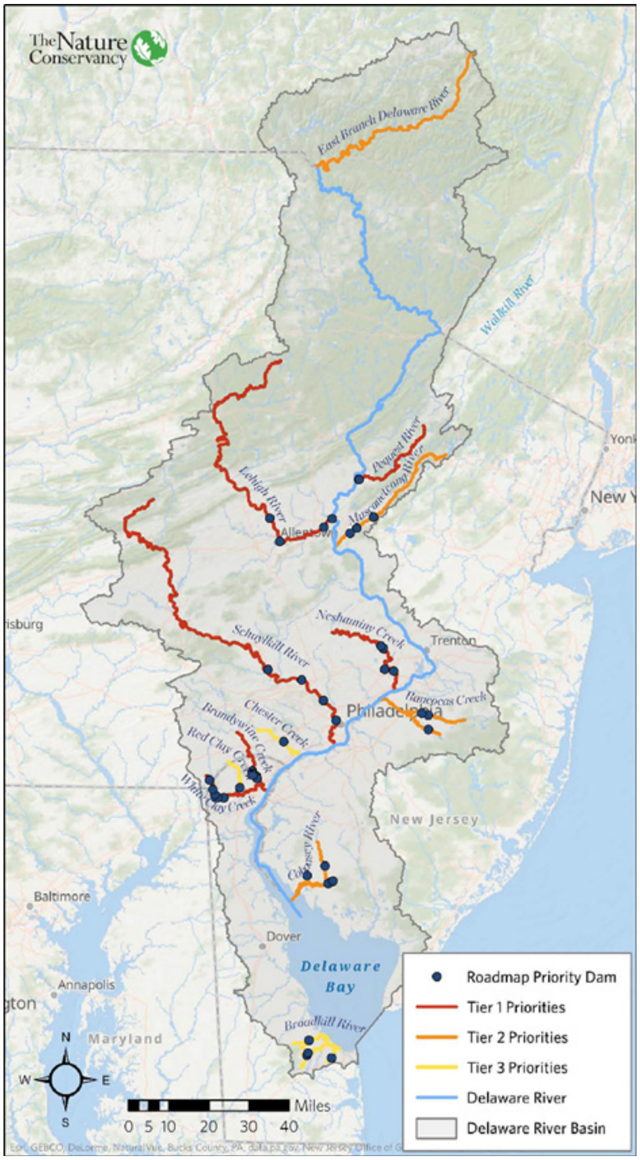

Figure 26. Priority ranking of dams and tributaries for restoration of American Shad and River Herring in the Delaware River Basin with Tier 1 being highest priority, Tier 2 a priority and Tier 3 is exploratory (taken from DeSalvo et al. 2022).

Both dam removals and fish passage facilities have been implemented in the Delaware River Basin to provide access to historic habitats. Unfortunately, traditional fish passage facilities have not typically been very effective in passing American Shad on the Atlantic Coast (Haro and Castro-Santos 2012), consistent with what has been observed for many fish passage facilities in the Delaware River Basin.

In the Schuylkill River, American Shad historically migrated 120 miles (160 rkm) upriver to Pottsville, Pennsylvania and spawning runs were estimated to be hundreds of thousands of fish (DeSalvo et al. 2022). Dam construction on the Schuylkill began in the 1700s and the construction of the Fairmount Dam (RM 8.7) in 1820 precluded shad runs to most of the river until fish passage was first installed at Fairmount Dam in 1979 (Perillo and Butler 2009). In the Schuylkill River, there are currently five remaining dams, and the lower four are outfitted with fish passage facilities (Figure 27), including Fairmount Dam (rebuilt in 2008), Flat Rock Dam (2007), Norristown Dam

(2007), and Black Rock Dam (2009). These fishways, in combination with several dam removals, have technically opened up 100 river miles to migratory fish in that river, but inefficiencies with fishways may still contribute to lack of habitat access for American Shad and river herring in the Schuylkill River and elsewhere in the Delaware River Basin. The first fishway on the Schuylkill at Fairmount Dam is well-maintained and operated by the Philadelphia Water Department. The Fairmount Fishway has passed an average of 1,000 American Shad per year in the past decade. The next dam upstream, Flat Rock, is maintained less frequently and has issues with debris accumulation at the fishway exit (USFWS 2017). Furthermore, the Flat Rock fishway was undergoing improvements and suffered damage in 2024 and is currently inoperable (Pennsylvania Fish and Boat Commission, personal communication with Dave Dippold June 11, 2024). Known issues with maintenance and operation have occurred at Norristown as well (USFWS 2017), and ultimately, very few migrating American Shad reach Black Rock Dam, which passed a total of 12 American Shad between 2011 and 2017 (USFWS, unpublished data).

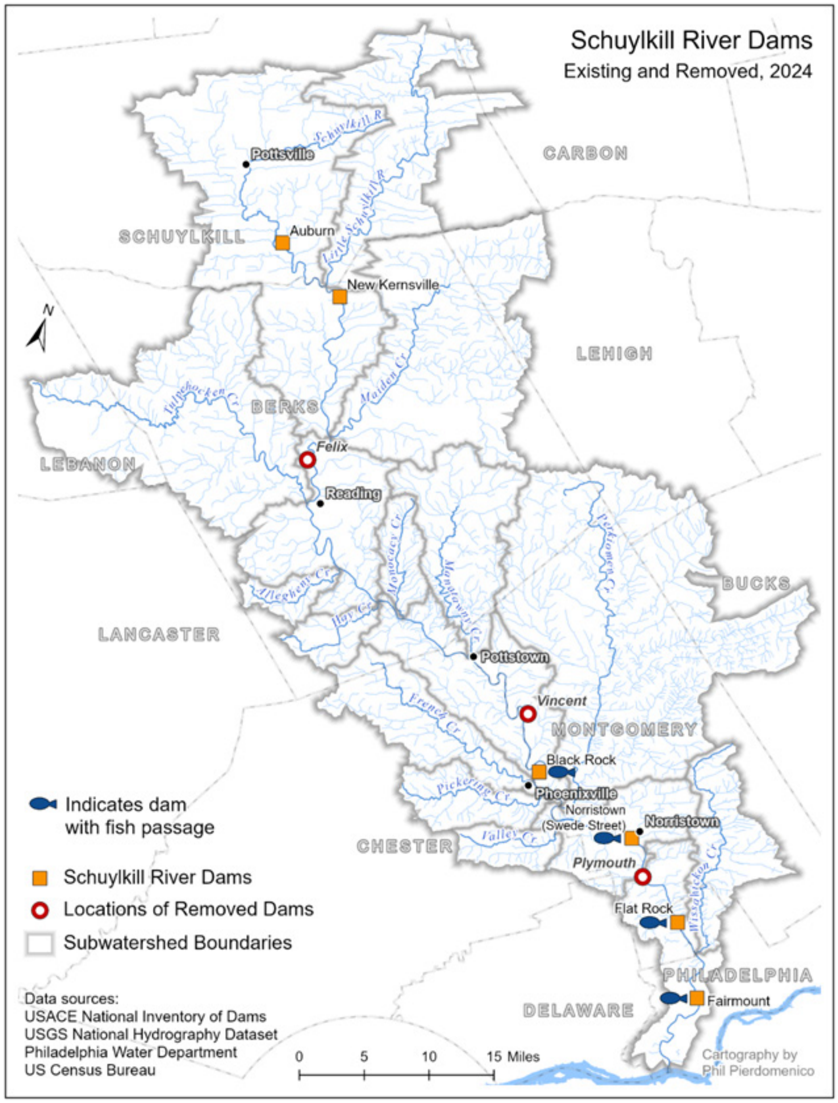

Figure 27. Locations of existing dams, removed dams, and fish passage facilities on the Schuylkill River.

