Chapter 5

Case Study #3: Bivalve Shellfish

Freshwater and estuarine bivalves represent some of our best sentinel indicators of ecosystem conditions. They furnish important ecosystem services by forming complex habitats, stabilizing sediments, filtering water, and recycling nutrients. Some, such as oysters are also commercially and historically important, and sustain a multi-million dollar industry in the Delaware system. Although lesser known and studied, many other bivalve species inhabit the Delaware Estuary in tidal marshes and freshwater systems. More than a dozen species of freshwater mussels are native to the Delaware watershed. These other bivalves also provide many services to the ecosystem and are sensitive indicators of water quality and habitat conditions over long time periods.

Unfortunately, many native bivalve taxa living in both non-tidal and tidal areas have experienced declining abundance, shrinking ranges, or local species extirpation. The loss of these rich living resources is thought to contribute to water and habitat degradation because of the diverse ecosystem goods and services that they provide. Many species of bivalve shellfish such as oysters and mussels can become so dense, forming reefs and beds, that they essentially build or modify the structural habitat so much that they are regarded as "ecosystem engineers" (Fig. 5-1). Declines in bivalves come from water-quality degradation, habitat loss or alteration, overharvesting, and disease. Without attention, the losses are likely to continue because of new pressures from development, climate change and other stressors.

Figure 5-1. Oysters are examples of ecosystem engineers, animals that build or enrich habitat.

5.1 Bivalves in the Delaware Estuary Watershed

Approximately sixty species of bivalves currently live in the Delaware Estuary, extending from headwater streams and lakes all the way to the mouth of Delaware Bay (see Appendix N and Maurer, 1974). This case is roughly categorized into Freshwater Mussels, Marine Bivalves, and Invasive Clams (Fig. 5-2.) This does not include many incidental marine species or a few Unionid mussels from the Chesapeake Basin that could straddle the watersheds within the State of Delaware.

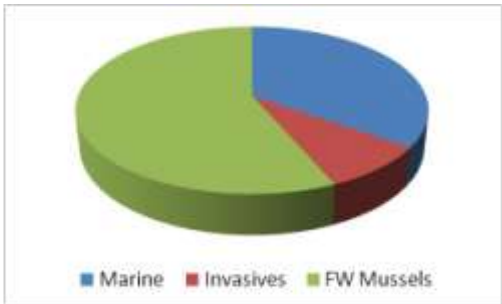
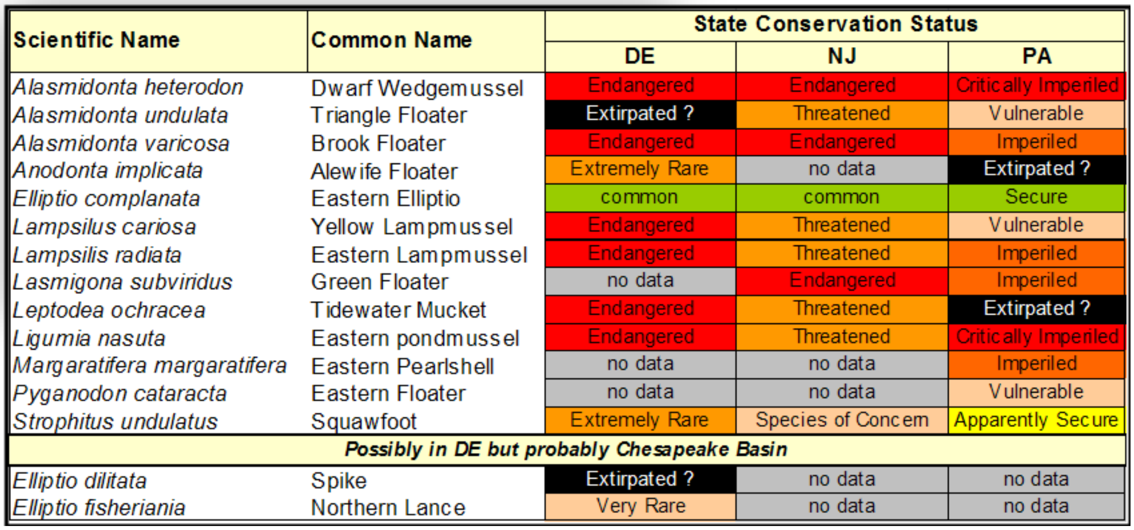


Figure 5-2. Different types of bivalve species in the Delaware Estuary watershed.

5.1.1. Freshwater Mussels. More than half of these species are native freshwater mussels (Orders: Unionidae, Margaratiferidae) that inhabit various ecological niches in lakes, small streams, and large rivers (Fig. 5-2.) About half of the native freshwater mussel species were historically found in the tidal freshwater region of the system. The current status of our thirteen native freshwater mussel species in the Delaware system is poor (PDE 2008, Appendix N) and is symptomatic of their nationwide status. North America has more biodiversity of Unionid mussels than anywhere in the world. Freshwater mussels are the most imperiled of all flora and fauna in the United States where 75% of our native 300 species are listed as species of conservation concern. Populations of “common” species are also in decline. In the Delaware system, twelve of our thirteen native species are listed as uncommon to rare with most being state listed endangered or threatened species (Table 6.1.) One species is a federally listed endangered species. The one species listed as common appears to be diminishing in range and population size, having been extirpated from many streams and not reproducing in others.

Table 5.1. Conservation status of native freshwater mussel species of the Delaware Estuary watershed as currently listed by Delaware, New Jersey and Pennsylvania.



Scientific Name	Common Name	State Conservation Status		
		DE	NJ	PA
Alasmidonta heterodon	Dwarf Wedgemussel	Endangered	Endangered	Critically Imperiled
Alasmidonta undulata	Triangle Floater	Extirpated ?	Threatened	Vulnerable
Alasmidonta varicosa	Brook Floater	Endangered	Endangered	Imperiled
Anodonta implicata	Alewife Floater	Extremely Rare	no data	Extirpated ?
Elliptio complanata	Eastern Elliptio	common	common	Secure
Lampsilus cariosa	Yellow Lampmussel	Endangered	Threatened	Vulnerable
Lampsilis radiata	Eastern Lampmussel	Endangered	Threatened	Imperiled
Lasmigona subviridus	Green Floater	no data	Endangered	Imperiled
Leptodea ochracea	Tidewater Mucket	Endangered	Threatened	Extirpated ?
Ligumia nasuta	Eastern pondmussel	Endangered	Threatened	Critically Imperiled
Margaratifera margaratifera	Eastern Pearlshell	no data	no data	Imperiled
Pyganodon cataracta	Eastern Floater	no data	no data	Vulnerable
Strophitus undulatus	Squawfoot	Extremely Rare	Species of Concern	Apparently Secure
Possibly in DE but probably Chesapeake Basin				
Elliptio dilitata	Spike	Extirpated ?	no data	no data
Elliptio fisheriania	Northern Lance	Very Rare	no data	no data

Freshwater mussels live in both non-tidal and tidal portions of the Delaware Estuary, which has the largest freshwater tidal prism in the world (PDE, 2006). Species distributions in non-tidal and tidal areas are determined mainly by the availability of suitable habitat and the availability of suitable fish hosts needed to complete their life cycles. Although some species historically live in both non-tidal and tidal areas, their current range is limited largely by dams on tributary streams that impact their fish hosts.

Figure 5-3. Shells from numerous species of freshwater mussels found along the Delaware River near Philadelphia in September 2009.

All species of native freshwater mussels appear to have become extirpated from some streams in the Delaware Estuary where they were once abundant, and declines in population sizes appear to be continuing elsewhere even for the one species listed as common. Nevertheless, sufficient numbers of mussels appear to remain to contribute materially to water quality (Appendix N.) Remnant populations of at least 5 native species were recently discovered in the urban corridor of southeastern PA where they presumably have survived because of the lack of dams (Appendix N). These animals merit special protection because they may represent the only indigenous genetic stocks from which to restore mussels into the non-tidal tributaries through propagation and relocation programs.

5.1.2. Marine Bivalves. Marine and estuarine bivalves appear to account for the bulk of the bivalve biodiversity and population biomass in the Delaware system (Appendix N.). This group includes the commercially important oyster, which because of careful management and active restoration still supports a multi-million dollar shellfishery. Oyster reefs are an important subtidal habitat type in Delaware Bay (Fig. 5-4.) Their historical and societal importance is also significant in the region (Appendix O.).

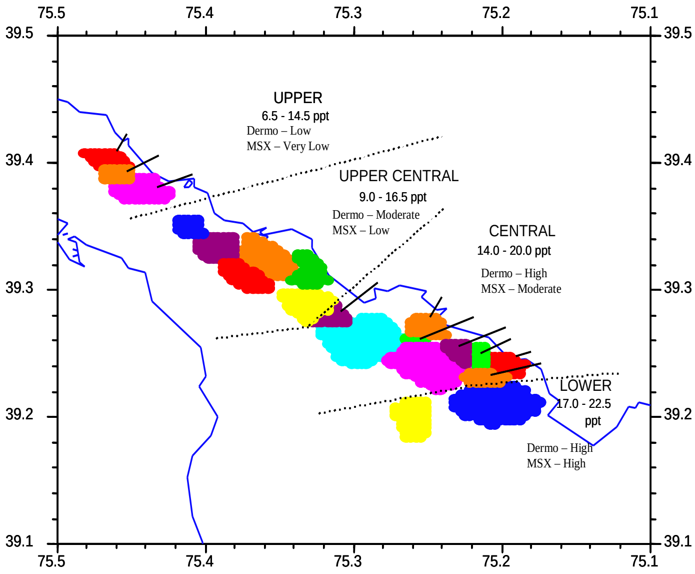


Figure 5-4. New Jersey seed beds of *Crassostrea virginica* in relation to salinity and disease susceptibility.

Oyster stocks are currently only a small fraction of historical levels due mainly to overharvesting in the late 19th and early 20th centuries, followed by high mortality from introduced diseases in the latter 20th century. These diseases remain a problem today, especially in dry years when salinities rise (see also Appendix O and Feature 5-1.). There is considerable variation in the growing conditions and disease prevalence in the different areas of the Delaware Estuary (Table 5-2.) The abundance and health of oysters on different reefs varies widely year to year, depending on environmental conditions which vary widely in time and space (Appendix O.)

Table 5-2. Summary of general growth and disease conditions for oysters in different areas of the Delaware Estuary, averaged over recent years.

	Lower Bay	**Central**	**Upper Cent.**	**Upper**	**Tributaries**
Recruitment	Excellent	Good	Low	Low	Patchy
Shell Reef Condition	Poor - Patchy	Excellent	Patchy	Good	Moderate
Food Availability	Excellent	Good	Poor	Poor	Good
Disease	Very High	Moderate	Low	Low	Low

Another prominent estuarine species is the ribbed mussel, which lives in dense intertidal beds along the seaward edges of salt marshes. Mussels bind tightly together and to the roots of *Spartina* plants using their hair-like byssal threads. The structure of these mussel beds can increase the resistance of the marsh shoreline to erosion, helping to stem marsh loss. Filter-feeding by these dense beds is thought to boost overall production of the marsh due to the fertilizing qualities of the mussel's deposits ((Bertness 1984; Jordan and Valiela 1982; Kuenzler 1961).

Besides oysters and ribbed mussels, the ecological importance of other species is difficult to assess because of limited information on their range and abundance.

Figure 5-5. Ribbed mussels, *Geukensia demissa*, attached to plant rhizomes and each other in an eroded clump along a salt marsh.

5.1.3. Invasive Clams. Two non-native species have become very abundant in the Delaware Estuary watershed. The Asian clam, *Corbicula fluminae*, is a small animal currently in high abundance in most freshwater areas of the watershed. Another abundant introduced species is the larger-sized clam, *Rangia cuneata*, which lives only in tidal areas straddling freshwater and brackish water. Although they are regarded as pests that might compete with native species, the shear abundance of these clams requires that they be examined in the context of climate change because they likely help to regulate water quality and some key ecological processes in areas where they reside.

