

Conserving Freshwater and Coastal Resources in a Changing Climate

A Report Prepared for The Nature Conservancy

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Cover photos:
Harold E. Malda (Top left and right), Stephen G Make (Top center), Alan W. Eckert Middle)

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Climate change presents significant challenges to both human and natural communities. A variety of climate-driven changes have already been observed, such as an increase of average global air and ocean temperatures and an increase in the occurrence and intensity of extreme weather events. These impacts are projected to continue into the future.

While a broad spectrum of interests, stakeholders and governments have engaged in international negotiations and action plans to reduce the sources of greenhouse gases that contribute to climate change, significant effort remains before this global phenomenon is controlled and mitigated. The persistence of previously emitted gases and uncertainties about future human responses in reducing emissions means we will continue to feel the effects of climate change for decades and most likely, centuries. It is important for organizations, agencies, and individuals working on environmental conservation to understand the probable ecological and societal effects of climate change and to identify and implement appropriate policies to plan for and adapt to climate changes and deploy on-the-ground conservation strategies that anticipate these changes.

The Changing Climate

Based on a range of scenarios for anthropogenic emissions of greenhouse gases, The eastern United States (defined for this report as the mid-Atlantic, New England and Great Lakes regions) is expected to see the following range of impacts by the end of the century:

• A rise in annual average temperatures for the Northeast of 3.5° - 12.5°F (1.9° - 6.9°C) and 4.9°- 9.5°F (2.7°- 5.3° C) in the Mid-Atlantic, with most of the warming occurring in winter months.

• A rise in winter temperatures of 6° - 14°F (3° - 8°C) and a rise in summer temperatures of 11° - 16°F (6° - 9°C) in the Great Lakes region.

• An increase in sea surface temperature of 5° - 8°F (2.2°- 4.4°C) by the end of the century.

Photography by Mark Godfrey

• Annual precipitation in the Northeast is anticipated to increase by 10% (about 4 inches) by 15% (about 6 inches) in the mid-Atlantic, and by 10-20% (about 3 to 6 inches) in the Great Lakes region.

• An increase in the frequency of droughts. Short-term droughts that currently occur in the Northeast once every 2 to 3 years are likely to occur on a yearly basis by the end of the century.

• An increase in the duration of the Northeast's low flow period for rivers and streams. Low flow may arrive a week earlier and extend several weeks longer into the fall. Predictions of stream flow changes in the Mid-Atlantic region are less certain, flow could decrease by 4% or increase by 27%.

• A sea-level rise of 2.5 - 13 inches by mid-century and 4 - 33 inches by the end of the century.

The most significant effects of climate change on aquatic ecosystems are predicted to be the following:

An increase in water temperature is predicted to negatively affect plants and other aquatic species living in these ecosystems. Species that are mobile may be pushed further north in pursuit of cooler waters while species which cannot migrate will be forced to adapt or perish. In addition, as increased water temperatures generally decrease water oxygen levels, even those species which are not adversely affected by warmer water may be threatened as a result of a lack of oxygen.

Changing weather patterns and altered water regimes may threaten aquatic ecosystems in a number of ways. An increase in high intensity storms may increase erosion of coastal beaches and wetlands and open more inland areas to storm effects. An increase in short term summer droughts may decrease freshwater levels, threatening species which depend on freshwater. These droughts may be compounded by a winter precipitation that falls more as rain than snow, threatening those ecosystems which depend on the annual high water and floods driven by snow-melt.

An increase in sea-level rise will lead to the deterioration of saltwater wetlands along much of the coast throughout the Eastern Region. Numerous species may be affected by this as they depend on these ecosystems for food, shelter, and as breeding grounds.

Lower lake levels in the Great Lakes will change the hydrology of near-shore habitats including important fringing wetlands and marshes. These wetlands are important breeding and stopover habitats for birds and nursery areas for fish and other aquatic organisms.

In light of these anticipated changes, immediate action is imperative. Climate driven changes are underway and it is necessary to implement programs which allow ecosystems to be resilient to and/or adapt to these changes.

Effects of Climate Change on Aquatic Ecosystems

The changing climate will have varying effects on different freshwater and coastal systems. These changes include:

River and Stream Ecosystems

Suitable habitat for 57 species of cold-water fish has been projected to decline up to 36% in U.S. rivers if air temperatures rise by 4°C. River and stream ecosystems will likely have changes in low and high flows, increased drought, flooding, and an increase in water temperature. This will likely cause isolation of nearby wetlands and a loss of habitat for wetland dependent fish.

Freshwater Wetlands

Freshwater wetlands are diverse ecosystems that will be vulnerable to a range of impacts from climate change. Bogs, which depend almost entirely on precipitation for their water, are vulnerable to extended droughts. In addition, a decrease in the snow pack will yield a weaker spring flood, threatening the wetlands and floodplains which depend on this seasonal inundation. Key wetland functions, like the assimilation of nutrients and storage of sediment may also be affected by the changing hydrologic regimes associated with climate change.

Lake Ecosystems

Lake ecosystems may face altered dissolved oxygen characteristics that aquatic species depend on for survival. Additionally, lake water temperatures may increase by up to 5.2°C, a condition expected to lead to a loss of habitat for cold and cool water fish in the Eastern Region. The response of lake ecosystems to climate change will likely include loss of ice cover, increased stratification, shifting thermal regions, and lowered lake levels.

Saltwater Wetlands

Saltwater wetlands are fragile and ecologically productive ecosystems which can drown if sea levels rise faster than the wetlands are able to build themselves up. Increased levels of salinity and decreased freshwater inputs may alter ecosystems and threaten a range of species. Finally, increased storm activity may damage wetlands along the coast.

Coastal Waters and Shorelands

Coastal marine systems, including coastal waters, bays, and estuaries, and adjacent shorelands including beaches, dunes, and barrier islands, are susceptible to sea-level rise that will increase the depth of coastal waters as well as push salinity to intrude deeper into estuaries. The projected increase in temperatures will also have pervasive effects on these ecosystems,


Photography by Stephen G. Maka

affecting vital processes including activity, feeding, growth, and reproduction of aquatic organisms. Shorelands are most susceptible to sea-level rise, which will inundate lowlands, erode beaches, and increase flooding.

Adapting to Climate Change

In light of these anticipated changes, action to increase and restore the resiliency of these systems is imperative.

Adaptation Planning

Before pursuing adaptation strategies a clear picture of the anticipated effects of a changing climate in specific places is often necessary. Analyses to support adaptation strategies include understanding current conditions (e.g. topography, hydrodynamics, vegetation or species distribution) and the anticipated impacts from climate change (e.g. change of temperature, precipitation change, sea-level rise). Geographic analyses are key to gaining this understanding. There are a variety of technological tools available for analyzing these impacts of climatic change on ecosystems. Various remote sensing techniques, including Light Detection and Ranging (LIDAR), which can provide detailed land elevation information, and satellite imagery of land cover, can provide critical information and be used by Geographic Information Systems (GIS) to provide maps of existing conditions and predicted changes. Models, including bioclimatic models of species ranges and distribution, hydrologic models, inundation models and circulation models can be useful in understanding how climate induced changes will affect physical and ecological processes.

Adaptation Strategies

Many existing environmental management tools have the potential to aid with increasing and restoring resiliency to aid these systems in adapting to climate change. Many of these techniques are not without consequences and their appropriateness will vary for different settings. Practitioners attempting to help ecosystems adapt to climate change should consider both the benefits and consequences of any technique. Adaptation techniques can be classified as **building resiliency, protection,** and **retreat** measures (modified from Warren, 2004).

Building Resiliency

Accommodation measures prepare and protect ecosystems to reduce the severity of climate change impacts.

- *Restore wetlands and marshes*
- *Remove dams and other stream barriers*
- *Manage dams to promote sustainability*
- *Protect environmental flows*
- *Manage fisheries harvest*
- *Use water efficiently*
- *Protect migration corridors*
- *Create buffer areas around freshwater systems*
- *Consider artificial aeration for some lakes and ponds*

Land Management

Protecting priority areas from current threats through land protection and management will be an important aspect of ensuring freshwater and coastal systems can adapt to changing climatic conditions.

- *Protect key natural freshwater areas*
- *Use conservation easements to provide protection on private lands*
- *Implement rolling easements that move as the shoreline/riverfront moves*
- *Use deed restrictions to protect private lands*

- *Ensure land use regulations accommodate natural processes*
    - o *Setbacks*
    - o *Zoning Overlay Districts*

Physical Protection Measures

A physical protection measure is designed to act as a physical barrier to protect an area from threats of a changing climate such as floods, storm surges and sea level rise.

- *Use bioengineering and other soft techniques*
- *Create and restore wetlands and marshes*
- *Create and restore dune systems*
- *Restore oyster reefs*
- *Consider beach nourishment projects*
- *Restore tidal hydrology*

Retreat Measures

Making room for migration of wetlands and other habitats or getting out of harm's way from sea-level rise or more intense river flows may on occasion require moving existing infrastructure.

- *Relocate infrastructure away from high hazard areas*
- *In some cases, consider assisting species migration*

Recommendations

The report makes three types of recommendations for conservation organizations: *Short term* recommendations are those which can be implemented immediately and demand relatively low start-up costs, *long term* recommendations are those which require greater investment of time and resources and *big picture* recommendations are those suggesting policy changes and partner engagement.

Short Term Recommendations

- *Include climate change considerations in all levels of decision-making.*
- *Land protection organizations should develop methods for evaluating individual freshwater and coastal properties based on climate change concerns.*
- *Develop long-term property management plans.*
- *Develop a "Climate Endangered Ecosystem" list.*
- *Foster collaboration between climate specialists and habitat specialists.*

Photography by Mark Godfrey

- *Foster Future Research:*
    - – *Foster collaboration between climate specialists and habitat specialists.*
    - – *Encourage scientists to incorporate climate change considerations into their research.*
    - – *Encourage more research projects that focus specifically on aquatic ecosystems and their predicted responses to climate change.*
    - – *Promote collaboration between scientists from different specialties in order to better understand how the health of one affects the health of others.*
    - – *Research the relationship between human related water resource management and water conservation for aquatic ecosystems.*

- *Research adaptation techniques for effectively preserving freshwater systems as they respond to climate change.*

Long Term Recommendations

- *Seek funding for LIDAR mapping.*
- *Support accurate, high resolution elevation mapping for coastal wetlands.*
- *Floodplain mapping should be updated to better predict future scenarios of hydrological systems.*
- *Prioritize protection over restoration of aquatic ecosystems.*
- *Establish long-term goals that consider mid-century and end of century climate predictions.*
- *Evaluate existing monitoring programs and implement additional programs.*
- *Promote the use of conservation methods which mimic natural processes.*
- *Promote the removal of existing and prevent the construction of new hard structures.*
- *Promote migration corridors.*
- *Pay special attention to north/south migration corridors.*

Big Picture Recommendations

- *Work with federal, state and local agencies to strategically maximize the number of aquatic ecosystems that are designated as protected areas.*
- *Promote regional planning which integrates climate change into land use and conservation strategies.*
- *Promote stricter wetland protection at all levels of government.*
- *Work with local land trusts and property owners to build a vision of the future for local properties that incorporates climate change considerations.*
- *Continue to work to reduce other anthropogenic stressors such as development, pollution, and wetland drainage.*
- *Partner with other environmental non-profits on climate change issues.*

This report documents both the vulnerability and resiliency of aquatic ecosystems. These natural areas have been under increasing stress for centuries, yet have managed to adapt and continue to thrive. Organizations devoted to protecting ecosystems at risk have an important role to play in preparing for and reacting to climate change. By integrating climate change concerns into their operations and the evaluation of their properties, conservation organizations will be better equipped to anticipate negative changes before they occur. This will allow conservation planning to become more proactive, providing freshwater and coastal ecosystems a greater chance of survival, a critical element for the health of the natural world as a whole.

