Climate Change and the Delaware Estuary

Three Case Studies in Vulnerability Assessment and Adaptation Planning

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Authors: **Danielle Kreeger**, Ph.D., Partnership for the Delaware Estuary
Jennifer Adkins, Partnership for the Delaware Estuary
Priscilla Cole, Partnership for the Delaware Estuary
Ray Najjar, Ph.D., Pennsylvania State University
David Velinsky, Ph.D., Academy of Natural Sciences of Philadelphia
Paula Conolly, Philadelphia Water Department Consultant
John Kraeuter, Ph.D., Rutgers University

Contributors: **David Bushek**, Ph.D., Rutgers University
Tracy Elsey-Quirk, Ph.D., Academy of Natural Sciences of Philadelphia
Tatjana Prša, Graduate Student, Villanova University
Kurt Philipp, Wetland Research Service
Sue Kilham, Ph.D., Drexel University

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Established in 1996, the Partnership for the Delaware Estuary is a non-profit organization based in Wilmington, Delaware. The Partnership manages the Delaware Estuary Program, one of 28 estuaries recognized by the U.S. Congress for its national significance under the Clean Water Act. PDE is the only tri-state, multi-agency National Estuary Program in the country. In collaboration with a broad spectrum of governmental agencies, non-profit corporations, businesses, and citizens, the Partnership works to implement the Delaware Estuary's Comprehensive Conservation Management Plan to restore and protect the natural and economic resources of the Delaware Estuary and its tributaries.

Table of Contents

List of Appendices

Climate Predictions

A. Najjar, R. "Analysis of Climate Simulations for us in the Climate-Ready Adaptation Plan for the Delaware Estuary." Pennsylvania State University, Department of Meteorology. December, 2009.
B. Najjar, R. "Potential Impact of Climate Change on Salinity of the Delaware Estuary." Pennsylvania State University, Department of Meteorology. March, 2010.
C. Najjar, R. "Analysis of heat waves in models and observations for the Delaware Estuary Watershed" Pennsylvania State University, Department of Meteorology. February, 2010.

Tidal Wetlands

F. Elsey, T. and D. Velinsky. "Tidal Wetlands Case Study: "Delaware Estuary Climate Ready Estuary Pilot, Vulnerability Assessment and Adaptation Planning." March 2010.
G. Industrial Economics Incorporated. "Application of Ecological and Economic Models of the Impacts of Sea-Level Rise to the Delaware Estuary" Industrial Economics Incorporated. March, 2010.
H. Velinsky, D., D. Kreeger and K. Philipp. Tidal Wetland Case Study Survey Results

Drinking Water

I. Conolly, P. and Thorpe, N. "Impacts of Climate Change on Drinking Water Supply: Findings from Existing Studies." December, 2009.
J. Thorpe, N. Drinking Water Resource List
K. Bennett, J. "Climate Change Impacts on Water Supply Wells in the Delaware River Estuary." Delaware Valley Regional Planning Commission. July, 2009
L. Bennett, J. "Conservation BMPs to Cut Demand of Potable Water" Intern synthesis of the Delaware Valley Regional Planning Commission. August, 2009.
M. Conolly, P. and P. Cole. Drinking Water Case Study Survey Results

Bivalve Shellfish

N. Kreeger, D. and Kraeuter, J. "Ecologically Significant Bivalve Mollusks of the Delaware Estuary." 2010
O. Kraeuter, J. "Oysters in the Delaware Bay – Climate Change." Rutgers Haskin Shellfish Research Laboratory. 2010
P. Kreeger, D. and P. Cole. Bivalve Shellfish Case Study Survey Results
Q. Natural Capital Team – Elliptio Service Rates

Executive Summary

The Delaware Estuary watershed and its natural resources will face a variety of challenges with climate change. Due to the many unique features of the Estuary, some aspects of changing climate may not be as severe here as in nearby watersheds and estuaries, whereas other changes may be more important. Since 2008, the Partnership for the Delaware Estuary has engaged experts from throughout the region to conduct an assessment of the vulnerabilities and adaptation options for three key resources of the Delaware Estuary: tidal wetlands, drinking water, and bivalve shellfish. These provide three case studies – a habitat case study, a human/water use case study, and a living resource case study – for looking at climate change impacts and how best to adapt to them here in the Delaware Estuary. These case studies represent the very first step in an adaptation planning process, the goal of which is to ensure the resiliency of this vast and valuable system as climate changes.

This image from the US Geological Survey, Dept. of the Interior depicts the Delaware Estuary from above with land areas in shades of green and open water in blue.

How Will Climate Change in the Delaware Estuary?

To answer this question, the Partnership enlisted the help of a predictions team led by Dr. Raymond Najjar from The Pennsylvania State University. This prediction team's work confirmed that climate models like those used by the Intergovernmental Panel on Climate Change (IPCC) are relatively good predictors of key elements of past climate in the Delaware Estuary region. The details of this work can be found in Chapter 2 and the appendices referenced there. Climate change resulting from two greenhouse gas emissions scenarios was investigated. The median projections of the 14 climate models for the end of this century are as follows:

- Temperatures will rise between 2 and 4 degrees Celsius, with substantially more warming in summer than in winter, resulting in more extreme heat days.
- Precipitation will increase by 7-9%, with substantially more increase in winter months, and 5-8 more days of heavy precipitation annually.
- The growing season will increase substantially (by 15-30 days annually) and the number of frost days will decrease substantially (by 20-40 days annually).
- Sea-level will rise by between .5 meters and 1.5 meters (or more).
- Sea-level rise will result in larger tidal volumes that bring more salt water up the estuary, and some of that salinity increase could be offset by increases in precipitation, at least during cooler months.

For temperature, precipitation and growing season metrics, the ranges of these predicted changes represent the difference between the high and low emission scenarios used in prediction models. The difference between the high and low ends of these predictions may not seem like much – for example, between 2 and 4 degrees Celsius of temperature increase. But the consequences to human populations and natural resources are expected to be dramatic between these two temperature outcomes. A one-degree rise is capable of causing local extinction or extirpation of some plants and animals, but a four-degree rise is likely to lead to mass extinction (Yohe et al., IPCC, 2007). These differences emphasize the importance of taking aggressive action to reduce greenhouse gas emissions as soon as possible.

However, for the next quarter century, predictions indicate that the Delaware Estuary (like the rest of the world) is locked into a climate change trajectory dictated by levels of greenhouse gasses already released. Even if all carbon dioxide emissions were stopped today, climate change will continue on this trajectory for many years. Therefore, in the short-term, the region will have to adapt to the forecast climate conditions.

How Will Climate Change Affect the Resources of the Delaware Estuary?

Assessing the effects of climate change on the vast and varied resources of the Delaware Estuary is a huge effort, and one that can only be accomplished over time, and with a tremendous commitment of resources. The three case studies examined here represent a small fraction of the effects that climate change will have on our region and broader society, including people and property. But they offer insights into how natural resources can be impacted by climate change, and how we can begin assessing those impacts and our options for adapting to minimize them. These case studies provide valuable information about the vulnerability of a select set of key resources, and changes that will impact them the most, based on the best available information and expert opinion.

More than 15 million people get their drinking water from the Delaware Basin.

An expert team led by Dr. David Velinsky of the Academy of Natural Sciences assessed five different elements of climate change for their impacts on two different types of tidal wetlands. For a full explanation of results, see Chapter 3 and the appendices referenced there. In summary, results indicate that tidal wetlands are most vulnerable to three of the elements assessed: increases rates in sea-level rise, salinity, and precipitation and storms. The top single concern to experts in our region is the effect of sea-level rise on Brackish/Saltwater Wetlands. These wetlands run a high risk of "drowning" as sea-levels rise in the Lower Estuary. On the other hand, freshwater tidal wetlands are thought to be highly vulnerable to all three of those elements, and especially to salinity effects. With plant communities that cannot tolerate high salinity levels and few areas left to migrate inland because of the built environment, the narrow fringe of freshwater wetlands remaining in the Delaware Estuary faces a combination of threats.

To assess climate change impacts on drinking water resources (specifically, surface water) a team of experts led by Paula Conolly of the Philadelphia Water Department examined impacts of potentially changing physical conditions in the Delaware Basin on drinking water. For a full explanation of results, see Chapter 4 and the appendices referenced there. Important concerns identified by the workgroup as ideal candidates for future study include potential damage to, and inundation of, drinking water infrastructure through flooding, sea-level rise, and storm surge. Drinking water treatment plants, pumping stations, and other infrastructure are located close to water resources and in the direct path of flooding and storm surges. Degraded source water quality is also of concern to drinking water experts. With potentially heavier precipitation and continued development of the watershed, runoff will increasingly contribute to both flooding and decreased water quality. Salinity intrusion exacerbated by sea-level rise and storm surge, and power outages and customer supply issues which could be influenced by increased flooding and storm surge are also major concerns for drinking water supplies.

Bivalve shellfish play a unique role as both a living resource to protect in the Delaware Estuary, and a source of habitat and water quality protection for the Delaware Estuary. The effects of five elements of climate change on bivalves in the Delaware Estuary were assessed by a team of shellfish experts led by Dr. Danielle Kreeger of the Partnership for the Delaware Estuary. For a full explanation of results, see Chapter 5 and the appendices referenced there. Overall, concern for freshwater mussels emerged as greatest among shellfish experts, based on vulnerability to the effects of storms, temperature, and precipitation. The life history of freshwater mussels makes them not only directly vulnerable to these effects, but also indirectly vulnerable through impacts to the fish hosts required to complete their life cycle, and impacts to the conditions the streams that serve as their habitat. The effect of sea-level and salinity on both freshwater tidal bivalves and saltwater bivalves, like oysters, is also a major concern. For oysters, sea-level rise and salinity combined with temperature increases will likely contribute to more virulent diseases that can take a great toll on oyster populations. Freshwater tidal bivalves cannot tolerate salinity, so sea-level and salinity increases would force their populations into smaller areas.

Planting oyster in the Bay for the Delaware Bay Oyster Restoration Project has demonstrated a $40 to $1 return on investment of federal dollars based on dockside value.

For all three case studies, the top concerns among experts are the vulnerabilities of key resources to sea-level rise and salinity changes, and flooding and precipitation effects. Whereas, many estuaries around the world are concerned with sea-level rise, the vulnerability to salinity rise in the Delaware Estuary is somewhat unique, and especially notable because this system has the world’s largest freshwater tidal prism.

What Are the Options for Making Key Resources More Resilient to Climate Changes?

Anticipating all of the options available to us to adapt to climate change, now and in the future, is impossible. However, the case studies provide us with a basic grasp of the most feasible and effective options available to us in the short term for protecting some key resources.

Allowing for landward migration was identified by tidal wetland experts as the most promising adaptation tactic for tidal wetlands. For a full explanation of results, see Chapter 3 and the appendices referenced there. For some tidal wetlands this can be facilitated by protecting the natural buffers alongside wetlands and instituting structure setbacks so that wetlands can make their way into those areas as sea-level rises. For areas where structures, roads, or other improvements are in the way of wetland migration, their removal (a type of strategic retreat) may be the best adaptation option. Experts also identified the installation of living shorelines as a promising adaptation tactic in places where they can be effective at stemming erosion. In addition, managing water flows was identified as a potentially important tactic for maintaining salinity balance by insuring adequate freshwater flows into the system. Determining where each of these tactics is appropriate will require development of a geospatial framework that integrates LIDAR, land use, and monitoring data.

Installations of “living shorelines” like these on the Maurice River, NJ can help prevent erosion of wetlands.

Drinking water experts selected one regional-level priority and one utility-level priority adaptation option for each major drinking water vulnerability identified. The options selected were identified by the workgroup as the most important actions needed now to address the vulnerabilities. Adaptations selected generally do not require extensive climate change modeling; they minimize current threats to drinking water supplies to provide a “cushion” for physical changes expected as a result of climate change, or they aim to improve current knowledge of conditions in the Basin order to facilitate future projections. To address potential degraded source water quality, forest protection in the Upper Delaware Basin was identified is the single most important action needed on a regional level. Improving monitoring of priority parameters, such as UV254, chlorides, turbidity, and other concerns for drinking water is the most critical utility level adaptation identified. With respect to the potential for increased spills and accidents, ensuring continued support for tools that facilitate region-wide communication during emergencies, such as the Delaware Valley Early Warning System, is key. Modernizing emergency response protocols is also essential at a utility level. For a full explanation of results, see Chapter 4 and the appendices referenced there.

The top three adaptation options identified by shellfish experts for assisting bivalve shellfish to adapt to climate change are direct restoration efforts: plant shell to restore oyster beds, propagate all bivalves and seed new reefs/beds, and restore forested areas along streams for freshwater mussels. Through these activities, populations of bivalves can be restored and strengthened to be more resilient to climate change. However, two more challenging adaptation tactics were also identified as imperative for bivalves. One of these is managing water flow to minimize the effects of flooding on freshwater mussels and salinity on oysters and freshwater tidal bivalves. The other is maintaining water quality for all bivalves. Both will require the concerted efforts of government agencies, conservation organizations, and local communities to be successful. For a full explanation of bivalve shellfish adaptation options assessment results, see Chapter 5 and the appendices referenced there.

Sampling teams look for freshwater mussels in headwater streams in Pennsylvania.

For all three case studies, the protection and/or restoration of buffers (of various types) and the management of water flows were identified by experts as critical actions for climate change adaptation. It's also important to note the two-way connection between adaptation options for bivalve shellfish and tidal wetlands and improving water quality and system resiliency. Maintaining water quality and system resiliency is important for sustaining tidal wetlands and bivalve shellfish – ***and vice versa***. Bivalve shellfish and tidal wetlands also play an important role in improving water quality and system resiliency, making investment in these resources extremely important.

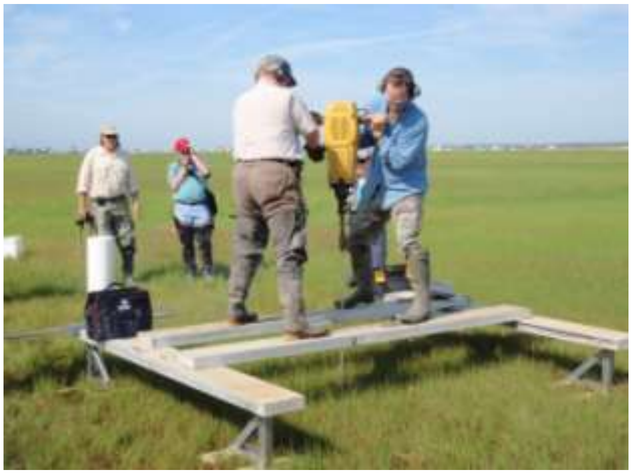
What Actions Are Recommended to Protect Key Resources?

The three case studies provide valuable insights into the actions we can take today and in the near future to help key resources adapt to climate change in the Delaware Estuary. A complete set of recommended actions is provided in each case study chapter; following is a synthesis that takes into account some of the key points and commonalities between case studies.

Take immediate action to protect buffers, plant shell, and protect drinking water infrastructure.

- Protect known forested streamside areas and undeveloped wetland buffer migration areas to benefit water quality and allow tidal wetlands to migrate.
- Continue/reinvigorate shell planting on existing beds for oyster restoration.
- Evaluate placement of new drinking water infrastructure with respect for potential exacerbated flooding.

Develop and fund a climate monitoring program for tidal wetlands, bivalve shellfish and drinking water quality. Indicators are needed to track both impairments (and possibly benefits) that result from climate change, such as the presence of oysters in intertidal areas. Scientific analyses should be directly relevant for managers. It should help to bolster our understanding of the benefits (a.k.a., ecosystem services) of these habitats and species to watershed health as well as the consequences of watershed management on these habitats and species. This information is crucial to carrying out each of the following recommendations, and to developing the more detailed projections and adaptations that will be required to ensure the resiliency of the Delaware Estuary to climate change. More monitoring at a utility level and regional level to detect trends in important parameters for drinking water, such as UV254, chlorides and turbidity, is a good example of a specific monitoring need.



Surface elevation tables like this one recently installed in neighboring Barnegat Bay, NJ can be used to monitor changing marsh conditions over time.

Develop watershed and estuarine hydrodynamic models to fill information gaps about the combined effects of key climate change drivers. Across all three case studies, vulnerability to sea-level rise and the need for flow management were common concerns. To better predict the effects of sea-level on local resources (and interacting with precipitation, flooding, and salinity) and to manage freshwater flows, improved information and modeling of flows in the watershed is greatly needed. This information is also critical for evaluating the combined effects of climate change with other major initiatives and events that could impact the Estuary, such as channel deepening, Marcellus gas drilling, and oil spills.

Develop a geospatial framework to identify priority tidal wetland areas to restore and protect, including:

- Vulnerable areas of tidal wetlands that could benefit from restoration or adaptation to increase or enhance the acreage that is sustainable. For example, living shorelines can be installed to slow erosion and stem marsh loss at seaward edges, and sediment budgets and hydrology can be engineered to help marshes build themselves up. These tactics help tidal wetlands maintain their elevation and health in relation to rising sea-levels.
- Lands in the buffer zone landward of current tidal marshes that have suitable elevation, slope and other traits can be managed to facilitate tidal marsh expansion into these areas. For example, tactics like strategic retreat, setbacks or conservation easements can be used to ensure unimpeded marsh migration.

Assess stream and shoreline conditions to identify priority bivalve populations for restoration, including:

- High quality areas for augmentation, where the current population is below the system's carrying capacity and can be augmented through hatchery propagation and outplanting of seed, relocation of gravid broodstock, and restoration or protection of forests along streams.
- Promising areas for reintroduction that currently are not colonized, where bivalves can be (re)introduced and supported through hatchery propagation and outplanting of seed, relocation of gravid broodstock, and restoration or protection of forested areas along streams.

Educate the broader resource management community about key Delaware Estuary resources, including:

- The importance of tidal wetlands and bivalves for watershed health and the effects of water quality and quantity on them.
- The importance of using green infrastructure to address local issues, build community amenities, and add to overall Basin resiliency in the face of climate change.

Rain gardens like this one planted with the help of volunteers in New Castle County, DE are one example of "green infrastructure."

Identify special protection or management areas based on key ecosystem goods and services furnished. Quantify the ecosystem goods and services furnished by key resources like wetlands, bivalves, and forests (for drinking water) in different locations and prioritize areas having the greatest natural capital. This does not apply to the main oyster beds in Delaware Bay, which are already carefully protected and managed.

Consider policy changes needed to facilitate climate change adaptation. The following were identified through the three case studies, but there are likely others:

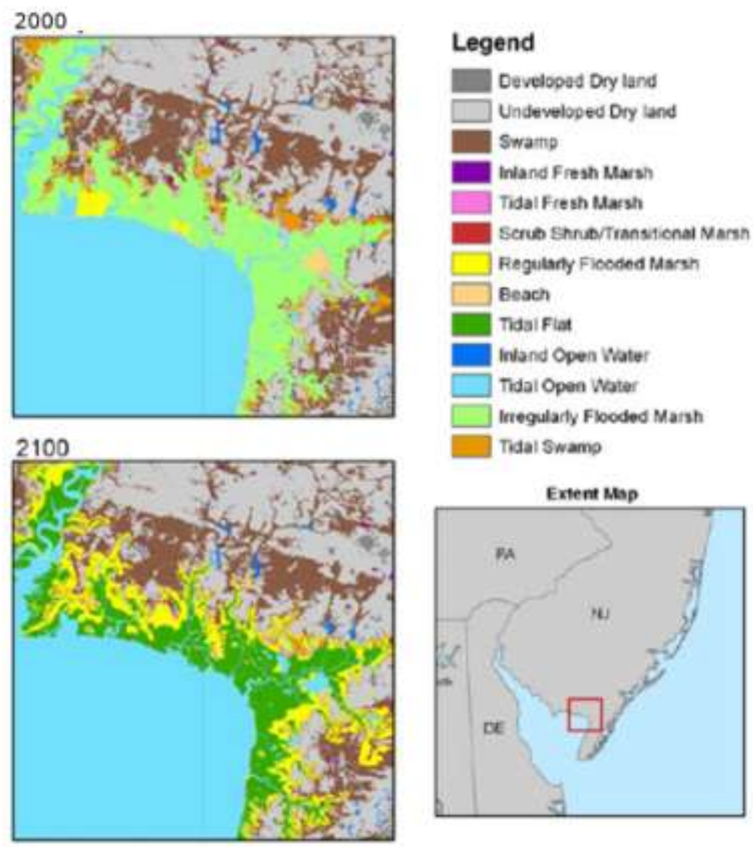
- Policies that focus on restoring to past conditions without taking into consideration future needs/conditions may not result in the best investment of public funds. Restoring certain plant communities or places may not be sustainable, nor the best use of funds.
- Some of the best future restoration opportunities for oysters lie within waters that are "closed" to oysters due to public health concerns.
- Permitting requirements for wetlands can prevent (or severely thwart) living shorelines from being used to prevent marsh erosion.
- Policies that prevent the interstate transfer of species can prevent mussels from being reintroduced to streams where they have been extirpated.
- Policies that acknowledge the direct value of forests to drinking water supply protection and that protect drinking water supplies from salinity intrusion are largely lacking.
- Policies and plans that guide the development of infrastructure should take changing conditions into account.

What Happens If We Don't Take Action?

Adaptation to climate change will happen, whether we take action or not. By taking action, we can choose to adapt in a way that protects our most valued resources. By not taking action, we are risking the likelihood of losing or damaging some of our most valuable resources (as indicated by vulnerability assessment results for each case study). To help inform decisions about what resources to protect, and at what cost, it's useful to consider "natural capital values" that measure the benefits provided by natural resources.

A team of experts led by Priscilla Cole, Science & Policy Fellow at the Partnership for the Delaware Estuary, was formed to assess the natural capital values associated with case study resources. There are many components of the natural capital values of these resources, including provisioning services (e.g., the value of oysters for food), regulating services (e.g., the value of forests for water filtration), cultural services (e.g., the value of mussels for jewelry), and supporting services (e.g., the value of wetlands for primary production). Calculating comprehensive values for all of these services is very complex, and beyond the scope of the case studies. However, some assessment of natural capital value was completed for each of the case studies to illustrate these values and their potential uses.

For tidal wetlands, this included a rigorous assessment of the loss of primary production value of tidal wetlands due to climate change. This work was completed by Industrial Economics (IEc) and is presented in more detail in Chapter 3.7.2. IEc used modeling to predict tidal wetland changes due to sea-level rise and found that 40,000 hectares of tidal wetlands would be lost across the whole Estuary by 2100, with a primary production service loss of 60 million kilograms over the century. Tidal wetlands provide a host of natural capital values, including flood protection, support for fisheries and shellfisheries, sequestering carbon, helping to maintain water quality, and others. A more complete inventory of these values is provided in Table 3.8. According to the report Valuing New Jersey's Natural Capital project completed in 2007, wetlands have the highest combined natural capital value of any land/habitat type assessed.



Industrial Economics used SLAMM model 6 to estimate wetland changes from climate change in 2100. This map series shows a loss of brackish marshes with conversions to salt marsh and mud flats by 2100.

For drinking water, a more rudimentary assessment was used to illustrate natural capital values associated with source water protection. This illustration is included as a feature box in Chapter 4. The hypothetical scenario it presents shows how even a relatively small amount of damage to drinking water infrastructure (1%) due to climate change could lead to significant supply shortages if demand grows at the same rate as population (2.5 million by 2050). It also illustrates how employing conservation BMPs to reduce demand and fill the shortage would be less expensive than the cost of filling the supply deficit with bottled water for only 2 days.

For bivalve shellfish, the natural capital values of different bivalve shellfish are compared and contrasted in Appendix Q. While only oysters boast value as a food and ecotourism resource, marsh mussels and freshwater mussels both share the oyster's other values, including shoreline stabilization and bio-filtration – two extremely valuable assets for water quality and watershed resiliency. The natural capital team estimates that the 4 billion adult Elliptio freshwater mussels in the Delaware Estuary currently filter 758 million kilograms of total suspended solids from streams annually. With a hypothetical 15% population decrease by 2050 due to climate change that filtering capacity would be reduced by 114 million kilograms. For perspective, total suspended solids are regulated in New Jersey with targets of 20-40 milligrams per litre.

Natural capital values can provide a very helpful tool for illustrating the value of resource protection, as shown here. With more rigorous assessment and better information, they can also guide decisions about where to invest in resource protection for the greatest benefit.