5.1.4. Life History Comparison. To understand how these different groups of bivalves might respond to changing climate, it is necessary to first understand key differences in their life history strategies and elements of their ecology that have caused past declines. Freshwater mussels belong to a very different evolutionary lineage than many estuarine and marine bivalves. As a generality, freshwater mussels are slower growing and much longer lived than estuarine species, 80-100 year old animals in many cases. By comparison, most marine bivalves live to be 5-10 years old.

Freshwater mussels typically cannot start reproducing until they are 5-8 years old and they then invest a lot of energy into maternal care, rather than growth. The high level of parental investment and use of a fish host are ways that these animals use to maintain themselves upstream in freshwater streams and rivers. In contrast, most marine species are prolific "broadcast spawners" that simply eject eggs and sperm into the water column, and the planktonic larvae are dispersed widely by currents. With good growing conditions, marine species can become reproductive in 1-2 years.

Freshwater mussels also have a very complicated reproductive cycle that requires an intermediary fish host to ferry their parasitic larvae, which are first brooded in the mantle cavity of adults. The distribution of mussels is completely dependent on the movements and population health of fish hosts, and various species of freshwater mussels are only adapted for specific species of fish. Therefore, when dams or other habitat alterations block fish passage, freshwater mussels are unable to reproduce, disperse, or swap genes with neighboring populations.

The complicated life history and slow growth of freshwater mussels explains why they are in such decline nationwide. When disturbances cause mortality, the populations are slow to rebuild.

5.2 Bivalve Shellfish – Approach to Assessing Vulnerability and Adaptation Options

The vulnerability of bivalve mollusks to climate change and potential adaptation options were assessed by a panel of eight experts on bivalve shellfish, comprised of scientists and managers from public, non-profit and academic sectors. Participants in the Bivalve Work Group included freshwater mussel experts, oyster experts, and benthic ecologists. For the purposes of this project, the Bivalve Work Group operated as a subgroup under the Climate Adaptation Work Group. Initial tasks completed by the Bivalve Work Group were to:

- Identify the main physical and chemical environmental factors that are likely to change with changing climate and also affect bivalves (Section 5.3.1.)
- Inventory the main climate change vulnerabilities of bivalves in terms of ecological or physiological consequences (Section 5.3.2.)
- Identify various adaptation options that might be used to lower the vulnerability of bivalves to climate change (Section 5.3.3.)

For the purposes of this report, the various species of bivalves living in the Delaware Estuary and its watershed were sorted into three categories based on the principal physical conditions with which they are adapted and which largely define their species ranges. By separating into groups adapted for different physical conditions, the Bivalve Work Group was able to more easily judge how changes in those physical conditions might affect them. The three bivalve groups were:

- Freshwater mussels living in non-tidal watersheds of the Delaware Estuary (FW Mussels),
- Bivalves that live in freshwater tidal areas of the Delaware Estuary (FWT Bivalves), and
- Bivalves that live in brackish and saltwater areas of the Delaware Estuary (SW Bivalves.)

Following development of inventories of climate drivers, vulnerabilities, and adaptation options for each of the three groups of bivalves (Section 5.3), The Bivalve Work Group then:

- Prepared a survey to rank the relative level of concern for how projected changes in five physical and chemical conditions might impact six different traits of bivalve health (Section 5.4),
- Used the survey format to poll experts and rank relative vulnerabilities for the three groups of bivalves listed above (Section 5.5),
- Used the survey to rank various adaptation options for their potential to address the vulnerabilities (Section 5.6),
- Reviewed additional supporting documentation regarding bivalve vulnerabilities and adaptation options (Section 5.7),

- Ranked the top vulnerabilities and adaptation options after synthesis of information in Sections 5.5-5.7 (Section 5.8),
- Prepared adaptation recommendations (Section 5.9.)

5.3 Bivalve Work Group Inventories

Climate change will affect innumerable direct and indirect ecological interactions, and the Bivalve Work Group did not attempt to develop comprehensive lists of climate drivers, vulnerabilities, and adaptation options. The intent of the Bivalve Work Group was to identify the most likely important drivers, direct effects and options that could be fairly analyzed in a short period of time as a first step toward climate adaptation planning.

5.3.1 Climate Drivers

Five climate drivers were identified that could potentially have major effects on bivalve mollusks, depending on the magnitude and rate of change. These are described below along with an initial orientation to how they might affect bivalve fitness in different areas of the Estuary.

Temperature. Based on our climate predictions, air temperatures in the Estuary are expected to rise between 1-4^{o}F by 2100 (Chapter 2). Water temperatures will likely follow the same trend. Extremes in temperature may also increase (e.g., in summer). Like all animals and plants, bivalve shellfish have defined physiological tolerance ranges for temperature (e.g., Read 1969; Compton et al. 2007). Minor and brief exposure to higher than acceptable temperatures might impair bivalves chronically, reducing reproductive output or slowing growth. More prolonged or frequent exposures to sublethal temperatures, or short exposures to temperatures that exceed their acute tolerance limits, can lead to mortality. For these reasons, an increase in extreme temperatures generally presents a greater challenge to bivalves than a modest increase in annual mean temperature.

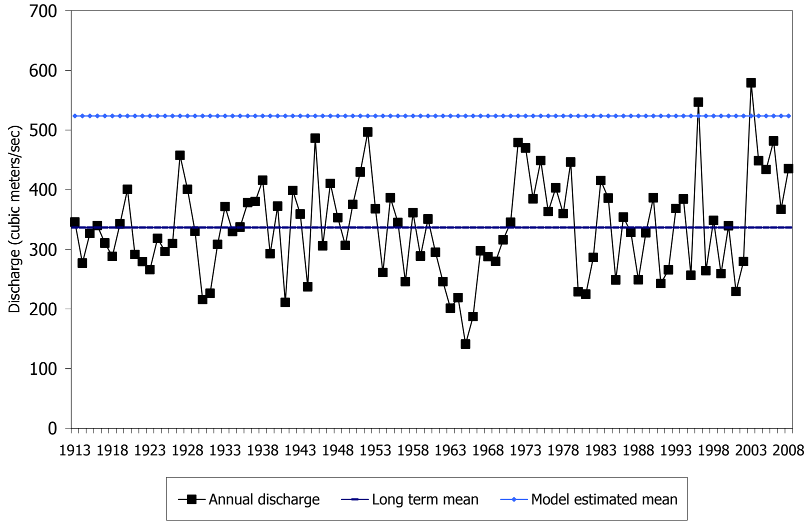


Figure 5-6. Flows on the Delaware River at Trenton, NJ, between 1913 and 2008.

Northern species that exist in the Delaware watershed, which are at the southernmost portion of their range, will be most vulnerable to this climate driver. On the other hand, slightly warmer temperatures (within tolerance ranges) may yield some benefits to warm-tolerant species such as oysters because of a lengthened growing season (Compton et al 2007.). This interpretation warrants caution, however, because indirect effects are myriad. Higher temperatures could potentially enrich conditions and fuel production by the microscopic plants from which these filter-feeders derive much of their nutrition, but some forms of phytoplankton could be detrimental. Another potential indirect effect is described in Feature 5-1, which describes how higher temperatures and salinities might promote disease organisms that impair oysters.

Precipitation. Precipitation and storm frequency/intensity patterns already appear to be changing to a wetter and stormier future state, possibly contributing to greater river flows (Figure 5-6.) Wetter and warmer winters will contribute to greater seasonal flooding, which can contribute to bed transport and scour bivalves living in non-tidal waterways. The loss of the snowpack due to temperature rises and increased storminess is likely to accentuate this effect, especially during winter.

Runoff from increased precipitation may help to offset salinity rise in the estuary, providing some positive feedbacks for estuarine species susceptible to higher salinity; however, the seasonal timing of this potential salinity suppression is very important. Oysters, for example, are most vulnerable to increased salinity during reproduction and summer growth, but net precipitation is not expected to increase significantly during summer and the added runoff from cool season precipitation is likely to pass out of the system prior to this time because of the loss of snow pack. A more oscillatory climate interspersed with summer droughts and floods would challenge many species adapted to more stable conditions of flow and water quality.

Sea Level and Salinity. Predictions of the rate of sea level rise for the Delaware Estuary region are being updated frequently. The Bivalve Work Group assumed sea level would rise one meter by 2100 and the salinity gradient would expand up the Estuary, most notably in the middle/upper estuary and tributaries. There are separate potential effects of sea level rise and salinity rise on bivalves, but the strongest effects are from an interaction of these factors; therefore, their effects were considered together. For oysters that live in the middle and upper estuary, the greatest concern is regarding a potential salinity increase, partly driven by sea level rise bringing more ocean water into the system. The two diseases that cause high oyster mortality are more virulent and prevalent at higher salinities, and these diseases currently define the downbay range of viable oyster populations (Figure 5-7, Feature 5-1, Appendix O.) Even a slight increase of only a few parts per thousand is likely to push oysters northward, and analysis over the past 50+ years suggests that the bulk of the oyster population has already shifted from the lower and middle beds to the upper middle beds Appendix O.)

Figure 5-7. Distribution of main oyster reefs in Delaware Bay in relation to salinity.

In the freshwater tidal portion of the Estuary, native unionids cannot tolerate any saltwater, and this zone appears to be home to high biodiversity of sensitive species (Appendix N). In the fringing salt marshes of Delaware Bay, greater erosion and wetland loss from sea level rise (Chapter 3) and increased storminess threatens ribbed mussels due to the potential loss of their habitat.

pH. The acidity and alkalinity of aquatic ecosystems is important for bivalve shellfish, which construct their calcareous shells through pH-sensitive calcification processes (e.g., Bayne 1976; Medakovic 2000; Gazeau et al. 2007.) Acidic conditions, such as are found in streams that receive acid mine runoff, make it impossible for bivalves to grow because they cannot produce new shell. This appears to be especially important for larvae and newly metamorphosed young animals, which are less tolerant of low pH than adults (e.g., Kurihara et al. 2007; Kurihara 2008.) Shell erosion can also occur in adults subjected to low pH, causing chronic and acute stress or death. Ocean acidification is a concern for all shelled animals because of increased carbonic acid that forms due to higher global levels of carbon dioxide (Gruber et al. 2005, Salisbury et al. 2008.) In the Delaware watershed, higher carbon dioxide levels may interact with degraded water quality to push freshwater mussels past pH tolerance limits, whereas, species living in tidal areas might be vulnerable to the same acidification processes happening in the oceans (Green et al. 2009, Gazeau et al. 2010.) The effects of pH on bivalves (and associated shellfisheries) and future changes in aquatic system pH are little described.

Storm Intensity and Frequency*.* Storms can contribute to physical disturbance of bivalves, especially species living in streams, intertidal areas, and shallow subtidal areas. Similar to precipitation, more severe storms can lead to greater flooding which causes bed transport and scouring in freshwater systems and more habitat destruction in shallow tidal and intertidal areas. Aquatic species are typically resilient and can tolerate the infrequent storm event if mortality does not occur; however an increase in disturbance frequency often pushes aquatic animals past tolerance limits by causing sustained chronic stress.

5.3.2 Inventory of Vulnerabilities.

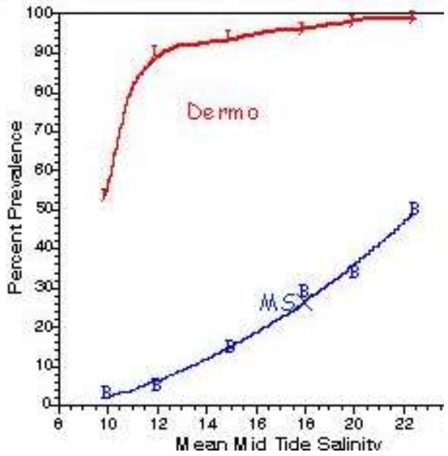


Figure 5-8. Prevalence of two important oyster disease agents, Dermo and MSX, in relation to salinity in Delaware Bay. Data from Susan Ford (HSRL).