Photography by Harold E. Malde

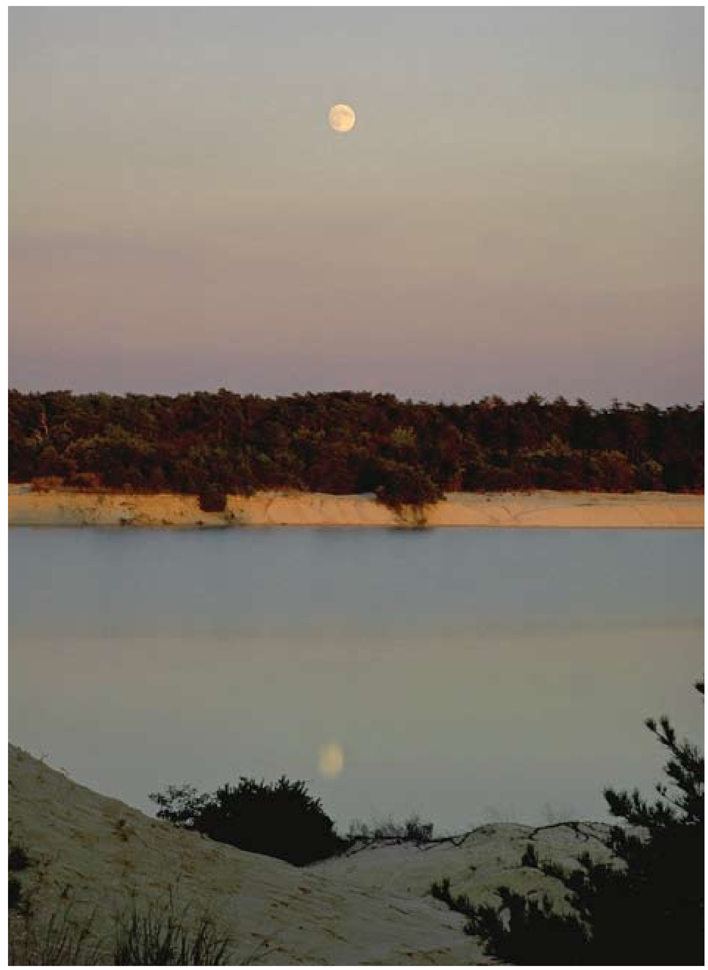
Climate change is already affecting aquatic ecosystems. Therefore, immediate action is imperative.

CHAPTER
1

Introduction

Climate change presents significant challenges to both human and natural communities. A variety of climate-driven changes have already been observed, such as an increase of average global air and ocean temperatures and an increase in the occurrence and intensity of extreme weather events. These impacts are projected to continue into the future.

While a broad spectrum of interests, stakeholders and governments have engaged in international negotiations and action plans to reduce the sources of greenhouse gases that contribute to climate change, significant effort remains before this global phenomenon is controlled and mitigated. The persistence of previously emitted gases and uncertainties about future human responses in reducing emissions means we will continue to feel the effects of climate change for decades and most likely, centuries. It is important for organizations, agencies, and individuals working on environmental conservation to understand the probable ecological and societal effects of climate change and to identify and implement appropriate policies to plan for and adapt to climate changes and deploy on-the-ground conservation strategies that anticipate these changes.


Photography by Harold E. Malde

This report provides a primer on climate change issues to help individuals and organizations in the eastern United States begin to factor in climate change into their freshwater and coastal conservation efforts. First, it provides an overview of the expected effects of climate change on aquatic ecosystems in mid-Atlantic and northeast regions, including the coastal states from Virginia to Maine and from Ohio east. Second, this report provides a brief overview of the most relevant technological and policy tools available for analyzing and adapting to these impacts. Finally, this report makes a series of recommendations to conservation organizations and policy makers on how to more effectively undertake conservation that anticipates changes in climate and the changes in ecosystems.

A key aspect of this work is the recognition that climate change is not the only stressor to aquatic ecosystems. These natural communities and ecosystems are already under threat from human activities such as development, agriculture, resource extraction, pollution, and over harvesting. Freshwater ecosystems play an integral role in the biodiversity and productivity of the planet, a source of water critical to all species. These systems provide a wide range of habitat types, are host to numerous unique and rare species, serve as important spawning and nesting habitat, and serve numerous other functions and values. Many of these ecosystems have a limited tolerance for disruptions outside their natural ranges of variability. Climate change poses a series of large, long-term and potentially catastrophic impacts that could forever alter, if not eliminate, many of the biodiversity and ecosystem services of aquatic ecosystems within the mid-Atlantic and Northeastern United States, as well as across the globe.

The health of aquatic ecosystems is intimately related to the well-being of the hydrologic realm in which they exist. Many of the predicted effects of climate change relate directly to changes in hydrology or weather patterns, which could in turn greatly affect freshwater and coastal areas.

Natural systems are constantly evolving and the ecosystems that exist today are a result of previous variations in climatic, geologic and biotic interactions over eons. However, the changes anticipated as a result of the concentration of carbon dioxide and other gases in the atmosphere are predicted to happen at an unprecedented rate, out pacing the ability for evolution to allow these species and communities to adapt. In addition, aquatic environments have been so altered by human influence that their ability for natural adaptation has, in many cases, been compromised.

CHAPTER

2

Climate Change Overview

The Earth's climate has changed, is changing, and will continue to change during the twenty-first century. Average global air and ocean temperatures have warmed, precipitation has increased in some areas while droughts have flourished in others, and intense weather events occur more frequently (Alley, 2007). The broadly accepted consensus among scientists is that these changes are occurring at a rate and to an extent significantly exacerbated by human activities, specifically the combustion of fossil fuels and changes in land-use, and that these changes are projected to continue. This global phenomenon presents a new and different threat to the conservation of the Earth's biodiversity.

Natural concentrations of heat-trapping gases, such as carbon dioxide (CO2) and methane (CH4), occur in our atmosphere. These gases absorb infrared radiation and limit its escape from Earth, much like the trapping of heat within a greenhouse, maintaining the planet's surface temperature to make life as we know it possible (Schneider, 2002). However, human actions are leading to an accelerated change in our planet's climate. For the past two centuries, the burning of fossil fuels such as coal, oil, and natural gas has propelled industrialization, has heated and lighted our buildings, powered our businesses and factories, and fueled our transportation. This burning of fossil fuels has also released greenhouse gases in quantities resulting in atmospheric concentration of these gases beyond any in recorded history.

Current Global Impacts of Climate Change

The Intergovernmental Panel on Climate Change has reported that global average surface temperature has warmed by 1.3°F (0.74° C) over the past century. During this period, sea level is estimated to have risen 0.17 mm/year and the rate of rise is increasing. Since the 1970's, the world has seen droughts of increased severity and length that spread across wider geographic areas. Subsequent observations of changed wind patterns and decreased snow pack and snow cover have also been made. The frequency of heavy precipitation events has increased (Alley, 2007).

Models, Scenarios, and Mitigation

These trends are expected to continue. Scientists from around the world have produced projections of the effects of climate change based on sophisticated climate models. Various models exist, the most complex of which are known as general circulation models (GCMs). These models analyze climate events by dividing the surface of the Earth into a grid composed of three-dimensional cells that measure a few degrees of latitude and longitude per side (Schneider, 2002). These models are useful in analyzing climatic events on a global scale; unfortunately, the basic unit is roughly the size of a small country such as Belgium, making regional projections more difficult. The accuracy of modeling technology continues to improve and regional accuracy can be enhanced by aggregating outputs from a number of different models (Environmental Protection Agency [EPA], n.d.).

Climate modelers use various future greenhouse gas emissions scenarios to create a range of outputs. These scenarios are based upon the different possible levels of human-induced greenhouse gas emission levels due to varying expectations of population change, development, and, most importantly, an increase or reduction in emissions.

Emissions reduction efforts are a key form of climate change mitigation. To date the high-profile international attempts to collaborate on mitigation policies, even if implemented, will fall short of needed actions. After years of negotiation and wavering political support, the Kyoto Protocol stands as the most comprehensive international treaty on climate change. However, the Protocol's targets translate into a global reduction of a mere 5-7% below 1990 emission levels by 2012, and fall far below the 80% reductions scientists are calling for currently.

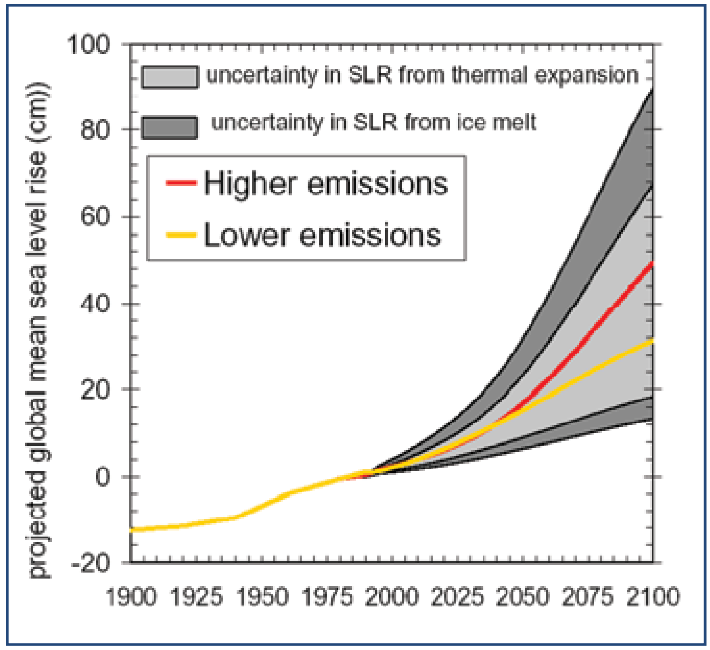
Cities, states, and national governments around the world are pledging to cut emissions. However, reducing emissions is a politically difficult process that requires investments of financial resources that will not happen overnight. In addition, emissions released today will continue to remain in the atmosphere for the next 50 years. For these reasons, though immediate and meaningful cuts in greenhouse gas emissions are a necessity, society also needs to heavily invest in gaining a better understanding of the effects of climate change and in preparing for these projected effects.

Global Projections of Climate Change

Current models and studies predict a continuation of these climatic changes into the next century. Globally, the range of emissions scenarios project a corresponding range of global average increases in surface air temperature in the current century from a low of 2°F to a high of 11.5°F (1.1° to 6.4° C). Sea level rise projections range from 7 – 23 inches (0.18 - 0.59 meters). Scientists now believe it to be very likely that hot extremes, heat waves, and heavy precipitation events will continue to be more frequent while snow cover is projected to diminish (Alley, 2007).

Climate Change and Biodiversity

Though loss of habitat is generally recognized as the greatest current threat leading to the extinction of species, climate change is likely to become an even greater threat to species' survival. Studies have projected that up to 18% - 35 % of all species will be 'committed to extinction' by 2050 as a result of changes in climate (Thomas, 2004). Changes in the timing and duration of seasons lead to incongruence in basic ecosystem functions such as flowering, nesting, migration, and feeding (WWF, n.d.) – that is the timing of natural processes will no longer occur during favorable climatic conditions. Expected habitat loss due to drying of lakes and streams, rising sea temperatures and vegetation change will be exacerbated by the inability for natural migration and retreat due to human urban and agricultural development. Rising sea temperatures threaten coral reefs through "bleaching," the break up of sea ice threatens polar bears' basic survival (hunting, mating, feeding), and warmer waters provide more hospitable conditions for diseases that can threaten marine life (Combes, 2005).



Courtesy of Union of Concerned Scientists (UCS 2006)

Figure 1. Model-simulated sea-level rise from 1900 to 2100

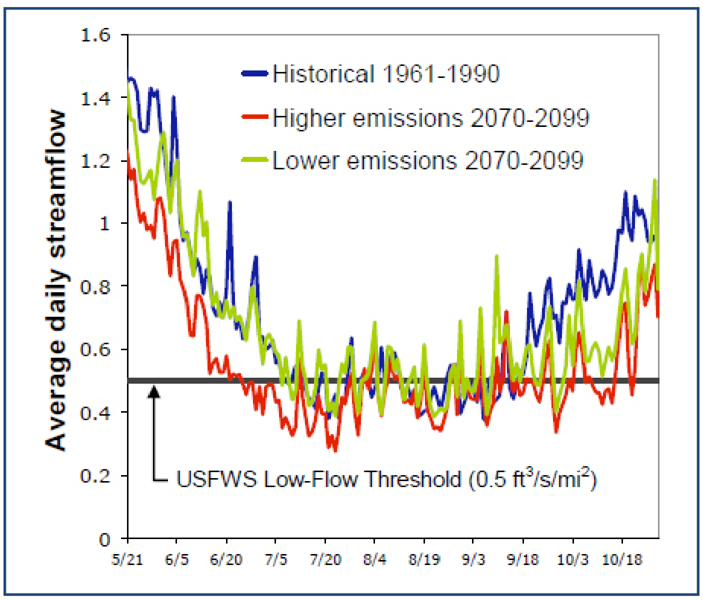
Regional Impacts

One of the challenges in predicting how ecosystems will respond to changes in climate is the uncertainty of climate projections, particularly on a local scale. While some predictions such as sea-level rise are fairly reliable, climate models do sometimes contradict one another, as is the case with weather pattern projections. This report covers a large geographic region, and thus, predictions for Maine will not necessarily hold true for Virginia. Nonetheless, keeping these uncertainties in mind, one can still take action based on what is known. If we wait for complete certainty before taking action irreversible damage will already have occurred.

While uncertainties remain, scientists' confidence in the ability of climate models to predict regional climate patterns continues to grow (Alley, 2007). Recent reports have used advances in modeling technology to create predictions for the United States' Northeast, Mid-Atlantic and Great Lakes regions (UCS, 2006; Najjar, 2000, Kling, 2003). This report summarizes these projections. The ranges used are based on low and high greenhouse gas emission scenarios for conditions at the end of the century, unless otherwise noted.