According to the NJ Natural Capital project completed in 2007, forests have the highest natural capital value for water quality protection of any land/habitat type assessed.

What's Next?

This report concludes the Partnership for the Delaware Estuary's pilot study under the EPA Climate Ready Estuaries Program, but **implementing the recommendations of this report is our highest priority "next step"**.

As previously noted, the case studies presented here are just a start to climate adaptation planning for the Delaware Estuary. A great deal of additional work is needed not just to fully understand and plan for impacts to the three resources assessed here, but also to assess climate impacts and adaptation options for the myriad other resources in the Delaware Estuary <u>not</u> addressed here. For example, experts on the drinking water workgroup acknowledged that their assessment does not adequately address groundwater, a critical source of drinking water for millions of people in the Delaware Estuary region. Given the potential threat of salt-water intrusion into groundwater supplies and relatively little information encountered by the drinking water workgroup about the impacts of climate change on our groundwater resources, this is an important area for investigation. Similarly, while the wetlands workgroup considered removal of structural impoundments (such as dikes, levees, weirs) as potential adaptation tactics, they did not assess the vulnerabilities of existing structures themselves. Given the hundreds, possibly thousands, of these structures throughout the Delaware Estuary, that some of these structures are not regularly inspected or maintained, and that they protect quite a bit of our built and natural environment, this is also an important area for investigation. These are just two examples of important resources that were outside the scope of this study, but for which vulnerability assessment and adaptation planning is clearly needed.

Many wetlands in the Estuary are squeezed up against impoundments and other structures, leaving no place for them to migrate if rising sea-levels push in.

Working with our partners to recognize and seize opportunities for adaptation planning to address *other* important Delaware Estuary resources is also an important "next step."

One of the most common threads across the case studies, and the experts who worked on them, is the need for more research and monitoring in order to better understand climate change impacts, and their effects on our natural resources and systems here in the Delaware Estuary. The lack of hard data on this is reflected in the survey methods employed by the case studies presented here, reliant largely on expert opinion. This provides some critical initial guidance, but leaves us with much more work to be done even for the three cases presented here. For rigorous adaptation planning that can be confidently used as the basis for making tough decisions about policies and investments, better data and information is needed. This is crucial to every aspect of adaptation planning, from improving predictions to implementing adaptation tactics. **Continuing to improve our knowledge base on climate change through research and monitoring is an ongoing "next step."**

Another common thread across the case studies is the need for education – especially of resource managers and decision-makers, but for all stakeholders in the region as well. The information gathered from these case studies is a great resource for helping people to make the connection between global climate change, and impacts on resources here in the Delaware Estuary. **We encourage our partners to use it for this purpose, and will do so ourselves as another ongoing "next step."**

Climate change will have a profound affect on our society that will go well beyond the resources examined here. As people and property become increasingly impacted, prioritizing resources will become increasingly challenging, and essential. So it's important that we begin taking the actions we can today for our most important resources, using the best available information.

Chapter 1

Introduction

The Delaware River has a duel identity as both a living river and a working river, which makes its Estuary one of many contrasts. It is a principal corridor for commerce that has sustained the region since America's colonial period and reached a zenith during the Industrial Revolution. Today, it continues to be a major strategic port for national defense and economic interests. The Estuary supports the 4th largest urban center in the nation and contains the world's largest freshwater port. The Estuary also sustains a wealth of natural and living resources, such as drinking water for millions of people, extensive tidal marshes that sustain vibrant ecosystems, and world-class habitats for horseshoe crabs, migratory shorebirds, and rare and endangered shellfish (Figure 1-1).

Ecologically Unique

- Over 200 fish species, both residents and migrants.
- Habitat for endangered species
- 185 natural-community types
- More than 405,000 acres of wetlands
- One of the largest freshwater tidal estuaries
- Largest breeding population of horseshoe crabs
- Second-highest concentration of shorebirds in North America

Economically Important

- Drinking water to over 15 million people
- Port system generates $19 billion annually
- World's largest freshwater port
- Multi million dollar oyster industry
- Second- largest refining petrochemical center nationally
- 70% of the oil shipped to the East Coast passes through

Figure 1-1. Examples of ecological and economic features of the Delaware Estuary

Like elsewhere in the United States and world, the Delaware Estuary watershed and its natural resources will face many challenges with climate change. Due to the many unique features of the Estuary, some aspects of changing climate may not be as severe here than in nearby watersheds and estuaries, whereas other changes may be more problematic. Hypothetically for example, modest rises in temperature could lengthen growing seasons or boost productivity for some signature species and help them compete with invasive species or keep pace with sea-level rise. On the other hand, sea-level rise will likely result in greater saltwater (salinity) reaching further up the estuary, threatening the many unique species adapted to our freshwater tidal area, which is the largest of its kind in the world.

Climate changes will occur alongside other changes in the fabric of the watershed. Continued rises in human population will increasingly tax our natural and built infrastructure, with anticipated loss of open space, fragmentation of natural habitats, and rising demands for clean water, as a few examples. Climate change and continued watershed change will interact in complex ways. Environmental resource managers will require new ways to predict climate impacts in order to adapt appropriately.

This report summarizes findings from our first significant effort at climate adaptation planning, whereby the Partnership for the Delaware Estuary worked with dozens of partner entities to characterize the array of issues that confront a few of our key natural resources and to begin to plan for how we might respond, to work proactively to stave off losses and take advantage of opportunities.

1.1 Climate Ready Estuaries – The Delaware Estuary Pilot

Climate Ready Estuaries (CRE) is an EPA program operated by the Climate Change Division and the Oceans and Coastal Protection Division. The mission is to work with the National Estuary Programs to: 1) assess climate change vulnerabilities, 2) develop and implement adaptation strategies, 3) engage and educate stakeholders, and 4) share the lessons learned with other coastal managers. In 2008, EPA funded six National Estuary Programs to create CRE pilots. The Partnership for the Delaware Estuary (PDE) was one of the original six pilots.

Through the CRE pilot funding, the Estuary Programs were given flexibility to design studies and adaptation plans according to the needs of their study areas, and up to 18 months to conduct the pilot. In the large and complex Delaware Estuary (Fig. 1-2,) three case studies were chosen representing major resource areas of concern in the system. These case studies consisted of tidal wetlands as a habitat resource, drinking water as a human/water resource, and bivalve shellfish as a living resource.

For each of the three case study resources, PDE:

- characterized the array of vulnerabilities to climate change using updated climate predictions,
- assessed the potential effectiveness of adaptation options to address those vulnerabilities, and
- developed recommendations for resource managers and stakeholders in the region.

Due to the short timeline and pilot nature of this project, our approach was primarily qualitative, relying principally on best scientific judgment and risk assessment methods. Our findings should therefore be considered preliminary, helping to guide next steps. More detailed, quantitative analyses will be needed to confirm and refine our findings leading to site-specific recommendations.

PDE recognizes that climate change effects are not occurring in a vacuum and must considered with other stressors to the system, Including such activities as dredging, water withdrawals, land use change, new energy development, legacy and emerging pollutants, and environmental hazards. Future refinements to these recommendations will need to consider the added complexity contributed by such ongoing watershed changes. Future adaptation efforts will also need to consider new information on future climate projections, which are frequently updated. Finally, efforts to build on this report will need to consider the multitude of other important natural resources in the Delaware Estuary, and their interactions. “Adaptive adaptation plans” will therefore be needed to build on this first effort.

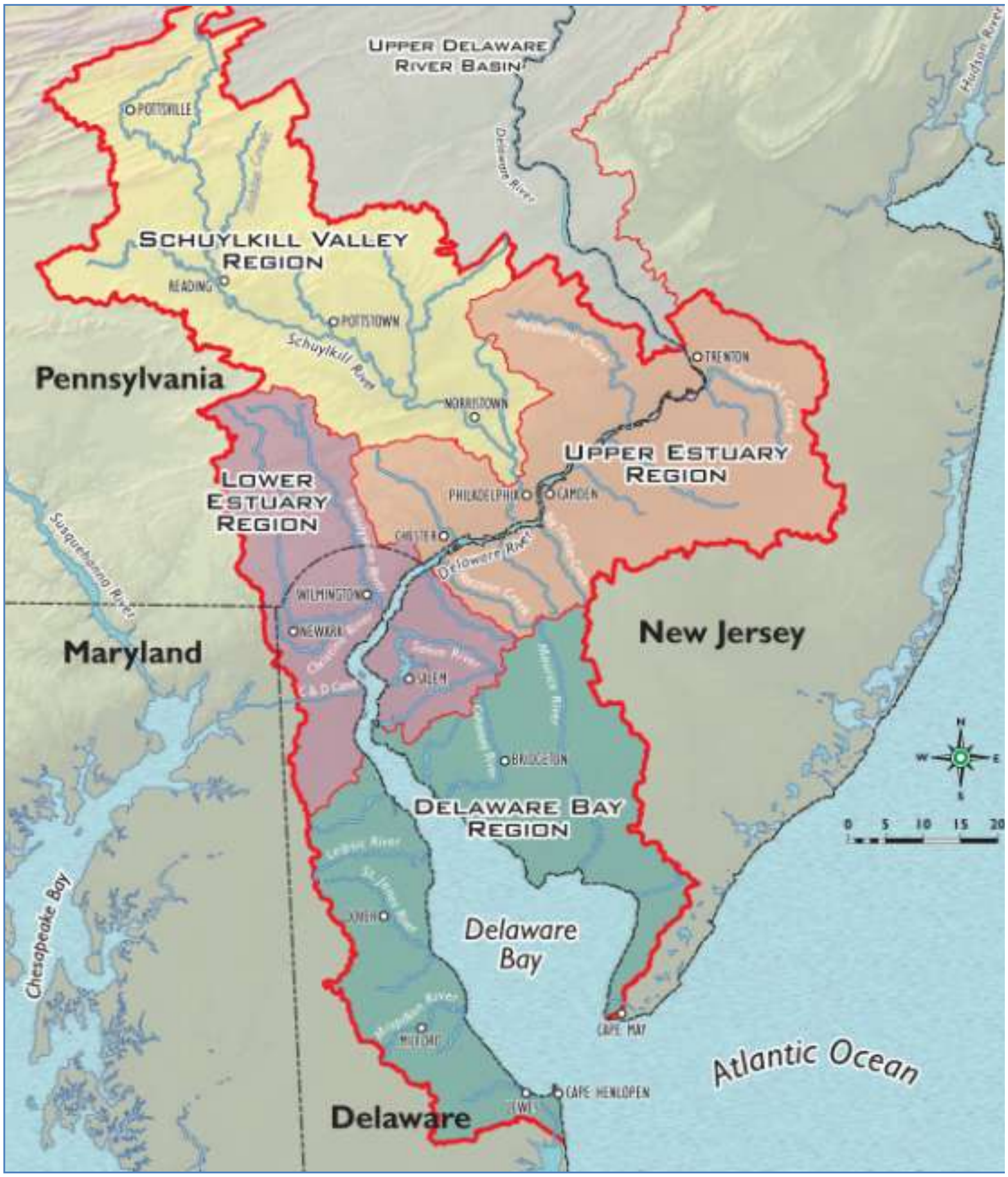


Figure 1-2. Map of the study area of the Partnership for the Delaware Estuary, a National Estuary Program. This comprises the lower 52% of the Delaware River Basin.

1.2 Approach

To assess vulnerabilities of our three case study resources (tidal wetlands, drinking water, bivalve shellfish) to changes in physical and chemical conditions associated with climate change, we first obtained updated and locally relevant predictions for expected changes in key environmental conditions between now and 2100 (Chapter 2.)

We then engaged scientists and managers with expertise in each of the three case study resources to identify and prioritize their concerns related to these expected changes in physical conditions (Figure 1-2). Information was gathered in a special workshop (September 2008), a climate session at the Delaware Estuary Science Conference (January 2009), in workgroup meetings, and through polling using Survey Monkey™. We asked our many partners to also furnish potential adaptation options for each case study resource. To augment the information contributed by these experts, we also performed a literature review for vulnerabilities and adaptation tactics related to the three case studies. This information was compiled into a concise inventory of potential vulnerabilities and adaptation measures.

Survey methods and a risk assessment approach were then used to gauge relative levels of concern (for vulnerabilities) and effectiveness (for adaptation tactics) by additional resource-specific experts in the broader science and management community in the Delaware Estuary or vicinity. This approach was useful in providing a first order ranking of relative concerns and the relative utility of adaptation measures for each of the three case studies based on best available expertise. It also exposed some knowledge gaps.

Potential vulnerabilities and adaptation fixes were then considered in the context of ecosystem goods and services (a.k.a., natural capital). Our eventual goal is to quantify the natural capital "costs" of climate change and "gains" of various adaptation tactics to inform investments in crucial life-sustaining ecosystem services. However, this analysis is only now beginning and this report is limited to some early discussion of future tradeoffs and information for strategic investment, where possible.

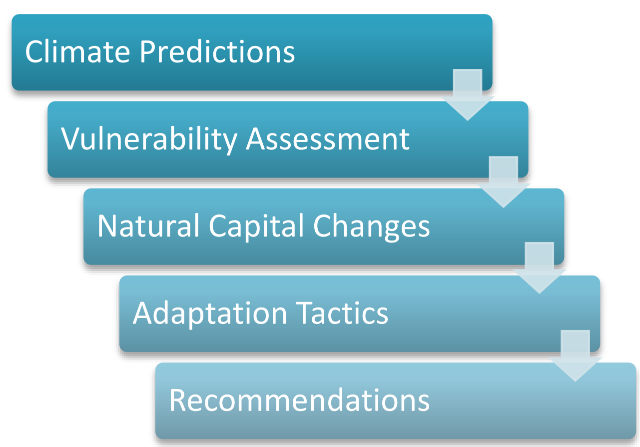


Figure 1-3. Approach for climate adaptation planning for each of three case study natural resources.

These activities were performed by multiple teams of experts brought together under a new Delaware Estuary Climate Adaptation Workgroup (CAWG), which was formed as a work group under the PDE Science and Technical Advisory Committee. The CAWG met quarterly. In addition, six subgroups of the CAWG were created to tackle specific tasks and steps in our approach (Fig. 1-3). The subgroups were Tidal Wetlands, Bivalve Shellfish, Drinking Water, Climate Predictions, Natural Capital, and GIS. Table 1-1 lists the main participants. Although our overall approach was comparable among the three case studies, some methods differed considerably. Additional details on the approach and methods, as well as the results, are provided in the sections below: Predictions (Chapter 2,) Tidal Wetlands (Chapter 3,) Drinking Water (Chapter 4,) and Bivalve Shellfish (Chapter 5.)

Table 1-1. Participants in the PDE Climate Adaptation Workgroup and six subgroups.

Climate Adaptation Workgroup (Chair: Dr. Ray Najjar)	
Tidal Wetlands	David Velinsky – Academy of Natural Sciences Kurt Phillip - Wetlands Research Service Tracy Quirk – Academy of Natural Sciences Danielle Kreeger, Angela Padeletti, Priscilla Cole – PDE
Bivalve Shellfish	Danielle Kreeger – PDE John Kraeuter – Rutgers University Priscilla Cole – PDE
Climate Predictions	Raymond Najjar (Chair) The Pennsylvania State University
Drinking Water	Paula Conolly (Chair) –Philadelphia Water Department Raymond Najjar – The Pennsylvania State University Lance Butler – Philadelphia Water Department Carol Collier – Delaware River Basin Commission Chuck Kanetsky - US EPA Region 3 Sue Kilham – Drexel University Chris Linn – Delaware Valley Regional Planning Commission Christine Mazzarella - US EPA Region 3 Amy Shallcross – Delaware River Basin Commission Alysa Suero - US EPA Region 3
Natural Capital Team	Priscilla Cole (Chair) – PDE Anthony Dvarskas – National Oceanographic and Atmospheric Administration Irene Purdy – US EPA Region 2 James Bennett – formerly DVRPC
GIS Team	Priscilla Cole – PDE Andrew Homsey – Water Resources Agency Paula Conolly – Philadelphia Water Department Chris Linn – Delaware Valley Regional Planning Commission James Bennett – Delaware Valley Regional Planning Commission
Other CRE Participants	Jerry Kauffman – Water Resources Agency Jennifer Adkins – PDE Jessica Rittler-Sanchez – DRBC Simeon Hahn – NOAA Amie Howell – US EPA Region 3

1.3 On the road to Adaptation Planning: Next Steps

There is some debate about what it means to be 'climate ready.' The initial Delaware Estuary CRE pilot has come to a close, but the work of climate adaptation planning is an ongoing process. Vulnerability assessments have only been carried out for three of the Estuaries' many resources, and these vulnerabilities could be expanded in further quantitative analysis and modeling. Likewise, the adaptation options and recommendations in this report have not undergone cost benefit analysis, nor have they been vetted through the larger constituent bases or stakeholder bodies necessary to carry them out. This report is the first of its kind for the Delaware system, and it is an important first step for climate adaptation planning. However, this is only the first of many steps that need to take place before the Delaware Estuary is truly Climate Ready.

Table 1-2 provides examples of other regional climate programs in the Delaware Estuary. The CRE pilot fills an important niche by focusing on specific resources at the geographic scale of the Delaware Estuary and watershed. In the future, greater information sharing and collaboration will be needed to link various climate adaptation efforts within the Delaware River Basin and Estuary.

Table 1-2. Examples of regional efforts to examine climate adaptation.

Regional Entities	Climate Change Interests	Mitigation Targets for Greenhouse Gases
Delaware River Basin Commission	Flooding, Inundation, Salinity	N/A
Philadelphia Water Department	Drinking Water, Intakes	N/A
Commonwealth of Pennsylvania	Energy, Forests, Carbon Emissions	30% reduction by 2020 (presented to the Governor Dec 18, 2009)
State of New Jersey	Carbon Sequestration, Air, REGGI Participant	Reduce emissions to 1990 levels by 2020 and 80% below 2006 emissions levels by 2050
State of Delaware	Sea-level Rise, Inundation, REGGI Participant	Stabilize emissions between 2009 - 2015, then reduce incrementally to a 10% reduction by 2019
Partnership for the Delaware Estuary	Natural Resource Adaptation Planning, Climate Predictions, Prioritization Using Natural Capital Analyses	N/A

For updated information, please visit us on the web:
http://www.delawareestuary.org/science_projects_climate_ready.asp

Chapter 2

Climate Predictions

Planning for climate change in the Delaware Estuary watershed first requires an understanding of the most current and locally relevant climate predictions. The Climate Adaptation Workgroup (CAWG) enlisted Dr. Raymond Najjar from The Pennsylvania State University to project changes in temperature, precipitation, sea-level, and a variety of metrics based on these variables (e.g., length of growing season, number of frost days, extreme precipitation, etc.) that can be expected between the present and 2100 under two greenhouse gas emissions scenarios (B1 and A2). Dr. Najjar, an oceanographer, has 10 years of experience in using climate model output for coastal and regional climate impact assessments ((Najjar, 1999; Najjar et al., 2010; Najjar et al., 2000; Neff et al., 2000; Shortle et al., 2009; Wu et al., 2009).

To provide these climate projections for the Delaware Estuary for the 21st century, fourteen different climate models were first contrasted to test their accuracy in predicting past conditions for the region (Appendix A). For this comparison, the geographic extent of the Delaware Estuary and its watershed were regarded as spanning three degrees in latitude and one degree in longitude. Therefore, the climate simulations were averaged over three grid boxes (Fig. 2-1).

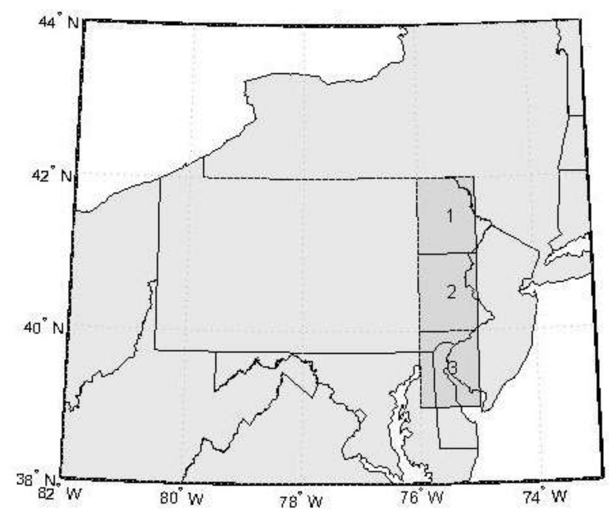


Figure 2-1. For climate modeling, the Delaware River Basin was represented by the three degrees of latitude (39-42^{o}N) and one degree of longitude (75-76^{o}W).

The model comparison indicated that the best past predictions resulted from use of all fourteen model outputs averaged together, rather than from any single model (Appendix A). The multi-model average was considered superior to any individual Global Climate model (GCM) (Appendix A). Therefore, this multi-model approach was used to project future conditions.

Table 2-1 summarizes results of 21st century climate predictions for the Delaware Estuary region. As noted above, models were used to hind-cast climate conditions in the past to expose the models' biases and accuracies. To predict future conditions, these biases (Table 2-1) must be corrected (Appendix A). Sections 2.1 to 2.3 describe expected climate conditions in the Delaware estuary watershed for the key metrics described in Table 2-1. In addition, Dr. Najjar compiled the latest literature on expected sea-level (Section 2.4) and salinity rise (Section 2.5).

Table 2-1. Climate predictions for temperature, precipitation, length of growing season, and number of frost days for the Delaware Estuary watershed during the period from present to 2100. A synopsis of model accuracy and confidence in future projections is provided in columns 3 and 5, respectively.

Climate Condition		Model Evaluation: Biases & Issues	21st Century Prediction	Confidence Levels
Temperature	Monthly Mean	Slight cool bias in winter and summer	Warming: 1.9 – 3.7°C median rise by late century; Substantially greater warming in summer months	High
	Inter-annual Variability	Slightly too much variability, but better with winter than summer		
	Intra-monthly Variability	Models' mean reproduces correctly, but there is a large spread among the individual models		
	Extreme Temp >80° F	Underestimates	Downscaled models show substantial increases	High
Precipitation	Monthly Mean	Wet bias in winter and spring and a dry bias in summer	Increase in Precipitation: 7 - 9% median increase by late century; Substantial increase in winter months	Medium
	Inter-annual Variability	Does not predict summer peak and winter minimum seen in observed conditions		
	Intra-monthly Variability	Mean reasonably captures, but too low in the summer		
Extreme Precipitation	Short Term Drought	Slight low bias	Substantial increases, but less than ¼ of models show declines	Medium
	Heavy Precipitation	Slight low bias		
Growing Season Length		Predicts accurately	Substantial increase by end of century	High
Number of Frost Days		Somewhat high	Substantial decline	High

2.1 Temperature

The models show high confidence that average annual temperatures will increase by the end of the 21st century by 2–4° C (Fig. 2-2). Carbon dioxide emissions will determine whether the lower or higher temperature is realized. More warming is expected in the summer months. The B1 scenario (lower emissions) predicts median summer temperature increases of more than 2° C, whereas the A2 scenario (higher emissions) is predicted to result in summers of about 4.5° C warmer than present by 2100. These conclusions are consistent with predictions by the Union of Concerned Scientists, which estimated that Pennsylvania summer temperatures could increase by 2–7° C depending on the emissions scenario (UCS, 2008; Field et al. 2007). Extreme summer heat days are also expected to rise by the end of the century (UCS, 2009; GCRP, 2009) and southern Pennsylvania could see between 50-70 days per year with temperatures over 90°F (UCS, 2008).

2.2 Precipitation & Extreme Weather Events

Annual mean precipitation is predicted to increase by 7-9% by the end of the 21st century (median projection). Higher increases are expected during winter months (Najjar 2009; GCRP 2009), with more than a 15% increase by 2100 under the high emissions scenario (Appendix A.) Three quarters of the models predict substantial increases in the frequency of extreme precipitation events including heavy precipitation and consecutive dry days. The U.S. Global Climate Research Program (GCRP) also predicted increases in extreme weather events and associated risks from storm surges (GCRP, 2009).

