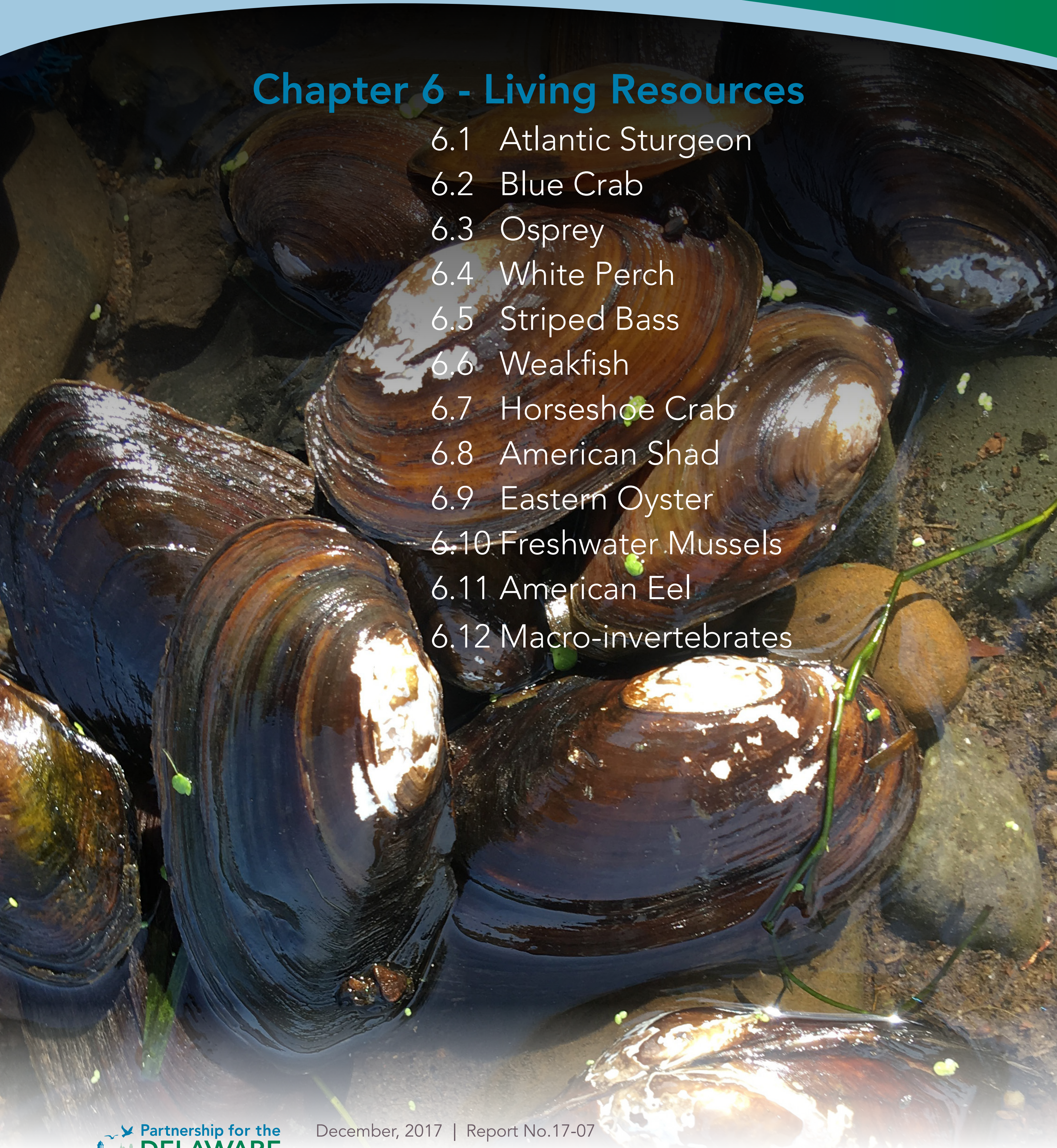
Chapter 6 - Living Resources



Partnership for the DELAWARE ESTUARY

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6. Living Resources

6.1 Atlantic Sturgeon

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6.1.1 Introduction

Historically, Atlantic Sturgeon, *Acipenser oxyrinchus oxyrinchus*, were reported in the Delaware River as well as most major rivers on the eastern seaboard of North America ranging from the Hamilton Inlet on the Atlantic coast of Labrador to the St. Johns River in Florida. The species is in the family Acipenseridae, a category of ancient bony fishes that have been able to survive as a group in contemporary environmental conditions (Detlaff et al. 1993). Atlantic sturgeon are late-maturing anadromous fish that may live up to 50 years, reach lengths up to 14 feet (4.3 m), and weigh over 800 pounds (364 kg). They are distinguished by armor-like plates called "scutes" and a long snout. They are opportunistic benthic feeders filtering quantities of mud along with their food, which consists of aquatic invertebrates (Vladykov and Greely 1963).

Mature Atlantic sturgeon (Fig 6.1.1) migrate from the sea to fresh water in advance of spawning. Females first mature at ages ranging from 7-19 years old in South Carolina to 27-28 years old in the St. Lawrence River. Males can be somewhat younger at first spawning. The Delaware River population of Atlantic sturgeon has been determined to be genetically similar to those of the Hudson River, but through range-wide genetic analysis of nuclear DNA at least 6 sub-populations were suggested including one for the Delaware River distinguishable from the Hudson River stock (King et al. 2001).

In the Delaware River, first-maturing females are likely to be at least 15 years old. Spawning occurs in flowing fresh waters with a hard bottom. Shed eggs are 2-3 mm in diameter and become sticky when fertilized frequently becoming attached to hard substrates or submerged detritus until hatching in several days. After hatching occurs, juveniles remain in fresh water for several years but have been documented to out-migrate to coastal areas in their 3rd year (Sweka et al. 2006). Once juveniles out-migrate from their natal river they are known to frequent distant estuary systems (Secor et al. 2000); tagged age-0 juvenile fish stocked in the Hudson River in 1994 were found in the Chesapeake and Delaware Bays in 1997 (Bain 1998).

Mature individuals also frequent estuaries distant from their natal river. Studies performed in the Hudson River using pop-up satellite archival tags showed that the majority of adult Atlantic sturgeon captured and tagged in the Hudson during spawning season eventually out-migrated to the mid-Atlantic Bight, but one individual traveled north to the Bay of Fundy and another went south to coastal Georgia (Erickson et al. 2011). Mature Atlantic sturgeon are of great potential commercial value for both flesh and roe, the latter being known as caviar. Although there is an occasional report of Atlantic sturgeons being caught with rod and reel, the species is not known for recreational fishing importance.

The portion of the Delaware River Basin available as habitat extends from the Delaware Bay to the fall line at Trenton, NJ, a distance of 140 river kilometers (rkm). Within this reach, habitat suitability is unknown due to anthropogenic effects on the historic habitat as a result of industrial development, dredging, and water quality issues. The exact spawning locations of Atlantic sturgeon in the Delaware River are unknown; based on reported catches in gill nets and by harpoons during the 1830s, they may have spawned as far north as Bordentown, south of Trenton, NJ (Atlantic Sturgeon Status Review Team 2007).

Figure 6.1.1 A) Young-of-year Atlantic sturgeon captured in the Delaware River in 2009. Photo courtesy of Delaware Department of Fish & Game; B) Mature Female Atlantic sturgeon. Photo credit: U.S. Fish & Wildlife Service.

6.1.2 Description of Indicator

The primary indicator is the catch per unit effort (CPUE) from the Delaware Division of Fish and Wildlife (DE DFW) (Park 2016), which has conducted targeted Atlantic sturgeon gill net surveys using variable mesh research gill nets in most years since 1991 with the exception of 1999-2000, 2002, 2005-2006, and 2013. The survey has changed both sampling sites and gear over time. Surveys prior to 2009 employed nets with multiple mesh sizes in each net, including both larger mesh sizes which target larger juveniles and adults, and smaller mesh sizes, which target young sturgeon from 0 to 3 years of age. From 1991-1996, the surveys focused on the location around Artificial Island, well below the mouth of the Chesapeake & Delaware Canal. Surveys from 1997 to 2008 included sampling at sites further upriver, including sites where young-of-the-year were later caught in 2009; no captures of young-of-year sturgeon occurred in these earlier years, however. Beginning in 2009, only smaller mesh nets (51 and 75 mm) were employed, targeting 0 to 3 year old sturgeon. All sample sites were moved far upriver from the Artificial Island area, including sites that had also been sampled from 1997 through 2008: Fort Mifflin (rkm 148), Tinicum Island (rkm 142), Marcus Hook anchorage (rkm 127), Marcus Hook bar (rkm 122) and Cherry Island Flats (rkm 119) (Fig 6.1.2). These were preferred areas as they were flat bottom sites free of snags, away from heavy ship traffic, near the freshwater-brackish water interface and out of the main channel in 3-8 m of depth.

A secondary indicator is the catch of juvenile sturgeon in the DE DFW research trawl survey program, consisting of the Adult Fish and the Juvenile Fish Surveys. The former employs an otter trawl net with a thirty-foot headrope, while the latter employs a sixteen-foot shrimp try net. These two surveys sample a fixed station design. The Juvenile Trawl samples sites in the lower River through the lower Bay from April through October mainly in near-shore areas, while the Adult Trawl samples only sites in deeper waters in Delaware Bay from March through December.

6.1.3 Present Status

In 2012, the National Marine Fisheries Service, under the authority of the Endangered Species Act, declared the New York Bight Distinct Population Segment of Atlantic Sturgeon to be endangered. The Delaware River spawning stock is included in this segment, along with the Hudson River stock. This declaration was controversial. The Endangered Species Act does not set a firm criterion for a finding that a species is endangered, leaving the decision to be possibly affected by subjectivity. Previously, due to low range-wide population levels, in 1998 a moratorium on all Atlantic sturgeon harvest in U.S. waters was adopted by the Atlantic States Marine Fisheries Commission, enforceable under the provisions of the 1993 amendments to the Atlantic Coastal Fisheries Cooperative Management Act (P.L. 82-721). The moratorium remains in effect to date with no permitted recreational or commercial harvest.

Hale et al. (2016) produced an estimate of the absolute abundance of juvenile Atlantic sturgeon in the Delaware River in 2014 based on tag-recapture data. The estimated abundance is 3,656 fish; as is common with tag-recapture-based estimates of absolute abundance, the confidence intervals are relatively wide, between 2,000 to 33,000 thousand fish (Hale et al. 2016), meaning that the abundance of juvenile sturgeon in the River ranges between several thousand to several tens of thousands.

While the results of Hale et al. (2016) are good news on the success of spawning in 2014, sampling efforts from 2009 through 2012 had sporadic results, suggesting that successful spawning did not occur in every year; specifically, no young-of-year fish were collected in 2010 and only one was collected in 2012. In several years during this period, dissolved oxygen levels were recorded at, below or near the criterion of 3.5 mg/l. At the median summer temperature of 27°C, 3.5 mg/l is only 44% of oxygen saturation. Inspection of the occurrence of low levels of dissolved oxygen and high temperatures in these four years suggested the possibility that few to no larvae may survive in the years with the lowest levels of dissolved oxygen, which may also be the years with the highest peak temperatures (Kahn and Fisher 2012). The youngest larvae

Figure 6.1.2 2009 sampling sites (yellow call out boxes) used as part of an early juvenile Atlantic sturgeon telemetry study by Delaware Department of Fish and Wildlife (DE DFW). Red dots are acoustic receivers. Map courtesy of DE DFW.

appear to be the most vulnerable to low oxygen levels, based on research on shortnose sturgeon, and the lowest oxygen levels usually occur in July, when larvae are only weeks old.

Results of the DE DFW gill net sturgeon surveys, employing a research net with a mix of different mesh sizes, show a steep decline in catch-per-unit of effort of larger juveniles (> 600 mm) from 1991 to the mid-1990s, with low levels continuing through to 2008, the last year in which the survey included the larger mesh sizes (Fig 6.1.3), indicating that relative abundance of these older juveniles declined during the 1990s, but the decline may not have been caused by a decline in the Delaware River spawning stock itself. Sub-adults of this size class seasonally wander to non-natal estuaries, so the decline may reflect declines in stocks from other rivers.

Beginning in 2009, the survey targeted smaller sturgeon (ages 0-3) exclusively, by employing only nets with small mesh. Catches of early stage juveniles (<600 mm total length) increased dramatically in 2009 including the capture of 34 young-of-year fish ranging in size from 178 to 349 mm total length (Fisher 2009) (Fig 6.1.3). Few, if any, young-of-year Atlantic sturgeon had been collected in decades prior to 2009. The DE DFW Juvenile Fish research trawl survey had previously captured three young-of-the-year sturgeon (1989, 1990, 1993) in locations upriver of Artificial Island (Cherry Island Flats and the western side of Pea Patch Island), but was not able to determine if these fish were Atlantic or shortnose sturgeon. The collection of over a score of young-of-year fish in 2009 and 2011 showed that successful spawning took place in the Delaware in those years and that there is some suitable spawning habitat available. Above average rainfall during the sampling period and targeted sampling, focused exclusively on early stage juvenile habitat with small mesh nets, could have contributed to the relatively large catch of early stage juveniles.

Recently, the sturgeon catches in the secondary indicator, the Adult Finfish and the Juvenile Finfish Research Trawl Surveys have increased in consistency, with the catch in 2011 showing the highest catch on record (Fig 6.1.4). The fact that both surveys have seen more consistent catches indicates that spawning success in the River may have become more consistent and of greater magnitude over the last decade.

The use of acoustic tagging methods have produced a large increase in our understanding of habitat used by this species. Scores of sturgeon captured in the Estuary have been tagged with acoustic tags, which transmit to receivers along the Estuary and into the Atlantic. Hundreds have been tagged with passive integrated transponders. Results from tracking acoustically tagged sturgeon (Simpson and Fox 2006) indicated that the present day lower limit of Atlantic sturgeon spawning is likely the upper limit of salt water intrusion near Tinicum Island (rkm 136) while the upper limit is likely at the fall line near Trenton, NJ (rkm 211).

In the late fall of 2009, 25 young-of-year sturgeon (262-349 mm total length) were tagged with acoustic transmitters made by VEMCO. All fish were released at the Marcus Hook anchorage (expanded map section) from September 24th to November 9th, 2009 with the majority of fish being released on October 27th. Manual tracking locations were used to determine fine scale habitat. In this monitoring approach, biologists used hand-held acoustic monitors to locate tagged fish. Weekly tracking ranged from the Delaware Memorial Bridge to the mouth of the Schuylkill River. During the tracking period several individuals moved upriver out of tracking range. Preliminary results indicate tagged early-stage juveniles are ranging from New Castle flats, DE to Roebling, NJ with the highest concentration located in the Marcus Hook anchorage (M. Fisher, formerly DE DFW, personal communication).

The passive receiver array system maintained by the DE DFW, Delaware State University and Environmental Research Consultants, Inc (ERC), comprises over 70 receivers in various locations throughout the Delaware Bay and River, the Chesapeake and Delaware Canal, and the coast of Delaware and New Jersey. The array collected over 40,000 detections from the 25 early stage juvenile sturgeon that were implanted with transmitters, including information on seasonal individual movement and behavior patterns of this 2009 year class of Atlantic sturgeon. Four individuals migrated upriver at different times over the winter months while

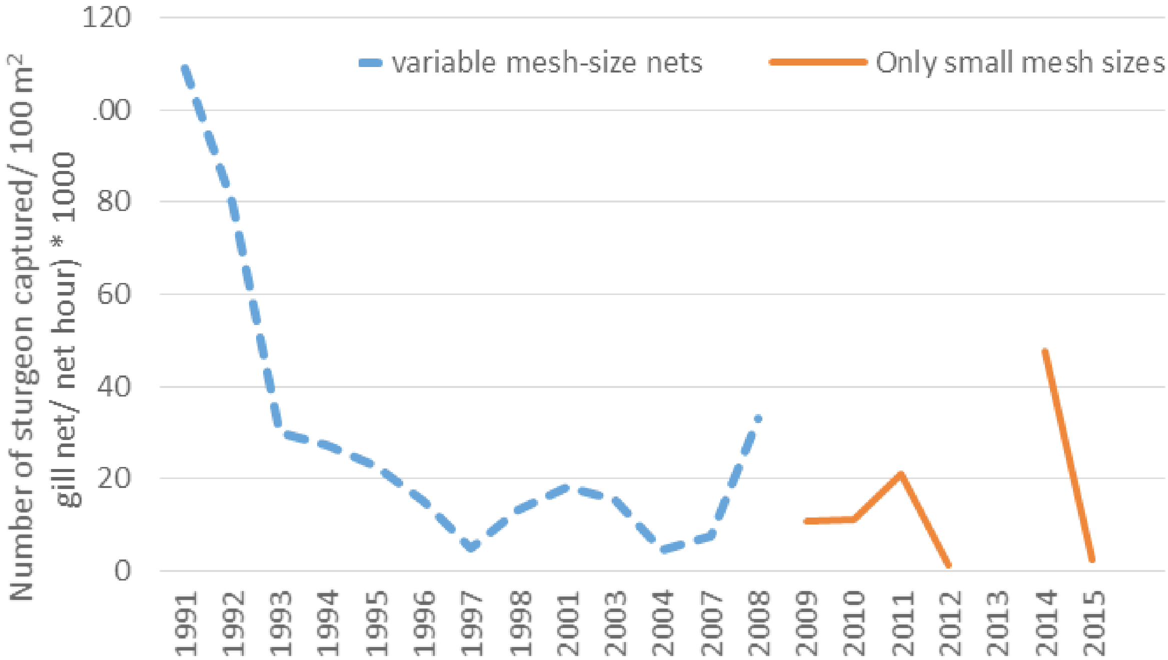

Figure 6.1.3 Primary indicator of sturgeon trend in abundance by age category in the tidal Delaware River and Bay, 1991 – 2015. Data from Park (2016). Number caught in 2008 was elevated due to use of telemetry to locate sampling sites. No sampling was conducted in 2013 due to the announcement of Endangered status in 2012.

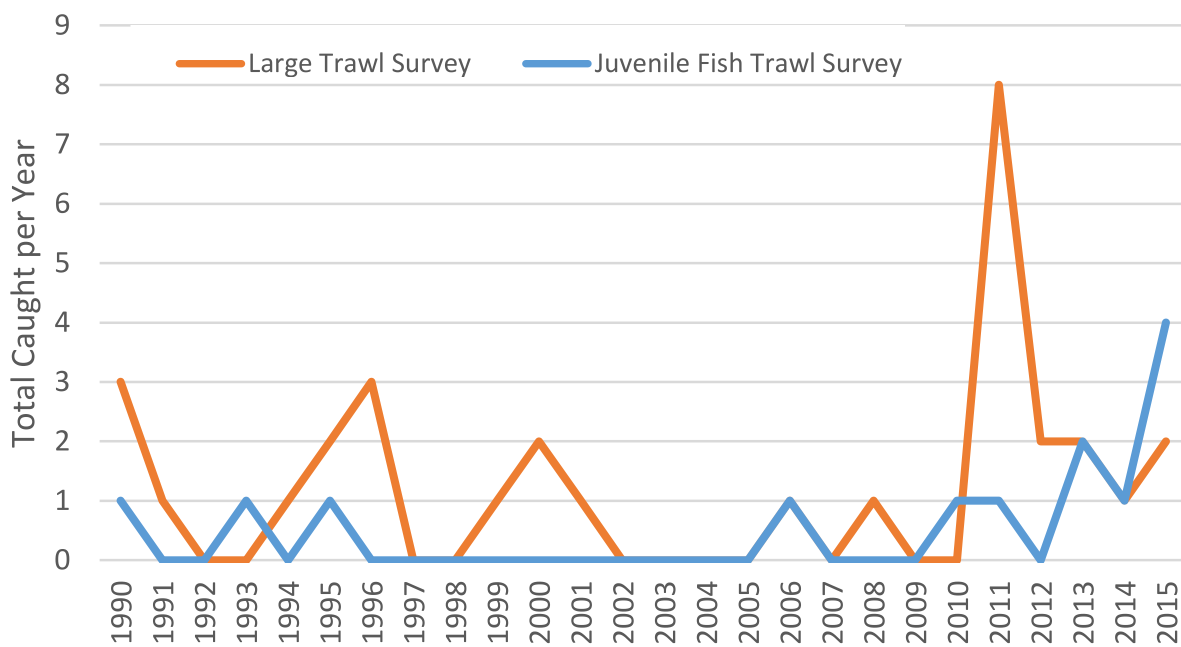

Figure 6.1.4 Secondary indicator of trends in abundance of Atlantic sturgeon in the Delaware Bay and River. Total number caught per year by the Delaware Division of Fish and Wildlife's Adult Fish Trawl Survey in Delaware Bay and the Juvenile Fish Trawl Survey in the Bay and River. Note that none of the sturgeon caught in the surveys were adults. Sampling design and total number of tows are basically identical each year.

others remained in a confined home range in between receivers. Detections ranged from New Castle, DE (rkm 105) to Roebling, NJ (rkm 199), well upstream of the head of tide, with individual movements of over 20 rkm per day. The highest concentration of these young-of-year fish occurred at the Marcus Hook anchorage. This location, just upriver from the Delaware-Pennsylvania border, is usually visually prominent due to one or more tankers riding at anchor. It should be noted that cooperation between researchers and compatibility of technology made these study results possible and is essential for understanding the movements of this species.

The presence of early-stage juveniles in the Marcus Hook anchorage is consistent with findings of Sommerfield and Madsen (2003), that the substrate composition between Marcus Hook and Tinicum Island (Fig 6.1.2) may represent suitable spawning habitat for Atlantic sturgeon. The majority of the hard-bottom substrate zones, particularly the coarse-grained bedload areas, either neighbor or are within the shipping channel. However, the presence of hard-bottom substrate within the shipping channel may also be a limiting factor in terms of spawning success, potentially exposing adult Atlantic sturgeon to mortality due to ship strikes (Brown and Murphy 2010).

The DE DFW and Delaware State University researchers record reports of sturgeon carcasses (Fig 6.1.5), which are attributed to strikes from tugs, tankers, and freighters. The DE DFW has placed a notice with a call-in phone number in the annual fishing guide. The guide is distributed to roughly 125,000 anglers annually. Social media is also employed as outreach to increase reports of sturgeon carcasses. An increase in observed reports occurred between 2010 and 2015 (mean annual reported was 19.6) compared to the period from 2005-2009 (mean annual reported was 8.2). The increase could be due to higher reporting rates from social media publicity efforts. However, it could also be due to increased sturgeon abundance or to a higher kill rate. The large majority of carcasses exceeded 1,500 mm, meaning they are of adult size. Delaware State University researchers will conduct a study of the rate that carcasses are reported in 2017. If the reporting rate can be estimated, then the magnitude of ship strike mortality can be estimated.

The Cooperative Endangered Species Conservation Fund provides grants to states and territories to participate in a wide array of voluntary conservation projects for candidate, proposed, and listed species. The most current Management Plan for Atlantic sturgeon was written by Taub (1990) and contains recommendations for increasing populations, but this plan is outdated and will likely be superseded by a Recovery Plan as required by the Endangered Species Act.

6.1.4 Past Trends

The Delaware River historically supported the largest population of Atlantic sturgeon in the United States. A historical reconstruction produced an estimated stock size large enough to include 180,000 mature females, exceeding estimated abundances of all other Atlantic sturgeon stocks by an order of magnitude (Secor 2002). In 1897, 978 fishermen, 80 shoresmen, and 45 transporters were engaged in the Delaware River sturgeon fishery (Cobb 1899). This heavy fishing in the late nineteenth century caused a severe stock decline. It is clear that Atlantic sturgeon underwent significant range-wide declines from historical abundance levels due to overfishing in the late 1800s (U.S. Departments of Commerce and Interior 1998). During the season of 1898, New Jersey fishermen caught 5,060 sturgeons valued at $19,375 and they prepared 1,067 kegs of caviar valued at $76,861. This does not include the catch from Delaware and Pennsylvania since their sturgeon fisheries were not canvassed that year (Cobb 1899).

Due to their migratory nature, high age to maturity, high longevity, and variable spawning periodicity, it is difficult to assess the size of Atlantic sturgeon populations using traditional fishery methods such as mark-recapture. Therefore, there are no detailed past population trends available other than the large decline in harvest levels mentioned previously from the late 19th century to levels in the mid-late 20th century when commercial harvest was still permitted. After the late 1800's, Atlantic sturgeon populations did not rebound to any appreciable extent in the Delaware, as evidenced by the average annual landings of only 897 pounds during the period from 1980 – 1987 (Taub 1990). Beginning in the first half of the twentieth century, the complete lack of oxygen in the Delaware River during the warmer months in the Philadelphia to Wilmington reach made it impossible for the native Delaware River stock to recover. Atlantic sturgeon have been described as more sensitive to oxygen levels than rainbow trout. This reach of the River may have included the spawning grounds, which have not been determined precisely to this day, and certainly included the nursery grounds for young sturgeon.

Brundage and Meadows (1982) compiled records of Atlantic sturgeon captured in the Delaware River and Bay from 1958-1980 and found that out of the 130 reported captures, none were in spawning condition and most were sub-adults (less than the minimum size for sexual maturity). They were most abundant in the Delaware Bay (rkm 0-55) in the spring and in the lower tidal river (rkm 56-127) in the summer.

Historic habitat for Atlantic sturgeon in the Delaware River has been significantly altered. Large-scale dredging to accommodate commercial shipping traffic has changed substrate composition and tidal flows (Di Lorenzo et al. 1993; Walsh 2004). Within the period 1877 – 1987, the mean depth of the Delaware River increased by 1.6m and the mean cross-sectional area increased by nearly 3,000 m^2 (Walsh 2004). By 1973, USACE estimated that nearly 154,000,000 m^3 of material had been removed from the Delaware Estuary (Walsh 2004). The channel deepening process increased the tidal range in the Upper Estuary; simultaneously, extensive water removals and diversions were occurring within the nontidal watershed, resulting in saltwater intrusion in the freshwater-tidal reach of the Estuary.

6.1.5 Future Predictions

The ongoing sampling efforts of the DE DFW have documented successful sturgeon reproduction in recent years. Assuming this reproduction continues, the stock should grow and potentially could develop exponential growth, which occurred with the Delaware River spawning stock of striped bass (Kahn et al. in press). There are some potential limiting factors, which must be considered, however.

One critical factor is dissolved oxygen. In the last two decades, hypoxia has become more frequent than in the decades immediately prior, to the surprise of biologists monitoring the River (T. Fikslin, DRBC personal communication). There appeared to be a preliminary indication of little to no reproduction in years with the lowest dissolved oxygen (Kahn and Fisher 2012). This analysis should be updated. The DRBC has determined that future increases in minimum levels of dissolved oxygen could be achieved as suggested earlier (Ad Hoc Task Force 1979) by reducing the biochemical oxygen demand due to nitrogen, and that could be done by increased aeration of solutions prior to discharges from industrial and sewage treatment facilities, primarily due to increased oxidation of ammonia, which could be accomplished without extreme costs.

Commercial and industrial activity could limit the growth of the Atlantic sturgeon population in the Delaware River, but effective regulation of pollution could counteract negative effects. Since large sub-adult and adult Atlantic sturgeon prefer deep water habitat, they are continually at risk of mortality due to ship strikes, because the deepest portions of the Delaware River are typically in the shipping channel. Increased shipping traffic and introduction of larger ships will likely increase the risk of ship strike mortalities for large sub-adult and adult fish. Between 2005 and 2008, a total of 28 Atlantic sturgeon mortalities were reported in the Delaware Estuary. Sixty-one percent of the mortalities reported were of adult size and 50% of the mortalities resulted from apparent vessel strikes. For small remnant populations of Atlantic sturgeon, such as that of the Delaware River, the loss of just a few individuals per year due to anthropogenic sources of mortality such as vessel strikes may continue to hamper restoration efforts. An egg-per-recruit analysis demonstrated that vessel-strike mortalities could be detrimental to the population if more than 2.5% of the female sturgeon are killed annually (Brown and Murphy 2010).

Even though dredging of the tidal Delaware River will likely continue as maintenance dredging and for increasing channel depth to accommodate larger ships, updated dredging windows have been developed by the Delaware River Basin Fish and Wildlife Management Cooperative (Co-op). Using known life history data, these dredging windows are formulated to reduce impacts on sturgeon and other fish from dredging and related activities and are currently being considered for implementation by the U.S. Army Corps of Engineers (USACE) in permitting dredging and related activities. To better characterize habitat use in the tidal Delaware River, Delaware River sturgeon researchers are continuing the use of acoustic tags on sturgeon to monitor their movements via an array of stationary acoustic receivers deployed in the Delaware River (Fig 6.1.2)

Since the Delaware stock was included in the populations listed as Endangered, a Recovery Plan for the species must be written that includes specific steps needed for population recovery. The Endangered Species Act also requires the designation of "critical habitat" for listed species when "prudent and determinable." Critical habitat includes geographic areas that contain the physical or biological features that are essential to the conservation of the species and that may need special management or protection. Critical habitat designations affect only Federal agency actions or federally funded or permitted activities. Federal agencies are required to avoid "destruction" or "adverse modification" of designated critical habitat. Relative to the Delaware River Atlantic sturgeon, this would apply to dredging activities which are currently permitted by the USACE in areas known to be utilized by Atlantic sturgeon for completion of their life cycle. Critical habitat may include areas that are not occupied by the species at the time of listing but are essential to its conservation. An area can be excluded from critical habitat designation if an economic analysis determines that the benefits of excluding it outweigh the benefits of including it, unless failure to designate the area as critical habitat may lead to extinction of the listed species.

Figure 6.1.5 Atlantic sturgeon of near-adult size (6 feet total length) found washed up in front of Baker's Bay Condominiums, PA (rkm 181) on June 12, 2010. This sturgeon has a propeller strike that runs laterally along the dorsal side of the fish through 5 dorsal scutes and the cranial area. Photo credit: Delaware Division of Fish and Wildlife.

6.1.6 Actions and Needs

Specific research goals could yield information that would be valuable in managing the population towards recovery. Continuation of telemetry studies could result in discovering areas of the river used by various life stages of the species, such as locations of spawning areas and early life stage nursery areas. Such knowledge could allow more effective management actions, such as potentially instituting effective dredging windows to protect fish at times when they congregate in known areas. Expanded study of ship strikes on sturgeon in the Delaware River is also needed to determine the level of population impact occurring and to determine ways to minimize that impact. Since small losses of broodstock can impact Atlantic sturgeon population growth in the Delaware, it is important to work with the shipping industry to develop means for reducing ship strikes.

Since the species is highly migratory, actions to rebuild the Delaware River stock could include: (1) reducing by-catch from near-shore and ocean commercial fisheries on the East Coast by increasing the number of observers on commercial fishing vessels and reducing the use and/or soak time of anchored gill nets, (2) designing and locating future tidal turbines for power generation in a manner which would strive to minimize mortality to distant migrants, and (3) continuing the use of the Coastal Sturgeon Tagging Database as a means to promote data sharing between sturgeon researchers. Kahn and Fisher (2012) presented evidence that the hypoxia occurring in and near the possible spawning areas and the known nursery areas of the River in recent years may be causing mortality of young-of-year sturgeon; the DRBC should raise the minimum criteria for dissolved oxygen in the River to reduce or eliminate this potentially devastating mortality that could be wiping out entire year classes of Atlantic sturgeon.