Temperature:

- Annual average temperatures are expected to increase by 3.5° - 12.5° F (1.9° - 6.9° C) for the Northeast (UCS 2006), and 4.9°- 9.5° F (2.7°- 5.3° C) in the Mid-Atlantic (Najjar, 2000), with most of the warming occurring in winter months.



Courtesy of Union of Concerned Scientists (UCS 2006)

Figure 2. Projected changes in duration of low streamflow in summer and fall months

- A rise in winter temperatures of 6° - 14°F (3° - 8°C) and a rise in summer temperatures of 11° - 16°F (6° - 9°C) in the Great Lakes region.
- In the Northeast, the number of days above 90° F (32.2°C) is anticipated to increase from a current average of 10-15 days per year to an average of 30-60 days per year by the mid-21st century. Similarly, the current average of 2-3 days per year over 100°F (37.8°C) may rise to up to 28 days per year (UCS 2006).

Sea Temperatures and Sea Level Rise:

- Sea surface temperature is expected to warm by 5° - 8° F (2.2°- 4.4°C) by the end of the century (UCS 2006).
- Globally, sea level is predicted to rise 2.5 - 13 inches by mid-century and 4 - 33 inches by the end of the century (UCS 2006).

Precipitation and Water Flows:

- Annual precipitation is anticipated to increase by 10% (about 4 inches) in the Northeast (UCS 2006), by 15% (about 6 inches) in the mid-Atlantic (Najjar 2000) and by 10 – 20% (about 3 to 6 inches) in the Great Lakes region (Kling 2003).
- Winter precipitation is expected to increase even more, up to 11-16 % by the middle of this century and 20-30% by the end of the century for the Northeast (UCS 2006).
- The intensity of precipitation (i.e. the average amount of rain that falls on any given rainy day) is expected to increase by up to 15% in the Northeast by the end of the century (UCS 2006) and the frequency of heavy rainstorms may double by the end of the century in the Great Lakes Region (Kling 2003).
- Droughts are predicted to become more frequent with short-term droughts that occur in the Northeast now once every 2 to 3 years occurring as often as once per year by the end of the century (UCS 2006).
- In the Northeast, the number of snow-covered days (days on which land is covered with snow) is predicted to decrease by 4-15 days by the end of the century (UCS 2006).
- The duration of the Northeast's low flow period for rivers and streams is expected to arrive a week earlier and extend several weeks longer into the fall (UCS 2006). Predictions of stream flow changes in the Mid-Atlantic region are less certain, flow could decrease by 4% or increase by 27% (Najjar 2000).
- The Northeast will see an increase in evaporation rates and a decrease in soil moisture in the summer and fall while experiencing an increase in soil moisture in winter and spring (UCS 2006).

Timing of Seasonal Phenomena:

- The Northeast will experience the start of summer (defined as growing degree days – those above 65°F) 6-11 days earlier, and it will extend 10-16 days longer into the fall by mid-century. The end of the century is projected to see a summer season that arrives 9-21 days earlier, and that extends 12 days to 3 weeks longer into the fall (UCS 2006).
- The growing season in the Northeast is predicted to be 2-4 weeks earlier by the middle of this century and 4-6 weeks longer by the end of the century (UCS 2006). The growing season in the Great Lakes region is expected to be 4 to 9 weeks longer (Kling, 2003).
- The length of the Northeast's snow season is expected to decline by 25-50% (UCS 2006).

Weather Patterns

Climate models predict changes in weather patterns throughout the eastern United States. The summer and fall months will be hotter and drier, with periods of extreme drought. This will cause evaporation rates to increase, effectively lowering the water levels throughout wetlands and the entire watershed (Moore et al., 1997). In addition, the ground may become drier which decreases its ability to absorb rain when it does fall, which then contributes to erosion (M. Kline, personal communication, April 13, 2007). Thus, during the winter and spring, when heavy precipitation events are predicted, the ground will be less able to absorb the influx of rainwater, and there will be large increases in the amount of stormwater runoff, carrying with it higher quantities of sediment, excess nutrients, and pollutants (Kling et al., 2003; Najjar et al., 2000).

CHAPTER

3

Responses of Freshwater and Coastal Ecosystems to Climate Change

Aquatic ecosystems encompass both freshwater and marine habitats. This report reviews the effects of climate change on freshwater ecosystems, including rivers, streams, lakes and wetlands, as well as on near-shore coastal ecosystems, including salt marshes, shorelands – barrier islands, beaches and dunes – and bays and estuaries.

Diverse species and natural communities depend on aquatic ecosystems for survival from fish, to amphibians, to carnivorous mammals (otter, mink) and migrating birds (herons, ducks), to scores of invertebrates (freshwater and estuarine mussels and clams), plants and microscopic organisms that make up the food chain. These systems are complex with many physical and biotic interactions keeping systems in a dynamic equilibrium. Therefore, climate change impacts must be considered for how they will affect a single species or natural community as well as the how they affect larger ecosystems. Climate change poses an additional threat to ecosystems already stressed by habitat loss and destruction, alteration of the hydrologic regime, pollution, exotic species, and overexploitation.

Following a brief overview of each aquatic habitat type, this chapter reviews the responses of each ecosystem, and examples of its component species, to the anticipated effects of climate change.

Responses of Rivers and Streams to Climate Change

Rivers and streams are characterized by flowing water that travels from smaller streams that combine to form larger river channels. Rivers and streams discharge into lakes, wetlands and oceans, providing crucial corridors for aquatic species to migrate and spawn (Baker & Marcus, 2002). River and stream habitats are the primary habitat for most species of freshwater fish. Small changes in climate can have major effects on freshwater ecosystems.

Increased Water Temperature

Rivers and streams are particularly vulnerable to increased temperatures because they are generally shallow and well mixed (Poff et al., 2002). Water temperature plays a crucial role in the overall health of river and stream ecosystems, in the distribution of species and in the growth rate of aquatic organisms. Moreover, increased water temperatures affect a wide range of species from invertebrates to salmonids (Caissie, 2006).

Stream temperatures are projected to experience a .9° C increase for each °C rise in air temperature (Schindler, 1997). In some places, water temperatures have already reached the lethal limits for some fish species. One analysis projected a loss of 12-15% of habitat for cool-water fish and a loss of 31-36% of habitat for cold-water fish in the United States (Mohseni, et al, 2003). Warmer water temperatures can also mean lower dissolved oxygen, which leads to poor water quality for aquatic species. Survival of many species may depend on their ability to migrate upstream to cooler waters. Thus, access to suitable migration corridors is necessary (Poff et al., 2002).

Case Study: Freshwater Mussels Responses to Climate Change

North America boasts the richest diversity of freshwater mussels in the world with 297 native species (Helfrich, L.A., Neves, R.J., Chapman, H., 2003) but they are also some of the most threatened species as 35 species are presumed extinct and 130 of the remaining species are endangered, threatened or listed as species of concern. Freshwater mussels burrow in sand and gravel in river and lake bottoms and are suffering from a range of threats, including water pollution, stream fragmentation from dams and other barriers, sedimentation, and invasive species (Helfrich et al., 2003).

In general, species of mussels that live in rivers and streams are thought to be more vulnerable to climate change than lake and pond dwelling species. Water temperatures above 27°C for extended periods can cause major negative effects for river-dwelling mussels in the mid-Atlantic region, causing low levels of dissolved oxygen, overheating and drying up of streams (W. Lellis, personal communication, April 23, 2007). With increased severity and duration of drought, lower water levels can expose mussels to predators such as muskrats and raccoons (D. Strayer, personal communication, April 12, 2007) and a decrease in groundwater inputs to rivers and streams could have a negative impact by reducing temperatures and water quality (W. Lellis, personal communication, April 23, 2007). Finally, as sea level rises, saltwater intrusion is likely to cause tidal habitat loss (D. Strayer, personal communication, April 12, 2007).

Photography by John Golden

Lake dwelling species, however, have the potential to expand their ranges due to increased algal production during extended summers and milder winters (W. Lellis, personal communication, April 23, 2007). Mussel growth is temperature dependent, with growth rates increasing in warmer years. Larger mussels have more young, so warmer temperatures could lead to larger, more fertile mussels (D. Strayer, personal communication, April 12, 2007). Climate change is thought to favor generalists and hurt specialists, however, which could lead to an overall loss of diversity among American mussel populations (D. Strayer, personal communication, April 12, 2007).

Some species exhibit lifecycle and habitat requirements that make them particularly vulnerable. For example, freshwater mussels have a parasitic period during their juvenile life stage where they attach to the gills or fins of fish (Hutchins, M., Craig, S.F., Thoney, D.A., & Schlager eds., 2003), a phase necessary to complete metamorphosis to the adult form (W. Lellis, personal communication, April 23, 2007). Some mussels use a limited number of fish species as hosts (Hutchins et al., 2003), some of which are cold water species, who also face severe threats from climate change. As coldwater fish populations are limited to more northern regiosn, the distribution of dependent mussel populations is likely to similarly shrink (J. Cordeiro, personal communication, April 12, 2007).

Distributed throughout the Eastern Region in cool, fast-flowing, freshwater streams, the freshwater pearl mussel (margaritifera margaritifera), uses only two fish species as hosts, one of which is the declining Atlantic salmon. Unsurprisingly, populations of this species have already been decreasing in the Eastern Region (Raithel, C.J., & Hartenstine, R.H., 2006), and in 2002 it was listed by the IUCN Red Book (Hutchins et al., 2003). As cold water fish disappear from an area, the freshwater pearl mussels that depend on them are left behind and are unable to reproduce. Populations may appear viable, but if not reproducing, are functionally extinct (J. Cordeiro, personal communication, April 12, 2007; D. Strayer, personal communication, April 12, 2007). One silver lining is the freshwater pearl mussel's life span of up to 200 years (Hutchins et al., 2003) so this species could again thrive if restoration and protection efforts allow its host species to return (D. Strayer, personal communication, April 11, 2007).

Photography by Bill Silliker Jr.

Altered River and Stream Flows

The timing and quantity of flow are important components of river hydrology. Magnitude, frequency, duration, timing, and rate of change are key attributes of the flow regime and are considered the 'master driver' of river systems (Poff, 1997). Changes to any of these five components can have dramatic effects on both aquatic and riparian species. As such, changes in climate that affect the flow regime could have dramatic effects on river ecosystems (Gibson et al, 2005).

Flows rise and fall seasonally with changes in precipitation, evaporation, and snowmelt. In the northeast and mid-Atlantic states, flow generally increases in the spring as snow melts, and decreases in the late spring and summer as trees and plants come out of dormancy from evapotranspiration and the rising temperatures. Although projections indicate that precipitation is expected to increase during winter as a result of climate change, reductions in the levels of low flows are expected as a result of earlier snowmelt and increased summer temperatures and evapotranspiration (Huntington 2003; Hayhoe et al., 2006). Also, more frequent droughts combined with more intense and sporadic precipitation events will result in more runoff and therefore less of the water will recharge groundwater. These climatic contributors to reduced flow would add to the existing drivers of low flow (M. Kline, personal communication, April 13, 2007).

Longer and more severe periods of low flow are likely to affect species in a number of ways. Areas such as the eastern United States that rarely experience periods of no-flow naturally will be particularly susceptible to ecological damage as no-flow conditions are a dramatic change from normal conditions (Poff et al., 2002). Small streams are especially vulnerable to low flow (P. Angermeier, personal communication, April 5, 2007). One study found that a 10% reduction in annual runoff caused almost half of small streams with few groundwater inputs to stop flowing in some years (Poff et al., 2002). Another analysis estimated that flow could be decreased in the New England and mid-Atlantic regions by 21-31% annually just from increased evaporation, with the largest change felt in northern states (Moore et al., 1997).

Decreases in flow have already been shown to cause major species extinctions in some parts of the world. Among freshwater fish, species that are adapted to live only in flowing waters are anticipated to be the most sensitive to climate change. Reduced flow and stream miles will have a particularly deleterious effect on these species (M. Bain, personal communication, March 22, 2007). Isolation also impedes migration and access to a variety of habitat types.

Sensitive species such as amphibians can be exposed to greater ultraviolet radiation (Poff et al., 2002) which is especially problematic in clear, shallow water bodies (Kling et al., 2005). In addition, community composition, diversity, size, structure of populations, spawning, and recruitment of fish have all been documented to be significantly affected by low flow and drought (Xenopoulos et al., 2005).

Drought and Low Flow in the Ipswich River, Massachusetts

The Ipswich River is located in Massachusetts 20 miles north of Boston. It begins in the town of Wilmington and flows 36 miles to empty into the Atlantic Ocean. The towns of North Reading, Middleton, and Topsfield fall completely within the Ipswich River Basin, which also encompasses sections of an additional 19 municipalities. Many of these towns draw from the Ipswich River Basin for their water supply. There are also additional towns that receive some of their water supply from the river whose borders do not fall within the Ipswich River Basin.