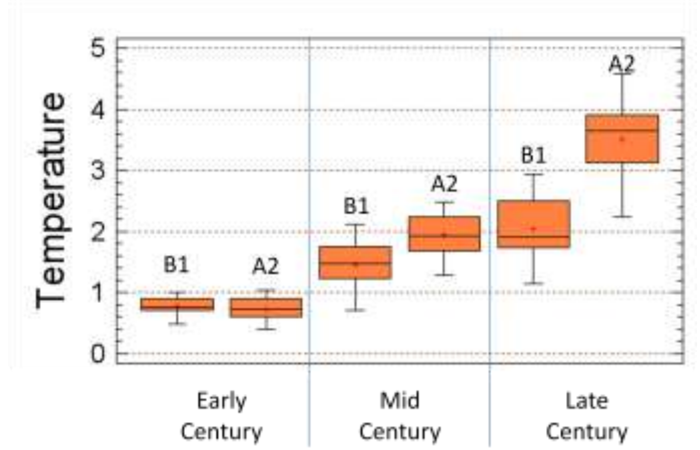


Figure 2-2. Box and whisker plots of temperature rise (°C) for three periods with respect to the late 20th century (1980-1999): 2011-2030 (early century,) 2046-2065 (mid century,) and 2080-2099 (late century) under low (B1) and high (A2) emissions scenarios. The box-and whisker plot shows quartile distributions (minimum, 25th percentile, median, 75th percentile, and maximum) of temperature change among the fourteen models used.

2.3 Other Climate Model Outputs

The length of the growing season will substantially increase: by about 15 days by mid-century and by up to 30 days by 2100 (Appendix A). Approximately 20 fewer frost days per year are predicted by mid-century and 40 fewer frost days by the end of the century under the higher emission scenario (Appendix A). With fewer frost days, Pennsylvania snow packs are expected to decrease and melt earlier (UCS, 2008). The loss of the winter snow pack, combined with higher winter precipitation, will contribute to greater winter flooding and lower amounts of springtime snowmelt runoff. These factors will affect the seasonal timing of freshwater supplies for drinking water and habitats dependent on snow melt.

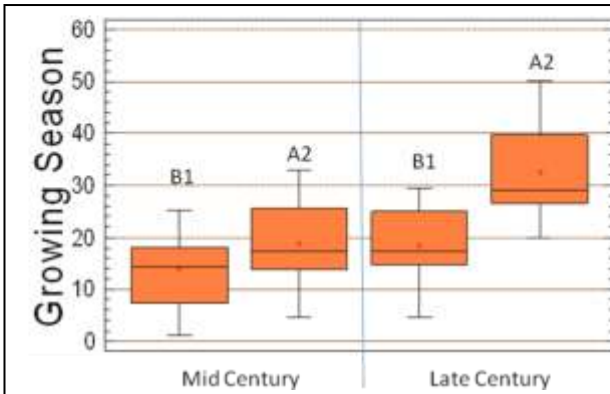


Figure 2-3. Box and whisker plots of growing season length changes for two periods with respect to the late 20th century (1980-1999): 2046-2065 (mid century,) and 2080-2099 (late century) under low (B1) and high (A2) emissions scenarios. The box-and whisker plot shows quartile distributions of the growing season length changes among the fourteen models used.

2.4 Sea-level

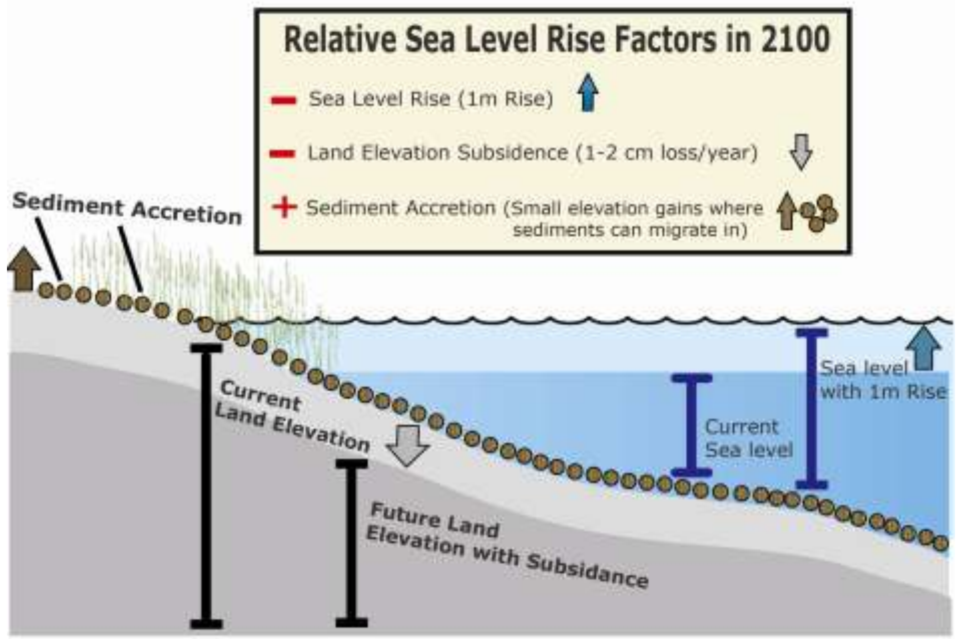


Figure 2-3. The effective rate of sea-level rise experienced at the land-sea surface in the Delaware Estuary is determined by the net elevation change from three factors: the actual rate of sea-level rise, the sinking elevation (subsidence) of the land, and the amount of sediment collected (accretion.)

The Mid-Atlantic States are anticipated to experience sea-level rise greater than the global average (GCRP, 2009). **Absolute sea-level rise** refers to the global rise of water resulting from melting ice sheets and expanding water as it warms. Some regional variation in absolute sea-level will occur because of gravitational forces, wind, and water circulation patterns (Appendix C). In the Mid-Atlantic region, changing water circulation patterns are expected to increase sea-level by approximately 10 cm over this century (Appendix C; Yin et al., 2009). Locally, two other factors contribute to relative sea-level rise: Subsidence and Sediment Accretion (Fig. 2-3.) Post-glacial settling of the land masses has occurred in the Delaware system since the last Ice Age. This settling causes a steady loss of elevation, which is called **subsidence**. Through the next century, subsidence is estimated to hold at an average 1-2 mm of land elevation loss per year (Appendix C; Engelhart et al., 2009). **Sediment Accretion** is a natural process in which suspended sediments in the water settle out and build up along shoreline habitats such as mud flats and wetlands. Accretion cannot occur on hard structures, where erosion is high, or where areas are sediment-starved from diversions. Rates of subsidence and accretion vary in different areas around the Estuary, but the greatest loss of habitat will occur where subsidence is naturally high in areas that cannot accrete more sediments to compensate for elevation loss plus absolute sea-level rise. All three factors must be taken into consideration to determine where habitat will persist, where it will be lost, and where it can be saved (Fig. 2-3) The net increase in sea-level compared to the change in land elevation is referred to as the rate of relative sea-level rise (RSRL). Our best estimate for RSLR by the end of the century is 0.8 to 1.7 m (Appendix C); additional local predictions for RSRL are shown in Table 2-2.

Table 2-2. Predicted rates of relative sea-level rise by 2100 from different sources.

Relative Sea-level Rise Predictions	
State of Delaware	Scenarios = 0.5 m, 1.0 m, 1.5 m
State of Maryland	0.61 m – 1.12 m
State of New York	Considering: Conservative 0.17 m – 0.53 m High Estimates 1.4 m
State of Maine	1.0 m
IPCC AR4, 2007	0.18 m to 0.59 m, excluding accelerated ice discharges from the Greenland and Antarctica ice sheets.
Appendix C, Rahmstorf (2007)	0.8 m – 1.7 m
U.S. Army Corps of Engineers	Planning with scenarios of 0.5m, 1.0m, 1.5m

2.5 Salinity

The Delaware Estuary has the largest freshwater tidal prism in the world. The freshwater tidal region extends about 70 river miles, and the salinity in areas more seaward changes very gradually. This feature makes the Delaware Estuary unique among large American estuaries because of the array of ecosystem services supplied to human and natural communities tied to the extended salinity gradient, such as the supply of drinking water for people and rare natural communities. Increasing sea-level will result in larger tidal volumes that bring more salt water further up the estuary. Sea-level rise could increase the tidal range in the Delaware system (Walters 1992), similar to expectations for the Chesapeake Bay (Zhong et al, 2008). Tidal range changes would also likely increase the salinity range over the tidal cycle (Appendix B).

Increased precipitation could help to offset the salinity rise, at least during cooler seasons. Current literature suggests that modest increases in annual streamflow and more substantial increases in winter streamflow can be expected over the 21st Century, resulting mainly from precipitation (Section 2.2.) However, precipitation is likely to become more variable with the potential for more intense storms and storm surges (Lambert and Fyfe, 2006). All of these factors will likely increase the variability of river flows, perhaps with higher winter runoff and lower or similar summer runoff, leading to increased variability in estuarine salinity (Appendix B).

To understand how river flows affect salinity in the estuary, Dr. Najjar and the CAWG obtained historical salinity data on computer punch cards from Rutgers Haskin Shellfish Research Laboratory. A card-reader was located at Penn State to enable these data, which extend back to 1927, to be digitized. With these data, Dr. Najjar was able to reproduce results from a 1972 Haskin report relating salinity to streamflow, and add more recent salinity data to quantify long term trends in the region (Appendix B). A preliminary analysis suggests that salinity is increasing more than can be explained by streamflow and simple models of the response of salinity to sea-level. This could be a result of other forces in the Estuary, such as successive channel deepening events that occurred during the period of analysis, and which could have also contributed to salinity intrusion upbay due to larger tidal volumes and bathymetric changes (Appendix B).

Chapter 3

Case Study #1: Tidal Wetlands

Coastal wetlands are arguably the Delaware Estuary's most important and characteristic habitat. There are two traits that distinguish this system from others. First, there is a near contiguous border of more than 150,000 hectares of tidal wetlands that fringe Delaware Bay and the lower estuary region. Second, the system has the largest freshwater tidal prism in the world, and the extended salinity gradient leads to a rich diversity of marsh types.

Tidal wetlands are at risk from a variety of climate change impacts, and there is growing concern that hastened wetland loss will translate into lost ecosystem service important for lives and livelihoods. Fifty percent of the original tidal wetlands along the Delaware Estuary have been lost to development and degradation associated with human activities, these losses are continuing today, and much more could be lost by climate change impacts.

3.1 Tidal Wetlands in the Delaware Estuary Watershed

The Delaware Estuary contains diverse tidal wetlands including a variety of types of emergent marshes and forested swamps. Some are flooded regularly by tides and others are irregularly flooded on spring tides or during storms. The most extensive types are marshes dominated by perennial vascular plants. The different marsh communities are mainly delineated by the salinity gradient (Fig. 3-1.) The effects of climate change were examined for the two most ecologically significant wetland types, freshwater tidal marshes and brackish/salt marshes.

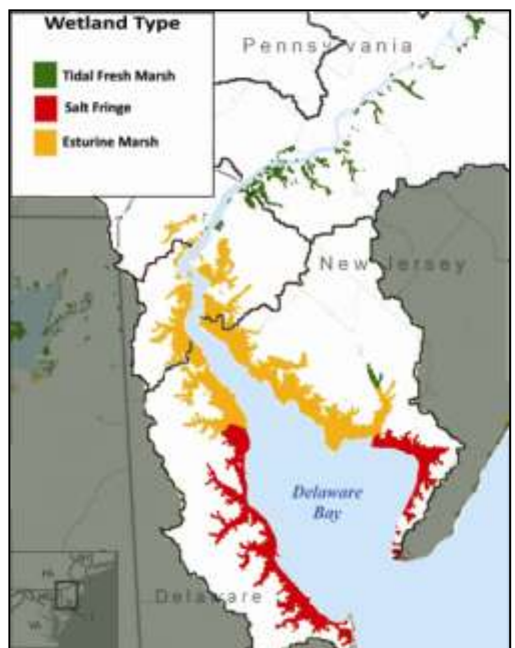


Figure 3-1. Tidal wetlands of the Delaware Estuary (Reed et al. 2008.)

3.1.1. Freshwater Tidal Marshes

Approximately five percent of the original acreage of freshwater tidal marsh remains, amounting to 11,709 hectares based on the latest available 1980s data from the National Wetland Inventory (Appendix G.) Nevertheless, the Delaware Estuary still supports more of this marsh type than any other estuary in the nation. New Jersey contains the greatest percentage, 7302 hectares, and Delaware and Pennsylvania contain 4527 and 380 hectares, respectively.

Freshwater tidal wetlands occur in the upper reaches of large tidal rivers beyond the reach of saltwater. Salinities are less than 0.5 ppt. The characteristic native vegetation species is diverse with dominant species such as wild rice, *Zizania aquatic*, cattails, *Typha* spp., and low marsh species such as arrow-arum, *Peltandria virginica,* pond-lily, *Nuphar lutea*, and pickerelweed, *Pontedaria cordata* (Westervelt et al. 2006). The invasive common reed, *Phragmites australis*, is also abundant, creating dense monotypic stands especially in areas where the natural hydrology has been altered. Freshwater tidal marshes are diurnally flooded and have wide tidal ranges vary from 0.5 to 3 meters (i.e., they are macrotidal.) They contain many rare plant communities and serve as habitat for species such as endangered short-nose sturgeon.

3.1.2. Brackish and Salt Marshes

More than 145,000 hectares of brackish and salt marshes remain in the Delaware Estuary, roughly half in Delaware and half in New Jersey (Appendix G.) These wetlands extend from Cape Henlopen to New Castle, Delaware, and from Cape May to Salem, New Jersey, forming a near contiguous border around Delaware Bay. Since European settlement, approximately a quarter to half of the brackish and salt water wetlands have been altered or converted for other purposes. Many were diked for agriculture, such as salt hay farming and cattle grazing. Others were impounded to create waterfowl hunting opportunities. As with other areas of the Atlantic coast, vegetated tidal marshes in the Delaware Estuary continue to be lost for various reasons. Between 1998 and 2004 alone, more than one percent of Atlantic coast tidal wetlands were destroyed (Stedman and Dahl 2008.)

Brackish and saltwater wetlands occur in the lower reaches of tidal tributaries and along the open shores of Delaware Bay. Salinities range between 0.5 ppt and 30 ppt. The characteristic native vegetation is less diverse than in freshwater tidal marshes particularly in the regularly flooded low areas of salt marshes due to the need for salinity tolerance. In the low marsh areas smooth cordgrass, *Spartina alterniflora*, is the functional and structural dominant species. In the irregularly flooded high salt marsh, important species include salt hay, *Spartina patens*, Saltgrass, *Distichlis spicata*,and high marsh shrubs such as groundsel tree, *Baccharis halimifolia* and Jesuit's bark, *Iva frutescens* along with the invasive form of common reed, *Phragmites australis*. Most salt marshes of the Delaware Estuary are diurnally flooded with narrower tidal ranges (< 1 m, microtidal) than the freshwater tidal marshes.

3.1.3. Ecological Importance of Tidal Wetlands

Tidal wetlands furnish essential spawning, foraging, and nesting habitat for fish, birds, and other wildlife. They function as the ecosystem's "kidneys," filtering contaminants, nutrients, and suspended sediments, allowing for higher water quality than would otherwise occur. Important finfisheries and shellfisheries are supported by tidal wetlands. They sequester more carbon than any other habitat in the watershed. And importantly, they represent our first line of defense against storm surge and flooding. Acre for acre, tidal wetlands likely provide more ecosystem services than any other habitat type in the watershed.

3.2 Tidal Wetlands – Approach to Assessing Vulnerability and Adaptation Options

The vulnerability of tidal wetlands to climate change and potential adaptation options were assessed by a Wetland Workgroup comprised of wetland scientists and managers from both public and private sectors. Participants included specialists in freshwater tidal marshes and salt marshes. For the purposes of this project, the Wetland Work Group operated as a subgroup under the Climate Adaptation Work Group. Initial tasks completed by the group were to:

- Identify the main physical and chemical environmental factors that are likely to change with changing climate and also affect tidal wetlands (Section 3.3.1.)

- Inventory the main climate change vulnerabilities of tidal wetlands in terms of ecological or physiological consequences (Section 3.3.2.)

- Identify various adaptation options that might be used to lower the vulnerability of tidal wetlands to climate change (Section 3.3.3.)

Following the development of inventories of climate drivers, vulnerabilities, and adaptation options for each of the two marsh types (Section 3.3), the Wetland Work Group then:

- Prepared a survey to rank the relative level of concern for how projected changes in four physical and chemical conditions might impact various indicators of wetland health (Section 3.4),
- Used the survey format to poll experts and rank relative vulnerabilities for the two marsh types (Section 3.5),
- Used the survey to rank various adaptation options for their potential to address the vulnerabilities (Section 3.6),
- Reviewed additional supporting documentation regarding tidal wetland vulnerabilities and adaptation options (Section 3.7),
- Ranked the top vulnerabilities and adaptation options after synthesis of information in Sections 3.5-3.7 (Section 3.8),
- Prepared adaptation recommendations (Section 3.9.)

3.3 Wetland Work Group Inventories

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

3.3.1 Climate Drivers

Four climate drivers were identified as most likely to affect tidal wetlands. These are described below along with an initial orientation to how they might affect wetland status in different areas.

Sea level rise. Sea level rise represents the greatest threat to tidal wetlands in the Delaware Estuary, the habitat situated on the "front lines". Tidal marshes maintain an elevation relative to sea level by the accumulation of dead plant matter and sediment. Whether marshes keep pace with sea level rise or not depends on many factors, such as their productivity, sediment supply from other areas, nutrient loadings, wave and current energies, and the rate of sea level rise. This is a delicate balance, and in any given marsh there typically both areas of erosion and drowning as well as areas where the marsh is expanding.

Until about 4000 years ago, the rate of sea level rise was faster than today (about 3 mm per year), and there was considerably less tidal wetland area along the Mid-Atlantic region because that rate was faster than marshes could keep pace with (Day et al. 2000, Najjar et al. 2000.) Then, the rate of sea level rise slowed to approximately 1 mm per year, which allowed tidal marshes to become established and maintain themselves along protected shorelines. During the last 100 years however, the rate of sea level rise in the Delaware Estuary has increased to 3-4 mm per year (Chapter 2.) During this same period, we began to see losses of tidal marsh (PDE 2008, Stedman and Dahl 2008,) presumably due to a mix of direct human impacts and the increased rate of sea level rise. With current projected rates of sea level rise of up to 10 mm per year or more in the coming century (Chapter 2,) it is plausible to expect there to be far more wetlands lost than gained.

The demise of tidal marshes with respect to sea level rise can occur in many ways. Seaward edge erosion can alter the ratio of shoreline edge to marsh area and increase channel and tidal creek scour (Fig. 3-2.) Another common pattern is drowning of interior areas of marsh, especially when insufficient sediments are delivered through tidal exchange or where plant productivity is low. In such cases, the surface elevation of the marsh falls below the threshold needed to keep pace with sea level rise and the marsh drowns (Reed 1995, Cahoon et al. 1999.)

Sea level rise in the Delaware Estuary is likely to be greater than the global average for many reasons (see Chapter 2.) Another local complication is subsidence, which refers to the sinking of land surfaces. Much of the land in the coastal plain of the Delaware watershed is losing elevation (ref.) Since the land is sinking while sea level is also rising, this creates a higher local "relative rate of sea level rise" (RSLR), which marsh communities must keep pace with.

Figure 3-2. Rapid erosion rates are occurring along the seaward margin of many Delaware Estuary salt marshes, as seen here within the mouth of the Maurice River, NJ.

Tidal flooding can only be tolerated by marsh vegetation to a certain physiological limit, so increases in tidal range associated with rising seas may also affect plant productivity, potentially creating a negative feedback, whereby reduced production compromises the ability to accumulate organic matter and grow vertically. Sparse vegetation traps less sediment. Once the marsh community begins to lose elevation relative to sea level, it can become more susceptible to storm surge erosion that accompanies storm events.

The vulnerability of tidal marshes to sea level rise can be exacerbated by the presence of excess nutrient loadings (Turner et al. 2004.) Recent studies have shown that excess nutrients can promote greater aboveground plant production at the expense of belowground production. Belowground production is important for peat formation (for vertical accretion) since much of the aboveground production decomposes in situ. Tall and leggy marsh plants tend to occur in nutrient-laden areas, and since there is little rhizome structure to hold place these marshes can be highly sensitive to storm surges. The Delaware Estuary has some of the highest concentrations of nutrients compared to other large American estuaries (Sharp et al. 1982, Sharp 1988, 1994,) however this system has not shown the tell-tale signs of eutrophication such as algal blooms, hypoxia, and fish kills. One reason for this is the natural high turbidity which inhibits phytoplankton production in many areas. Although relatively unstudied, the extensive fringing tidal wetlands might also be serving as a nutrient sink. More study is therefore warranted to ascertain whether nutrient loadings compound the vulnerability of tidal wetlands to the effects of sea level rise.

Sediment supply from rivers is also needed for marshes to maintain themselves with sea level rise. In recent decades the supply of sediments entering the estuary from major rivers has been decreasing. Maintenance dredging of the shipping channel removes more sediment each year than is imported from the rivers. It is unclear whether sediment management practices, channel configuration and depth, and changing hydrodynamics associated with sea level rise contribute to sediment deficits for tidal marshes.

Tidal inundation into formerly non-tidal areas can also create opportunities for invasive species, such as *Phragmites australis.* This invasive has been observed colonizing former freshwater forested wetlands following meadow dike breaches (K. Philipp, D. Kreeger, Pers. Commun.)

Salinity. The effects of salt water on tidal marshes are problematic for freshwater tidal marshes and freshwater tidal swamps that cannot tolerate salinities greater than half a part per thousand. Salt water intrusion into freshwater areas can occur in short bursts during storms or over longer time periods with relative sea level rise. In either case, shifting salinity zones will drive shifts in marsh communities.

Not only plants, but animal and microbial communities will be altered by salt intrusion particularly in poorly flushed areas (Weston, 2006; Craft et al., 2008, Weston et al., 2009). As plants with a low salt tolerance become stressed, less productive and die, marsh communities shift to salt-tolerant species.

Conversion to saline conditions can also alter soil types, affect evapotranspiration rates, and alter anaerobic decomposition rates. Typically, carbon dioxide (CO_2) gets reduced to methane (CH_4) in freshwater marshes, and a shift to sulfate (SO_4^{-3}) reduction in salt marshes will increase the rate at which organic matter is decomposed, increasing the loss of carbon stored in marsh soils.

Temperature. Increased temperatures will boost production and decomposition rates, but also lead to reduced soil moisture and increased salinity because of greater evapotranspiration. The associated stress from desiccation and/or salinity could offset the higher productivity. Increased temperatures will also promote the northern migration of southern species.

Precipitation and Storm Events. Changes in precipitation patterns are projected to bring an increase in the frequency of both droughts and heavy precipitation storm events, whereas changes in storm intensity could bring greater threats of storm surge and flooding. Projected increases in cool season precipitation will help to offset increases in salinity during the non-growing times of the season, and during the growing season it may be hotter with no marked change in precipitation (Chapter 2.) Taken together with projected increases in strong storms, it is likely that weather will be more oscillatory with greater abrupt swings in salinity and flooding. In salt marshes, such oscillations are believed to contribute to marsh die-back (browning) (Bason et al. 2007.) Low rainfall periods can lead to oxidation of soils and extremely high soil salt concentrations, detrimental to all but extremely halophytic species. When soils are then suddenly flooded and become reduced, they can become toxic to marsh plants.

In both salt and fresh water wetlands, increased desiccation or flooding can also alter sediment supply and erosion. Productivity may be affected by changes in rainfall. Excessive or abrupt shifts in drought, heat waves, and "unseasonably" wet or cold periods can also overwhelm the physiological tolerance limits of some plants and animals.

In general, an increase in precipitation should offset some negative effects of relative sea level rise and salinity increases on tidal wetlands. Aboveground productivity of salt marsh plants is correlated with precipitation patterns, with greater production occurring in years of high precipitation in wetland areas with relatively high salinity levels (De Leeuw et al. 1990, Gross et al. 1990). However, increased frequency and intensity of storm events will impair tidal wetlands through wind, wave, and surge effects. Such disturbances could also make marshes more susceptible to aggressive, non-native species invasions.