Six aspects of bivalve health were identified for use in vulnerability assessments. These are described below along with an initial orientation to how they might vary among the three bivalve groups in relation to potential changes in climate drivers within the Delaware Estuary.

Physiological Health**.** The success of animals and plants depends largely on organismal-level fitness. The nutritional status, presence and severity of stressors, interactions with predators and competitors, and suitability and availability of habitat mainly affect individual animals such as bivalves, and then the resulting physiological health affects the status at the population level. Therefore, any aspect of climate change that might impair or benefit the fitness of single bivalves was considered here, including indirect factors such as the abundance and quality of food resources, presence and virulence of diseases, water quality, predation, as well as the direct affects of the physical drivers on maintenance metabolism, stress, and the net production available for growth and reproduction. For example, small changes in salinity can have large effects on the prevalence of oysters diseases (Figure 5-8), which impair oyster physiological health in Delaware Bay.

Figure 5-9. A juvenile freshwater mussel *Elliptio complanata*, following metamorphosis.

Reproductive Success. Bivalve mollusks in the Delaware Estuary watershed reproduce using different strategies (Section 5.1.4.) Changes in physical and chemical conditions can potentially short-circuit reproduction by freshwater mussels if the fish hosts needed for larvae are themselves impaired or otherwise limited in movement. Estuarine species that are broadcast spawners can be affected by shifts in circulation patterns during times when planktonic larvae are in the water column. All bivalve larvae metamorphose into juveniles at some point, and the larval, metamorphosis, and early juvenile stages (Fig. 5-9) are the most sensitive to water quality and environmental conditions; therefore, any degradation of water quality or stress on these early life history stages could effectively curtail recruitment.

***Change in Habitat Support*.** Bivalves live on or in the sediment or are attached to firm surfaces. The availability of suitable habitats for bivalves can be potentially affected by climate change. For example, ribbed mussels that live attached to the rhizomes of marsh plants could become impaired by the erosion and net loss of tidal marsh (Fig. 5-10.) Freshwater mussels could be affected by higher instability of stream bottoms that suffer greater bed transport due to higher river flows. Oysters that cement onto shell reefs could be impaired if storm energy or ocean acidification erode reef habitats. Any physical or chemical factor that could impair bivalves by undermining the availability or quality of essential habitat was considered as a "habitat support" outcome.

Figure 5-10. Ribbed mussels, *Geukensia demissa*, living along the seaward edge of salt marshes in the Delaware Estuary.

***Interactions with Invasive Species*.** Two important non-native bivalve species live in abundance in the Delaware Estuary (Fig. 5-11, Section 5.1.3.) Although these species do not directly colonize the shells of native bivalves in the same way as invasive zebra mussels do in other areas, there may be indirect competitive interactions that could be affected by changes in climate. In addition, new introductions of non-native species could be increasingly likely as species ranges begin to shift more rapidly. Non-native species already present, along with any new introductions, could become more invasive in character. The Bivalve Work Group considered potential interactions with invasive species to include both direct ecological effects as well as indirect effects, such as may occur by non-native predator species.

Figure 5-11. Asian clams, *Corbicula fluminae*, collected from the Brandywine River, PA.

Figure 5-12. Healthy populations of bivalves have wide size class distributions.

Population Productivity. Secondary production by populations of bivalves is determined partly by the physiological status of the bulk of the members of the population, the reproductive success of the population, and the mortality rate. Generally, a fit population is able to allocate a portion of its production for reproduction, enabling sustainable numbers and a balance between the birth rate and death rate. Healthy populations typically have a diverse size class distribution with large numbers of young animals and some old animals (Fig. 5-12.) Typically, significant changes in physical and chemical environmental conditions will affect the carrying capacity for bivalve populations, and this will be most apparent in terms of population productivity.

***Shifts in Species Composition or Ranges*.** Warmer temperatures and higher salinities are likely to drive northward shifts in the suitable conditions for whole communities and species assemblages, including bivalves. Some bivalves, such as estuarine species that produce planktonic larvae, will have no difficulty dispersing into suitable new habitats. Other bivalves, such as freshwater species with complex life history strategies, are likely to have great difficulty dispersing northward because of barriers to dispersal by fish hosts (Fig. 5-13.) This will be most problematic for freshwater mussel species that rely on non-diadromous fish which cannot swim through saltwater, as well as mussels needing diadromous fish that are blocked on streams and rivers by dams, tide gates, and related structures.

Figure 5-13. Apparent distribution of two mussel species in Pennsylvania in 1919, both of which appear now to be extirpated from southeast Pennsylvania (Ortmann 1919.)

5.3.3 Inventory of Adaptation Options

The Bivalve Work Group identified ten potential management tactics for helping bivalve mollusks adapt to climate change in the Delaware Estuary watershed. Some of these are applicable to specific bivalve species or habitat zones. Some tactics are straightforward restoration activities, but these also should be considered as climate adaptation activities because of the increased resilience imparted by newly restored bivalve populations. In many cases, only a subset (or one) native species currently lives in streams that once held 7-8 species. By refilling such niches with restored bivalve stocks, the overall bivalve assemblage would perform greater net ecosystem services that benefit each other and overall stream ecology. Similarly, rebuilding oyster stocks (i.e., restoration) or stemming loss of ribbed mussels in eroding marshes (protection) could be more cost effectively today than trying to do so tomorrow, and would yield the added benefit of sustained ecosystem services that helps buffer the system against storms and other climate-associated disturbances. Ten adaptation options are described below along with an initial orientation to how they might address key vulnerabilities by this living resource.

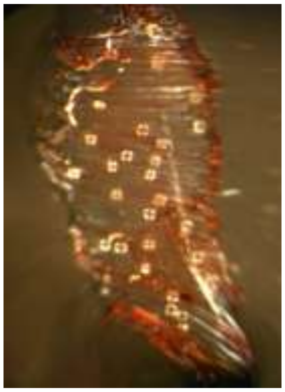


Figure 5-14. Tactics for restoring freshwater mussels are being developed in the Delaware Estuary. In this photo, baby mussels are shown attached to the gill of a host fish held in captivity at Cheyney University, PA.

***Monitor/Research Vulnerability Impacts*.** Although not a direct measure, the effectiveness of any climate adaptation tactic in alleviating stress on natural resources will depend on how much we know about changing climate conditions, the associated condition of the resource, cause-effect relationships between climate drivers and resource fitness, and the scientific basis for adaptation efforts. Information gathering, research studies, and baseline and ongoing monitoring will ensure that adaptation efforts realize best possible outcomes for the resource. Once adaptation projects are funded, monitoring will also be needed to track success and adaptively manage future investments to maximize benefits.

Hatchery Propagation and Restocking of Populations. In cases where the natural reproduction of native bivalve species is impossible or should be augmented, assisted reproduction may be warranted to ensure a sufficient population biomass exists to perform essential ecosystem services. Effective hatchery methods were developed more than 100 years ago for marine species, and recent advances now permit freshwater mussels to be spawned and propagated in hatcheries (Fig. 5-14.) Restocking can be used to reintroduce bivalves into areas where they had become extirpated, facilitate gene exchange among disparate populations that once exchanged genes, or to simply boost population biomass in aging populations that are incapable of reproducing naturally. In all cases, proper care can be taken to ensure genetic stocks are suitable and indigenous to the local areas.

Transplants of Broodstock to Expand Ranges. In addition to hatchery propagation, gravid adults might be transplanted from remnant populations into areas that once held the species but currently does not. This tactic can be less expensive than hatchery propagation (see above) but offers less control over outcomes since it is difficult to monitor reproductive success by relocated adults. The main objective of this tactic is to save imperiled species which currently might reside in only one or two remaining locations.

Metapopulation Expansion for Common Species. Hatchery and transplant tactics could also be used to strengthen the resilience and ecosystem services performed by common species that currently have a fragmented metapopulation, such as the freshwater mussel, *Elliptio complanata*. Due to a variety of factors, even common species have become highly fragmented in distribution, making them more vulnerable to climate change effects.

Restoration of Extirpated Rare Species. Some species or assemblages of bivalves may have become fully extirpated from some subwatersheds, perhaps even the entire Delaware River Basin. In cases where their extirpation can be documented and a source of genetically similar broodstock can be acquired nearby (e.g. Susquehanna River Basin), native species might be returned to their ecological niches by either relocation or hatchery-based restoration programs.


Figure 5-14. In southeastern PA, remnant mussel beds are located only in areas with healthy riparian buffers.

Dam Removals to Assist Dispersal on Fish Hosts. Fish passage barriers represent probably the single greatest threat to freshwater mussels during past, present and future conditions. By impeding passage of both resident and diadramous fishes, freshwater mussels lose their ability to reproduce. Therefore, concerted efforts to remove dams, tidal gates, and other barriers to fish movement are certain to benefit any bivalve species that disperses through these means.

***Assisted Migration (of southern species) to Fill Open Niches*.** As species ranges shift northward with climate, some niches will likely open permanently, particularly in freshwater non-tidal areas. If no suitable species exists in the Delaware River Basin to fill that niche, it might be attractive to consider introducing a more southern species to ensure that the niche is filled and associated ecosystem services are being performed. Unionids are generally amenable to translocation (Cope et al. 2003.) Assisted migration is a new concept with numerous potential disadvantages and advantages to be considered (Hunter 2007; McLachlan et al. 2007, Marris 2008).

***In-stream and/or Riparian Habitat Enhancements*.** Many native species, especially freshwater mussels, appear to be most numerous today in streams with more natural riparian corridors and stream bottom conditions (Fig. 5-14.) In areas where development and agriculture have altered riparian coverage, mussel populations appear to be more severely degraded or have become completely extirpated. Therefore, freshwater mussels would likely benefit from riparian and in stream restoration and preservation programs, which could be augmented with direct restoration tactics.

***Water Quality Management*.** Filter-feeding bivalves capture microscopic particles as food. The high ratio of surface area to volume of these particles makes them very effective at taking up many classes of contaminants. By feeding on vast quantities of such small particles, bivalves are therefore exposed to more particulate contaminants than other animals. Bivalves also use an efficient countercurrent system for gas exchange, whereby large volumes of water are passed over their gills, which also provides high exposure opportunities for dissolved forms of contaminants. For these reasons, bivalves are particularly sensitive to water quality. Bivalves are helpful in remediating water quality, but they can be killed easily by certain forms of chemicals such as copper. Sustaining and improving water quality in prime bivalve growing areas is therefore viewed as a tactic for helping these animals adapt to climate change.

***Water Quantity (Flow) Management*.** The maintenance of “ecological flows” is important for all bivalves living in the Delaware Estuary watershed. Most freshwater mussels die if they are exposed to air for periods of more than a day, such as when a river bed dries up. On the other hand, very high flows from flooding can impair the same animals by physical disturbance.

For species living in freshwater tidal areas, river flows are critically important for maintaining the freshwater character, helping to maintain saltwater lower in the estuary. Even brief exposure to salinities over 0.5 ppt can kill most freshwater mussel species.

Lower in the system, oysters are most productive in areas where salinities are low enough to hold diseases at bay, and any major change in river flow, especially the mainstem Delaware River (60% of freshwater inputs to estuary), could be harmful to oysters. The management of river flows is expected to be increasingly important as sea level rise will tend to bring more salt water up the estuary.

As temperatures and evapotranspiration rise in summer, more water may need to be released to sustain living resources in the rivers and estuary. Summer is also the time of year when water is most in demand.

5.4 Bivalve Shellfish - Survey Methods

Climate change vulnerabilities and potential adaptation options were examined separately for freshwater mussels (FW Mussels), freshwater tidal bivalves (FWT Bivalves), and saltwater bivalves (SW Bivalves). The Bivalve Work Group relied on the initial inventory (Section 5.3) to prepare a survey, which was sent to more than forty scientists and managers in the mid-Atlantic region having expertise with marine and/or freshwater bivalves.