Ground water withdrawals and diversion of surface waters in the Ipswich River basin have been shown to greatly decrease the flow of the river, which has led to an increase in low flow and drought periods. In some places, there is enough of a reduction in streamflow, that sections of the river dry up completely during the summer. Additionally, land use changes and increases in the amount of impervious surfaces in the headwaters of the Ipswich River Basin have been shown to reduce infiltration and to decrease base flow. Damming and subsequent impoundment of the river has created additional interruptions in flow that have led to pond like conditions that restrict the movement of fish and other aquatic biota.


Photography by Harold E. Malde

The Ipswich River is primarily made up of warm-water fish species that are tolerant of low flow periods and impoundment. Compared to neighboring rivers, there are fewer fluvial dependent and specialist species. The presence of stocked trout shows that the Ipswich River can support cold-water fish, although decreased flow and the resulting warmer temperatures will likely limit their ability to survive. The water withdrawals of the Ipswich River have also led to fish and mussel kills during dry years, as well as a general decrease in the ecological integrity of the Ipswich River Basin.

The Ipswich River provides a good example of the possible impacts of climate change on river and stream ecosystems. Periods of low flow and drought are anticipated to increase with climate change. The Ipswich River shows that increased fish and mussel kills during the summer are likely as well as a species shift towards warm-water, fluvial generalists. The role of groundwater depletion in freshwater ecosystems is also made clear by this example. As summers become drier and longer, the possibility of increased demand for water supply could have serious implications for the viability of freshwater ecosystems. Implementation of improved water flow management and other conservation techniques will be necessary to safeguard these ecosystems.

The production of plankton depends on nutrients being washed downstream with precipitation. If the severity of droughts increases during important stages in the life cycle of fish, newly hatched young could suffer from a lack of nourishment (J. Olney, personal communication, April 9, 2007). If rivers and streams experience increased drying, aquatic insects could be limited in their ability to drift downstream to adequate wetted habitat. As these insects are an important food source for many species, this could negatively affect the ecosystem as a whole (S. Gephard, personal communication, April 5, 2007).

Climate change is also expected to alter the timing of high flows. The annual peak flow that occurs in spring has already been documented to occur up to two weeks earlier since 1970 in some New England rivers. Earlier flow dates are generally attributed to earlier snowmelt due to increased temperature (Hodgkins et al., 2003).

The timing of spring peak flow can greatly affect many species' life cycles. For example, many diadromous fish time their in- and out-migrations to spring and fall flows. Hayhoe et al. (2006) found that survival of Atlantic salmon (*Salmo salar*) could be negatively affected, "if spring peak migration of juvenile salmon from freshwater rivers…becomes out of phase by as much as 2 weeks…" due to earlier spring flows.

Table 1. Rivers and Streams: Impacts of Climate Change

Climate Driven Change	Anticipated Effects on Rivers & Streams	Potential Response of Rivers & Streams
Increased summer temperatures	• Decreased summer flow and • increased drought	Isolation of stream habitats and remnant pools; decreased access, migration to some habitat types
Earlier snowmelt	Earlier spring high flow	Effects on species with life cycles timed to high spring flow
• Increased severe storm events; • increase in winter precipitation	Increase in flooding	Increased silt, pollution and dislodged stored organic carbon Decreased breeding habitat for amphibians, migratory shorebirds and waterfowl
Increased air temperature Decreased streamflow	Increased water temperature	Loss of suitable habitat for cool and cold-water dependent species Less dissolved oxygen leads to lower water quality

The format for the charts in this section were adapted from Kling, 2003.

Some species of fish time their reproduction to avoid the peak flow by laying their eggs early enough to hatch before the spring flow. High winter flows can destroy these eggs by washing them away (Poff et al., 2002). High flows that occur after droughts may also increase pulses of high acidity into rivers, streams and other waters. This could halt or reverse the recovery of species affected by acid deposition (Kling 2005)

Photography by Harold E. Malde

Increased Flooding of Rivers and Streams

Despite the drier conditions that are projected for summer months, flooding is estimated to increase in this region due to climate change. This is a result of the increases in both the intensity and frequency of precipitation events, in combination with the expected 20-30% increase in winter precipitation (Hayhoe et al., 2006). Changes in flood magnitude and frequency have been linked historically with small increases in precipitation and temperature. Greater floodwaters could increase silt and pollution in rivers, increase erosion, dislodge stored organic carbon (an important food source for many species) (Poff et al., 2002) and decrease breeding habitat for amphibians, migratory shorebirds and waterfowl (Kling et al., 2005). Flooding disrupts habitats, which can be beneficial to some invasive species, so threats to native species may be an increasing problem with

Atlantic Salmon (*Salmo salar*): A possible indicator of increased temperature in the Northeast

The Atlantic salmon has been proposed as a possible indicator species for temperature changes in the Northeast (Steve Gephard, personal communication, April 5, 2007). Enough is known about the biology of Atlantic salmon to describe their range of optimal temperature conditions which then allows for inference of climate change effects (Reist et al., 2006).

Within the American Northeast, Connecticut is considered the southern most extent of the Atlantic salmon range, since waters further south are too warm to support this species. Increased temperatures will force them to abandon the lower Connecticut portion of their range and only populations in rivers further north will survive (Steve Gephard, personal communication, April 5, 2007). In addition, species typically are adapted to grow and reproduce within the bounds of certain temperature tolerance ranges. As the temperatures approach the extreme of these ranges, there are declines in these processes, as has been documented in growth with juvenile Atlantic salmon (Roessig et al., 2004). Roughly 30°C is the lethal limit for a juvenile salmon. Currently, almost no rivers within the Atlantic salmon's natural range reach this limit; however, with climate change predictions of increased temperatures, rivers could begin to reach this lethal temperature (Steve Gephard, personal communication, April 5, 2007).

Courtesy of U.S. Fish and Wildlife Service, Timothy Knepp

climate change (K. Nislow, personal communication, March 21, 2007). Increased precipitation could also pose a threat to the recruitment of some fish species, as the newly hatched young could be washed away by flood waters (J. Olney, personal communication, April 9, 2007). Floods do have some benefits, however, such as habitat creation for some fish and invertebrates and movement of sediments downstream.

Responses of Freshwater Wetlands to Climate Change

Freshwater wetlands are fertile ground for vegetation which in turn support an abundance of animal life. The species that inhabit freshwater wetlands have adapted to variable soil moisture conditions and are often unable to survive in any other type of ecosystem (Poff et al., 2002). Different types of freshwater wetlands are determined largely by the sources of water that sustain them. The driving force behind all freshwater wetland systems is the hydrologic regime, referred to as the hydro-period – the pattern of water depth, precipitation events, snowmelt, duration, frequency, and seasonal timing of flooding that govern a wetland's biodiversity and productivity (Poff et al., 2002).

Because many wetlands have been extensively altered by development in past centuries, these resources are especially vulnerable to climate change-induced stresses, such as alterations in the amount, timing and temperature of water on which these ecosystems depend (Poff et al., 2002). Depending on the type of its hydro-period, some wetlands may be more suited to withstand the impacts from climate change while others are more likely to face serious threats and the possibility of being permanently altered or eliminated.

Drying of Bogs

Characterized by an accumulation of spongy peat deposits and acidic, nutrient-poor water, bogs are a relatively uncommon type of wetland, and thus a critically important habitat for species dependent on these conditions, including sedges, pitcher plants, cotton grass and orchids. Of all the freshwater wetlands, bogs are likely to be the most vulnerable to the expected climate changes in water regime.

Bog ecosystems are primarily supported by rainwater, and receive little to no input from nutrient-rich groundwater or stream runoff (EPA, 2007). Therefore, their water levels are determined by the balance of precipitation levels and evaporation rates (Moore et al.,

Photography by Harold E. Malde

tions, will threaten the reproductive success of certain species of frogs and salamanders (Kling et al., 2003). Coupled with increased water temperatures, species could be forced to either migrate or face serious survival risks.

When water levels are adequate, wetlands often connect to one another by channels and pools. This fluidity is a mechanism that promotes diversity, productivity, and mobility within wetlands. As wetlands become drier due to increased air temperatures and evaporation rates, isolated pools will form, fragmenting the wetlands. As a result, natural migration corridors will be lost as species become isolated within the wetland, unable to migrate to a new habitat as conditions change (Kling et al., 2003).

1997). The expected increase in the intensity and frequency of summer and fall droughts will result in replenishing the water in bogs less frequently. When coupled with increased evaporation rates as air temperature rises, it will be more difficult for some bogs to stay within necessary saturation limits. These periods of extreme drying could have dramatic effects on oxygen levels in the soil as well as on vegetation within the bogs (Moore et al., 1997; Poff et al., 2002). Given these changes, experts predict that many bogs in TNC's Eastern Region could be eliminated due to climate change (Moore et al., 1997).

Drought-Induced Loss of Connectivity in Marshes, Swamps and Fens

Some of the most common types of wetlands found in this region are marshes, swamps, and fens (i.e. mineotrophic) which are nutrient rich, frequently or continually inundated by water and able to support an abundance of diverse plants and animals (Moore et al., 2000; EPA, 2007).

The water supply of freshwater marsh, swamp and fen ecosystems is recharged primarily by surface run off, rainfall and groundwater. As a result of these multiple inputs, these ecosystems will likely be more resilient than bogs in the face of increased drought and decreased precipitation in the summer (Kling et al., 2003; Moore et al., 1997). However, increased summer and fall droughts could lower or change water levels enough to affect vegetation and species survival rates. The early onset of spring, as well as the summer drought conditions, will threaten the reproductive success of certain species of frogs and salamanders (Kling et al., 2003).

Deeper pools exist within wetlands that can withstand certain levels of drought, serving as "refugia" for wetland plants and animals until water levels are restored to a suitable level (Kling et al., 2003). However, the increased droughts that are predicted with climate change may increase evaporation sufficiently to eliminate even these deeper pools, leaving species without fertile habitat and threatening a wide range of organisms (Kling et al., 2003). Water level plays a vital role in the health of the wetland ecosystems. If water saturation in the soil is compromised, wetlands will cease to be wetlands (Moore et al., 1997).

Photography by Tina McCoy

Table 2. Freshwater Wetlands: Impacts of Climate Changes

Climate Driven Change	Anticipated Effects on Freshwater Wetland	Potential Response of Wetland
• Lower summer water levels • More frequent droughts	• Increase of isolation and fragmentation within wetlands • Drying of bogs	• Loss of habitat, migration corridors; Organisms dependent on water for mobility may be threatened • Amphibian and fish reproduction fail more often in drier years • Loss of hydrologic connections to riparian zones and groundwater systems
Decrease in precipitation falling as snow, resulting in a meager snow pack	Annual spring flood may occur earlier and be weaker than current patterns	Vegetation shift as the less flood-tolerant species out-compete those which need predictable inundation
Warmer Temperatures	• Increase in evaporation • Decrease in dissolved oxygen in the water	• Exacerbates the already low summer water levels • Survival of species compromised due to lack of oxygen • Species at southern extent of their range may become extinct
Increased winter storm intensity	• Wetlands more vulnerable to intense wind and rain activity • Increase in storm-water run-off carrying pollutants, sediment and excess nutrients	• Wetlands may be compromised or destroyed • Increased pollution levels in surrounding water sources as wetlands ability to filter is compromised

Loss of Wetland Filtering Capacity

The combination of more frequent droughts and heavy storms is likely to reduce the capacity of wetlands to filter sediment and pollutants. Less filtering will yield increased levels of sediments and toxins in the surrounding waters. Additional pollution could enter the ecosystem as water levels drop in rivers and lakes and a greater amount of soil is exposed to the air. Increases in oxygen concentration within the soil, especially when coupled with acid deposition, may trigger the release of metals such as cadmium, copper, lead and zinc into the environment. These additional loadings could amplify problems in areas where there are already an elevated prevalence of heavy metal contamination such as near industrial discharges (Kling et al., 2003).

The level of overall nutrients being delivered into the wetlands may decrease in summer as the freshwater sources, which typically provide the majority of nutrients, are compromised by drought conditions (Kling et al., 2003). Despite an increase in decomposition rates from increasing temperatures, the warmer air and water combined with fluctuating water levels are likely to reduce the wetland's capacity to assimilate nutrients and other materials transported in stormwater runoff (Kling et al., 2003).