On the Lehigh River, fishways have been built at Easton Dam (rebuilt in 2001), Chain Dam (rebuilt in 2001), and Hamilton Street Dam (1983), technically opening up 24 river miles to migratory fish. The Easton and Chain Dam fishways were assessed for fish passage by counting fish passing the viewing windows from 1996 to 2011 (PFBC 2010, DRBFWMC, unpublished data). The Easton Dam passed between 400 and 4,800 American Shad annually during that time and Chain Dam passed about 28% of what passed the Easton Dam (Figure 28). More recently, the Easton Fishway has experienced significant sedimentation and lack of maintenance that likely renders this fishway ineffective and potentially inoperable at times (personal communication, Jesus Morales, U.S. Fish and Wildlife Service Fishway Engineer). On the nearby Bushkill River, five dams were removed from the lower river between 2021 and 2024, reconnecting this historic tributary habitat back with the Delaware River mainstem (American Rivers 2019).

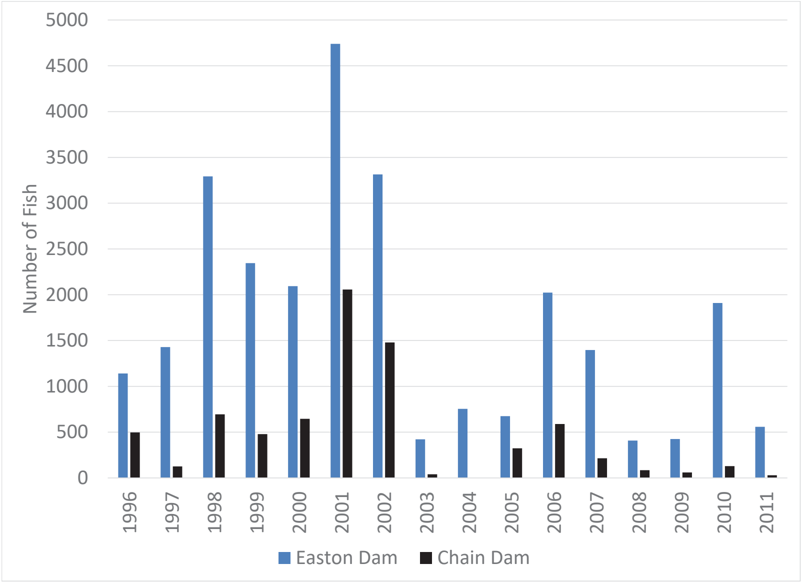

Figure 28. American Shad passage counts at the viewing windows of the Easton and Chain Dam fishways on the Lehigh River. Note Chain Dam was not monitored in 2004.

The Brandywine-Christina Basin, located in Delaware and Pennsylvania, was historically important habitat for American Shad and river herring and is largely inaccessible at this time. A total of 14 dams occur in the Brandywine River in American Shad and river herring habitat (DeSalvo et al. 2022). The first dam in Wilmington, Delaware was removed in 2019. Additional removals and fish passage facilities are being considered at upstream dams through the cooperative effort of the Brandywine River Restoration Trust. On White Clay Creek, a total of eight dams are located in historic spawning habitats. Removal of the first dam on White Clay Creek occurred in 2014 and additional dams are being evaluated for removal (DeSalvo et al. 2022).

In northern New Jersey, the Paulins Kill, Pequest River, and Musconetcong River are significant tributaries with historic American Shad and river herring habitat. Habitat restoration work and dam removals have been conducted on these rivers over the past two decades to improve access (American Rivers 2019, De Salvo et al. 2022). In the Paulins Kill, three significant barriers occurred in the historic spawning and nursery habitat for American Shad and river herring, and all have been removed, including the Columbia Lake Dam (2019), Paulina Dam (2023), and County Line Dam (2022). In the Pequest River, the Cedar Grove Dam, located at river mile 3.5 was the first dam removal completed on this river in 2024, though two dams continue to block the tributary near its confluence with the Delaware River. On the Musconetcong River, several dams have been removed, notably the Finesville (2011) and Hughsville (2016) Dams. The next significant barrier to migratory fish movement in this river is the Warren Glen Dam.

In all, over 150 dam removals have occurred in the Delaware River Basin (American Rivers 2019), many of which have occurred in historic spawning and nursery habitat of American Shad and river herring. Dam removals are an effective way to provide access to historic habitats and usually require no long-term maintenance, unlike fish passage facilities. Fish passage facilities currently exist on 11 of the 45 priority dams in historic American Shad and river herring habitats in the Delaware River Basin as identified by The Nature Conservancy (DeSalvo et al. 2022). As suggested in the preceding summaries of habitat access in the Schuylkill and Lehigh rivers, relatively few of the fish passage facilities are monitored or maintained during the fish passage season and passage effectiveness at many of the fishways is thought to be nominal at best (USFWS 2017, De Salvo et al. 2022).

Besides the examples from the Schuylkill and Lehigh rivers on fish passage facility effectiveness, a recent study in New Jersey shed additional light on fish passage effectiveness in the Delaware River Basin. In the heavily urbanized Cooper River, runs of American Shad and river herring were extirpated by the 1970s due to poor water quality and exacerbated by the construction of the Kaighn Avenue Dam in 1938 (Keller et al. 2024). Water quality improvements through time have supported return of American Shad and river herring runs to the river, and a fishway was installed at the dam in 1998. By 2004, low numbers of American Shad and Blueback Herring juveniles were being collected. In a directed study conducted from 2022 to 2023, adult American Shad and river herring were collected both upstream and downstream of the Kaighn Avenue Dam, though fish densities were much higher downstream of the dam compared to upstream, despite a fish ladder being present (Keller et al. 2024). This study further supports the inefficiency of the fish passage facility on this dam.

Future efforts are planned in several Delaware River tributaries to continue to conduct dam removals and installation of fish passage facilities where dam removals are not possible. Focused watershed efforts continue on the Brandywine[2], Musconetcong[3], and

2 https://brrt.org/) accessed March 5, 2025.

3 https://www.musconetcong.org/) accessed March 5, 2025.

Paulins Kill [4] Rivers as well as a number individual projects at various locations throughout the watershed. Pennsylvania continues to be a national leader in dam removal projects, many of which occur in the Delaware River Watershed[5].