Atmospheric CO_2. Increased atmospheric CO_2 concentrations will affect the composition of wetland plant communities by shifting conditions to be more suitable for plants that fix carbon using a C_3 pathway instead of the C_4 pathway. This is important because the current functional dominant plants of Delaware Bay salt marshes are *Spartina* grasses that are C_4 species. Species that will be favored will be sedges and rushes that are currently more common in brackish and freshwater wetlands. While not being directly harmful to C_4 plants, increased CO_2 concentration will stimulate C_3-species (Curtis et al. 1990, Rozema et al. 1991), helping them better compete with C_4 plants (Curtis et al. 1990, Ehleringer et al. 1991). Potentially, this shift in species could lower productivity since C_4-species are more efficient in fixing C, and overall resilience to disturbance could be reduced since the C_3 species are not as good at conserving water (Chapin et al. 2002).

Over all plant species, elevated carbon dioxide levels will increase overall productivity of tidal marshes, potentially helping these wetlands accrete faster and keep pace with sea level rise (Langley et al. 2009.) Increasing atmospheric CO_2 will also affect transpiration rates through greater leaf CO_2 exchange over shorter periods of time. Stomates can be opened for shorter periods of time to allow for this exchange, which will cut water loss through these tiny pores thereby helping the plants stave off desiccation stress. Taken together, elevated CO_2 will have both positive and negative effects of tidal marsh ecology and it is difficult to predict net outcomes.

3.3.2 Inventory of Vulnerabilities.

Numerous aspects of tidal wetland health were identified for use in vulnerability assessments. These are briefly described below with an initial orientation to how they might vary between the two wetland types in relation to changes in climate drivers within the Delaware Estuary.

Shifts in Community Species Composition. The presence of various community assemblages of plants and animals is largely determined by the geomorphology, salinity and temperature. As these conditions change in tidal marshes of the Delaware Estuary, the dominant vascular plants will shift along with associated invertebrates. Species that use a C4 photosynthetic pathway will be favored over C3 plants. Invasive species also tend to be effective competitors under disturbed conditions. Shifts in dominant plant species may affect the net ecosystem services furnished by tidal wetlands (Roman and Daiber 1984.)

Desiccation of Marsh Sediments. Wetland condition is obviously sensitive to the wetness of the soil. With rising temperatures and more oscillatory weather (Chapter 2,) sediments in tidal marshes are projected to experience more frequent periods of both dryness and saturation. Frequent alternation of dryness and wetness can affect sediment geochemistry and lead to the formation of free radicals that are toxic to marsh rhizomes, potentially contributing to episodes of marsh dieback.

Change in Habitat Support. The value of tidal marshes as habitat for fish and wildlife is closely tied to the vegetation type, structural integrity and productivity of the vascular plants (Minello and Zimmerman 1983, 1992). Since changes in climate conditions are projected to affect the plants in various ways, their habitat support value will also change.

Productivity. In general, increased temperature and CO_2 will promote greater primary production by vascular plants (Kirwan et al. 2009, Langley et al. 2009) and secondary production by bacteria and animals is expected to follow. However, plant production is sensitive to many factors, such as species composition, salinity, storms, tidal range and nutrient conditions.

Ability of Accretion Rate to Equal RSLR Rate. Tidal marshes must accumulate organic matter and sediments (accretion) at a rate that matches the net change in water level to be sustainable. Local changes in water level in the Delaware Estuary differ from global sea level changes due to many factors (Chapter 2,) and the ecologically meaningful, net change is referred to as the rate of relative sea level rise (RSLR). In many areas of the Estuary, the RSLR appears to exceed the accretion rate of tidal marshes, particularly in the microtidal salt marshes of Delaware Bay and particularly on the New Jersey side of Delaware Bay (Kearney et al. 2002, Kreeger and Titus 2008.) Freshwater tidal marshes of the upper estuary experience macrotidal conditions and are closer to river-derived sediment supplies, and they therefore appear less vulnerable to this factor.

Ability for Landward Migration. With more rapid rises in the sea, the best hope for tidal marshes may be landward migration into suitable natural areas. During landward migration, low marsh species move into high marsh areas, and high marsh species take over upland habitats. Salt marshes also replace brackish and freshwater marshes. Landward migration occurs if there is a gentle slope, suitable sediment, and no barriers. But in the Delaware Estuary, migration is impeded in many areas because of coastal development and hard structures (PDE 2008.) In these areas, community shifts will favor low marsh species until ultimately tidal flooding limits plant survival and marsh areas convert to open water or intertidal mud flats (Section 3.7.2.)

Change of Marsh Area. The total area of tidal wetlands will be determined by the balance of acreage gained through landward migration and lost through conversion to open water or mud flats (Section 3.7.2.) There are likely to be local exceptions where marshes expand seaward, but the expected net change in marsh area is expected to be negative.

Increased Tidal Range. The configuration of the Delaware Estuary is such that tidal amplitude increases in the uppermost areas, ranging from about one meter in Delaware Bay to more than 3 meters in tidal tributaries toward Trenton, New Jersey. Tidal range effects many geomorphological, biogeochemical and ecological processes. As the total tidal volume of the Delaware Estuary increases with sea level, tidal range in the upper estuary is expected to increase, with concomitant effects on marsh ecology.

Ratio of shoreline edge to marsh area. Sea level rise and associated erosion are increasing the area of open water within tidal marshes of the Delaware Bay. Tidal creeks appear to be widening, and interior areas of many marshes are ponding. This trend leads to a net increase in the amount of shoreline edge relative to the total area of vegetated marsh. The ratio of edge to area affects many important marsh functions, such as the usefulness as habitat, productivity, and susceptibility to erosion.

Rate of Channel Scour. As tidal creeks widen within marshes, tidal amplitude increases, and the flushing volume per tide increases with sea level, the hydrodynamic scouring of channel bottoms is expected to also increase. Channel scouring contributes to erosion, potentially producing a positive feedback whereby greater erosion contributes to more open water, tidal flushing and scouring (Day et al. 1998)

Storm surge susceptibility. Storms can have positive and negative effects on tidal marshes. The surge associated with some types of storms can deliver needed sediments that help marshes accrete and keep pace vertically with rising sea level (Reed 1989) On the other hand, storms can be physically damaging and erosive for marshes, and they can decimate freshwater tidal marshes if saltwater accompanies the surge.

Salt Water Intrusion to Fresh Water Habitats. Animals and plants that are adapted to freshwater tidal and brackish conditions are intolerant of rising salinity. Salt stress associated with gradual increases in sea level will slowly but inevitably push these species assemblages further up the estuary and tidal tributaries (see Feature 3.1). The effects of storms can be more sudden if salt water is driven into freshwater areas.

Salt exposure/stress event. Salt marshes are uniquely adapted to seawater exposure, but extreme temperatures and droughts can lead to hypersaline (over 100 psu) conditions on the high marsh. These brines, also called salt pannes, stunt plant growth and can beyond the physical limits of many animals. Although they are a natural feature of salt marshes, changing climate conditions could lead to more hypersaline conditions in more areas, in turn decreasing marsh production and habitat support.

3.3.3 Inventory of Adaptation Options

The Wetland Work Group identified six potential management tactics for helping tidal wetlands adapt to climate change in the Delaware Estuary. Some of these are more applicable to specific marsh types or areas. Some tactics are straightforward restoration activities that double as climate adaptation tactics. Adaptation options are described below along with an initial orientation to how they might address key vulnerabilities by the principal types of wetland habitats.

Watershed flow management. River flows are largely regulated in the upper portions of the Delaware watershed to provide drinking water for people (Chapter 4.) Flows can also be managed to safeguard the public from floods and to ensure sufficient flows to protect environmental health, offset negative impacts of drought, storm surge, and sea level rise in the Estuary. Since freshwater tidal wetlands are vulnerable to storm surge, sea level rise and salinity, flow management represents an adaptation measure for sustaining these habitats.

Figure 3-3. A living shoreline being installed along an eroding salt marsh in Delaware Bay.

Strategic retreat. Strategic retreat is defined in different ways. It sometimes refers to the planned relocation of built structures and development from the coast to areas inland, thereby providing a more natural protective buffer to avoid the devastating effects of natural disasters that occur in the coastal zone. For example, the relocation of the Cape Hatteras Lighthouse (Titus et al. 2009a) was a form of strategic retreat. Strategic retreat can also refer to the acceptance that an area will become inundated by open water, and therefore not be developed. In the case of tidal marshes or other natural habitats, one management option is to accept that some areas will not be selected for preservation efforts if they are not deemed appropriate for protective structures to preserve human development.

Structure setbacks. Structure setbacks prohibit development on land that is expected to erode or be inundated within a given period of time. Structure setbacks can prevent erosion or flood damage as well as allow wetlands to migrate inland as sea level rises. Two counties in Delaware currently prohibit development in the 100-year floodplain along the Delaware River and Delaware Bay (Titus et al. 2009a).

Creation of buffer lands. The creation of buffer lands requires the protection, maintenance, and/or establishment of natural habitat types that lie between developed lands and tidal wetlands. This allows tidal wetlands to migrate inland with less impact to human development.

Living shorelines. Living shorelines are natural enhancements to marsh edges that are typically eroding and which provide much greater ecosystem services than traditional structural solutions to erosion such as bulkheads and rip rap. Living shorelines soft armor the marsh edge using natural or degradable materials such as plants, shell, stone, and other organic materials (Fig. 3-3.) Living shorelines typically slow shoreline retreat by augmenting natural stabilization processes.

Building dikes, bulkheads, and tide gates. Dikes are impermeable earthen walls designed to protect areas from flooding or permanent inundation by keeping the area behind them dry. Many areas of the Delaware Estuary that were once tidal wetlands have been diked for other purposes such as waterfowl hunting and salt hay farming. Dikes are usually associated with a drainage system to channel flood water away from vulnerable lands and infrastructure. Due to the long period of sea level rise since many dikes were built around the Delaware Estuary, many diked lands are below mean low water, requiring pumping systems to remove rainwater and seepage (Titus et al. 2009a). According to the Delaware Coastal Program office, no dikes or levees within the State of Delaware are capable of standing up to a one meter rise in sea level.

Bulkheads are walls built in the shallow subtidal or intertidal zone to protect adjacent uplands from erosion by waves and current. Bulkheads hold soils in place but they do not normally extend high enough to protect against storm surge (Titus et al. 2009a). Although bulkheads can be used to protect against erosion, they impair ecological processes and are inferior habitats for fish and wildlife (e.g., Bilkovic and Roggero 2008).

Tide gates are barriers across small creeks or drainage ditches that permit freshwater to exit during ebb tides but prevent tidal waters to enter on flood tides (Titus et al. 2009a). They are effective at permitting low-lying areas just above mean low water to drain without the use of pumps, but they can impede natural ecological processes in areas that were often former tidal wetlands.

3.4 Tidal Wetlands – Survey Methods

Climate change vulnerabilities and potential adaptation options were examined separately for freshwater tidal wetlands and brackish/saltwater wetlands. The Wetland Work Group relied on the initial inventory (Section 3.3) to prepare a survey, which was sent to more than forty wetland scientists and managers in the region.

Survey Monkey™ was used to construct and operate the poll. Each respondent was first asked to rank the relative vulnerability of a particular wetland metric (Section 3.3.2) in response to a particular climate change driver (Section 3.3.1), and this was repeated for each of the two marsh types. Respondents were provided with the most current predictions tailored to our estuary watershed (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 asked to consider all direct and indirect ecological relationships. They were also encouraged to “think outside the box” about adaptation options, and not to limit themselves those consistent with current management practices. Managers currently operate under place-based paradigms for “no net loss,” which resist dynamic habitat changes in the coastal landscape. Perspectives on the relative importance of various ecosystem goods and services provided by wetlands might change over time, resulting in concomitant shifts in policies and priorities for flood protection, habitat restoration, strategic retreat, invasive species control, mosquito control, waterfowl management, and fisheries management, as examples. Management paradigms will shift in the future as these perspectives evolve.

Survey respondents were also asked to consider all responses and ratings in comparative fashion across the entire survey. For example, the vulnerability of freshwater tidal marshes to salinity intrusion was compared relative to the potential vulnerability of salt marshes to storms.

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 answer, ranging from no confidence to high confidence. Therefore, respondents with more expertise or knowledge for some situations were permitted to adjust their confidence higher than for situations that they are less familiar with.

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 Appendix H.)

Not all climate change impacts are expected to impair tidal wetlands, and some positive benefits might occur. In answering questions about ecosystem services, respondents were ask to discern whether the "vulnerability" would lead to a net "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 adaptation options listed in Section 3.3.3 to offset the vulnerabilities. Respondents were asked to rank both the tactic's effectiveness and feasibility as high, medium or low. Effectiveness and feasibility responses were weighted, averaged among the respondents, and then multiplied together to derive a composite score. Table 3-1 lists the most important vulnerabilities that were identified due to changes in the five physical drivers, along with potential adaptation options.

Table 3-1. Principal climate drivers, tidal wetland vulnerabilities, and adaptation options in the Delaware Estuary that were identified by the Wetland Work Group.

Climate Drivers	Wetland Vulnerabilities	Adaptation Options
Sea Level Rise	• Shifts in Community Species Composition • Ability of Accretion Rate to Equal RSLR Rate • Ability for Landward Migration • Change of Marsh Area • Increased Tidal Range • Ratio of shoreline edge to marsh area • Rate of Channel Scour • Storm surge susceptibility	• Monitor/Research Vulnerability • Beach/marsh nourishment • Elevating homes/structures • Dikes and Bulkheads - short term management or removal • Structure Setbacks; Strategic Retreat • Rebuilding infrastructure • Creation of Buffer Lands • Living Shorelines
Salinity Range Increase	• Shifts in Community Species Composition • Salt Water Intrusion to Fresh Water Habitats; Change in Habitat Support • Salt exposure/stress event • Productivity; Invasive Species	• Monitor/Research Vulnerability • Watershed flow management • Salt barrier • Strategic Retreat; • Creation of Buffer Lands
Temperature Change	• Shifts in Community Species Composition • Desiccation of Marsh Sediments • Change in Habitat Support • Productivity; Invasive Species	• Monitor/Research Vulnerability
Precipitation & Storm Events	• Shifts in Community Species Composition • Salt exposure/stress events • Change in Habitat Support • Productivity • Desiccation, flooding or erosion • Sediment supply • Physical impacts by wind, waves and surge	• Monitor/Research Vulnerability • Beach/marsh nourishment • Elevating homes/structures • Dikes and Bulkheads - short term mgmt. or removal to create incentives for landward migration • Structure Setbacks; Strategic Retreat • Rebuilding infrastructure • Prioritize lands to preserve • Living Shorelines
Atmospheric CO_2 increase	• Shifts in Community Species Composition • Productivity	• Monitor/Research Vulnerability • Carbon Trading (acquisition incentives for landward migration)

3.5 Tidal Wetlands – Vulnerability Assessment

The relative vulnerability of the two types of tidal wetlands to changes in climate conditions, as judged by wetland specialists who responded to the survey (Section 3.4) is discussed below in Sections 3.5.1 (Freshwater Tidal Wetlands) and Section 3.5.2 (Brackish/Saltwater Wetlands.) Since there were many different cause-effect results (2 wetland types, 5 climate drivers, 10 wetland outcomes), only example data are shown here for the predicted impacts and associated confidence in the survey rankings. Full survey responses are provided in Appendix H. To summarize the relative differences among wetlands and climate drivers, impact and confidence responses were integrated into a composite vulnerability index, which is shown in Section 3.5.4.

3.5.1 Vulnerability of Freshwater Tidal Wetlands

Estimated impacts varied among the five climate drivers, but the relative importance of the drivers depended on which aspect of freshwater tidal wetland status was examined. The vulnerability to salinity rise was the topped ranked driver that could affect the plant community composition of freshwater tidal wetlands, followed by sea level rise (see blue bars in Fig. 3-4.) This was because any exposure to saltwater is likely to cause acute stress for plants (and animals) that are adapted to freshwater conditions. Temperature rise and changes in precipitation and storms were regarded with moderate concern, whereas marsh vulnerability to increased levels of carbon dioxide was rated as the least concern for the drivers in the poll. Survey response confidence also varied but was generally high for all drivers except carbon dioxide changes.

Shifts in community composition was one of the top-rated vulnerabilities of freshwater tidal wetlands. Changes in habitat support, landward migration potential, and the net change in marsh area were also viewed as high concerns for survey respondents (see Appendix H for full responses.) Changes in productivity and interactions with invasive species were rated as lowest concerns overall.

In general, tidal freshwater wetlands were viewed as being most vulnerable to salinity rise, followed by sea level rise, followed by storms and precipitation changes, followed by temperature and carbon dioxide changes (Appendix H.) Salt water intrusion into upper estuary areas is expected to squeeze suitable habitat for freshwater tidal wetlands because their landward migration is impeded by the fall line as well as by >85% development in the immediate one kilometer landward (Battelle 2006.) In transitional salinity areas, freshwater tidal marshes will be replaced by brackish marshes, thereby causing major shifts in species composition (e.g., plant, animal and microbial), and likely altering many functions of habitat support for fauna (see also Section 3.7.2.)

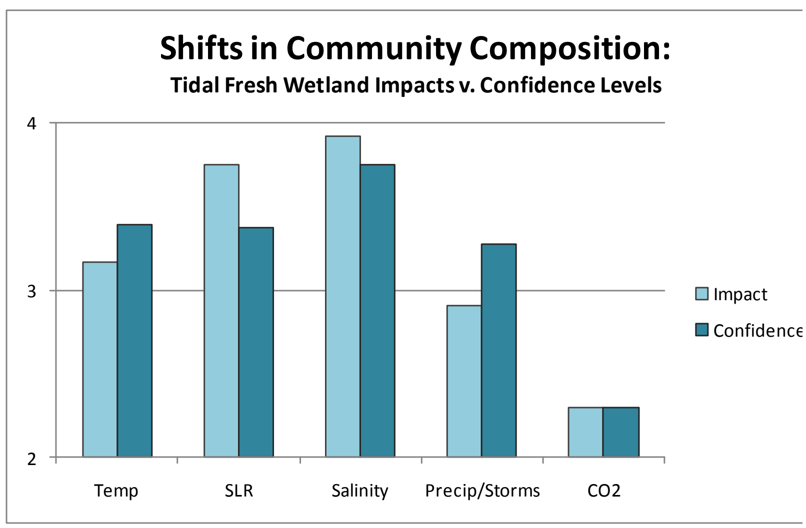


Figure 3-4. Relative levels of concern regarding the potential impact of changing conditions on the **community composition of tidal freshwater wetlands** (light blue) and relative confidence in these projections (dark blue.)

3.5.2 Vulnerability of Brackish/Salt Water Wetlands

Sea level rise elicited the greatest concern for brackish and salt marshes out of the various physical and chemical drivers that may change with climate. The greatest vulnerabilities are predicted to be the inability to keep pace with sea level rise through vertical accretion, the inability to migrate landward, shifts in species composition (Fig. 3-5,) loss of suitable marsh area, increased seaward edge erosion, and increased susceptibility to storm surge. Also of high concern was an expected increase in tidal range and a change in the ratio of marsh edge to interior area, both of which are expected to increase with an increasing rate of sea level rise.

Similar to freshwater tidal wetlands, the estimated impacts of changing climate on brackish/salt water wetlands varied among the five climate drivers. Sea level rise clearly elicited the most concern. However, brackish/salt marshes were regarded as also vulnerable to temperature rise, salinity rise, and changing storm and precipitation conditions. Increased atmospheric CO_2 was not rated as being as important (Fig. 3-5.) Survey response confidence varied, being highest for sea level rise effects and lowest for the effects of carbon dioxide changes.

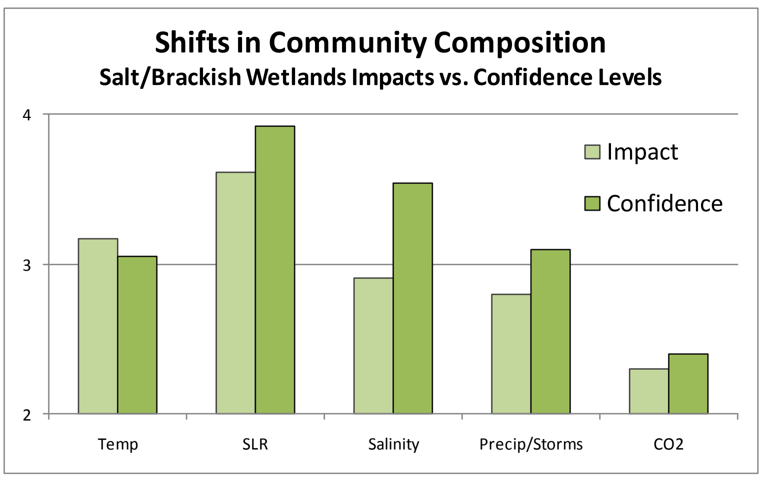


Figure 3-5. Relative levels of concern regarding the potential impact of changing conditions on the **community composition of brackish and saltwater wetlands** (light green) and relative confidence in these projections (dark green.)

The most vulnerable of the various wetland responses was deemed to be overall marsh area (see Appendix H for full responses.), followed closely by the landward migration ability, vertical accretion rate, amount of edge erosion, and shifts in community composition (shown in Fig. 3-5). For all these responses, the most significant climate driver was sea level rise. Wetland status metrics that were not rated as much of a concern included the amount of channel scouring, the amplitude of the tidal range, and interactions with invasive species (e.g., see Appendix F.)

Table 3-2. Relative levels of concern regarding the potential impact of changing temperature, sea level, salinity, precipitation/storms and carbon dioxide on the various aspects of the status of tidal freshwater wetlands and brackish/saltwater wetlands in the Delaware Estuary.

Vulnerability Assessment - Tidal Wetlands

	Tidal Fresh	Tidal Salt/Brackish
	Temperature Change	
Shifts in Community Species Composition	Med-High	Med-High
Desiccation of Marsh Sediments	Med-Low	Low
Change in Habitat Support	Med-Low	Med-Low
Productivity	Med-Low	Med-High
Invasive Species	Med-Low	Med-Low
	Sea Level Rise	
Shifts in Community Species Composition	High	Highest
Ability of Accretion Rate to Equal RSLR Rate	Med-High	Highest
Ability for Landward Migration	High	Highest
Change of Marsh Area	High	Highest
Increased Tidal Range (Upper River)	Med-High	High
Ratio of shoreline edge to marsh area	Med-High	High
Rate of Channel Scour	Med-High	Med-High
Storm surge susceptibility	High	Highest
Seaward edge erosion	High	Highest
	Salinity Range Increase	
Shifts in Community Species Composition	Highest	Med-High
Salt Water Intrusion to Fresh Water Habitats	Highest	Med-High
Salt exposure/stress event	High	Med-Low
Change in Habitat Support	Highest	Med-Low
Productivity	Med-High	Med-Low
Invasive Species	Med-Low	Med-Low
	Precipitation & Storms	
Shifts in Community Species Composition	Med-High	Med-Low
Salt exposure/stress events	Med-High	Med-Low
Change in Habitat Support	Med-Low	Med-Low
Productivity	Med-Low	Med-Low
Desiccation, flooding or erosion	Med-High	Med-Low
Sediment supply	Med-High	Med-Low
Physical impacts by wind, waves and surge	Med-High	Med-High
	Atmospheric Carbon Dioxide	
Shifts in Community Species Composition	Low	Low
Productivity	Low	Low

5.5.3 Comparison of Tidal Wetland Vulnerabilities

Composite vulnerability indices for freshwater tidal wetlands and brackish/saltwater wetlands were contrasted among various responses that might result from each of the five climate drivers. Since most responses were not applicable between the two wetland types, only one example is shown in Figure 3-6.

Survey respondents rated freshwater tidal wetlands and brackish/saltwater wetlands as similarly vulnerable to temperature and precipitation storms, and atmospheric carbon dioxide effects were considered to be less of a concern for both marsh types. The top two concerns were sea level rise (more for brackish/saltwater wetlands) and salinity rise (more for freshwater tidal wetlands).

The relative vulnerability index (combined impact and confidence) for various cause-effect relationships was compared between freshwater tidal wetlands and brackish/saltwater wetlands (Table 3-2). In general, there was a greater number of moderate to high vulnerabilities for cause-effect scenarios for freshwater tidal marshes than brackish/salt marshes. But the most consistently strong survey responses were for brackish/salt marshes exposed to elevated sea level. All aspects of brackish/saltwater wetlands were viewed as at least moderately vulnerable to sea level rise with six out of the nine metrics being rated the highest vulnerability index. There was comparatively less concern for the effects of other changes in climate conditions on brackish/saltwater wetlands. The Wetland Workgroup noted that these wetland metrics are just examples of the myriad processes and elements of marsh ecology that might be affected by changing climate (e.g., see Feature 3-1.)

