Appendix N

Ecologically Significant Bivalve Molluscs of the Delaware Estuary

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I. Importance of Bivalves

There are societal and ecological reasons for maintaining large populations of filter feeders in aquatic ecosystems. Where abundant, 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. Filter-feeders are effective at accumulating many classes of contaminants and so they are useful in assessing water and sediment contamination in specific areas and for specific time periods. The health of individual bivalves and assemblages of bivalves can directly indicate the health of the aquatic ecosystem.

The goal of this report is to provide an orientation to the types of bivalves living in the Delaware Estuary watershed as a basis for assessing climate change effects on this living resource group. Special attention is therefore paid to the environmental needs and associated ecosystem services for species of bivalves that are abundant in the system.

In the Delaware Estuary and its watershed, there are approximately 60 species of bivalve mollusks living in headwater streams and lakes, large streams and rivers, freshwater tidal areas, and in the brackish and saline portions of the Estuary (Table N-1). All but two of these are native to the basin. Although a few species are benthic deposit-feeders, most native species are filter-feeders.

The commercial and historical importance of bivalves in the Delaware Estuary is well established (see also Kraeuter, Appendix O). It is said that there were more millionaires per square mile in Port Norris NJ, the seat of the oyster shellfishery in Delaware Bay, than anywhere else in the United States at the peak of the oyster industry. Oysters were one of the area's most important natural resources until stocks diminished during the 20th century due to a variety of factors, including overfishing earlier in the century and two non-native oyster diseases in the second half of the century. Today, oysters remain a viable commercial resource in Delaware Bay, and recent shellplanting restoration activities have helped to sustain this shellfishery as well as provided significant ecological benefits.

Filter-feeding represents one of the most important ecosystem services provided by bivalves. Large volumes of water must be processed to remove sufficient microparticulate material to meet the bivalves' nutritional demands. They generally filter out all forms of small particles, and then they sort captured particles prior to and after ingestion. Sorted particles that are not used are bound in mucous and rejected as pseudofeces and feces, both of which are deposited on the bottom. Filtering and biodeposition by bivalves has the net effect of removing small suspended particles from the water column and transferring them to the bottom, where they can then be used by other plants and animals.

Filter-feeding (aka "biofiltration") rates vary seasonally, among species, and with differing environmental conditions; however, in general all species of bivalves in the Delaware watershed are highly effective, filtering more than 1 liter of water per hour per gram dry tissue weight, during the warmer times of the year. Collectively, they are estimated to filter at least 100 billion liters of water every hour during summer across the watershed (Kreeger, unpublished.)

Bivalve mollusks can be grouped taxonomically, but for the purposes of this report they are grouped based on the areas of the Delaware Estuary watershed within which they reside. Bivalves living in non-tidal areas above the fall line and in freshwater tidal areas (salinity <0.5 ppm) mainly consist of native species freshwater mussels (Order Unionidae) and the non-native Asian clam (*Corbicula fluminae* Muller, 1774). Bivalves living in tidal areas vary mainly depending on the salinity zone that they reside in, oligohaline (salinity 0.5-5 ppm), mesohaline (5-18 ppm), and polyhaline (>18 ppm). Tidal species are also grouped as either subtidal (live below mean low water) or intertidal (live between mean low and high water,) which may be important for some climate change factors such as sea level rise.

The array of ecosystem goods and services furnished by three example bivalves in the Delaware Estuary watershed is summarized in Table N-2, grouped according to the categories used in the Millennium Ecosystem Assessment (2005). Oysters (*Crassostrea virginica* Gmelin, 1791) are an example of a subtidal polyhaline species living mainly on reefs in Delaware Bay. Oysters are valued mainly for their commercial, habitat, and biofiltration services. Marsh mussels (a.k.a., ribbed mussels, *Geukensia demissa* (Dillwyn, 1817) are an intertidal polyhaline and mesohaline species that lives associated with tidal salt marshes, and they are especially valued for their biofiltration and shoreline stabilization services. Freshwater mussels (up to 14 species, such as *Elliptio complanata* Lightfoot , 1786) 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 climate change and continued watershed development.

Table N.1. Bivalve shellfish in the Delaware Estuary, with salinity, range and relative abundance.