Besides physical barriers to fish passage that exist on many Delaware River tributaries, other factors that limit access to historic habitats stem from water quality issues in the estuary and tributaries (see section 5.4) and water management in the upper Delaware River Basin. Water releases from the New York City reservoirs at Cannonsville, Pepacton, and the Neversink impact shad distribution and spawning success in both the East and West branches of the Delaware River. Cold water releases in the West Branch from the Cannonsville reservoir first occurred in 1964. Juvenile shad were routinely caught in the West Branch prior to the initiation of these cold-water releases (Miller et al. 1982). Releases in the early years could drop the water temperature in the West Branch as much as 26°F (14 ° C) and those impacts extended down river for 43 miles to Callicoon. Water temperatures in the West Branch in the summer are consistently below 50°F (10 ° C) in spring and summer, with slight temperature increases in the fall (Miller et al. 1982, USGS gage 0142500 at Stilesville, New York[6]). Although water temperatures increase somewhat closer to the confluence of the West Branch with the East Branch at Hancock, New York, water temperatures are typically below 68°F (20 °C), even in the warmest summer months (USGS gage 01427000 at Hancock, New York[7]). The cold-water releases in the West Branch preclude that system from supporting spawning and nursery habitat for American Shad (Miller et al. 1982). Lack of cold-water releases in the East Branch has allowed American Shad to continue to reproduce in that system. In early years of reservoir management, the lack of water releases from Pepacton and Neversink reservoirs contributed to thermal stress and increased mortality of American Shad in the East Branch (Miller et al. 1982). Over the years, flow releases from all reservoirs have been modified, and are most currently operated under the Flexible Flow Management Program (FFMP 2017) that generally improves thermal and flow conditions for all fish in the upper Delaware River Basin, though the West Branch continues to be too cold for successful American Shad spawning and rearing.

5.3 Predation

The complex life history of American Shad and river herring presents a range of encounters with predators in each life stage and in the varied habitats they occupy. As forage fishes, American Shad and river herring are an important food source for many aquatic species

4 https://www.nature.org/en-us/about-us/where-we-work/united-states/new-jersey/stories-in-new-jersey/the-columbia-lake-dam/) accessed March 5, 2025.

5 https://www.americanrivers.org/media-item/american-rivers-report-2024-tied-for-most-ever-dams-removed-in-us-underscoring-momentum-for-river-restoration/ accessed March 5, 2025.

6 https://waterdata.usgs.gov/nwis/uv?01425000 accessed March 5, 2025

7 https://waterdata.usgs.gov/nwis/uv?site_no=01427000&legacy=1 accessed March 5, 2025

and facilitate energy transfer among trophic levels (Hare et al. 2021). Predation occurs in both freshwater and marine habitats from fishes, birds, mammals, and macroinvertebrates (Greene et al. 2009). Although limited information is available on direct predation studies in the Delaware River Basin, predation research on American Shad and river herring from adjacent or nearby populations can provide insight as the food webs have many overlapping predator species.

5.3.1 Riverine Predation

Like many fish species, American Shad and river herring are broadcast spawners and do not provide any care for offspring. Once eggs are expelled from a female, eggs disperse through the water column and are immediately susceptible to predation from a variety of fishes. As broadcaster spawners, egg predation can be mitigated as hundreds of thousands of eggs can occupy the water column during a spawning event. Additionally, as mentioned in previous sections, spawning occurs after sunset over months and at different locations throughout the watershed further increasing the predators encountered. Once suspended eggs settle into the substrate, benthic fishes and macroinvertebrates are added as suspected predators. As eggs hatch into larvae, motility remains limited, continuing predation from fishes and macroinvertebrates. American Shad eggs, larvae, and juveniles are preyed upon primarily by American Eel (*Anguilla rostrata*) and Striped Bass (*Morone saxatilis*) or any fish large enough to consume them, while Alewife larvae are preyed upon by White Perch (*Morone americana*), Yellow Perch (*Perca flavescens*) and Spottail Shiners (*Notropis hudsonius*) (Walburg and Nichols 1967, Greene et al. 2009). Of these predator species, Striped Bass and White Perch are estuarine species, but can occur in freshwater upstream to at least Trenton, New Jersey for Striped Bass[8] and New Hope, Pennsylvania for White Perch (Lorantas et al. 2005). The American Eel is prevalent throughout the freshwater portion of the river as well as a variety of game and non-game fish, including those encountered during Pennsylvania Fish and Boat Commission seine surveys for juvenile American Shad (modified list in Appendix A). All freshwater species listed are potentially predators that may opportunistically feed on American Shad and river herring eggs, larvae, and juveniles if encountered. Past studies in the Susquehanna River Basin investigated predation of stocked American shad larvae and found all fish species collected downstream of stocking events ingested larvae (Johnson and Dropkin 1992).

As the season extends, larger juvenile American Shad and river herring migrate throughout the waterway. As fish increase in size, they become more attractive to mammals, birds, and larger piscivorous fishes. Noll and Vile (2024) sought to investigate predation rates on juvenile American Shad by examining stomach contents of suspected predators captured during Pennsylvania Fish and Boat Commission's non-tidal juvenile American Shad seine survey in 2022. Under the conditions of the study, stomach contents categorized as

8 NJDEP| Fish & Wildlife | Delaware River Striped Bass Recruitment Seine Survey

"fish" were collected from Black Crappie (*Pomoxis nigromaculatus*), Largemouth Bass (*Micropterus salmoides*), Rock Bass (*Ambloplites rupestris*), and Walleye (*Sander vitreus*). In these predatory fish, 18 had fish in their stomach contents, and four of the stomachs contained juvenile American Shad. Although temperature requirements for Brown Trout (*Salmo trutta*) and Rainbow Trout (*Oncorhynchus mykiss*) generally preclude successful reproduction for American Shad, in places where spawning and rearing habitat overlap with trout habitat, predation of American Shad egg, larvae, and juveniles are likely to occur.

Adult American Shad are generally large enough to avoid predation by most native fish in the freshwater areas of the Delaware River, though Striped Bass, predatory birds (cormorants, eagles, herons) and river otters may still consume adult shad (Greene et al. 2009, ASMFC 2020). There are a number of non-native predatory fish species in the freshwater Delaware River that can prey on shad and herring that will be covered later in this section.

5.3.2 Estuarine Predation

American Shad and river herring also occupy the estuarine waters of the Delaware Estuary and Delaware Bay. Similar to the juvenile American Shad seine surveys conducted by the Pennsylvania Fish and Boat Commission in freshwater, the New Jersey Department of Environmental Protection conducts a seine survey in the Delaware Estuary targeting young-of-year Striped Bass. This survey also encounters juvenile American Shad, river herring and several potential predatory fish (Appendix B). In addition to the seine survey, the Delaware Division of Fish and Wildlife conducts two trawl surveys in the Delaware Bay that also can provide insight on potential predators of American Shad and river herring (Oleynik et al. 2024). Likely predators of American Shad and river herring captured in the estuary surveys include: Atlantic Croaker (*Micropogonias undulatus*), Bluefish (*Pomatomus saltatrix*), Hogchoker (*Trinectes maculatus*), Scup (*Stenotomus chrysops*), Spot (*Leiostomus xanthurus*), Smooth Dogfish (*Mustelus canis*), Spotted Hake *(Urophycis regina*), Striped Bass, Weakfish (*Cynoscion regalis*), and White Perch. A literature review by Greene et al. (2009) also lists juvenile/estuarine American Shad and Alewife predation from American Eel, Bluefish, Striped Bass, Weakfish, birds, and aquatic mammals.

Striped Bass are notable predators of migrating river herring in estuaries as they head to upstream spawning habitats. Predation can occur at a level significant enough to perpetuate a local collapse of river herring populations (summarized in Hare et al. 2021). The impacts of Striped Bass predation on American Shad are less clear. In the Connecticut River, there was substantial evidence to indicate Striped Bass populations caused a decline in American Shad populations (Savoy and Crecco 2004) and predation by Striped Bass on river herring is prevalent in a number of systems (Walter and Austin 2003). However, a review of Striped Bass and American Shad populations by the Atlantic States Marine Fisheries Commission in 2020 could not find a clear relationship between increasing Striped Bass abundance and declining American Shad populations, suggesting other factors besides Striped Bass predation may be limiting or reducing American Shad populations (ASMFC 2020).