Survey Monkey™ was used to construct and operate the poll, which required about 45-60 minutes for respondents to complete. Each respondent was first asked to rank the relative vulnerability of a particular health metric (six metrics, Section 5.3.2) in response to a particular climate change driver (five drivers, Section 5.3.1) for FW Mussels. This amounted to thirty cause-effect queries for FW Mussels. The same set of questions was posed for FWT Bivalves and then SW Bivalves, and so ninety cause-effect queries were answered by each respondent to perform the vulnerability assessment survey.

Respondents were provided with the most current predictions tailored to the Delaware Estuary Watershed (from Chapter 2) and they were asked to answer the questions to reflect the period from present to 2100 using these best current projections (e.g., for 1 m sea level rise.)

Survey participants were also asked to consider real world ecological relationships that might include indirect effects and feedback relationships as well as simple direct effects. As examples, salinity rise could harm oysters indirectly by favoring oyster diseases, and temperature rise could harm freshwater mussels indirectly by harming fish hosts for their larvae. On the other hand, respondents were asked to not assume that some current policy impediments or regulatory hurdles will continue to exist. Policies and management paradigms might evolve.

For each cause-effect query, respondents were asked to rank their level of concern from no concern to high concern. Respondents were asked to consider their relative concern levels for each of the ninety cause-effect relationships in comparison to the other eighty-nine. Therefore, they were asked to apply their ratings in comparative fashion across the entire survey; e.g., pH effects on freshwater mussels versus salinity effects on oysters. This approach was designed to obtain a summary view of the relative concern among different taxa groups and areas of the watershed.

Each rating of concern for a specific cause-effect relationship was paired with a query of the respondent's relative level of confidence in the concern rating, also ranging from no confidence to high confidence. Therefore, respondents with more expertise or knowledge for some types of bivalves were permitted to adjust their confidence lower for questions regarding bivalves with which they are less familiar.

Vulnerability rankings were assigned scores from 1-5, and confidence rankings were also scored 1-5 (low to high). These weightings were then multiplied together per respondent to calculate a composite weighting for the vulnerability that integrated concern level and confidence level. Therefore, a respondent who expressed high concern but low confidence for a cause-effect relationship may yield a composite score identical to another respondent who expressed low concern but high confidence. This was one limitation of this risk assessment approach, whereby the net vulnerability could become biased to the low side simply because of a weak understanding by respondents or by insufficient data. For certain purposes, we therefore recommend that raw impact scores may be more useful than composite scores that integrate confidence (both results are provided in appendices.)

Not all climate change impacts are expected to cause problems for all bivalve shellfish, and some positive benefits might occur. In answering questions about vulnerabilities, respondents were not asked to discern whether the “vulnerability” would lead to a negative or positive outcome; rather, they were simply asked to note whether the particular cause-effect relationship would occur with climate change. To determine whether the outcomes might be beneficial or harmful to the bivalve resource, for each cause-effect relationship, respondents were also asked to predict the net change in ecosystem services that might occur as a result. Allowed responses were “positive change,” “no net change,” “negative change,” or “not sure.”

Finally, for each cause-effect relationship, respondents were asked to rank the relative effectiveness and feasibility of the array of ten potential adaptation options listed in Section 5.3.3 in terms of helping to offset any vulnerabilities. Respondents were first asked to rank the tactic’s effectiveness as either high, medium or low, and they were then able to rank the feasibility as either high, medium or low. Effectiveness and feasibility responses were weighted, averaged among respondents, and then multiplied together per adaptation tactic to derive its composite score.

5.5 Bivalve Shellfish – Vulnerability Assessment

The relative vulnerability of the three different types of bivalves to changes in five types of climate conditions, as judged by experts who responded to the survey (Section 5.4,) is discussed below in Sections 5.5.1 (Freshwater Mussels), Section 5.5.2 (Tidal Freshwater Bivalves,) and Section 5.5.3 (Saltwater Bivalves.) Since there were ninety different cause-effect results (3 bivalve groups, 5 climate drivers, 6 bivalve fitness outcomes), only example data are shown here for the predicted impacts and associated confidence in the expert rankings. Full survey responses are provided in Appendix P. To summarize the relative differences among bivalves and climate drivers, impact and confidence responses were integrated into a composite vulnerability index, which is shown in Section 5.5.4.

5.5.1 Vulnerability of Non-Tidal Freshwater Mussels

Estimated impacts varied among the five climate drivers, but the relative importance of the drivers depended on which aspect of freshwater mussel fitness was examined. For example, changes in storm frequency or intensity was the topped ranked driver that could affect habitat support for freshwater mussels (i.e., availability and quality of suitable habitat), followed by changes in precipitation (Appendix P.) Changes in pH were regarded as posing the least threat to freshwater mussel habitat support. Survey response confidence was generally high for all 30 cause-effect predictions for the vulnerability of freshwater mussels.

In comparison to the habitat support vulnerability, species composition and ranges of freshwater mussels were viewed as most vulnerable to changes in temperature (blue bars in Fig. 5-15.) Species composition and ranges are threatened by temperature because it is the primary environmental parameter that determines where mussels can and cannot live. As water temperatures rise across the basin, some northern adapted species are likely to become extirpated and no mechanism exists for southern species to migrate north to fill any niches that open. Again, pH was not seen as much of a problem by comparison.

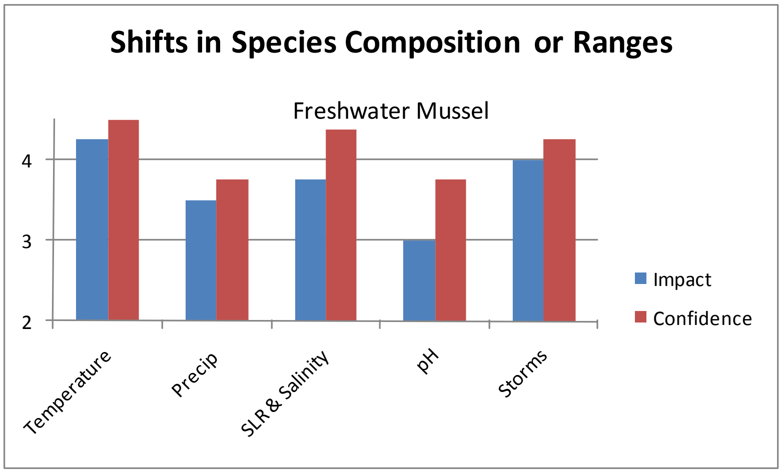


Figure 5-15. Relative levels of concern regarding the potential impact of changing physical and chemical conditions on **species composition and ranges** of freshwater mussels (blue) and relative confidence in these projections (red.)

Taken together, freshwater mussels were considered most vulnerable to temperature and storminess changes, and the specific fitness responses that were deemed most of concern was species composition or ranges, reproductive success, and habitat support (Appendix P.)

5.5.2 Vulnerability of Freshwater Tidal Bivalves

Sea level rise and salinity rise were rated as the top concern for bivalves living in the freshwater tidal areas of the watershed, as evidenced by Figure 5-16. In fact, moderate to very high concern was expressed regarding the threat of sea level and salinity rise for all six measures of bivalve fitness. Survey respondents all expressed high confidence in this cause-effect pairing.

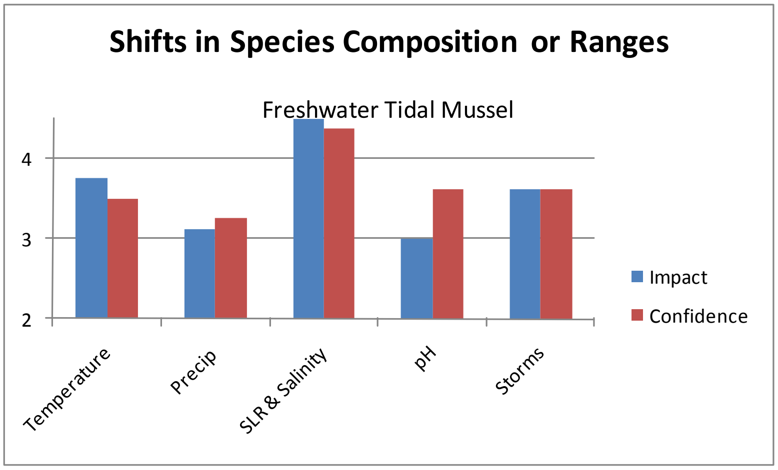


Figure 5-16. Relative levels of concern regarding the potential impact of changing physical and chemical conditions on **species composition and ranges** of tidal freshwater bivalves (blue) and relative confidence in these projections (red.)

In contrast, the vulnerability of freshwater tidal bivalves to temperature, precipitation, pH and storminess was seen as much lower than the vulnerability to salinity. Compared with non-tidal freshwater mussels, only sea level and salinity changes were rated as a higher concern for freshwater tidal bivalves, and all other factors were viewed as more worrisome for non-tidal mussels.

5.5.3 Vulnerability of Saltwater Bivalves

Compared with freshwater bivalves in both non-tidal and tidal waters, the general level of concern was lower for saltwater bivalves experiencing changes in the five climate drivers. Estuarine and marine species can disperse more easily than freshwater mussels that must rely on fish hosts to reach new areas to colonize. In addition, some climate drivers such as temperature and precipitation are buffered by the larger water volumes in the tidal saltwater portion of the estuary. The general level of confidence in survey responses was lower for saltwater species than for freshwater bivalves.

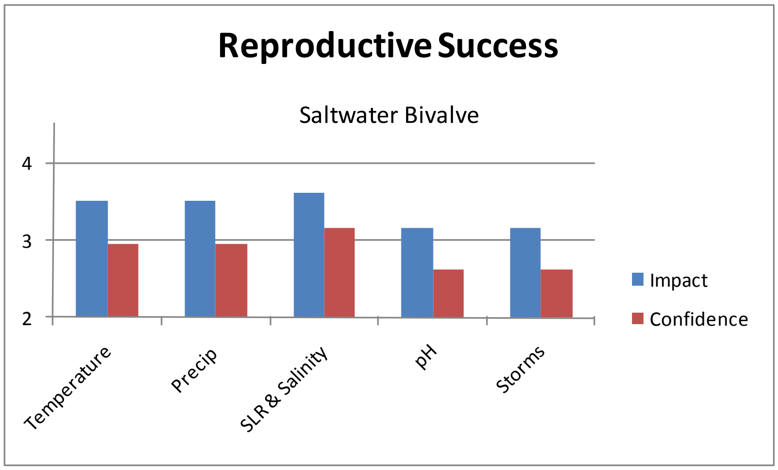


Figure 5-17. Relative levels of concern regarding the potential impact of changing physical and chemical conditions on **reproductive success** of saltwater bivalves (blue) and relative confidence in these projections (red.)

Changing climate conditions were viewed as potentially a concern with regard to some cause-effect relationships with saltwater species. For example, rising sea levels and salinity were seen as the greatest threat to the reproductive success of saltwater bivalves (Fig. 5-17,) presumably due to the beneficial effects of even small increases in salinity on the virulensce and prevalence of oyster diseases (Appendix O.) In contrast, changes in storminess were viewed with higher relative concern for habitat support (Appendix P.) In this case, the erosion of salt marshes and oyster reefs could diminish the availability or quality of suitable habitat for ribbed mussels and oysters, respectively (Appendix N.)