#	Scientific Name	Common Name	‰ Salinity	Range	Relative Abundance
1	*Alasmidonta heterodon*	Dwarf Wedgemussel	0	FW	rare
2	*Alasmidonta undulata*	Triangle Floater	0	FW	rare
3	*Alasmidonta vaircosa*	Brook Floater	0	FW	rare
4	*Anodonta implicata*	Alewife Floater	0	FW	rare
5	*Elliptio complanata*	Eastern Elliptio	0	FW, FWT	locally abundant
6	*Lampsilus cariosa*	Yellow Lampmussel	0	FW, FWT	uncommon
7	*Lampsilis radiata*	Eastern Lampmussel	0	FW	rare
8	*Lasmigona subviridus*	Green Floater	0	FW	rare
9	*Leptodea ochracea*	Tidewater Mucket	0	FW, FWT	rare
10	*Ligumia nasuta*	Eastern Pondmussel	0	FW, FWT	locally common
11	*Margaratifera marfaratifera*	Eastern Pearlshell	0	FW	rare
12	*Pyganodon cataracta*	Eastern Floater	0	FW, FWT	locally common
13	*Strophitus undulatus*	Squawfoot	0	FW, FWT	rare
14	*Elliptio dilitata**	Spike	0	FW	rare
15	*Elliptio fisheriania**	Northern Lance	0	FW	rare
16	*Corbicula fluminae*	Asian clam	0-2	FW, FWT	abundant
17	*Rangia cuneata*	Atlantic rangia	0-10	FWT	abundant
18	*Brachiodontes recurvus*	Hooked mussel	08-15	SW	emphemeral abundant
19	*Geukensia demissa*	Ribbed Mussel	05-30	SW	abundant
20	*Barnea truncata*		13-25	SW	uncommon
21	*Cyrtopleura costata*		13-25	SW	uncommon
22	*Amygdalum papyria*		08-25	SW	uncommon
23	*Mya arenaria*	Soft-shelled Clam	05-20	SW	locally common
24	*Macoma balthica*		10-25	SW	locally common
25	*Bankia goudi*		15-35	SW	uncommon
26	*Teredo navalis*	Common shipworm	15-35	SW	uncommon
27	*Macoma tenta*		15-25	SW	uncommon
28	*Solen viridis*		13-28	SW	uncommon
29	*Ensis directus*	Jack knife clam	13-28	SW	locally abundant
30	*Siliqua costata*		15-25	SW	uncommon
31	*Tagelus plebeius*	Stout razor clam	13-30	SW	uncommon
32	*Mulinia lateralis*		13-28	SW	uncommon
33	*Corbula contracta*		20-30	SW	uncommon
34	*Crassostrea virginica*	American oyster	13-30	SW	abundant
35	*Solemya velum*		17-25	SW	uncommon
36	*Mysella planulata*		15-25	SW	uncommon
37	*Anomia simplex*		15-30	SW	uncommon
38	*Pitar morrhuana*		17-30	SW	uncommon
39	*Mercenaria mercenaria*	Hard-shell Clam	15-30	SW	locally common
40	*Tagelus divisus*		15-25	SW	uncommon
41	*Lyonsia hyalina*		18-30	SW	uncommon
42	*Tellina agilis*		13-35	SW	uncommon
43	*Tellina versicolor*		20-35	SW	uncommon
44	*Anadara ovalis*		15-30	SW	uncommon
45	*Argopecten irradians*	Atlantic bay scallop	20-35	SW	uncommon
46	*Gemma gemma*		18-30	SW	uncommon
47	*Anadara transversa*		18-30	SW	uncommon
48	*Noetia ponderosa*		17-30	SW	uncommon
49	*Mytilus edulis*	Blue mussel	20-35	SW	emphemeral common
50	*Petricola pholadiformis*		15-29	SW	uncommon
51	*Pandora gouldiana*		23-35	SW	uncommon
52	*Astarte undata*		25-35	SW	uncommon
53	*Nucula proxima*		25-35	SW	uncommon
54	*Venericardia borealis*		25-35	SW	uncommon
55	*Cerastoderma pinnulatum*		25-35	SW	uncommon
56	*Donax fossor*		29-35	SW	uncommon
57	*Abra aequalis*		29-35	SW	uncommon
58	*Yolida limatula*		25-35	SW	uncommon
59	*Spisula solidissima*	Atlantic surf clam	27-35	SW	locally common
60	*Arctica islandica*	Ocean quahog	30-35	SW	uncommon

** Chesapeake Basin species that might exist in lower Delaware River Basin*

Table N-2. 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 (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	✓✓✓	✓✓	✓✓✓

II. Ecologically Significant Species

For the purposes of the Partnership for the Delaware Estuary, an "**Ecologically Significant Specie**s" is any animal or plant species that meets at least one of the following criteria:

- Functional Dominant Species - an exceptionally abundant species that performs a significant portion of ecological functions; e.g., many bivalves. Loss of functional dominants would result in a fundamental shift or collapse of ecological functions,
- Structural Dominant Species - a species that is sufficiently abundant to be habitat-forming across significant areas of bottom; e.g., oyster reefs and mussel beds. Loss of structural dominants would impair other species that use those habitats.
- Keystone Species - a species that is not necessarily abundant but which can govern abundance of dominant species or ecological processes; e.g., predator species such as starfish or whelks that can control bivalve populations,
- Imperiled Species - a native species that is rare and vulnerable to extirpation from the watershed or extinction; e.g., dwarf wedgemussel, a federal listed endangered species,
- Hallmark Species – a native species that is especially associated with the watershed; e.g., horseshoe crabs in Delaware Estuary, or a
- Commercial Species - animals and plants that provide significant economic benefits to a watershed are public trust resources; e.g., oysters in Delaware Bay.

In the Delaware Estuary, bivalves tend to be functional and structural dominants wherever they are abundant. In addition, species like oysters are commercially important, and most of our native freshwater mussel species are imperiled to some degree. Therefore, as a taxonomic assemblage, bivalve mollusks meet multiple criteria for being ecologically significant species in this "National "Estuary. There a host of additional bivalves that occur throughout the system, but are rarely biomass dominants. Incidental species also exist that are not imperiled, and these are not inventoried in this report.

To qualify as a functional or structural dominant, bivalves need to be sufficiently abundant to materially affect bulk biogeochemical, benthic-pelagic coupling, sediment stabilization, or habitat support processes. Abundance is determined by the bulk biomass of the bivalve population, which can be achieved by having very high numbers of small individuals or moderate/high numbers of larger sized animals. In addition to dominating functional processes, functional dominant bivalves therefore also tend to dominate the faunal biomass, often outweighing all other animals combined.

II.1. Non-Native Species. Importantly, some non-native species have become very abundant in the Delaware Estuary watershed. The Asian clam, *Corbicula fluminae* (Müller, 1774) is a small-sized (< 2 cm shell height) non-native species that currently resides in high abundance in most freshwater areas of the watershed. Although more research is needed to understand the functional importance and invasive character of this species, it appears to meet the requirements of being a functional dominant and is therefore regarded as an ecologically significant species even as it is viewed as a pest.

II.2. Ecologically Significant Species in the Delaware Estuary Study Area. The study area for the National Estuary Program, the Partnership for the Delaware Estuary, is the lower 52% of the Delaware River Basin. This area covers 6,827 square miles, extending from the headwaters of the Schuylkill River Basin to the mouth of Delaware Bay, but does not include the mainstem Delaware River drainage basin above Trenton, NJ. Although the focus of the Program is this study area and especially the tidal portion, attention is given to the entire Delaware River Basin where scientific needs warrant. For example, dwarf wedgemussels are a federal endangered species which has been extirpated from the Program's study area but still can be found in the upper basin, and they are therefore considered ESS for the basin.

The most obvious of the ecologically significant bivalve genera in different zones of the Delaware Estuary study area are:

Freshwater – *Elliptio*, *Corbicula*
Oligohaline – *Rangia, Ischadium, Corbicula*
Mesohaline – *Crassostrea, Geukensia, Ischadium, Mya*
Polyhaline – *Crassostrea, Mercenaria, Geukensia, Tagelus, Mya, Ensis, Mytilus*

One other species that can occur in large numbers and biomass is *Mulinia lateralis* (Say, 1822), but high abundance of this species is temporally ephemeral.

As noted above, these ecologically significant species assist in maintaining water quality by removing phytoplankton and suspended materials from the water and depositing them on the bottom. This process augments nutrient recycling, at least locally. In the sections below, these ecologically significant species are discussed in order of their prevailing location within the watershed.