6.1.7 Summary

In summary, the current abundance of the Atlantic sturgeon population in the Delaware River is lower than the historic peak population prior to the late 19th century. The Delaware River spawning stock, once the largest on the Atlantic coast, was declared Endangered in 2012. Furthermore, shipping traffic in the Bay and River is causing some mortality by ship strikes. However, a recent peer-reviewed estimate of the abundance of juveniles in the River ranges between 2,000 and 33,000 fish (Hale et al. 2016). This is positive evidence of ongoing reproduction in the Delaware. Research is producing increasing information on habitat choice based on acoustic transmitters. Over the last decade and a half, dissolved oxygen levels in the River have sometimes dropped to levels of concern in summer, when young sturgeon are the most vulnerable (Kahn and Fisher 2012). This species has been described as more sensitive to dissolved oxygen than rainbow trout by one biologist. Increasing the "criteria" for dissolved oxygen to reduce the frequency of hypoxia would protect young sturgeon from potential sporadic mortality.

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6.2 Blue Crab

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6.2.1 Introduction

The blue crab (*Callinectes sapidus;* Fig 6.2.1) is a member of the swimming crab family Portunidae and inhabits estuarine habitats throughout the western Atlantic, from Nova Scotia (although rare north of Cape Cod), along the Gulf of Mexico and Caribbean, to northern Argentina, and along western South America as far south as Ecuador (Williams 1979).

Figure 6.2.1 Adult Blue Crab. Photo credit: LeeAnn Haaf, Partnership for the Delaware estuary.

Blue crab spawning occurs primarily in the summer months in mid to lower Delaware Bay with peak larval abundance occurring in August (Dittel and Epifanio 1982). Larvae are exported from the Estuary into the coastal ocean where they undergo a 3-6 week, seven stage, zoeal development period in surface waters (Epifanio 1995; Nantunewicz et al. 2001). Models describe an initial southward transport of zoeae along the inner continental shelf within the buoyant estuarine plume after exiting the Estuary (Epifanio 1995, Garvine et al. 1997). Northward transport back toward the Estuary is provided by a wind-driven band of water flowing northward along the mid-shelf. Across-shelf transport into settlement sites in Delaware Bay is accomplished by coastal Ekman transport tied to discrete southward wind events (nor'easters) in the fall. These discrete wind events may have a large effect on larval recruitment and settlement success in the Bay and strongly influence year class strength.

Females mate immediately after their pubertal molt into sexual maturity, usually late in their first year of life (late spring, summer). Sperm is stored over their remaining lifetime from this single mating event. Mated females can begin producing eggs in that summer and early fall over multiple clutches, continuing through to a second spawning season (Churchill 1921; Van Engle 1958; Darnell et al. 2009). Darnell et al. (2009) observed up to seven clutches for females in North Carolina. Prager et al. (1990) estimated fecundity per batch as over $3x10^6$ eggs.

Blue crabs hold an important ecological role as opportunistic benthic omnivores, with major food items including bivalves, fish, crustaceans, gastropods, annelids, nemertean worms, plant material, and detritus (Guillory et al. 2001). Post-settled blue crabs have been shown to have a key effect on infaunal community structure, particularly through major predation on bivalves such as the eastern oyster (*Crassostrea virginica*) (Eggleston 1992), quahog (*Mercenaria mercenaria*)(Sponaugle and Lawton 1990), common rangia (*Rangia cuneata)* (Darnell 1958), soft-shell clam (*Mya arenaria)*(Blundon and Kennedy 1982; Smith and Hines 1991; Eggleston et al. 1992), and other bivalve species (Blundon and Kennedy 1982), and through indirect mortality on infaunal species from mechanical disturbance of sedimentary habitats caused by foraging (Virnstein 1977).

The primary predators on blue crabs appear to be fish, with more than 60 known fish predator species (Guillory et al. 2001). Blue crabs are known to be a common component of both juvenile and adult striped bass in Chesapeake Bay, albeit with great variability in relative importance among studies (Speir 2001). Although there have been recent investigations on the potential negative effect of the recovered striped bass stock on the Chesapeake Bay blue crab stock, no connection with decreasing blue crab population numbers has been supported (Booth and Martin 1993; Speir 2001).

Another very important source of predation on blue crabs occurs from cannibalism, as blue crabs make up as much as 13% of the diet (Darnell 1958). Cannibalism appears to increase with increasing crab predator size and is heaviest during the period of juvenile recruitment (Mansour 1992). Adult predation may be a key factor in density-dependent regulation of juveniles (Peery 1989).

Overfishing and stock sustainability became serious concerns during a period of rapidly rising fishing effort and three-fold increase in landings from 1985-1995. Fears of overfishing intensified after bay-wide landings from Delaware and New Jersey peaked at a record 12.7 million pounds in 1995 and then subsequently dropped by more than 46% in 1996.

Concern for the stock in 1998 prompted the 138th General Assembly of the State of Delaware to direct its Division of Fish and Wildlife to prepare a fishery management plan and quantitative assessment of the stock. Subsequent stock assessments revealed high fishing mortality rates in Delaware Bay in close proximity to the management threshold (fishing mortality F=1.3) suggesting that the stock was fully exploited (Helser and Kahn 1999; Wong 2010).

6.2.2 Description of Indicator

Perhaps the most-studied fishery species in Delaware, the blue crab has been very closely monitored since 1978 with monthly trawl surveys conducted by the Delaware Division of Fish and Wildlife (DE DFW). Using biological information collected from these surveys, together with year-round collections of landings reports, the DE DFW assesses the size and status of the Delaware Bay blue crab stock on an annual basis. This annual stock assessment is funded by the National Atmospheric and Oceanic Administation (NOAA).

6.2.3 Present Status

The blue crab stock in Delaware Bay supports a multi-million dollar fishery. Over 6.2 million pounds were landed in 2015 (most-recent data) in the bistate fishery in Delaware Bay, roughly equal to the 43-year average (6.4 million pounds) (Fig 6.2.2), with a dollar value at dockside of $12 million. Annual Delaware Bay harvest is generally split equal between the two States (51%:49%, DE:NJ).

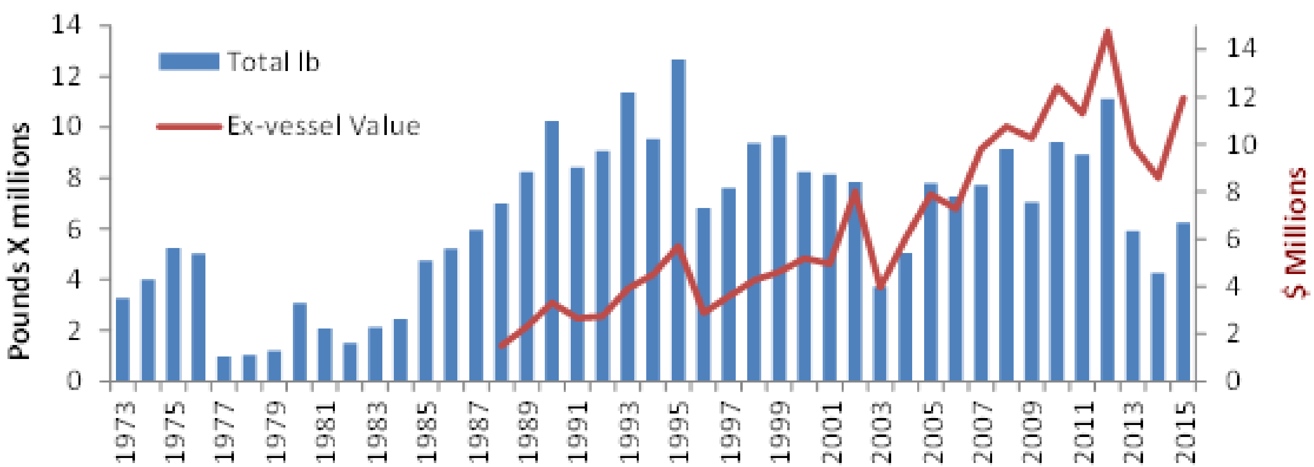

Figure 6.2.2 Total commercial and recreational landings (in pounds, lb) and commercial ex-vessel value in the States of Delaware and New Jersey.

In the State of Delaware, the blue crab is by far the most important and valuable commercial fishery. Its annual landings in weight are typically 50% greater than the combined landings of all other Delaware fisheries. Its ex-vessel value in dollars nearly triples the value of all other fisheries combined (Wong, unpublished).

The blue crab is the most heavily harvested recreational fishery species in Delaware Bay, exceeding 2 million crabs annually (Wong, unpublished). Recreational harvest accounts for about 3% and 15% of the total landings in Delaware and New Jersey, respectively.

The pot fishery, by far, harvests the majority (86%) of Delaware's crab landings and value (Fig 6.2.3). Male crabs make up about 2/3 of the pot landings, in stark contrast to the female-dominated winter dredge fishery landings (Fig 6.2.4).

Stock Size and Status The Delaware Bay blue crab stock is currently at healthy levels of abundance and at safe levels of fishing mortality. Population modeling indicates that the stock has recently risen to 174 million crabs, above the 38 year mean and median of 153 and 116 million (Fig 6.2.5) (Wong, unpublished). Fishing mortality rates are at levels below overfishing thresholds after declining appreciably since 2012.

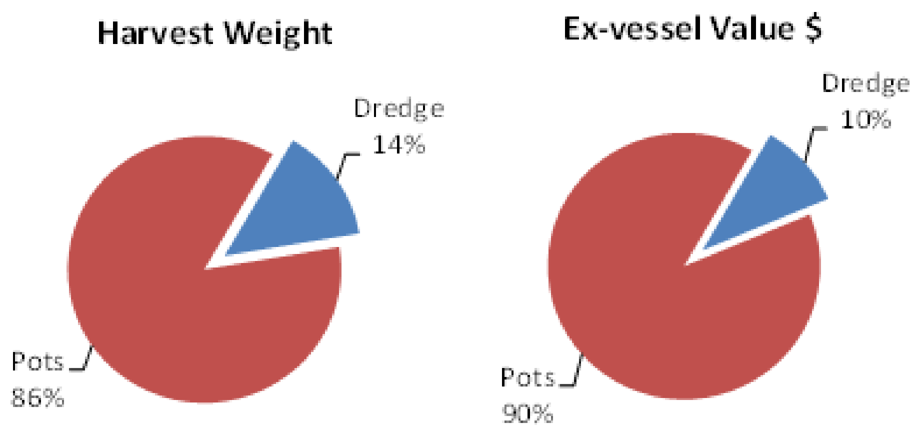

Figure 6.2.3 Total harvested weight and ex-vessel dollar value by gear type over the most-recent five years of Delaware landings data.

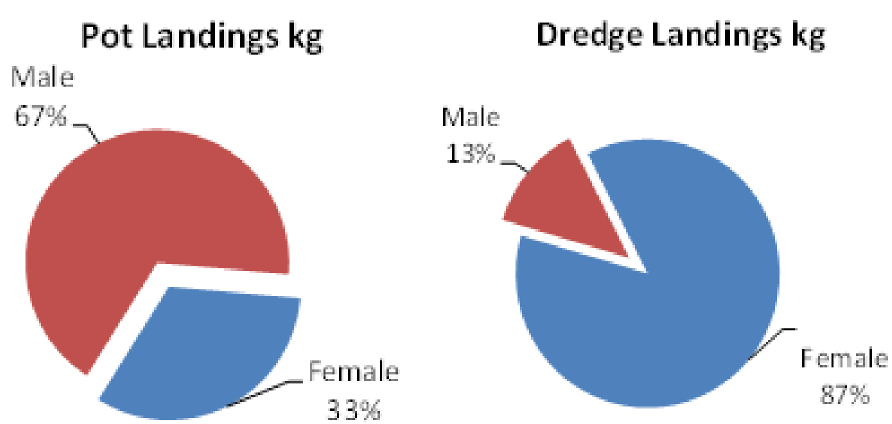

Figure 6.2.4 Sex-composition of pot and dredge fishery landings over the most-recent five years of Delaware landings data.

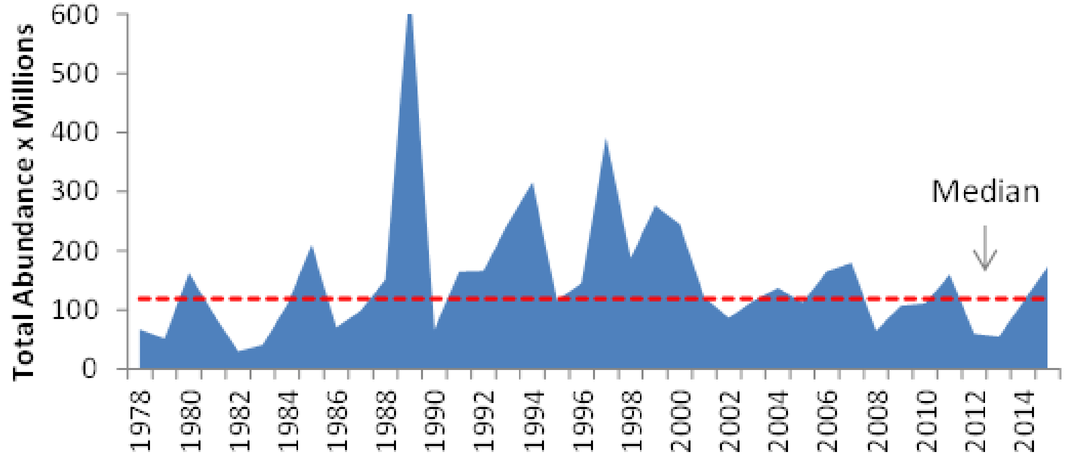

Figure 6.2.5 Stock size estimates from annual population modelling (Wong unpublished).

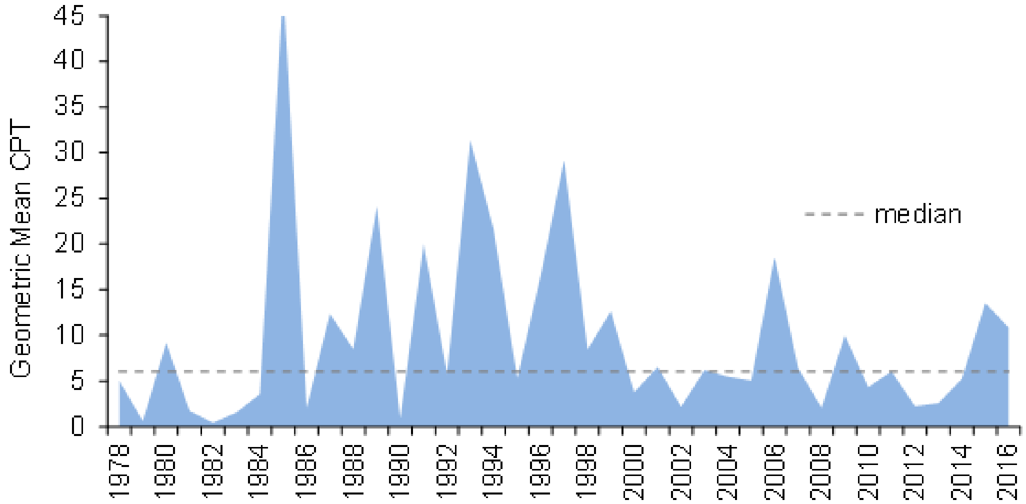

Figure 6.2.6 Young-of-the-year blue crab relative abundance from the DE DFW Delaware Bay trawl survey.

6.2.4 Past Trends

A period of high blue crab productivity occurred for about 15 years from 1985 to 1999 (Fig 6.2.6). During this period, DE DFW crab indices were at or above median levels for 13 of 17 years. Weak year classes occurred in 2000 and 2002, beginning a prolonged 15 year period of lower juvenile recruitment. In 2015 and 2016, the DE DFW has observed robust juvenile recruitment, perhaps signaling an end to this current low productivity period.

6.2.5 Future Predictions

The near-term outlook for the stock and fishery is promising given robust juvenile recruitment in 2015 and 2016. Young-of-the-year (YOY) recruitment is typically a good predictor of future fishery landings (Wong, unpublished) (Fig 6.2.7). With ostensibly warming water temperatures in the future, stock productivity could increase through a broadening of the spawning season and an increase in the number of egg clutches per year.

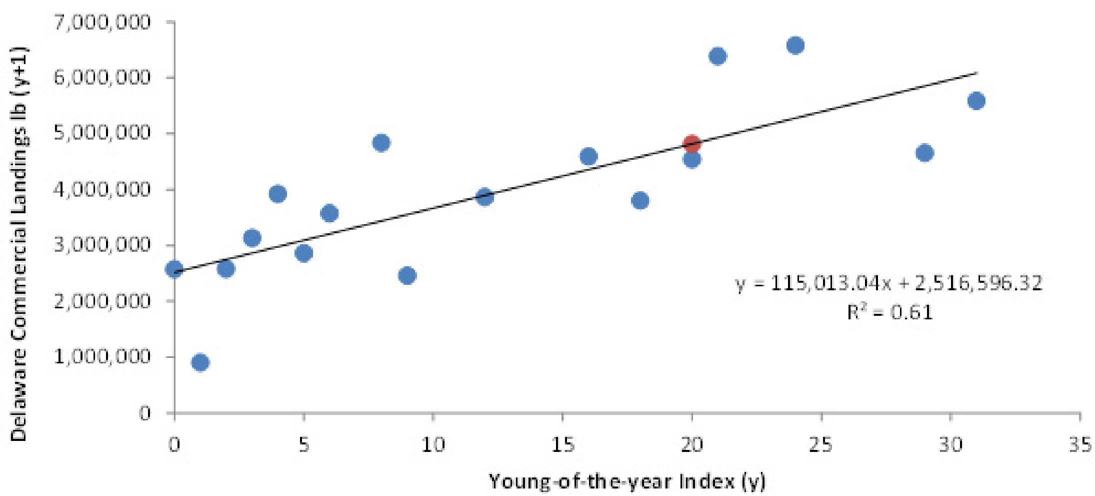

Figure 6.2.7 YOY abundance as a predictor of ensuing Delaware commercial landings.

6.2.6 Actions and Needs

Continued close monitoring of stock abundance through monthly trawl surveys and accurate reporting of fishery landings are needed to protect and manage this important fishery stock.

6.2.7 Summary

In recent years, from 2005 to 2012, high levels of exploitation rates were observed, driven by poor recruitment and below average stock abundance. However, after bottoming in 2012, juvenile recruitment has rebounded substantially, rising to above-average levels in 2015 and 2016. Low levels of harvest from 2013 to 2015 have allowed adult abundance to climb to its highest level in 16 years. Population modelling indicates that the total stock has risen to 174 million crabs, above 38 year norms (Wong, unpublished). Consequently, fishing mortality rates have declined appreciably, existing at levels safely below overfishing thresholds. The Delaware Bay blue crab stock is currently at healthy levels of abundance, and at safe levels of fishing mortality. The near-term outlook is promising given robust juvenile recruitment in recent years.

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6.3 Osprey

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6.3.1 Introduction

One of the largest birds of prey in North America, the osprey (*Pandion haliaetus;* Figure 6.3.1) eats almost exclusively fish, which makes up 99% of their diet. Osprey are found on all continents except Antarctica, generally near large bodies of water. Ospreys arrive in Delaware Bay in early March and begin nesting by mid March. They use a variety of nest sites including: live or dead trees, man-made nesting platforms, utility poles/structures, channel markers, and duck blinds. Young fledge in the early summer. Wintering occurs in the Caribbean, Central America and South America.

Figure 6.3.1 Adult Osprey diving talons first to catch fish prey. Photo credit: Lenni Gabriele.

Osprey are highly adapted for capturing fish. Some of their adaptations include: oily feathers to reduce water absorption, spikes on their feet to aid in grasping slippery fish, and a reversible outer toe helping them keep a secure grip on fish. At times osprey may plunge completely underwater in pursuit of their prey. Bald eagles (*Haliaeetus leucocephalus*) and great horned owls (*Bubo virginianus*) are known to take fledgling osprey. Raptors and other birds will take over osprey nests. Bald eagles are well known to rob osprey of the fish they have caught.

6.3.2 Description of Indicator

Both New Jersey and Delaware have osprey monitoring and conservation programs. Nest checks by aerial or ground observers are conducted by staff and volunteers to determine active nests and productivity between the end of April and mid-July. Each state works independently on their monitoring programs so timing and the survey areas are different (Delaware focused effort in Inland Bays until 2007 and New Jersey surveyed state-wide), and the reports upon which this indicator is based are produced independently (Figure 6.3.2).

6.3.3 Present Status

Ospreys appear to be doing well in Delaware Bay. Productivity, as measured by fledglings observed, is higher than needed for a stable population. Population levels may be close to what is believed to have been the level prior to the widespread use of Dichlorodiphenyltrichloroethane (DDT). A recent study by U.S. Geological Survey of osprey nesting in Delaware concludes that contaminants are below levels that would cause concern.

Table 6.3.1 Osprey nesting success during 2003, 2007, and 2014 in Delaware.

	2003	2007	2014
Active Nests in DE	119	173	197
Successful Nests in DE	77	136	103
Nestlings	135	293	424

Active Nest = eggs or chicks seen in nest during at least 1 survey
Successful Nest= at least one chick reach banding age

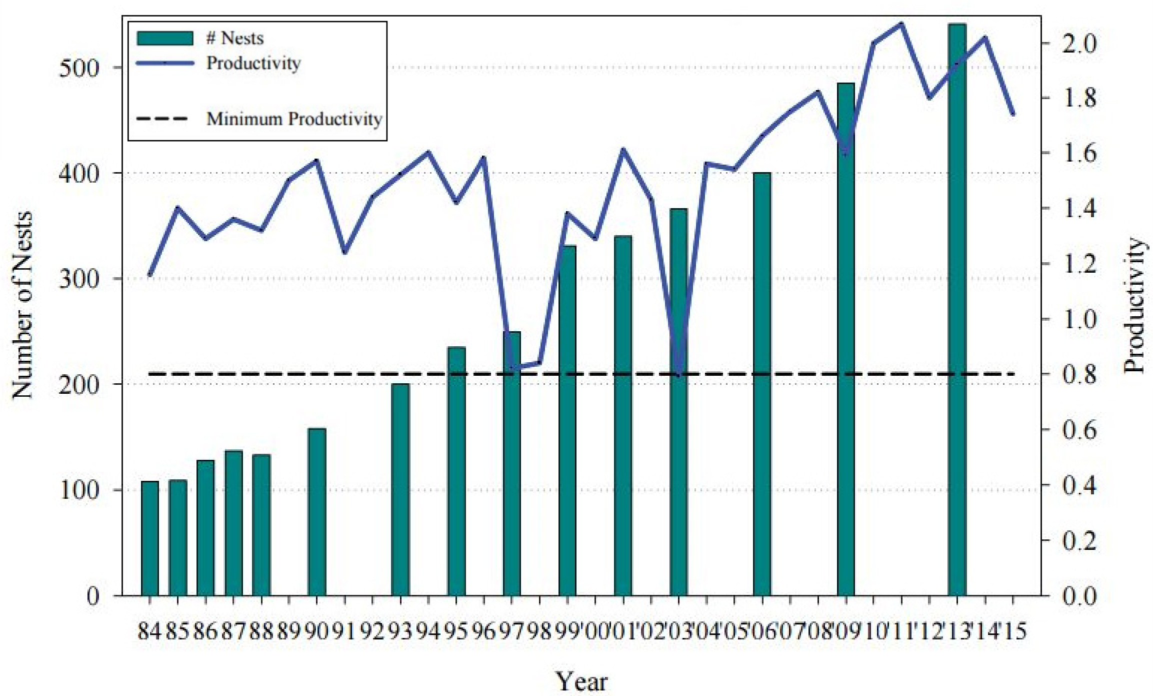

Figure 6.3.2 Osprey nesting population (bar) and productivity in terms of young fledged per nest (heavy line) 1984-2015 in New Jersey.

6.3.4 Past Trends

Historically abundant, osprey populations declined precipitously in the Northeast from the 1950s through the 1970s, due to the widespread use of DDT to control mosquitoes. Since DDT was banned, osprey populations have been slowly rebuilding, aided by reintroduction programs. Delaware Bay populations remained depressed due to high organochloride and polychlorinated biphenyl (PCB) levels into the 1990s. Since then, levels of organochlorides have lowered and productivity has improved.

6.3.5 Future Predictions

The outlook for osprey is good in Delaware Bay. Disturbance is generally not an issue, they adapt well to anthropogenic activities. Contaminants have been reduced and levels in osprey continue to decline. Expectations are that osprey will continue to show success in Delaware Bay.

6.3.6 Actions and Needs

Volunteers are needed for monitoring nests and productivity. Since osprey readily use artificial platforms and structures for nesting, those interested in establishing nesting structures, or that have questions about osprey should contact the State agencies responsible for bird conservation:

NJ: http://www.conservewildlifenj.org/protecting/projects/osprey/

DE: http://www.dnrec.delaware.gov/fw/NHESP/information/Pages/Contacts.aspx

6.3.7 Summary

Osprey populations in Delaware Bay are a success story. They demonstrate the value of reducing contaminants in our environment and taking conservation actions. In addition, the success of osprey conservation shows how volunteers can make a difference.

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6.4 White Perch

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6.4.1 Intoduction

White perch (*Morone americana;* Fig 6.4.1) are one of the most abundant fish in the Delaware Estuary and probably the most widespread, found in nearly all the waters of the Delaware Estuary, from the lower bay to uppermost reaches of the Estuary's many tidal tributaries. White perch support important recreational and commercial fisheries throughout the Estuary. The Delaware Estuary white perch population is currently in good condition and is not overfished.

Figure 6.4.1 White Perch. Photo credit: Jenny Paterno Shinn.

White perch are closely related to striped bass, but the white perch is a much smaller fish. Although the Delaware state record white perch was 2 pounds 9 ounces, any white perch over one pound is considered large. Delaware Estuary white perch display anadromous tendencies in that large aggregations of white perch move into the tidal tributaries in spring to spawn and then out into the deeper waters of the Estuary to overwinter, but, unlike striped bass, white perch rarely leave the Estuary. White perch numbers in the Delaware Bay and River typically increased during the fall and remained high through winter, then decreased during the spring and summer (Miller 1963, PSEG 1984), while white perch numbers in the tidal tributaries showed the opposite trend (Smith 1971). However, white perch were caught year-round in both the Delaware Estuary (de Sylva et al 1962) and the tidal tributaries (Smith 1971), so the evidence was inconclusive about the extent of white perch movements. In addition, landlocked white perch populations have thrived for years in most of the freshwater ponds in the headwaters of Delaware Estuary tidal tributaries (Martin 1976).

White perch spawn in the Delaware River (Miller 1963, PSEG 1984) and most of the Delaware Estuary tidal tributaries (Miller 1963, Smith 1971, Clark 2001). Spawning occurred from early April through early June, but May was usually the peak spawning month (Miller 1963, Smith 1971, PSEG 1984). Young-of-the-year white perch, like the adults, were found in both the Delaware Estuary (PSEG 1984) and the tidal tributaries (Smith 1971). Young-of-the-year white perch were found throughout the year in the lower salinity reaches of all sampled tidal tributaries (Clark 2001).

White perch feed almost exclusively on small invertebrates from their larval through juvenile stages, and then add fish to their diet as they reach maturity (PSEG 1984). Almost all male white perch are sexually mature in two years and almost all female white perch are sexually mature in three years (Wallace 1971). Delaware Estuary white perch have been aged to ten years old and some may live longer than that, but white perch older than six years old were rare (Clark 2001).

White perch tolerate a wide range of environmental conditions, as would be expected of such a ubiquitous fish. White perch were caught at water temperatures ranging from 2.2° C (Rohde and Schuler 1971) to 35.5° C (Clark 1995) and at salinities ranging from freshwater (Shirey 1991) to 35 parts per thousand (Clark 1995). White perch catch per unit effort was greatest in fresh and oligohaline waters of Delaware tidal tributaries (Clark 2001), suggesting that white perch preferred low salinity water. Smith (1971) caught white perch at a dissolved oxygen level of 2.2 parts per million (ppm) in Blackbird Creek and Clark (1995) caught white perch at a dissolved oxygen level of 2.0 ppm in a high-level tidal impoundment near the Little River, but neither report indicated whether the fish showed signs of stress at those low dissolved oxygen levels.

White perch were among the top five finfish species landed commercially in Delaware during each year of the last decade, which is not surprising since gourmets consider the white perch to be one of the finest tasting fish in the world. Landings averaged 77,868 lbs during 2010 through 2015, with the highest landings, 157,947 lbs, reported in 2011. Most fishing effort for white perch was expended during late fall through winter and into early spring. Delaware Bay was the source for most commercially-caught white perch, but substantial landings also came from the Delaware River and several tidal tributaries of the Delaware Estuary. New Jersey white perch landings in the Delaware Estuary counties (Salem and Cumberland) averaged 24,333 lbs per year during 1995 through 2000, with the highest landings, 42,000 lbs, reported in 2000.

White perch were among the top ten fish species harvested recreationally in Delaware annually since 2000. The mean estimated recreational harvest during 2000 through 2015 was 36,311 pounds, with the highest harvest, 97,789 pounds, reported in 2010.

6.4.2 Description of Indicator

This indicator uses the white perch young-of-the-year (YOY) index derived from the Delaware Division of Fish and Wildlife's (DE DFW) Juvenile Finfish Trawl Survey. The juvenile finfish trawl survey used a 16' trawl to sample 39 inshore Delaware Bay and River stations monthly during April through October. The YOY index was calculated as the geometric mean number of YOY white perch caught per tow by the juvenile finfish trawl survey during June through October in Delaware Bay and River (Greco 2016). This index is an indicator of year-class strength and may indirectly be an indicator of future spawning stock abundance. For this index, the median value from 1990 through 2016 was 0.26 YOY white perch per tow (Fig 6.4.1). During four of the five years from 2012 through 2016, the annual index was below the median. Although the white perch YOY index has not been used as a predictor of future spawning stock abundance or future commercial catches, the low YOY index values of the last five years may be a factor in the decrease in commercial landings reported during 2013 through 2015.

6.4.3 Present Status

The fact that the white perch YOY index was below the time series median YOY index value during four of five years since 2012 suggests that the Delaware Estuary white perch spawning population has had poor spawning success during this period. Delaware white perch commercial landings exceeded 100,000 lbs. in 2009, 2010, and 2011, which is the only time landings have exceeded 100,000 lbs. for three consecutive years in the 1951 through 2010 time series. Landings have since declined and were below the time series mean in 2015. This suggests the population has declined since its recent high level.