5.3.3 Atlantic Ocean Predation

American Shad and river herring range the Atlantic Ocean from the Gulf of St. Lawrence, Canada to the St. Johns River, Florida and migrate seasonally, which allows for substantial predator interactions in the Atlantic Ocean. As important forage fishes, ocean predation on American Shad and river herring extends to many species including fishes, seabirds, marine invertebrates, and mammals (Green et al. 2009, ASMFC 2020, Hare et al. 2021, DRBFWMC 2022, Brown et al. 2024). While some animal groups are more likely to occur in specific regions, such as pinnipeds in northern waters (Leach et al. 2022), other groups occur coastwide, such as whales, dolphins, porpoises, tunas, billfishes, and sharks. Specific to Delaware River American Shad, data from the New Jersey Department of Fish and Wildlife's tagging program revealed 60 percent of American Shad tagged at Reed's Beach, Cape May County, New Jersey, were recaptured outside of the Delaware Basin and ranged from the St. Lawrence River, near Quebec, Canada to the Santee River in South Carolina (DRBFWMC 2022).

Ocean harvest of American Shad reveals the wide distribution along the coast and beyond boundary waters as reports of American Shad were recorded outside the 200-mile limits of Mid-Atlantic and New England states (DRBFWMC 2022). In addition to migratory patterns, American Shad and river herring can occupy different zones in the water column; the Atlantic States Marine Fisheries Commission (2020) reported incidental catch of American Shad in large-mesh gill nets, small-mesh bottom trawls, and paired midwater trawls. Similarly, the Northeast Area Monitoring and Assessment Program Trawl Survey, indicated limited information on predation, however four predator stomachs from 2007-2017 were identified to contain American Shad (two Spiny Dogfish (*Squalus acanthias*); one Monkfish (*Lophius sp.*); and one Striped Bass) (ASMFC 2020). While Striped Bass are commonly identified as an influential predator, mature American Shad do not appear to be an important food item for them along the Atlantic coast (ASMFC 2020).

Brown et al. (2024), in a review of northwest Atlantic *Alosidae*, noted several ocean predators. Alewife have been shown in diets of demersal groundfish and have been suggested to influence ocean predator movement behavior. Blueback Herring predation in the ocean is mostly attributed to Atlantic Cod (*Gadus morhua*), Atlantic Halibut (*Hippoglossus hippoglossus*), Bluefish, Hake spp., Spiny Dogfish, Striped Bass, Weakfish, seals, gulls and terns. American Shad, in the ocean, are preyed on by Bluefin Tuna (*Thunnus thynnus*), Kingfish (*Scomberomorus cavalla*), sharks, and porpoises.

5.3.4 Predation by Invasives

Several of the riverine predatory species are not native, but introduced due to their recreational value, such as Black Bass spp., Brown Trout, Channel Catfish (*Ictalurus punctatus*), Muskellunge (*Esox masquinongy*), and Rainbow Trout (DRBFWMC 2021). Additionally, Common Carp, known throughout United States rivers, may predate anadromous fish eggs and can account for substantial biomass within occupied systems (Waldman and Quinn 2022). Though previously introduced species have become naturalized to river systems, new and invasive fish species have increased in numbers or expanded their range within the Delaware River Basin in recent years, including the Blue Catfish (*Ictalurus furcatus*), Flathead Catfish (*Pylodictis olivaris*), Northern Snakehead (*Channa argus*), Freshwater Drum[9] (*Aplodinotus grunniens*), and Asian Swamp Eels (*Monopterus albus*) (DRBFWMC 2021, Smith et al. 2021, DeSalvo et al. 2022). Northern Snakehead were first documented in the Delaware River Basin in 2004, and currently have a widespread distribution in the Basin[10]. Although large Northern Snakehead are unlikely to prey on adult American Shad and river herring, snakeheads are known to consume juvenile river herring. Blue Catfish and Flathead Catfish are known to consume American Shad and river herring (Figure 29; Schmitt et al. 2017, Schmitt et al. 2019, Stark et al. 2024). Blue Catfish are more recent invaders of the Delaware River, with first reports around 2020 and currently range from mid-Delaware Bay to Trenton, New Jersey[11]. Flathead Catfish were first observed in the Delaware River Basin at the Fairmount Fishway in the Schuylkill River in 1999 and their range has been expanding since that time (Smith et al. 2021). Both catfish species can attain a large size and seem to favor feeding at river barriers and areas of constriction where they can effectively target American Shad and river herring (Schmitt et al. 2017). In the Delaware River Basin, Flathead Catfish are known to occupy the fishways in the Schuylkill River (Figure 30; DeSalvo et al. 2022) where they can predate on American Shad and river herring as they attempt to pass upstream. Additional invasives species present in adjacent waterbodies could also impact American Shad and river herring populations if they were to be transferred to the Delaware River Basin, including the Round Goby (*Neogobius melanostomus*) through direct predation on eggs and larvae and the zebra mussel (*Dreissena polymorpha*) by disrupting the ecosystem (Waldman and Quinn 2022, Chang et al. 2024). As populations of introduced and invasive species increase and ranges expand, American Shad and river herring populations can be particularly stressed considering populations are already at low levels (ASMFC 2020).

As naturalized non-native fish and invasive fish species occur throughout the Basin their removal is unlikely, therefore restoration potential for American Shad and river herring could be permanently altered (DRBFWMC 2021). Changing environmental conditions and water quality improvements may alter American Shad and river herring distribution

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9 https://nas.er.usgs.gov/queries/CollectionInfo.aspx?SpeciesID=946&State=PA

10 https://nas.er.usgs.gov/viewer/omap.aspx?SpeciesID=2265

11 https://nas.er.usgs.gov/viewer/omap.aspx?SpeciesID=740

in the Delaware River Basin, which may expose these fish to changing levels of predation depending on distribution and abundance of non-native piscivorous fish.

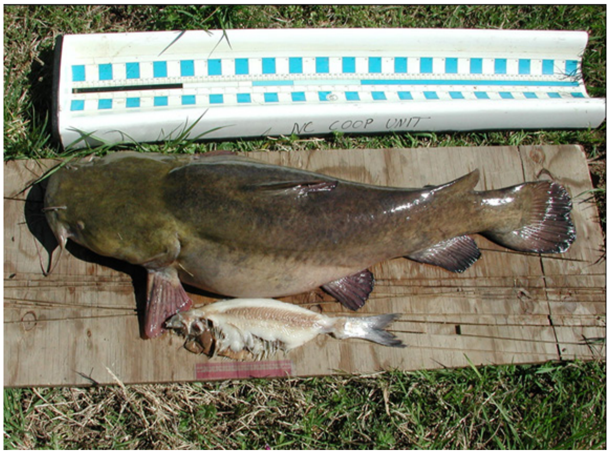

Figure 29. Flathead Catfish with American Shad in stomach contents (photo credit J. Hightower).

Figure 30. Flathead Catfish and Channel Catfish in the Flat Rock Fishway on the Schuylkill River after draining in July 2017 (photo credit U.S. Fish and Wildlife Service).