III. Freshwater Habitats

With the exception of the introduced species, *Corbicula fluminae*, all of the bivalve species living in the non-tidal watershed and the tidal freshwater zone are native species of freshwater mussels (Order: Unionoida), consisting of approximately twelve species of unionids (Family: Unionidae) and one margaratiferid species (Family: Margaratiferidae). Two additional species might reside in the Delaware portion of the watershed (Table N-3.) Of the thirteen species of freshwater mussels believed with certainty to be native to the Delaware Estuary, only one is regarded as common or secure on state heritage lists, and this is the eastern elliptio, *Elliptio complanata* (Lightfoot, 1786.)

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

The current status of native mussel species of the Delaware Estuary is symptomatic of the situation across North America. Freshwater mussels are the most imperiled of all the flora and fauna in the United States, which has more mussel biodiversity than anywhere else in the world (Williams et al. 1993.) Not only are we losing species and seeing ranges shrink, even the one species listed as common is becoming patchy in distribution and its overall population abundance and resilience appears to be in decline. Many tributaries of the Delaware Estuary are now devoid of all mussels, even common species, where they once held numerous species that occupied different ecological niches. For example, Ortmann (1919) extensively surveyed mussel distributions in Pennsylvania and recorded about seven species in the Delaware Estuary study area, such as in Darby, Chester, Ridley, and Brandywine Creeks, and the lower Schuylkill

River. Today however, only one species can be found above the head of tide in only a subset of these streams, and it is only located in a few reaches.

3.1 Freshwater Non-Tidal

Species of bivalves that require freshwater conditions 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. Some species historically inhabited both non-tidal and tidal freshwater habitats, but the current range for many is limited by the presence of large numbers of dams on tributaries. Despite trend in recent dam removals (PA is leading the nation in rate of dam removal), many species of native freshwater mussels appear to be continuing to decline (Fig. N-1). For example, as recently as 2000 a few live specimens of the creeper (*Strophitus undulatus* Say 1817) and eastern elliptio (*Elliptio complanata*) were found in White Clay Creek in PA, but extensive surveys by PDE staff during 2007-2009 failed to locate any live mussels.

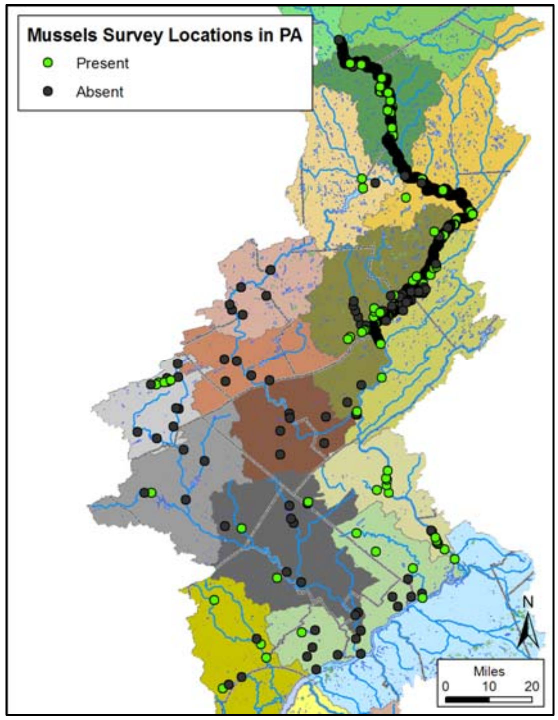

Figure N-1. Presence and absence of freshwater mussels in Pennsylvania locations where they were historically reported as surveyed by various researchers since 1980.

There are three bivalves that are considered ecologically significant species currently living in the freshwater non-tidal portions of the Delaware River Basin.

<u>*Elliptio complanata*</u>. A natural freshwater mussel assemblage typically consists of aggregated populations of several species, occupying different niches within the stream. This assemblage would collectively filter greater volumes of water, perform more ecosystem services, and likely be more resilient to disturbance than if only one species existed. In non-tidal areas of the Delaware Estuary and River Basin, the latter is the case. For example, in the upper mainstem Delaware River, >98% of the biomass and abundance of freshwater mussels is represented by *E. complanata* (W. Lellis, unpublished.) In streams of southeast PA, often *E. complanata* is the only species encountered.

Even though the current mussel population appears to be greatly reduced in the Delaware Estuary study area, the vestigial bed of *E. complanata* can have a measurable effect on water quality. For instance, the relic population of 500,000 *E. complanata* that still resides in a six-mile reach of the lower Brandywine Creek is estimated to filter >1 billion liters and remove 26 metric tons of dry suspended solids (TSS) each summer season (Kreeger, unpublished.) Approximately 4 billion *E. complanata* are estimated to reside in the Delaware River Basin today, and they collectively filter about 10 billion liters of water per hour in the summer. Still, many streams contain no mussels at all, and in streams such as the lower Brandywine the population of *E. complanata* appears to be old and may not be reproducing.

Although there are many reasons for the past and ongoing declines of our freshwater mussel taxa (Bogan 1993), one of the main problems is dams which block fish passage because mussels depend on fish hosts for larval metamorphosis and dispersal. It is currently thought that many streams have sufficiently improved in water quality and are capable of sustaining viable mussel populations, but there is no natural way for mussels to redistribute into those waters if dams block fish movements. Taken together, these observations suggest that the current remnant mussel population represents only a fraction of the system's carrying capacity for mussels. A current goal of the Partnership for the Delaware Estuary is restore the diversity, abundance, and distributions of the native freshwater mussel assemblage where possible as part of a watershed-wide bivalve restoration strategy aimed at improving water quality and meeting habitat restoration goals. This restoration program is first targeting *E. complanata* by attempting to expand its range back to earlier conditions and build population biomass through a mix of relocation and hatchery propagation tactics using genetic stocks indigenous to the program study area.

Alasmodonta heterodon (Lea, 1830.) One of our native freshwater mussels is a federal endangered species, dwarf wedgemussels, *A. heterodon* . The distribution of this species was once much wider across the watershed than it is today. For example, Ortmann (1919) reported finding dwarf wedgemussels in the Schuylkill Valley. Currently, it is found only in a few areas of the upper Delaware River. As a state and federal listed endangered species, *A. heterodon* is ecologically significant to the Delaware River Basin even though it is no longer found in the lower reaches and the study area of the National Estuary Program.