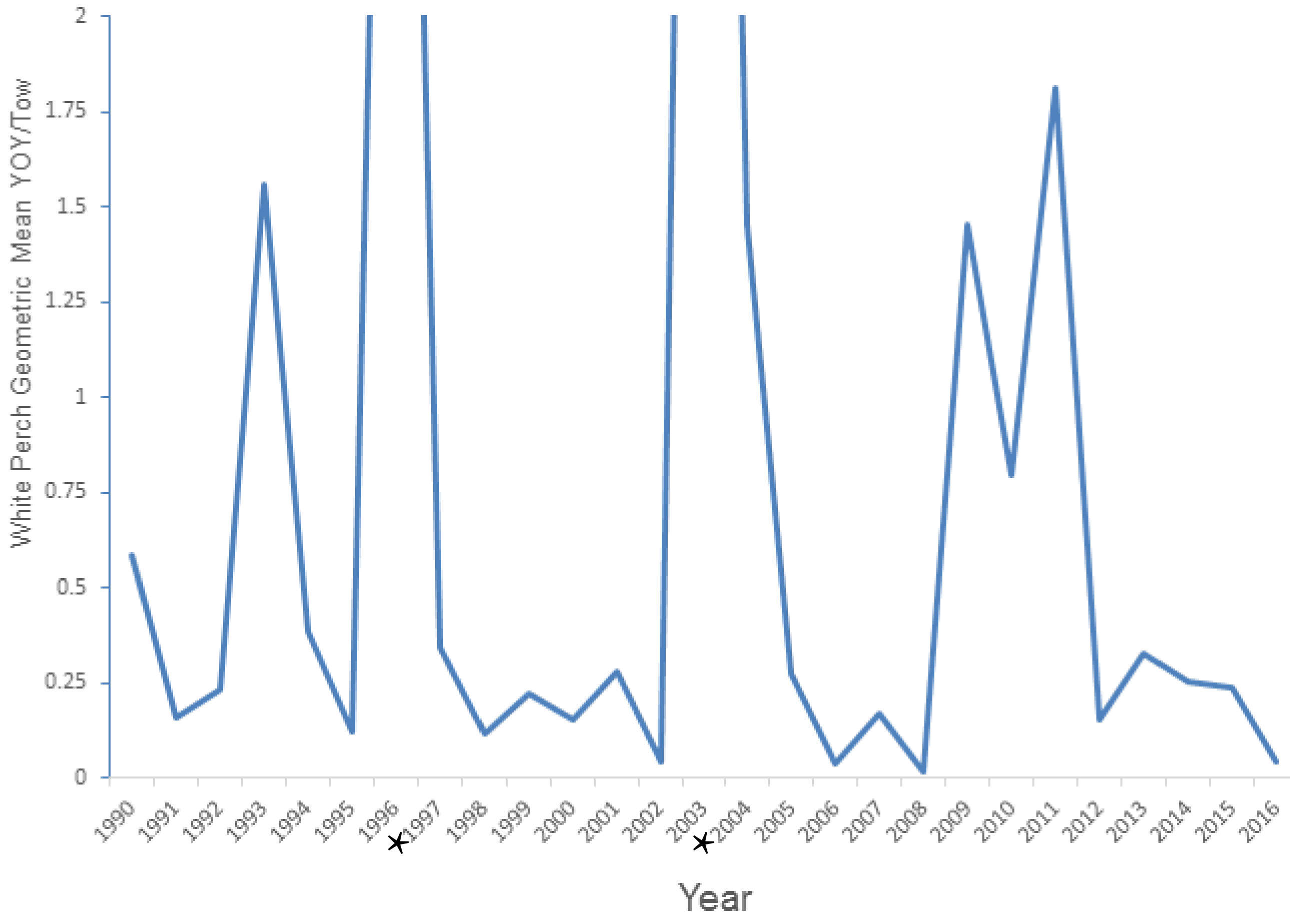

Figure 6.4.2 White perch YOY index (number of YOY white perch caught per trawl tow) from the DE DFW Juvenile Trawl Survey for 1990 through 2016. Index scale was truncated to better show index values around median. The 1996 value was 4.84 and the 2003 value was 6.35.

6.4.4 Past Trends

Delaware white perch commercial landings were the longest time series of data available to assess past trends in white perch abundance (Fig 6.4.3), but white perch landings were affected by several factors other than the white perch population, such as fishing effort, conditions during the fishing season, gears used, etc. Delaware white perch landings were high for several years during the 1950s, were low during most of the 1960s and 1970s, rose during the 1980s, and were near or above the time series mean during the 1990s through 2015. While Delaware's precipitous decline in commercial landings since their historic peak in 2011 may be the result of poor fishing or market conditions during the following years, it may also be a result of poor recruitment to the fishery during this time as suggested by the low YOY index during 2012 through 2016. Both the YOY index and the commercial landings suggest that the Delaware Estuary white perch population undergoes cyclical expansions and declines.

6.4.5 Future Predictions

The white perch's ability to inhabit almost all waters of the Delaware Estuary may buffer it from some of the extreme population fluctuations seen in other species, but habitat protection, particularly for areas of the Estuary in which white perch spawn, is important for the continued viability of this fish. Past trends suggest that white perch will continue to support important commercial and recreational fisheries in the Delaware Estuary for the foreseeable future.

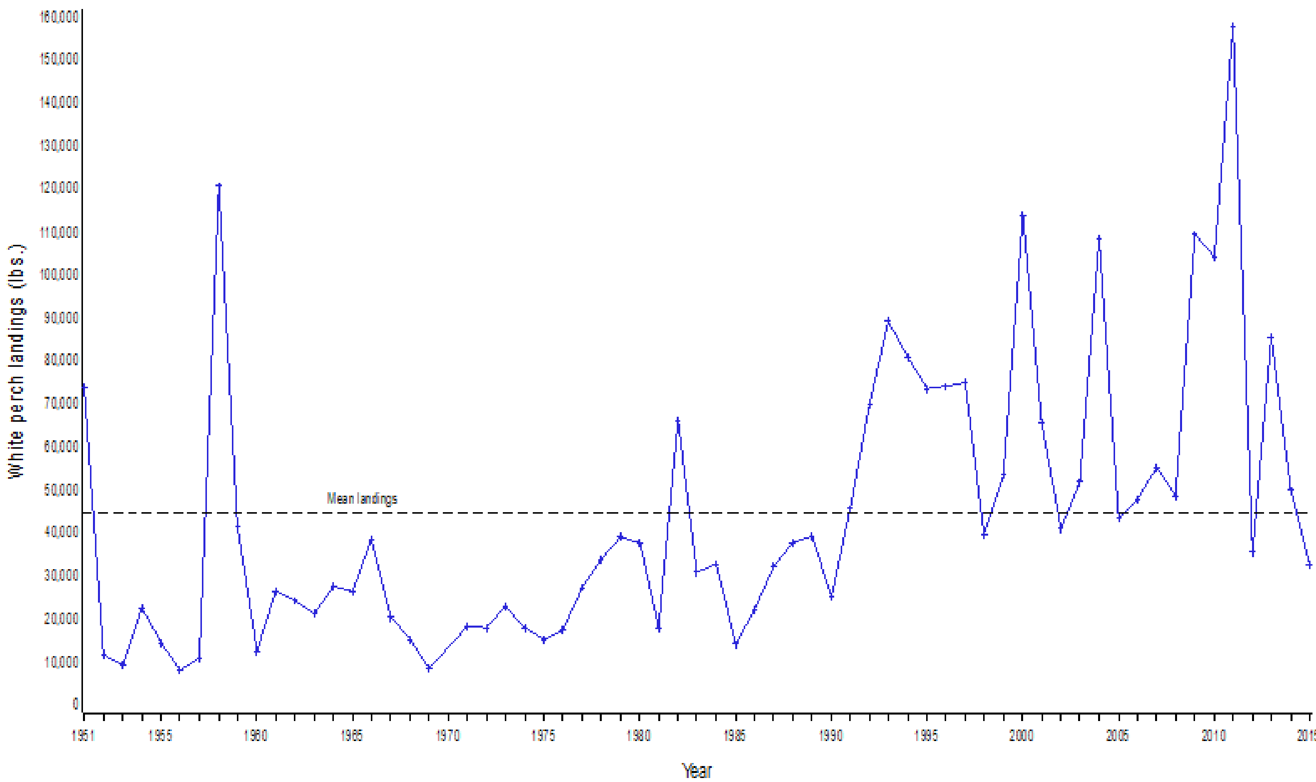

Figure 6.4.3 Delaware commercial white perch landings (lbs.) 1951 through 2015

6.4.6 Actions and Needs

The 8-inch minimum size limit for white perch, established by Delaware in 1995, has been effective in allowing almost all white perch to spawn at least once before recruiting to the fisheries. All states in the Delaware Estuary should establish an 8-inch minimum size for white perch to ensure that most white perch may spawn before they recruit to the fisheries.

White perch often spawn in areas of the Delaware River and in the upper reaches of Delaware Estuary tidal tributaries that have been subject to intense development pressure in the past 50 years. These are spawning habitats for many fish species, including white perch, and these habitats should be protected.

6.4.7 Summary

White perch are one of the most abundant and widespread fish in the Delaware Estuary. The species supports important commercial and recreational fisheries. Although the white perch population in the Delaware Estuary seems to be maintaining itself, some basic management measures will ensure the population continues to thrive.

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6.5 Striped Bass

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6.5.1 Introduction
Striped bass (*Morone saxatilis*; Fig 6.5.1) are large, predatory fish of the family Moronidae with dark horizontal stripes extending from the opercula to the caudal peduncle. This species has been found to inhabit tidal creeks and rivers, jetties, beaches, and relatively open water in the Bay, River and ocean depending upon age and time of year. Striped bass are frequently referred to as rockfish because of a historic association with oyster reefs which were known as oyster rocks in the Mid-Atlantic region. Some younger, smaller individuals inhabit portions of the Delaware River Estuary year round, unlike other potentially large predators such as weakfish, bluefish, large sharks, and sea turtles which occur within the estuary seasonally. The Delaware Division of Fish and Wildlife (DE DFW), hereafter the Divsion, has conducted a survey to measure spawning stock biomass since 1996. Additionally, the Division has started to explore the use of acoustic telemetry to better identify migratory corridors and trends in habitat utilization. Preliminary results coupled with older tagging studies indicate that a large portion of the Delaware River spawning stock, primarily females, engage in a spring coastal migration to southern New England and eastern Long Island; mature females spawn in the River prior to migrating up the coast annually. However, male bass remain in the Estuary or nearby ocean waters year round. Further, the DE DFW has found evidence of exchange between the Chesapeake and Delaware Bays via the Chesapeake and Delaware Canal, indicating these fish use the canal as a migratory corridor between estuaries.

Figure 6.5.1 Adult Striped bass. Photo credit: Kurt Cheng, Partnership for the Delaware Estuary.

Once considered extirpated by some biologists prior to the improvement of dissolved oxygen (DO) levels in the 1980s, the Delaware River population is now one of the major spawning stocks on the Atlantic coast, along with the Hudson River and Chesapeake Bay stocks. Management action for striped bass can be traced as far back as pre-Colonial times, when use of striped bass for fertilizer was banned. The Delaware River spawning stock declined greatly by the mid-twentieth century, in response to frequent, prolongued periods of hypoxia and anoxia in the late spring through early fall in the spawning grounds from Philadelphia through Wilmington reaches (ASMFC 1981; Kahn et al., in press), with some areas having persistent DO concentrations at zero during the summer months in the 1950s and 1960s (Sharp 2010). The Delaware River oxygen content increased during the 1970s and 1980s due to the Clean Water Act, which produced pollution reduction and upgrades to the sewage treatment plants along the River. During the 1980s, production of striped bass young-of-year increased gradually with a large surge in 1989 (Fig 6.5.2). In 1998, the Atlantic States Marine Fishery Commission (ASMFC) declared the Delaware River stock recovered, based on a report by Kahn et al. (1998).

Striped bass feed on a number of fishes and invertebrates throughout their life cycle with a general increase in prey size concomitant with individual growth. Younger bass feed primarily on smaller invertebrates including zooplankton, insects, worms, and amphipods. However, juveniles will also feed on fish larvae and small pelagic fish species as growth and ontogeny progress. Larger bass have been found to predominately prey on small pelagic fish species such as anchovies, river herring, Atlantic silverside, and Atlantic menhaden (Griffin and Margraf, 2003) with secondary prey items including larger invertebrate species (e.g. blue crab, Atlantic rock crab, and American lobster; Pruell et al. 2003; ASMFC 2013).

Striped bass spawning grounds exist in tidal fresh water in the Delaware River generally above detectable concentrations of salinity. However, the DE DFW has observed spawning activity in nearby tidal waters with salinities ranging from 0.5 – 5.0 ppt. Similarly, a previous study demonstrated that bass successfully spawned within a narrow range of very low salinities (0.70-1.5 ppt) in the Chesapeake and Delaware Canal

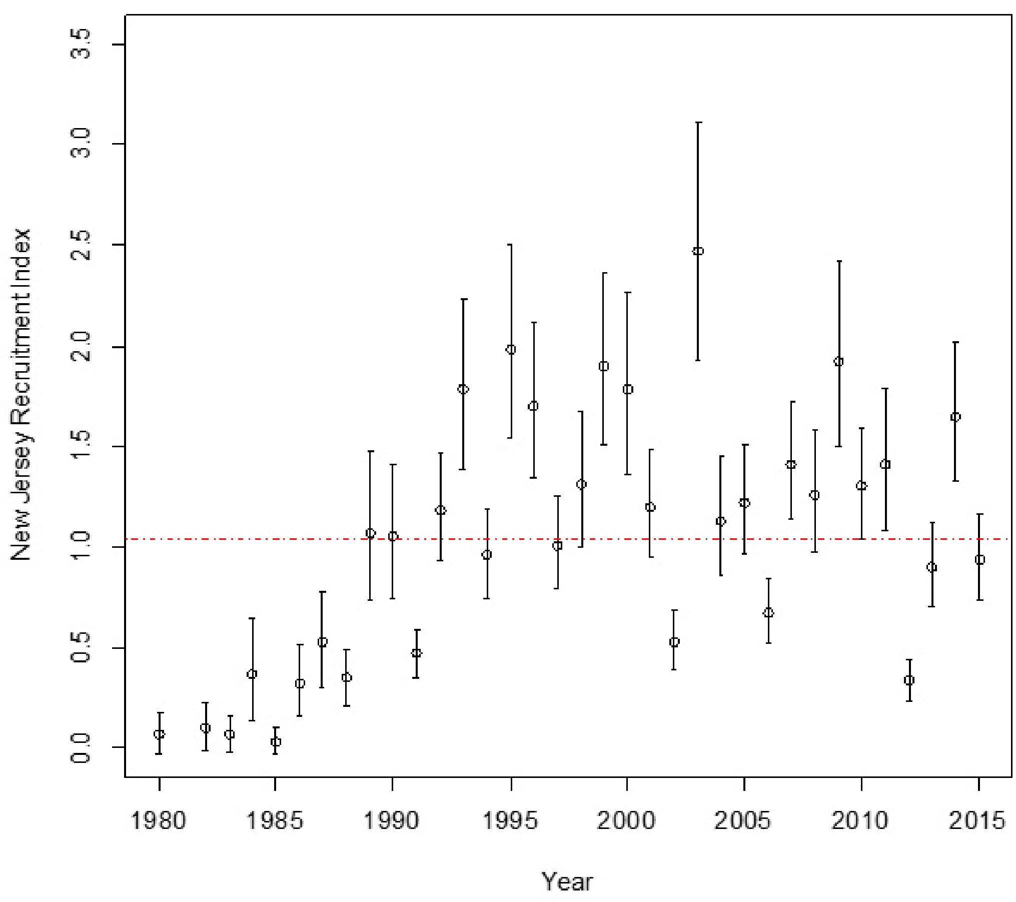

Figure 6.5.2 The annual Delaware River Recruitment Index, the geometric mean number of young-of-year bass caught per seine haul, with the time series mean shown by the red dashed line. Source: New Jersey Division of Fish and Wildlife.

(Johnson and Koo 1975; Greene et al. 2009). The Delaware spawning survey usually finds more fish in April in Delaware waters from the Delaware Memorial Bridge up to the Delaware-Pennsylvania line. However, the New Jersey shore is typically where the majority of spawners congregate, along with the Cherry Island Flats, which are shoals in the River opposite Wilmington. As the season progresses into May, the temperature and salinity tend to increase, and spawning bass are more commonly collected in Pennsylvania waters up to the Philadelphia Navy Yard. Spawning usually terminates by the end of May. By September, young-of-year bass are several inches long, and do not typically exceed four inches before November.

In addition to being integral to the ecology of the Estuary, striped bass are of economic benefit to both the State of Delaware and the State of New Jersey. Delaware has a commercial fishery targeting the species. Currently, this fishery has the highest economic value of any of Delaware's commercial fin fisheries and is second only to the commercial blue crab fishery in terms of total ex-vessel value in the state. In 2015, Delaware commercial fishers generated more than $550,000 in ex-vessel value from striped bass landings (Fig 6.5.3). However, the State of New Jersey has banned the commercial harvest of striped bass for decades. Despite the difference between the commercial activities of the two states, both Delaware and New Jersey have a large recreational fishery, which ranks as one of the most popular in both states. The species is one of a few inshore species that can achieve big game size, with occasional fish exceeding 50 pounds.

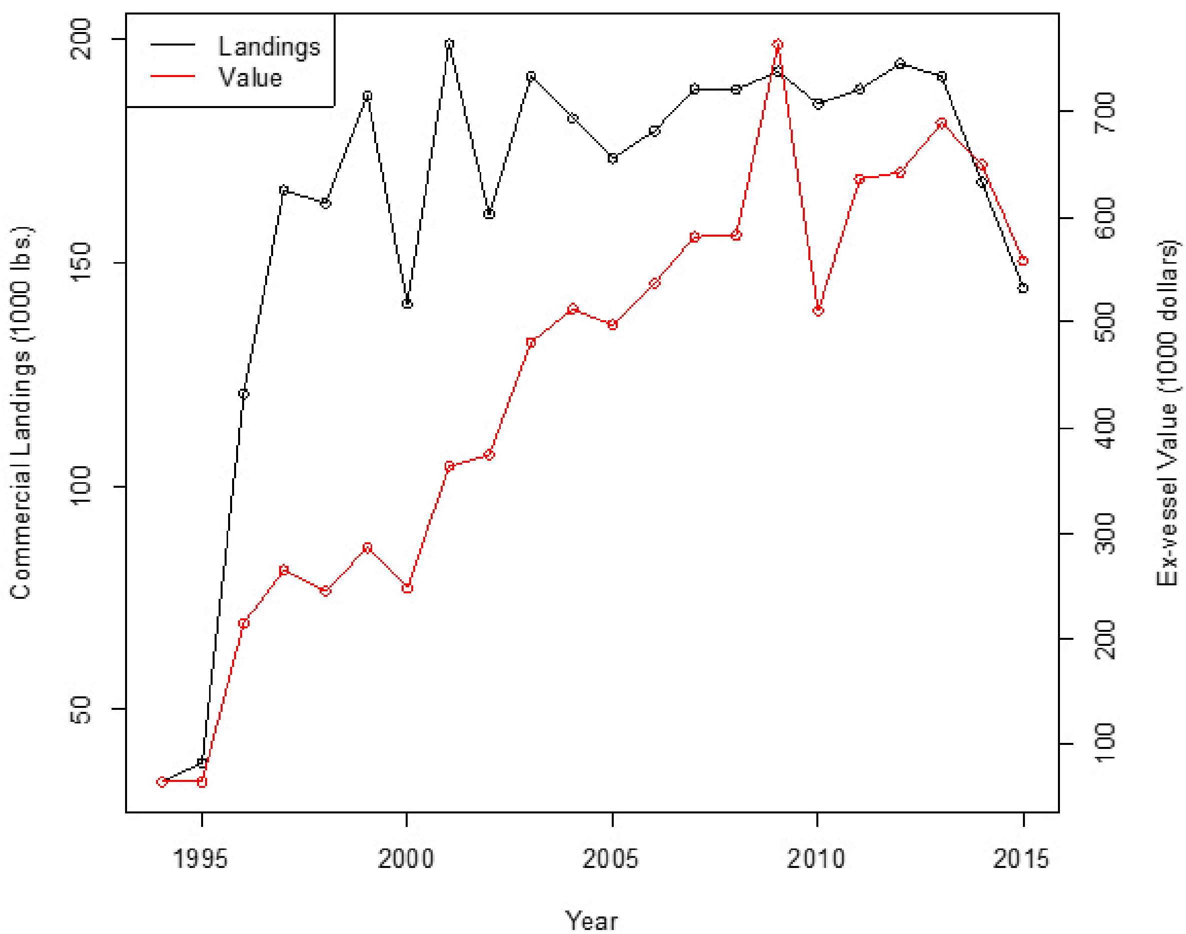

Figure 6.5.3 The total annual landings and ex-vessel value of commercially caught Striped bass in the State of Delaware.

6.5.2 Description of Indicator

Two indicators from the Delaware River Estuary serve to measure the relative health of the striped bass population: the Delaware Spawning Stock Survey and the New Jersey Recruitment Survey. Both surveys use a geometric mean to provide a quantitative annual index of two biological parameters to compare performance through time. The first index, a geometric mean of the number caught per unit of electrofishing effort on the spawning grounds in April and May, is a measure of the reproductively capable abundance of the stock (Fig 6.5.4). The second index, the geometric mean of the number of young-of-year bass caught per seine haul, is a measure of the annual reproductive output of the stock (Fig 6.5.2).

6.5.3 Present Status

Survival to age one varies annually in response to a multitude of factors, including but not limited to, adult spawning intensity, hydrodynamic properties, growth, quantity and quality of larval prey, and corresponding larval condition. A large year class at the young-of-year stage often results in a greater number of recruits into the fishery several years later. Regardless of the observed fluctuations between years, the overall status of the Delaware River spawning stock is positive suggesting that current management practices are sustainable.

6.5.4 Past Trends

Striped bass are presently harvested at sustainable levels along the Atlantic coast (ASMFC 2016). Improvements to water quality and a successful management regime are cited as the principle reasons for the dramatic improvement in the population. Within the Delaware River Estuary, the annual Spawning Stock Survey index has varied from 0.86 to a high of 4.10, with a mean of 2.34 from 1996-2015 (Fig 6.5.4). The index was generally higher from 1996-2005 compared to the period from 2005-2015. However, a great deal of inter-annual variability is present in the index.

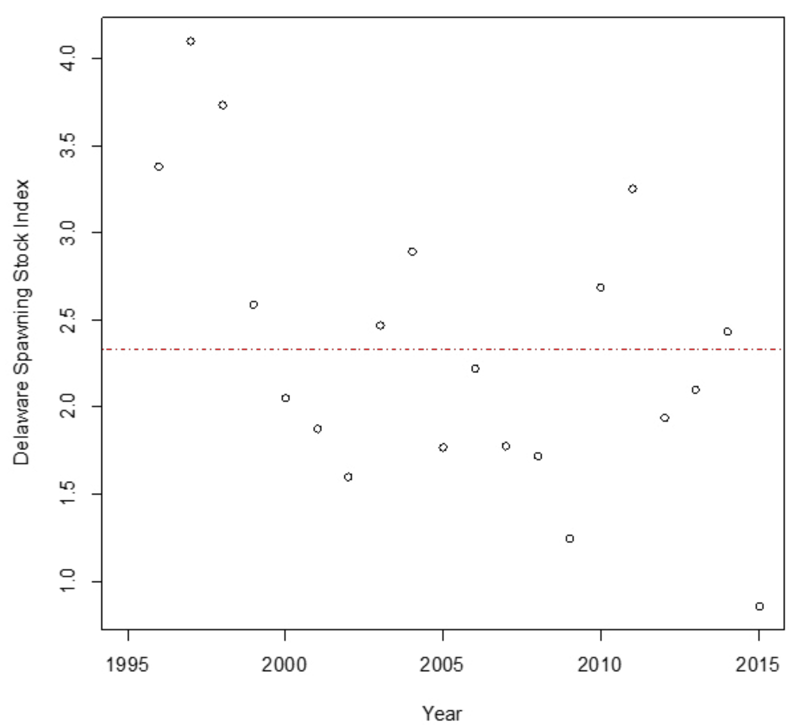

Figure 6.5.4 The annual Delaware Spawning Stock Survey index with the time series mean shown by the red dashed line.

The annual New Jersey Recruitment Survey index has ranged from 0.03 to 2.47, with a time series mean of 1.04 from 1980-2015 (Fig 6.5.2). Similar to the Spawning Stock Survey index, the recruitment index was below the time series mean in 2015, but above it in 2014 demonstrating substantial inter-annual variability. Further, the coast wide status of the stock was recently determined to be not overfished, nor was the stock currently experiencing overfishing relative to the biological reference points (ASMFC 2016).

6.5.5 Future Predictions

The striped bass fishery is managed under relatively conservative regulations to maintain high levels of spawning stock biomass. The current reference points were enacted to protect a coastwide spawning stock biomass target of 125% of the 1995 levels (the year the species was declared recovered by the ASMFC). When examining the number of striped bass caught per recreational trip in Delaware, a similar pattern of high inter-annual variability compared to the Delaware Spawning Stock Survey becomes apparent (Fig 6.5.5), demonstrating the inherent irregularity in annual harvest. Despite a lower value observed in 2015, the recreational catch per trip was generally higher in the last twenty years than the time series average suggesting that the species has been managed to maintain relatively high levels of productivity.

6.5.6 Actions and Needs

In order to ensure sustainable levels of future harvest, we need to continue monitoring long term trends in biomass and recruitment, responding when necessary with management action.

6.5.7 Summary

Striped bass are large, predatory fish that are important to the ecology of the Delaware River Estuary and the economy of the surrounding states. In response to conservative historical management measures and improved habitat availability and thanks to enhanced water quality conditions, the species has rebounded

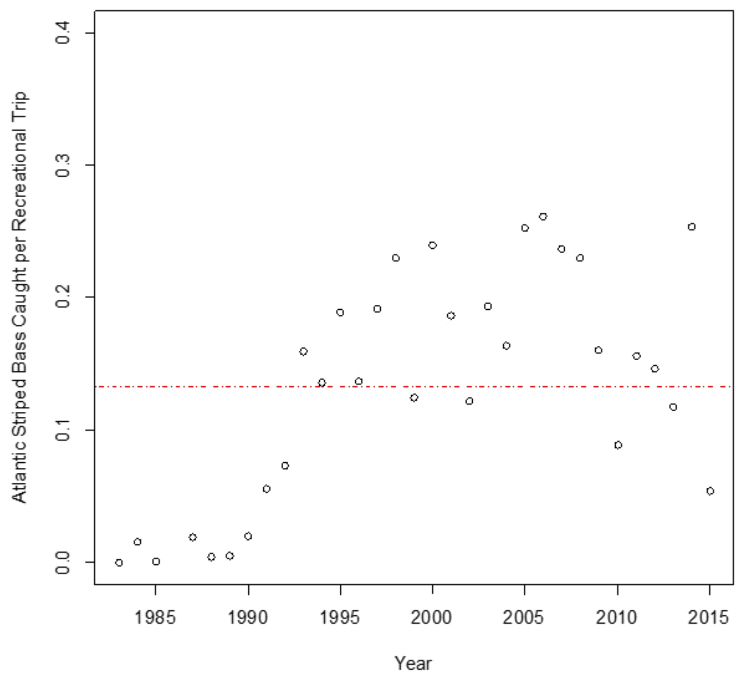

Figure 6.5.5 The annual index of recreationally caught Striped bass caught per trip with the time series mean shown by the red dashed line.

from historic lows to new highs in abundance. This stock has come to represent a significant management success and continues to provide a sustainable fishery resource. In order to continue to sustainably harvest striped bass, we will need to continue long-term monitoring programs and advance our mathematical modelling to better approximate the dynamics of an ever changing environment.

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6.6 Weakfish

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6.6.1 Introduction

Figure 6.6.1 Weakfish landed in the Delaware Bay. Photo credit: Jenny Paterno Shinn.

Weakfish (*Cynoscion regalis;* Fig 6.6.1) is a marine fish that is member of the drum family Sciaenidae. Locally, weakfish often go by other common names such as grey trout or sea trout; although they are of no relation to the "true" trout family Salmonidae. Weakfish occur along the Atlantic coast from Nova Scotia, Canada to southeastern Florida, but are most common from New York to North Carolina. Weakfish once dominated Delaware's recreational and commercial landings in the 1970s and 1980s, and the species was named the Delaware State Fish in 1981. With the onset of spring and the warming of coastal waters, adult weakfish begin a northerly inshore migration from offshore waters off the Carolina coast to nearshore coastal waters and estuaries to spawn. Spawning in the Delaware Estuary occurs in the shallows and on shoals in the middle and lower Bay and generally begins in May with sporadic, secondary spawning taking place throughout the summer. Larger weakfish, over several pounds, which were extremely common in the 1970s and 1980s and less so in the later 1990s, spawn in the spring and then leave the Bay. These larger fish may then migrate to southern New England. Younger, smaller adult weakfish tend to stay in the Bay all summer, and could spawn more than once. From late spring through early fall, young-of-year weakfish are found throughout the Estuary from the lower Bay up into the Delaware River. In recent years, Age 0 weakfish have started to appear in surveys in mid to late June. Young weakfish are fast growing, often reaching a length of six- to eight-inches before leaving the Bay in the fall to migrate south as water temperatures decline.

Weakfish feed on a variety of prey ranging from invertebrates like crustaceans and mollusks to various fish species. Younger fish feed on mysid shrimp, also known as opossum shrimp, and sand shrimp, which can be very abundant in mats of grass detritus washed out of marshes. Larger weakfish are more piscivorous, feeding mainly on other fish, primarily members of the Clupeidae family like Atlantic Menhaden. Larger weakfish are also cannibalistic, feeding on young-of-year weakfish (Merriner 1975; Thomas 1971).

Weakfish abundance and catches have been declining coastwide since the late 1990s. A coastwide stock assessment completed in 2006 found natural mortality had increased beginning in 1996, eventually causing the stock to decline (ASMFC 2006). That assessment developed a hypothesis that predation and possibly competition from striped bass and spiny dogfish caused the large increase in natural mortality that led to the weakfish decline. Although coastwide young-of-the-year indices remained relatively steady with low levels of adult harvest, the population did not show signs of recovery. A stock assessment conducted in 2009 examined other potential factors that could affect natural mortality in addition to predation, including seasonal variables such as water temperature and large-scale, environmental phenomena including the Atlantic Multidecadal Oscillation (NEFSC 2009). However, the 2009 assessment was unable to identify a driving factor affecting mortality, although competition and predation from striped bass and spiny dogfish were not ruled out. The most recent peer reviewed assessment conducted in 2016 utilized several methods to estimate time-varying mortality including the relationship between catch and the Atlantic Multidecadal Oscillation (ASMFC 2016). As with the 2009 assessment, the 2016 assessment supported the hypothesis that natural mortality has increased since 1996 but was unable to determine the underlying cause or causes.

6.6.2 Description of Indicator

The primary indicator of weakfish productivity in the Delaware River Estuary is the mean catch per nautical mile of weakfish in the adult groundfish research trawl survey, conducted using a 30-foot otter trawl net in Delaware Bay by the Delaware Division of Fish and Wildlife. This survey has been conducted since 1966 (1966-71, 1979-84 and 1990 – present) and is conducted monthly from March through December at nine fixed stations in Delaware Bay.

Weakfish relative abundance in the 30-foot trawl survey has generally followed a declining trend since 1996 (Fig 6.6.2) and total mortality estimates have correspondingly increased. Despite annually ranking among the top one or two (by number) fish species encountered in the trawl survey, weakfish abundance remains below the historical average for the survey. However, abundance did increase in 2015 following three consecutive years of declining abundance (Greco 2016). The age structure of weakfish remains truncated similar to the age structure found in the early 1990s with 88% of survey catch being less than age two.