5.4 Water Quality

Historically, poor water quality in the tidal zone of the river is thought to be one of the leading causes of the decline of American Shad populations in the Delaware River. Significant pollution problems occurred in a 60-mile section of the tidal estuary between Wilmington, Delaware and Trenton, New Jersey. Though concerns over water quality were first noted around 1800, the most degraded state of the river occurred by the 1940s due to high organic loads to the river depleting dissolved oxygen levels (Kauffman 2010). Periods of zero dissolved oxygen occurred from Mid-May to early December in the Philadelphia area (from Chester, Pennsylvania (rkm 132) to the Benjamin Franklin Bridge (rkm 161), Miller et al. 1982). Not only did the poor water quality of the tidal river eliminate spawning and juvenile American Shad habitat in that section of the river, but it also created a seasonal barrier that limited the time period for safe migration upstream or downstream through that portion of the river (Friedersdorff 1976). Poor water quality in the tidal river was attributed to eliminating repeat spawning for American Shad by effectively creating a zone of no dissolved oxygen that killed shad while migrating back to the ocean after successfully spawning upstream (Sykes and Lehman 1957, Friedersdorff 1976). In the 1950s, 98% of adult American Shad were first-time spawners, which was substantially more than the Connecticut River (35%) and Hudson River (51%) (Sykes and Lehman 1957). In some years, even juvenile American Shad migrating through the tidal river in the fall suffered heavy mortality due to poor water quality, primarily low dissolved oxygen (Sykes and Lehman 1957). Juvenile survival through the lower river was thought to be higher in years with higher rainfall that may have diluted the pollutants in the tidal river and increased dissolved oxygen levels (Sykes and Lehman 1957).

Established in 1961, the Delaware River Basin Commission was created to address pollution and mitigate flooding within the watershed. By the late 1960s, the Commission implemented waste load allocation requirements for treatment facilities, leading to significant reductions in the carbonaceous biochemical oxygen demand (CBOD) of discharged wastewater (DRBC 2022). In 1967, the Delaware River Basin Commission established a designated aquatic life use of "maintenance" for resident and migratory fish moving through the estuary. This meant that dissolved oxygen levels should be at least 3.5 mg/L to ensure that fish can survive in that section of river, acknowledging that propagation would not be supported by this level of dissolved oxygen. Since the regulatory requirements of the late 1960s, a relatively steady improvement to water quality and the resulting dissolved oxygen levels in the tidal river has occurred over the past six decades (Figure 31). As a result of the improvements to water quality in the estuary, abundance of American Shad as well as other species substantially increased by the 1990s (Weisberg et al. 1996).

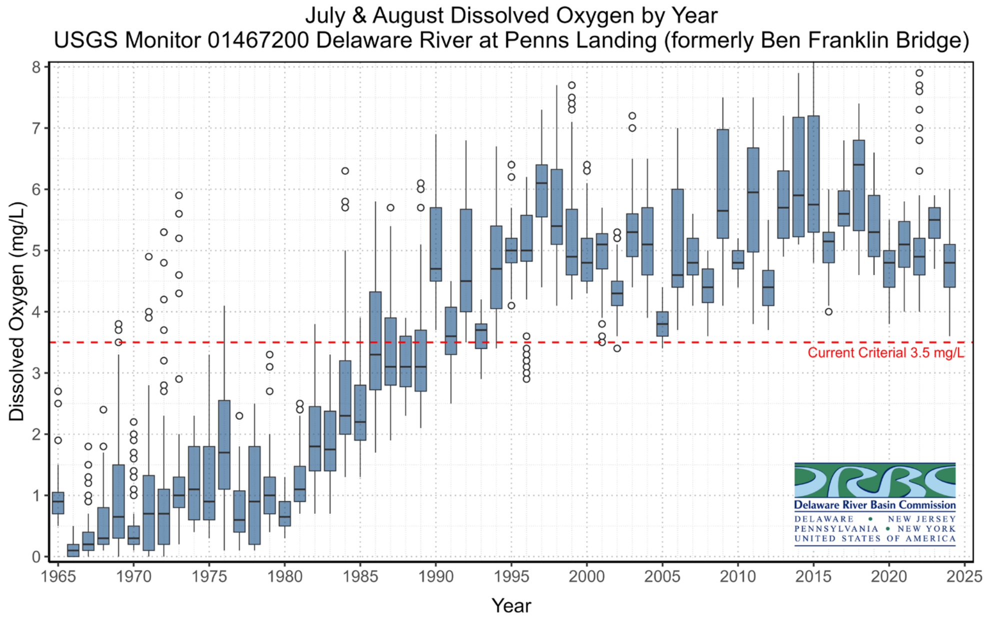

Figure 31. Dissolved oxygen levels in the Delaware River estuary from 1965-2024. Source: Delaware River Basin Commission (https://www.nj.gov/drbc/library/images/DO_July-Aug_DelRvr_PennsLanding1965-2024.jpg, accessed March 24, 2025)

In the past decade, the estuary generally experiences summertime dissolved oxygen levels at 5 mg/L or higher, which would support propagation for American Shad, river herring, and many other species. In 2017, the Delaware River Basin Commission initiated the process for a rule change to officially recognize propagation as an aquatic life use in the Delaware River Estuary (DRBC 2017). This proposed rule change would memorialize the decades-long improvement to dissolved oxygen levels and prohibit the backsliding of water quality parameters in the future. Working with the Delaware River Basin Commission, the Environmental Protection Agency (EPA) is currently in the rule-making process to develop new water quality criteria for the Delaware River Estuary to increase the dissolved oxygen requirements to support propagation as a designated use (Federal Register 2023). In response to the improvements in dissolved oxygen, springtime fisheries surveys in the estuary the past several years have been encountering increased abundance of adult American Shad (Pennsylvania Fish and Boat Commission, personal communication), indicating that spawning may be occurring in the estuary again after more than a century of being precluded from reproducing in that section of the Delaware River.

In addition to the Delaware River estuary, poor water quality in its tributaries also hindered successful reproduction (Friedersdorff 1976). The Cooper River in New Jersey is experiencing a return of shad coinciding with improving water quality conditions (Keller et al. 2024). Historically, American Shad were also precluded from spawning in the Schuylkill River due to significant industrial activity, mining, and other forms of development within the watershed that severely impaired water quality (Kauffman et al. 2011). Shad runs have returned to the Schuylkill River following a suite of regulations and industry changes that have improved water quality in more recent years. However, there are still substantial areas of land development in the Basin that has the potential to negatively impact water quality and subsequent reproduction and recruitment of American Shad and river herring (Figure 32).