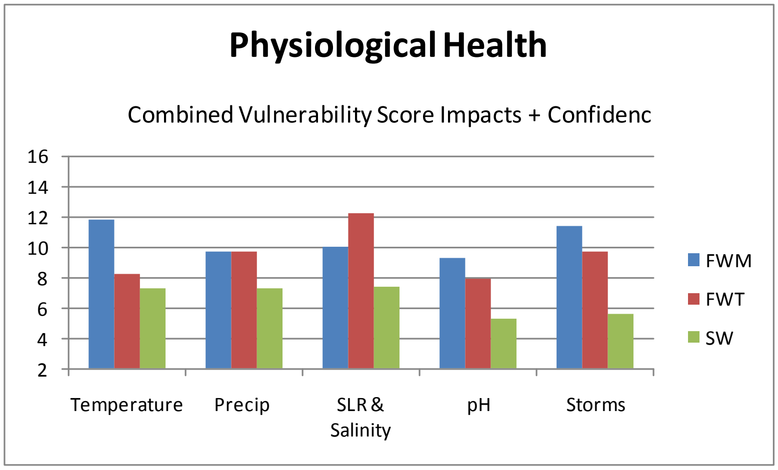


Figure 5-18. Relative vulnerability index for the **physiological health** of freshwater mussels (FWM), freshwater tidal bivalves (FWT) and brackish/saltwater bivalves (SW) exposed to future changes in temperature, precipitation, sea level/salinity, pH and storms by 2100.

5.5.4 Comparison of Bivalve Vulnerabilities

Composite vulnerability indices for freshwater mussels, freshwater tidal bivalves, and salt water bivalves were contrasted for each of the six fitness responses that might result from each of the five climate drivers.

Physiological Health. Highest concern (considering both the impact and confidence) for the physiological health of bivalves was expressed for freshwater tidal bivalves that might experience changes in sea level and salinity (Fig. 5-18.) Also meriting high concern were the effects of temperature and storminess on non-tidal freshwater mussels. The lowest concern was for pH effects on saltwater bivalves, and pH was not as much of a concern as other climate drivers for any of the bivalve groups. As noted in Section 5.5.3, there was more general concern for the effects of climate change on freshwater species over salt water species.

Reproductive Success. Threats to bivalve reproduction were rated as greater for freshwater species over saltwater species in all cases (Appendix P.) Reproduction by non-tidal species was viewed as more vulnerable than other for other bivalve groups to changes in temperature, precipitation, pH and storminess, whereas, sea level and salinity rise were a greater threat to reproductive processes of freshwater tidal species, as might be expected. Sea level and salinity rise was also seen as the greatest climate risk for reproduction by saltwater species.

Habitat Support. Survey respondents rated changes in storminess as the greatest overall threat to the habitat support aspect of the system (Appendix P.) Both freshwater mussels and saltwater bivalves appear to be most vulnerable to changes in storm intensity and frequency. The second greatest vulnerability to habitat support was viewed as changes in sea level and salinity for freshwater tidal bivalves. Precipitation changes were viewed as a particular concern for freshwater mussels living in streams that could experience high flows. Survey responses ranked changes in storminess, sea level/salinity, and precipitation as the greatest concerns for habitat support for bivalves.

Interactions with Invasive Species. Non-native species might become more invasive if changing climate conditions boosts their competitive advantage over native species, for example. Concern for this scenario was not as high as for other potential fitness metrics. The vulnerability index for invasive species interactions was <10 for all groups of native bivalves and for all climate drivers (Appendix P.) The greatest relative vulnerability was for freshwater tidal bivalves that experience changes in sea level and salinity, presumably because non-native species such as *Corbicula fluminae* and *Rangia cuneata* are perhaps slightly more tolerant of slightly saline conditions compared to native freshwater mussels.

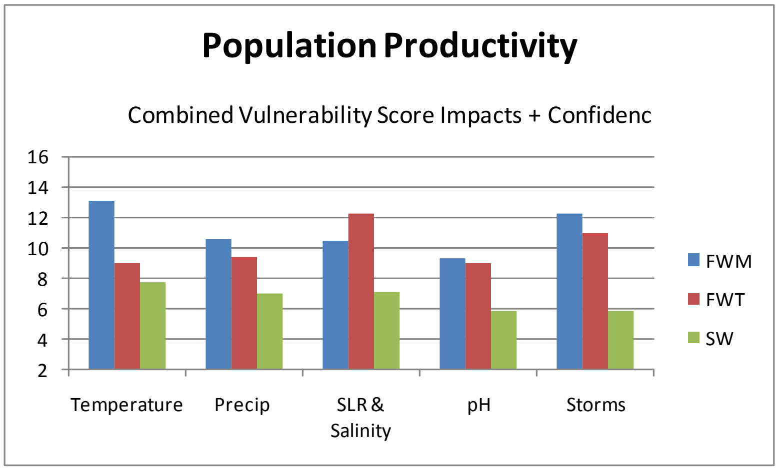


Figure 5-19. Relative vulnerability index for the **population production** of freshwater mussels (FWM), freshwater tidal bivalves (FWT) and brackish/saltwater bivalves (SW) exposed to future changes in temperature, precipitation, sea level/salinity, pH and storms by 2100.

Population Productivity. Overall productivity by bivalve populations was rated as most vulnerable to changes in temperature for freshwater mussels, followed by storminess effects on freshwater mussels, followed by sea level and salinity changes affecting freshwater tidal bivalves (Fig. 5-19.) Similar to most other fitness responses, freshwater tidal bivalves were perceived as most vulnerable to sea level and salinity rise.

Shifts in Species Composition or Ranges

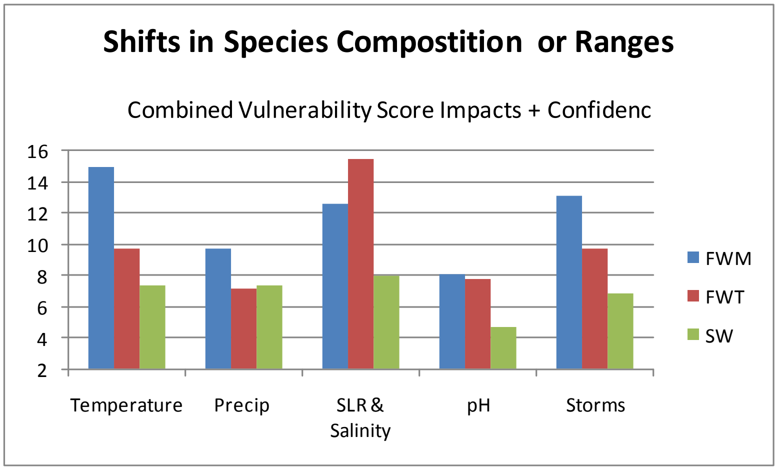


Figure 5-20. Relative vulnerability index for shifts in **species composition or ranges** of freshwater mussels (FWM), freshwater tidal bivalves (FWT) and brackish/saltwater bivalves (SW) exposed to future changes in temperature, precipitation, sea level/salinity, pH and storms by 2100.

The vulnerability of species ranges and composition was the most variable of the fitness metrics, ranging in vulnerability index between about 4 and 15 (Fig. 5-20.) The greastest vulnerability in species composition and range was rated to be for freshwater tidal bivalves threatened by increases in sea level and salinity, followed closely by the potential risk of higher temperatures on assemblages and ranges for freshwater mussels. Salinity intrusion into the freshwater tidal reaches of the mainstem Delaware River and other tidal tributaries is expected to constrain the range of habitat for freshwater-adapted species. While this may seem to benefit some saltwater species, which would see an increase in appropriate salinity conditions, sea level rise and salinity pose additional threats even for salt-tolerant animals (Appendix N) Even freshwater mussels living in non-tidal areas could be threatened by sea level and salinity rise; e.g. if small non-tidal creeks and impoundments get converted to tidal waters, or if diadromous fish that serve as larval hosts are impaired by these climate drivers. Changes in sea level, strominess, and temperature appeared to be the top concerns for bivalve species composition and ranges.

Taken together, vulnerability indices generated by the Bivalve Work Group survey suggested that there was greater concern for the effects of climate change on freshwater mussels living in both non-tidal and tidal areas than for saltwater-tolerant species living in Delaware Bay. In part, this result may have been due to the balance of expertise of survey respondents since more freshwater mussel experts responded to the survey than marine species experts, leading to lower confidence in projected risks to marine species. In part, however, this reflects key differences in the life history strategies of these different groups of bivalves. Saltwater species and invasive species living in the freshwater tidal zone are able to easily disperse and colonize new areas if environmental conditions change; whereas, freshwater mussels require fish hosts for larval dispersal and those hosts are subject to numerous man-made and natural barriers. In addition, the flashy nature of non-tidal freshwater habitats makes them more vulnerable to extremes in conditions compared to the larger-bodied tidal waters.

5.6 Bivalve Shellfish - Adaptation Options

Restoration activities such as planting and seeding juveniles represent examples of adaptation tactics that could become increasingly important with changing climate for maintaining and restoring bivalve populations (Fig. 5-21,) as well as building overall ecosystem resilience. In this context, many activities that have traditionally been viewed as "restoration" can also be considered as "climate adaptation" activities. Respondents to the Bivalve Work Group survey rated the feasibility and effectiveness of ten types of potential adaptation tactics that were described in Section 5.3.3 in terms of their ability to offset vulnerabilities of bivalves living in the three areas: freshwater mussels in non-tidal areas, freshwater tidal bivalves, and saltwater bivalves.

Figure 5-21. Shellplanting is a successful tactic for boosting recruitment and enhancing oyster populations in Delaware Bay.

Table 5-5. Relative effectiveness and feasibility of ten adaptation options for addressing vulnerability of freshwater non-tidal mussels (FWM), freshwater tidal bivalves (FWT), and brackish/saltwater bivalves (SW) to projected shifts in **temperature** by 2100.

	Combined Scores - Effectiveness + Feasibility		
	FWM	FWT	SW
Monitor/Research Vulnerability Impacts	Highest	Highest	Med-High
Hatchery Propagation and Restocking of Populations	Med	Med-High	Med-Low
Transplants of Broodstock to Expand Ranges	Med	Med	Med-High
Metapopulation Expansion for Common Species	Med	Med-Low	
Restoration of Extirpated Rare Species	Low	Low	
Dam Removals to Assist Dispersal on Fish Hosts	Med-High		
Assisted Migration (of southern species) to Fill Open Niches	Low	Low	
In-stream and/or Riparian Habitat Enhancements	Highest	Med-High	
Water Quality Management	Med	Med-High	Med
Water Quantity (Flow) Management	Med	Med	Med
Shellplanting on Seed Beds (Oysters)			Highest
Shellplanting or Living Shorelines Along Marshes/Tributaries			Med-High

5.6.1 Adapting to Temperature Changes

Although monitoring and research is not a direct measure to benefit populations of bivalves, this activity was rated as most important for addressing the vulnerability to projected temperature changes (Table 5-5,) especially in freshwater systems that may experience greater temperature changes than saltwater areas. Studies will be needed to identify specific assemblages most at risk and to prioritize other adaptation measures that can be taken. Therefore, monitoring and research will facilitate more effective and efficient climate adaptation.

In saltwater areas, two adaptation tactics were viewed as more important than monitoring and research: metapopulation expansion and water quality management. An example of matapopulation expansion might be the creation or augmentation of oyster reefs in areas that might be more sustainable in the future. Water quality management could be important to ensure that food quality and quantity are sufficient for bivalves and that these animals are not impaired by contaminants that could become more problematic under higher temperatures.

In contrast, the restoration of extirpated rare species and assisted migrated of southern species (i.e., for freshwater mussels) was not regarded as promising for offsetting temperature stresses, by comparison. Much more effective or feasible measures appear to exist to help freshwater mussels adapt to temperature rises, such as the removal of fish passage impediments and enhancements to instream and riparian habitats. Hatchery propagation and transplantation of vulnerable freshwater mussels was also seen as moderately hopeful for addressing temperature vulnerabilities.

5.6.2 Adapting to Precipitation Changes

Besides monitoring and research, the best adaptation tactics to address precipitation changes appeared to differ among bivalve groups (Table 5-6.) Water quality management was seen as having the greatest promise for addressing the effects of precipitation changes on freshwater mussels, whereas, in-stream and riparian enhancements appeared most hopeful for freshwater tidal bivalves. In contrast, flow management was seen as a beneficial option for averted precipitation effects on saltwater species. There was considerable variability in adaptation option rankings for this climate driver.

Table 5-6. Relative effectiveness and feasibility of ten adaptation options for addressing vulnerability of freshwater non-tidal mussels (FWM), freshwater tidal bivalves (FWT), and brackish/saltwater bivalves (SW) to projected shifts in **precipitation** by 2100.