Feature 3-1. Marsh Soil Microbes and Sea Level Rise

By Tatjana Prša, Graduate Student, Villanova University

Microbial organisms in marsh soils could be impacted by sea-level rise, therefore changing decomposition rates of organic materials. The marshes ability to keep pace with sea-level rise relies on a fine balance between decomposition rates and accumulation of organic matter in the soils. In freshwater marshes contain predominantly methanogenic and saltwater marshes contain mostly sulfate-reducing bacteria. Studies by Drs. Melanie Vile and Nathaniel Weston of Villanova University, suggest that within three months of saltwater intrusion, sulfate reduction rates increase significantly in freshwater marshes, and saltwater marshes shift towards a more diverse community of microbes. Since the overall rate of decomposition is faster with sulfate-reducing bacteria, freshwater soils would decay organic matter at an accelerated rate, releasing more carbon dioxide speeding up saltwater intrusion. Increased decomposition in freshwater marshes may compromise their ability to keep pace with sea-level rise. These results paint a troubling picture for freshwater marshes that experience saltwater intrusion in the Estuary.

3.5.4 Associated Changes in Ecosystem Services

Survey participants were asked to estimate whether ecosystem services furnished by freshwater tidal wetlands will increase, decrease, or not change in response to each cause-effect relationship (e.g., salinity rise affecting community composition.) An increase in salinity was predicted by more survey takers to have an overall negative effect on ecosystem services (Fig. 3-8.). Comprehensive results for ecosystem service outcomes from other cause-effect relationships are provided in Appendix H. Less than 15% of respondents were uncertain for these cause-effect scenarios.

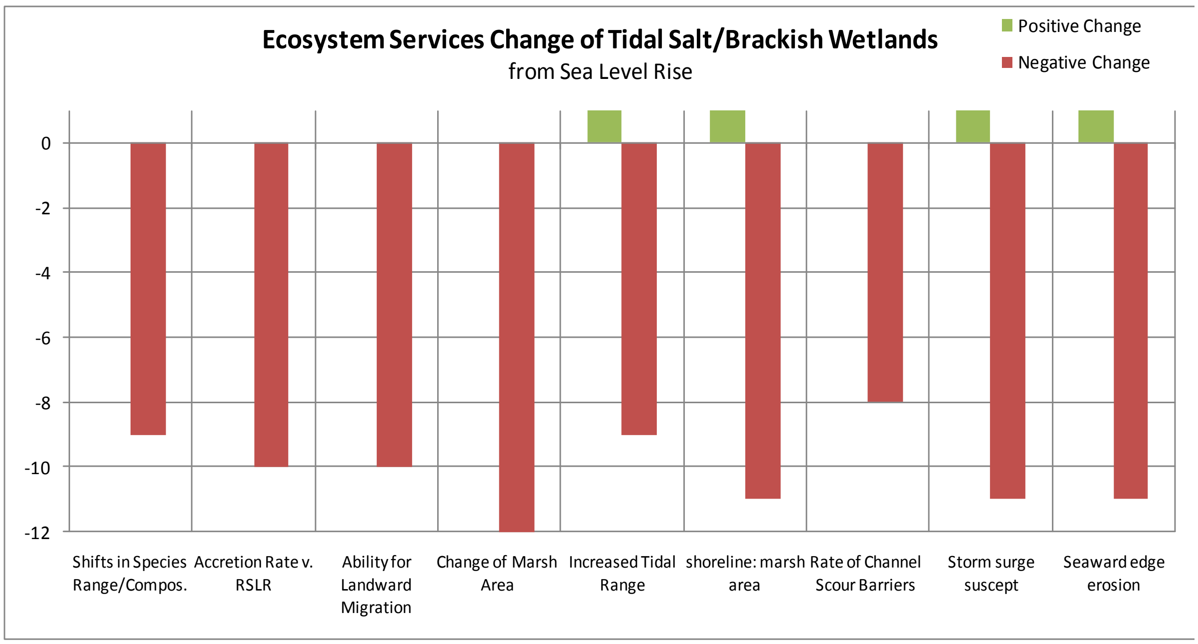


Figure 3-9. Number of survey participants who predicted either net positive or net native changes in ecosystem services by saltwater and brackish wetlands in response to projected rises in sea level by 2100. Survey responses indicating no net change or uncertain change are not shown.

Sea level rise was also viewed by more respondents as likely to cause net decreases in services by freshwater tidal wetlands, however a minority also predicted some positives (Fig. 3-9.) An increase in sea level will have a negative effect on brackish/salt marsh area, and so this was thought to directly reduce ecosystem services through a loss of habitat. See Appendix H for more expected ecosystem service outcomes. Important net losses of services were also predicted for the inability of tidal wetlands to move inland in response to seal level rise and salt water intrusion due to impediments to landward migration, getting squeezed and losing area. Only one positive ecosystem service outcome was predicted by the balance of survey takers, and this was for the effect of elevated carbon dioxide on tidal wetland productivity (Appendix H.)

3.6 Tidal Wetlands - Adaptation Options

Numerous climate adaptation tactics exist that can potentially help address the vulnerabilities of tidal wetlands. As a first effort to prioritize which of these offer the most promise, respondents to the Wetland Work Group survey rated the feasibility and effectiveness of various adaptation tactics that were described in Section 3.3.3 in terms of their ability to offset vulnerabilities of tidal wetlands. Their responses are summarized in Table 3-3 and more detail on the relative effectiveness/feasibility ratings are provided in Appendix H.

Table 3-3. Comparison of the effectiveness and feasibility of various potential adaptation options for addressing the main vulnerability of tidal freshwater wetlands and brackish/saltwater wetlands exposed to changing sea level, salinity, precipitation/storms, and carbon dioxide levels by 2100 in the Delaware Estuary.

Adaptation Options	Tidal Fresh	Tidal Salt/Brackish
Sea Level Rise		
Beach/marsh nourishment	Med-High	Med-Low
Elevating homes/structures	Med-Low	Med-Low
Dikes, Bulkheads, and Tide Gates	Med-High	Med-High
Structure Setbacks	High	Med-High
Rebuilding infrastructure	Med-High	Med-High
Strategic Retreat	Highest	Highest
Creation of Buffer Lands	Highest	High
Living Shorelines	High	High
Salinity Range Increase		
Watershed flow management	High	Med-High
Salt barrier	Low	Low
Strategic Retreat	Med-High	Med-High
Creation of Buffer Lands	Med-Low	Med-Low
Precipitation & Storms		
Beach/marsh nourishment	Low	Med-Low
Elevating homes/structures	Low	Med-Low
Dikes, Bulkheads, and Tide Gates	Med-Low	Med-High
Structure Setbacks	Med-High	Med-High
Rebuilding infrastructure	Med-Low	Med-High
Strategic Retreat	Med-High	Med-High
Creation of Buffer Lands	Med-Low	Med-High
Living Shorelines	Med-High	Med-High
Atmospheric Carbon Dioxide		
Carbon Trading	Med-High	Med-High

Activities that facilitate the landward migration of tidal marshes were rated as having the greatest promise, especially for addressing the vulnerabilities associated with sea level rise (Table 3-1.) These activities include clearing the path to allow for landward migration of tidal marshes (strategic retreat), structure set-backs, and creation of buffer lands between development and marshes (e.g. forests) to allow for landward migration. These were ranked highest for both freshwater tidal and brackish saltwater wetlands (Table 3-1.) Adaptation options for dealing with sea level rise were ranked higher than tactics for addressing salinity, storms, and carbon dioxide.

To address salinity rise, survey respondents indicated that watershed flow management is the best adaptation option, especially for helping reduce the higher vulnerability of freshwater tidal wetlands to saltwater.

Carbon trading was the only adaptation option identified for offsetting the negative effects on atmospheric CO_2 on both tidal fresh and tidal brackish/salt water wetlands. This was considered a moderate to highly effective and feasible option.

Living shoreline tactics that can help to reduce erosion and enhance ecosystem services were also rated highly for addressing both sea level rise and storms/precipitation. Bulkheads, dikes and tide gates were rated similarly for their effectiveness in decreasing marsh vulnerability. On the other hand, sediment nourishment, the elevation of structures (to allow for more tidal flow,) and creation of salt barriers were given low marks by survey respondents (Table 3-3.)

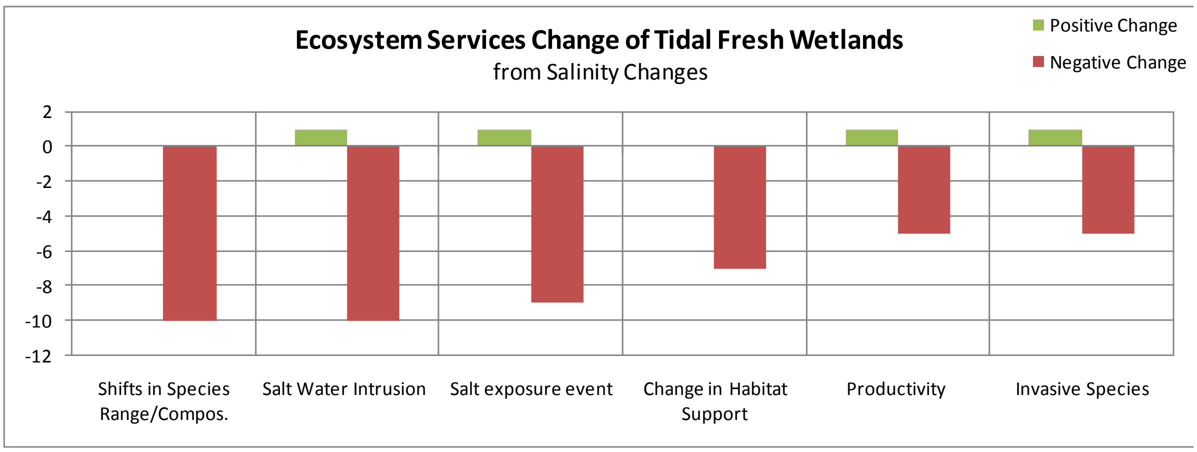


Figure 3-8. Number of survey participants who predicted either net positive or net native changes in ecosystem services by tidal freshwater wetlands in response to projected rises in salinity by 2100. Survey responses indicating no net change or uncertain change are not shown.

3.7.2 Future Changes in Tidal Wetland Ecosystem Services

In support of the Climate Ready Estuaries pilot, EPA awarded a Technical Assistance grant for Industrial Economics (IEc) to more accurately predict climate change impacts on tidal wetlands and corresponding ecosystem services changes in the Delaware Estuary (Appendix G.) Rates of primary production were examined as an example ecosystem service. In addition, the IEc analysis included a comparison of projected outcomes from two different types of wetland restoration efforts at two time periods (2020 and 2050).

Table 3-4. Data used by IEc to forecast future changes in tidal marsh acreage in the Delaware Estuary using the Sea Level Affecting Marsh Model (SLAMM.)

Inputs for SLAMM model
National Wetlands Inventory Data
Sea Level Rise Predictions: IPCC & Titus
Elevation Data
Accretion Rate Data
Tide Gauge Data
Erosion Rate Data

Wetland Acreage. IEc used Version 6 of the Sea Level Affecting Marshes Model (SLAMM) to predicted changes in wetland acreage, transitions of wetland types, and potential wetland migration areas following a similar approach to that used by Craft et al. (2009.) Twenty-three wetland classes were used based on the attributes adopted by the National Wetlands Inventory (NWI). The SLAMM model incorporated data linking various physical factors to marsh change (Table 3-4,) thereby calculating acreage gains and losses in each of the wetland classes (including tidal flats and open water). Therefore, the total acreage remained constant even though there were predicted to be big shifts from some habitat types to others.

Table 3-5. Predicted acreage changes for tidal marshes, open water and tidal flats, scrub-shrub swamps, and other habitats in the Delaware Estuary by 2100 using the Sea Level Affecting Marsh Model (SLAMM, see Appendix G.)

		Marsh	Open Water/Tidal Flats	Scrub-Shrub/Swamp	Other
Upper Estuary	PA	1,717	98	-71	-1197
	NJ	4,468	192	-1,902	-2758
Lower Estuary	PA	-1814	5,821	-500	-3507
	NJ	-930	14,250	-2,661	-10,659
Delaware Bay	PA	-21,331	49,914	6,584	-21,998
	NJ	-24,668	36,254	-7,007	-4,560

Table 3-5 summarizes the net change in the principal habitat categories analyzed with SLAMM. Across the whole estuary, 42,558 hectares of tidal wetland are predicted to be lost, with most being located along the microtidal shorelines and tributaries of the Delaware Bay region. In addition, 50,236 hectares are expected to be lost from adjacent habitats that are more landward, including scrub-shrub swamps, non-tidal wetlands, and uplands. The SLAMM analysis predicts that these losses will translate into a net gain of 106,529 hectares of open water and tidal flat habitat. Outputs from the SLAMM model were put into GIS to show an example of how the various habitat types, including tidal wetlands, are predicted to change between the present and 2100 in southwestern New Jersey (Fig. 3-10.) By 2050,

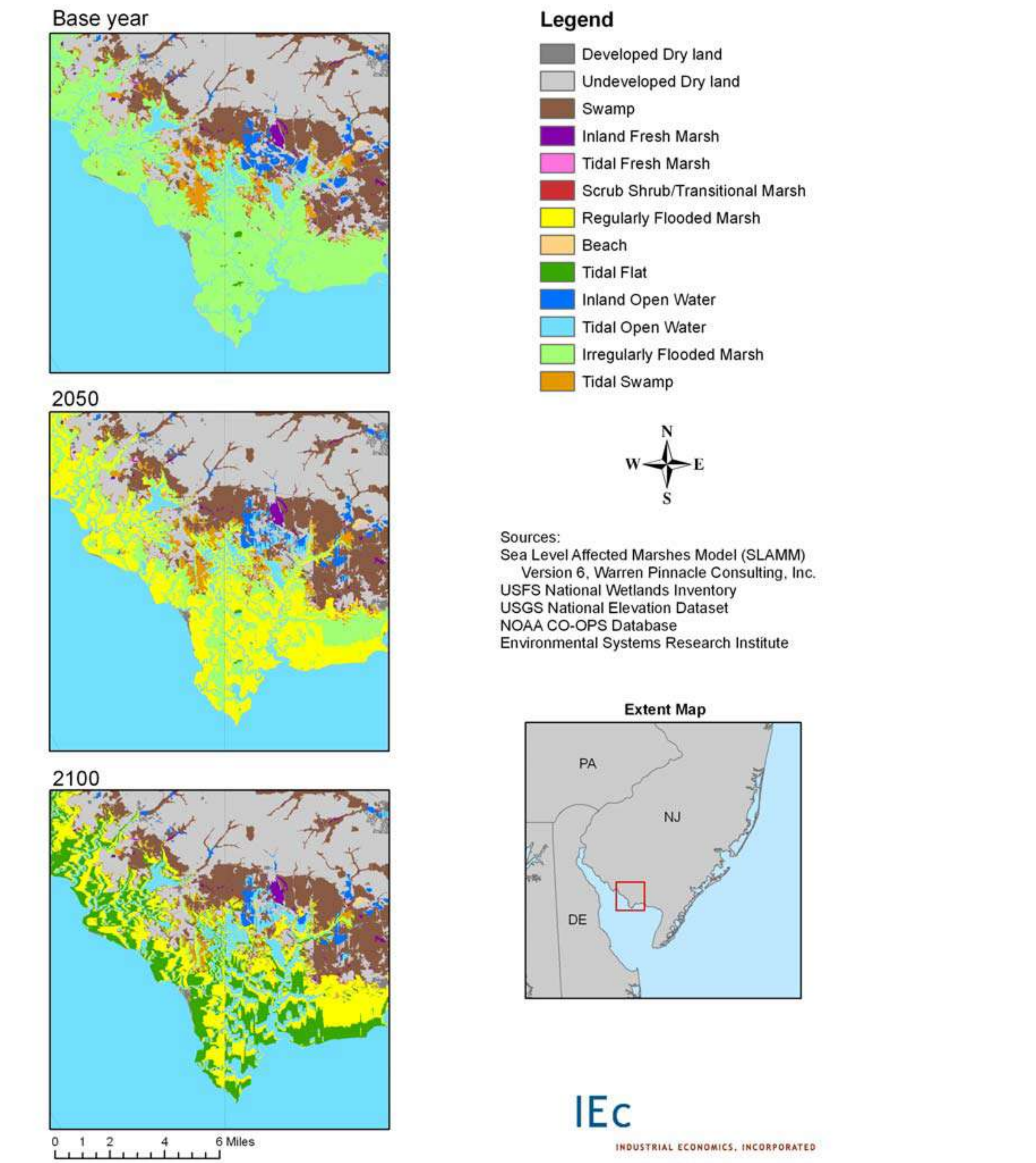


Figure 3-10. The geographical coverage of thirteen habitat types (see legend) in an area of southwest New Jersey at present (1980s NWI data) and as predicted by SLAMM in 2050 and 2100.

many of the irregularly flooded marshes are expected to turn into regularly flooded mashes. Then at the end of the century, many of these marshes will transition into mudflats or open water as interior areas of marsh begin to break up and tidal creeks widen.

Wetland Services Change. Industrial Economics used the Habitat Equivalency Model (HEA) to predict ecosystem service changes that would accompany the predicted changes in seven habitat categories from the SLAMM model (Table 3-6.) The HEA tool was first developed to access natural resource damages from oil spills and to calculate how much restoration would be needed to offset those damages. For our purposes, HEA considered climate impacts as the ‘damage’. HEA compares the losses of habitat and potential gains from restoration (or climate adaptation) activities using a unit of scale called a Discounted Service Acre Year (DSAY). This unit of measure incorporates time, allowing non-linear changes in condition, function, or dollars to be captured using principles of ecological and economic compounding. DSAYs can therefore be used to more effectively promote “no net loss” of wetlands by making it easy to figure out exactly how much loss is occurring and how much restoration is needed at any point in time. HEA analysis can be extended to be used for any ecosystem service. For this study, primary productivity was selected because of the availability of literature on this metric. Specifically, IEc ran HEA analysis on only the “primary production for consumption,” meaning the proportion of total production that could be readily consumed by animals.

Table 3-6. Habitat types contrasted for their relative primary production services using Habitat Equivalency Analysis (HEA.)

Habitat Types used in HEA
Regularly Flooded Marsh
Irregularly Flooded Marsh
Tidal Fresh Marsh
Scrub/Shrub Marsh
Tidal Swamps
Tidal Flats
Tidal Open Water

To estimate whether restoration practices might reasonably be used to offset projected losses of wetland acreage and services, IEc used HEA to calculate the total cost of one example restoration tactic if that tactic were to be implemented to preserve all vulnerable tidal wetlands. To do this, living shorelines were considered a preventative measure which could be used to offset future wetland losses through the end of the century. Assuming living shorelines would be installed in 2020, the projected costs (in today’s dollars at that date) to armor all tidal wetlands was projected to be $29 billion (Table 3-7; see Appendix G for calculations.) This price tag may seem large, but if effective this restoration option would be used to combat all wetland losses occurring over a 90 year period (by 2100.) In contrast, if wetlands are allowed to degrade with no intervention, by the year 2050 enough wetlands would be lost or severely degraded so that complete restoration would be required to restore acreage if that was deemed necessary. This full restoration option would include costs of fill management, regrading, creation of tidal creeks, and re-vegetation. The cost of the full restoration tactic in is calculated to be $39 billion (in today’s dollars at that date; Table 3-7). Therefore, $10 billion (in today’s dollars) could be saved with early intervention in 2020 using living shorelines compared to full restoration later, in 2050. Preventative wetland measures are not only the cheaper climate adaptation option in terms of implementation costs, but they would also maintain all of the attendant ecosystem services (not valued here) provided by the wetlands that would otherwise be lost in the interim until restoration would hypothetically occur.

Table 3-7. Comparison of the habitat equivalency outcomes and associated costs for two adaptation approaches for addressing projected tidal wetland losses: 1) use of living shorelines in 2020 to stem future losses and 2) restoration of lost wetlands in 2050 (see also Appendix G.)

REGION	STATE	DISCOUNTED SERVICE ACRE YEAR LOSS[1]	DISCOUNTED PRIMARY PRODUCTIVITY LOSS (THOUSAND KG)	RESTORATION ACREAGE	ESTIMATED COST OF RESTORATION (BILLION $2009)
Prevention in 2020 **(Living Shorelines)**					
Lower Estuary	Delaware	-22,950	-2,461	1,832	$ 1.04
	New Jersey	-36,384	-3,902	2,904	$ 1.65
Delaware Bay	Delaware	-239,686	-25,704	19,128	$ 10.9
	New Jersey	-269,223	-28,871	21,485	$ 12.2
TOTAL		**-568,243**	**-60,938**	**45,348**	**$ 25.8**
Restoration in 2050					
Lower Estuary	Delaware	-22,950	-2,461	4,422	$ 1.59
	New Jersey	-36,384	-3,902	7,010	$ 2.52
Delaware Bay	Delaware	-239,686	-25,704	46,178	$ 16.6
	New Jersey	-269,223	-28,871	51,869	$ 18.6
TOTAL		**-568,243**	**-60,938**	**109,478**	**$ 39.3**

The methodology presented in Appendix G promises to help evaluate the trade-offs associated with various adaptation tactics, thereby assisting resource managers in deciding how to best stem losses of wetland acreage and ecosystem services due to climate change. In some cases, strategic retreat or no action might be the realistic scenario. However when adaptation tactics are sought and contrasted to proactively address the effects of climate change, the relative costs and benefits of adaptation options can be contrasted using HEA for different locations and at different installation dates.

3.7.3 Natural Capital of Tidal Wetlands in the Delaware Estuary Watershed

Besides being valued for their primary production (as in Section 3.7.2), tidal wetlands are hot spots for many other ecosystem services (Figure 3-11). The Natural Capital Team identified many of these and assigned the ecosystem goods and services to categories used in the Millennium Ecosystem Assessment (2005.) (Table 3-8.) Generally, tidal wetlands provide flood protection, support fisheries and shellfisheries, sequester carbon, and help to maintain water quality, among others.

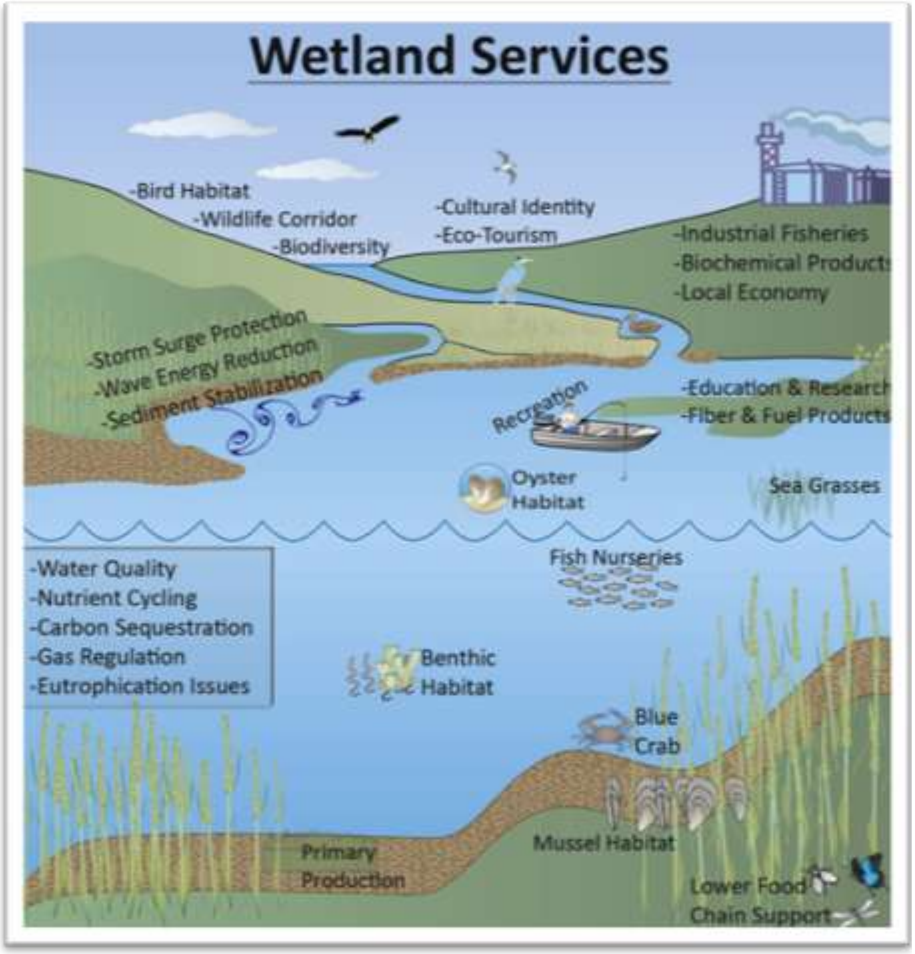


Figure 3-11. Portrayal of the diverse ecosystem services furnished by tidal wetlands in the Delaware Estuary (see also Table 3-8.)