Altered Flooding of Floodplain Forests

A key source of water for floodplain forests and wetlands is the flood regime of the river, stream or lake along which they exist (Sorenson et al., 1998). Water levels fluctuate in time with the flooding, evaporation and soil saturation (Moore et al., 1997; Department of Ecology, 2007). Floodplains also receive water directly from rain, groundwater and surface run-off but are adapted to the cycles of inundation and disturbance associated with flood events. Because they are adapted to these disturbance regimes, they may be less affected than some wetlands by increased evaporation rates that result from rising temperatures (Moore et al., 1997). However, these ecosystems are complex, and the ways in which climate and hydrology jointly affect floodplains is not currently well understood (Nislow, personal communication, 2007).

The greatest threat to floodplain forests is likely to come from expected changes in the flood regime (Nislow, personal communication, 2007). Floodplain forests associated with large rivers are dependent on the spring flood, driven by snowmelt in the spring. Flooding plays a critical role in preparing the ground to receive new seeds. The trees have adapted to this schedule, dispersing their seeds as the floods recede.


Photography by Mark Godfrey

The seeds and seedlings can tolerate only a certain intensity of flooding, thus if they are dispersed at an inappropriate time, they will die from lack of – or too much water – threatening the entire suite of species adapted to a particular flood pattern (Poff et al, 2002).

A change in the timing of the snowmelt may be compounded by the increase in summer and fall droughts. Unlike the arid Southwest, extreme droughts have not been a regular element of Northeastern climate. Plants in the Southwest have adapted to grow deep roots quickly, which seek out the groundwater before the surface moisture has evaporated (Nislow, personal communication, 2007). Northeastern plants do not have this ability. If droughts become more common, their roots might not grow deep enough or fast enough to tap into the groundwater before the upper portion of the soil dries out. Areas along larger riverbanks are typically coarse grained and well drained, and would therefore be particularly at risk (Nislow, personal communication, 2007).

The aggregate result of these climate changes could result in a series of species shifts in floodplain forests. As the floods regimes change, those plants that are less flood tolerant may be able to out compete those species which depend on annual flooding (Sorenson, personal communication, 2007). There is a high probability that invasive species, which are quick to adapt, will rapidly colonize and flourish in this new territory, changing the nature of floodplain forests permanently (Poff et al, 2002).

Responses of Lakes to Climate Change

Lakes vary in size from less than one acre to several thousand (EPA, 2007a). Most lakes are less than 65 feet deep, but occasionally exceed a depth of more than 1300 feet. Lakes account for about 40% of the earth's freshwater supplies (Dixon, 2002).

The "trophic" classification of a lake – ranging from oligotrophic to eutrophic – indicates its productivity and nutrient content. Eutrophic lakes are nutrient-rich and have higher production of algal biomass and a high mineral content. The water quality in eutrophic lakes is often poor as there is a high level of phytoplankton (suspended algae) which clouds the water. Zooplankton is also produced in high numbers, which feed a range of small fishes that support a productive ecosystem (Kevern, King, & Ring, 1996).

Water temperatures in lakes may increase by up to 5.2°C if CO_2 levels double from baseline conditions (Fang, et al., 2004a). The response of lake ecosystems to climate change will likely include loss of ice cover, increased stratification, shifting thermal regions and lowered lake levels (Kling, 2003).

Loss of Lake Ice Cover

Lake ecosystems in the Northern states go through an annual cycle of freezing in the winter and melting and mixing in the spring. Air temperature is thought to be the most crucial factor in determining lake ice-out dates (the day the majority of ice has broken up on a lake) (Hodgkins, et al., 2002). In an analysis of ice-out trends from 1850-2000, Hodgkins et al. found 19 of the 29 New England lakes studied showed earlier ice-out dates over the 150-year period.

As the ice-out date falls earlier in the year, lakes spend less time under ice cover. Ice cover plays an important role in lake ecosystems because its presence prevents oxygen exchange between the atmosphere and the water. Lake ice also limits light penetration of the water, which then inhibits photosynthesis in underwater plants (Fang & Stefan, 1998). Both of these processes limit the dissolved oxygen (DO) in the water. When DO levels drop too low, mortality and growth impairment are more likely in fish (Fang & Heinz, 2000). This process can lead to winterkill where fish die, often in large numbers, due to lack of available oxygen. Winterkill usually occurs in shallow (up to 13ft deep), eutrophic lakes in northern latitudes (Fang et al., 2000) and is a natural process that helps shape the food web of the lake.

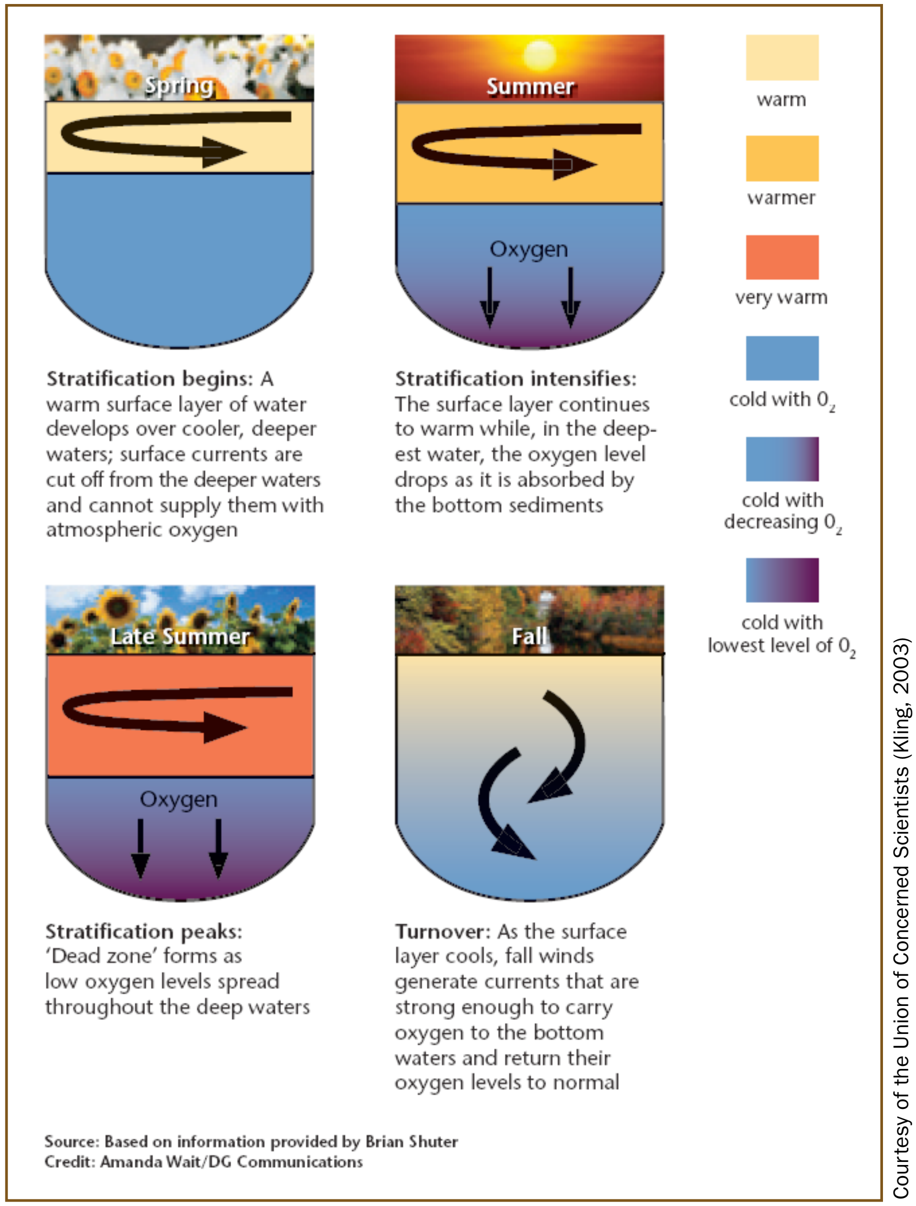


Figure 3. Lake Stratification and the Development of "Dead Zones"

With climate change, winterkill is projected to be eliminated in shallow eutrophic lakes due to loss of ice cover (Fang et al., 2000). The species that winterkill affects may seem to benefit from this scenario, but winterkill is an important ecological dynamic that reduces competition for the surviving fish and increases water clarity due to shifts in predation (EPA, 2007b).

Prolonged Lake Stratification

After the ice-out in early spring, most temperate lakes go through the process known as spring turnover. After the ice melts and the spring air temperatures increase, the temperature of the surface water increases from 0°, also increasing in density. When the surface temperature reaches the same temperature as the water near the bottom of the lake, there is very little resistance to mixing. This allows wind to mix the lake from top to bottom, as the water densities are the same (Kevern et al., 1996).

A number of important changes take place during the mixing process. Oxygen is circulated from the surface to re-oxygenate water throughout the lake. At the same time, the nutrients from the bottom of the lake are brought to the top. Eventually the surface temperature becomes so warm, and therefore light, that mixing stops and stratification begins. After the lake is stratified, the water at the bottom of the lake loses oxygen until the lake is remixed in late fall. If a lake bottom contains a greater amount of rotting biomass, oxygen depletion occurs more rapidly (Kevern et al., 1996).

There is a balance between spring mixing, fall mixing and summer stratification. If the summer stratification period lasts too long, summerkill can occur, where higher mortality and lower production rates can lead to fish deletion from a lake (Fang et al., 2004). As winters get shorter with a changing climate, spring remixing occurs earlier which leads to a longer period of summer stratification and increased risk of oxygen depletion and deep-water dead zones (Kling et al., 2005).

Photography by Avi Hesterman

Shifting Thermal Regions

As water temperatures change, lake habitats will change in their ability to support aquatic life. Fish depend on specific ranges of temperature within which physiological functions, such as growth, activity, and swimming performance, are maximized. In some instances, a specific life stage will have an optimum temperature (Coutant, 1990), especially the reproductive stages. Cold-water fish have a niche centered around 15° C, cool-water fish around 24° C, and warm-water fish around 28° C (Shuter & Meisner, 1992). When optimum temperatures are not available, fish will move to the best alternative conditions, a change that may result in a decrease in metabolic efficiency (Coutant, 1990).

Changes in thermal habitats are not uniform across lake types. Very large lakes like the Great Lakes that are deep and large are anticipated to experience an increase in suitable thermal habitats for all species with an increase of temperature. This is because there will be increased areas of warmer waters while the fish and other species in the deeper layers of water will benefit from the slight warming. In smaller, shallower lakes the warmer water will reduce the habitat available for cold water fish (Poff, et al., 2002).

In a comprehensive series of studies that looked at 27 lake types in 209 locations in the continental United States, Fang et al. evaluated the differing effects of changing thermal niches on warm, cool, and cold-water fish (2004a, b & c). The number of locations that can support cold-water fish (five types of salmon, four types of trout and one variety of whitefish) habitat is projected to decrease by 38%, resulting in fewer lakes able to support cold water fish. Additionally, the area of lakes that cannot support cold-water fish is expected to extend significantly further north (Fang et al., 2004b).

The study found that for lakes of medium depth and size, warm-water fish (four species of bass, shad, carp and catfish among others) could survive in all 209 locations despite potential increases in temperature. Some lakes in the south central and southeastern United States are expected to experience a loss of cool-water fish due to increased summerkill, the highest percentage of which will occur in shallow lakes (Fang et al., 2004a).

Lower Lake Levels

Earlier runoff, increased evaporation, and changes in stream in flow are predicted to lower lake levels in the mid-Atlantic and northeastern United States (Kling et al., 2005). Even large lake systems, like the Great Lakes, may experience decreased lake levels that are greater in magnitude than the anticipated rate of sea level rise. Issues related to permanent lowering of lake levels include isolation of lake-fringing wetlands, possibly

Table 3. Lakes: Impacts of Climate Changes

Climate Driven Change	Anticipated Effects on Lakes	Potential Response of Lakes
Decrease in winter ice cover	Increase of dissolved oxygen (DO) levels	• Winterkill in shallow eutrophic lakes disappears • Distribution of species affected as different types of species survive in higher numbers through the winter
Shorter winters	Duration of summer stratification extended	Summerkill can occur from an increase in depleted oxygen and dead zones
Increased water temperatures	Change in thermal regions	• Loss of habitat for cool and cold-water species in small shallow lakes • Species at the southern extent of their range become extinct
Increased air temperatures	Lower lake levels	• Isolation of wetlands & shoreline exposed • Stressful on wetland- dependant aquatic species

leading to a reduction in habitat for fish species that depend on wetlands for spawning and nursery habitat (Poff et al., 2002).

Responses of Coastal Ecosystems to Climate Change

Coastal marine systems are among the most ecologically and socio-economically vital on the planet (Harley et al., 2006). Each aspect of climate change, from higher seas to warmer ocean temperatures, will have a related suite of effects on each coastal ecosystem.

Responses of Bays and Estuaries

An estuary is defined as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted by freshwater derived from land drainage". Nearshore coastal waters in the vicinity of an estuary may be coupled chemically and nutritionally with that estuary, changes in one of these aquatic systems may affect the other (Kennedy, 1990).