	Combined Scores - Effectiveness + Feasibility		
	FWM	FWT	SW
Monitor/Research Vulnerability Impacts	Highest	Highest	Highest
Hatchery Propagation and Restocking of Populations	Med-Low	Med-Low	Med-Low
Transplants of Broodstock to Expand Ranges	Med-Low	Low	Med
Metapopulation Expansion for Common Species	Med-Low	Low	
Dam Removals to Assist Dispersal on Fish Hosts	Med		
Restoration of Extirpated Rare Species	Low	Low	
Assisted Migration (of southern species) to Fill Open Niches	Med	Low	
In-stream and/or Riparian Habitat Enhancements	Low	Med-High	
Water Quality Management	Highest	Med-Low	Med-Low
Water Quantity (Flow) Management	Med-Low	Med	Med
Shellplanting on Seed Beds (Oysters)			Med-High
Shellplanting or Living Shorelines Along Marshes/Tributaries			Med-High

5.6.3 Adapting to Sea Level and Salinity Changes

As with other climate drivers, monitoring and research was rated as the most beneficial adaptation option for addressing projected changes in sea level and salinity (Table 5-7.) Management of water flow was viewed as one tactic to help freshwater species adapt to salinity and sea level rise. For saltwater species, management of water quality was seen as a top option, however it is unclear what this means specifically. Hatchery propagation, transplants and metapopulation expansion were also viewed as having potential for addressing sea level and salinity vulnerabilities to saltwater bivalves.

Table 5-7. Relative effectiveness and feasibility of ten adaptation options for addressing vulnerability of freshwater non-tidal mussels (FWM), freshwater tidal bivalves (FWT), and brackish/saltwater bivalves (SW) to projected shifts in **sea level and salinity** by 2100.

	Combined Scores - Effectiveness + Feasibility		
	FWM	FWT	SW
Monitor/Research Vulnerability Impacts	Med-High	Highest	Highest
Hatchery Propagation and Restocking of Populations	Med-Low	Med-Low	Med-High
Transplants of Broodstock to Expand Ranges	Med-Low	Med-Low	Med-High
Metapopulation Expansion for Common Species	Low	Med-Low	
Restoration of Extirpated Rare Species	Low	Low	
Dam Removals to Assist Dispersal on Fish Hosts	Med		
Assisted Migration (of southern species) to Fill Open Niches	Low	Low	
In-stream and/or Riparian Habitat Enhancements	Med-Low	Med	
Water Quality Management	Med-Low	Med-Low	Med-Low
Water Quantity (Flow) Management	Med	Med	Med-Low
Shellplanting on Seed Beds (Oysters)			Med-High
Shellplanting or Living Shorelines Along Marshes/Tributaries			Med

5.6.4 Adapting to pH Changes

Acidity was considered as the least worrisome of the five climate drivers, as judged by survey respondents (Section 5.5.) This is fortunate because few of the adaptation options were viewed as very helpful in addressing the vulnerability to pH changes. Beside monitoring and research, water quality management was expressed as potentially effective at helping saltwater bivalves, but it is not clear how this would be implemented.

5.6.5 Adapting to Storminess Changes

The management of water quantity (flow) and instream or riparian habitat enhancements were viewed as having high potential for addressing problems for freshwater mussels that might be caused by changes in storm intensity or frequency (Table 5-8.) This makes sense because storms will likely lead to high flows, causing erosion and bed transport. Instream and riparian projects can buffer these effects and careful flow management through reservoirs or stormwater control can alleviate peak flows. In contrast, bivalves living in freshwater tidal areas were not perceived as potentially benefitting from these actions and no actions besides monitoring and research were rated as highly effective.

There appear to be more adaptation tactics available that might be effective at helping saltwater species adapt to changes in storminess. Metapopulation expansion, rare species restoration, and broodstock transplants were all deemed highly effective. This likely reflect the belief that oysters, mussels and clams may need refugia from severe weather, and projects to seed them into these areas would help to establish such protected areas.

5.6.4 Adaptation Options Compared Among Climate Drivers

In general, a greater number of moderately effective adaptation tactics appear available to address bivalve vulnerabilities resulting from changes temperature and storminess, as compared to precipitation, pH and sea level/salinity. The utility of different tactics will vary depending on the region of the estuary and the specific vulnerabilities that exist there. For example, management of river flows is probably the only effective tactic at averting the effects of salinity on freshwater mussels that reside nearest the saline reaches of the tidal freshwater prism; however, improvement in habitat for these animals in upper freshwater tidal areas (i.e., toward Trenton) could help to offset losses due to sea level and salinity rise. Similarly, higher salinities threaten oysters because oyster diseases are more virulent and prevalent in warmer, saltier conditions. Creation of new reefs and oyster stocking in areas of low salinity might create refugia from diverse climate change impacts. There is considerable overlap in many of these adaptation options.

Table 5-8. Relative effectiveness and feasibility of ten adaptation options for addressing vulnerability of freshwater non-tidal mussels (FWM), freshwater tidal bivalves (FWT), and brackish/saltwater bivalves (SW) to projected shifts in **storminess** by 2100.

	Combined Scores - Effectiveness + Feasibility		
	FWM	FWT	SW
Monitor/Research Vulnerability Impacts	Highest	Highest	Med-High
Hatchery Propagation and Restocking of Populations	Med-Low	Med-Low	Med
Transplants of Broodstock to Expand Ranges	Med-Low	Med-Low	Med-High
Metapopulation Expansion for Common Species	Med-Low	Med-Low	
Restoration of Extirpated Rare Species	Low	Low	
Dam Removals to Assist Dispersal on Fish Hosts	Med-Low	Low	
Assisted Migration (of southern species) to Fill Open Niches	Low	Low	
In-stream and/or Riparian Habitat Enhancements	Highest	Med-High	
Water Quality Management	Med	Med-Low	Med-Low
Water Quantity (Flow) Management	Highest	Med-High	Med
Shellplanting on Seed Beds (Oysters)			Highest
Shellplanting or Living Shorelines Along Marshes/Tributaries			Highest

5.7 Additional Information

The survey by the Bivalve Work Group represented a first step in the characterization of various vulnerability concerns and adaptation options (Appendix P.) However, statistical analyses of survey responses showed that in most cases the average relative rankings were not statistically different due to high variability and low sample sizes. Therefore, additional information was obrtained to help fill information gaps, prioritize future actions, and guide decision-making. Analysis of past datasets was used to strengthen future projections for one ecologically significant bivalve(Section 5.7.1; Appendix O.) In additional, tradeoffs between potential natural capital benefits on climate adaptation investments is examined in Section 5.7.2; Appendix Q.) Future research will still be needed to strengthen the scientific basis for climate adaptation plans for bivalve resources.

5.7.1 Oyster Populations in Delaware Bay: Past, Present and Future

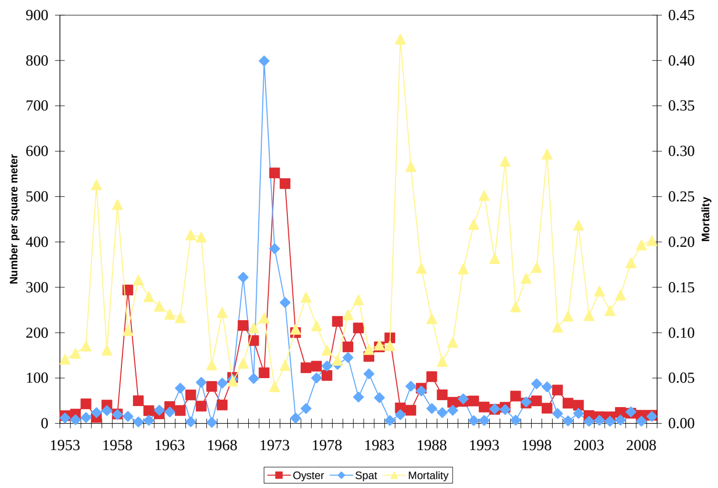


Figure 5-22. Bay wide oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

Extensive historical data on the population size of New Jersey oyster beds exist dating back more than fifty years. Oyster population trends were examined in relation to concurrent temperature and salinity records to discern whether these climate drivers have changed during this span, and if so, to determine if they correlated with oyster population health and the location.

There have been substantial changes in the oyster resources in Delaware Bay since the beginning of monitoring in 1953. Since then MSX (*Haplosporidium nelsoni*) and dermo (*Perkinsus marinus*) became epizootic in the bay in 1957 and 1989, respectively. Since their initial proliferation MSX has had a second epizootic in 1985, which apparently allowed the oyster population to develop some resistance (National Academy of Science, 2004). Dermo remains a significant factor with periodic epizootics. The distribution of these two diseases is affected by temperature and salinity (Burreson, et al., 1994, Dungan and Hamilton, 1995, Ford, 1985, Ford and Haskin, 1988, Haskin and Ford, 1982, Soniat, 1985). Over time, oyster populations have peaked and waned primarily in response to the diseases that impact them. Mortality and low spat settlement have substantially reduced oyster populations over time (Fig. 5-22.)

Oysters exist along a salinity gradient and can be found across the bay and in tidal tributaries and marshes. The main locations for the New Jersey oyster beds are shown in Figure 5-23. Analysis of historical data shows that there has been an upbay shift in oyster population distribution over time. This is most likely related to salinity, which effects oysters both directly, and indirectly through the diseases that effect them. However, many other factors also impact the distribution of oysters across the estuary.

River flow, temperature and salinity effect spat development and mortality in a way that is difficult to predict. The relationship between these variables changes over time and across the estuary. However, overall, the Upper Central region has been more sensitive than the Central region to temperature, salinity and river flow, probably because it has been less affected by disease. This suggests that any increase in disease related mortality in this region will have a greater impact that in the Central region.

Vulnerability of Oysters to Climate Change. Analysis of past data suggests that the following pieces of information must be factored into oyster vulnerability analysis.

- The oyster population in Delaware Bay is more limited by disease than by recruitment.
- The geographic configuration of the Delaware Estuary (narrow above the Upper Central region) means that, while the oyster resource can migrate up estuary in response to increased salinity, the total population of oysters could decline due to loss of area. Over 80% of the area occupied by the seed beds is in the Central and Upper Central portions (Table 1). The potential for lateral expansion of the estuary due to sea level rise would not be sufficient to provide equivalent areas for reef expansion.
- Seasonality is important for projecting climate change effects. The earlier the spring warming, the longer the warm period tends to last, leading to higher resulting salinity and greater possibility for dermo to become epizootic. If sea level rise affects the salinity in Delaware Bay as much as is predicted in the Chesapeake Bay (1.4 to 3.2 psu) (Najjar et al 2010), and this is coupled with reduced summer river flows, the probability for increased dermo induced mortality is higher. If this mortality occurs it will most likely result in more severe losses over the Upper Central portion of Delaware Bay. In one example estimate, projected changes in flow, temperature and salinity suggest that a drop of 71% in oyster population size will occur in the Upper Central region by 2100, balanced in part by an increase of 38% in the Upper region (little change in lower regions.) Overall, this estimate yields a 21% drop in the seed bed oyster population to 0.888 x 10^9. These potential decreases could greatly reduce oyster harvest.