Table 3-8. Summary of ecosystem goods and services provided by tidal wetlands in the Delaware Estuary, grouped as in the Millennium Ecosystem Assessment.

Milenium Ecosystem Assessment 1º Service	2º Service	3º Service	4º Service
Provisioning	Food	Fisheries Support	
		Algae and invertebrate production	
	Genetic Materials	Phragmites control research	
	Biochemical Products	Research in Antifungal Agents	
	Fiber and Fuel	Cellulose stock	
Regulating	Sequestration	Carbon	Carbon Caps, mitigation
	Sediment Stabilization	Erosion control	Meet TMDLs for sediment
	Storm Protection/ Wave Attenuation/ Flood Protection	Protect Property Values and infrastructure	
	Gas Regulation	Carbon Sequestration	
		Oxygen production	
	Water Quality	Sequestration, Filtering	TMDLs: Nutrients, Pollutants
Cultural/Spiritual Human Well Being	Recreation	Bird watching, hunting, boating	
	Spiritual and Inspirational	Native American Uses	
	Educational	University reasearch & school projects/trips	
	Aesthetic Value	Landscape pictures, paintings, open space	
Supporting	Habitat	Wildlife, shellfish, insects	
	Biodiversity	Maintain Plant Communities	
	Production	Primary Production	
	Water Cycling/Hydrologic Regime		
	Nutrient Cycling/Biogeochemical Processes	Maintain trophic cycles, soil building	

3.8 Tidal Wetlands - Synthesis

Climate change is likely to affect different types of tidal wetlands in different ways in the Delaware Estuary. For freshwater tidal wetlands, a unique feature of the Estuary, the greatest threat was found to be the expected rise in salinity of the upper Estuary. Plants and animals that comprise these wetlands are intolerant of even brief exposure to seawater. As sea level rises and more saltwater begins to mix in, freshwater tidal marshes will shrink as they are replaced by brackish communities. Landward migration of freshwater tidal marshes is virtually impossible because more than 85% of buffer lands in the upper estuary are developed and expected to be maintained as such. For these reasons, the most vulnerable elements of tidal freshwater wetlands are loss of habitat acreage, shifts in community composition, and the concomitant loss of habitat support for any fish and wildlife that depend on these rare habitats.

In addition to their vulnerability to salinity, freshwater tidal wetlands are threatened by the physical effects of rising sea level, such as erosion of seaward edges, an amplified tidal range, and exposure to more frequent storm surge. Increases in storm intensity and frequency will hasten the conversion of some freshwater tidal marshes to brackish marshes, possibly dominated by invasive species that thrive under more frequent disturbance regimes. Sediment supply is expected to be ample for these marshes since they are closer to sources of sediment brought to the estuary by large rivers, and greater precipitation during cooler months could lead to more sediment-laden runoff. For this reason, freshwater tidal marshes are expected to keep pace (vertically) with rising seas in areas that are not exposed to saltwater despite the expected increase in tidal range.

Brackish and salt marshes were examined together, although there are notable differences in species assemblages that occur along the very broad salinity gradient in the Delaware Estuary. In contrast to freshwater tidal wetlands, these saltwater adapted wetlands are most vulnerable to sea level rise which will interact with various other stressors to push many marshes past their sustainable threshold. The lower portion of the Delaware Estuary is microtidal, meaning that the tidal range is small and there is little vertical relief across the expansive marshes that form a near contiguous fringe around Delaware Bay. In most areas, the rate of sea level rise is expected to increase to up to 10 mm per year or more, probably exceeding the ability of tidal marshes to keep pace since recent accretion in most areas is less than this. Marshes grow vertically by accumulating dead plant matter as well as by trapping suspended sediments brought in with the tides. But sediment deficits, nutrient loadings, and projected increases in storm energy disrupt normal accretion rates, and all of these factors are certain to change with changing climate contributing to stress on native plant species *like Spartina alterniflora*, which is the dominant species of extensive low marsh communities.

Not all projected effects are negative. Increased carbon dioxide levels, combined with nutrients, might boost overall productivity and help these marshes keep pace through organic matter accumulation in some areas. On the other hand, the species that are most likely to benefit from higher CO_2 levels are different from the current biomass dominants. Paradoxically, nutrient loadings can decrease organic matter accumulation by favoring aboveground production over belowground production. Aboveground production is more apt to wash out of the marsh following senescence, and tall plants with little rooting are more vulnerable to physical dislodgement during storms. These reasons explain why some marshes can look very lush and healthy just before they collapse.

The top five climate change vulnerabilities for tidal wetlands in the Delaware Estuary are summarized in Table3-6, considering all available information examined in this study.

Table 3-6. Top five vulnerabilities of Tidal Wetlands to climate change in the Delaware watershed, ranked by the Wetland Work Group.

Ranking	Vulnerability
1	Sea Level Rise Effects on Brackish/Saltwater Wetlands
2	Salinity Effects on Freshwater Tidal Wetlands
3	Sea Level Rise Effects on Freshwater Tidal Wetlands
4	Precipitation and Storm Effects on Freshwater Tidal Wetlands
5	Precipitation and Storm Effects on Brackish/Saltwater Wetlands

The latest version of SLAMM (Sea Level Affecting Marshes Model) helped to predict how tidal marshes and adjacent natural areas on the landward and seaward sides will respond to rising sea levels (Section 3.7.2). Using our climate predictions (Chapter 2) and best available acreage data for the uplands, non-tidal wetlands, tidal wetlands, mud flats and open water, SLAMM outputs indicated that more than 45,000 acres of natural areas that are currently landward of tidal wetlands will be converted to tidal wetlands by 2100. This gain in tidal wetlands is expected to be more than offset however by an increase of more than 105,000 acres in unvegetated tidal flats and open water, mainly in brackish/saltwater wetlands. The net effect is predicted to be a loss of more than 40,000 acres of tidal wetlands, roughly a tenth of current acreage. Projected losses of tidal wetlands are similar in Delaware and New Jersey.

All natural habitats provide ecosystem services; however, the combined services furnished by tidal marshes exceed those of the other habitats examined in this analysis, leading to a substantial net loss. For example, primary production is expected to decrease by more than 60,000 metric tons. Loss of associated carbon sequestration services by tidal marshes will be felt doubly because of lost future services combined with the release of formerly sequestered carbon by erosion of peat from marshes converted to open water. Similarly, the loss of 10% of the system's tidal wetlands could hamper efforts to establish nutrient criteria since these extensive tidal marshes are thought to be important for maintaining water quality in the Delaware Estuary.

In order to adapt to climate change, greater attention will need to be paid to the current plight and functional significance of our wetland resources. Management of these habitats is governed by an outdated paradigm that seeks to sustain them in the same places as they exist today. There is also limited system-level appreciation for the effects on tidal wetlands of watershed flow, sediment supply and nutrient loadings, as examples. Tidal wetlands are so extensive in the Delaware Estuary that a 10% loss (or more) is certain to affect fisheries, water quality, flood protection and more.

In the Delaware Estuary, watershed flow management should be considered the most effective and feasible adaptation option for offsetting the most vulnerable climate change driver to tidal fresh water wetlands, a salinity increase. A salinity increase in freshwater tidal marshes will probably occur quickly during a storm event or drought, and river flow managers should consider tidal freshwater wetland protection along with other factors in setting flow targets to potentially offset salinities above 0.5 ppt. A longer term watershed flow plan should account for the incremental build-up of salinity.

Freshwater tidal wetlands would also benefit from a dedicated effort to set aside and preserve natural areas, or to remediate dilapidated developed areas, to facilitate their landward migration. This is especially challenging in the urban corridor of the upper estuary where there is little opportunity. However, conversion of poorly used city properties to natural areas provides additional ecosystem services for society, such as added recreational opportunities, flood protection and temperature modulation.

In the extensive brackish and salt marshes of the lower estuary and especially around Delaware Bay, the most beneficial adaptation options are also ones that facilitate landward migration. In this region, there is greater opportunity because much of the 1 km buffer landward of tidal marshes in undeveloped. Agricultural lands abound here, and farmers or other landowners could be provided with incentives to donate or sell easements to protect marsh buffers. There are many types of easements along rivers and estuaries. A "rolling conservation easement" is designed to permit landward marsh migration. Made between a willing property owner and an easement holder/purchaser (such as the state, or a conservation organization), a rolling conservation easement allows the property owner to continue development and use of the property, but prohibits armoring of the shoreline to prevent inundation (Titus 1998.) So as sea level rises, the marsh can advance unimpeded, and the rising tide eventually causes more and more of the property to fall under public ownership (from mean high tide seaward).

Strategic retreat, defined here as the removal of infrastructure that would otherwise be protected, is also an option in some areas although it is costly. Along the Delaware Estuary, a 1 m rise in sea level would inundate at least 1000 hectares and perhaps up to 10000 hectares of agricultural land, 280–1040 hectares of barren land, 210–1760 hectares of developed land, 590–4280 hectares of forested land, and 80 – 130 hectares of open water (e.g., impoundments,) and 900–2420 hectares of non-tidal wetlands (Gill et al. 2009). Many of these areas could be managed to facilitate tidal marsh development depending on such factors as slope, sediment condition, and hydrodynamics.

Smart landward retreat requires adoption of a new paradigm that accepts coastal landscapes as dynamic. Structures and policies that seek to fix habitats in place are counter to natural processes and will thwart the ability of tidal wetlands to sustain themselves, especially as the rate of sea level rise increases. Therefore, proactive climate adaptation should prohibit and remove construction in areas vulnerable to the effects of sea level rise and allow for coastal habitats to undergo their natural successional march across the coastal zone.

In the short term, however, shore protection will be needed in some areas to allow enough time to build needed capital or engineering prowess to perform strategic retreat. Careful planning will also be needed to use LIDAR and other emerging technologies to forecast where future shorelines will be most sustainable. New development must be set back far enough from estuarine shorelines or at a sufficient elevation so that structures and policies are designed conservatively to accommodate a significant acceleration in the rate of sea-level rise (Titus et al. 2009a). In undeveloped areas where shore protection may be unnecessary and certainly ineffective at maintaining tidal wetland extent and services over the long term, strategic retreat is the best option (displayed in blue; Figure 4). Living shorelines are promising and cost effective tactics that slow erosion along seaward margins of tidal wetlands, buying time for them to establish themselves inland, while also boosting habitat service values.

Discerning between undeveloped lands and ecologically and economically important lands will be critical for targeting conservation and restoration efforts in response to sea-level rise and its effects. Preserving undeveloped, vulnerable lands also offers a significant opportunity to avoid placing people and property at risk to sea level rise and associated hazards including storm surge, coastal flooding, and erosion.

The costs of wetland conservation and expansion are associated primarily with capital costs of land purchases and/or easements in areas identified as critical to buffering against the impacts of sea-level rise. Funding for tidal marsh preservation and expansion must be increased, perhaps fueled by our increasing understanding of the value of the ecosystem services provided by these habitats.

The Wetland Work Group identified many other adaptation options that ranked lower in terms of either their projected benefits or their feasibility. As new information and technologies develop, some of these may become more promising. As examples, development of carbon trading markets could help focus attention on the carbon sequestration services provided by tidal marshes, especially salt marshes which appear to sequester more carbon than any other habitat in the Mid-Atlantic. The beneficial use of dredge material and marsh nourishment with sediments also represents a potential tactic to help them keep pace with sea level areas where those measures are feasible. Sediment supply for tidal marshes appears to be an important determinant of their carbon sequestration capacity (Mudd et al. 2009). It will also be important to ensure marshes receive the necessary sediment subsidy through regional sediment management practices.

The top five climate adaptation options for sustaining or enhancing tidal wetlands in the Delaware Estuary watershed are summarized in Table 3-7, considering all available information examined in this study. This list does not include monitoring and research activities.

Table 3-7. Top five adaptation options to assist tidal wetlands in adapting to climate change in the Delaware watershed, ranked by the Wetland Work Group.

Ranking	Adaptation Tactic
1	Strategic Retreat for Landward Migration
2	Natural Buffers for Landward Migration
3	Living Shorelines to Stem Erosion
4	Manage Water Flow to Maintain Salinity Balance
5	Structure Setbacks for Landward Migration

In addition to these adaptation tactics, participants also stressed the importance of research and monitoring in climate change adaptation planning. In order to determine the effectiveness of adaptation plans and tactics, research and monitoring will be necessary to develop geospatial planning tools relevant for local decision-makers, to track changes in environmental conditions, and to set appropriate benchmarks for gauging success of adaptation measures. Because of uncertainties regarding the rate and severity of climate-related effects and the rapidly changing science and tools that will underlie any climate plan, climate change adaptation will require frequent reassessment and perhaps realignment of plans and actions; i.e., an "adaptive adaptation plan" will need to be refreshed frequently to sustain the tidal wetlands of the Delaware Estuary.

3.9 Tidal Wetlands - Recommendations

The following recommendations were provided by the Wetland Work Group to help sustain tidal marsh habitats in the Delaware Estuary.

1. Identify and protect areas adjacent to tidal wetlands that are suitable for wetland migration. Allowing wetlands to migrate inland is the highest priority adaptation action. Adjacent undeveloped areas with suitable elevation, slope, and no physical impediments to migration should be treasured and protected where recognized. However, since many of these lands may not be easily recognized, a geospatial framework incorporating LIDAR, land use, and monitoring information is needed to identify them, based on location in the buffer zone, suitable elevations, slopes, and other traits. A variety of measures can be used to protect these areas for marsh migration, including: strategic retreat, set backs for building/development, incentives or buyouts for farmers, and conservation easements to ensure that marsh migration can progress unimpeded.

2. Identify and restore areas where living shorelines (or other restoration techniques) can slow erosion and stem marsh losses. The same geospatial framework referenced in 1. above is needed to identify vulnerable areas of tidal wetlands that could benefit from restoration/adaptation projects to increase the amount of acreage that is sustainable. Identifying areas with suitable edge conditions, energy conditions, and ownership conditions for living shorelines should be a priority based on assessment results. This process could also identify areas for other types of adaptation, for example, where dikes could be removed from impounded former tidal marshes and a thin layer of sediment could be applied to raise their elevation.

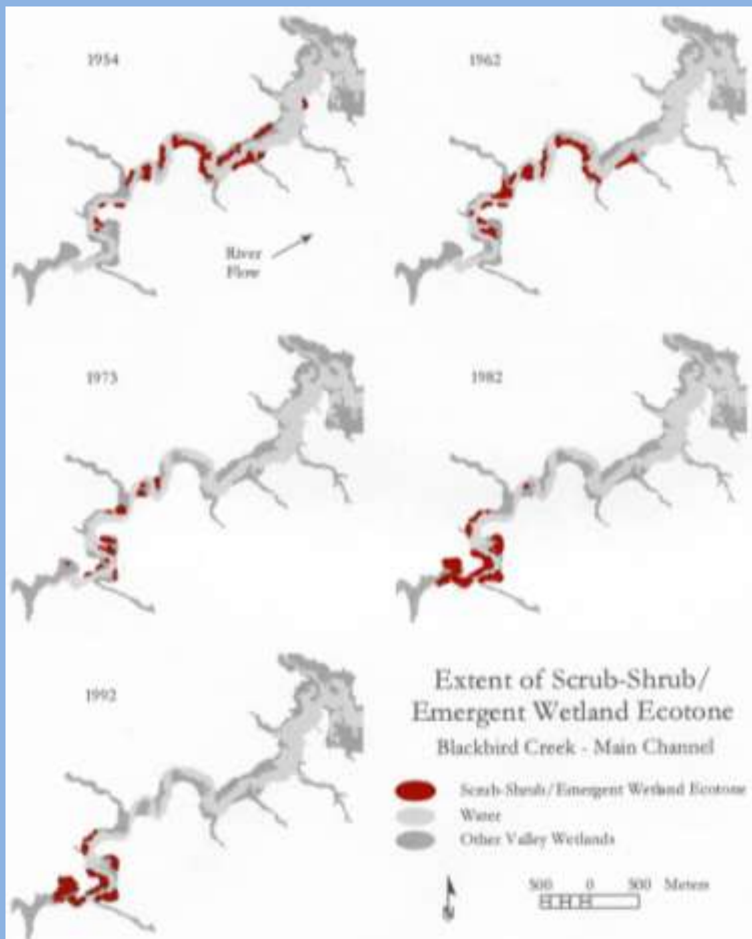
3. Develop indicators to track both impairments (and possibly benefits) to tidal wetlands from climate change (e.g., see feature 3-2) and monitoring to support them. Scientific analysis should be directly relevant for managers, helping to bolster our understanding of the benefits of these habitats to 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. Identify special protection or management areas based on those areas with the greatest natural capital value based on key ecosystem services furnished by tidal wetlands. Repeat the analysis of production services in this study for carbon sequestration, which is increasingly being valued as a mitigation tactic for climate change. Results of the NJ Natural Capital study could be transferred to the entire Delaware Estuary region using the association of natural capital values to land use / land cover types.

1. Educate the broader resource management community regarding the importance of tidal wetlands for watershed health and also the effects on water quality and quantity on wetland habitats. Much of the future for tidal wetlands hinges on having suitable flows, sediments and water quality. In turn, tidal wetlands can hePlp managers attain water quality targets, preserve fisheries, and provide flood protection.

Tidal wetlands are a hallmark feature of the Delaware Estuary and they supply more ecosystem goods and services than any other natural habitat. A coordinated, watershed-based approach to tidal wetland preservation and landward migration is needed to help these habitats adapt to climate change.

Feature 3-2. Scrub-Shrub as an Indicator of Change



A scrub-shrub wetland typifies a community in transition. Many emergent wetlands, left undisturbed, will gradually be replaced through succession by woody vegetation. Estuarine scrub / shrub wetland includes all tidal wetlands dominated by woody vegetation less than 5 meters in height. Such wetlands occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent. Therefore, the time series maps shown the left indicate that the salinity line may be migrating upstream in the Blackbird Creek. Scrub-shrub wetlands help stabilize stream banks and provide cover for birds and other wildlife.

-Vinton Valentine, Kurt Philipp & Laura Whalen

Chapter 4

Case Study #2: Drinking Water

4.1. Drinking Water in the Delaware Estuary Watershed

The Delaware River, its bay, and 216 tributaries provide a source of drinking water for over 17 million people, or over 5 percent of the United States population. Approximately 88 percent of drinking water taken from the Delaware River watershed is from surface water and approximately 12 percent is from groundwater. The City of Philadelphia's drinking water supply, servicing over 1.4 million people, comes exclusively from surface water sources. In addition to the Estuary's population, much of New York City also gets its drinking water from reservoirs in the upper Delaware Basin. Approximately 736 million gallons of water per day are exported for populations in New York City and northeastern New Jersey.

Drinking water providers in the Basin encounter numerous challenges to the quality and availability of their supply. Drinking water suppliers must share the resources of the Basin with other large water users such as power generation and industry which make up approximately 95% of total water use in the tidal Delaware Basin. Suppliers depend on sound, science-based decision-making by state and federal regulators to ensure appropriate and equitable flow allocation. Water quality stresses from wastewater and industrial discharges, stormwater and agriculture runoff, discharges from abandoned mines, and other influences all pose serious threats to the ability of water providers to consistently deliver safe drinking water. Anticipated population growth in the region is likely to increase demand for drinking water and exacerbate water quality problems by increasing burdens on wastewater infrastructure and potentially eliminating forests critical to water supply protection.

Potential effects of climate change on the Delaware Basin include warmer air and water temperatures, increased frequency and intensity of severe precipitation, and reduced snowpack. Such altered conditions in the Basin may aggravate existing water quality and quantity problems and potentially create new stresses for water supplies. For example, increases in precipitation in the region could lead to increased runoff, increased streamflow, higher groundwater levels, increased flooding and changes to watershed vegetation and forest cover in the Delaware Basin. These conditions could damage drinking water treatment plants and infrastructure, inundate treatment plants and pump stations and further degrade water quality. Increased temperatures alone from climate change could increase potable water demand from drinking water supply systems.

4.1.1. Drinking Water Case Study

The purpose of the CRE Drinking Water Supply Case Study is to consolidate and evaluate information about climate change, potential effects on conditions in the Delaware Basin, and the impacts of these potential effects on drinking water supply. The focus of this effort is primarily on surface water supplies in the Lower Basin and Philadelphia's water supply in particular. Specific goals of the case study are as follows: (1) develop an inventory of potential conditions in the Basin which could be altered due to effects of climate change and catalog the possible impact of these changing conditions on drinking water surface supplies; (2) evaluate results from Goal 1 to identify potential planning priorities; (3) identify opportunities for drinking water providers, with support from other stakeholders, to increase their overall adaptive capacity in the face of current challenges and future uncertainty; and, (4) identify priority research needs.

The potential breadth of impacts to drinking water from climate change, combined with current threats to water quality and availability, necessitate strong leadership from water providers and state, local and federal government. The future of our drinking water supplies also depends on the education, cooperation and commitment of Basin communities. The information in this report provides these groups with a preliminary road map to help navigate the substantial uncertainty associated with future change.

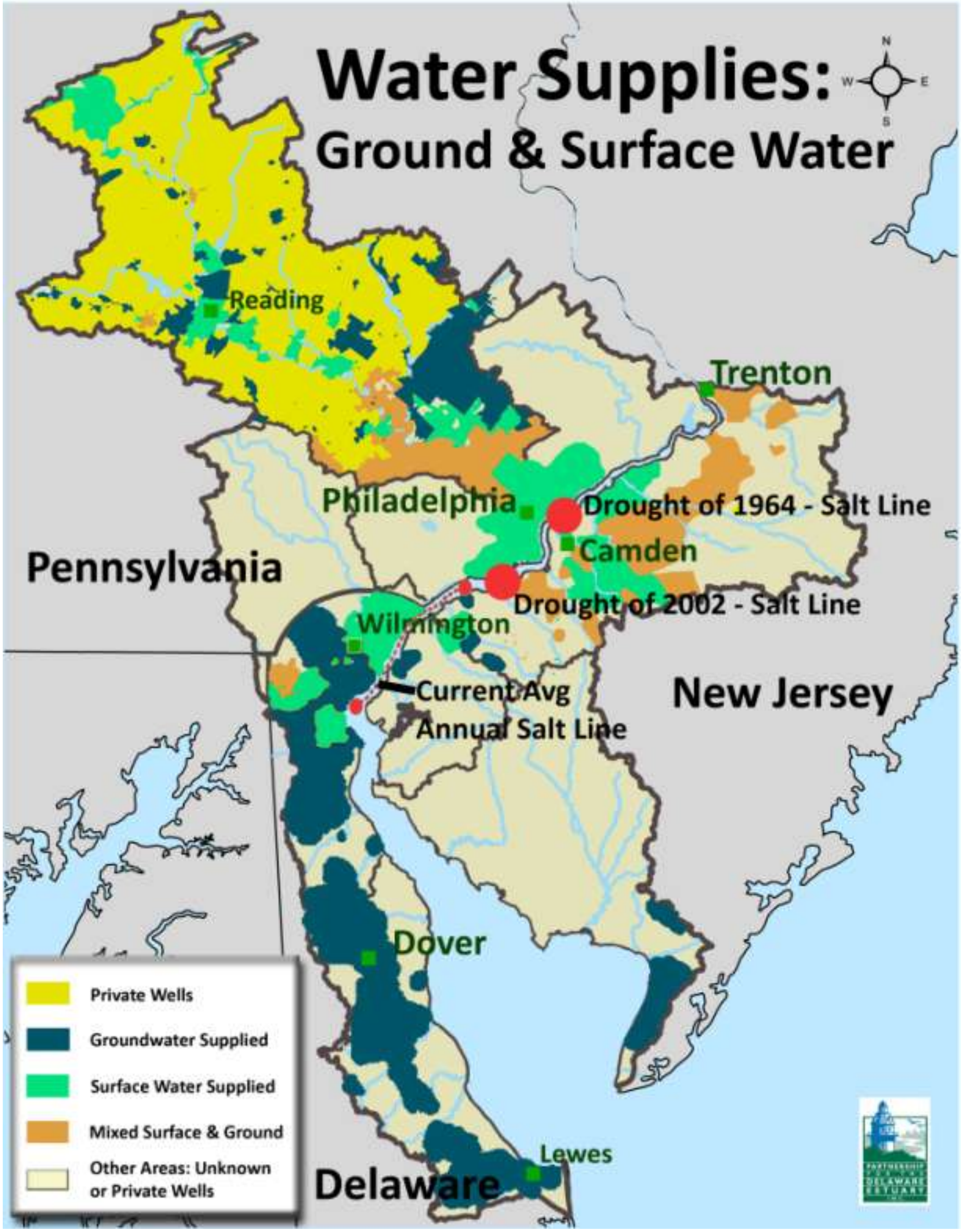


Figure 4.1. The map above shows the service areas of community water supply systems in the estuary. The major cities in the northern parts of the estuary get much of their water from surface water or a mix of surface and ground water. Parts of the Schuylkill River watershed and most of southern Delaware rely exclusively on ground water. The location of the salt line is important to drinking water suppliers in the Upper Estuary. Sea level rise and storm surges can push the salt line further up the Delaware Bay, leading to potentially high chloride and sodium concentrations at the drinking water intakes for Philadelphia and Camden.