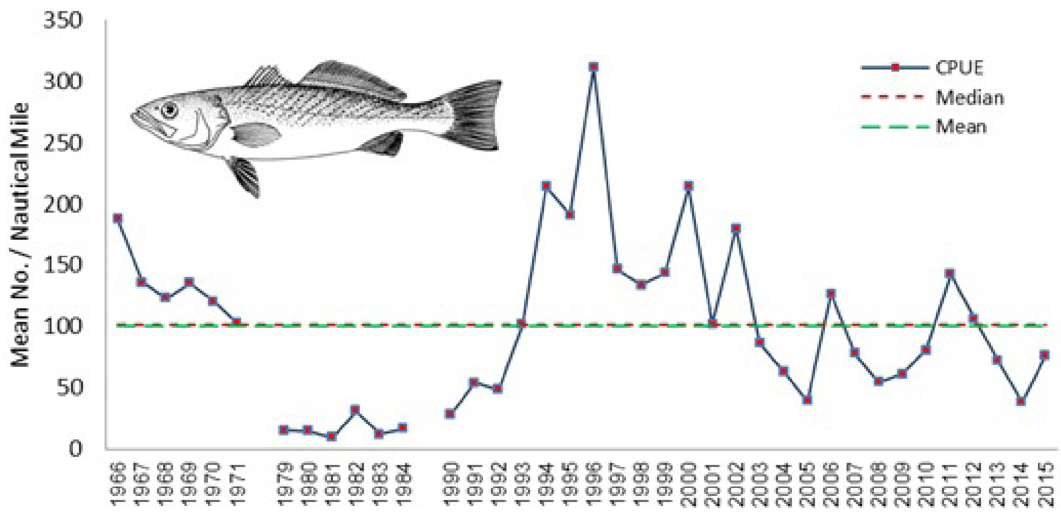

Figure 6.6.2 Weakfish relative abundance (mean number per nautical mile), time series (1966 – 2014) mean and median as measured in 30-foot trawl sampling in Delaware Bay.

A secondary indicator of weakfish productivity in the Delaware River Estuary is the index of relative abundance of young-of-the-year weakfish as measured by the Delaware Division of Fish and Wildlife's Juvenile Finfish Research Trawl Survey. This survey has been conducted annually since 1980 and samples monthly from April through October at 33 fixed stations in the Delaware Bay and River utilizing a 16-foot semi-balloon otter trawl. Abundance of young-of-year weakfish declined in 2015 relative to 2014 and dropped slightly below the time series mean (Fig 6.6.3) (Greco 2016).

Weakfish annually rank among the top species taken in the juvenile trawl. However, as with the relative abundance in the 30-foot trawl survey, the young-of-the-year index for weakfish has also followed a declining trend since 1996 (Fig 6.6.2). Recent recruitment levels have been above or near the historical average and, given the propensity of weakfish to reach sexual maturity by age 1, as studied by Nye et al. (2008), the above average recruitment could lead to an increase in the spawning stock biomass for the species, unless current very high levels of natural mortality continue.

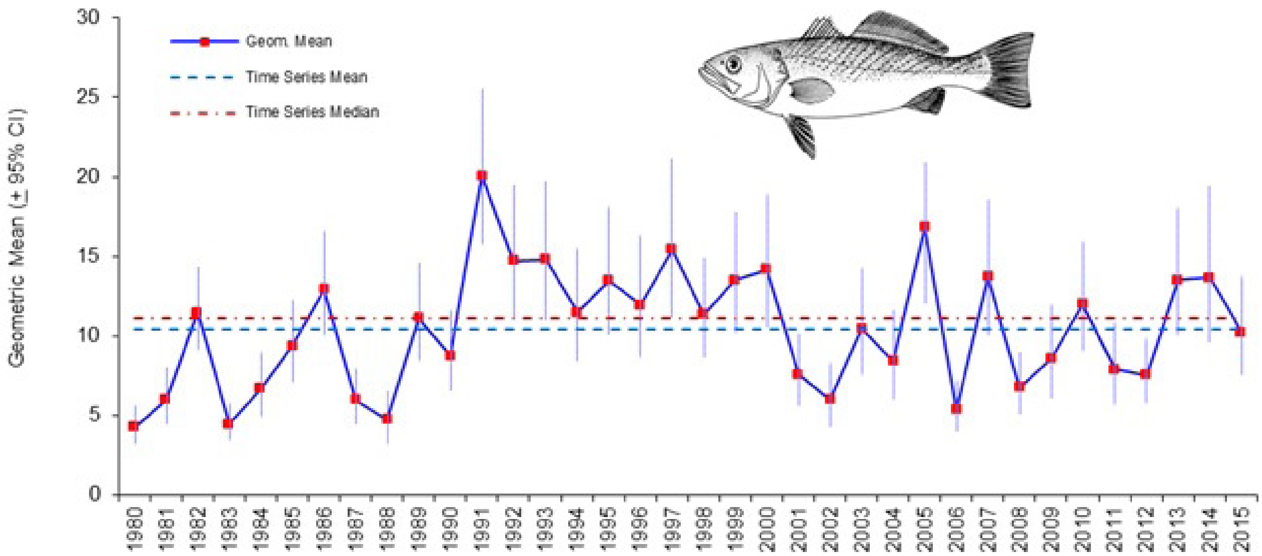

Figure 6.6.3 Relative abundance of young-of-year weakfish from 1980 through 2015, time series mean and median as measured by 16-foot trawl sampling in the Delaware Estuary.

6.6.3 Present Status

Despite a small increase in adult weakfish abundance in Delaware's adult trawl survey in 2015 and despite the fact that young-of-year recruitment in the estuary fluctuates around the historical average, the coastwide weakfish stock is considered depleted and has been for the past 13 years as detailed in the latest peer reviewed stock assessment (ASMFC 2016). Under the new reference points proposed in the latest assessment, the stock is considered depleted when the coastwide estimated spawning stock biomass is below 30% of the estimated average biomass over the period 1982-2014. The 2016 assessment estimated the spawning stock biomass to be 5.62 million pounds in the terminal year of the assessment (2014). Despite slight increases in total abundance and spawning stock biomass in recent years, the stock is well below the spawning stock biomass threshold and has been since 2003. Results of the latest assessment indicated that overfishing is not occurring, since total mortality ($Z = 1.11$) was below the current threshold ($Z = 1.36$). However, the assessment indicated that natural mortality has been increasing since the mid-1990s. As such, the weakfish population has been experiencing high levels of total mortality, which has prevented the stock from recovering (ASMFC 2016).

6.6.4 Past Trends

Weakfish were at moderate abundance prior to the 1970s, when they began an explosive rise in abundance and size. By the late 1970s, Delaware Bay had become famous throughout the Mid-Atlantic region as a destination for catching trophy-sized weakfish in the spring spawning run. By the late 1980s, this fishery declined somewhat; however, the Delaware commercial fishery landed over 200,000 pounds of weakfish as late as 2001. The Atlantic States Marine Fisheries Commission imposed significant fishery restrictions coastwide in the mid-1990s, and, in response, abundance and catches initially began to increase through the late 1990s, before declining during the 2000s. So, although the fishery has not regained the high catches and trophy sizes seen in the 1970-1980 period, it did produce higher catches of legal size weakfish for many in the mid- to late-1990s, before its ultimate decline. By 2007, Delaware commercial landings declined to 27,000 pounds. By 2010, no directed fishery was allowed on the Atlantic coast; only a small amount of bycatch was legal.

6.6.5 Future Predictions

The 2016 stock assessment indicated that in recent years, slight increases coastwide in total abundance, spawning stock biomass, and recruitment of age 1 fish have occurred. However, the stock remains well below the recommended threshold.

6.6.6 Actions and Needs

More investigation is warrented to examine causes of weakfish declines (ASMFC 2016), although some factors have been identified.

6.6.7 Summary

Currently, weakfish reproduction continues at moderate levels. Survivorship to catchable size, however, has declined greatly, to the point that catches of legal-size weakfish are uncommon in Delaware Bay. The cause of the decline has been linked to factors such as predation by striped bass and spiny dogfish, competition with striped bass for menhaden and, changes in environmental conditions (ASMFC 2006, NEFSC 2009). However, the most recent stock assessment (ASMFC 2016) claimed that explicit factors leading to the decline of weakfish require more investigation.

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6.7 Horseshoe Crab

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6.7.1 Introduction

Horseshoe crabs (*Limulus polyphemus)* are benthic (or bottom-dwelling) arthropods that use both estuarine and continental shelf habitats (Fig 6.7.1). Although it is called a "crab," it is grouped in its own class (Merostomata), which is more closely related to the arachnids than blue crabs and other crustaceans. Horseshoe crabs range from the Yucatan Peninsula to northern Maine, with the largest population of spawning horseshoe crabs in the world found in the Delaware Bay.

Figure 6.7.1 Horseshoe Crabs spawning. Photo credit: Gregory Breese, U.S. Fish and Wildlife Service

Each spring, adult horseshoe crabs migrate from deep Bay waters and the Atlantic continental shelf to spawn on intertidal sandy beaches. Beaches within estuaries, such as the Delaware Bay, are believed to be preferred because they are low energy environments protected from wind and waves, thus reducing the risks of stranding during spawning events. Spawning generally occurs from March through July, with the peak spawning activity occurring on the evening new- and full-moon high tides in May and June.

Horseshoe crabs are characterized by high fecundity, high egg and larval mortality, and low adult mortality. Horseshoe crabs spawn multiple times per season, laying approximately 3,650 to 4,000 eggs in a cluster. Adult females lay an estimated 88,000 eggs annually. Egg development is dependent on temperature, moisture, and oxygen content of the nest environment. Eggs hatch between 14 and 30 days after fertilization.

Juvenile horseshoe crabs generally spend their first and second summer on the intertidal flats, usually near breeding beaches. As they mature, horseshoe crabs move into deeper water, eventually into areas up to a few miles offshore. Horseshoe crabs molt 16 to 17 times over 9 to 11 years to reach sexual maturity. Based on growth of epifaunal slipper shells (*Crepidula fornicata*) on their prosoma, horseshoe crabs live at least 17 to 19 years.

Larvae feed on a variety of small polychaetes and nematodes. Juvenile and adult horseshoe crabs feed mainly on molluscs including razor clam (*Ensis* species), macoma clam (*Macoma* species), surf clam *(Spisula solidissima*), blue mussel (*Mytilus edulis*), wedge clam (*Tellina* species), and fragile razor clam (*Siliqua costata*).

Shorebirds feed on horseshoe crab eggs in areas of high spawning densities such as the Delaware Bay. Horseshoe crab eggs are considered essential food for several shorebird species in the Delaware Bay, which is the second largest migratory staging area for shorebirds in North America. Shorebird predation on horseshoe crab eggs has little impact on the horseshoe crab population since horseshoe crabs place egg clusters at depths greater than 10 centimeters, which is deeper than most shorebirds can probe. Eggs utilized by shorebirds are brought to the surface by wave action and burrowing activity by spawning horseshoe crabs. The eggs brought to the surface not consumed by shorebirds or other predators desiccate in a short time in the sun, so do not contribute to productivity of the horseshoe crab population.

It is believed that adult and juvenile horseshoe crabs may make up a significant portion of the diet of the loggerhead sea turtle (*Caretta caretta*) in Delaware. Horseshoe crab eggs and larvae and adults are also a seasonally preferred food item of a variety of invertebrates and finfish, including sharks.

Historically, human activity appears to have resulted in reduced numbers of spawning crabs at two time periods. Between the 1850s and the 1920s, it is estimated that over one million horseshoe crabs were harvested annually for fertilizer and livestock feed. More recently horseshoe crabs have been taken in substantial numbers (e.g., over 5 million pounds in 1996) to provide bait for other fisheries, including (primarily) the American eel and conch fisheries. Since the early 2000s, harvest of horseshoe crabs for bait has been restricted multiple times and currently there is a moratorium on female harvest for bait in the Delaware Bay region.

Horseshoe crabs are also collected by the biomedical industry to produce Limulus Amebocyte Lysate (LAL). This industry bleeds individuals and releases the animals live after the bleeding procedure. LAL is used world-wide to test medical products such as flue serum, pace makers, artificial joints, and other items to help ensure public safety from bacterial contamination. No other known procedure has the same accuracy as the LAL test. If LAL became unavailable, it could take years to find a universally accepted replacement. Mortality associated with this use is estimated to be around 5-30%.

6.7.2 Description of Indicator

This indicator uses the Spawning Survey, which is conducted under the direction of the Atlantic States Marine Fisheries Commission's (ASMFC) Interstate Fishery Management Plan for Horseshoe Crab. The survey provides levels of spatial and temporal coverage that are effective for understanding trends in spawning activity at the bay-wide scale. Begun in 1999, this survey is published annually as a report to the ASMFC.

Beaches are sampled by volunteers using a stratified random approach. Sampling occurs 2 days prior, day of, and 2 days after the peak moon events (full and new moons) and at the highest of the daily high tides, which is the second or evening high tide. Protocol and data sheets and training are provided to volunteers. Each beach is sub-sampled using quadrats along transects that have random starts. Approximately 100 quadrats are sampled per beach. The quadrats are placed at the high-tide line and all horseshoe crabs that are at least halfway in the quadrat are counted and differentiated by sex (Figs 6.7.2 and 6.7.3).

The objective of the spawning survey was to estimate an index of spawning activity based on horseshoe crab density. It is important to recognize that this survey gives an estimate of density and should not be used to estimate population size. Instead it provides a useful measure of relative abundance or density of spawners and trends in spawning density.

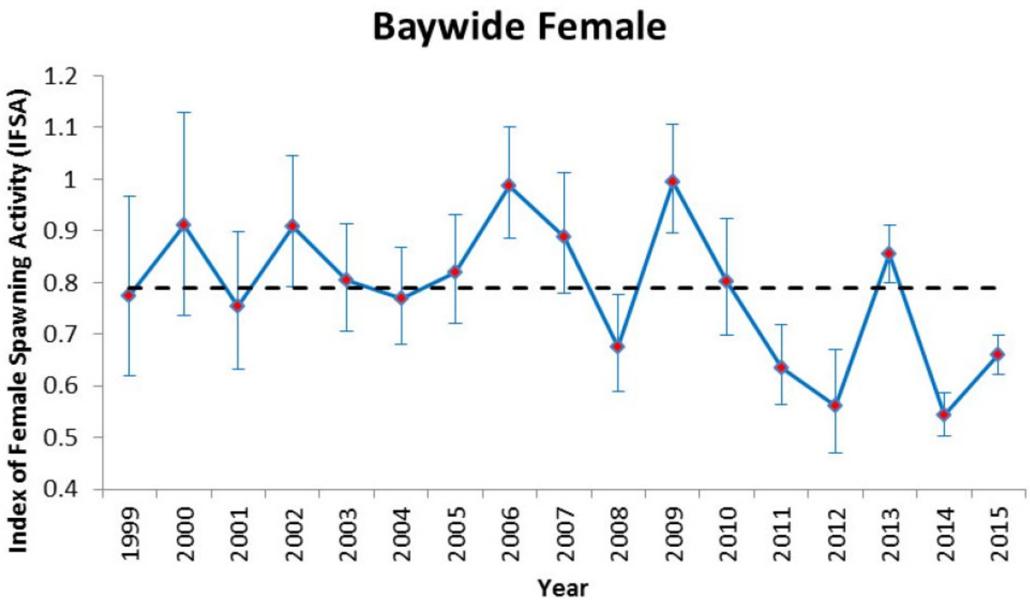

Figure 6.7.2 Index of female horseshoe crab spawning activity (IFSA) for the Delaware Bay from 1999 to 2015. Error bars are 90% confidence intervals. The dashed line is the mean value for the time series.

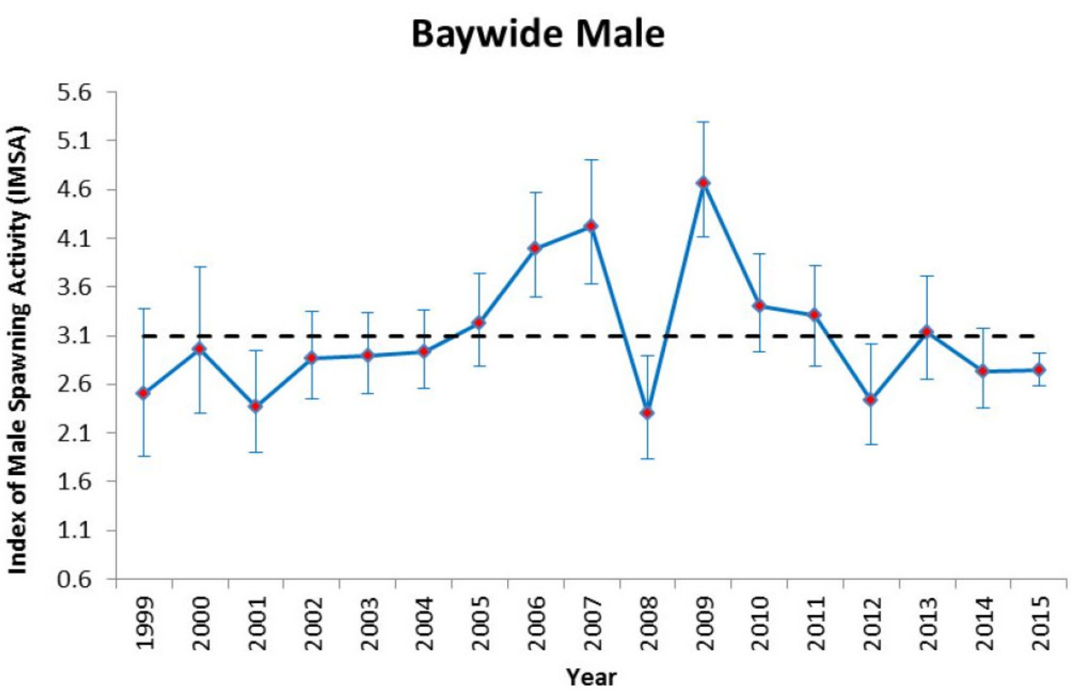

Figure 6.7.3 Index of male horseshoe crab spawning activity (IMSA) for the Delaware Bay from 1999 to 2015. Error bars are 90% confidence intervals.

6.7.3 Present Status

The latest report available is the 1999-2015 Spawning Survey Report, published May 25, 2016. In 2015 spawning peaked during the second lunar period sampled (May 16 – May 20). Spawning is well correlated with water temperatures.

6.7.4 Past Trends

Little data is available for measuring trends prior to 1990, but the population probably declined in the early 1900s due to overharvest and then increased through the 1970s. Bait overharvest led to another decline in the 1990s. The index of female spawning activity in both states exhibited a slightly negative slope, and the declining trend was statistically significant in Delaware. Baywide male spawning activity showed no significant trend from 1999 through 2015; though, the slope was positive.

6.7.5 Future Predictions

The ASMFC has implemented monitoring programs and restricted harvest of horseshoe crab with stated goals of maintaining a sustainable population for current and future generations of the fishing and non-fishing public, migrating shorebirds, and other dependent wildlife, including federally listed sea turtles. The National Marine Fisheries Service has established a horseshoe crab sanctuary off the mouth of Delaware Bay, the Carl N. Shuster Sanctuary. Watermen have voluntarily implemented the use of bait bags that reduce their need for bait by preventing bait from being consumed by non-target species. The Biomedical Industry has voluntarily implemented management practices to reduce stress to animals being held for bleeding. These measures can be expected to allow the spawning population to increase over time by reducing harvest and indirect mortality.

While there are indications the management actions to limit harvests, combined with voluntary reductions in bait use by watermen, will allow the population to increase, the current population trend for females does not yet show a positive trend and does not appear to be spawning at densities high enough to provide sufficient surface eggs to support historic levels of shorebirds during the spring stopover. Because horseshoe crabs are long-lived and do not reproduce until at they are 8-12 years old, it can take a decade or more for management actions to result in a measurable increase in the spawning population.

6.7.6 Actions and Needs

In order to better understand horseshoe crab population trends and their interaction with shorebirds, a cooperative effort between the ASMFC, States, US Geological Survey, and the US Fish & Wildlife Service has resulted in an Adaptive Management Framework for recommending harvest levels based upon population models that link red knot populations with horseshoe crab populations. Under this Framework, competing models that describe the dependence and interaction of red knots and shorebirds can be evaluated over time by monitoring the populations. Two monitoring programs are essential to implement this Framework: The Horseshoe Crab Trawl Survey and the Shorebird Monitoring Program at Delaware Bay. It will be critical to ensure funding for these two monitoring programs in order to increase our understanding and reduce our uncertainty regarding how these two populations interact.

6.7.7 Summary

Management of horseshoe crab harvest coupled with voluntary measures by the bait and biomedical industries can be expected to allow spawning populations of horseshoe crabs in Delaware Bay to increase over time. However, due to overharvest in the past, and the length of time needed (8-12 years) for horseshoe crabs to reach maturity, populations have not yet shown significant increases in terms of spawning densities relative to what were believed to be historical levels. Shorebirds dependent upon eggs that are exhumed by wave action and high densities of spawning horseshoe crabs are still at low levels and it is unclear whether current levels of surface eggs are high enough to support current levels of red knots and other shorebirds during typical weather conditions.

Since a portion of the red knot population that passes through Delaware Bay winters at the tip of South America and breeds in the high Arctic, other factors outside of Delaware Bay can, and probably are, affecting these populations. Work to help better understand the dependence of red knots on Delaware Bay is being carried out, in part, through a cooperative Adaptive Management Framework.

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Suggested Citation for this Chapter

Breese, G. 2017. "Chapter 6.7 - Horseshoe Crab" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07, pp. 251-255.

6.8 American Shad

Desmond M. Kahn, PhD

Fishery Investigations

6.8.1 Introduction

American shad (*Alosa sapidissma*) is an anadromous species that is native to most major river basins on the Atlantic Coast of North America, including the Delaware River. It is a member of the family *Clupeidae*, or the herring family. The American shad has a lustrous green or greenish blue back with silvery sides and a white belly (Fig 6.8.1). Individuals may live up to 11 years and reach lengths over 20 inches. They are a popular, hard-fighting sport fish that can be taken on rod and reel using lures known as shad darts and flutter spoons, and they also have commercial value.

American shad are opportunistic feeders, whose freshwater diet includes copepods, crustacean zooplankton, cladocerans, aquatic insect larvae, and adult aquatic and terrestrial insects. After emigrating to offshore areas, American shad feed on the most readily available organisms, such as copepods, mysid shrimps, ostracods, amphipods, isopods, euphausids, larval barnacles, jellyfish, small fish, and fish eggs (ASMFC 2010). American shad spend most of their life at sea along the Atlantic coast and enter freshwater as adults in the spring to spawn. Stocks are river specific; that is, each major tributary along the Atlantic Coast appears to have a discrete spawning stock due to high fidelity to return to their natal tributary to spawn. In the fall or subsequent spring, juveniles emigrate from freshwater and estuarine nursery areas and join a mixed-stock, sub-adult coastal migratory population. Three primary offshore summer aggregations of American shad have been identified:
1) Bay of Fundy/Gulf of Maine, 2) St. Lawrence Estuary, and 3) off the coast of Newfound and Labrador.

Figure 6.8.1 Adult Shad caught in Schuylkill River, PA. Photo credit: Philadelphia Water Department.

After four to six years, individuals become sexually mature and migrate to their natal rivers during the spring spawning period. American shad that spawn north of Cape Hatteras are repeat spawners, while almost all American shad spawning south of Cape Hatteras die after one spawning season (ASMFC 2010). Repeat spawning has been documented for Delaware River shad via analysis of scales that reveal growth patterns, including patterns indicative of repeat spawning. In the Delaware, there can be as many as 5 year classes of adult shad participating in a spawning migration; however, the majority of spawning is represented by two age classes (Delaware River Basin Fish & Wildlife Management Cooperative 2016).

American shad have ecological, economic, cultural, and social significance (ASMFC 2010). Ecologically, they play an important role in freshwater, estuarine, and marine environments during their anadromous life cycle. They influence food chains by preying on some species and serving as prey for others throughout all life stages. Economically, American shad have supported valuable commercial fisheries along the entire Atlantic coast. In the late 1890s, the Delaware River had the largest annual commercial shad harvest of any river on the Atlantic Coast. The harvest began to decline rapidly in the early 1900s. Despite efforts in the late 1800s to increase the shad population through legislation and a massive program of artificial propagation, the shad fishery eventually collapsed. Sharp (2010) reports that a 1912 measurement indicates that the dissolved oxygen level was below the current legal requirement of 3.5 mg/L. Detectable water pollution in the River at Philadelphia was reported. By the 1940s, the commercial shad fisheries were mainly limited to the lower reaches of the River and Bay below Pennsylvania (ASMFC 2007). Culturally, American shad were and are of significance to Native Americans, European colonists, and contemporary Americans who reside near and/or fish in rivers that supported or continue to support spawning runs. Many communities celebrated and still celebrate the arrival of shad by holding festivals to mark the occasion. The most comprehensive account of the role that American shad has played in the culture of North America since colonization by Europeans is that written by John McPhee). Research from *The Founding Fish*, (McPhee 2002) documents the relevance of American shad in seventeenth and eighteenth-century America.

6.8.2 Description of Indicator

To investigate the status of this indicator, we used the following data:

- An annual relative abundance index in the upper, nontidal portion of the River, indicating the relative abundance of the annual spawning run. The index is the annual mean catch-per-haul rates from the Lewis Haul Seine operation at Lambertville, NJ. This fishery is a semi-commercial, government-supported, long term fishery operation that has recorded the number caught per seine haul since 1920. The Delaware River Fish and Wildlife Cooperative Committee subsidizes this haul seine because of its value as an index of the spawning runs. Very few fish are actually landed from this operation.
- Commercial harvest data from the Delaware Division of Fish & Wildlife and the New Jersey Division of Fish and Wildlife.

6.8.3 Present Status

The portion of the main stem Delaware River available as habitat extends up into the East and West Branches above Hancock, NY representing over 300 miles of unobstructed main stem access. However, all major tributaries to the main stem Delaware are dammed creating numerous blockages to historic spawning and rearing habitat. The two major tributaries, namely the Schuylkill and the Lehigh Rivers, do have existing fish passage facilities in place at many of their dams, but these are variable in their ability to facilitate upstream passage of American shad.

Tidal reach There is commercial fishery in the Delaware and New Jersey portions of the Estuary with mandatory reporting beginning in 1985 for Delaware and in 2000 for New Jersey. In New Jersey, as of 2016 there were 71 permits issued (31 commercial and 34 incidental) to allow catch of American shad. A total of 45 permitted fisherman reported landings during the 2016 season. A small minority of these permit holders actually land shad in any year; for example in 2010, only 14 fishers landed shad. American shad are also caught as bycatch in Delaware's commercial striped bass fishery that has a season beginning on March 1 and extending through April 31. Currently, commercial harvest levels are relatively low (Fig 6.8.2); in 2015 31,183 pounds were landed, while the peak landings in the last 10 years were in 2007, at 134,266. Since shad landed weigh on average about four pounds, these amount to 795 fish and 33,566 fish, respectively.

The trend of decreasing commercial harvests is not viewed as a reflection of decreasing stock size but rather the result of fewer commercial fisherman in addition to a shift toward the harvest of the more valuable striped bass which are present in the estuary during that American shad migrate through (R. Allen, New Jersey Division of Fish & Wildlife and D. Kahn Delaware Dept. of Fish & Game, personal communication).

Nontidal reach The Lewis Haul Seine fishery at Lambertville, New Jersey is several miles above Trenton. This fishery has provided the mean annual catch per seine haul for an amazing 91 years, which makes it one of the most extensive time series of relative abundance data in the world. Currently the abundance level of the spawning runs are moderate. As discussed below under past trends, factors regulating abundance of American shad in the Delaware include dissolved oxygen levels and a probable negative effect of striped bass via predation.

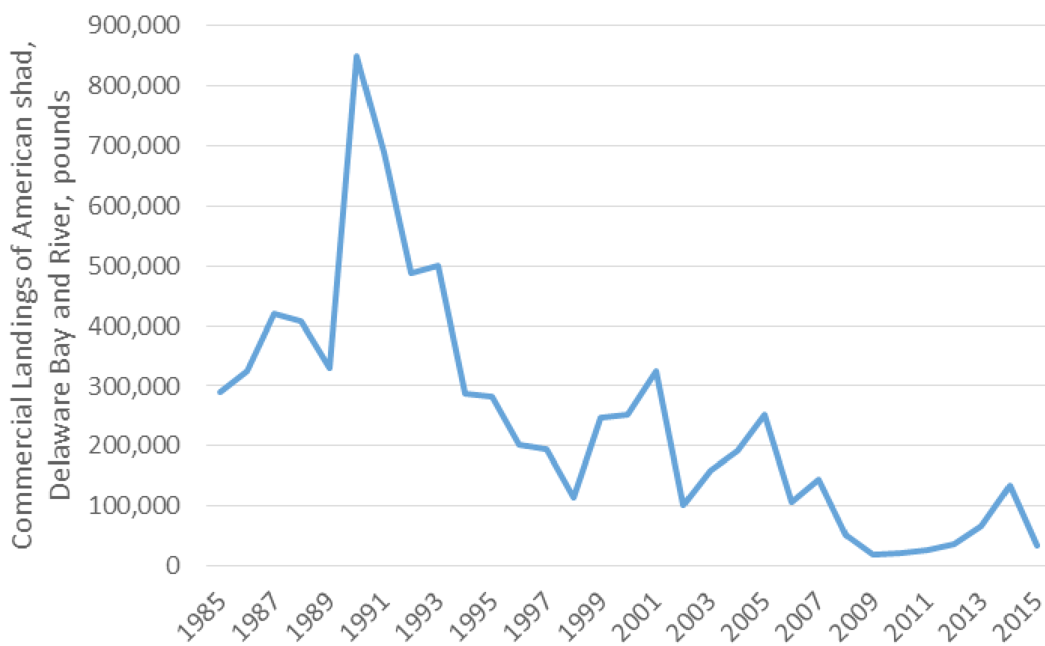

Figure 6.8.2 Commercial landings of American shad from the Delaware River and Bay. Delaware landings are from 1985 through 2015; New Jersey landings are only included from 2000 through 2015. Data supplied by the Delaware Division of Fish and Wildlife and the New Jersey Division of Fish and Wildlife.

6.8.4 Past Trends

The harvest began to decline rapidly in the early 1900s due to water pollution and dams on major tributaries. Despite improved state legislation and regulation, and a massive program of artificial propagation of shad stocks in the late 1800s, the shad fishery eventually collapsed under the combined pressures. By 1950, the urban reach of the Delaware River was one of the most polluted stretches of river in the world (ASMFC 2007). Pollution continued to be a major factor until passage of the Federal Clean Water Act in 1972. This Act was instrumental in the elimination of the "pollution block" of low or no dissolved oxygen in the region around Philadelphia. By 1973 the majority of spawning took place above the Delaware Water Gap more than 115 river miles upstream. American shad can now freely pass through this area during the spring spawning run as well as the fall out-migration.

In the late 1890s, the Delaware River had the largest annual commercial shad harvest of any river on the Atlantic Coast, with some estimates of up to 19 million pounds in a given year, although the accuracy of these estimates is questionable. As the Lewis Haul Seine data begins in 1925, abundance is low to moderate from 1925 through 1945. This was likely influenced by poor water quality, since very poor dissolved oxygen readings were detected as early as 1915 by the Philadelphia Water Department, below the current required 24-hour average level of 3.5 milligrams per liter. By 1948, abundance was near zero until a spike in the early 1960s, which returned to former low levels by 1966. However, as pollution controls were enacted under the federal Clean Water Act beginning in 1972, the runs increased by the late 1970s and through the early 1990s to very high levels, producing a booming recreational fishery in Pennsylvania and New Jersey. By the early 1990s, however, the runs began to decline, dropping to very low levels in the 2000s. Fishery managers responded by closing down a gill-net fishery along the ocean coastline in late winter and early spring by 2005; abundance did not increase, however.