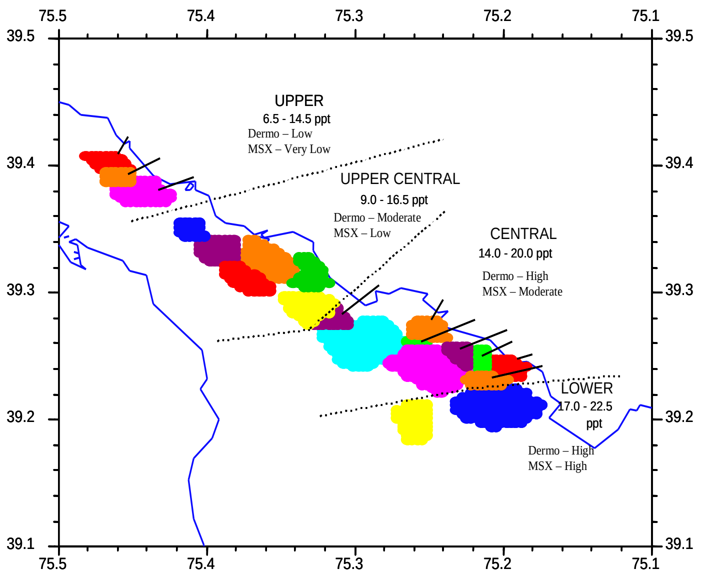


Figure 5-23. Location of New Jersey seed beds of *Crassostrea virginica* in relation to salinity and disease susceptibility.

Feature Box: Sea Level Rise and Oyster Disease

Eastern oysters have been historically important along the eastern seaboard and continue to be important today. Despite dramatically reduced populations, they still form an important commercial fishery, a growing aquaculture industry and remain important to the ecology of coastal ecosystems. During the past six decades oysters have been plagued by two devastating parasitic protozoans: *Haplosporidium nelsoni* causes MSX disease and *Perkinsus marinus* causes Dermo disease, both of which are lethal to oysters, but of no consequence to humans. The predominant factors controlling these diseases are temperature and salinity. Populations are responding positively to MSX by developing resistance, but such is not the case for Dermo. Oysters can live throughout the estuarine environment in salinities from 5 to 35 psu, but tend to do best in mesohaline waters of 10-25 psu. In general, as salinity increases, so does the intensity of MSX and Dermo. Dermo also tends to increase with temperature. As a result, the lower salinity regions further up an estuary tend to act as a refuge from disease. Hence, as climate change warms water and pushes higher salinity waters up estuaries, disease pressure is expected to follow. Oysters will likely respond by move further up estuary, but the amount of habitat available usually decreases as estuaries become more constricted further upstream. This combination suggests that oyster populations may decline further as sea level continues to rise. *–David Bushek*

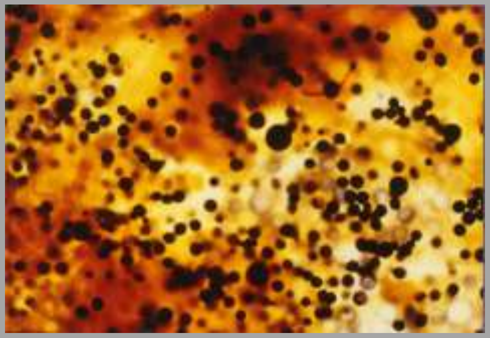


Figure. Black spots indicate Dermo infested

- The timing and intensity of droughts and rainfall events is also important for projecting climate change effects. It is likely that under the scenario just described, the resource would decline even further if a 1960’s or 1980’s drought is superimposed on these potential climate change salinity increases. These effects could be potentially offset by changes in the timing and intensity of rainfall events.

Based on past data which documented a shift in the bulk of the oyster population from the Central to the Upper Central beds, it is plausible to predict a continued shift upbay even though there are fewer suitable areas in the narrower upper region. Any factor that increases mortality up bay from its current position will therefore reduce the population simply because of the limited area of bay bottom involved. Since oyster reefs are an important habitat type for the Delaware Estuary, cascading ecological effects would likely follow if substantial loss of reefs occurred in the Upper Central part of the bay.

The net overall response of the oyster population to changing climate is difficult to predict, and other factors could be important as well. For example, the increase in water volume brought about by sea level rise may alter important hydrodynamic relationships in the estuary, also potentially affecting oysters in myriad ways. The Delaware Estuary is typically a well mixed system (Sharp et al. 1986), but the added volume and increased temperature could lead to greater stratification (Naijar et al. 2010). Increased winter and spring river flow due to wetter winters could benefit spat settlement. However, increased advection due to stratification could increase salinity which would increase mortality, potentially reducing spat set in the following year.

Adaptation Options for Oysters. Analysis of past data suggests that Oysters will not disappear from the Delaware Estuary, but their populations and regional density may shift and these shifts may be dramatic. It also suggests that the following pieces of information be factored in to the analysis of oyster adaptations.

- The importance of shell to the oyster resource cannot be overemphasized. Powell et al. (2003) reported that the half life for oyster shell in Delaware Bay was on the order of 5 to 10 years and that in order to sustain harvest it will be essential to continue to replenish shell removed from the system. One way to compensate for loss of high quality oyster grounds in higher salinity areas would be.to increase the areal extent of the oyster grounds in lower salinity areas. This could be done with shelling programs, but shell is a precious resource and such programs are expensive.

- An impediment to performing oyster restoration and climate adaptation project is the concern over human health if reefs are developed in areas closed to commercial harvest but still potentially subject to poachers. Many low salinity areas have degraded water quality.

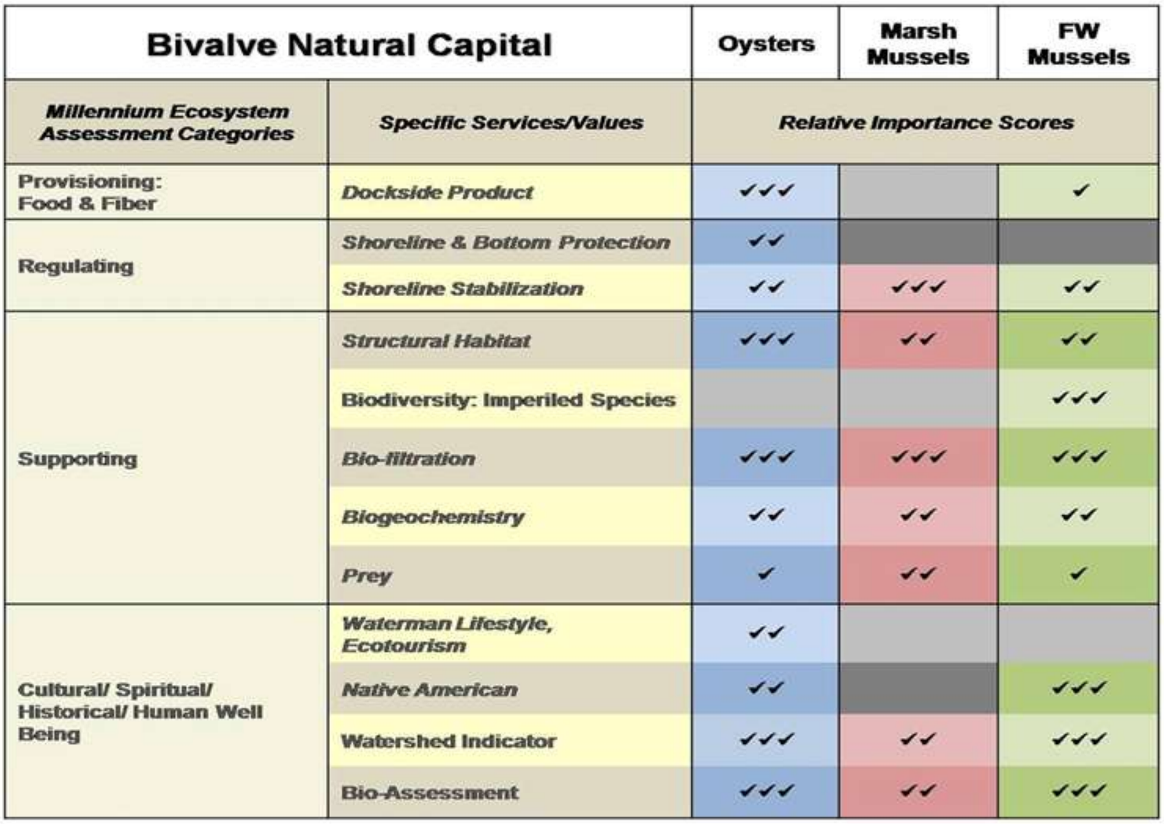
- Aquaculture could also be utilized to assist with adaptation to climate change. Converting the current oyster production system to more intensive aquaculture could augment harvests, and aquaculture can also facilitate genetic selection to promote disease resistance.

Figure 5-24. Freshwater mussels often aggregate in nature, as seen here in an Oregon river (photo: J. Brimbox, Confederated Tribes of the Umatilla.) Densities of up to 70 mussels per square meter were recorded in the lower Brandywine River, PA (Kreeger, unpublished.)

5.7.2 Natural Capital of Bivalves in the Delaware Estuary Watershed

As summarized in Table 5-9 below, bivalve shellfish in the Delaware Estuary watershed perform a diverse array of ecosystem services, and each of these services represents “natural capital” that can be considered as similar to capital values for built infrastructure, and publicly traded goods and services. Oysters (*Crassostrea virginica*), which are a subtidal species living mainly on reefs in Delaware Bay, are valued for their commercial, habitat and biofiltration services. Marsh mussels (a.k.a., ribbed mussels, *Geukensia demissa*,) are an intertidal species that lives in salt marshes and are valued for their biofiltration and shoreline stabilization services. Freshwater mussels (13 species, e.g., *Elliptio complanata*) are valued for their biofiltration services and biodiversity. All of these bivalves were once more prominent than they are today, and they are increasingly threatened by continued watershed development, disease, system alterations, and climate change (see below).

Table 5-9. Summary of the relative natural capital values for three example **bivalve mollusks living in the Delaware Estuary watershed, with key** ecosystem goods and services grouped in categories from the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005.)



Bivalve Natural Capital		**Oysters**	**Marsh Mussels**	**FW Mussels**
Millennium Ecosystem Assessment Categories	***Specific Services/Values***	***Relative Importance Scores***		
Provisioning: Food & Fiber	***Dockside Product***	✓✓✓		✓
Regulating	***Shoreline & Bottom Protection***	✓✓		
	Shoreline Stabilization	✓✓	✓✓✓	✓✓
Supporting	***Structural Habitat***	✓✓✓	✓✓	✓✓
	Biodiversity: Imperiled Species			✓✓✓
	Bio-filtration	✓✓✓	✓✓✓	✓✓✓
	Biogeochemistry	✓✓	✓✓	✓✓
	Prey	✓	✓✓	✓
Cultural/ Spiritual/ Historical/ Human Well Being	***Waterman Lifestyle, Ecotourism***	✓✓		
	Native American	✓✓		✓✓✓
	Watershed Indicator	✓✓✓	✓✓	✓✓✓
	Bio-Assessment	✓✓✓	✓✓	✓✓✓

There are societal and ecological reasons for maintaining large populations of filter feeders in aquatic ecosystems. Where abundant (e.g., Fig. 5-24,) they help to maintain water quality, stabilize substrates, decrease erosion, and create beneficial habitat complexity. Some species such as oysters are also commercially and historically important. As filter-feeders, they are effective at accumulating many classes of contaminants and so they are very useful in assessing water and sediment contamination in specific areas and for specific time periods. In fact, they are world renowned "sentinel bioindicators," meaning that the health of individual bivalves and assemblages of bivalves can directly indicate the health of the aquatic ecosystem.

Filter-feeding represents one of the most important ecosystem services provided by bivalves. Large volumes of water must be processed to remove sufficient food to meet the bivalves' nutritional demands. They generally filter all forms of small particles and what they do not use mostly gets bound in mucous and deposited as nutrient-rich particles on the bottom. These biodeposits have the net effect of fertilizing the bottom, benefitting benthic algae, plants, and macroinvertebrates. Removal of particles from the water column also benefits bottom plants and algae by improving light penetration. In addition to filtering suspended solids and particulate nutrients from water, many species of bivalves are capable of removing and digesting bacteria and other pathogens which can threaten human health (Wright et al. 1982; Kreeger and Newell 1996). Although limited bivalve abundance data precludes rigorous estimates, the collective filtration of all bivalves in the Delaware River Basin plausibly exceeds 100 billion liters per hour (=100 million cubic meters per hour) during the summer (Appendix Q.).