Other water quality factors may influence survival and recruitment of American Shad and river herring in the Delaware River Basin, including salinization, turbidity, and emerging contaminants. Chloride levels in the freshwater portion of the Delaware River have been increasing in recent decades due to application of road salts and other de-icing compounds (Figure 33). Increased levels of chlorides can have negative impacts on fish and other aquatic species (Hintz and Relyea 2019), though direct impacts to American Shad and river herring reproduction and recruitment are unknown. American Shad are also sensitive to turbidity and siltation which can hamper reproductive success at levels >100 mg/L (Kjelland et al. 2015). Environmental contaminants may pose both lethal and sub-lethal risks to American Shad and river herring; however, these threats remain under-researched, and many of the associated pollutants are not yet subject to regulatory oversight

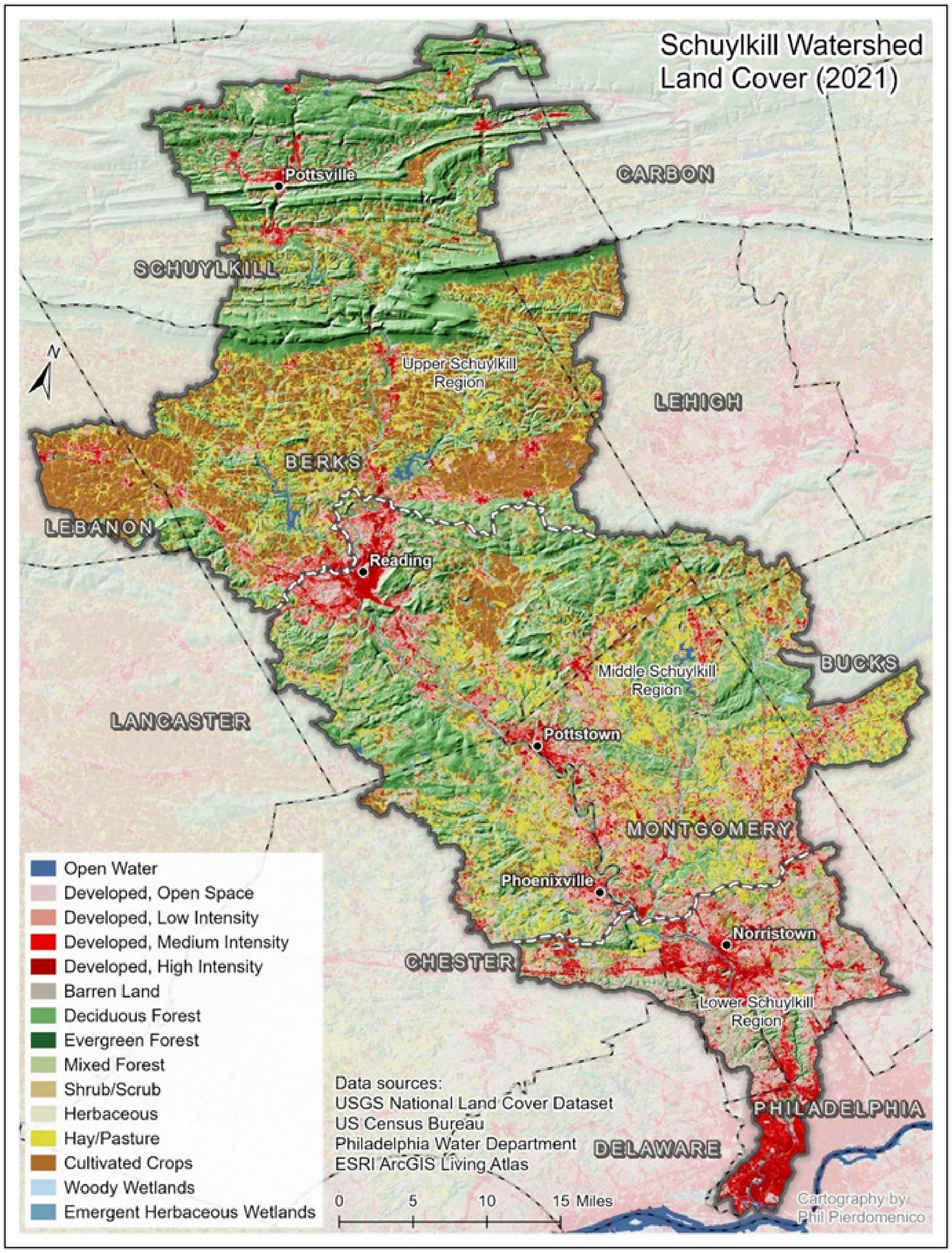

Figure 32. Schuylkill River Basin land use coverage in 2021.

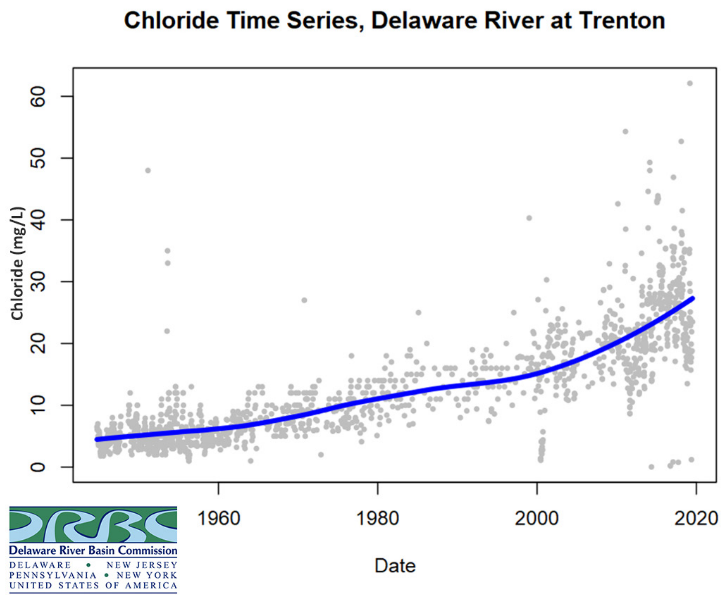

Figure 33. Chloride levels in the Delaware River at Trenton, New Jersey (https://www.nj.gov/drbc/library/images/chlorides_trenton_timeseries_drbc.jpg, accessed March 24, 2025).

5.5 Dredging, Channelization and In-Water Work

The Delaware River Basin, particularly in the estuary and bay, frequently is subject to in-water construction activities to support transportation improvements, including deepening river channels and constructing and repairing piers and bridges. In-water work, such as pile-driving, channel dredging, and other habitat alterations, can impact American Shad habitat use and behavior through generation of underwater noise, increased sedimentation, and lowered dissolved oxygen levels.

American Shad and river herring are particularly sensitive to underwater noise (Mann et al. 2001, Reine and Dickerson 2014). The frequency and severity of the noise can cause avoidance behavior or even injury and mortality (Hastings and Popper 2005). Noise generated during spawning migrations can move fish off course, potentially requiring them to exert extra energy to avoid noisy areas. Underwater noise can also alter the distribution of juvenile fish, precluding access to available rearing habitats (Hastings and Popper 2005). Dredging and in-water construction can impact water quality (Reine et al. 1998). American Shad eggs and larvae suffer mortality when exposed to sediment plumes (Wilber and Clarke 2001). Sediment accumulation may obstruct gill function in adult Shad, diminishing their respiratory efficiency and capacity to uptake dissolved oxygen (Greene et al. 2009). Dredging results in increased channelization which can increase water velocities and reduce habitat variability in migration corridors, requiring an increase in energy spent during spawning migrations (Greene et al. 2009). To minimize impact of in-water work to American Shad and river herring, the Co-op has developed a time-of-year restriction document to recommend when certain in-water activities should be avoided in the Delaware River Basin (DRBFWMC 2012).