Corbicula fluminae. Collectively, *Corbicula* might represent the bulk of the filter-feeding biomass in the upper Estuary region where they may play a role in improving water quality and light penetration for submerged aquatic vegetation (Phelps 1994.) Asian clams are increasingly being valued as bioindicators of contaminants (Hartley and Johnston 1993; Phelps 1993). They also appear to be selectively preyed on by muskrats and might represent an important modern food resource for imperiled sturgeon, an ecologically significant fish species. On the other hand, Asian clams might be deleterious to native species indirectly through food competition or other factors.

Asian clams were first reported in the Delaware Estuary in the Trenton area in the early 1970s, and they quickly spread throughout the freshwater tidal and then up into non-tidal areas (Crumb 1977.) In recent years, Asian clams have periodically experienced mass mortality events, such as during March 2008 in a tidal tributary in New Jersey and in August 2008 in the Schuylkill River above Philadelphia. The cause for these events is not understood, but may be due to periodic food limitation or shifts in environmental conditions (Weitere et al. 2009.) During these incidents it became apparent just how dense *Corbicula* populations had become because of widespread foul odors and clogged water intakes by the decaying tissues of these animals. Currently, Asian clams are not valued and are viewed as a pest, and so they are not being targeted for conservation or climate adaptation analyses. However, based on their abundance and presumed importance for key ecological functions they are considered ecologically significant species of the Delaware Estuary.

3.2 Freshwater Tidal

The freshwater tidal zone of the Delaware Estuary extends about 65 river miles along the Delaware River from Trenton NJ to approximately Wilmington DE, including many tidal areas of larger tributaries such as the Schuylkill and Christina Rivers. Once fringed with extensive freshwater tidal wetlands, today only approximately 5% of these marshes remain.

Ecologically significant bivalves of the freshwater tidal zone include two of the same species found in non-tidal areas, *E. complanata* and *C. fluminae*. In addition, a second non-native clam species can be found in this zone, *Rangia cuneata.*

Figure N-2. Freshwater mussel sampling locations, summer 2009.

Importantly, recent discoveries suggest that the freshwater tidal portion of the Delaware Estuary harbors far more diversity of native freshwater mussel species than the non-tidal portion, presumably because of the prevalence of dams and other fish passage blockages on tributary streams. Paradoxically, some of the best diversity in the entire watershed may exist in the urban corridor around Philadelphia (Figure N-2.) In spring and summer 2009, PDE staff and partners performed reconnaissance surveys for freshwater mussels in shallow subtidal, mud and sand-dominated areas in the vicinity of Philadelphia as part of the Delaware Estuary Benthic Inventory study. Using an oyster dredge on an EPA vessel, approximately 40 dredge tows were made over a span of 3 days. This effort was augmented with casual surveys from shore and via wading. Although taxonomic verification is still needed, preliminary analysis suggests that six species of native Unionid mussels were found as either live specimens or shells from recently dead mussels:

- Eastern Elliptio, *Elliptio complanata*
- Yellow Lampmussel, *Lampsilis cariosa* (Say 1817)
- Tidewater Mucket, *Leptodea ochracea* (Say 1817)
- Eastern Pondmussel, *Ligumia nasuta* (Say 1817)
- Eastern floater, *Pyganodon cataracta* (Say 1817)
- Squawfoot, *Strophitus undulatus*

One of these species, *L. ochracea*, was believed to possibly be extirpated from the state of Pennsylvania, and several others are listed as threatened or vulnerable. Two species, eastern pondmussels and eastern floaters, appeared to be sufficiently abundant in areas to warrant more study of their ecosystem service contributions, perhaps being future candidates for ecological significance status.

Contingent on verification, this discovery could be important because it may mean that the only remaining genetic broodstock for multiple native species resides in vulnerable urban areas. If these taxa can be protected, new propagation and restoration tactics may soon be able to draw on these populations to restore species back into their former non-tidal streams and rivers. More study is clearly warranted of freshwater mussels in the non-tidal zone.

Elliptio complanata. Based on PDE surveys in 2009, the eastern elliptio appears to be sufficiently abundant in the freshwater tidal zone to be considered an ecologically significant species. As described above, where abundant populations of *E. complanata* have significant beneficial effects on diverse ecosystem processes and water quality in non-tidal streams and rivers, and there is no reason to doubt this isn't similarly true in tidal freshwater areas.

The role of bivalve populations in regulating water quality and ecosystem processes will depend largely on two factors: 1) their overall population biomass and 2) the "contact time" between their biomass and the total water volume passing by per unit time. The tidal freshwater prism of the Delaware Estuary is believed to be the largest in the world. The population biomass of freshwater mussels such as *E. complanata* is mainly relegated to shallow subtidal habitats along shorelines and islands. More study is needed to quantify the population biomass of *E. complanata* and other native Unionid species (e.g., *Pyganodon cataracta, Ligumia nasuta)* in this area in order to estimate their ecosystem effects.

Corbicula fluminae. In bottom surveys between Trenton and the C&D Canal during 1992 and 1993, bivalves comprised more than 80% of the total infaunal biomass, vastly outweighing polychaetes, oligochaetes, and various benthic arthropods combined (Environmental Consulting Services, 1993.) Based on similar sampling during the Delaware Estuary Benthic Inventory in 2008, it is likely that *C. fluminae* dominated the bivalve biomass. At some stations during this 2008 survey, grab samples of the bottom consisted almost entirely of live Corbicula. "Corbicula beds" have been captured on recent acoustic surveys of bottom conditions as part of the Delaware River and Bay Benthic Mapping Project by the Delaware Coastal Program, appearing to cover extensive areas of flats, such as near Marcus Hook PA. In this area, there is speculation that these dense beds of Asian clams may be helping to improve water clarity, thereby benefiting submerged aquatic vegetation (SAV) which appears to be increasing in abundance. Exploratory surveys by PDE and EPA staff as part of the DEBI revealed extensive SAV beds along the shorelines near the mouth of the Schuylkill River, around Tinicum Island, and near the mouth of Darby Creek. Sturgeon might also derive benefits from feeding on *Corbicula* in this freshwater tidal zone. Based on their sheer abundance and assumed importance for water quality and ecology, *C. fluminae* is regarded as an ecologically significant species in the freshwater tidal zone of the Delaware Estuary.