A hypothesis developed from extensive studies on the Connecticut River is that declines during the 1990s and 2000s in abundance of American shad and river herring have been caused by the unprecedented increase in historical times of the abundance and size of striped bass and the predation they conduct (Savoy and Crecco 2004). That hypothesis held up to statistical testing and is supported by numerous publications showing that striped bass prey on alosids during spring in rivers, including consumption of adult shad. The Delaware River spawning stock of striped bass was declared restored by the Atlantic States Marine Fisheries Commission based on a report by Kahn et al (1998). Based on the corroboration of this predation hypothesis in the Connecticut River stocks, the hypothesis was tested for the Delaware River spawning stock as part of the stock assessment of the Delaware River stock by the Delaware River Cooperative Fish and Wildlife Management Technical Committee (DRBFWMC 2011). This test consisted of a correlation or regression analysis of the relative abundance of striped bass in the waters of the state of Delaware from the Marine Recreational Information Program and the mean catch-per-haul index of American shad relative abundance from the Lewis Haul Seine fishery. A negative correlation or regression (depending on the way this analysis is perceived) corroborates the hypothesis. This negative relationship is, in fact, highly significant (Fig 6.8.3), supporting the hypothesis that striped bass predation is a major cause of the decline in shad abundance from the peak levels in the 1980s and early 1990s.

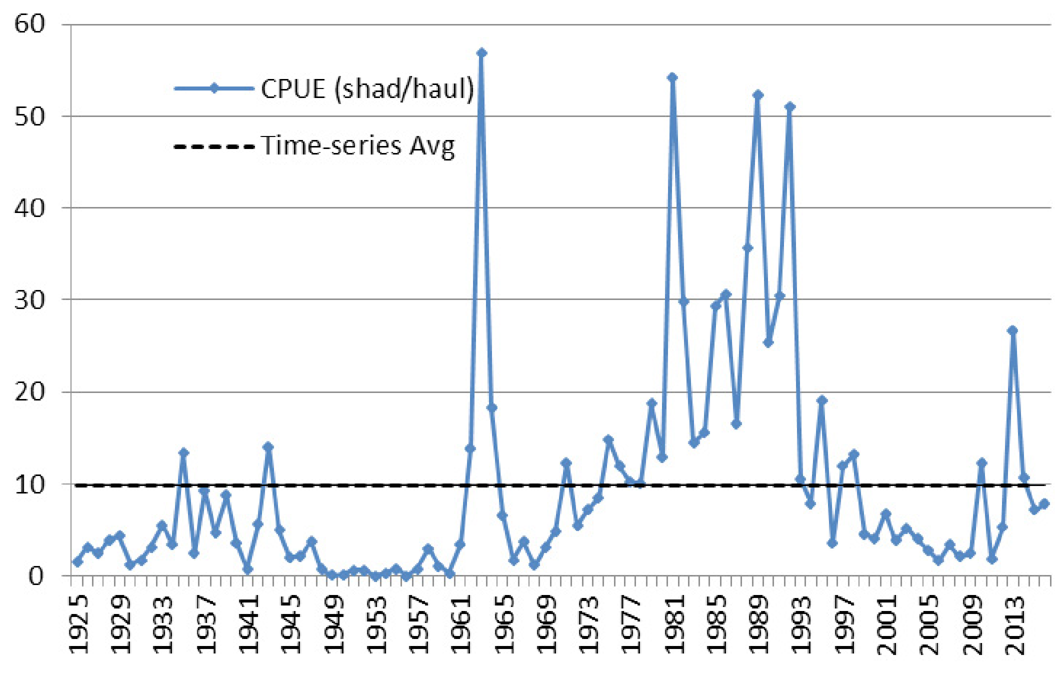

Figure 6.8.3 Mean annual catch per seine haul of American shad in the nontidal Delaware River at Lambertville, New Jersey in the Lewis Haul Seine fishery from 1925 through 2016. Data supplied by the Lewis Haul Seine operation.

6.8.5 Future Predictions

The current fishery for the Delaware River stock of American shad has been found sustainable under current recreational and commercial conditions (Delaware River Basin Fish & Wildlife Management Cooperative 2011, 2016). The current management plan for the Delaware River stock has precautionary benchmarks that could be used to trigger management actions designed to prevent stock collapse, established by the Delaware River Basin Fish and Wildlife Management Cooperative. An overall population increase could be realized with on-going attempts to improve fish passage on both the Schuylkill and Lehigh Rivers. Dam removal activities also on-going in the Brandywine and Musconetcong Rivers will also provide access to historic spawning areas for American shad, allowing a potential increase in the population. However, the predation hypothesis seems to predict that, if the current conservative management of striped bass by the Atlantic States Marine Fisheries Commission continues, the resulting predation pressure from the high number of very large striped bass will likely prevent a major increase in shad abundance in the Delaware.

6.8.6 Actions and Needs

Any improvement in restoring access to blocked habitat through dam removal or improvements in fish passage devices on existing dams would facilitate population increases for American shad in the Delaware River.

Currently, there is no vehicle funding specific for protection and enhancement of the Delaware River shad population. However, a recently passed federal law, the Delaware River Basin Conservation Act, could establish a federal program at the U.S. Fish and Wildlife Service to coordinate and prioritize restoration efforts for numerous species and habitats throughout the Delaware River watershed. Currently, however, this act lacks funding. Restoration activities that would benefit American shad should be considered for use of a portion of any funds supplied, particularly dam removal and fish passage.

6.8.7 Summary

In summary, the current condition of the American shad population in the Delaware River is healthy but moderate when compared to the boom period of the 1980s and 1990s. Although no data exists prior to 1925, reported landings from the late 1800s were enormous, and of questionable accuracy, although they suggest the Delaware River shad stock was far more abundant than it is today. In addition to environmental and social benefits, increases in the population of American shad would provide economic benefits through increased revenues for local communities from recreational angling and commercial fishing. The Delaware River stock of American shad has been twice found to be sustainable under current conditions, with the establishment of benchmarks established by the Delaware River Basin Fish and Wildlife Management Cooperative. These benchmarks are designed to react to declining trends in abundance. Statistical testing could not reject the hypothesis that striped bass predation is negatively correlated with American shad abundance in the Delaware: the potential mechanism is the documented predation on shad by striped bass. This evidence suggests that, if striped bass abundance remains high, American shad abundance in the Delaware will remain moderate to low.

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Suggested Citation for this Chapter

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6.8.9 Schuylkill River American Shad Stock Restoration

L. H. Butler and J. A. Perriilo • Philadelphia Water Department

The Schuylkill River, the largest tributary to the Delaware River, supported large numbers of American shad (*Alosa sapidissima*) until the construction of dams and lock systems in the early 1800's. Historical records indicate that shad and river herring (Alewife, *Alosa pseudoharengus* and Blueback Herring, *A. aestivalis*) ascended the Schuylkill River as far upstream as Pottsville (160 rkm), but have not done so since 1820, when Fairmount Dam was built (Mulfinger and Kaufmann 1981). For more than 150 years, American shad appeared to have been extirpated from the Schuylkill drainage (Sykes and Lehman 1957) until their presence in the tidal portion was revealed by Pennsylvania Fish and Boat Commission (PFBC) biologists in the 1970's. Since its inception in 1979 and subsequent rehabilitation in 2009, the Fairmount Dam Fishway has served as a focal point for scientists to ascertain the status of the shad spawning migration as well as the efficacy of fish passage through Fairmount Dam (Fig 6.8.9.1). Standardized community surveys conducted between April 1st and July 1st by the Philadelphia Water Department (PWD) below the dam enable researchers to measure relative abundance of *A. sapidissima* through a metric known as Catch-Per-Unit-Effort (CPUE). Similarly, time-lapse video monitoring during spring migration at the dam also provides vital information on the efficiency of the ladder to pass fish and the proportion of *A. sapidissima* that are successfully navigating through the fishway.

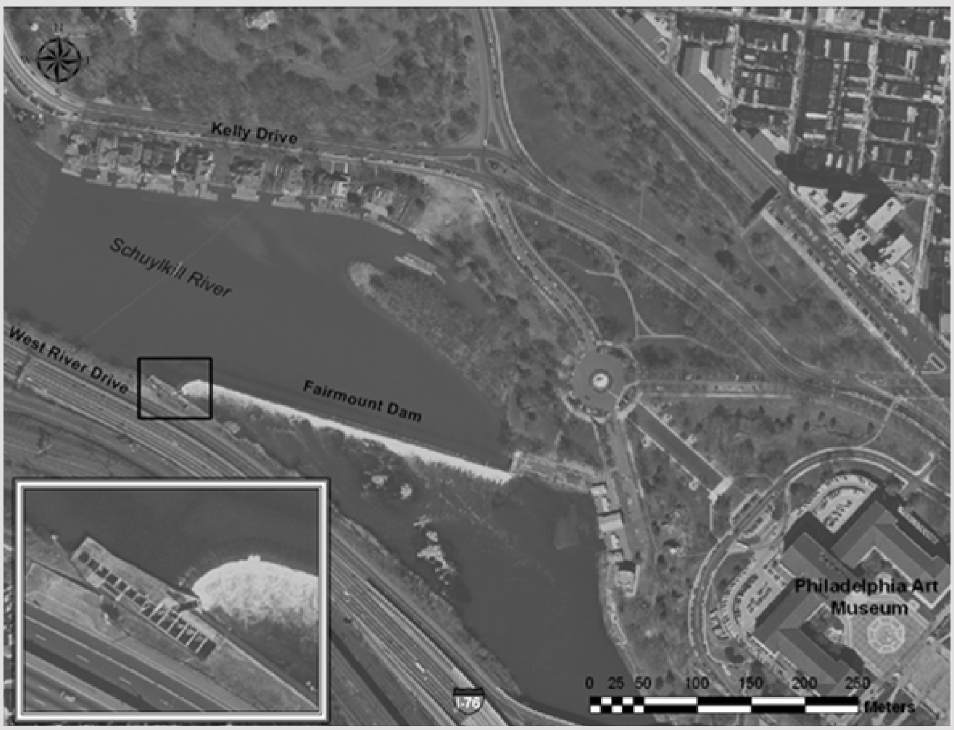

Figure 6.8.9.1 Aerial view of Fairmount Dam and vertical slot fishway (left insert) located on the west bank of the Schuylkill River at river km 13.6, Philadelphia, Pennsylvania. Courtesy: Perillo and Butler (2009).

Between 2004 and 2015, the relative abundance of American shad below the Fairmount Dam has shown high interannual variability, with the highest CPUE values occurring in 2010 and 2011 (13.43 and 15.80 fish/minute, respectively) (Fig 6.8.9.2). Prior to the restoration of the Fairmount Fishway in 2009, the highest number of shad passing through the dam was only 254; however, in 2011, 3,366 American shad successfully navigated through the Fairmount Fishway to upstream spawning grounds. In 2013 however, operational issues with the downstream regulating gate limited the efficiency of shad passage, and in 2014, severe flooding in the

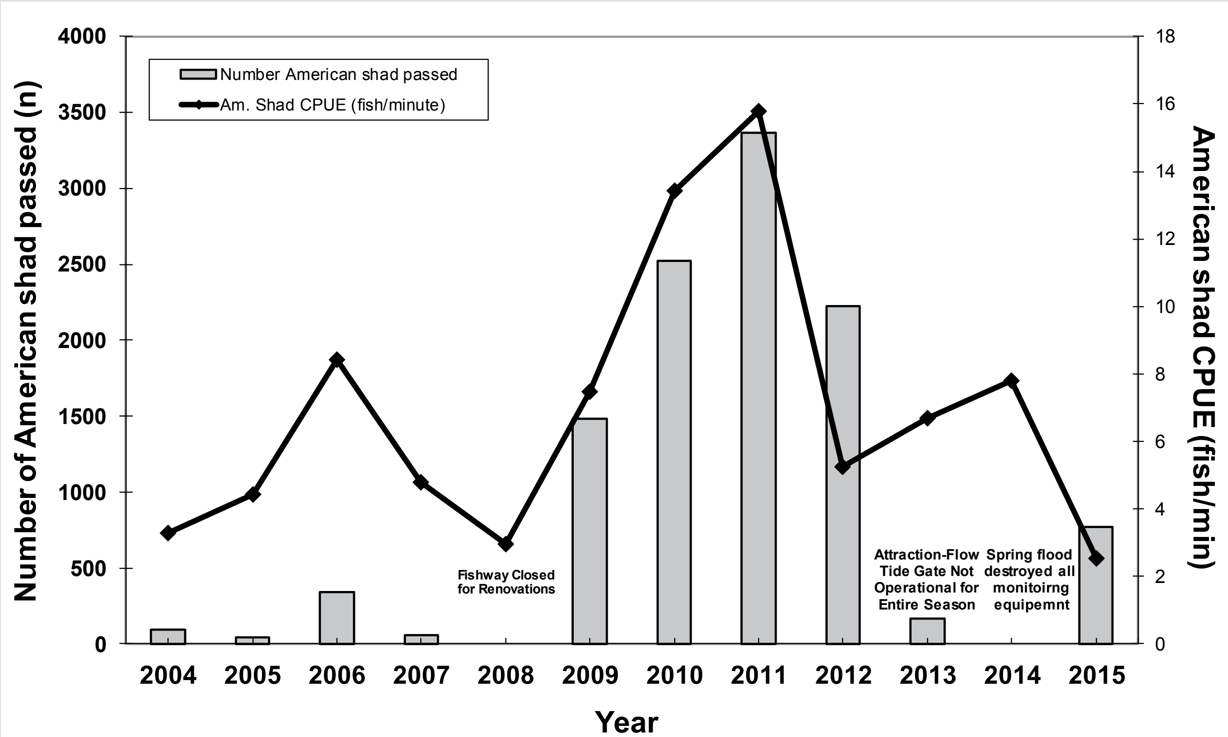

Figure 6.8.9.2 American Shad *(A. sapidissima)* passage and relative abundance at the Fairmount Dam (2004-2015). *Courtesy:* J.A. Perillo and L.H. Butler (Philadelphia Water Department).

fishway's monitoring room contributed to the loss of all video equipment and monitoring data.

Despite the low catch-per-unit-effort value of shad below the dam for 2015 and the low number of American shad passing through the fishway (n=771), it should be noted that the total number of all species of fish that passed through the fishway in 2015 (between April 1st-July 1st) was the highest in the 36-year history since the construction of the fishway in 1979. In total, 58,922 fishes representing 20 species successfully passed through the Fairmount Fishway. Of the 20 species documented ascending the fishway, 52,923 Gizzard Shad (*Dorosoma cepedianum*) were recorded. This suggests that the fishway can pass greater numbers of American shad provided they arrive in greater abundance below the dam.

To improve the density of American shad returning to the Schuylkill River, Philadelphia Water Department is developing a pilot program aimed at augmenting existing American shad stocking conducted by the Pennsylvania Fish and Boat Commission. Presently, PWD scientists have implemented a study at the Fairmount Fishway using live tank-spawning techniques. This 3-5 year study is intended to identify the relative success of alternative spawning techniques, bolster returning shad numbers to the Schuylkill River, and provide scientists with insight on the level of effort needed to implement a full-production facility.

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6.9 Eastern Oyster

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6.9.1 Introduction

Oysters are a dominant structural and functional member of the Delaware Bay benthos. The species native to Delaware Bay is *Crassostrea virginica* (Gmelin 1791), commonly called the eastern or American oyster (Fig 6.9.1). Eastern oysters are reef builders that provide hard substrate and create structural complexity in an environment otherwise dominated by sand and mud. This species occurs from Nova Scotia to Florida, throughout much of the Gulf of Mexico and south to Brazil. In some areas like South Carolina and Georgia, it can form extensive intertidal reefs but in Delaware Bay it is predominantly subtidal where it is protected from freezing and ice scour. In addition to providing habitat for many other species, oysters filter large quantities of water that enhance nutrient cycling within the system. Oysters have been harvested from Delaware Bay since pre-colonial times, and current harvests are carefully managed to support a sustainable fishery. Oysters have also been cultivated in Delaware Bay for more than a century in both intertidal and subtidal habitats of the lower Delaware Bay.

Figure 6.9.1 Oyster reef exposed at low tide in the Mispillion River, DE. Photo credit: Spencer Roberts, Partnership for the Delaware Estuary.

Oysters occur throughout Delaware Bay from Artificial Island to the mouth of the Bay and extend up into tributaries until salinity falls below tolerable average levels of about 5 ppt. Some oysters live intertidally, often on or within ribbed mussels along creek banks or attached to other hard substrates, natural or otherwise, within the lower intertidal zone. Nevertheless, the vast majority of the oyster population exists subtidally on reefs or beds that occur in the upper portion of the Bay above Egg Island Point on the New Jersey side and Port Mahon on the Delaware side upbay to Artificial Island. About 90% of the oysters in this region occur on the New Jersey side of the Bay.

Oysters may begin spawning in Delaware Bay as early as May or as late as September, but most spawns take place in July and August. Females can release all their eggs at once or partially spawn multiple times, but an average mature female may produce 2 to 60 million eggs during a single spawn. Typical spawns in a hatchery yield 1 to 15 million eggs. The fertilized eggs produce free swimming larvae within 24 hours that remain in the water column for two to three weeks before attaching to whatever hard substrate they can find, preferably clean oyster shell. During this process known as "setting" or "settlement", the settling larvae glues its left valve to the hard substrate then undergoes a metamorphosis, losing its ability to swim and taking on the morphology of a juvenile. Subsequent growth rate depends on the temperature, salinity, and food availability of the site where the oyster attaches and varies both seasonally and annually. By fall the young-of-year (YOY) oysters can range in size from a few millimeters to 40 or 50 mm with an average of around 25 mm. Little or no growth takes place during the winter, and young oysters are heavily preyed upon by oyster drills, flatworms, small crabs, and other predators. By the next fall most surviving oysters reach 30 to 65 mm depending on the location within the salinity gradient. Lower salinity areas have slower growth, but there are fewer predators so survival is better. Average growth to market size (3 inches = 76 mm) typically takes from 3 to 6 years in Delaware Bay, again depending on the location along the salinity gradient.

The oyster and the oyster reef assemblage are important to the general ecology of the Bay. The assemblage of organisms that develop on an oyster reef was recognized in the late 1800s as a community and described as a biocoenose by Möbius. This concept was the forerunner of what we now know as community ecology. In addition to the structure that oysters provide, they are also a major functional part of the ecosystem because oysters filter water for food. This filtration process removes particulate material from the water column and deposits it on the sediment surface where some of it becomes food for other organisms or is broken down by bacteria. This filtration and deposition is an important pathway for nutrient cycling in estuaries. In some estuaries, oyster filtration can clarify water enough to increase light penetration and facilitate growth of seagrasses but Delaware Bay is so turbid that this facilitation does not occur.

Two oyster diseases are present in Delaware Bay. MSX is caused by *Haplosporidium nelsoni*, and dermo or Perkinsosis is caused by *Perkinsus marinus*. Both pathogens are protozoans and neither affects humans, but they are eventually lethal to oysters. There is clear evidence that the native oyster population has developed a relatively high level of resistance to MSX (Ford and Bushek 2012), but resistance to dermo has not developed to any major extent (Bushek et al. 2012). Since 1989 dermo has been a major factor controlling oyster population levels on the higher salinity oyster beds in Delaware Bay from Ship John Light south.

6.9.2 Description of Indicator

The commercially harvestable oyster beds of the New Jersey portion of Delaware Bay have been surveyed in the fall and winter since 1953 (Fegley et al. 2003). In the earlier years, the survey took place from September throughout the winter, but since 1989 the period has been reduced to about one week in the last part of October to early November. A random stratified sampling method divides each of the beds into 0.2-min latitude x 0.2-minute longitude grids (~ 25 acres or 10,171 m_2) (Fig 6.9.2). Each bed is divided into three strata that are defined by surveys of the bed areas that are scheduled on a 10-year rotation. The bed area survey data are then divided into high quality, medium quality, and low quality. These represent high-density areas containing 50% of the population, medium-density areas containing 48% of the population, and low-density areas containing 2% of the oyster population. For the fall survey the grids in the high and medium quality categories are randomly sampled with the number of grids in each strata dependent on the variability of the particular bed as determined by the area survey and past sampling. Low quality grids are not sampled and the abundance of oysters on those grids, about 2% of the population, are never used in setting quota for annual harvest which averages less than 2% of the population contained within the high- and medium-quality areas. The annual fall survey is supplemented by regular monitoring of disease, mortality, and harvesting at weekly to monthly intervals. Details are published in annual stock assessment reports available at http://hsrl.rutgers.edu/SAWreports/index.htm

The oyster resources in the State of Delaware are about 10% of those in New Jersey because the habitable area on the Delaware side is smaller. The Delaware Division of Fish and Wildlife also conducts an annual survey of the Delaware oyster beds. It is less intensive than that of New Jersey, but it too relies on dredge samples and counts of live, dead, and newly set oysters to establish the upcoming annual harvest quota. For at least the past two decades, representatives from the Delaware Division of Fish and Wildlife have presented information from their survey at the stock assessment workshop.

6.9.3 Present Status

Population levels and harvest levels have been relatively steady at between 1 and 2 billion individuals and 70,000 to 100,000 bu (bu = 37 qts = 35 L), respectively, since 2002 in spite of a historically unprecedented period of low settlement that extended from 2000 through 2007 (Fig 6.9.3). The low recruitment coupled with the oyster disease dermo has reduced oyster stocks on the lower seed beds, but an active management program has sustained the overall levels of oyster abundance while permitting harvest. Subsequent increases in recruitment have stabilized the population.

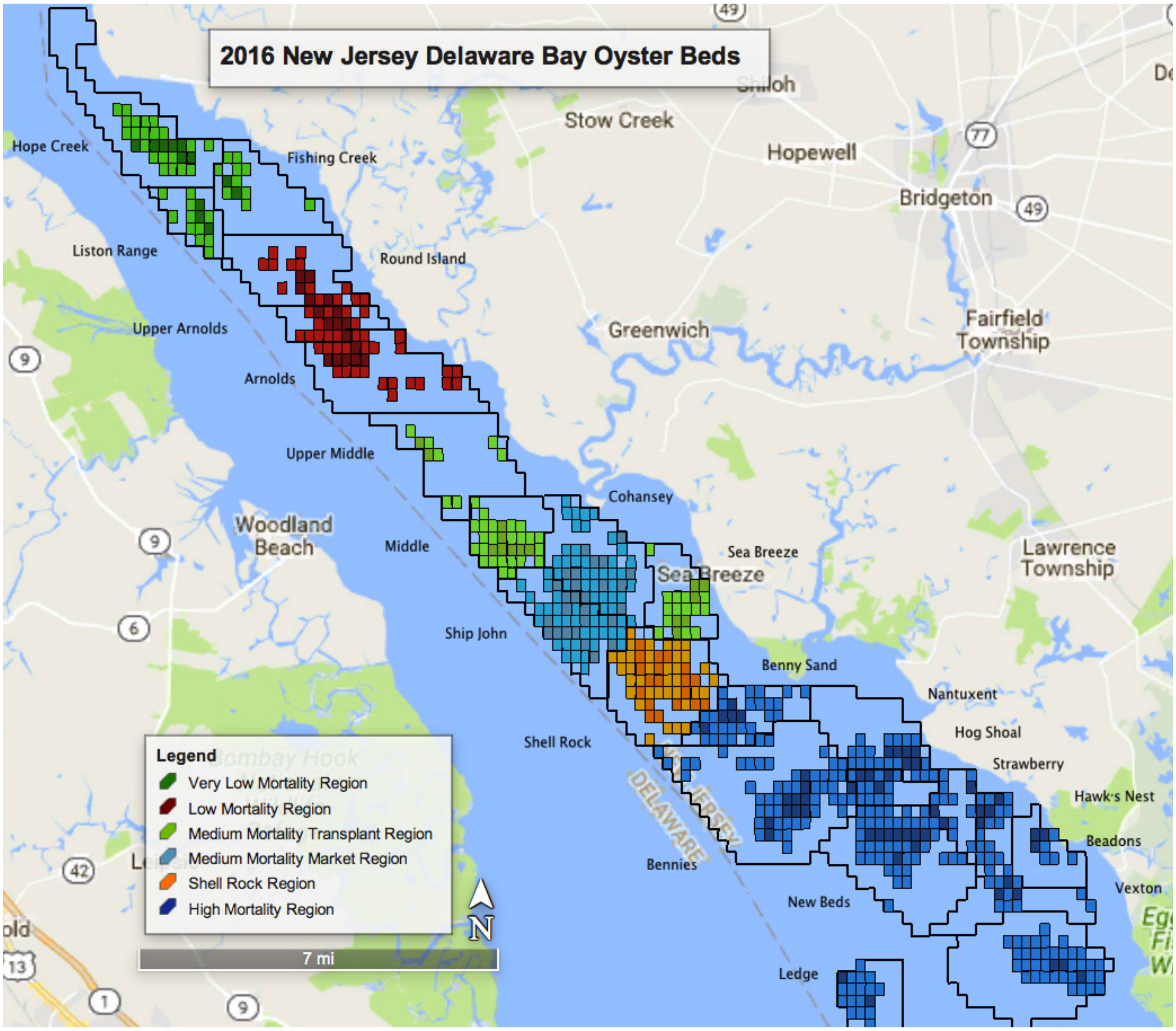

Figure 6.9.2 The assessed oyster beds of Delaware Bay, NJ grouped as regions (see Legend) with the 2016 strata designations. Black outlines indicate complete boundary of each bed with the high and medium quality strata grids in dark and light colors, respectively. The colors indicate region groupings although strata designations are within-bed not within-region. Clear blue areas in each bed indicate its low quality stratum. Annual assessments include samples from each bed's high and medium quality strata only. Each grid is 0.2" latitude x 0.2" longitude, approximately 25 acres (101,175 m^2 or 10.1 hectares). Courtesy of the Haskin Shellfish Research Laboratory, Rutgers University

Although Delaware has also developed quantitative estimates of absolute abundance, the Division of Fish and Wildlife relies primarily on estimation of trends in relative abundance. Population dynamic trends presented by Delaware at the annual stock assessment workshop tend to mirror trends on the New Jersey side.

6.9.4 Past Trends

There were substantial oyster harvests from Delaware Bay in the middle 1800's, and by the latter part of that century extensive importation of seed onto leased bottom in the lower Delaware Bay enhanced the numbers

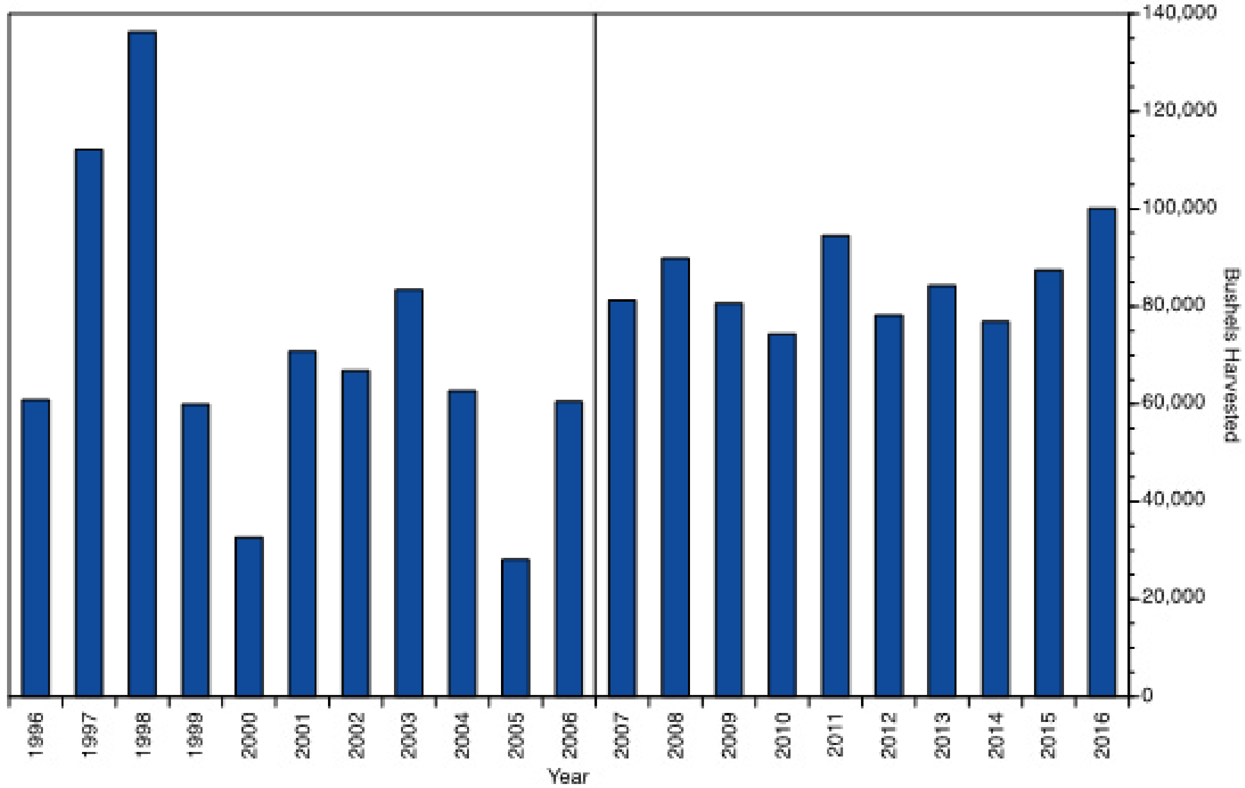

Figure 6.9.3 Oyster landings, in bushels, from the New Jersey Delaware Bay oyster beds from 1996 through 2016. Courtesy Haskin Shellfish Laboratory, Rutgers University.

of market oysters over what the Bay alone could produce. Active survey of the seed bed resource did not take place until 1953, and annual records are available since that date (Fig 6.9.4). The survey was initiated during a period of low abundance and just a few years before the oyster disease MSX substantially reduced the total numbers of oysters in the Bay. The following decade was a period of low abundance, but it was followed, from the late 1960's until the mid 1980's, by a period of high abundance. This was terminated by another MSX epizootic in 1985, and the emergence of dermo in 1989 which has dominated the population dynamics across the oyster beds ever since. In the late 1950's the natural oyster bed oyster population averaged about 2.8 billion adult individuals and it currently is about 1.75 billion individuals. In the peak years of the 1970's to the mid 1980's the average oyster population was tenfold higher at 17 billion individuals during a period when disease pressure was virtually non-existent.

6.9.5 Future Predictions

Management of this resource relies on annual survey data. Because the intensity of oyster diseases and recruitment success cannot be predicted, the only mechanism available for resource management decisions is the annual update of the oyster population information. There is no evidence that harvest has had substantial effects on the population dynamics of oysters in Delaware Bay since at least the late 1960's. Current recruitment levels indicate the stock is not recruitment limited, but may be substrate limited indicating that until the amount of habitat increases, likely via persistent large-scale shell planting, then the population will remain at this level. Presently, the oyster industry taxes itself at a rate that ensures it replaces what shell it harvests. Profit margins are such that increased taxes for shellplanting are not likely to be a viable mechanism for increasing shellplanting efforts which, ideally, would be on the order of half a million to a million bushels of shell a year. Current efforts are between 100,000 and 200,000 bushels.