Feature Box: Salinity and the Philadelphia Baxter Intake

The Baxter water intake facility provides drinking water to nearly 1 million people, including 60% of the population of Philadelphia and 155,000 Bucks County residents. Baxter is located in the tidally-influenced fresh waters of the Delaware River. It receives freshwater flow from the upstream non-tidal Delaware River, which pushes salt levels down below Baxter. At the same time, tidal waters from the Delaware Bay push salt levels up river towards Baxter. When flow in the Delaware River decreases during drought, the tidal waters push salt further northward towards Philadelphia. Releases from existing reservoirs upstream of Philadelphia are needed to provide enough water during droughts to keep salt at acceptable levels. Since the Baxter plant is a conventional treatment facility, it is not capable of removing salt from the source water. Levels of 250 mg/L chloride or greater at Baxter may require Philadelphia Water Dept. (PWD) to stop withdrawing water from the Delaware River at this site. Any salt present in the source water passes through the plant and distribution system to customers, which may pose unacceptable health risks for sensitive dialysis patients and those on sodium restricted diets. To remove salt at Baxter would require a costly desalination facility. Otherwise, recent analysis by PWD demonstrates that flow targets at Trenton, as defined by the Delaware River Basin Commission Water Code, must be kept at least at current levels to protect the Philadelphia water supply under present day climate conditions.

4.2. Drinking Water – Approach to Assessing Vulnerability and Adaptation Options

The vulnerability of drinking water supply to climate change and potential adaptation options were assessed by a Drinking Water Workgroup comprised of regional scientists and managers from both public and private sectors. For the purposes of this project, the Drinking Water Work Group operated as a subgroup under the Climate Adaptation Work Group. Tasks completed by the workgroup include:

- Created an inventory of available literature on drinking water issues related to climate change (Appendix J);
- Prepared a review document based on the literature inventory (Appendix I);

- Identified the main physical and chemical environmental factors that are likely to change with changing climate and also affect drinking water supply systems (Section 4.3.);
- Identified the specific impacts, or vulnerabilities, of changing environmental factors on drinking water supply systems (Section 4.3);
- Prepared a survey to rank the relative level of concern for how projected changes in physical factors might impact drinking water supply systems served by surface water (Section 4.4);
- Used the survey format to poll experts (Section 4.5);
- Identified priority adaptation options that might be used to lower the vulnerability of drinking water supplies to climate change (Section 4.6.);
- Identified research needs to improve estimates of changing physical conditions and impacts of those changing conditions on drinking water supplies (Section 4.7) and,
- Prepared final recommendations (Section 4.8).

4.3. Drinking Water Vulnerabilities

Using the results of a literature search (Appendix I) and input from regional drinking water experts, the Drinking Water Case Study workgroup developed an inventory of potential conditions in the Basin which could be altered due to effects of climate change and catalogued the possible impact of these changing conditions on drinking water surface supplies. Table 4.1 below includes the results of the inventory. Possible impacts on the water supply, referred to as vulnerabilities, appear across the top of the table. Conditions in the Basin due to climate change which could lead to those impacts, referred to as drivers, appear along the left side of the table. An "X" indicates where a physical driver may impact the corresponding vulnerability. For example, the physical driver of increased river discharge and stream flow may impact supply in 3 ways: 1) cause damage to infrastructure, 2) influence reservoir levels, and 3) facilitate degradation of source water quality.

Table 4.1. Drinking Water Supply Vulnerabilities plotted against the physical drivers which might cause those vulnerabilities. An "X" indicates a possible driver/vulnerability relationship.

Supply Vulnerabilities→

Physical Drivers ↓	Degraded Source Water Quality	Upstream Movement of Salt	Salt Intrusion in Aquifers & FW Habitats	Inundation of Treatment Plants & Pump Stations	Damage to Infrastructure	Power Outages & Customer Supply issues	Impacts to Reservoir Levels	Decreased Supply Availability	Increased Spills and Accidents
sea level rise	**X**	**X**	**X**	**X**	**X**				**X**
storm surge	**X**		**X**	**X**	**X**	**X**	**X**		**X**
extreme flooding	**X**			**X**	**X**	**X**	**X**		
flooding	**X**			**X**	**X**	**X**	**X**		
decreased river discharge & stream flow	**X**	**X**					**X**	**X**	
changes in watershed veg. & forest cover	**X**				**X**				
increased runoff	**X**				**X**		**X**		
disruptions to aquatic ecosystems	**X**	**X**	**X**						
decreased groundwater levels	**X**	**X**					**X**	**X**	
increased freq. of short-term drought	**X**		**X**				**X**	**X**	
increased # and intensity of wild fires	**X**				**X**	**X**			
increased river discharge and stream flow	**X**				**X**		**X**		
increased groundwater levels	**X**				**X**		**X**		
lightning and electrical disturbances						**X**			**X**

Water supply vulnerabilities are defined as follows:

Degraded Source Water Quality

Refers to changes in water quality which could lead to interference with drinking water treatment effectiveness and/or increases in parameters that can pass through conventional treatment and potentially cause illness among some customers.

Upstream Movement of Salt Line

Refers to the possible upstream migration of the 250 mg/L chloride isochlor in the Basin. Upstream salt line movement is an indicator of increased salinity for surface water supplies in the Basin. Salinity is not removed during conventional drinking water treatment and may include constituents problematic to certain customers.

Salt Intrusion in Aquifers and Freshwater Habitats
Refers to possible increases in salinity of groundwater and freshwater which may feed Basin surface waters. Salinity is not removed during conventional drinking water treatment and may include constituents problematic to certain customers.

Inundation of Treatment Plants & Pumping Stations
Refers to flooding of pumps, monitoring equipment and other structures crucial to collecting surface water from the Basin and/or treating raw water.

Damage to Infrastructure
Refers to the destruction of pumps, monitoring equipment, and other structures crucial to collecting surface water from the Basin and/or treating raw water.

Power Outages and Customer Supply Issues
Refers to possible interruptions to the ability of water providers to supply drinking water consistently for reasons not otherwise captured.

Impacts to Reservoir Levels
Refers to changes in expected reservoir levels which dictate how much water is available for various uses including drinking water in the Basin.

Decreased Supply Availability
Refers to possible decreases in flows needed to serve drinking water supplies, possibly leading to difficulties for water suppliers in meeting peak demand (i.e., demand during summer months).

Increased Spills and Accidents
Refers to the possible increased frequency of upstream spills, fires and accidents which could lead to toxic contamination of downstream water supplies.

4.4 Drinking Water - Survey Methods

Once the inventory of drivers and vulnerabilities was completed, the workgroup developed a survey to capture regional drinking water expert opinions on the potential impact of the physical drivers on the vulnerabilities. The survey was also designed to capture respondents' opinions about the science available to determine potential impacts. For each physical driver/vulnerability combination identified as having a relationship in table 4.1, survey respondents were asked to provide two rankings on a scale of 1 (lowest) to 5 (highest). The first ranking, referred to as the impact ranking, reflects the respondent's opinion of the physical driver's potential ability to impact the vulnerability. The second ranking, referred to as the confidence ranking, reflects the confidence of the respondent in the information available to determine potential impact levels. It is important to note that the rankings are based on the opinion and knowledge base of the respondents and not an extensive analysis of available research. Surveys were distributed to all 6 members of the Drinking Water Workgroup via e-mail and 4 responses were received.[1] Survey results were collected and compiled by the Drinking Water Workgroup lead and CRE coordinator.

4.5 Drinking Water - Survey Results

Table 4.2 represents the compilation of survey results for each supply vulnerability. Impact rankings from the returned surveys were averaged to produce a total impact score for each driver/vulnerability combination. Similarly, confidence rankings were averaged to produce a total confidence score for each driver/vulnerability combination. For each driver/vulnerability combination, the impact and confidence scores were multiplied to produce a combined score.

A grading system of Highest, High, Med-High, Med-Low, and Low was assigned according to the distribution of combined scores.

Impact, Confidence, and Combined scores are shown only for the first vulnerability for demonstration purposes. All other vulnerability/driver combinations are shown alongside just their final rankings.

The final rankings help identify the drivers of greatest importance, which are highlighted dark red and orange. Higher scores reflect drivers with potentially significant impact where information is more readily available and accurate. This provides some guidance as to where to focus planning efforts with respect to drinking water supply and climate change vulnerabilities.

The survey results are best interpreted as a ranking of the drivers which are of most concern to each vulnerability. The survey does not attempt to rank the vulnerabilities relative to each other, but it does show the driver/vulnerability areas for which suppliers should start to plan. For example, the vulnerability 'Degraded Water Quality' is most at risk from sea level rise, increased runoff, and changes in watershed vegetation and forest cover. 'Power Outages and Customer Supply Issues' is most at risk from extreme flooding and storm surge. Relative to each other, degraded water quality may have more impact to water suppliers than power outages depending on the extent and timing of the vulnerability.

According to the survey results, sea level rise will be a great concern to water quality for source and finished water. Treatment plants and pumping stations will have to plan for disruption from flooding, sea level rise and storm surges. Likewise, damage to supply infrastructure is most likely to occur because of sea level rise and flooding. Survey respondents did not think that wild fires would be much of an issue for power outages and customer supply issues.

[1] Survey respondents included representatives of the Philadelphia Water Department, Environmental Protection Agency Region III, Penn State University, and Drexel University.

Table 4.2. Results from the Drinking Water Workgroup Survey

Damage to Drinking Water Infrastructure		Impact Score	Confidence Score	Combined Score	Final Ranking
Drivers	sea level rise	2.3	5.0	11.7	High
	extreme flooding	3.0	4.0	12.0	High
	increased runoff	2.7	3.0	8.0	Med-High
	storm surge	2.7	3.5	9.3	Med-High
	flooding	2.7	3.5	9.3	Med-High
	increased river discharge and stream flow	2.5	2.3	5.8	Med-Low
	changes in watershed vegetation and forest cover	2.0	3.0	6.0	Med-Low
	increased groundwater levels	2.0	1.0	2.0	Low
	increased number and intensity of wild fires	1.3	1.0	1.3	Low

Impacts to Reservoir Levels		
	increased runoff	Med-Low
	increased frequency of short-term drought	Med-Low
	decreased river discharge and stream flow	Low
	decreased groundwater levels	Low
	increased river discharge and stream flow	Low
	increased groundwater levels	Low
	extreme flooding	Low
	storm surge	Low
	flooding	Low

Inundation of Treatment Plants & Pumping Stations		
	extreme flooding	High
	storm surge	High
	sea level rise	High
	flooding	High

Increased Spills and Accidents		
	storm surge	Med-High
	lightning and electrical disturbances	Med-Low
	sea level rise	Low

Degraded Source Water Quality		
	sea level rise	Highest
	increased runoff	High
	changes in watershed vegetation and forest cover	High
	increased river discharge and stream flow	Med-High
	decreased river discharge and stream flow	Med-High
	disruptions to aquatic ecosystems	Med-High
	disruptions to distribution systems	Med-High
	flooding	Med-High
	extreme flooding	Med-Low
	increased frequency of short-term drought	Med-Low
	storm surge	Med-Low
	increased groundwater levels	Low
	decreased groundwater levels	Low
	increased number and intensity of wild fires	Low
Upstream Movement of Salt Line		
	sea level rise	Highest
	decreased river discharge and stream flow	High
	decreased groundwater levels	Low
	disruptions to aquatic ecosystems	Low
Decreased Supply Availability		
	increased frequency of short-term drought	Med-High
	decreased river discharge and stream flow	Med-Low
	decreased groundwater levels	Med-Low
	Increases in demand	Med-Low
	increased number and intensity of wild fires	Low
	storm surge	Low
Power Outages & Customer Supply Issues		
	extreme flooding	High
	storm surge	High
	lightening and electrical disturbances	Med-High
	flooding	Med-High
	increased number and intensity of wild fires	Low
Saltwater Intrusion in Aquifers and Habitats		
	sea level rise	Highest
	storm surge	High
	increased frequency of short-term drought	Low
	disruptions to aquatic ecosystems	Low

In summary, the vulnerability/driver combinations in Table 4.3 below have scores of High or Highest in the above evaluation and provide ideal starting points for drinking water supply planning in the Lower Basin with respect to climate change. This guidance is most helpful in identifying areas suitable for further analysis to better quantify effects of physical drivers on drinking water vulnerabilities. This quantification will likely require aggregation and modeling of available information in order to refine predictions about specific outcomes for water supplies due to climate change. Specific recommendations for these analyses are explored in Section 4.7.

Table 4.3. Priority Vulnerabilities with their Physical Drivers.

Priority Drinking Water Vulnerabilities	Responsible Physical Drivers
Damage to Drinking Water Infrastructure	Flooding; sea level rise
Inundation of Treatment Plants and Pumping Facilities	Flooding; sea level rise; storm surge
Degraded Source Water Quality	Increased runoff; changes in watershed vegetation and forest cover; sea level rise
Upstream Movement of Salt Line/Salinity Intrusion in Aquifers and Habitats	Sea level rise; storm surge
Power Outages and Customer Supply Issues	Flooding; storm surge

4.6 Drinking Water - Adaptation Options

The analysis in Section 4.5 is most useful in identifying areas suitable for further study to refine estimates of the specific effects of physical drivers on drinking water vulnerabilities. These areas of recommended study are described in section 4.7. Another important aspect of climate change planning is to identify adaptations that increase the resiliency of water utilities and the Basin against the effects of climate change. As more detailed analyses become available, more specific adaptations can be identified. For the purposes of this plan, however, the workgroup identified reasonable actions that drinking water utilities and regional stakeholders can take now to help prepare for climate change while more detailed evaluations of climate change and its impacts on drinking water supplies are underway.

Adaptations identified by the workgroup are listed below in Section 4.6.1. For each vulnerability identified above, the workgroup selected one priority regional level action and one utility level action. These actions were regarded by the workgroup as the single most important steps in guarding against a particular vulnerability. Selected adaptations generally address one or more climate change vulnerabilities without requiring extensive climate change modeling. They may also minimize current threats to drinking water supplies in order to provide a “cushion” for physical changes expected as a result of climate change. Many of the selected actions improve current knowledge of conditions in the Basin in order to facilitate future projections.

In general, climate change will likely exacerbate existing threats and challenges to drinking water supplies. Therefore, the actions listed represent source water protection measures needed to address current and future challenges. The prospect of climate change only adds emphasis and urgency to development of regional support for drinking water supply protection.

4.6.1 Inventory of Adaptation Options

Degraded Source Water Quality

Regional Level Action ~ Protect Forests

Forest protection in the upper Basin is the single most important action needed to minimize degradation of drinking water supply quality. Forests assimilate nutrients, filter out waterborne sediments, hold soils in place to prevent erosion, and act like a sponge to hold rain water which is then slowly released to replenish streams and groundwater supplies. Municipal governments must develop a strategy for development to avoid clearing of forested and buffered areas. The importance of protecting forests for the preservation of drinking water supplies must be legally acknowledged on a state and federal level.

Also Addresses: Impacts to Reservoir Levels; Decreased Supply Availability

Involves: Environmental Protection Agency (EPA), Delaware River Basin Commission (DRBC), state government, municipal government

Utility Level Action ~ Improve Monitoring of Priority Parameters

Improved monitoring of parameters of concern to drinking water supplies, such as UV254, chlorides, dissolved organic carbon, total organic carbon, *Cryptosporidium*, etc., is needed. These parameters are likely to be impacted by changing conditions in the basin. Monitoring becomes even more important if water quality becomes further degraded due to the physical drivers associated with climate change. Monitoring data will be valuable in examining future changes to intake locations, sources, or alternative treatment technologies which may be necessary in the future. A comprehensive program with other utilities and monitoring entities that coordinates samplings spatially, agrees on a standard set of parameters, and includes a sampling schedule that ensures maximum utility for analysis of climate change impacts is recommended.

Also Addresses: Increased Spills and Accidents

Involves: DRBC, EPA, state government, drinking water utilities

Decreased Supply Availability/Impacts to Reservoir Levels

Regional Level Action ~ Support Green Stormwater Infrastructure

Green stormwater infrastructure solutions that emphasize infiltration can manage stormwater, improve water quality, revitalize communities, and help mitigate potential effects of climate change such as the heat island effect. If implemented on a large scale, green infrastructure can help maintain groundwater and baseflow levels in the Basin which may be critical to meet water demands especially during periods of low precipitation.

Also Addresses: Degraded Water Quality, Impacts to Reservoir Levels

Involves: EPA, DRBC, state government, municipal government

Utility Level Action ~ Evaluate Drought Readiness and Response Plans

Water utilities should evaluate drought response plans to identify vulnerabilities, fill gaps and develop needed contingency plans. Historical droughts should be evaluated to determine efficacy of usage restrictions. Utilities should examine the impact of large upstream consumptive users on their water availability. Agreements should be explored with upstream users for usage contingency plans during drought.

Also Addresses: Impacts to Reservoirs

Inundation of Treatment Plants and Pump Stations/Damage to Drinking Water Treatment Infrastructure

Regional Level Action ~ Update 100-year and 500-year Floodplain Maps

Regardless of the quality of science available to determine the impacts of climate change on physical conditions in the Basin, specific inundation risks can only be effectively evaluated with updated shoreline topographical information.

Utility Level Action ~ Evaluate Placement of New Construction and Materials Resiliency

Drinking water utilities should evaluate the placement of new construction, monitoring equipment, and other infrastructure to avoid low-lying areas or locations vulnerable to storms and other harsh weather conditions. Ranges of potential flooding should be evaluated using the best available science. Adaptations can be refined as more information becomes available about specific impacts of sea level rise, potential increases in streamflow and other changes in the basin that pose a risk to drinking water utilities. Utilities should also evaluate and incorporate use of more resilient construction materials during day-to-day upgrades.

Increased Spills and Accidents/Power Outages and Customer Supply Issues

Regional Level Action ~ Support the Delaware Valley Regional Early Warning System

The Delaware Valley Regional Early Warning System notifies drinking water utilities in the event of accidental contamination in certain areas of the Delaware Basin. The system provides critical information to utilities so they can respond swiftly and appropriately to unexpected threats. Efforts to expand and improve this system must be supported to ensure the continued protection of drinking water supplies in the Basin.

Addresses: Increased Spills and Accidents

Involves: EPA, DRBC, state government, USCG, municipal government, Offices of Emergency Management

Utility Level Action ~ Evaluate Emergency Response Protocols

At the same time that regional emergency response protocols are being evaluated, water suppliers should conduct assessments of their individual utility emergency response protocols to identify vulnerabilities, fill gaps and develop needed contingency and customer communication plans. Revisiting emergency response plans can help protect utilities in the event of unexpected accidents or spills which may become even more prevalent with changing physical conditions in the Basin.

Addresses: Increased Spills and Accidents, Power Outages & Customer Supply Issues

Upstream Movement of Salt Line/Salinity Intrusion in Aquifers and Freshwater Habitats

Regional Level Action ~ Support Policies that Protect Drinking Water Supplies from Salinity Intrusion

Analyses by the Philadelphia Water Department demonstrate that streamflow targets at Trenton as defined by the Delaware River Basin Commission must be kept at least at current levels to protect the Philadelphia water supply under present day climate conditions. As more information about effects of climate change on physical conditions in the Basin becomes available, flow management policies in the Basin must be evaluated and modified to ensure continued protection of drinking water supplies.

Utility Level Action ~ Evaluate Customer Notification Needs and Protocols

Analyses show that sodium and chloride are steadily increasing in the main stem Delaware most likely because of increased development, road salts application, and inputs from wastewater and drinking water treatment. These parameters are not removed during conventional drinking water treatment and could pose problems for special needs customers such as dialysis patients and certain industries. Impacts of climate change on conditions in the Basin may exacerbate rising salinity. Water utilities should evaluate current salinity levels to determine if more frequent notification to special needs customers is required.

4.7. Drinking Water – Identify Priority Research Needs

As discussed above, survey results identify priorities for water suppliers, government agencies and other key decision makers with respect to climate change and drinking water supplies. This guidance is most helpful in identifying key research needs with respect to climate change. The survey allows water suppliers and regulators to identify priority science gaps among the myriad research needs and substantial uncertainty associated with future change. Focusing on these key research needs will provide more information necessary to refine planning and adaptation efforts.

Survey results point to two main categories of research needs: Physical Drivers and Impacts of Physical Drivers on Drinking Water Supplies. The first category, Physical Drivers, focuses on increasing the understanding of how global climate model results translate to changing Delaware Basin conditions such as streamflow. The second category, Impacts of Physical Drivers on Drinking Water Supplies, aims to quantify the potential impact of physical drivers on drinking water supply vulnerabilities, such as the impact of changing streamflow on salt line movement. The first category of research needs is described below in Section 4.7.1. The second category of research needs is described in Section 4.7.2.

4.7.1. Research Needs – Physical Drivers

Research needs on Physical Drivers are based on topics identified in the workgroup survey as having a high impact score and low confidence score. A low confidence score indicates that the workgroup was not assured of the availability of data on the physical drivers that impact supply. These drivers have a large potential for impact, but require more localized climate predictions to assist in identifying impacts of climate change on physical conditions in the Basin. These drivers were flagged as priorities requiring more research. Table 4.4 summarizes research priorities in this category.

Table 4.4 Recommended areas of further research on physical drivers

Drivers	Delaware Basin Specific Research
▪ Decreased/increased river discharge and streamflow ▪ Decreased/increased groundwater levels ▪ Increased runoff ▪ Increased frequency of short-term drought ▪ Disruptions to aquatic ecosystems ▪ Increases in demand	▪ Precipitation predictions (volume and intensity) and implications for priority drivers ▪ Air temperature and heat index predictions and implications for priority drivers ▪ Impacts of climate change on snowpack and implications for priority drivers ▪ Regional water demand projection ranges (seasonal and peak) based on population growth, development, temperature/heat index changes, and a potentially longer growing season

4.7.2 Research Needs – Impacts of Physical Drivers on Drinking Water Supplies

Research needs in this category focus on topics identified as having a high potential impact score and a low confidence score in the workgroup survey. A high confidence score indicates that the workgroup was certain of the availability of data on the physical drivers that impact supply. Yet available information about physical drivers requires further modeling and study in order to quantify specific effects on supply vulnerabilities. Recommendations in this category are outlined in Table 4.5.