Rising Seas

Sea level rise, one of the effects of climate change about which scientists are most certain, can have tremendous implications for coastal environments. An increase in water depth affects the complex interactions that take place in the coastal environment. Tides and tidal currents, distribution of turbulent energy, shoreline configuration, near-shore depth distribution, sedimentation patterns, and estuarine-river interaction will be affected (Roessig et al., 2004). While most marine species are expected to be able to adapt to predicted rates of sea level changes (though they may be greatly affected by changing temperatures and related changes in ecological processes), more significant ecological changes could result from decreased habitat availability within a particular depth zone. For example, intertidal habitat area may be reduced by 20-70% over the next 100 years in ecologically important North American bays, especially where steep topography and anthropogenic structures (e.g. sea walls) prevent the inland migration of mudflats and sandy beaches (Harley et al., 2006).

Responses of Coastal Wetlands

Coastal wetlands are areas of high productivity due to the high influx of nutrients from freshwater and tidal sources. These nutrients not only sustain the wetland, but are trapped within the intricate root system, making this a rich habitat for spawning, nesting and stop-over sites for many species of birds, fish and invertebrates (Najjar et al., 2000; Poff et al., 2002). During heavy storms, salt marshes buffer the shoreline and help to mitigate erosion from high wave activity. Their filtration capabilities also allow them to absorb pollutants and excess nutrients from storm runoff and serve to prevent toxins from contaminating the ocean.

Photography by Harold E. Malde

As with freshwater wetlands, saltwater wetlands are unique and complex ecosystems comprised of species that have specific adaptations in order to thrive. However, these adaptations are only suitable across a certain range of water levels (Poff et al., 2002) and of salinity levels. Saltwater wetlands are maintained by a delicate balance of the rate of sea-level rise, upward accretion, erosion from wave activity and sediment deposition (Hartig et al., 2002). A change in any of these factors could threaten the viability of the wetland.

"Drowning" of Salt Marsh

Saltwater wetlands can tolerate a certain amount of sea level rise as they are able to build up vertically if they receive adequate sediment deposition, either from tidal inundation or freshwater inputs (Najjar et al., 2000; Hartig et al., 2002). The sediment is captured in the intricate root system of marsh grasses and thus these wetlands rise in elevation over time (Hartig et al., 2002).

If sediment accumulates too quickly, tides no longer cover the marshes and they are denied the sediment necessary for continued vertical accretion until the area can once again be flooded on a daily basis (Hartig et al, 2002; Titus, 1991). This balance stands to be disrupted as sea level rises at an accelerated rate. Along the mid-Atlantic shore, sea level is now rising at a rate of 4.2 mm annually and saltwater wetlands cannot keep pace (Hershner, personal communication, 2007). When this sort of imbalance exists, the marsh may actually begin to drown as it spends more and more time completely submerged (Hartig et al., 2002; Poff et al., 2002). A study conducted on Connecticut's wetlands showed that only those saltwater wetlands with high accretion rates stood a chance of surviving through the middle of this century. By 2080, even many of those with high accretion rates will most likely be underwater (Gorntiz et al., 2004).

If vertical accretion rates do not exceed the long-term rate of sea-level rise, marshes have adapted to migrate inland, away from the rising sea (Donnelly & Bertness, 2001; Titus, 1991). As this happens, the higher dry land will convert to transitional saltwater wetland vegetation that is flooded a few times throughout the year; transitional wetlands will convert to high marsh, high marsh will convert to low marsh, and the low marsh will become mudflats and then open water (Titus, 1991).

However, the ability to shift away from the coast is determined by the availability of land, as well as the slope of the land directly behind the saltwater wetland (Titus, 1991). If the slope of the abutting land is steeper than the saltwater wetland itself, it will have trouble migrating upslope. In addition, if the land abutting the saltwater wetland has been developed with seawalls or roads, there is a good possibility that the wetland will not be able to physically migrate. In Maine, for example, some marshes are accreting faster than the sea is rising, but abutting human development is impeding their migration, and thus they are very likely to be inundated by sea level rise (Dionne, personal communication, 2007).

Finally, the change in sea level and a heightening of storm intensity will bring stronger wind, rain and waves, all of which may damage the saltwater wetlands

Jamaica Bay, Long Island: Marsh Restoration

Elders Point Island in Jamaica Bay Gateway National Park is currently the focus of a $13 million restoration project. The project is the result of collaboration between the Army Corps of Engineers, the National Park Service, the State of New York, and the New York/New Jersey Harbor Estuary Program. The restoration plan includes restoring the existing vegetated areas and the sheltered and exposed mudflats by placing dredged sand to raise the marsh elevation to promote low marsh growth. The Corps will place 270,000 cubic yards of sand that was dredged from various channels in the New York harbor. In this project, approximately 70 acres of marsh will be restored. The restoration will include the planting of almost 1 million plants and grasses that help maintain the health of the marsh including Spartina alterniflora (smooth cordgrass), Spartina patens (salt hay), and Distichis spicata (spike grass).

Photography by Alan W. Eckert

and threaten their overall stability (Titus, 1991; Poff et al., 2002). As barrier beaches and dunes are swallowed by the rising sea, the wetlands behind them may become more susceptible to off-shore storm damage.

Salt Water Intrusion

As sea level rises, the ocean will encroach landward and estuarine salinity will increase (Najjar et al., 2000, Kennedy, 1990). If there are physical barriers such as waterfalls or dams in the upper estuary region, then the salt-water may intrude into the entire water body, leaving species that are freshwater spawners or specialists without a freshwater refuge (Steve Gephard, personal communication, April 5, 2007). For example, eastern oysters in central and upper Chesapeake Bay have a refuge from two lethal diseases in salinities below 12 parts per thousand (ppt), and from two species of predatory snails in salinities below 20 ppt. Because oysters are relatively immobile after they settle out of the plankton, they will be at risk as these diseases and snails move up-estuary after salinities increase. Clearly, the low salinity refuge from these pests would also move farther up into the estuary, but hard substrate necessary for oyster settlement is rare or absent in upper regions of estuaries (Kennedy, 1990). Also, as species migrate inland they face a greater threat from pollutants and human influences that can be prevalent along inland waterways (Najjar et al., 2000).

Sea-level rise may also increase salinity levels across the range of coastal wetland ecosystems, (which shift from salt marsh near the sea to brackish water and then freshwater tidal wetlands furthest inland) (Titus, 1991). Climate change-induced sea-level rise may produce an intrusion of saltwater deeper into these ecosystems, lowering the freshwater content and turning tidally-influenced freshwater wetlands into brackish or saltwater marshes (Sorensen, 1984). Thus, salt-tolerant species may move further inland (Titus, 1991; Roesigg et al., 2004) while freshwater spawners or specialists may end up without a freshwater refuge (Steve Gephard, personal communication, April 5, 2007).

Sea level rise can also alter the composition of saltwater wetland vegetation. Typically, the lower marsh is flooded by tides and then exposed for portions of each day. This area tends to be mudflats dominated by smooth cordgrass (*Spartina alterniflora*), which is able to oxygenate substrates (Donnelly & Bertness, 2001; Hartig et al., 2002). As the saltwater wetlands move further inland, the composition of both land and vegetation changes. The area that is irregularly flooded by the tide is typically more diverse, made up of a variety of species such as salt hay (*Spartina patens*), spike grass (*Distichlis spicata*), and black rush (*Juncus gerardi*) that are excluded from the lower marsh due to low substrate oxygen levels (Donnelly & Bertness, 2001; Hartig

Photography by Harold E. Malde

et al., 2002). In the upper marsh, however, these species thrive and the smooth cordgrass is competitively excluded.

This pattern will change as sea levels continue to rise, however. Oxygen levels will decrease as the upper portions of saltwater wetlands are flooded more frequently by tides, making it difficult for the varied species of vegetation to survive. Smooth cordgrass, however, thrives in this environment and may begin to dominate the upper portions of the wetland as well as the lower areas. As this happens, the diverse saltwater wetland will transform into a mudflat with less productivity and species abundance (Hartig et al., 2002).

Precipitation Changes

As periods of drought become more prevalent in summer and fall, water levels in freshwater bodies that flow into saltwater wetlands will decrease, further perpetuating the concentration of salinity. Hull and Titus' study conducted on the 1964 drought conditions in Delaware Bay, showed that the saltwater boundary advanced 50 km upstream from its average position (as cited in Najjar et al., 2000). The shift altered the salinity of a large portion of the ecosystem, negatively affecting aquatic species and the water supply.

The heavy rains projected for winter and spring will bring changes to saltwater wetlands. The increased stormwater runoff will carry greater amounts of sediment, nutrients, and pollutants into the wetlands, which put additional stress on ecosystems. Increased sediment may hinder filter feeding by invertebrates, and will also decrease water clarity which could affect photosynthesis (Najjar et al., 2000). In addition, the rapid increases in nutrient levels will speed up plankton productivity, decreasing oxygen levels (Najjar et al., 2000). Dissolved oxygen content may be further inhibited with the deluge of freshwater runoff, which will sit on top of the denser saltwater, preventing the mixing of oxygen and nutrients between the two layers (Najjar et al., 2000). The storm runoff may also carry with it increased levels of toxins that will pollute the delicate wetland ecosystems (Najjar et al., 2002).

Warming Water and Decreased Dissolved Oxygen

Saltwater wetlands will face additional challenges with increased water temperatures, as shallow water is particularly susceptible to changes in ambient air temperature. As the water within saltwater wetlands increases in temperature, the species living there will be influenced. For example, Magnuson et al. suggested that fish can function productively within 2º Celsius above or below their particular "thermal niche," the temperature range within which they are most metabolically productive and able to obtain the optimal growth rate (Coutant, 1990). Once this range is exceeded, the fish sacrifice some amount of metabolic efficiency (as cited by Coutant, 1990). With projected ocean warming of 2.2 - 4.4º C by the end of the century, fish species that depend on estuaries and salt marshes to spawn may experience compromised ability to reproduce (Najjar et al., 2002; Coutant, 1990).

The impacts are not limited to fish. As water temperature increases, the capacity of the water to carry dissolved oxygen diminishes (Najjar et al., 2000, Kling et al., 2003) affecting the survival of fish and other aquatic organisms. As estuarine environments require very specific conditions, species are often eliminated rather than replaced (Kennedy, 1990 as cited by Najjar 2000). An overall shift in the aquatic species found within saltwater marshes could result.

Table 4. Saltwater Wetlands: Impacts of Climate Change

Climate Driven Change	Anticipated Effects on Saltwater Wetland	Potential Response of Saltwater Wetland
Sea-Level Rise	• Inundation of wetlands • Increased salinity	• Wetlands drown in place; transition into mudflats • Species which are less tolerant to saltwater may be threatened, replaced
Warmer Temperatures	• Increase in evaporation • Decrease in dissolved oxygen (DO) in the water	• Exacerbates already low summer water levels • Increase of soil salinity could threaten plant species • Species at the southern extent of their range may become extinct
Increased storm intensity; Increased intensity of precipitation	• Coastal wetlands more vulnerable to intense wind and wave activity • Increase in storm-water run-off carrying pollutants, sediment and excess nutrients	• Wetland habitats may be damaged or destroyed • Increased pollution levels of surrounding water sources as wetlands ability to filter is compromised

An important change from warming temperature is the lowering of dissolved oxygen in estuarine waters. For each 1ºC that water warms, oxygen solubility (the capacity to dissolve oxygen) decreases by about 2%. Changes in oxygen concentration also affect biotic factors. Higher temperatures raise the metabolism of cold-blooded aquatic animals (invertebrates, amphibians, fish, and reptiles), thereby increasing the metabolic need for oxygen. Particularly in areas already experiencing anoxic (oxygen depleted) waters such as the Chesapeake Bay, the impact will only increase, though the magnitude is not certain (Najjar et al., 2000).

The effect of rising temperatures varies among and within species, but can affect a wide range of vital processes, including activity, feeding, growth, and reproduction of aquatic organisms (Harley et al., 2006). Summer months will be especially stressful for many species, such as adult striped bass (Morone saxatilis). Already low oxygen levels cause this species to minimize or stop growing altogether in the hot months of July to September. They may move to avoid the hypoxic waters, but then may be forced into a "habitat squeeze" if there is limited suitable habitat available (Secor, personal communication, April 5, 2007). Rapid temperature shifts could have other serious effects on fish populations as many species are very sensitive to thermal stress, especially if shallow water or long distances prevent the fish from finding a thermal refuge.

Responses of Aquatic Species: Migration or Genetic Adaptation?

Climate-scale changes in temperature are expected to cause changes in the spatial distributions and migration patterns of many species found in the region (Mountain, 2002). Migration patterns of anadromous fish may be at particular risk since they have evolutionarily adapted to certain temperature cues to return to freshwater to spawn (Hershner, personal communication, March 21, 2007). Therefore, changes in the timing of migration and a general northward shift in distribution are expected for many species (Mountain, 2002).