5.6 Impingement/Entrainment (I&E)

There are forty water intake systems at energy projects in the Delaware River Basin that rely on withdrawal of surface water from the Delaware River and tributaries to cool their industrial processes (Thompson and Pindar 2021). This withdrawal results in mortality of fish and other aquatic organisms by either becoming trapped against the intake screens (impingement) or by passing through the plant's condenser cooling system and being returned to the river (entrainment). Organisms entrained in cooling water systems may suffer physical injury from contact with condenser equipment or experience thermal stress from elevated water temperatures during passage through the facility, potentially resulting in sub-lethal effects or mortality. Although total impingement/entrainment of American Shad and river herring is currently unquantified, some projects can entrain millions of eggs and tens of thousands of juveniles, resulting in potentially substantial cumulative impacts (ASMFC 2020).

In a study conducted by the U.S. Environmental Protection Agency (EPA) examining impingement and entrainment (I&E) impacts at twelve major thermoelectric water intake structures in the Delaware River estuary from 1978 to 1998, annual losses of age-1 equivalent American Shad, Alewife, and Blueback Herring were estimated (EPA 2002). Determining Age-1 equivalents applies natural survival estimates to the eggs, larvae, and juveniles that were killed through I&E, to generate the number of individuals that would have otherwise reached age 1. The annual average of I&E losses of age-1 equivalents during the study were 23,615 Alewife, 2,122 American Shad, and 103,606 Blueback Herring. The Salem Nuclear Generating Station was estimated to be the largest withdrawal facility in the estuary during that time period (EPA 2002).

Changes to I&E impacts have occurred in the Basin since the 2002 report from EPA. In 2014, EPA enacted new regulations requiring best available technology to be used at cooling water withdrawal facilities that used more than 2 million gallons per day (MGD) to reduce I&E impacts (Federal Register 2014). About three-quarters of the current thermoelectric facilities in the Delaware Estuary meet this level of daily water withdrawals, triggering the requirement of additional protections from I&E losses. In recent years, some coal-fired plants have closed or been converted to more efficient energy generating stations, requiring less cooling water withdrawals and lessening the I&E impacts on aquatic resources of the river.

However, the lower portion of the Delaware River Basin continues to produce large amounts of power, ranking second in the country within a HUC-6 boundary with facilities generating nearly 20,000 MW of power annually (Thompson and Pindar 2021). The primary sources of power are nuclear, natural gas and coal, and most cooling systems are still once-through systems with cumulative withdrawals from all projects at more than 3,500 MGD (Thompson and Pindar 2021). Withdrawals have declined in the Basin for thermoelectric projects since the early 2000s. Forecasting through to 2060, withdrawals are expected to decline slightly but continue to stay above 3,000 MGD.

Although it is assumed that decreased withdrawals in recent years combined with best management practices at larger thermoelectric water intake facilities are reducing the I&E losses for American Shad and river herring, data have not been collected in recent years to assess I&E impacts to these species. In addition, American Shad may now be spawning in the estuary, coinciding with improved water quality, that may increase their susceptibility to I&E losses (DRBFWMC 2022).

5.7 Shifting Environmental Conditions

Among marine species, diadromous fish such as American Shad, Alewife and Blueback Herring are predicted to be highly vulnerable to the impacts of ongoing shifts in environmental conditions (Hare et al. 2016). Due to their life history, the production, abundance, and distribution of these species are influenced by factors occurring both within estuarine habitats as well as throughout the broader oceanic environment. Potential shifts in water temperature, salinity, dissolved oxygen, pH, circulation patterns, and hydrology may all therefore have variable and disproportionate impacts on diadromous fish populations compared to other fish species (Staudinger et al. 2024). American Shad and river herring also exhibit sensitivity attributes such as habitat specificity and complex reproductive strategies that may limit their ability to adapt to novel conditions (Morrison et al. 2015).

Temperature changes, in particular, represent a key influence on future outcomes for American Shad and river herring populations. Temperature is considered a driving factor in fish physiology due to its direct connection with growth and overall fitness (Magnuson et al. 1979; Wagner et al. 2017). Recent laboratory studies have shown that exposure of juvenile Alewife and Blueback Herring to higher temperatures may result in lower survival and smaller size (Guo et al. 2021; Guo et al. 2022). Similarly, coast-wide modeling of American Shad growth rates and survival suggest that increasing temperatures will reduce individual fish size and lead to increased mortality (Gilligan-Lunda et al. 2021). Though survival rates have an obvious effect on population dynamics, trends toward smaller individuals may also negatively impact species abundance. Similar to other fish, smaller adult American Shad and river herring are likely less fecund and produce fewer offspring than larger individuals (Olney and McBride 2003; McBride et al. 2016; Marjadi et al. 2019).

In addition to physiological implications, temperature changes may impact the timing and success of diadromous fish reproduction. Although factors such as photoperiod, water flow, and turbidity influence the spawning phenology of anadromous fish, temperature is considered the primary trigger for spawning of American Shad and river herring (Leggett and Whitney 1972; O'Connell and Angermeier 1997). Movement toward spawning grounds, initiation of spawning, and egress from freshwater habitats have all been found to occur within specific temperature windows for each species (Greene et al. 2009). Timing of spawning migrations has already been observed shifting 1-3 weeks earlier in multiple species due to earlier warming of water temperatures in the spring (Ellis and Vokoun 2009; Lombardo et al. 2020). Earlier and more-rapid vernal warming in river systems may further truncate the spawning windows of American Shad and river herring by inducing earlier egress of adults (Lombardo et al. 2020).

Changing weather patterns and the potential for increased stochasticity in stream flow and water levels could also negatively impact the spawning and recruitment success of diadromous species. Given that American Shad and river herring exhibit homing to their natal spawning grounds, individuals may not have the ability to shift their spawning habitats to new locations when conditions become unfavorable (Lynch et al. 2015). Together, altered hydrological conditions, compressed spawning season length, and the high potential for mismatch with other seasonal environmental variables are likely to threaten the future production of American Shad and river herring.

Changing environmental conditions will also impact the oceanic life phase of American Shad and river herring. Though responses to temperature vary depending on population and life stage, species distributions on a broad scale are often tied to preferred thermal ranges (Araújo and Peterson 2012). Shifts are expected both in the distribution and abundance of zooplankton communities that serve as a food source for adult shad and river herring, as well as the predators that target or compete with these fishes (Richardson and Schoeman 2004; Portner and Peck 2010; Barton et al. 2016; Nack et al. 2019). For American Shad, Alewife, and Blueback Herring, rising ocean water surface temperatures already present suboptimal foraging conditions and have been associated with an observed shift in their distribution northward along the Northeast Atlantic shelf region (Nye et al. 2009; Friedland et al. 2013). Poleward shifts are expected to continue for many Northeast Atlantic fish stocks in the future. In combination with changing ocean circulation patterns, these shifts in distribution and abundance for multiple species will impact energy budgets and predator-prey relationships for American Shad and river herring at sea. However, the exact implications and magnitude of potential trophic effects caused by these changes are currently unknown and warrant further study (Hare et al. 2021).

Research suggests that the combined impacts of shifting environmental conditions are likely to reduce available habitat and increase mortality for American Shad and river herring across different phases of their life cycle. Though potential broad-scale effects of threats such as increasing ocean acidification are not well-understood for fish species, it is likely that these variables will further complicate the response of American Shad and river herring to warming and shifting conditions. The negative population outcomes caused by these changes will only serve to exacerbate the effects of current threats already described herein (e.g. dams, predation) (Cobb 2020, German et al. 2023). Additionally, studies have suggested that sensitivity increases under low abundance scenarios, such that smaller populations will have a greater likelihood of being impacted by future changes (Lynch et al. 2014).