Table 4.5. Top research needs for quantifying the impacts to water utilities from changing physical drivers

Vulnerability	Delaware Basin Specific Research
Damage to Drinking Water Infrastructure	▪ Evaluate impacts of potential flooding, sea level rise and storm surge on infrastructure vulnerability; use historical information about impacts of flooding on infrastructure as guideline ▪ Consider impact of direct temperature change on infrastructure vulnerability
Inundation of Treatment Plants and Pumping Facilities	▪ Evaluate impacts of flooding, sea level rise and storm surge on the vulnerability of drinking water infrastructure to temporary and permanent inundation using updated floodplain maps
Degraded Source Water Quality	▪ Evaluate impacts of sea level rise on parameters of concern to drinking water supplies including *Cryptosporidium*, *E.coli*, *Giardia*, turbidity and suspended sediment, alkalinity, pH, dissolved metals, buffer capacity, dissolved organic carbon, dissolved oxygen, aquatic health and biochemical oxygen demand ▪ Factor in changes in runoff, watershed vegetation and forest cover as more information about these changes becomes available ▪ Consider effects of direct temperature change on parameters of concern ▪ Examine effects of changes in watershed vegetation and forest cover and direct temperature effects on migration patterns of waterfowl and pathogen transport
Upstream Movement of Salt Line/Salinity Intrusion in Freshwater Aquifers and Habitats	▪ Model effects of sea level rise and storm surge on salinity levels at drinking water intakes ▪ Factor in changing streamflow as more information becomes available
Power Outages and Customer Supply Issues	▪ Evaluate effect of flooding and storm surge on possible increased disruptions on ability to provide service; use historical data on service interruptions as guideline

The workgroup also identified the assessment of vulnerabilities and adaptation options regarding groundwater supplies (which were not part of this effort) as a major gap in knowledge/information related to drinking water that needs to be addressed.

Feature Box: A Hypothetical Exercise for Demonstration Purposes

In the year 2000, demand for drinking water in the watershed of the Delaware Estuary was around 164 billion gallons annually. Currently, the mean cost to treat and supply is about $5/1000 gallons of water (Corrozi and Nelson, 2008), meaning that the Estuary spends around $820 million annually on drinking water supply. Over the next century, the Estuary population is anticipated to grow by 83%. This number was calculated using two different population project models called Straight and Cohort which used 2000 Census data for the counties in the Delaware Estuary. See Table 4.6 for the output of these models on population projections. Realistically, technology improvements and water saving practices would likely prevent water demand from increasing at a 1:1 ratio with population growth. But for this hypothetical exercise, let's assume that an increase in population will result in a proportionate increase in water demand.

Table 4.6. Population Predictions

Year	Estimated Population	Population Increase
2000	6,441,769	--
2050	8,902,778	38%
2100	11,793,956	83%

If we assume that water demand per person holds at 2000 Census numbers, then water demand will increase by 38% at 2050 and 83% by 2100. Population growth alone may put great strain on drinking water supplies, and climate change will only add to the problem. Salinity rise around the freshwater intakes and flooding are among the many climate change impacts that may lead to physical damage and corrosion of infrastructure. Even 1% damage to drinking water infrastructure from climate change added to a 2050 population growth of 2.5 million people (Table 4.7) could put pressure on supply systems.

As drinking water suppliers reach capacity and infrastructure is damaged from climate change, this region will have to pursue alternatives to the current supply system. In a worst-case scenario, this shortage would be filled with bottled water at a cost of just under $1 billion per day, which is probably not a realistic long-term option. Fortunately, demand for water per person can be reduced by employing conservation BMPs proposed by the California Urban Water Conservation Council (UWCC) such as low flow toilets and gray water landscaping (App. L). Using an analysis of BMP costs and savings from the UWCC, we calculated that BMPs could be employed to fill this shortage for $1.2 Billion/yr – less than the cost of filling the supply deficit with bottled water *for only 2 days*.

Based on this hypothetical exercise, the Natural Capital Team recommends that water planners should consider projections of population growth and potential risks from climate change in their long range supply plans. Better planning could help water suppliers avoid some emergency situations. In addition, water planners should consider using demand cutting alternatives to address population growth, rather than simply increasing supply with new intakes and treatment plants. Often, it is assumed that the only way to address increasing demand is to meet it with increased supply. Water planners in the Delaware Estuary should be educated about demand cutting alternatives, such as those used by the California Urban Water Conservation Council (App. L).

4.8 Drinking Water – Conclusions

The above analysis provides an inventory of the potential impacts of climate change on the Basin and the implications of those impacts on drinking water supplies, suggestions for actions that help guard against drinking water vulnerabilities, and recommendations for future study. The following key messages arise from the analysis:

- Of the drivers assessed, sea level rise, storm surge, and flooding are likely to have high impact for many of the drinking water vulnerabilities identified. Future study should focus on quantifying the effects of these drivers on risks to drinking water supplies.
- Climate change will likely exacerbate existing threats and challenges to drinking water supplies. The prospect of climate change adds emphasis to the importance of regional support for source water protection.
- Both utility level and regional level actions are critical to improving the resiliency of drinking water supplies to the effects of climate change.
- Forest protection is the single most important action in protecting regional water supplies from water quality degradation. It is also critical to guarding against potential decreases in supply availability and impacts to reservoir levels.
- Ensuring continued support and funding for tools such as the Delaware Valley Early Warning System that facilitate region-wide communication during emergency is also a critical regional adaptation to climate change.
- Evaluating placement of new construction with respect to expected sea level rise and updating drought and emergency response plans are critical adaptations at a utility level.
- Understanding the interactions of various climate change factors on flow and drinking water supply and demand is complicated, but can be improved by monitoring and methodical modeling of the various flows and factors in the watershed.

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.

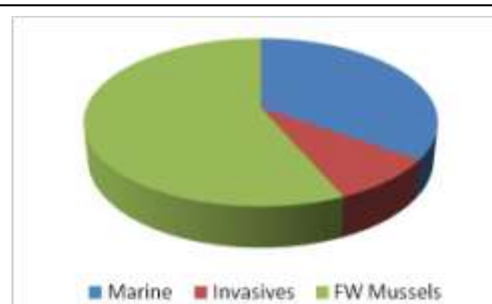


Figure 5-2. Different types of bivalve species in the Delaware Estuary watershed.

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.).

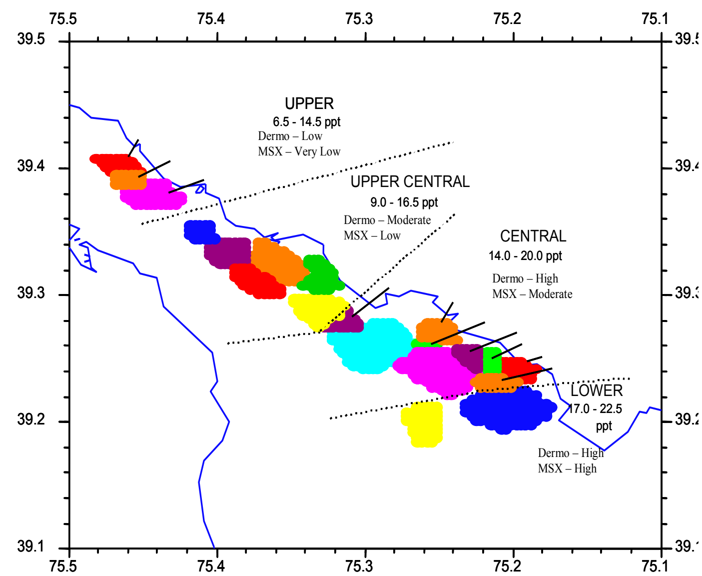


Figure 5-4. New Jersey seed beds of *Crassostrea virginica* in relation to salinity and disease susceptibility.

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).

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

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

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.

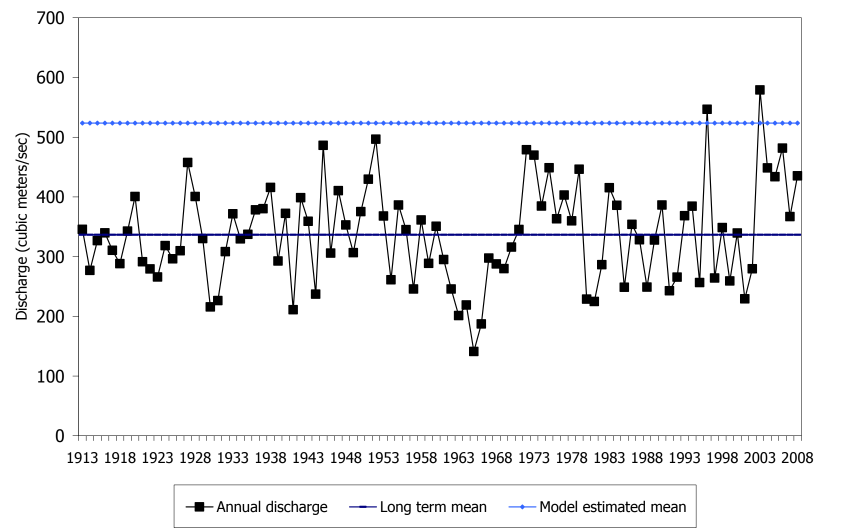


Figure 5-6. Flows on the Delaware River at Trenton, NJ, between 1913 and 2008.

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.

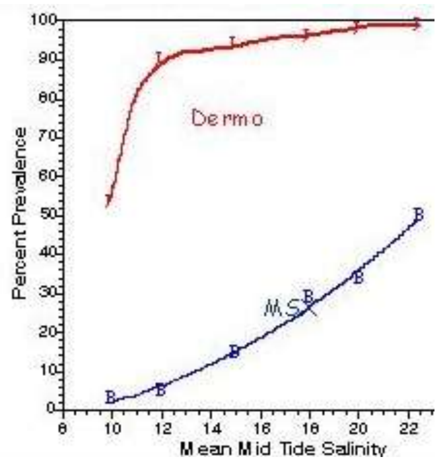


Figure 5-8. Prevalence of two important oyster disease agents, Dermo and MSX, in relation to salinity in Delaware Bay. Data from Susan Ford (HSRL).

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 effects 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.

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

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

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 5-12. 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.

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.

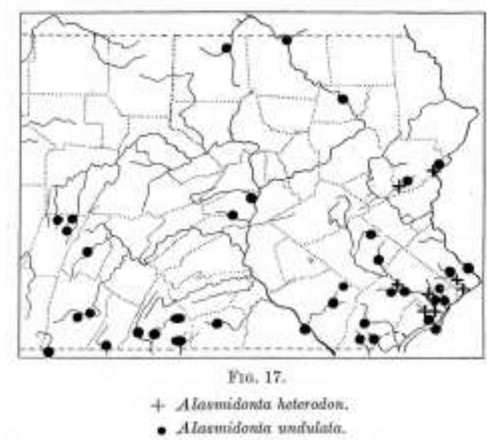


Figure 5-13. Apparent distribution of two mussel species in Pennsylvania in 1919, both of which appear now to be extirpated from southeast Pennsylvania (Ortmann 1919.)

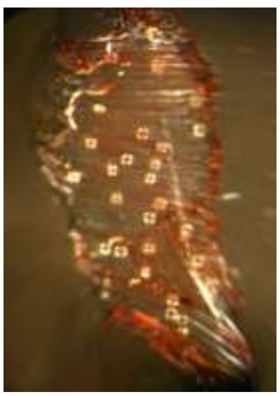


Figure 5-14. Tactics for restoring freshwater mussels are being developed in the Delaware Estuary. In this photo, baby mussels are shown attached to the gill of a host fish held in captivity at Cheyney University, PA.

***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.

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.

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

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.

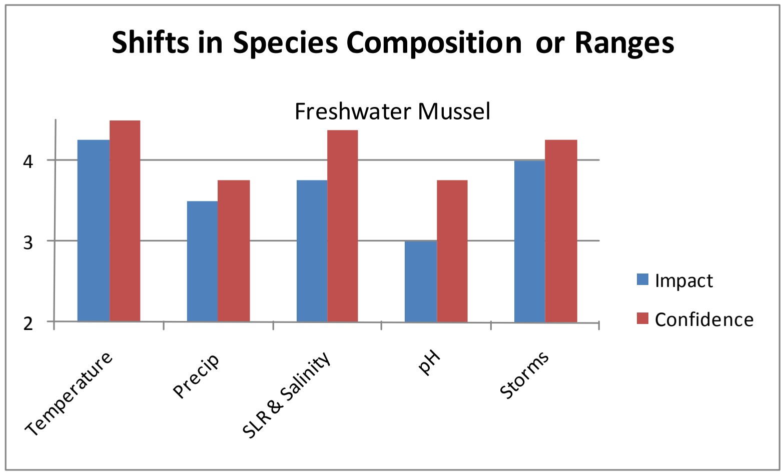


Figure 5-15. Relative levels of concern regarding the potential impact of changing physical and chemical conditions on **species composition and ranges** of freshwater mussels (blue) and relative confidence in these projections (red.)

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.

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.)

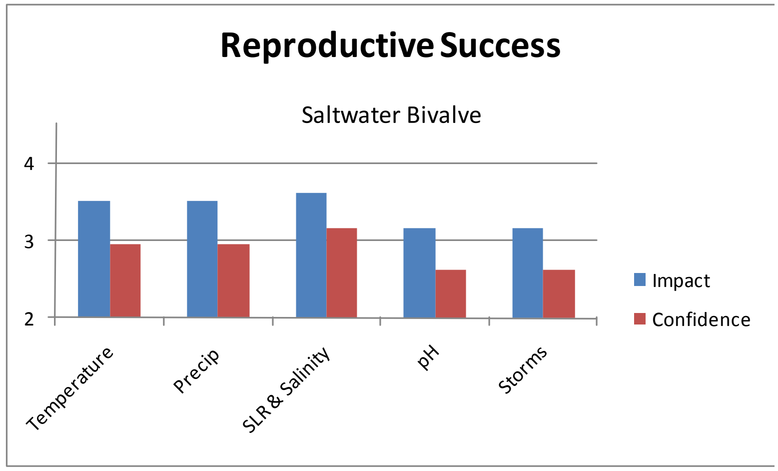


Figure 5-17. Relative levels of concern regarding the potential impact of changing physical and chemical conditions on **reproductive success** of saltwater bivalves (blue) and relative confidence in these projections (red.)

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.

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 estury. The general level of confidence in survey responses was lower for saltwater species than for freshwater bivalves.

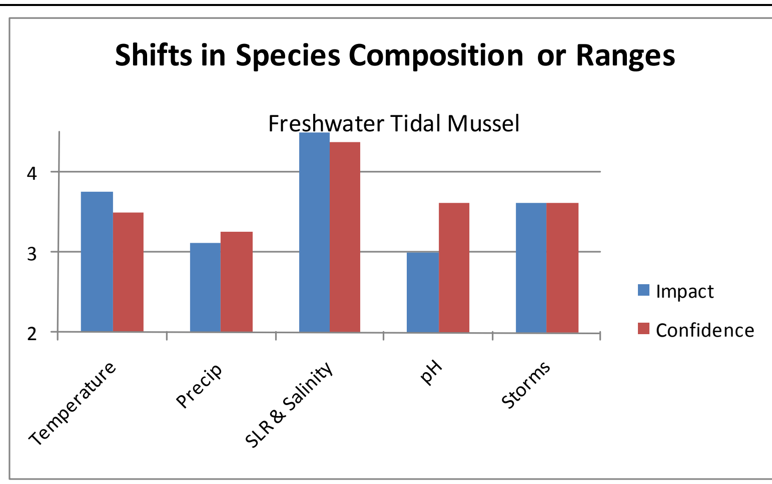


Figure 5-16. Relative levels of concern regarding the potential impact of changing physical and chemical conditions on **species composition and ranges** of tidal freshwater bivalves (blue) and relative confidence in these projections (red.)

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.)

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.

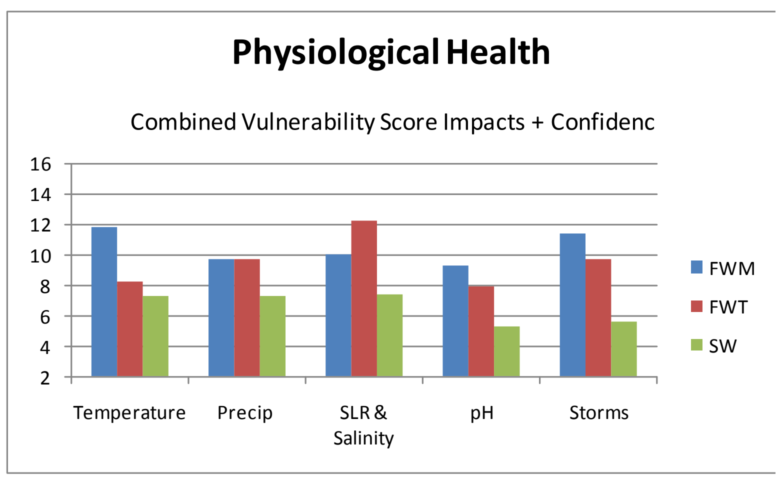


Figure 5-18. Relative vulnerability index for the **physiological health** of freshwater mussels (FWM), freshwater tidal bivalves (FWT) and brackish/saltwater bivalves (SW) exposed to future changes in temperature, precipitation, sea level/salinity, pH and storms by 2100.

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.

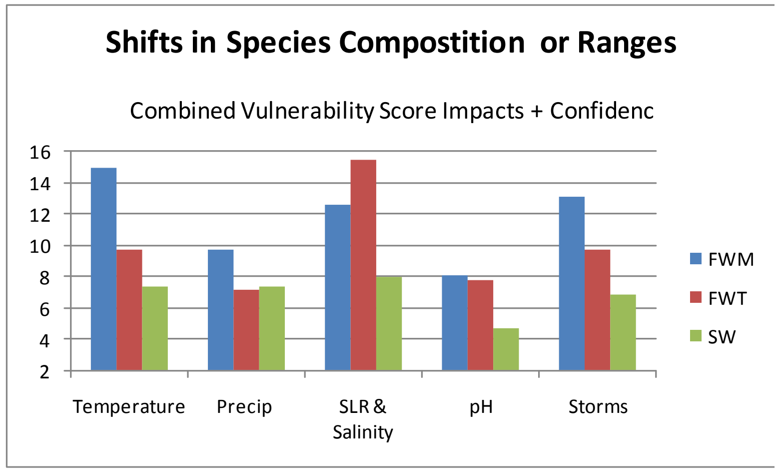


Figure 5-20. Relative vulnerability index for shifts in **species composition or ranges** of freshwater mussels (FWM), freshwater tidal bivalves (FWT) and brackish/saltwater bivalves (SW) exposed to future changes in temperature, precipitation, sea level/salinity, pH and storms by 2100.

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

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

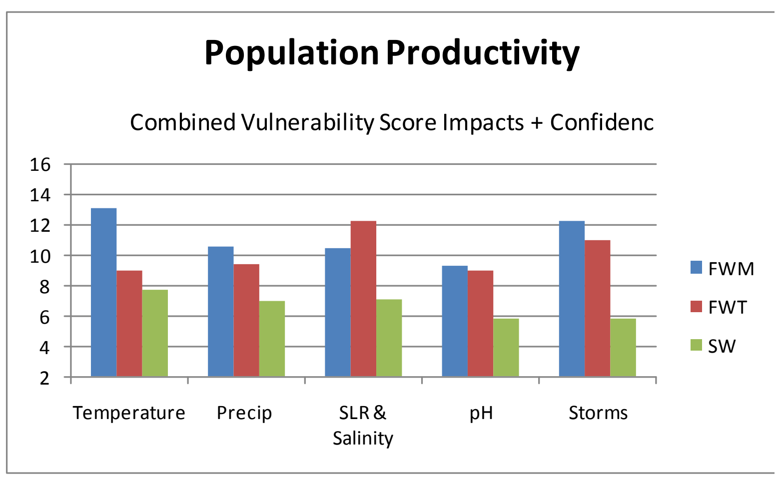


Figure 5-19. Relative vulnerability index for the **population production** of freshwater mussels (FWM), freshwater tidal bivalves (FWT) and brackish/saltwater bivalves (SW) exposed to future changes in temperature, precipitation, sea level/salinity, pH and storms by 2100.

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

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

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.

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	[redacted]	
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

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.

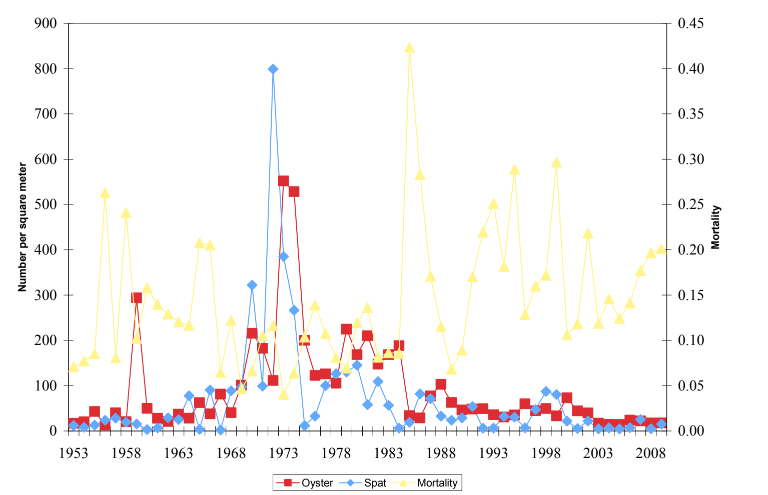


Figure 5-22. Bay wide oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

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 0.888×10^9. These potential decreases could greatly reduce oyster harvest.

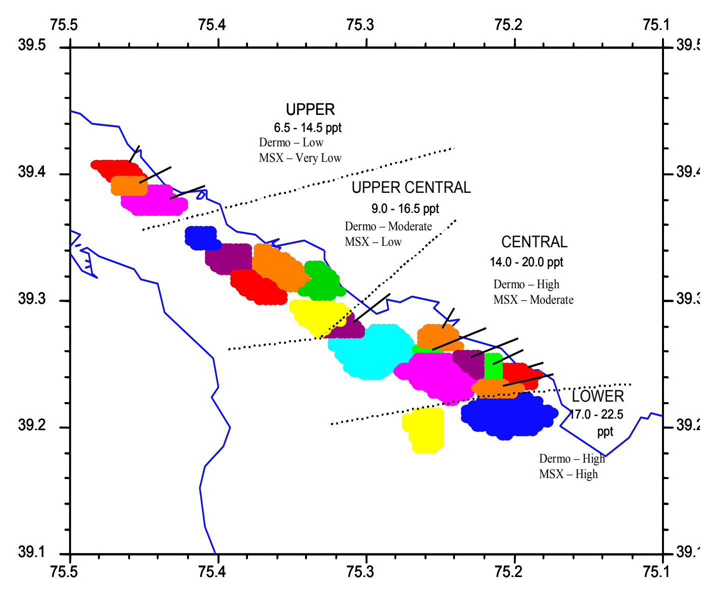


Figure 5-23. Location of New Jersey seed beds of *Crassostrea virginica* in relation to salinity and disease susceptibility.

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*

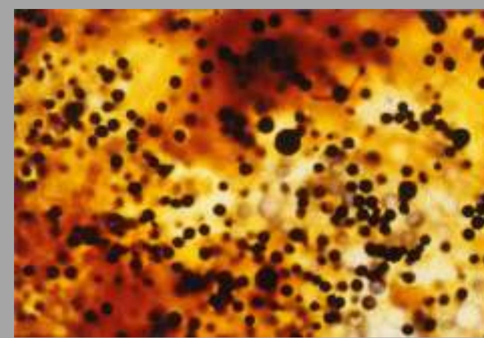


Figure. Black spots indicate Dermo infested

- 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 shelflish 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

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

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.

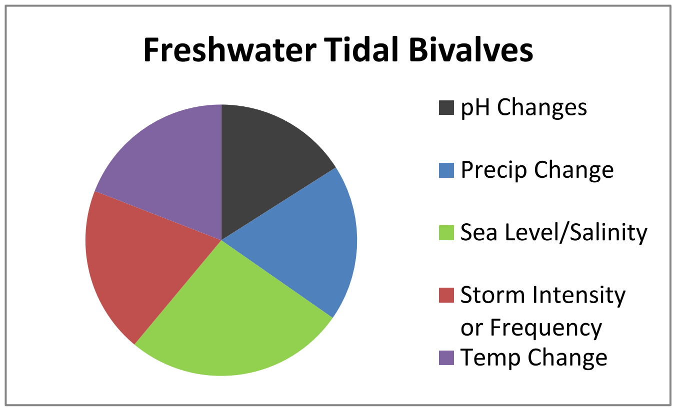


Figure 5-25. Relative vulnerability of freshwater tidal bivalves to changes in five climate conditions.

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.)

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.

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