To test whether natural capital concepts can help to inform climate adaptation planning in the Delaware Estuary, a subgroup of the Climate Adaptation Work Group performed a literature search to identify ecosystem services performed by our most abundant species of freshwater mussel: *Elliptio complanata.* Nine ecosystem services were identified: production, water clearance rate, suspended solids removal, chlorophyll removal, sediment enrichment, phosphorus remineralization, nitrogen remineralization, sediment stabilization, and provision of invertebrate habitat (Appendix Q.) Based on limited abundance data (W. Lellis, USGS; D. Kreeger, PDE; unpublished), the total population of *E. complanata* across the Delaware Estuary watershed is estimated to consist of about 4 billion adults (Kreeger unpublished.) This population size estimate was contrasted with literature information on rates of services. The current population of *E. complanata*, which appears greatly reduced in many areas relative to historic conditions, still appears to be capable of performing high levels of services that have a direct bearing on water quality and ecosystem functioning. These mussels collectively filter more than 30 billion cubic meters of water per year, for example.

We assume that populations of *E. complanata* will continue to decline without intervention. If this decline was a 15% loss of biomass by 2050, for example, associated services would decline by 0.37% every year (Appendix Q.) Acting now to protect and restore *E. complanata* could substantially decrease water quality impacts felt at 2050. Furthermore, since *E. complanata* populations appear well below their carrying capacity today, significant opportunity exists to improve water and habitat quality with restoration, potentially imparting more resilience to the system. Every year that no action is taken to avoid losses of *E. complanata*, the amount of investment required to replace lost services grows. More analysis is needed to determine the relevance of mussel population health for water quality management, but indications are that water quality standards could be more easily met for nutrients and other pollutants if greater investments were made in natural infrastructure such as mussel beds (Appendix Q.)

Augmentation of *E. complanata* and other bivalves represents a potentially effective tactic toward improving water quality, reaching environmental targets, and helping to build resilience in the face of changing climate. Since bivalves supply so many ecosystem goods and services, their presence and abundance in the system can be a barometer of overall environmental health and resilience to disturbance. Efforts to preserve and restore bivalve shellfish are therefore not only helpful for this specific taxonomic group but also promote buffering capacity and climate preparedness for the overall aquatic ecosystem.

5.8 Bivalve Shellfish - Synthesis

Climate change is likely to affect bivalve shelfish in many different ways in the Delaware Estuary. Some changes in physical and chemical conditions pose a great threat to animals living in the system's non-tidal lakes, streams and rivers than in the tidal estuary, whereas other climate drivers threaten estuarine species more than non-tidal species.

Not all projected effects are negative. Some species such as oysters might experience a longer growing season, eventually gain two recruitment events per year instead of one, and be able to colonize intertidal habitats that are currently not viable due to winter freeze kills. Oyster populations living in the Southeastern United States are large despite the high disease levels, warmer temperatures and high salinity. These same conditions promote disease related mortality in the Delaware Bay. The current hypothesis is that the growing conditions for Carolinian oysters fuels high productivity that enables populations to "outgrow" the disease pressure. At some point in the future, it is plausible that oysters in Delaware Bay might expand their range along the intertidal shorelines and experience similarly high productivity, assuming they also have access to sufficient high quality foods and water quality. On the other hand, in the short term oysters are vulnerable to even modest increases in salinity, without yet gaining the potential long-term benefits. Oysters will not disappear from Delaware Bay. But it is uncertain where they will be sustainable in sufficient numbers to support a commercial fishery since the main population biomass appears to be moving upbay into areas that are geographically constrained by narrower rivers.

With the exception of this hypothetical "Carolinian oyster" scenario, we expect there to be far more losers than winners in terms of bivalve mollusk responses to climate change. The most imperiled bivalves are the diverse species of freshwater mussels (unionids) that inhabit lakes, streams and rivers. These animals are already the most imperiled of all fauna and flora within both the Delaware River Basin and the nation. Habitat degradation and alteration and water quality degradation appear to be the main factors bringing most of these species to the brink, with most native species being extirpated from most of their historic range and population declines and fragmentation being seen for the few "common" species. Nevertheless, even the current vestigial mussel assemblage appears capable of performing important ecosystem services that might help maintain water quality, and they therefore merit attention for both conservation and ecosystem reasons.

To reproduce and disperse naturally, freshwater mussels require fish hosts for their larvae. The presence of dams and other barriers to fish passage short circuits the life history strategy of these animals and impedes any natural means for species distributions to shift northward with changing climate. In contrast, estuarine species are able to readily disperse their planktonic larvae and colonize new areas.

Changes in physical conditions are also likely to be more oscillatory for species that live in smaller volumes of water, such as flashy streams. Like all animals, bivalves have physiological tolerance limits for temperature, pH and salinity. Therefore, while the effects of climate change on basic metabolic and production rates of bivalves may change incrementally with gradual changes in average environmental conditions, short exposures to extreme high temperatures, low pH and saltier water are likely to be more damaging.

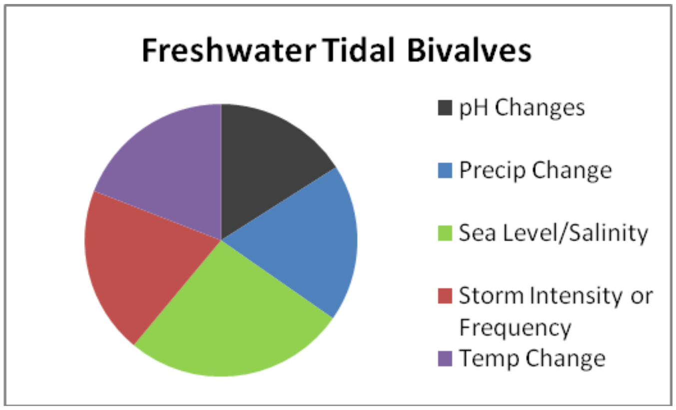


Figure 5-25. Relative vulnerability of freshwater tidal bivalves to changes in five climate conditions.

Changes in temperature and storminess (frequency or intensity) appear to pose the greatest threats to freshwater mussels, whereas salinity and sea level rise pose high threats to estuarine species. This is especially true for bivalves adapted to the Delaware Estuary's unique freshwater tidal zone. All five climate drivers examined in this study were viewed by a panel of experts as posing at least some threat to bivalves (e.g., see Fig. 5-25 for freshwater tidal bivalve vulnerabilities.)

Table 5-10. Top five vulnerabilities of bivalve mollusks to climate change (Delaware watershed), ranked by the Bivalve Work Group.

Ranking	Vulnerability
1	Storm Effects on Freshwater Mussels
2	Sea Level and Salinity Effects on Freshwater Tidal Bivalves
3	Temperature Effects on Freshwater Mussels
4	Precipitation Effects on Freshwater Mussels
5	Sea Level and Salinity Effects on Saltwater Bivalves

The top five climate change vulnerabilities for bivalves in the Delaware Estuary watershed are summarized in Table 5-10, considering all available information examined in this study.

In order to adapt to climate change, greater attention will need to be paid to the current plight of our bivalve resources. Management of these living resources is governed by an outdated paradigm that seeks to sustain or restore them for mainly conservation or exploitation reasons. They are viewed as animals that can be affected by environmental conditions, but they are not currently valued for all of their beneficial effects ***on*** environmental conditions. As ecosystem engineers that build their own habitat to the benefit of many other species, beds of mussels and reefs of oysters could also be managed as habitat. Moreover, their diverse ecosystem services should be appreciated and incorporated into broader watershed management, such as related to water quality and flow (e.g. for achieving TMDLs.)

The top five climate adaptation options for sustaining or enhancing bivalves in the Delaware Estuary watershed are summarized in Table 5-11, considering all available information examined in this study. This list does not include monitoring and research activities, which were the top recommended adaptation activity as judged by survey respondents.

Table 5-11. Top five adaptation options to assist bivalve mollusks in adapting to climate change in the Delaware watershed, ranked by the Bivalve Work Group.

Ranking	Adaptation Tactic
1	Plant Shell for Oysters
2	Propagate all Bivalves and Seed New Reefs/Beds
3	Restore Riparian Buffers for Freshwater Mussels
4	Manage Water Flow to Minimize Effects of Flooding on Freshwater Mussels and Salinity on Oysters and Freshwater Tidal Bivalves
5	Maintain Water Quality for all Bivalves

One current impediment to managing sustaining populations of bivalves is a lack of funding. Despite very successful outcomes, the oyster shellplanting project in Delaware Bay recently ran out of funding. A minimum of $1 million per year is needed to maintain positive shell balance and thereby sustain the oyster resource. Attempts to restore freshwater mussels using new hatchery-based propagation technologies also remain largely unfunded here and across the nation. Monitoring is needed to track changes in bivalve populations. Currently, there are only limited survey data available for freshwater mussels in many areas of the watershed, and the apparent "kingpin" of basin-wide water processing, the ribbed mussel, has never been surveyed extensively despite apparent losses due to eroding marsh habitats.

Additional impediments to climate adaptation activities for bivalves are policy barriers and insufficient scientific information to inform decision-making. For example, current regulations prohibit interstate transfers for many species of freshwater mussels, but in some cases the sole remaining genetic broodstock that could be drawn upon to restore species ranges might exist in one state or another within the Delaware River Basin. More science is also needed to understand the potential advantages and disadvantages of assisted migration, which represents a potential tactic to help freshwater mussels shift ranges northward since human structures (dams) and increasingly salty estuaries block natural migration. Policies to protect human health such as the ban on oyster restoration in closed waters also represent challenges for climate adaptation because some of the best growing areas for oysters in the future exist in areas that are closed to harvest. New tactics such as shellfish-based living shorelines are promising for helping to cut marsh loss while also benefitting bivalves, but it is still easier to get a permit to build a bulkhead than to create a living shoreline in Delaware Bay.

5.9 Bivalve Shellfish – Recommendations for Next Steps

The following recommendations were provided by the Bivalve Work Group to help sustain bivalve mollusk resources in the Delaware Estuary watershed.

1. Plant shell to restore oyster populations. Shell planting on oyster beds has proven to be a successful way to increase recruitment and restore populations of oysters. A model for shell planting has been developed by the Delaware Bay Oyster Restoration Task force and is in place, but just in need of funding.

2. Restore or create shellfish reefs/beds where feasible. This will require first assessing stream/shoreline information to identify where such activity can be supported. High quality areas where current populations are below the system's carrying capacity are candidates for restoration/augmentation of the population for biodiversity and/or biomass. Promising areas that are not currently colonized are good candidates for reintroducing native species. Adaptations tactics that can be employed include hatchery propagation and outplanting of seed, relocation of gravid broodstock, and habitat enhancements (e.g. dam removals, riparian reforestation, living shorelines, reef creation, oyster shell planting.) Up-bay expansion of oysters and reintroduction of extirpated mussels are two examples.

3. Develop indicators to track impairments (and possibly benefits) to bivalve shellfish and to help guide management of the system for salinity balance (through flow management) and water quality. Indicators such as the presence of oysters living in intertidal areas should be included, as well as the monitoring to support them. Monitoring should include surveys for the presence and abundance of significant species, resulting in a geospatial inventory of locations of high abundance. Scientific analysis should be directly relevant for managers, helping to bolster our understanding of the benefits of these species to watershed health as well as the consequences

of watershed management on these habitats. This information is critical to carrying out the other recommendations presented here.

4. Educate the broader resource management community regarding the importance of bivalves for watershed health and also the effects of water quality and quantity on bivalves. Much of the future for bivalves hinges on having suitable flows, water quality, and food conditions. In turn, bivalves can help managers attain water quality targets.

A coordinated, watershed-based approach to bivalve shellfish restoration and climate adaptation is warranted because healthier bivalve communities in the non-tidal areas benefit estuarine species, and vice versa (by helping diadromous fish). When linked, fresh- and salt-water species restoration will yield the best natural capital outcomes. Science-based restoration can be strategically positioned to provide pollutant interception, erosion control, sustainable harvests, and climate adaptation.