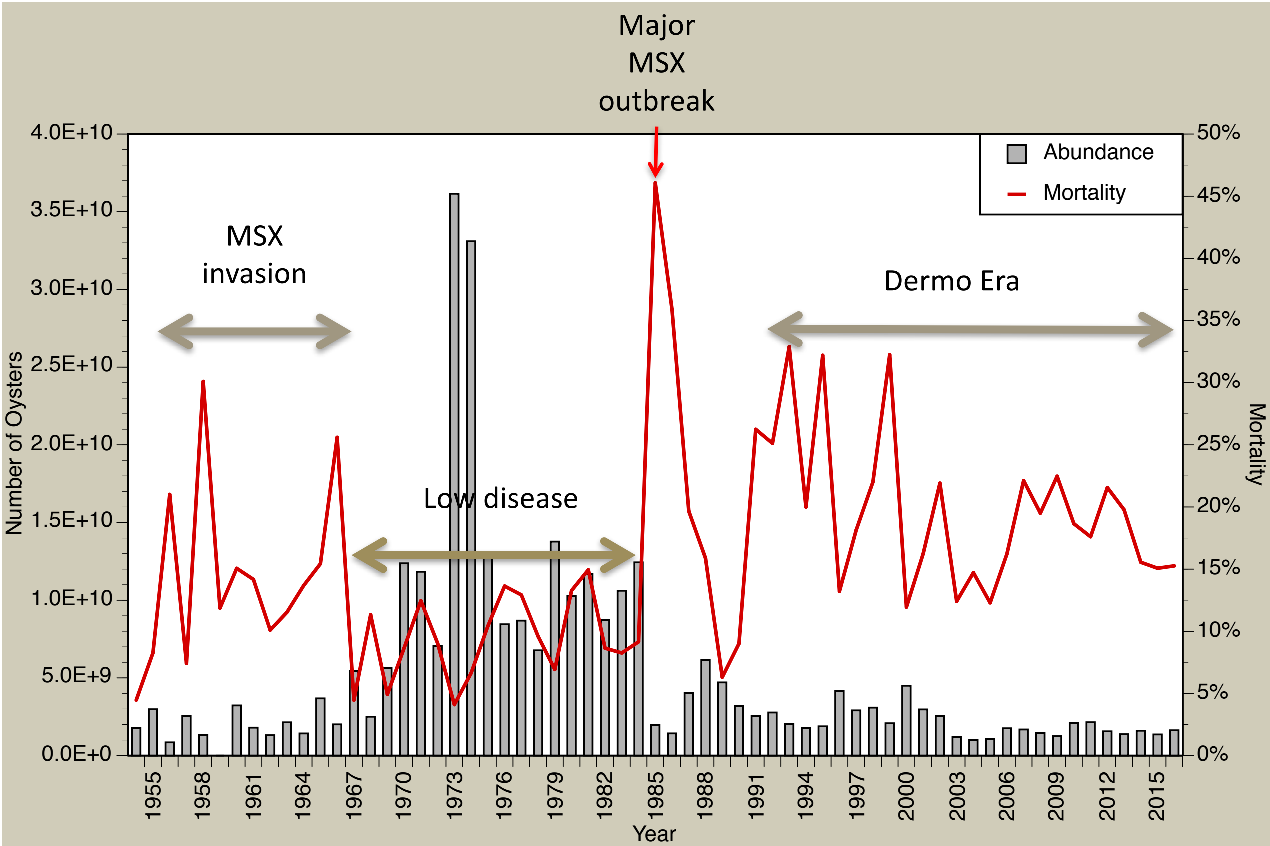

Figure 6.9.4 Annual estimates of oyster abundance on the New Jersey oyster beds in Delaware Bay from the Haskin Shellfish Laboratory annual dredge survey from 1954 through 2016, and annual total mortality estimates for the population.

Climate Change As long as the oyster population dynamics in higher salinity areas is controlled by dermo and MSX, changes in the oyster population will be linked to salinity levels. The funnel shape geomorphology of Delaware Bay makes the area available for development of oyster reefs less from the mouth of the Bay toward the fall line. Combining this geomorphology with ongoing sea-level rise suggest that the area available for prime oyster habitat will be reduced in the future. Other factors such as channel deepening, extraction of ground water, and consumptive use of Delaware River freshwater supplies all imply that salinity will rise even if climate change causes increased rainfall. Because freshwater in the Delaware River/ Bay system is actively managed, man made decisions may have more effects on the oyster population than modest climate change. If the most pessimistic climate change scenarios take place, there are likely to be such profound changes to the Delaware Bay system, and its human inhabitants that any change to the oyster resources will be of secondary or tertiary importance to the maintenance or movement of infrastructure. In 2011, however, excessive rainfall from Tropical Storms Lee and Irene depressed salinity throughout the Bay for several weeks causing up to 75% mortality on the uppermost beds (Munroe et al. 2013). It appears that those beds are recovering rapidly with higher than anticipated recruitment, but the flashiness of the system and its ability to produce freshets with similar impacts is expected to increase in frequency with climate change.

Oyster Aquaculture Oyster aquaculture is primed for growth in Delaware Bay with new developments in breeding for disease resistance and growth as well as technological advances in cultivation systems. Policies and regulations are being developed to guide this growth in a sustainable manner. Growth in intertidal aquaculture has already occurred, but has slowed due to potential concern about conflicts with federally listed threatened species. An adaptive management system has been employed to help work through these conflicts for the benefit of all. Meanwhile, advances in gear technology are being explored to facilitate growth of oyster aquaculture away from red knots, the threatened species that is currently raising concern.

6.9.6 Actions and Needs

The maintenance of the annual oyster population and oyster disease surveys is essential to management of this resource used to support the wild fishery. Efforts need to be made to evaluate the Hope Creek, Fishing Creek, and Liston Range oyster bed population dynamics. Plans need to be developed to manage the likely continued rise in salinity in Delaware Bay and its importance to the long-term viability of key oyster beds. At a minimum, development of a Bay wide monitoring system for temperature and salinity should be implemented. As possible additional parameters such as pH, dissolved and particulate nutrients, chlorophyll, and total suspended solids could be added. Plans for enhancing recruitment through shell planting need to be continued and expanded.

6.9.7 Summary

The oyster is a keystone species in the Delaware Estuary in that it provides a habitat, a harvestable resource, and a key link in ecosystem nutrient cycling. The oyster population abundance in Delaware Bay is currently controlled by a balance between recruitment and disease related mortality. Both of these processes respond to environmental factors such as the annual temperature cycle and salinity (freshwater input) and thus cannot be predicted. This unpredictability makes annual surveys a key to sustainably managing the resource. Recent good settlement of young indicates that the adult population will increase in the next few years. Shell planting to enhance recruitment is a mechanism for increasing population abundance, and should be continued and expanded.

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6.10 Freshwater Mussels

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6.10.1 Description of Indicator

Freshwater mussels are filter feeding bivalve mollusks that live in lakes, rivers, and streams (Fig 6.10.1). Similar to oysters, freshwater mussels increase water clarity, enrich habitats, and furnish other important ecosystem functions such as stabilizing bed erosion (for summaries of ecosystem services, see: Kreeger and Kraeuter 2010; Anderson and Kreeger 2010).

The potential beneficial effects of healthy mussel beds on water quality are generating increasing research and restoration interest. Although vastly depleted in numbers and species richness compared to historical conditions, enough freshwater mussels appear to remain in the Delaware River Basin to materially contribute to water quality by their filtration. For example, Kreeger (2008) measured the abundance of *Elliptio complanata* in the Brandywine River and used survey data from Dr. W. Lellis (2001) (U.S.Geological Survey) to estimate that there are at least 4 billion adult mussels of this species across the Basin. Pairing these survey data with measured physiological processing rates, this species was estimated to filter about 10 billion liters of water per hour across the Basin, which is roughly 250 times the volume of freshwater entering the tidal estuary (Kreeger and Kraeuter 2010). More recently, a similar approach was used to estimate that representative beds of freshwater mussels in the tidal Delaware River upstream from Philadelphia filter more than a million gallons of water and 8 tons of suspended particles per day per hectare (Fig 6.10.2) (Kreeger et al. 2013).

Freshwater mussels grow more slowly than their marine counterparts. They also live longer (50 years or more) and have complicated reproduction strategies dependent on fish hosts. As long-lived, relatively sedentary creatures that process large amounts of water over their soft tissues, freshwater mussels are particularly sensitive to water quality and contaminants. The health, population abundance, and species diversity of freshwater mussels therefore represent excellent bioindicators of freshwater systems, particularly over long periods of time. Unfortunately, freshwater mussels are typically not sampled effectively as part of traditional macroinvertebrate assessments (Section 6.12), and so data on the status and trends of freshwater mussel populations are scarce.

6.10.2 Present Status

Freshwater mussels are the most imperiled of all animals and plants in North America (Nobles and Zhang 2011), which has the world's greatest diversity of this taxonomic group (> 300 species). More than 75% have special conservation status (Williams et al. 1993). At least 12 species are native to the Delaware River Basin (Ortmann 1919, PDE 2008, Campbell and White 2010); however, all but one species is currently reported to be uncommon (PDE 2008).

Figure 6.10.1 Freshwater mussels from the tidal Delaware River in May 2016. Photo credit: Danielle Kreeger, Partnership for the Delaware Estuary.

The leading causes of mussel decline in the Delaware River Basin are habitat and water quality degradation. Since freshwater mussels rely on fish, usually species-specific relationships, for successful reproduction dams that block fish passage can disrupt reproduction and gene flow (McMahon 1991, Neves 1993).

To assess present status, survey data were analyzed for the past 20 years from the portions of Delaware, New Jersey, and Pennsylvania that comprise the Delaware River Basin. Data were not available from the State of New Jersey (except limited recent Partnership for the Delaware Estuary surveys), and survey data were lacking for many areas of Delaware and Pennsylvania. Our analysis suggests that the overall condition of freshwater mussel populations is poor in streams where dams and other factors have progressively eliminated or reduced mussel populations over the past 100 or more years (Thomas et al. 2011).

Joint surveys in southeastern Pennsylvania by the Partnership for the Delaware Estuary (PDE) and the Academy of Natural Sciences of Drexel University between 2000 and 2010 found that only 4 of >70 stream reaches contained any freshwater mussels (Thomas et al. 2011). Even the most common native species are presently patchy in distribution and limited in abundance. Furthermore, most mussel populations that have been found appear to lack juveniles and be comprised mainly of older individuals, suggesting that many populations in Piedmont streams are not successfully reproducing. In contrast, recent surveys for freshwater mussels in Coastal Plain streams of southern Delaware and New Jersey suggest mussel populations are not as degraded (Cheng and Kreeger 2015). Similarly, extensive surveys of the undammed and tidal reaches of the mainstem Delaware River have revealed sometimes large beds of mussels (5-100 per square meter) (Lellis 2001, 2002, Kreeger et al. 2011). Several species found in the tidal Delaware River in 2010-1011 were previously believed to have been extirpated from the basin because they had not been reported in the published literature since Ortmann's surveys 100 years earlier (Ortmann 1919). Importantly, recent quantitative surveys of the Delaware River between Philadelphia, PA, and Trenton, NJ, revealed several locations with large numbers of juvenile mussels and up to 6 mussel species (Kreeger et al. 2013, 2015).

The condition of mussels on Coastal Plain streams and the tidal Delaware River is also healthier, as evidenced by lower shell erosion, richer tissue biochemistry, and a diverse population size range, compared to mussel populations in Piedmont streams, especially those with dams and stormwater impairments (Kreeger and Padeletti 2011, Gray and Kreeger 2014, Cheng and Kreeger 2015).

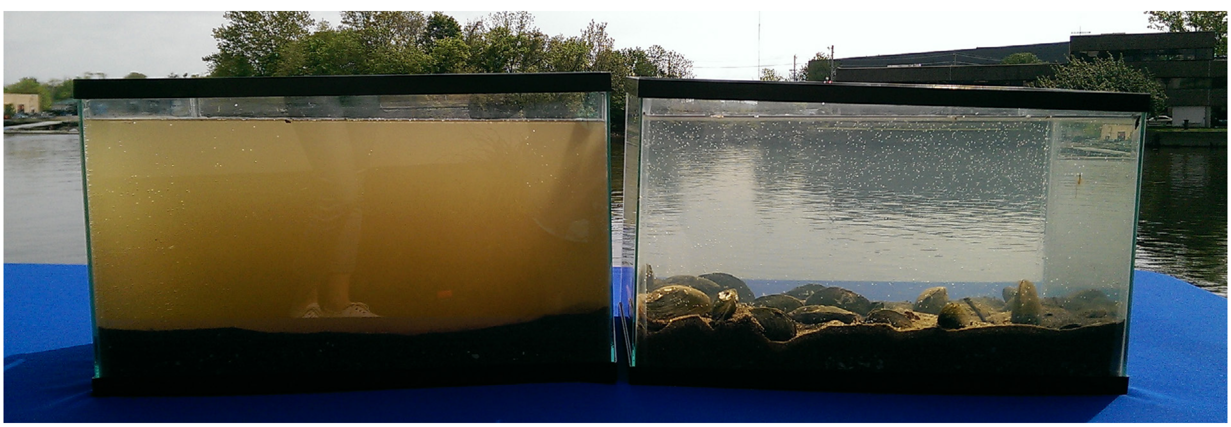

Figure 6.10.2 Freshwater mussels are filter-feeding bivalves that efficiently remove microparticulate matter, resulting in improved water clarity, greater light penetration, and beneficial transformation of many filtered pollutants. In this outreach demonstration from May 2015, both tanks received the same water, but the addition of 15 live mussels to the tank on the right had dramatically enhanced water quality within 4 hours. Photo credit: Danielle Kreeger, Partnership for the Delaware Estuary.

6.10.3 Past Trends

The most comprehensive historical regional mussel survey was conducted in Pennsylvania between 1909 and 1919 (Ortmann 1919). However, even by that time, dams and water quality degradation may have already affected mussel communities. Nevertheless, the study provided an excellent benchmark for gauging long-term trends in the mussel assemblage for the past 100 years.

Ortmann (1919) reported about 12 species of native mussels from the Delaware River Basin, most of which were present at that time in southeastern Pennsylvania (Fig 6.10.3). Although species richness was highest in the mainstem Delaware River even then, at least five species were present in several tributary watersheds, including the Schuylkill and Brandywine.

In contrast, figure 6.10.3 depicts the current species richness of native mussels (Thomas et al. 2011) for those sub-watersheds where surveys have been completed since 1996. Although the richness appears to have been preserved in the mainstem Delaware River and a few tidal tributaries in New Jersey, only one or no species has been detected in recent years in most surveyed tributary streams of Delaware and Pennsylvania (Fig 6.10.3).

A comparison in figure 6.10.3 also suggests that the range of native mussel occurrence has shrunk significantly during the last 100 years in streams where historic and recent survey data exist. This decline appears to be continuing. For example, no mussels have been found since 2002 in the upper White Clay Creek, Pennsylvania, despite annual surveys by PDE; whereas, two species were found there as recently as 1998-2001 (Fig 6.10.3).

6.10.3 Future Predictions

Since the decline of native mussel biodiversity has been attributed to habitat and water quality degradation, the future prospects for freshwater mussels are likely to hinge on careful watershed management. Human population is expected to grow by 80% this century in the basin, which threatens to exacerbate the stressors that have been affecting mussels for probably hundreds of years.

Climate change also threatens freshwater mussels (Kreeger et al. 2011) because of increased thermal stress and stormwater. Freshwater mussels are especially sensitive to bed instability and inputs of fine sediments to the system, and so stormwater and flood scouring represent threats that are expected to increase with climate change (Kreeger et al. 2010). Salinity rise also threatens mussels living in freshwater tidal areas. Since freshwater mussels depend on fish hosts for larval dispersal, it is unlikely that southern mussel species will be able to expand northward to fill niches that open if northern species are extirpated. The northern pearlshell, *Margaratifera margaratifera*, is an example of a cold-adapted species that uses brook trout as a host – its present distribution in southeast Pennsylvania is constrained to a few cold headwater streams and below reservoirs in the upper Schuylkill Basin which release colder water from the bottom. Assisted migration of warm-adapted southern species represents a potential climate adaptation tactic, but the willful introduction of species that are not native to this region might carry unforeseen risks and is at odds with current management paradigms.

Enhanced conservation and restoration efforts have the potential to offset projected continued declines in freshwater mussels (Kreeger and Padeletti 2011). Given the severely weakened status of freshwater mussel richness, range, and abundance, it is vital that any extant populations be protected. Although some streams may no longer be as suitable for mussels as they were historically, results from pilot reintroduction trials during 2007-2017 at more than a dozen locations in Delaware and Pennsylvania (Gray and Kreeger 2014, Kreeger et al 2014, 2015, Cheng and Kreeger 2017) suggest the majority of historic streams and ponds are still capable of sustaining mussels, but natural recolonization is prevented because of inhibited movements of suitable fish hosts. Mussel restoration in these areas can be accomplished by improving fish passage or

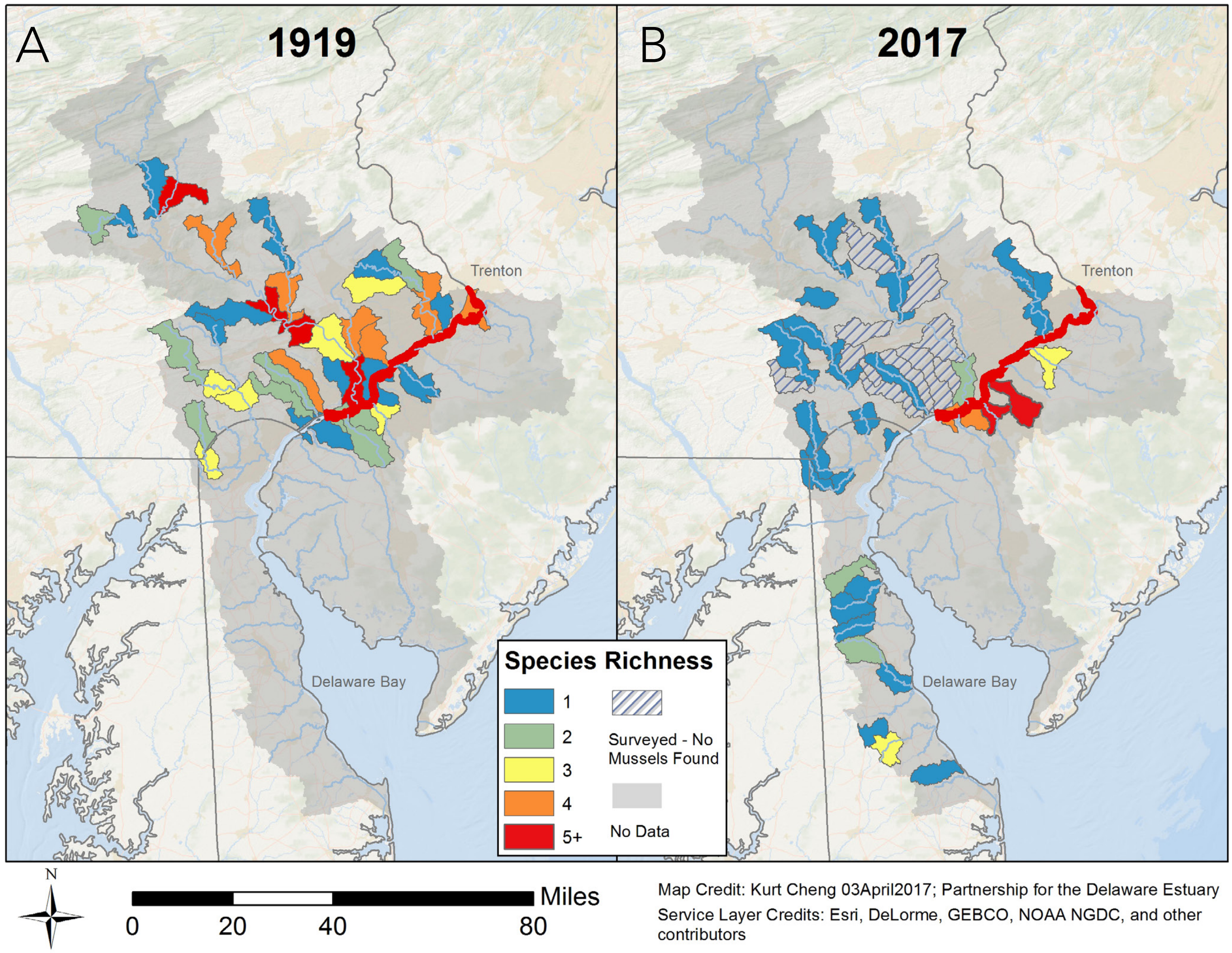

Figure 6.10.3 A) Species richness of native freshwater mussels reported in surveys conducted between 1919-1996, based on available data obtained by PDE. Surveys were primarily conducted by W. Ortmann prior to 1920 and A. Bogan during the 1980's. B) Species richness of native freshwater mussels reported in surveys conducted between 1996-2016. Surveys were primarily conducted by PDE with assistance in some areas by the Academy of Natural Sciences of Drexel University, Philadelphia Water Department, and Environmental Protection Agency Region 3 dive unit.

stocking of hatchery-propagated mussel seed. New restoration approaches such as building mussel beds within urban living shoreline projects have the potential to also boost mussel carrying capacity via habitat enhancement. Growing interest in mussel-mediated ecosystem services, such as water quality benefits, could energize mussel restoration in the Delaware River Basin.

6.10.4 Actions and Needs

More proactive freshwater mussel monitoring for species presence and population health is needed across the Delaware Estuary and River Basin. Freshwater mussels are not targeted in routine macroinvertebrate assessments, and so mussel surveys are rarely performed despite their value for assessing long-term status and trends of aquatic health. Hence, survey data are not available for most sub-watersheds of the Basin for at least 20 years, if ever. Improved coordination and data sharing among states and PDE would also facilitate development of better indicators and a coordinated watershed restoration strategy.

New survey technologies for mapping mussel beds and suitable habitats are being developed and should be marshalled to fill vital data gaps, identify mussel conservation areas, and help prioritize restoration areas. Critical habitat for mussel beds should be mapped and protected. The confirmation of freshwater mussel propagation and rare species in the tidal freshwater zone of the Delaware River is important because these represent potential source populations and broodstock to support the restoration of genetically appropriate mussels in other areas of the Basin.

We now have the technology to propagate juvenile mussels in a hatchery and rear them quickly in ponds for use in restoration projects. Monitoring of restoration outcomes is aided by electronic tagging methods, and biochemical and physiological fitness measures (e.g., Kreeger and Padeletti 2011, Gray and Kreeger 2014, Cheng and Kreeger 2014). More research is also needed on the habitat suitability traits that underpin mussel carrying capacity, which would directly benefit restoration practitioners interested in stream bed remediation or living shoreline projects.

Finally, additional research is needed to improve current models of the ecosystem service benefits of mussel conservation and restoration. Recent estimates suggest that the healthiest natural mussel beds in the tidal Delaware River may filter more than 1,000 pounds of nitrogen per hectare per year, but this number might be enhanced to >3,300 pounds per hectare per year in a designed nutrient bioextraction project (Kreeger et al. 2017). However, more research is needed to study the fate of the filtered matter and to predict whether mussel beds yield enough net nutrient removal to justify investments by water quality managers.

6.10.5 Summary

A robust community of freshwater mussels should be spread throughout the freshwater ecosystem and include diverse species that fill different ecological niches. Unfortunately, the present status of the dozen native species of freshwater mussels is poor in most areas of the Delaware River Basin, especially in Piedmont streams and areas with impediments to fish passage. Poor status was judged by the reduced biodiversity, abundance, and range for this taxonomic group. Continued watershed development and climate change represent increasing threats. Careful watershed management combined with more vigorous mussel conservation and restoration would help to offset these past and future threats to freshwater mussels. The few areas that still harbor healthy, diverse, and reproductive mussel beds, such as a few areas of the mainstem Delaware River, merit careful protection. Many areas that have lost mussel beds can now be restored using new technologies. Growing research is strengthening our understanding of the water quality benefits of healthy mussel assemblages and the economic basis for an increased restoration investment. The greatest improvements for water and habitat quality will likely be achieved by a basin-wide shellfish strategy that conserves and restores native bivalves living in different niches throughout the river-to-sea continuum.

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6.11 American Eel

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6.11.1 Introduction

American eels (*Anguilla rostrata*) are very unique among fishes of the Delaware River Estuary. Being catadromous, eels spend most of their lives in fresh and estuarine water, only returning to the open ocean to spawn (Fig 6.11.1). It is believed that all American eels spawn in the Sargasso Sea off the southern coast of the United States (Miller et al. 2014). American eels are also semelparous, meaning they spawn once and die. Larval stage eels (leptocephali) hatch from buoyant eggs, are leaf-like in shape, and drift on ocean currents westward to the eastern Gulf of Mexico and Atlantic coast of the U.S. All American eels are currently believed to spawn in one aggregation, and therefore offspring, with few exceptions, are genetically indistinguishable (Cote et al. 2013). Larval eels are not believed to return to the particular waters from which their parents came, but rather to migrate up the coast with the Gulf Stream and to move inshore in a randomized fashion. Recent findings suggest that ingressing juvenile eels are capable of conspecific cueing, using olfaction to select waters that are already occupied by other eels (Schmucker et al. 2016).

As leptocephali reach the continental shelf, they metamorphose into clear, very small eels known as glass eels and begin their inland migrations in late winter and early spring. Some eels will move far up into nontidal portions of Delaware River tributaries, often very small streams. Others remain in brackish water in tidal tributaries of the Bay and River. Once glass eels reach freshwater, they undergo pigmentation, eventually reaching the "yellow" phase of their life history, named as such for their yellow-green coloration. American eels spend most of their life in the "yellow" stage, residing in tributaries and the Delaware River for up to 30 years (Able and Fahay 1998) until they reach sexual maturity and the last stage of their life cycle, the "silver" phase. A number of physiological changes occur during the silvering process: the skin thickens, the body fattens, the shape and color of the pectoral fins change, the digestive tract degenerates, and the eyes become enlarged. These changes are thought to be beneficial for migration through the open ocean back to the Sargasso Sea (Facey and Van den Avyle 1987).

Figure 6.11.1 American eel caught in the Schuylkill Basin, Pennsylvania. Photo credit: Philadelphia Water Department.

Delaware and New Jersey have significant commercial fisheries for yellow eels in the Bay and it's tidal tributaries. Delaware landings have historically ranged above 100,000 pounds until 2008 when shortages in bait supply, namely female horseshoe crab, suppressed more recent annual landings (Fig 6.11.2). Eels are used by recreational fishers for bait to catch striped bass and large pelagic fishes such as tunas and billfish. A fairly robust bait market exists in the southeastern United States as well for cobia, catfish, and land-locked striped bass. Size of bait eels varies dependent upon the quarry targeted, but all must meet the legal minimum size of nine inches. The second market for eels is a food market both in this country and in Europe, where they are regarded as a delicacy. Eels are shipped live or frozen to Europe.

Delaware's eel fishery is reliant on a source of good bait; fishers say that, much of the year, the only bait that will catch significant numbers of eels is female horseshoe crabs. With the restrictions on horseshoe crab harvest along the Atlantic coast, availability has dwindled and the price of bait has increased to about $3 per crab in some areas. The price of bait has negatively impacted Delaware's eel landings in two ways. First, the catchability of other bait types including fish wracks and blue crabs is not as great as it is for horseshoe crabs. Secondly, many eel fishermen accustomed to catch rates of pots employing horseshoe crab baits have left the fishery presumably due to a decline in profitability. As a result, a sharp decline in commercial landings have been observed since regulations were enacted (2007) banning the harvest of female horseshoe crabs in the Delaware Bay region (Fig 6.11.2).

The American eel population is managed under regulations developed by the Atlantic States Marine Fisheries Commission. Coast-wide populations have declined in recent years, thought to be due to several potential factors, including the relatively slow rate of maturation, high levels of stage specific mortality, fishing mortality on a wide range of year classes prior to spawning, continued habitat loss in the form of dams and other impediments to upstream migration, and changes in oceanic conditions. Additionally, the introduced Asian parasite, *Anguillicola crassus,* is now wide-spread in the American eel population, as it has been documented in every State on the Atlantic coast. Relatively little is known about the overall effects this parasite has on the population, but the fact that it weakens, and in some cases, totally destroys the eel's swim bladder intuitively equates to a negative impact on infected eels. The United States Fish & Wildlife Service (USFWS) conducted a review of the species status in order to determine whether it should be listed under the Endangered Species Act (ESA). The USFWS had previously concluded in 2007 that there was no basis for listing eels as threatened or endangered. After reviewing the data again in 2015, the USFWS decided that listing the American eel under the ESA was again not warranted (USFWS 2015).

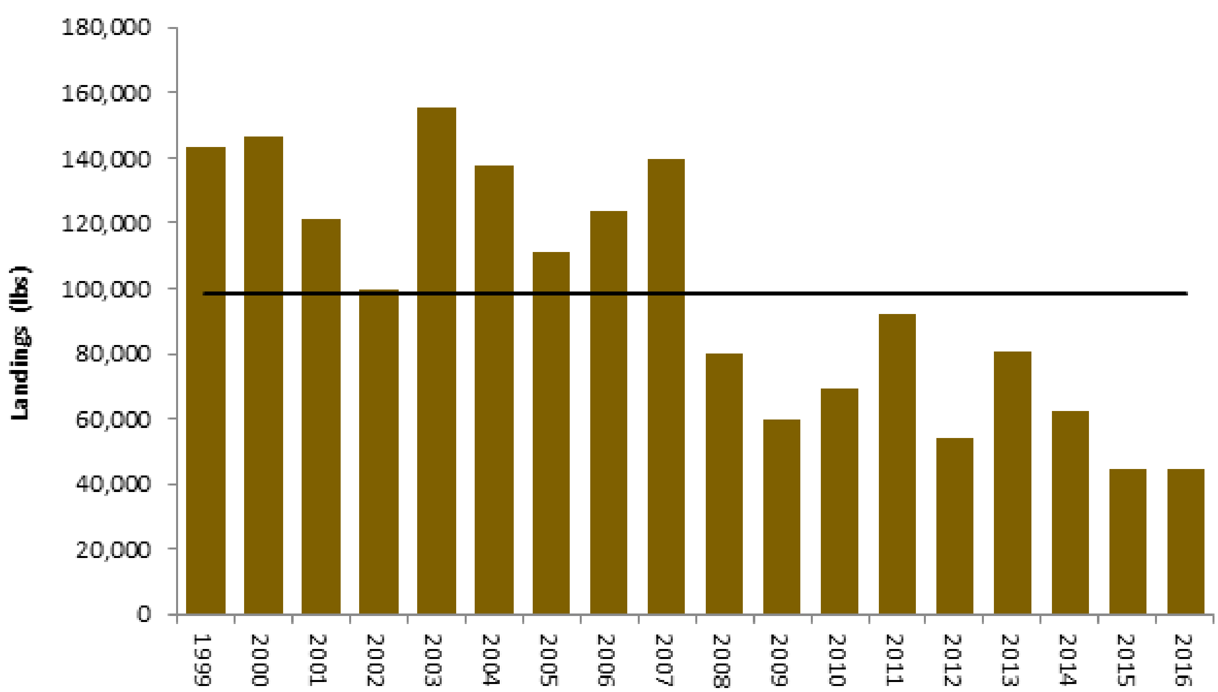

Figure 6.11.2 Delaware American Eel landings for the years 1999 – 2016. The black line represents mean landings for the time series.

6.11.2 Description of Indicator

The index of eel relative abundance is developed from 13 trawl survey stations in the lower Delaware River by the DE DFW Juvenile Finfish Trawl Survey. The net is a 16-ft (4.8-m) semi-balloon trawl with a 0.5-in (1.3-cm) cod end liner towed by 62-ft (19-m) R/V First State. The geometric mean catch-per-tow, using catch data collected from April through June, is used to estimate an index of abundance (Fig 6.11.3). Catch typically consists of eels from ages 0 to 7, with 3 years of age representing the most frequent age observed in the catch (DE DFW Unpublished data). All eels captured in this survey are yellow-phase.