Rangia cuneata (Sowerby, 1831). The introduced clam species, *R. cunaeata*, is also considered to be ecologically significant in the Delaware Estuary. Adult *Rangia* are much larger than *Corbicula*, averaging 3-6 cm in shell height. They appear to be abundant in both the freshwater tidal and oligohaline areas of the Estuary. In areas of the Chesapeake Bay where *C. fluminae* and *R. cuneata* are abundant, water quality models indicate that the bivalves significantly reduce phytoplankton concentrations when hydraulic residence time is high, leading to 14-40% removal of carbon, 11-23% removal of nitrogen, and 37-84% removal of phosphorus (Cerco and Noel 2010.)

IV. **Oligohaline Habitats** (0.5 to 5 ppm Salinity)

The oligohaline portion of the Delaware Estuary is characterized by consistently very low salinity. This zone is fringed extensively with freshwater tidal marshes in the upper portion and brackish marshes in the lower portion.

4.1 Intertidal Oligohaline

There are no data to suggest that bivalves exist in the intertidal zone of oligohaline areas of the Delaware Estuary, and certainly do not attain significant population abundance intertidally. Limited faunal surveys of freshwater tidal marshes have been conducted, and no intertidal bivalves were found (ANSP 1998, Kreeger Unpubl.) Therefore, we conclude that no ecologically significant species exist in the intertidal oligohaline zone of the Estuary.

4.2 Subtidal Oligohaline

Little is known about benthic bivalves living subtidally in the oligohaline and freshwater tidal zones of the Delaware Estuary. Most studies of benthic communities in this area have used gear that is inefficient at collecting bivalves, which may be large in individual body size but dispersed spatially. Surveys of benthic communities tend to target small-sized, numerically abundant macroinvertebrates, primarily animals such as insects, annelids and arthropods. Grab sampling gear is used for these surveys; e.g., the National Coastal Assessment, the 2008 cruise of the Delaware Estuary Benthic Inventory which targeted soft bottom habitats. Grab samplers only survey a very small area of bottom and they are therefore very inefficient at capturing numerically sparse animals of a large size. For sampling larger areas, dredge and sled samplers are needed such as the oyster dredge that was found useful for sampling large bivalves in 2009 in the freshwater tidal zone (see above.) However, this gear has never been used in the oligohaline zone of the Delaware Estuary to our knowledge. Nevertheless, sufficient information exists to indicate that one ecologically significant bivalve species inhabits the subtidal oiligohaline zone of the Delaware Estuary.

Rangia cuneata. Subtidal oligohaline sections of the Delaware Estuary including tidal creeks in marsh areas can be inhabited by the clam *Rangia cuneata* (Sowerby, 1831). This species can be locally abundant and an important contributor of the overall biomass.

The lower salinity part of this zone can also be inhabited by the exotic *Corbicula fluminae* (see above). This species can occur in very high densities in the freshwater tidal zone but is limited in the oligohaline zone by periodic increased salt concentration. Until more information is obtained, this species is not regarded as an ecologically significant species in this zone.

V. **Mesohaline** (5 to 18 ppm Salinity)

The mesohaline portion of the Delaware Estuary is characterized by variable partial salinity. This zone is fringed extensively with brackish marshes in the upper portion and salt marshes in the lower portion.

5.1 Intertidal Mesohaline

One bivalve species is ecologically significant in the intertidal mesohaline zone.

Geukensia demissa. Limited survey data exist to document the abundance and size class distribution of ribbed mussels in tidal marshes of the Delaware system, and these data are mainly from salt marshes fringing Delaware Bay (Daiber 1982, Kreeger, unpublished). Ribbed mussels have a remarkably broad tolerance range for both salinity (>70 ppt) and temperature (>56°C) for at least short durations (Lent 1969). The ideal salinity ranges between 12-30 ppt. Therefore, they can live in some mesohaline marshes but appear to be more dominant in polyhaline marshes (see below.)

Ribbed mussels are uniquely adapted to intertidal life in the detritus-dominated tidal marsh. They are perhaps the only bivalve in the world capable of digesting significant proportions of detritus derived from marsh plants (Kreeger et al. 1988, 1990). It is thought that they can do this in part because of their intertidal lifestyle whereby they have more digestion time when the tide is out and they are emersed. *G. demissa* actually grows faster when held intertidally compared to subtidally when they can feed all the time (Gillmor 1982.). The species is generally relegated to the intertidal zone because their thin shells make them vulnerable to predators such as blue crabs (Seed 1982.)

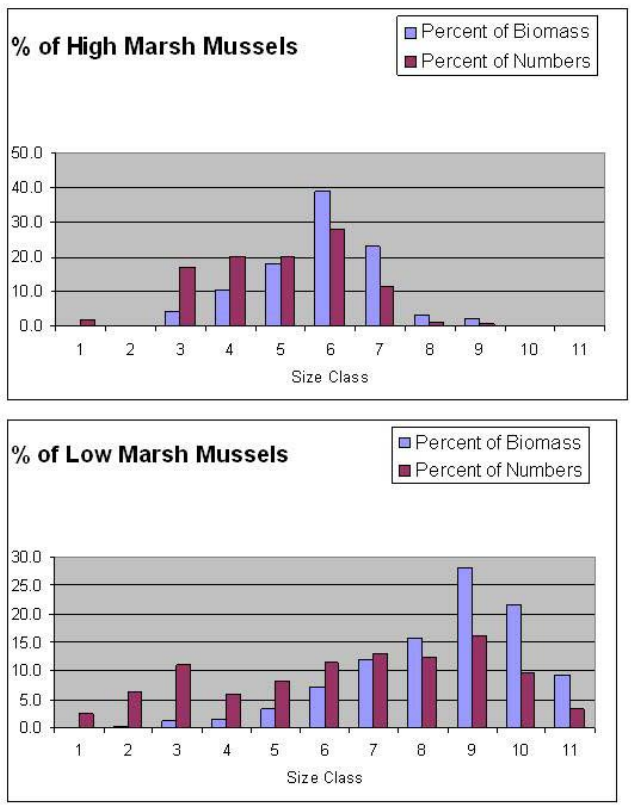

Figure N-3. Average densities and sizes (cm shell height) of ribbed mussels living in tidal marshes fringing the Broadkill River of lower Delaware (Kreeger unpublished.)