The equator-ward edge of the ranges of high-latitude or cold-tolerant species may retreat towards the poles. For example, if Chesapeake Bay becomes as warm as the southeast Atlantic or Gulf of Mexico, species with northern affinities that are absent to the south (e.g., the


Photography by Alan Eckert

commercially important soft clam, Mya arenaria) could be eliminated from the Bay if water temperatures reach levels that inhibit successful reproduction or that are lethal. Meanwhile, lower-latitude or warm-tolerant species may expand their ranges poleward, however, these shifts may not be as rapid as poleward range contractions, because successful invasions of new habitat require not only physically tolerable habitat but also suitable food supply and no unfamiliar predators, pathogens, or competitors to impede the invaders (Kennedy, 1990). For example, if prey species are more heat sensitive than predator species, the prey may be eliminated from portions of the predator's range. Stressed organisms may fall prey to more robust predators or pathogens, face competition from invasive species or may be unable to produce viable young (Kennedy, 1990). The negative effects of disease are likely to become more severe, as pathogens are generally favored by warmer temperatures relative to their hosts. Direct climatic impacts on one or a few "leverage" species could drive the response of an entire system (Harley et al., 2006).

In addition, distributional shifts in response to increased temperature may not necessarily be latitudinal but may include vertical displacements to deeper, cooler waters. Many marine species occur in shallow or intertidal waters in the cooler reaches of their ranges, but are found progressively deeper near the warmer limits of their distributions. In an analogous manner, as temperatures change in response to anthropogenic warming, the current shallow water populations of these species may retreat into cooler deep waters. Such submergence in response to global warming, however, may disrupt community-wide trophic interactions, including loss of prey species or introduction of competitors. It may also reduce the population size of the migrant group, because deeper waters will not support the same biomass as more productive surface waters (Fields et al., 1993).

As temperatures change, not all populations will necessarily shift their ranges in response. Some that stay in place may either adapt genetically or live under suboptimal conditions. Because most marine organisms have body temperatures that differ little from the surrounding water temperature, they will need to adapt to environmental warming if they do not migrate to cooler areas (Fields et al., 1993). There are changes in enzymes and proteins that can help adjust the metabolism of the organism and allow it to survive higher temperatures. These adjustments may allow species to survive in their current habitats despite an increase in ambient temperature (Fields et al., 1993).

Historically, fish have been able to adapt and survive in other stressful times. For example, the white perch (Morone americana) has been in existence for roughly 1,000 to 2,000 years, which required them to overcome other environmental obstacles (David Secor, personal communication, April 5, 2007). The presence of genetic variability within the species will allow some level of adaptation to changing temperatures and species occurring over a wide thermal range will generally have a broader range of genetic variability from which to draw (Fields et al., 1993). Although data are sparse, studies suggest that changes in average habitat temperature of only a few degrees Celsius are sufficient to favor selection for adaptive differences (Fields et al., 1993).


Photography by Bill Silliker Jr.

Eelgrass (*Zostera marina*): A possible indicator of increased temperatures in the Mid-Atlantic Region

Eelgrass is a critically important species for the Chesapeake Bay area, an area that is the southern limit of its natural range. Eelgrass is considered a keystone species within its ecosystem, providing critical habitat for declining juvenile blue crab populations, as well as preferred refuge and forage areas for soft clams and juvenile fish (Carl Hershner, personal communication, March 21, 2007).

Eelgrass in the Chesapeake presently grows well during the cooler months but dies back during warm summer periods (Short & Neckles, 1999). An increase in average annual temperature, as predicted with climate change, is expected to decrease productivity and distribution. Unlike longer-lived species such as some fish that have a "storage effect" and can delay reproduction for a better year, eelgrass is an annual crop and cannot wait for optimal conditions. There is also almost no chance for any physiological adaptation to warmer temperatures (David Secor, personal communication, April 5, 2007). Because of its critical role in the Chesapeake Bay ecosystem and because eelgrass is at the southern edge of its range, the Chesapeake Bay may be a good candidate to demonstrate the shift of species due to climate change.

Photography by Richard Herrmann

Responses of Shorelands (Barrier Islands, Beaches and Dunes) to Climate Change

The United States Geological Survey (USGS) defines barrier islands as long, narrow strips of sand forming islands that protect inland areas from ocean waves and storms. Beach dunes are defined as low hills of drifted sand in coastal areas that can be bare or covered with vegetation (National, 1995). In general, shorelands are important features of the coastal zone that are vital habitat for many species and serve to protect inland areas from storms and storm surges.

In the last three decades, the barrier islands of the U.S. Atlantic coast have been transformed from tranquil fishing villages to thriving recreational centers that host millions of visitors each weekend (Titus, 1990a). These same sites are also habitat for many organisms. For example, during their migration and over wintering, most shorebirds depend on intertidal sand for their foraging habitat. The ability of a site to support large numbers of shorebirds is largely determined by the amount of habitat and by the density, availability, and seasonal predictability of their invertebrate prey. Sites with greater densities of invertebrates typically support higher shorebird densities (Galbraith et al., 2002) making them ecologically valuable and a focus for protection.

Inundation of Beaches and Barrier Islands

Global warming is projected to raise sea level approximately one meter by the end of the century. Such a rise would inundate lowlands, erode beaches, and increase the risk of flooding (US EPA, 1989).

Inundation, possibly the most obvious impact of sea level rise, refers to the conversion of dry land to wetland and the conversion of wetland into open water (EPA, 1989). Some of the most vulnerable areas are the recreational barrier islands and spits (peninsulas) of the Atlantic Coast. Coastal barriers are generally long and narrow with the ocean on one side and a bay on the other. Typically, the ocean front side of an island ranges from five to ten feet above high tide, and the bay side is two to three feet above high water. Thus, even a one-meter sea level rise would threaten much of this area with inundation (EPA, 1989). For example, with the use of a simple shoreline inundation model in which all land with an elevation less than 61cm was assumed to be flooded, it was estimated that 91 km2 of Delaware

Table 5. Coastal Ecosystems: Impacts of Climate Change and Responses

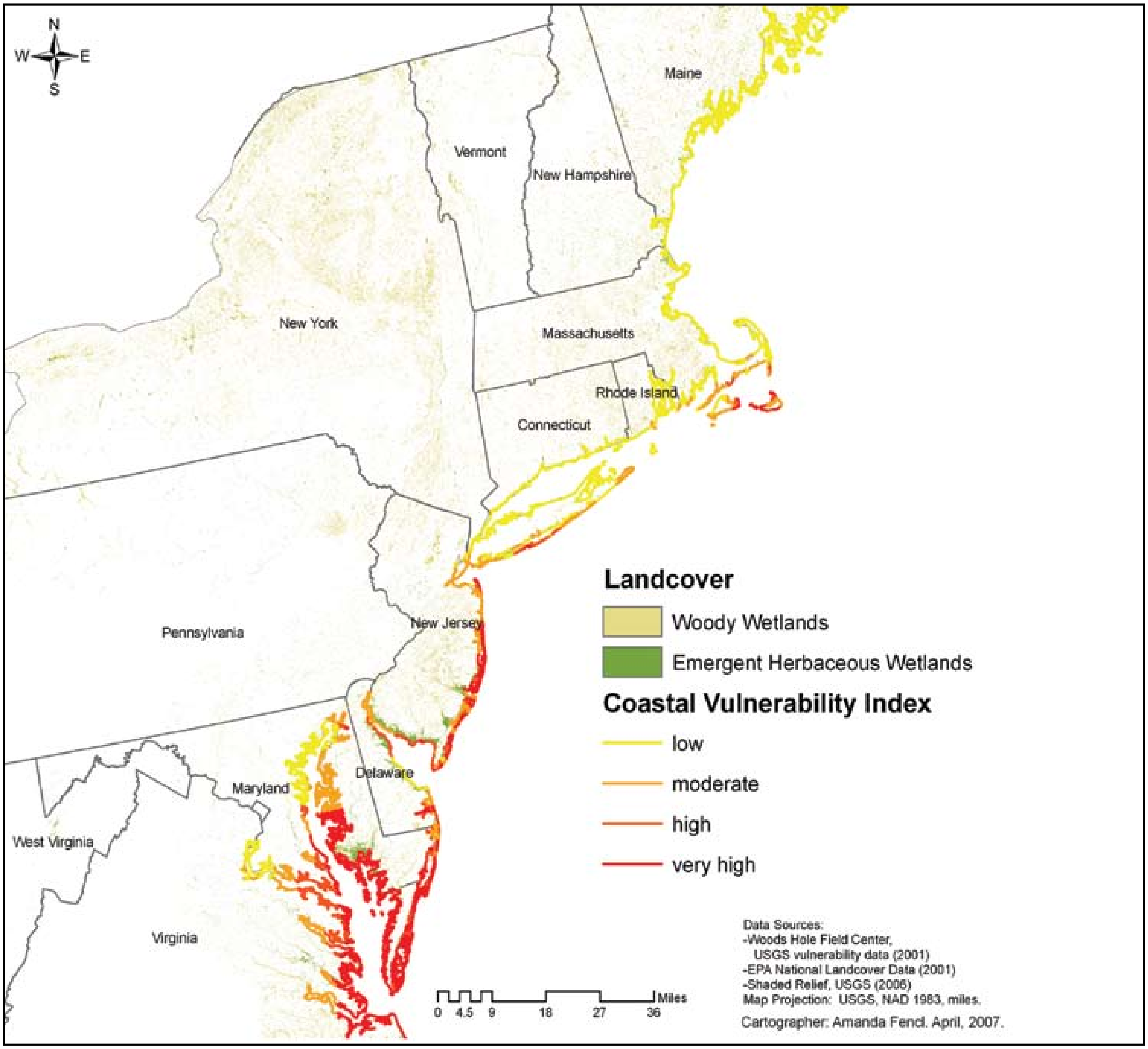
Climate Driven Change	Anticipated Effects on Coastal Region	Potential Response of Coastal Region
Sea-Level Rise	Inundation of Low-lying Shorelands	• Intensify rate and extent of coastal erosion • Loss of habitat for shoreline ecosystems • Increase flooding along the coast
Sea-Level Rise	Increase depth of coastal waters	• Loss of habitat for shallow water specialists • Loss of inter-tidal habitat • Complex interactions of hydrodynamic processes (tides, currents, distribution of turbulent energy, sediment patterns etc.)
Sea-Level Rise	Intrusion of saltwater further into estuaries	• Loss of freshwater spawning ground • Loss of habitat for low salinity- tolerant species • Increase of salinity- tolerant species including pests and predators
Increased Temperatures	Negative effects on all vital processes of aquatic organisms (activity, feeding, growth, & reproduction)	• Shift in species latitudinal or vertical • Species attempt to survive in sub-optimal conditions • Possible genetic adaptation of species to warmer water

would be under water, or about 1.6% of the total land area of the state (Najjar et al., 2000).

Over 70% of the world's sandy beaches are retreating. Beaches and barrier islands are narrowing or shifting landward, in part due to ongoing sea-level rise and in part due to land subsidence. Accelerated sea-level rise may intensify the rate and extent of coastal erosion (Gornitx et. al., 2001). Although erosion is more difficult to predict than inundation, Bruun (1962) showed that as sea level rises, the upper part of the beach is eroded and deposited just offshore in a fashion that restores the shape of the upper part of the beach profile with respect to sea level. The "Bruun Rule" implies that a one-meter rise would generally cause shores to erode 50 to 200 meters along sandy beaches, even if the visible portion of the beach is fairly steep (Titus, 1990b). Erosion threatens the high part of barrier islands, and is generally viewed as a more immediate problem than the inundation of the bay side of the island.

Also, on coastal barrier islands, wave erosion may transport sand in a landward as well as a seaward direction, a process commonly known as "overwash." By gradually transporting it landward, overwash can enable a barrier island to rise with sea-level as it moves landward. Finally, sea level rise could affect the shoreline and barrier islands by increasing the risk of flooding. Flooding would increase along the coast for three reasons: (1) Storm surges would build on a higher base. If sea level rises one meter, an area flooded with 50cm of water every 20 years would now be flooded with 150cm every 20 years. In addition, surges would also penetrate further inland. (2) Beaches and sand dunes currently protect many areas from direct wave attack. By removing these protective barriers, erosion from sea level rise would leave some areas along ocean coasts more vulnerable. (3) Higher water levels would reduce coastal drainage and thus would increase flooding attributable to rainstorms (Titus, 1990b; EPA, 1989).

Map 1. Regional Coastal Vulnerability



• **See Appendix A for explanation of Coastal Vulnerability Index.**

CHAPTER

4

Adaptation of Aquatic Ecosystems to Climate Change

What is Adaptation?