A linear regression line was found to best represent the index as a function of year, which explains a statistically significant portion of the annual variability (P = 0.01, R^2 = 18.3). Such patterns raise the possibility of decadal-scale oscillations in climate affecting recruitment into the stock. Changes in cyclical climatic events have been found to affect patterns of abundance through cumulative effects on ecosystem processes including, but not limited to spawning success, primary productivity, and larval transport (Nye et al. 2014).

6.11.3 Present Status

Eel abundance in the Estuary as represented by the index, has increased in recent years with the last two years exhibiting the highest abundance estimates of the time series (Fig 6.11.3). All indications from anecdotal accounts from fishermen and biologists are that eel abundance is currently very high. Glass eel abundance surveys in Delaware and New Jersey have documented above average recruitment over the past four years. Although these surveys do not occur within the Delaware River watershed, they generally speak to recruitment trends in the region.

6.11.4 Past Trends

Abundance declined somewhat during the 1980s, but increased to higher levels in the mid-2000s. Sykes and Lehman (1957) reported that eel weirs were so numerous on the nontidal Delaware River that they trapped and killed many, if not most, young-of-year shad migrating downriver in early fall. These weirs targeted the

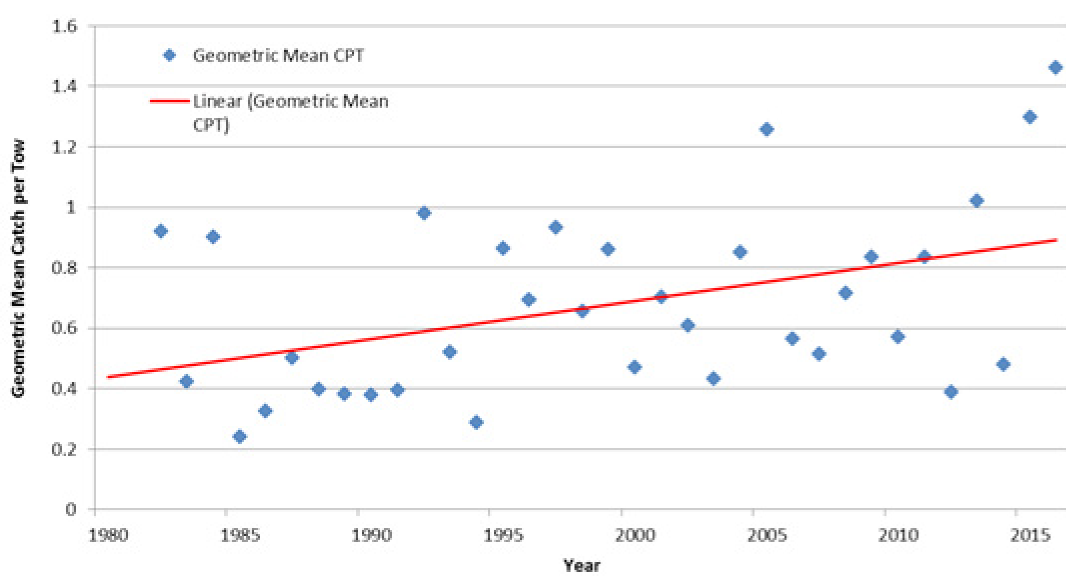

Figure 6.11.3 Index of relative abundance of American eels in the tidal Delaware River, based on catch per tow at 13 stations from April-June annually. The index is the geometric mean catch per tow. The predicted line was fitted as a linear regression, P = 0.01, R2 = 18.3%.

so-called silver eel stage, which are adults migrating down river and out to spawn in the Sargasso Sea. Smiley (1884) described "hundreds of traps" in the River between Lackawaxen, PA and Hancock, NY. The relatively high number of fishing weirs would suggest much heavier fishing mortality occurred on silver eels many decades ago. In recent years, nine weirs have been operating in the Delaware River, in New York. Due to the panmictic nature of the American Eel population, high fishing mortality in the upper Delaware River may not affect the number of new recruits arriving from the Sargasso Sea annually.

6.11.5 Future Predictions

There are no apparent bases for future predictions, but the coast wide nature of the spawning aggregation suggests that even if the Delaware Estuary spawning numbers would decline, the Estuary could still receive relatively high levels of annual recruits.

6.11.6 Actions and Needs

Although the main stem of the Delaware River is un-dammed, hundreds of dams still block passage along its tributaries; many are low-head dams under private ownership and in poor operating condition. In addition, there are thousands of culverts for roads that cross the tributaries. And in many areas the riparian forested buffer along the streams has been removed, leaving the stream exposed to sun and dramatically increased non-point source sediment and pollution run off. Fish passage and riparian restoration would help improve habitat for eel by increasing connectivity and improving in-stream habitat by providing shade and structure in these tributaries.

6.11.7 Summary

Eel populations in the Estuary declined in the late 1980s and increased in the mid-2000s. This increasing trend has continued through to 2016. Annual recruitment in Delaware has been well above average for the past four years. Harvest controls put in place through interstate management of the resource should bode well for sustainability of the fishery. Habitat initiatives such as dam removal, when practical, open up quality habitat in the upper portions of Delaware River tributaries.

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6.12 Macroinvertebrates

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6.12.1 Introduction

Freshwater benthic macroinvertebrates (Fig 6.12.1) are a useful indicator of the ecological integrity of the Delaware River watershed for several reasons. A variety of macroinvertebrates live in every aquatic environment, and they are functionally important in several ecological roles. They are widely acknowledged to be good indicators of water quality because they are directly impacted by changes in water quality. Furthermore, they have been studied extensively in all parts of the Delaware River Basin.

In spite of these facts, it is difficult to aggregate and summarize data about this indicator for a multi-state area like the Delaware River Basin. This is because the various organizations that produce data (including state environmental agencies) all use different methods of sampling and analysis. Because of the differences in methods, only an approximate comparability between the data from different sources can be assumed. The best that can be done is take advantage of the fact that all states distill their findings into grades of condition (e.g. good, fair, poor). Assuming a rough comparability between these grades of condition, data from various sources can be brought together and presented side-by-side to approximate a basin-wide assessment.

An explanation of how this complex situation came about may help explain what this indicator tells us about the ecology of the Delaware River Basin broadly. The discussion may also help readers to appreciate something about benthic macroinvertebrates and their importance, and to understand more about the way environmental agencies perform water quality management in the United States.

6.12.2 Description of Indicator

The word "benthic" indicates animals that live on, or in, the substrate at the bottom of a waterbody. The word "macroinvertebrates" designates invertebrate animals that are large enough to be seen without the aid of magnification. In aquatic habitats, benthic macroinvertebrates are a broad group of organisms representing several phyla. The group includes roundworms, flatworms, mollusks, and several kinds of arthropods. Insects are a particularly important class of animals in the group, because of their abundance and diversity in the freshwater biota.

To be more precise, the indicator being discussed here is freshwater benthic macroinvertebrates that live in streams. Thus, those macroinvertebrates that live in lakes, ponds, wetlands, and tidal waters are excluded. These distinctions are primarily made because the nature of the information most easily available, is mostly for "wadeable" streams. Wadeable streams are relatively easy to survey, and these smaller waterbodies are where most states have focused their sampling efforts.

Most states have been sampling and compiling data about benthic macroinvertebrates since the 1970s or 1980s. The reason lies in what these animals say about the water quality of the environments in which they live. Using a procedure called "bioassessment," the biological condition of macroinvertebrate communities is analyzed to provide information about pollution and other water quality problems. In most states, bioassessment is used for multiple purposes, but the most widespread application of bioassessment is for

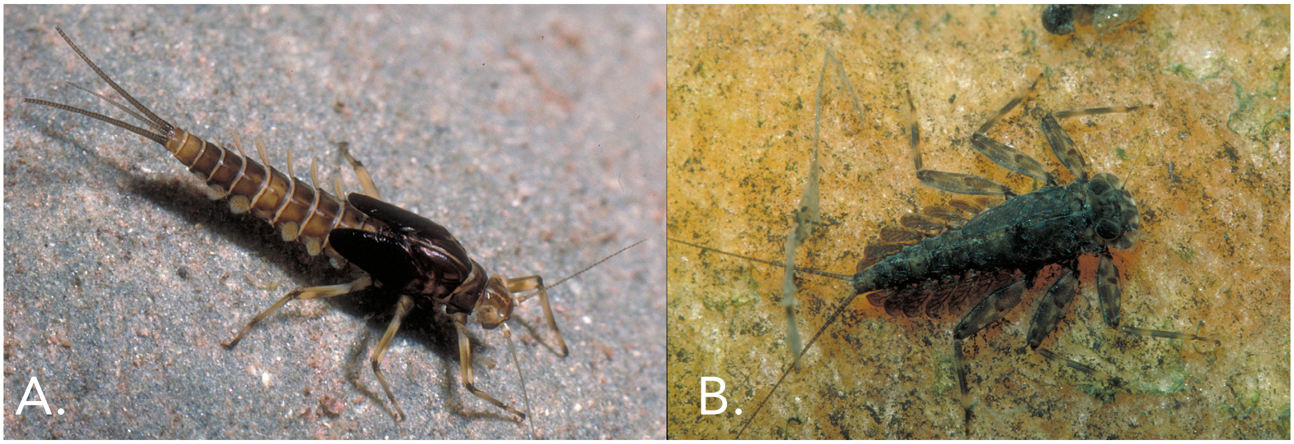

Figure 6.12.1 Mayfly larva, genera: A) *Baetis* and B) *Epeorus*. Photos credit: David H. Funk

the purpose of assessing a state's streams for the attainment of water quality standards. This program of assessment follows from the states' obligations under the Federal Clean Water Act.

The Federal Clean Water Act (and its amendments through 1987) requires states to develop water quality monitoring programs. States report to the U.S. Environmental Protection Agency (USEPA) on the quality of their waters using the biennial "305 (b) report" and the "303 (d) list." In most states, these biennial reports are now usually merged into a single document called the "Integrated Assessment" or the "Integrated List." The states are charged with assessing their waterways' conditions for various water uses, including, for example, public water supply, recreation, or aquatic life. The condition of macroinvertebrate communities is usually connected specifically to aquatic life uses. Results of bioassessments are used to determine if a waterway is "attaining" or "not attaining" the State's water quality standard, a threshold condition determined by the state.

Over the past 20 to 30 years, bioassessment has become increasingly important to environmental agencies, as advances have been made in the scientific understanding of water pollution and its effects. It is now widely acknowledged that biological indicators represent an essential means of determining the condition of natural waters. Some of the reasons for this are:

- Bioassessments provide information that is directly relevant to the goals of water pollution law (that is, that waters should be able to support aquatic life)
- Bioassessments provide information about long-term, chronic, or episodic stressors that are otherwise difficult to monitor.
- Bioassessment methods can be used to assess fish or periphyton (algae) in addition to macroinvertebrates. However, macroinvertebrates may be the most broadly useful of these biological groups, for reasons that include the following:
    - Macroinvertebrates are relatively easy to sample and analyze,
    - Macroinvertebrates are less mobile than fish, and thus they provide a better representation of the condition of a particular location, and
    - Macroinvertebrata are abundant and utilize diverse niches, which allows for a detailed determination of their condition over a wide gradient.

A bioassessment protocol is a set of standard practices describing how streams should be surveyed to produce data about ecological condition. Methods of collection and analysis must be standardized and consistently applied if data are to be comparable. However, there is no single macroinvertebrate protocol that is universally applicable in all circumstances. Natural variation sometimes dictates that protocols should differ, for the assessment of streams from substantially different environments. In addition, the needs and resources of the organization doing the sampling sometimes determines what protocol will be applied, since there are some protocols that demand more time and resources, while others can be done more rapidly. While there are broad similarities between many of the protocols, they usually differ from one another in their various details. A brief discussion of some of the variables will illustrate the reasons for all of this complexity. Every macroinvertebrate bioassessment protocol must include a description of each of the steps listed below. Within each of these four steps, there can be variations in methodology, as indicated by the following discussion.

1. Sampling: According to most protocols for wadeable streams benthic macroinvertebrates should be sampled using hand-held nets. The bioassessment protocol specifies details such as the exact shape of the net, the size of the mesh, and how the net should be handled in a stream. The protocol describes how to select sampling sites in the field and how to combine the material from grab samples to make a composite. The protocol further specifies how many organisms are needed to make a representative sample (typically between 100 and 300 individuals), and provides techniques for ensuring that those organisms are picked from the sample using an unbiased randomization method.

2. Identifying organisms: The bioassessment protocol specifies whether a collection of organisms will be identified in the field and returned to the stream alive, or preserved and identified in a laboratory. Field methods usually involve family-level identification, while laboratory methods often provide for identification to genus or to species. Laboratory analysis requires more time and effort, but provides more information. Whether the identification is done in the field or the lab, the product of this step is a list of the macroinvertebrate taxa found at a site, along with the number of individuals of each taxon.

3. Applying bioassessment metrics: The list of organisms produced in the previous step is analyzed by applying bioassessment metrics. This involves various methods of grouping and counting the organisms by types (by taxa). A variety of bioassessment metrics have been presented in scientific literature. Some metrics involve counting the number of different taxa found in a sample (assessing sample diversity); while other metrics involve counting the number of individuals of certain taxa or in certain groups of taxa (assessing community structure). Applying metrics often requires grouping taxa together by what is known about their ecological roles or characteristics. For example, there are several commonly-used metrics that take into account the relative "pollution tolerance" of the various taxa. Applying any metric to the list of taxa for a sample produces a numerical score. It is generally agreed that no single metric provides enough information to stand alone as a means of assessing water quality. Therefore, most states apply a suite of several metrics.

4. Applying an index: An Index of Biological Integrity (IBI) is a method of combining and integrating the information from several bioassessment metrics. It involves applying a series of mathematical transformations to each sample's metric scores and then combining them to give a single numerical index score. Typically, an index score for the so-called "reference condition" is developed using data from sites that are known to be undisturbed and that are judged to be appropriate reference sites based on regional and ecological considerations. Sample data are compared to reference conditions using the numerical scores calculated using the index. Increasing degrees of disturbance (or pollution) are indicated by scores that range further and further from the reference score. For state agencies, one of the main purposes of their bioassessment work is to identify those streams that are divergent enough from the reference condition that they are determined to be "not attaining" the state's

water quality standards for aquatic life use. Typically, the threshold that is used to determine attainment are linked to a particular numerical score using the appropriate index.

The "Present Status" and "Past Trends" sections of this chapter are based on data from five different sources, namely the four Delaware River Basin states and the Delaware River Basin Commission (DRBC). These five organizations all use different macroinvertebrate protocols in their programs for stream assessment. In addition to this interstate variability, there is also intrastate variability, because some states actually use more than one protocol to account for natural variation. A brief description is provided of how each of the organizations that contributed data has designed their respective programs for producing macroinvertebrate data.

Delaware Delaware is a small state with relatively little natural variability, but it does straddle a significant eco-regional divide. Delaware's land area is divided between the Middle Atlantic Coastal Plain eco-region and the Northern Piedmont eco-region. In the Coastal Plain, where streams have a low-gradient character, the state's bioassessment program specifies the use of the protocol developed by an USEPA-sponsored, multi-state workgroup called the Mid-Atlantic Coastal Streams Workgroup (USEPA 1997). In the Piedmont, the state specifies the use of methods documented in USEPA's 1999 Rapid Bioassessment Protocols report (Barbour et al. 1999). The structural and ecological differences between coastal plain streams and piedmont streams dictate several differences between the two protocols. For both stream categories, Delaware specifies that macroinvertebrate samples are to be preserved and identified in a laboratory, with most taxa identified to genus. Both protocols also utilize a multi-metric index. Of the assessment stations that make up the data set for Delaware's Delaware Estuary Basin, 46% are from the Piedmont and 54% are from the Coastal Plain.

Pennsylvania In 2006, after 10 years of effort, Pennsylvania completed their first statewide bioassessment survey, which was done using a modified version of the USEPA Rapid Bioassessment II Protocol from the document referenced above (Barbour et al. 1999). This method used field identification of organisms and family-level taxonomy. At about the same time, the state decided to refine their biomonitoring program and implement major changes to the bioassessment protocols. Pennsylvania's new program is called the Instream Comprehensive Evaluation (ICE). In it, the State's streams are divided into three major ecological categories, each of which is assessed by a different protocol. Each protocol specifies particular sampling methods, and how metrics and index calculations should be applied. These protocols are briefly described below.

The largest group of streams in Pennsylvania is categorized as riffle-run streams, which are assessed using the "Freestone Streams" protocol. The method specifies making a certain number of collections from shallow gravel-bottom or cobble-bottom riffle habitat, and then compositing and randomly sub-sampling to give a 200-organism sub-sample. The sub-sample is preserved and identified in a laboratory to genus, and a multi-metric IBI is applied to the taxa list. The preferred seasons for sampling are between November and May, so as to avoid sampling during the summer emergence period of many important insects. However, a method for "Freestone Streams, Summer Samples" is also available, for when agency workload requires that stream assessments continue through the summer months. The "Summer Samples" method provides a modified analysis to account for the effects of seasonal emergence on the invertebrate community. (During the summer months, many insects emerge as winged adults, and their aquatic forms are notably absent from stream-collected samples. In light of this, practitioners of bioassessment have two choices. They may avoid sampling during the time of year when the benthic community is likely to be altered by emergence, or they may develop protocols that are specifically tailored to each particular seasonal condition.) Freestone Streams account for 91% of the assessments performed in Pennsylvania's Delaware River Basin.

Pennsylvania's second stream category is the low-gradient streams that are lacking in riffle habitat. Pennsylvania uses the phrase "Multi-Habitat" to refer to this stream category and protocol. For Multi-Habitat sites, the sampling methods are designed to provide a means of capturing representative organisms from several specific kinds of habitats (including, for example, coarse submerged debris, submerged aquatic vegetation, and deposits of coarse particulate organic matter). A specific multi-metric analysis and IBI are applied. This category is somewhat similar to the Mid-Atlantic Coastal Plain Streams "Coastal Plain" streams discussed above in the "Delaware" section, as well as to the "Coastal Plain (Non-Pinelands)" category discussed below in the "New Jersey" section. However, the analogy is not exact, because many of Pennsylvania's Multi-Habitat sites are not in the coastal plain but in low-gradient topography in plateau regions, such as the Pocono region of northeast Pennsylvania. Multi-Habitat assessments account for 7% of the assessments performed in Pennsylvania's Delaware River Basin.

The third category of streams, limestone streams, is assessed using the protocol for '"True" Limestone Streams.' This method is specifically for spring-fed streams with high alkalinity and constant year-round temperature. These streams are considered ecologically unique and are important as cold-water fish habitat. The protocol specifies the collection of two samples from riffle habitat, composited and sub-sampled to make a 300-organism sample, followed by laboratory-identification of organisms to genus. A specific multi-metric analysis and IBI are applied. Limestone Streams account for 2% of the assessments performed in Pennsylvania's Delaware River Basin.

New Jersey From the early 1990s through 2008, New Jersey's biennial Integrated Assessment reports were based on a type of Rapid Bioassessment Protocol that used family-level taxonomy. During this period, all of the state's freshwater streams were assessed using the same index, which was known as the "New Jersey Impairment Score" (NJIS). However, like Pennsylvania, New Jersey revised their bioassessment program in the 2000s to make it more technically rigorous. Stream assessments are now based on genus-level taxonomy; and three different protocols are used, according to the major ecoregions of the state. The three protocols are: the High Gradient Macroinvertebrate Index (HGMI), which applies to the streams of Highlands, Ridge and Valley, and Piedmont ecoregions; the Coastal Plain Macroinvertebrate Index (CPMI), which applies to the Coastal Plain excluding waters considered Pinelands waters; and the Pinelands Macroinvertebrate Index (PMI), which applies to Pinelands waters. Each of these three protocols has particular sampling methods, assessment metrics, and an index. In the network of assessment stations for New Jersey's Delaware River Basin, 44% of stations are assessed by the HGMI, 37% by the CPMI, and 19% by the PMI.

New York New York's biological monitoring program began in 1972, with the first surveys done on the state's large rivers, using artificial substrate samplers. Since 1984, New York has used a "Rapid Assessment" method in the state's wadeable streams, for both special studies and as part of the statewide ambient water quality monitoring program. In 1987, the statewide program was re-designed to use a rotating cycle of monitoring and assessments called Rotating Integrated Basin Studies (RIBS). Under the current RIBS schedule, chemical and biological monitoring is conducted in all of the state's 17 major drainage over a five-year period. Riffle habitat is targeted for biological sampling of wadeable streams. Non-wadeable waters are monitored using artificial substrate samplers. The index period for wadeable stream sampling is from July through September. Individual metrics characterizing the benthic macroinvertebrate community are combined to form a multi-metric index called the Biological Assessment Profile. There is no differentiation of streams by eco-region; however, modification of the sampling methods and assessment metrics are used for low-gradient, sandy-bottom streams. Samples are preserved and identified in the laboratory to genus or species.

DRBC As an interstate agency, DRBC takes responsibility for assessing the mainstem Delaware River where it forms a border between states. Since 2001 DRBC has collected benthic macroinvertebrate samples annually at about 25 fixed sites on the Delaware River. These sites range from Hancock, NY (river mile 331/533 km) to just above the head-of-tide at Trenton, NJ (river mile 137/220 km). All samples are collected from gravel- or cobble-dominated riffle habitats. Sampling generally occurs in the late summer, with the central sampling window being August and September. The samples are preserved for laboratory identification, and the organisms are generally identified to genus. The analysis methodology used for the 2010 Integrated Assessment is based on a multi-metric IBI with a 100-point range. In their Integrated

Assessment report, DRBC discusses how these numerical results can be graded for the purpose of assessing attainment of water quality standards, but they also indicate that this analysis is preliminary. The agency plans to refine it with additional data and additional statistical work.

6.12.3 Present Status

For this Technical Report, the status of macroinvertebrates in the nontidal Delaware River Basin is determined using the data produced by the States for their biennial water quality reporting. All four basin states and DRBC report results of water quality monitoring to USEPA for the biennial 303(d) list, sometimes called the Integrated List of Waters, or the Integrated Assessment. For this Technical Report, the states have provided the most recent bioassessment data they were able to share, and for the most part it comes from the data that they used to prepare the 2010 Integrated List. Some state-by-state details are given in the sections below, and in the accompanying figures.

Delaware Present status is given by data from 87 individual assessments, performed between 2006 and 2009. Four grades of condition are reported: excellent condition, good condition, moderately degraded, and severely degraded. The aggregated data are presented in figure 6.12.2, figure 6.12.3, and figure 6.12.4.

Pennsylvania Present status is given by data from 914 assessments, spanning more than 10 years of time. Each station is reported as either "attaining" or "not attaining" the state-determined regulatory threshold for aquatic life use. The aggregated data are presented in figure 6.12.5., figure 6.12.6, and figure 6.12.7.

New Jersey Present status is given by data from 301 stations. The statewide program Ambient Biomonitoring Network (AMNET) has produced several rounds of survey results for each of the state's major basins. However, the current survey, known as AMNET Round 4, is not yet complete, and the NJ Department of Environmental Protection (NJDEP) was not able to share the unfinished data for the Lower Delaware River Basin. Therefore, this report presents recent data (AMNET Round 4, performed between 2007 and 2012) for only the Upper Delaware River Basin (141 stations), and older data (AMNET Round 3, performed between 2002 and 2007) for the entire Delaware River Basin (301 stations). Four grades of condition are used: excellent, good, fair, and poor. The aggregated data are presented in figure 6.12.8, figure 6.12.9, figure 6.12.10, figure 6.12.11, and figure 6.12.12..

New York Present status is given by data from 78 stations, collected 10 years. Four grades of condition are reported: non-impacted, slightly impacted, moderately impacted, and severely impacted. The aggregated data are presented in figure 6.12.13, figure 6.12.14, and figure 6.12.15.

DRBC Present status is given by data from 23 stations, collected in 2008 and 2009. Stream condition is given as a numerical score according to the IBI that the agency uses. The aggregated data are presented in figure 6.12.16. (Certain stations sampled by DRBC are not included in this figure because they were not sampled throughout the entire period.)

Considering the Delaware River Basin as a whole, it appears that there may be some broad regional conclusions that can be drawn from the bioassessment data. New York is the state with the lowest percentage of low-scoring stations, and apparently the best overall condition. Delaware is the state with the highest percentage of low-scoring stations; and New Jersey and Pennsylvania are in between.

For the three states whose bioassessment programs include multiple ecoregional indices, a comparison of the ecoregional differences shows somewhat similar trends in each state. The analogous categories of Piedmont (Delaware), Freestone (Pennsylvania), and High-Gradient (New Jersey) have somewhat better conditions than the corresponding low-gradient categories: Coastal Plain (Delaware and New Jersey) and Multi-Habitat (Pennsylvania). These observations suggest that the condition of benthic macroinvertebrates is generally better in the upper portions of the Delaware River Basin, farther from the coast, and closer to

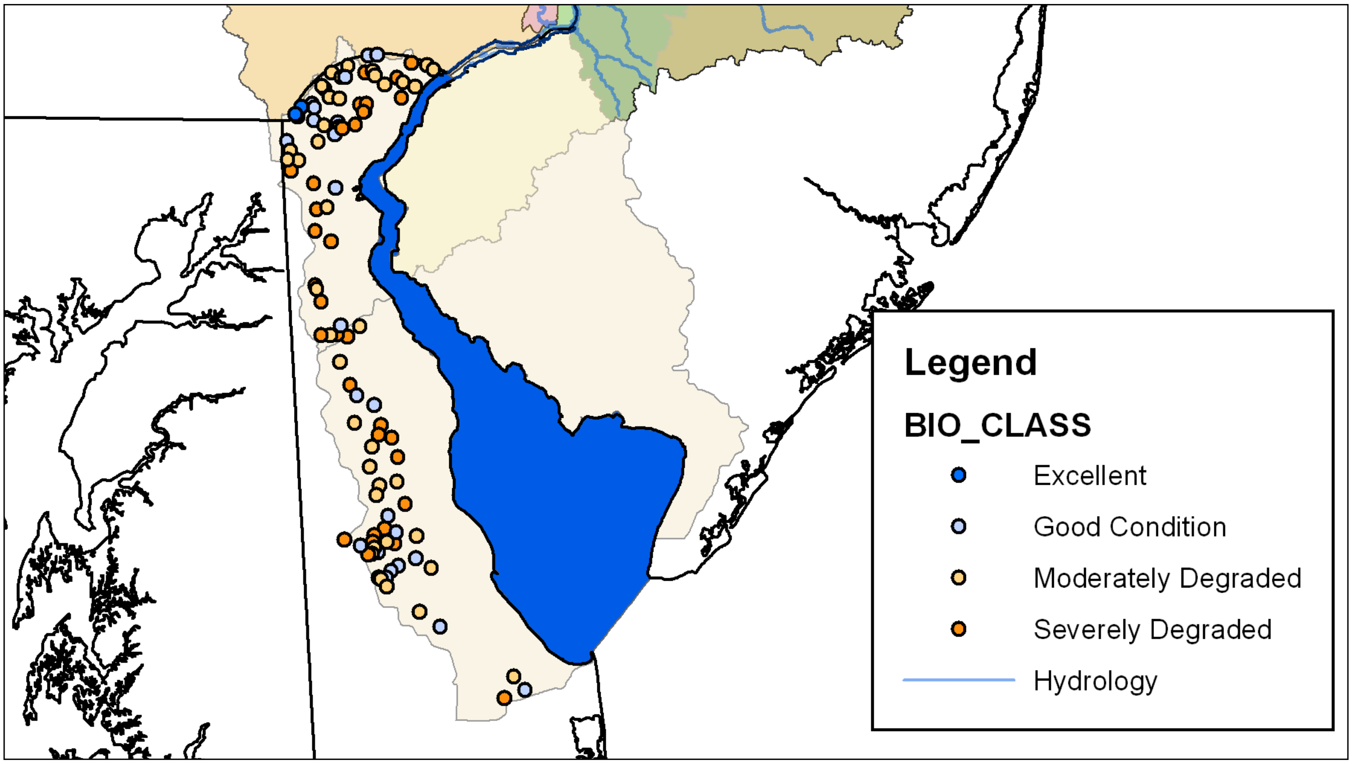

Figure 6.12.2 Delaware's Delaware Estuary Basin: map showing the locations of macroinvertebrate bioassessment stations.

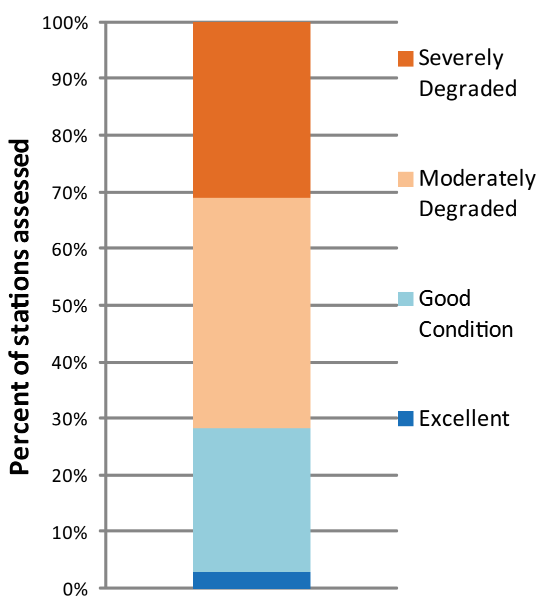

Figure 6.12.3 Bioassessment Station Data for Delaware's Delaware Estuary Basin.

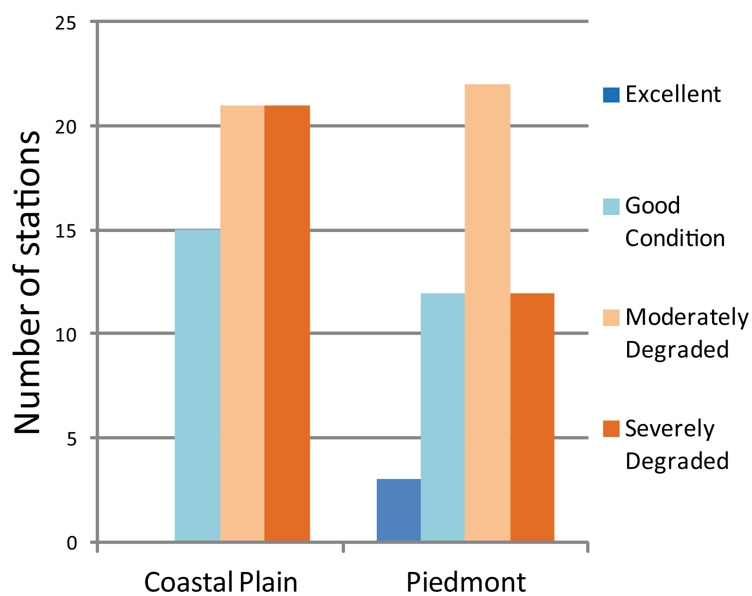

Figure 6.12.4 Bioassessment station data for Delaware's Delaware Estuary Basin, Data grouped by Eco-Region/Index (87 stations).