Ribbed mussels live in mutualism with vascular plants, most principally smooth cordgrass, *Spartina alterniflora* (Bertness 1984). The plants provide a surface (rhizomes) for mussels to attach, and the mussels produce nutrient-rich biodeposits that fertilize the plants. Both densities and sizes of *G. demissa* are greatest along the marsh edge (i.e., low marsh) where food is most plentiful (Fig. N-3). They live in lower densities across high marsh areas where they tolerate up to 16 hours of air exposure per day (Lent 1969.) The species is the only known bivalve that can respire aerobically when held out of water, and they exhibit air gaping behavior as a cooling tactic on warm days when the tide is out.

Ribbed mussels form dense beds on the edges of salt marshes where they bind tightly together and to the plant roots 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. The filter-feeding and biodeposition of these dense beds is thought to be so significant as to boost overall primary productivity of the tidal marsh due to the fertilizing qualities of the mussel deposits (Kuenzler 1961; Jordan and Valiela 1982).

Based on the best estimate of suitable tidal marsh habitat and abundance surveys, the collective filtering capacity of *G. demissa* in the Delaware Estuary is estimated at 60 billion liters of water per hour in summer, more than any other bivalve in the Delaware River Basin (Kreeger, unpublished.) Here and elsewhere along the eastern seaboard, they are regarded as a functional dominant species in intertidal mesohaline and polyhaline marsh habitats (Jordan and Valiela 1982; Kreeger and Newell 2001) and so they are considered an ecologically significant species of the Delaware Estuary.

5.2 <u>Subtidal Mesohaline</u>

One bivalve species, eastern oysters, is thought to be ecologically significant in the subtidal mesohaline zone. There are some other species that might actually be ecologically important, but which are poorly studied.

For example, the hooked mussel*, Ischadium recurvum* (Rafinesque, 1820), can be locally abundant and mixed with oysters, but there are no comprehensive data on distribution or abundance in the Delaware system.

There are limited reports of live *Mya arenaria* within the Delaware Bay system, but occasional individuals are found. The deep burrowing nature of this species prevents it from being sampled by any of the standard grabs, dredges or other gear. It is possible that significant populations exist in this or other portions of the estuary, but there is no information.

Hard clams, *Mercenaria mercenaria* (Linnaeus, 1758), is only a minor species in the mesohaline portion of Delaware Bay because of high turbidity and in this area it is at the lower end of its salinity tolerance.

<u>*Crassostrea virginica*</u>. Species such as oysters, *Crassostrea virginica*, are important for many reasons, as discussed above. Oysters support recreational and commercial fishing and aquaculture, thus offering a connection between our increasingly urban population and the natural system. Areas from which bivalve shellfish are harvested for consumption must meet the highest quality standards (even higher than swimming water quality) and thus bivalve shellfish are natural ambassadors for good water quality at the same time as directly helping to maintain water quality.

In addition to their importance for commercial and water quality reasons, reef forming species such as oysters also provide a hard substrate in an area of sand and mud bottom otherwise devoid of such structural components. The structure increases habitat complexity and offers other species a substrate in an otherwise inhospitable environment, leading to "biological hotspots" for increased diversity and abundance.

In the deeper waters of the mesohaline Delaware Estuary, *C. virginica* dominates the biomass of bivalve resources. Oyster reefs occur from Hope Creek to about Fortescue, NJ. Additional oyster assemblages are found in the tributaries (Fig. N-4). Current estimates are that oysters are near historic lows in the subtidal areas of Delaware Bay. The long term data set (from 1953) did not include beds above Round Island and the long term data comparisons are based on the data from Round Island to about Egg Island Point. The past year (2008) is the first year all of the beds above Round Island were sampled. Based on this recent survey of NJ seed beds, the current estimate of the oyster population size in the subtidal portion of the system is 1.571 x $x10^9$ oysters >20mm. Approximately 25% of these animals live in the mesohaline zone. Oysters are not surveyed on the leased grounds, in rivers or creeks on either side of the Bay. The Delaware reefs are much smaller in extent than those on the NJ side, and so there are probably about 2 billion oysters alive in the subtidal zone today, taken together.

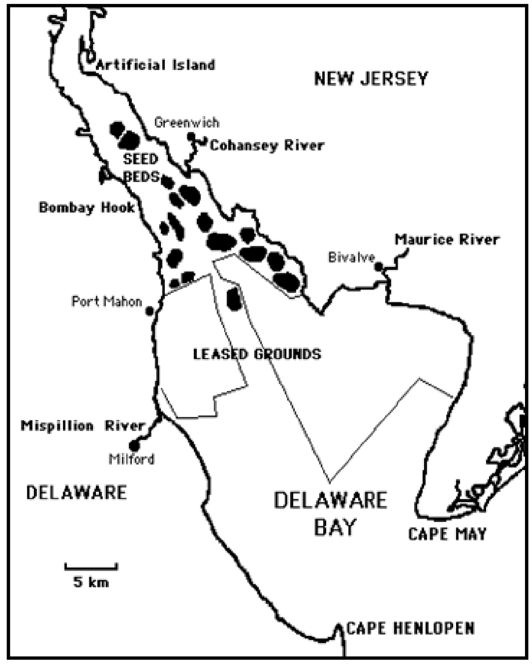

Figure N-4. Location of main seed beds of *Crassostrea virginica* in the Delaware Estuary.

The oyster beds exist along a salinity gradient, being party mesohaline and partly polyhaline. The salinity is a major factor in controlling oyster recruitment and survival. Two diseases that are virulent to the oyster: MSX, *Haplosporidium nelsoni* and Dermo, *Perkinisus marinus* are, in part, controlled by the salinity structure of the Estuary. In general, disease in the mesohaline portion is not a factor for the uppermost beds and is only at medium levels for the beds in the lower portion of this zone. The interactions between hard substrate, recruitment, predation and disease are the factors that control the abundance of oysters in any given portion of the Delaware estuary.

VI. **Polyhaline**– (18 to 30 ppm Salinity)

The polyhaline portion of the Delaware Estuary is characterized by consistently high salinity, greater than half full seawater. This zone is fringed extensively with salt marshes around Delaware Bay and along tidal tributaries such as the Mispillion and Broadkill Rivers in Delaware and the Maurice River in New Jersey. Here, bivalves become more characteristically marine in diversity.