6. Actions Needed to Improve Abundance and Expand Distribution

To effectively enhance the abundance of American Shad and river herring in the Delaware River Basin, resource managers require updated and comprehensive information on the sources of mortality affecting these depleted populations. In recent years, commercial fishing landings have been well documented and are likely occurring at levels that do not significantly impact the population. Other sources of mortality are less well understood, such as mortality resulting from the catch-and-release recreational fishery, impingement and entrainment (I&E) impacts, offshore fisheries, predation by invasive fish, and changing climate conditions. Specific actions that could benefit populations of American Shad and river herring in the Delaware River Basin include:

- Conduct a creel survey to determine recreational fishing pressure on American Shad and potential mortality caused by the catch-and-release fishery. Consider additional recreational fishery regulations if the mortality from the recreational fishery is contributing to population decline.
- Evaluate level of impingement and entrainment of American Shad and river herring at large water intake structures. Implement management practices at those facilities to reduce or eliminate impingement and entrainment losses for early life stages.
- Strengthen oversight and assessment of offshore fishing activities, and advocate for reductions in bycatch for those fisheries that are impacting American Shad and river herring of Delaware River Basin origin.
- Conduct studies to better quantify predation on various life stages of American Shad and river herring in the freshwater river, estuary, bay, and ocean habitats.
- Evaluate level of predation on American Shad and river herring by invasive fish, such as Flathead Catfish, Blue Catfish, and Northern Snakehead, particularly at barriers to migration for adults and in nursery habitats for juveniles.

- Continue to support habitat connectivity projects, particularly dam removals in tributaries to support access to historic habitats. Evaluate projects after construction to ensure they are providing intended access.
- Evaluate passage effectiveness, and improve or replace, as needed, existing fish passage facilities on tributaries to the Delaware River.
- Evaluate potential changes in spawning and nursery areas in the Basin because of improving water quality in the estuary and improved access to tributaries.
- Evaluate impacts of changing environmental conditions on reproductive success, age structure, size distribution, predation, growth, and survival.

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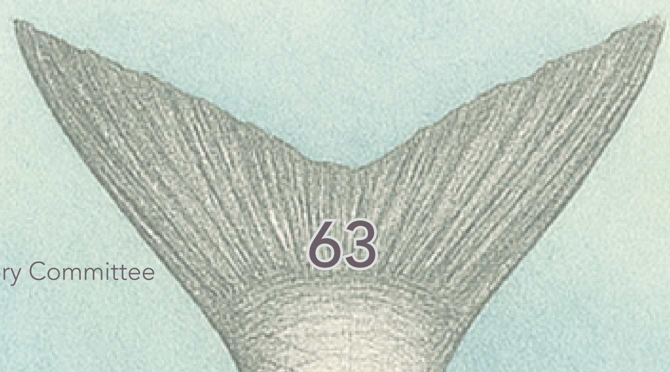

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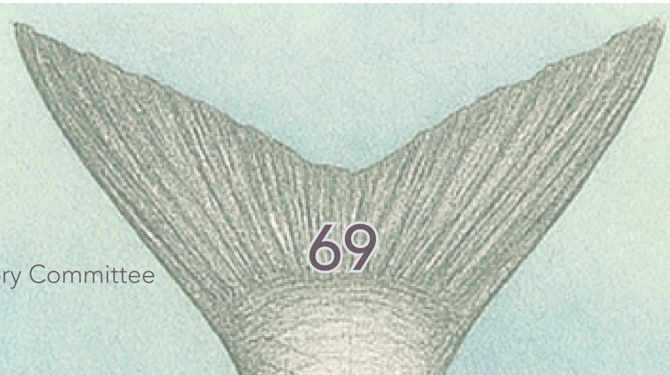

Appendix A.

Fish species recorded during PAFBC juvenile American Shad seine surveys which appeared in each of the recent survey years (2017, 2019, 2022, 2023, 2024).

Common Name	**Scientific Name**
American eel	*Anguilla rostrata*
Banded Killifish	*Fundulus diaphanus*
Black Crappie	*Pomoxis nigromaculatus*
Bluegill	*Lepomis macrochirus*
Channel Catfish	*Ictalurus punctatus*
Common Carp	*Cyprinus carpio*
Common Shiner	*Luxilus cornutus*
Fallfish	*Semotilus corporalis*
Largemouth Bass	*Micropterus salmoides*
Pumpkinseed	*Lepomis gibbosus*
Redbreast Sunfish	*Lepomis auritus*
Rock Bass	*Ambloplites rupestris*
Smallmouth Bass	*Micropterus dolomieu*
Shield Darter	*Percina peltata*
Spotfin Shiner	*Cyprinella spiloptera*
Spottail Shiner	*Notropis hudsonius*
Swallowtail Shiner	*Notropis procne*
Tessellated Darter	*Etheostoma olmstedi*
Walleye	*Sander vitreus*
White Sucker	*Catostomus commersonii*
Yellow Perch	*Perca flavescens*

Appendix B.
Species collected by the New Jersey Department of Environmental Protection during their young-of-year triped Bass seine survey since 1980.

Common Name	Common Name	Common Name
Alewife	Gizzard Shad	Shiner/Minnow Species
American Eel	Golden Shiner	Shortnose Sturgeon
American Shad	Goldfish	Silver Perch
Atlantic Croaker	Gray Snapper	Silverside Species
Atlantic Herring	Greater Amberjack	Smallmouth Bass
Atlantic Menhaden	Green Sunfish	Smallmouth Flounder
Atlantic Needlefish	Harvestfish	Southern Kingfish
Atlantic Silverside	Herring Species	Spanish Mackerel
Banded Killifish	Hickory Shad	Spot
Banded Sunfish	Hogchoker	Spotfin Shiner
Bay Anchovy	Horse-eye Jack	Spottail Shiner
Black Bullhead	Inland Silverside	Striped Anchovy
Black Crappie	Inshore Lizardfish	Striped Bass
Black Drum	Killifish Species	Striped Bass Hybrid
Blackcheek Tonguefish	Largemouth Bass	Striped Cusk-eel
Blue Crab	Longear Sunfish	Striped Killifish
Blueback Herring	Mosquitofish	Striped Mullet
Bluefish	Mummichog	Summer Flounder
Bluegill Sunfish	Muskellunge	Sunfish Species
Bowfin	Naked Goby	Temperate Bass Species
Bridle Shiner	Northern Hog Sucker	Tessellated Darter
Brown Bullhead	Northern Kingfish	Threadfin Shad
Brown Trout	Northern Pipefish	Tiger Muskie
Carp	Northern Puffer	Walleye
Catfish Species	Northern Snakehead	Weakfish
Chain Pickerel	Northern Stargazer	White Catfish
Channel Catfish	Pumpkinseed Sunfish	White Crappie

Continued on the next page

Comely Shiner	Quillback	White Mullet
Creek Chub	Rainwater Killifish	White Perch
Creek Chubsucker	Redbreast Sunfish	White Sucker
Crevalle Jack	Redfin Pickerel	Windowpane Flounder
Dace Species	Rock Bass	Winter Flounder
Eastern Silvery Minnow	Rough Silverside	Yellow Bullhead
Fallfish	Scup	Yellow Perch
Flathead Catfish	Sheepshead	
Fourspine Stickleback	Shiner Species	