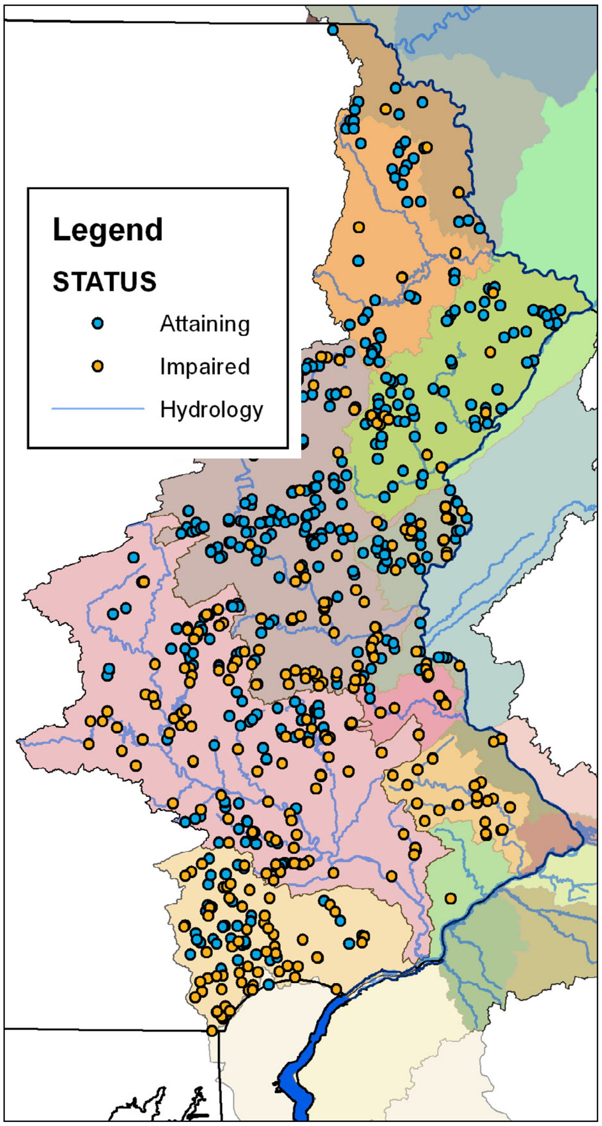

Figure 6.12.5 Pennsylvania's Delaware River Basin: Map showing the locations of macroinvertebrate bioassessment stations.

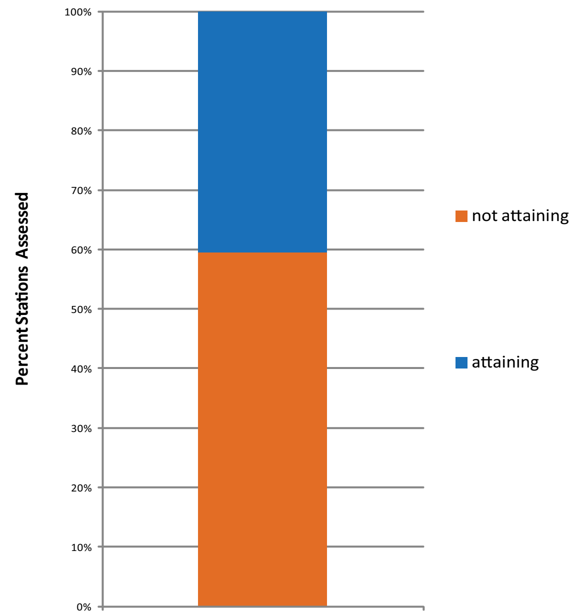

Figure 6.12.6 Bioassessment Station Data for Pennsylvania's Delaware River Basin (914 stations).

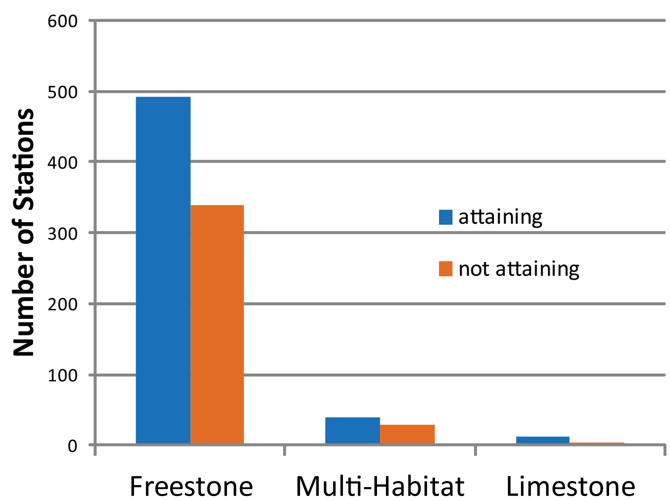

Figure 6.12.7 Bioassessment Station Data for Pennsylvania's Delaware River Basin, Grouped by Eco-Region/Index (914 stations).

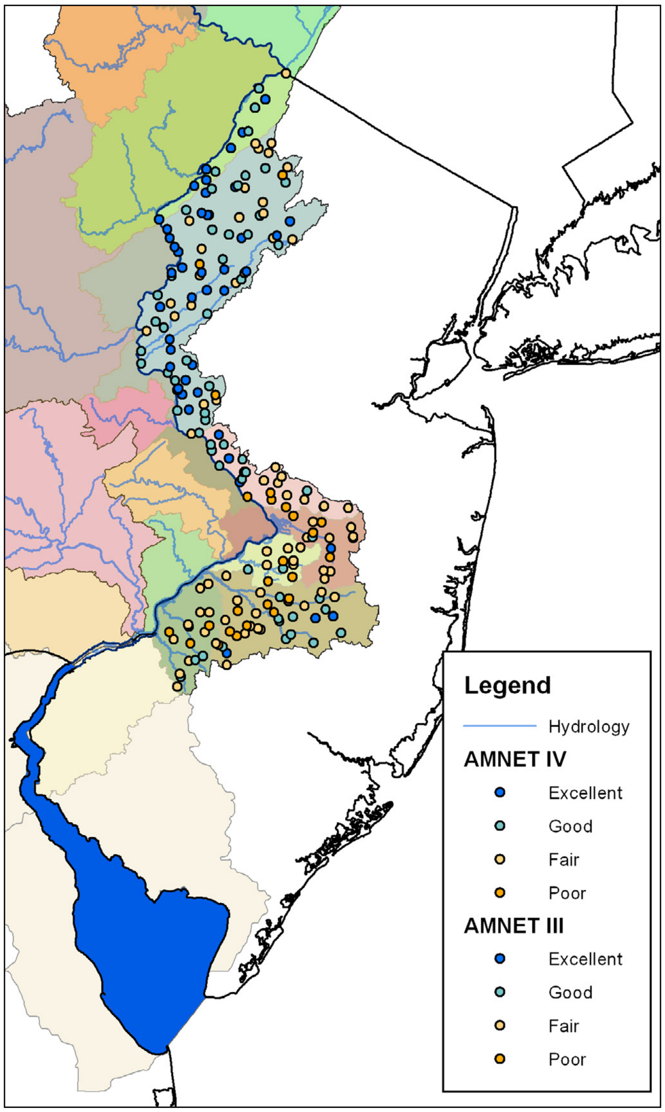

Figure 6.12.8 New Jersey's Delaware River Basin: Map showing the locations of macroinvertebrate bioassessment stations

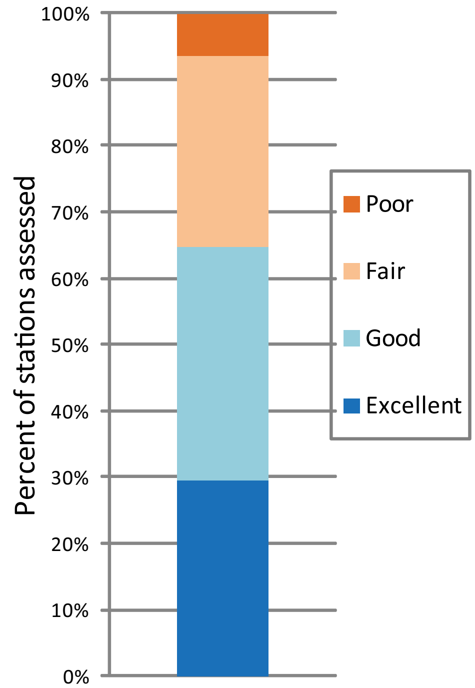

Figure 6.12.9 Bioassessment Station Data for New Jersey's Delaware River Basin, AMNET 4 Survey with 141 stations (2007-2012).

Figure 6.12.10 Bioassessment Station Data for New Jersey's Delaware River Basin, AMNET 3 Survey with 301 stations (2002-2007).

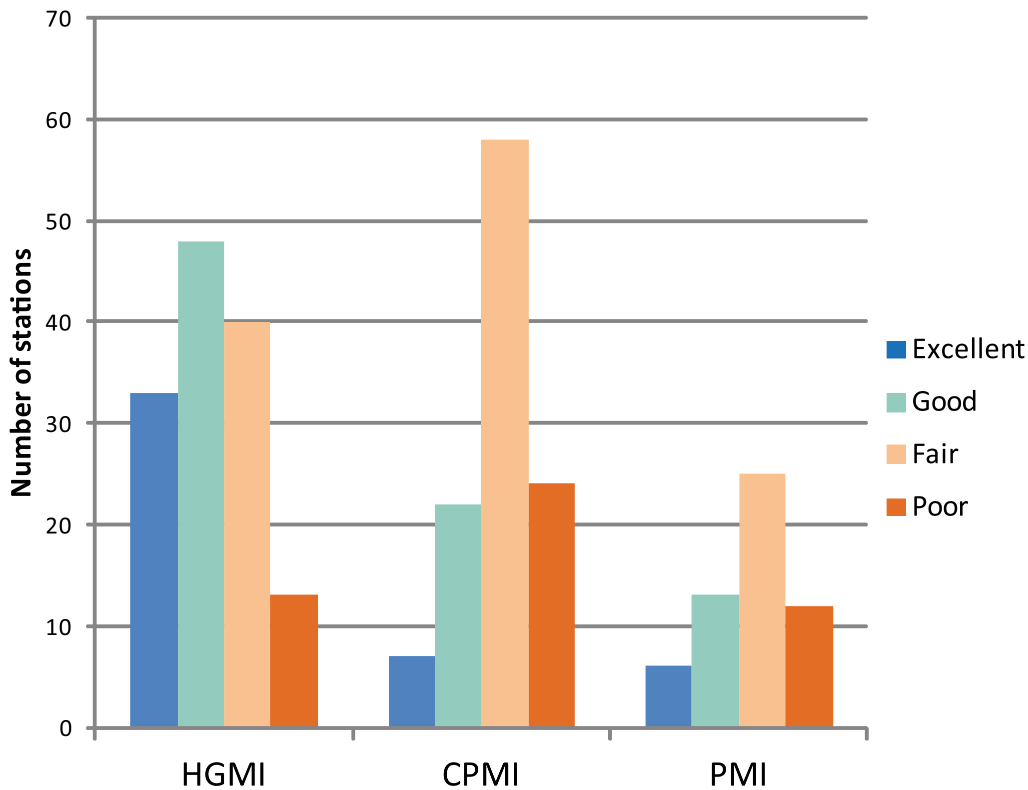

Figure 6.12.11 Bioassessment Station Data for New Jersey's Delaware Basin, Data Grouped by Eco-Region/Index (301 stations).

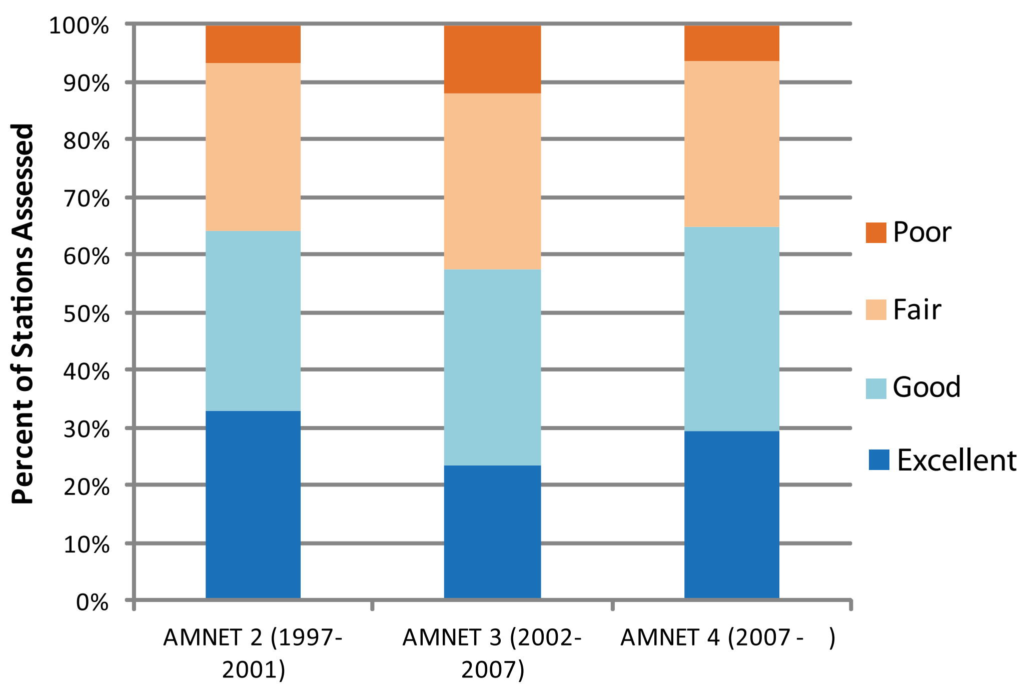

Figure 6.12.12 Bioassessment Data for Three Successive Surveys of New Jersey's Upper Delaware Basin (approximately 140 stations).

"headwaters." This corresponds to what may be expected based on a general understanding of water quality problems in this Basin. Good water quality is generally expected (hence macroinvertebrate quality) to correlate negatively with urban land cover, which is mostly in the Lower Basin, and positively with forested land cover, which is mostly in the Upper Basin.

The data suggested the above conclusions, as if the data was from a basin-wide survey, however this is not exactly the case. The data presented in this report, particularly for the states of Delaware and Pennsylvania, may not represent a random selection of sites, as would have been ideal if this had truly been a basin-wide survey of ambient conditions. In Pennsylvania this is due to the fact that the state has not yet completed a full survey of the Basin using their revised bioassessment protocol. In Delaware, the available data is skewed towards lower-quality waterways, which were prioritized for monitoring in recent years.

Benthic macroinvertebrate community condition is affected primarily by water quality and habitat disturbance. There are many reasons why conditions at a particular site may appear to be degraded. Furthermore, the Basin being discussed is large and diverse. For these reasons, it would probably be inappropriate to draw further conclusions from the data presented. When biomonitoring results cause a state agency to list a stream as "impaired," the agency is supposed to attribute the impairment to a "source" and a "cause." The Integrated List for each state contains information about these "source" and "cause" determinations for each listing, but the terminology that is used is complex. Because of this complexity, an attempt was not made to gather or analyze "source" and "cause" information for the present report. Readers who are interested in examining the sources and causes of impairments listed by the states are referred to the Integrated List documentation for each of the states.

6.12.4 Past Trends

Monitoring of trends is one of the stated goals of the biomonitoring program in most of the states. However it is more easily said than done. Reporting trends is difficult at the present time, because of the nature of the available data. In Delaware and Pennsylvania, sufficient data was not obtained to present any kind of trend. Several more years of work will be necessary before meaningful time series will be generated for Pennsylvania and Delaware.

We can discuss trends for New Jersey, New York, and for the mainstem Delaware River (DRBC data), based on the collected data.

New Jersey New Jersey's AMNET program has completed several rounds of sampling at an established set of stream stations. Round 2 of the AMNET program was performed between 1997 and 2002, round 3 between 2002 and 2007, and round 4 began in 2007 and is still unfinished. (There was a round 1 in the 1990s, but it was not as comprehensive as the subsequent surveys, and cannot be compared with the others on a station-by-station basis.) Although results for AMNET rounds 2 and 3 were originally reported using the NJIS index, the NJDEP was able to re-analyze the original data from those surveys using the more detailed taxonomy of the new indices. They have prepared a table which shows condition assessments for 144 stream stations in the Upper Delaware River Basin for these three rounds of survey. (The agency's analysis of data for the Lower Delaware River Basin for AMNET 4 is still incomplete.) These Upper Basin results are presented in aggregate in our figure 6.12.12.

Based on the data as shown in figure 6.12.12, the general condition of benthic macroinvertebrates in the streams of New Jersey's Upper Delaware River Basin appears to have fallen slightly between round 2 and round 3, and then improved again in round 4. However, it would be inappropriate to draw firm conclusions from such a limited set of data. In fact, the data do not necessarily indicate a general degradation of conditions between rounds 2 and 3, followed by a recovery. Instead, it seems likely that the apparent differences between these respective surveys may be within the range of variation that can be expected for repeat applications of the bioassessment method.

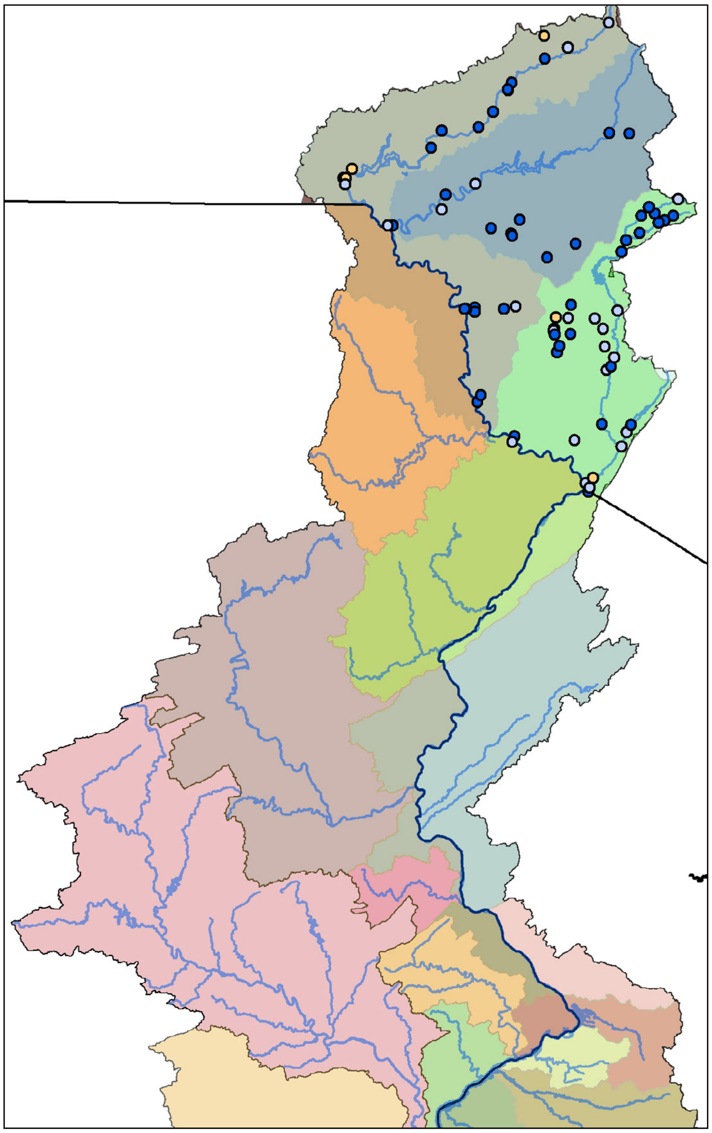

Figure 6.12.13 New York's Delaware River Basin: Map showing the locations of macroinvertebrate bioassessment stations.

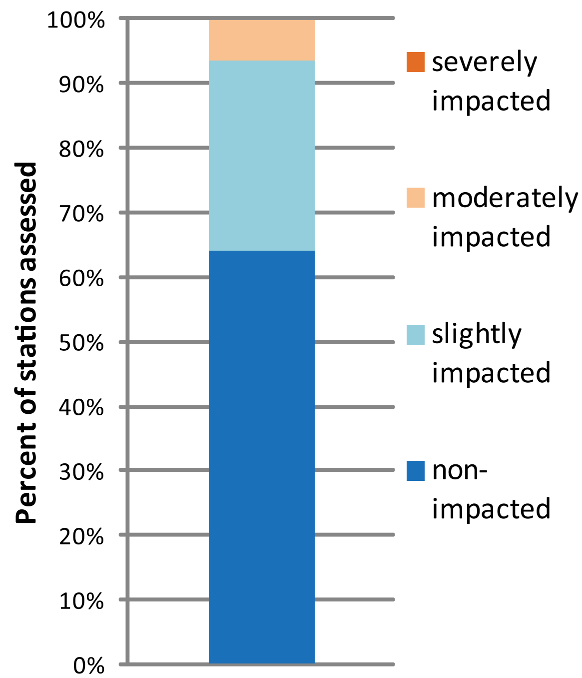

Figure 6.12.14 Bioassessment Station Data for New York's Delaware River Basin (78 stations).

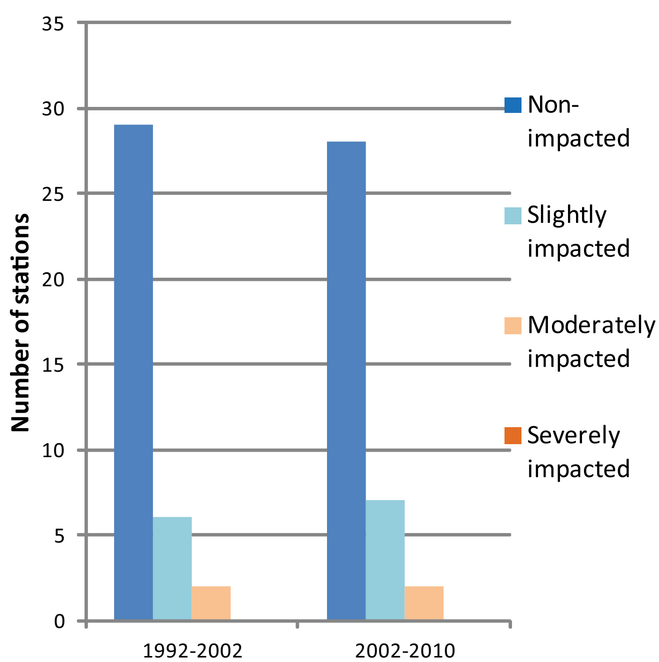

Figure 6.12.15 Bioassessment Station Data for New York's Delaware River Basin, comparing data from two successive decades (37 stations).

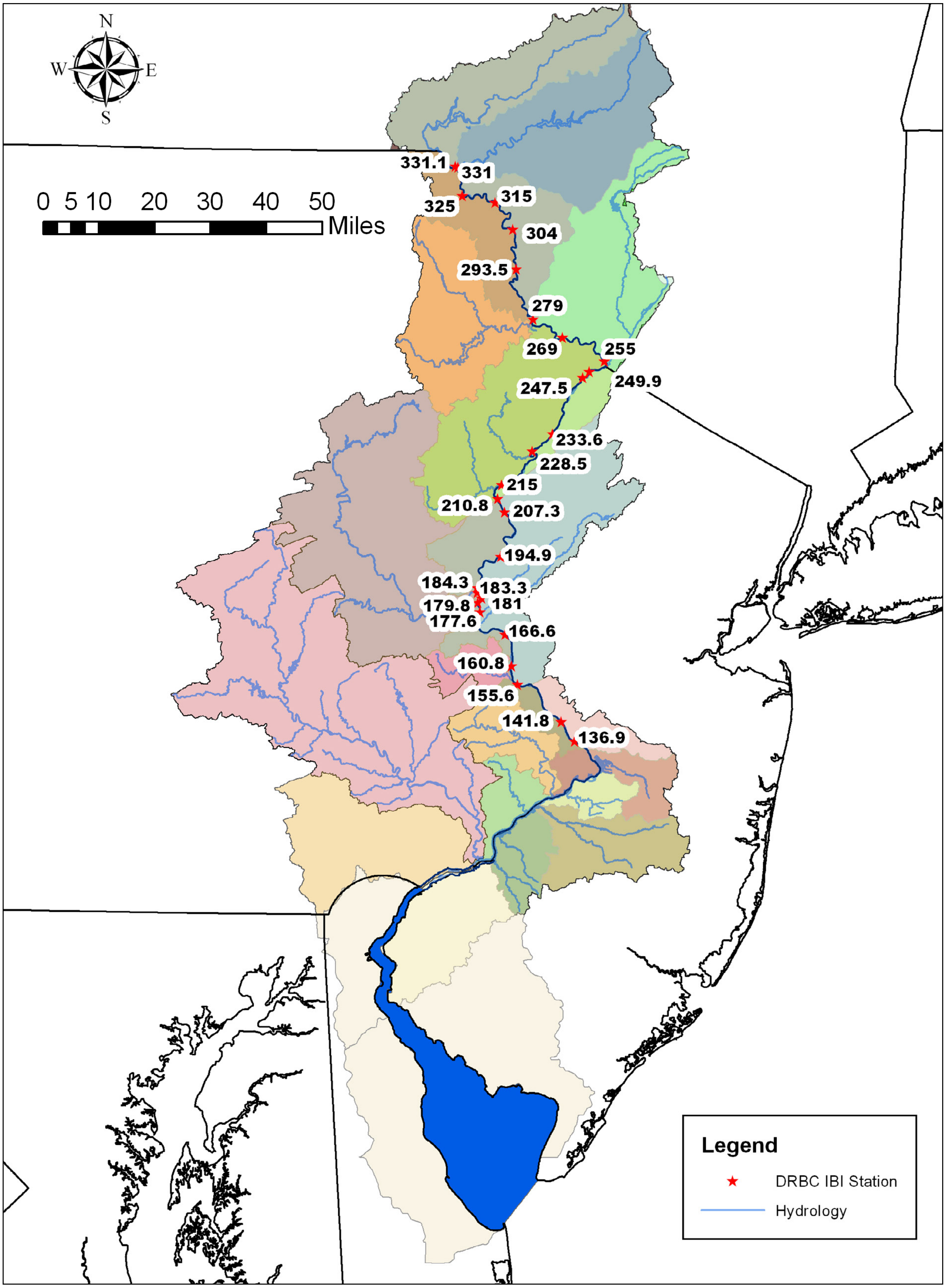

Figure 6.12.16 DRBC mainstem sampling locations.

New York Over the years, New York has collected multiple rounds of data for a certain number of stations in the Delaware River Basin. In 2004, the state published a report entitled "30-Year Trends in Water Quality of Rivers and Streams in New York State Based on Macroinvertebrate Data, 1972-2002." (The report is available on line at http://www.epa.gov/bioindicators/pdf/NYSDEC30yrTrendsReport.pdf). That report compared the results of surveys conducted between 1992 and 2002 to an earlier set of data collected before 1992.

For the present report, the recent data (2003 – 2010) was compared to the data from the 1990s that appears in the state's "30-Year Trends" report. The comparison reveals that the changes that occurred from the 1990s to the 2000s were very small. The total number of stations with assessment data in both decades was 37. Of those, 28 scored the same both times, while 9 scored differently. Five stations changed from "non-impacted" to "slightly impacted," and four others changed from "slightly impacted" to "non-impacted." Thus the overall difference in the Basin appears to be very small. Figure 6.12.15 presents this comparison as a chart.

DRBC Because DRBC's sampling team has returned to the same stations for several years on a regular basis, their data set appears to offer an opportunity to look at bioassessment data in a time series. Some of these data are presented as a chart in figure 6.12.17. Based on the data, there is year-to-year variability, but it appears that there are no clear trends.

DRBC's technical staff believe that some of the variability observed here can be attributed to particular events or conditions. It is thought that a severe summer drought or a major flood can affect aquatic life enough to produce anomalous scores using the bioassessment metrics and index. At least one example of this seems to be evident in DRBC's data. There is a noticeable drop in bioassessment index scores for 2006 at several stations along the River, which may be attributed to the effects of a major flood that occurred in late June of that year, shortly before the macroinvertebrate sampling was conducted (Personal Communication, Erik Silldorff).

6.12.5 Future Predictions

The future condition of the benthic macroinvertebrates in the Delaware River Basin can be expected to follow the various causes of waterway impairment. Any attempt to project future conditions in the Basin would be speculative, particularly in light of the challenges of determining past trends from macroinvertebrate data.

6.12.6 Actions and Needs

Bioassessment of macroinvertebrates is a well-established practice in state environmental agencies, and it may be expected to continue for the foreseeable future. Bioassessment has become a core element of the regulatory system for protecting water quality in the United States. Over time, it may be expected that the uses of bioassessment data will be refined as the datasets grow and as organizations gain experience with the interpretation of information produced.

The fact that the states all use different methods is frustrating to anyone who is interested in making interstate comparisons. At present, there is no particular movement towards requiring the standardization of methods. However, as states gather more data and gain a better understanding of how to use it, and with continued improvements in data management, there is reason to hope that meaningful interstate comparisons may become more readily available in time.

6.12.7 Summary

Benthic macroinvertebrates are a diverse and important natural resource. They are well known to people who are concerned with water quality and watershed health, but ignored or taken for granted by most people in the general public. Macroinvertebrates are not normally considered for specific management actions of any

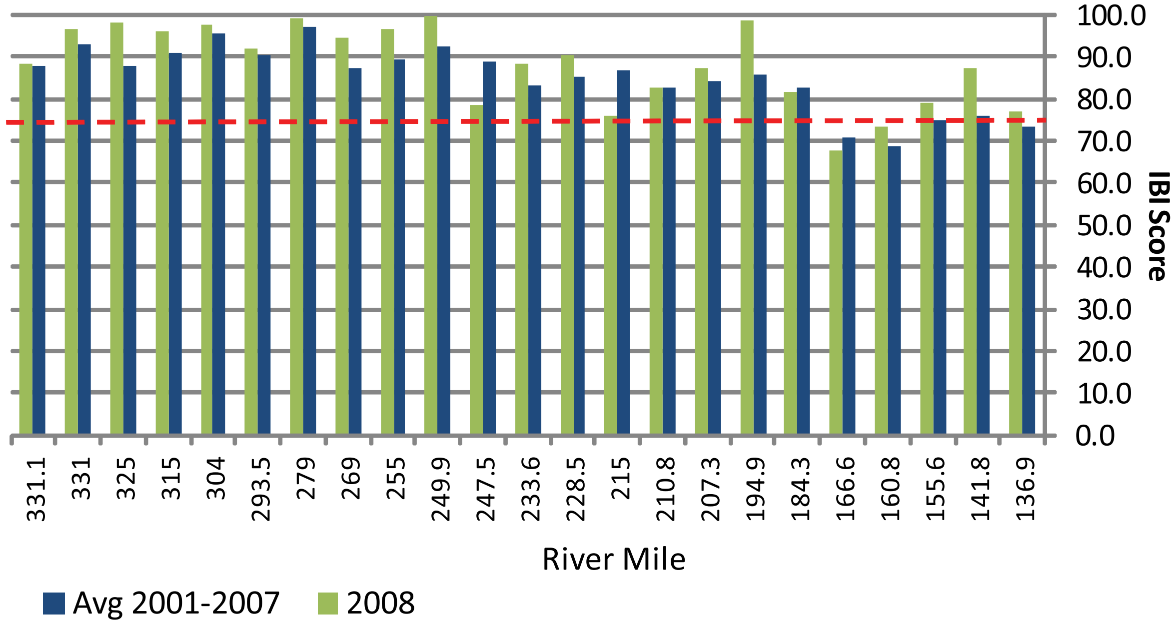

Figure 6.12.17 Bioassessment Station Data for Mainstem Delaware River By River Mile.

kind. The management actions that affect benthic macroinvertebrates are essentially the same management actions that affect water quality and aquatic habitats. It is expected that macroinvertebrates can be allowed to thrive by preventing water pollution and by protecting or restoring natural habitat conditions in waterways.

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