6.1 Intertidal Polyhaline

One bivalve species is ecologically significant in the intertidal polyhaline zone, the same as for the mesohaline zone (ribbed mussels, see below).

Interestingly, oysters, *Crassostrea virginica*, do live in the lower intertidal zone of many of the same marshes. Here, young oysters tend to settle onto shells of the larger and older ribbed mussels that begin to slump into tidal creeks as marshes erode or as the collective growth and mass of mussel beds cause slumping edges. The intertidal distribution of oysters appears to be mainly set by winter temperatures since oysters cannot tolerate freezing conditions during emersion like ribbed mussels. In years following warmer winters, intertidal oysters appear to fare quite well, only to be eventually decimated by a winter freeze kill.

In addition to oysters, the intertidal polyhaline zone contains nuermous incidental species on mud flats which can become emersed on low tides, but little information is available to document these species or their abundances. Populations of hard clams (*Mercenaria mercenaria* (Linnaeus 1758), razor clams (*Tagelus plebeius* Lightfoot 1786, and *Ensis directus* Conrad 1843) and hooked mussels (*Ischadium recurvum* Rafinesque 1820*)* are reported from many of the intertidal flats of the lower bay. Blue mussels (*Mytilus edulis* Linnaeus 1758) are common on intertidal structures such as rock jetties and piers, but there is little natural hard substrate like this in the system.

Geukensia demissa (Dillwyn 1817). See intertidal mesohaline zone above for more information on this species. An average of 208,000 ribbed mussels >1 cm shell height were estimated to live in each hectare of tidal salt marsh (Kreeger unpublished, see Fig. N-3). Containing >200 kg dry tissue biomass per hectare, these filter-feeding mussels are certain to out-weigh all other fauna combined and are considered to be functional dominants in salt marsh ecology (Jordan and Valiela 1982). Limited surveys in southern NJ polyhaline marshes show similar densities. More survey data are needed to establish the landward and upbay distribution limits for *G. demissa*. Ribbed mussels are the ecologically significant species of bivalve in the intertidal polyhaline zone.

6.2 Subtidal Polyhaline

One bivalve species is ecologically significant in the intertidal polyhaline zone, the same as for the mesohaline zone (oysters, see below).

In this zone, the hard clam (*Mercenaria mercenaria*) can add substantially to overall biomass, but there are no data on the resource. Delaware Bay is not as significant a hard clam producer as the coastal lagoons and Raritan Bay in northern New Jersey. This may be due to the relatively high turbidity of the Delaware system and reduced productivity of the hard clam in areas where the suspended sediments exceed 20 mg/L for substantial periods.

There are a number of other large, deep-burrowing bivalves that can be expected in the subtidal areas of Delaware Bay, including *Tagelus plebeius, Mya arenaria* and *Ensis directus*. These deep burrowers are widely distributed both north and south of Delaware Bay and are mostly limited to the polyhaline region. There are few data to indicate whether they are more than locally important, and it is unclear if these species are ecologically significant as defined above. At least one study found high abundances of *Tellina* and *Ensis* in grab samples after a fresh set of juveniles (>2,500 and >25,000 m^{-2}, respectively; Haskin et al. 1978.) In that study, hard clams were reported to be more abundant in the upper end of the survey area than near the mouth of Delaware Bay. Blue mussels (*Mytilus edulis*) can also be found subtidally in Delaware Bay, but ephemerally due to predation or possibly high summer temperatures it is believed (Howe and Leathem 1984.)

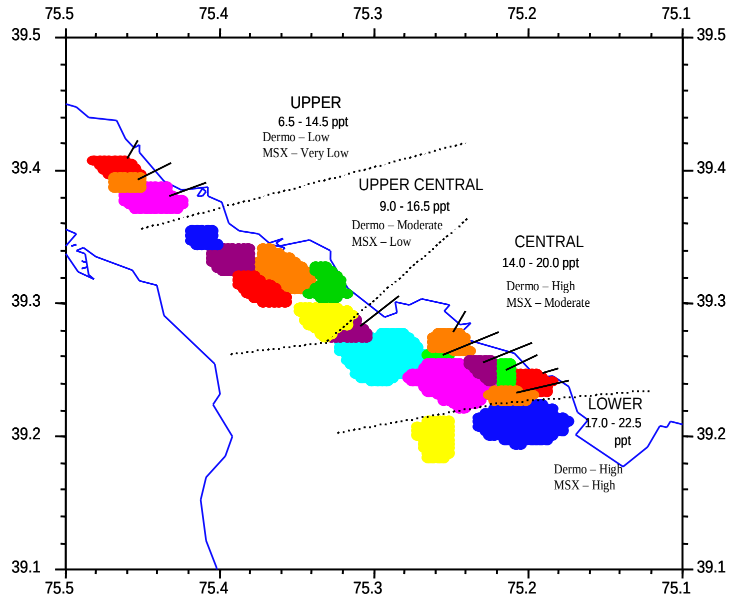

Figure N-5. New Jersey seed beds of *Crassostrea virginica* in relation to salinity and disease susceptibility.

Crassostrea virginica (Gmelin, 1791). In the deeper waters of the polyhaline Delaware Estuary the Eastern oyster is probably the dominant biomass of bivalve resources. Suitable environmental conditions occur across much of the subtidal polyhaline region, and additional oyster assemblages are found in the tributaries. The abundance of oysters below the seed bed area is largely unknown, but there are substantial known resources in the area near the mouth of the Maurice River. Additional oysters are scattered throughout the large area of the lower bay that is leased.

Although oysters can live in many of these lower bay areas, they generally do not mainly because of the indirect effects of high salinity favoring oyster diseases that are not native to the system. The interactions between hard substrate, recruitment, predation and disease are the general factors that control the abundance of oysters in any given portion of the Delaware Estuary, but disease has been the major driver over the past 50 years in higher salinity areas. Largely because of these diseases, oysters are currently estimated to be near historic lows in abundance (Kraeuter, Appendix O.) The salinity gradient is the major factor that controls oyster recruitment and survival.

The two diseases that are virulent to the oyster are MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinisus marinus)*, both of which are controlled in part by the salinity structure of the Estuary (Fig. N-5.) All of the oysters in the polyhaline region are infected with one or both of these diseases. Some resistance to MSX has developed in the native oyster population, but there is little evidence of resistance to Dermo. All of the seed beds in the polyhaline zone are designated "high mortality beds" and these beds and all other areas in the polyhaline area are subject to epizootic losses due to oyster disease (for more information see Kraeuter, Appendix O.).

VII. Summary

Sixty species of bivalves are described in this report as currently living in the aquatic habitats of the Delaware Estuary watershed. Of these, 13-15 species are native freshwater mussels, many of which are imperiled. Two are invasive non-native species that are currently very abundant. Eight species of estuarine/marine bivalves are discussed. Of these, only six are meet our criteria as ecologically significant species (Table N-4.)

As more is learned about the other species, some might warrant adding to this list. For example, some of our native freshwater mussel species may become so imperiled that they become ecologically significant based on conservation concerns over their extreme rarity. Some of our poorly studied deep burrowing estuarine species could be considered important as more is learned about their abundance and associated ecosystem services.

Table N-4. Six species of ecologically significant bivalve mollusks currently living in the Delaware Estuary watershed.

<table>
<tr><th>Freshwater</th><th>Oligohaline</th><th>Mesohaline</th><th>Polyhaline</th></tr>
<tr><td>Alasmidonta heterodon</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Elliptio complanata</td><td></td><td></td></tr>
<tr><td colspan="2">Corbicula fluminae</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Rangia cuneata</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Geukensia demissa</td></tr>
<tr><td></td><td></td><td colspan="2">Crassotrea virginica</td></tr>
</table>

7.1 Ecosystem Goods and Services

The general array of ecosystem goods and services furnished by three of our six ecologically significant species (ESS) was shown above in Table N-2. To illustrate the relative contributions of these three ESS to the ecology and water quality of the Delaware Estuary, Kreeger (unpublished) estimated their collective water processing capacity during summer temperatures based on their current estimated abundance, distribution, and associated physiological rate functions. The ribbed mussel, *Geukensia demissa*, was estimated to filter 60 billion liters per hour. Approximately 10 billion liters per hour was estimated to be filtered by *Elliptio complanata* and another 10 billion liters per hour by *Crassostrea virginica*.

Considering the enormous population of non-native *Corbicula fluminae* and *Rangia cuneata*, along with all of the incidental bivalve species, it is therefore reasonable to assume that more than 100 billion liters of water are currently filtered every hour by bivalve mollusks (=$1x10^8$ m^3 hr^{-1}). This represents about 2500 times the volume of freshwater entering the tidal estuary every hour (39,000 m^3 hr^{-1}; Pape and Garvine, 1982.) This comparison between the combined water processing capacity of bivalves and river inputs should not be construed as suggesting that these animals are “treating” that volume of water since not all filtered material is removed from the system and much of the water flowing through the system may never contact a bivalve. More rigorous analysis is needed to understand system hydrodynamics, residence times of water in the vicinity of bivalve populations, refiltration effects of bivalves, and so forth.

However, it is plausible to conclude that the combined water quality benefits provided by both native and non-native bivalves are substantial, not to mention the other services summarized in Table N-2.

7.2 Status and Trends of Bivalve Molluscs in the Delaware Estuary Watershed

Oysters and freshwater mussels were used as environmental indicators in the most recent State of the Delaware Estuary report (PDE, 2008). Oyster stocks were described as being in fair condition, capable of still supporting a viable commercial shellfishery but being greatly depressed relative to historic conditions. The trend in oyster populations was considered stable.

Freshwater mussels were assigned the lowest grade, continue to trend toward poor status overall. Most species of unionids are vulnerable to local extinction and are currently exitirpated from much of their former range in the Delaware Estuary watershed.

As we look to the future, climate change and continued watershed change will interact to challenge many of our native bivalve species. Continued growth in human populations and development of the watershed will increasingly tax our water resources. Current abundances of freshwater mussels appear directly correlated to the health of deciduous riparian forests, and their distributions are largely determined by fish passage. Therefore, there is hope that increased conservation and restoration of riparian areas, combined with dam removals and mussel propagation efforts, might stem the current losses of mussel species and population abundance.

Some aspects of climate change could provide modest benefits to some species freshwater mussels, since longer growing seasons could lead to increased productivity. However, higher temperatures also lead to higher maintenance energy demands, and it remains to be determined whether temperature rises might benefit some species. Cold-adapted species such as the eastern pearlshell, *Margaratifera margaratifera*, are likely to be extirpated from the Delaware Estuary; even now this species can only be found in a few locations below cold water, bottom release reservoirs. To make matters worse, the preferred fish host for *M. margaratifera* is the brook trout, which is also a coldwater species that is vulnerable to temperature rise. Without human help (e.g., assisted migration), more southern species will not be able to migrate north into the niches being opened up by species such as *M. margaratifera.* The effects of precipitation changes, pH, and other factors are still poorly understood. There is some evidence that warmer temperatures could be more beneficial to invasive species such as *Corbicula* than native unionids (Weitere et al. 2009), perhaps leading to competitive advantages.

In the tidal estuary, warmer temperatures and longer growing seasons are unlikely to significantly affect the bivalve species. Estuarine and marine species also have the advantage of broadcast dispersal strategy without impediments such as dams to interfere if southern species shift their distributions northward. As long as the estuary does not become fresher or unanticipated changes such as new diseases appear, many of species adapted to the mesohaline and polyhaline areas can be expected to maintain or increase their abundance within the system. The main threat to ESS is the potential need to shift oyster distributions up the estuary to follow the migrating salinity contours, which are controlled on the seaward side by disease-associated mortality at higher salinities. There is some uncertainty about the availability of suitable substrate for oyster reefs further northward in the system because the river constricts and much of the bottom is softer and deeper.

To predict future status and trends in bivalve populations and associated ecosystem goods and services, we must continue to learn lessons from past status and trends and work to fill vital data gaps regarding the current distribution of species in the system. Taken together, we estimate that freshwater mussels are probably the most vulnerable bivalves in the watershed in terms of both species and ecosystem services. However, at least two ecologically significant estuarine and marine species may also be in jeopardy. Ribbed mussels, which may be the most biomass dominant species in the system, are threatened with loss of the marsh habitat that they reside in due to sea level rise, erosion and limited ability for tidal marshes to retreat inland. Oysters, which are commercially important and provide diverse services, are threatened with rising salinity and lack of suitable habitat should they need to redistribute northward. More analysis and monitoring will be needed to improve our ability to assess changing conditions and manage these important resources wisely.

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