In climate change literature, the term "adaptation" is used in a number of ways, including adjustments in human behavior to reduce vulnerability of societies and natural systems to climate change (Toman & Bierbaum, 1996). This report defines adaptation as measures taken to prevent or moderate the effects of climate change on freshwater and coastal ecosystems.

Why Adapt?

Not only is climate already changing, it will continue to change for decades because past emissions will persist in the atmosphere – even if efforts to reduce future emissions are successful. Though biological systems have the ability to adapt naturally to environmental changes, there is a high probability that human-induced climate change will alter conditions at a rate much faster than species may be able to adapt. In addition, this natural ability to adapt will be hindered by human-developed barriers that are already causing stress on ecosystems such as habitat loss and fragmentation (Easterling, 2004).

Adaptation Planning

Before adaptation strategies can be pursued, a clear picture of the anticipated effects of a changing climate in specific places is often necessary. Differences in species distributions or topography can vastly change the expected climate effects and any adaptation plan must be developed accordingly. Analyses to support adaptation strategies include understanding current conditions (e.g. topography, hydrodynamics, vegetation or species distribution) and the anticipated impacts from climate change (e.g. change of temperature, precipitation change, sea-level rise). Geographic analyses are key to gaining this understanding.

A variety of technological tools for gathering and evaluating data are useful for the analysis of climate change. This chapter provides a brief overview of data gathering, modeling and mapping tools that have proven useful in gaining this understanding.

Remote Sensing

Remote sensing techniques (such as taking photographs from airplanes and gathering data from satellites) are often used to obtain spatially explicit information (Conway, 1997). Two that are particularly relevant are Light Detection and Ranging (LIDAR) and satellite imagery.

Figure 4. Satellite image of New York captured from Landsat

Courtesy of the U.S. Geological Survey

Light Detection and Ranging (LIDAR)

LIDAR is a remote sensing tool used to examine an area in finer detail and show physical characteristics of topography. LIDAR measures the time it takes for pulses of laser light to strike a target and return so the distance between the object and the sensor can be calculated (Kavaya, 1999). Coupled with a Global Positioning System (GPS), LIDAR can very accurately measure elevation (to within 6 inches), data that is particularly helpful in analyses of water flow and sea-level rise.

LIDAR can also examine terrain and vegetation characteristics by measuring forest canopy. In addition, LIDAR can make continuous measurements that demonstrate the change in tree growth or the volume of biomass (Wulder et al., 2007), data that is useful in examining the long-term impacts of climate change on vegetation.

LIDAR can also measure bathymetry in coastal regions. Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS) uses lasers to measure energy reflections and then calculates water depth by using the difference in time between the reflection from the surface and the reflection from the sea bottom. The U.S. Navy has used SHOALS surveys to make nautical charts, monitor beach nourishment and erosion, and maintain channels and harbors (Irish & Lillycrop, 1999). LIDAR data are currently available primarily for coastal areas. Gathering new LIDAR information is relatively expensive but the technology can be an important tool for site-specific or project-specific applications.

Satellite Imagery

Satellites relay vast numbers of images of Earth's land mass, coastal boundaries, and coral reefs. The U.S. Geological Survey (USGS) has acquired millions of images from six earth satellites called Land Remote-Sensing Satellite (Landsat) for more than thirty years. Landsat 5 and Landsat 7 continue to capture hundreds of images everyday (USGS, 2005). As these satellites stay in a single orbit and therefore fly over the same area repeatedly, long-term changes can be seen. This information is useful in analyzing inundation data from past flood events (Overton, 2005) or to examine changes in snow and ice cover (Conway, 1997).

A satellite image is comprised of multiple wavelengths of electromagnetic radiation, each of which emphasizes a geographic feature (vegetation, water, or biomass) (Conway, 1997).

Satellite images show geographic features similar to those in aerial photographs (which are recorded on film as opposed to being generated by computer) but analysis of the different spectrums in satellite images can be used to distinguish particular features, such as vegetation. For example, the images gathered from Landsat can be used to show general images of the land as well as to analyze the progress of deforestation or sediment deposition from rivers (USGS, 2005). Obtaining satellite images from government agencies such as NASA or USGS is relatively easy, providing efficient analysis of large areas at a relatively low cost. However, with remote sensing from a satellite, it is difficult to accurately examine details of an area such as land elevation and specific vegetation types. Therefore, other technological tools are needed for these purposes (Bates et al., 2006).

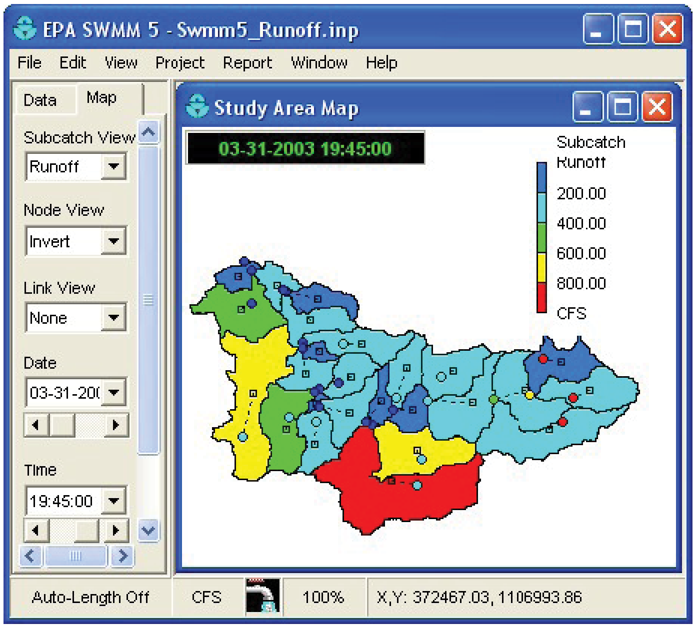
Modeling

Modeling of ecologic and hydrologic systems are often used to understand processes associated with freshwater and coastal systems and can be used to predict how changes in temperatures, precipitation and circulation will affect these systems.

Bioclimatic Envelope Model

Species distribution is important to consider when examining the effects of climate change on ecosystems (Araújo et al., 2005). By measuring species distribution, hotspots of endangered species can be identified to establish species conservation plans (Johnson & Gillingham, 2005), or to estimate the risk of extinction (Thomas et al., 2004). The relationship between climate variables and the boundaries of a species' territory is called the "bioclimatic envelope" or "climate envelope." Bioclimatic envelope modeling can be used to project current and future species distributions, and to estimate which areas are the best candidates for conservation because they will likely do well despite changes in climate (Beaumont et al., 2005).

Figure 5. Image of a Stormwater management model



Courtesy of the U.S. Environmental Protection Agency

The present version of the bioclimatic envelope model uses up to 35 climatic parameters, including annual mean temperature, maximum temperature of the warmest period, annual precipitation, precipitation of the coldest quarter, radiation seasonality, and the highest period of moisture index. Data is first collected from the habitat and geo-coded using historic and current distribution data. Secondly, each climatic parameter is calculated at every geo-coded site. Next, a statistical summary – the "bioclimatic envelope" – is made of each climatic parameter's range, obtained as mean, standard deviation, minimum, maximum and percentile value. Finally, the potential distribution of the target species is mapped. Matches within the "bioclimatic envelope" show the area where the species can live. The impacts of climate change are assessed by examining the potential distribution of the target species and the potential changes to the climatic parameter (Lindenmayer et al., 1991).

Several studies have found bioclimatic envelope models to be a useful tool to survey the reaction of various species to climate change. However, criticisms of the model include the lack of examination of interactions between species or dispersion of species (Pearson & Dawson, 2003). Some ecosystems are too complex to predict an accurate distribution of species, but the bioclimatic envelope is superior in making species-specific projections, and modeling impacts from climate change.

Hydrological Modeling

Another group of models can be used to assess the impacts of climate change on the hydrology of aquatic systems.

- *HSPF, Hydrologic Simulation Program – Fortran* is a public domain software package that was developed to provide continuous flow simulation coupled with stream water quality simulation for rural watersheds. The model uses lumped parameters to characterize sub-basins within the modeled watershed, which are additive in the downstream direction (personal communication, Bjerklie, 2007).
- *SWMM (Storm Water Management Model)* was developed by the EPA in the 1970's as a single storm event model and has since been upgraded to include a continuous watershed runoff modeling system. Initially designed to model the quantity and pollutant loading of stormwater runoff from urbanized areas, the model can also be used in rural basins. Similar to HSPF, the model uses lumped parameters to characterize sub-basins, which are additive in the downstream direction. Groundwater is simulated as a series of reservoirs with transfer coefficients associated with each sub-basin (personal communication, Bjerklie, 2007). SWMM has been used to assess the impacts of climate change on stormwater runoff and the data is then used to project the effects on the watershed and ecosystems in the area (Denault et al., 2006).
- *PRMS (Precipitation-Runoff Modeling System),* developed by the USGS, simulates watershed response to precipitation within defined hydrologic response units (HRU's). Each HRU is defined by physical characteristics including slope, soil type, vegetation type, aspect, elevation and precipitation distribution. PRMS can simulate daily surface water yields at defined outlet locations, or can model peak flows using smaller precipitation time steps. Groundwater is simulated in a similar manner as HSPF and SWMM. Recent work has successfully linked the PRMS and the USGS ground-water flow model (MODFLOW) to create a new coupled model called GSFLOW,

which will be especially valuable for simulating ground water/surface water interactions and the unsaturated zone above the water table (personal communication, Bjerklie, 2007).

Inundation models

Climate driven increases in sea-level rise, storm intensity, and spring flows may lead to the flooding of rivers and streams and the inundation of wetlands and coasts. Inundation models make projections by using data from previous flooding events, topography of the area, stream flow data (Overton et al., 2006) and storm intensity data (Mcinnes et al, 2003). Satellite imagery and LIDAR are useful tools to gather information needed on topography or past flooding events (Bates et al., 2006). Inundation modeling has been used to evaluate the influence of changing storm tides due to climate change on the northeastern coast of Australia (Mcinnes, 2003). The USGS also uses this model to simulate the impacts of sea-level rise on the Blackwater National Wildlife Refuge on the eastern shore of Chesapeake Bay (Larsen et al, 2004).

Circulation models

For coastal systems circulation models can help understand how changes in temperature, freshwater inflows and offshore currents and water quality effect coastal and estuarine systems. The basic circulation models are called Ocean General Circulation Models (OGCM). These can be coupled with atmospheric models to predict climate changes.

Two basic types of OGCMs include modular ocean models, which were specifically designed to understand large scale wind and temperature driven circulation patterns. In contrast, the terrain-following coordinate models were designed for coastal applications as they focus on understanding how bottom features and shorelines affect eddys and smaller circulation patterns.

Mapping

Geographic Information System (GIS) is a computer-based method of recording, analyzing, combining, and displaying geographic information. GIS maps can show roads, habitat types, sensitive areas, soil types, or any other feature that can be mapped. GIS is useful for integrating various geographic information, such as satellite images, modeling results, or demographic information to analyze the relationships within the data (USGS, 2007). GIS can show quantities such as maximum and minimum value, distributions or concentrations, changes over time, and differences in degree of a climate impact (ESRI, 2006). GIS is particularly good at simulating a variety of landscape projections under different climate change scenarios because it can clearly show changes in flooding or inundation (Brown, 2006).

Adaptation Strategies

Many existing environmental management tools have the potential to aid with adaptation to climate change. These techniques are not without consequences and their appropriateness will vary for different settings. Practitioners attempting to help ecosystems adapt to climate change should consider both the benefits and consequences of any technique. Adaptation techniques can be classified as **building resiliency, physical protection,** and **retreat** measures (modified from Warren, 2004).

Building Resiliency

Accommodation measures prepare and protect ecosystems to reduce the severity of climate change impacts. These strategies promote the enhancement of natural resilience through protection of ecosystems and through ecosystem restoration. Prevention of current stresses such as habitat loss, pollution, and resource extraction are important methods of enhancing species' resilience to climate change. Land management, including, zoning, and development regulations are types of resiliency measures that can be used to protect areas at risk from climate change (Kojima, n.d.; Warren, 2004).

Freshwater Buffer Zones: Buffer zones protect the area immediately surrounding a water body, wetland or other resource by limiting encroachment of incompatible uses. A common practice is to place buffers along streams and riverbanks to either protect the water quality of a river and stream and/or to prevent development in floodplain areas. These zones not only serve to protect freshwater resources but allow vegetative communities to shift and migrate in reaction to wetter or drier periods (Hartig et al., 1997).

Table 6. Technology Tools

Technology tool	Description	Benefits	Limitations
Satellite image	Provides photographic images via satellite	• Data gathering is relatively easy and cheap • Appropriate for gathering general data and for evaluations of large geographic areas	It is difficult to gather detailed data of specific locations
LIDAR	Models elevation, canopy height, biomass and bathymetry	• Can gather detailed data for small geographic areas • Can gather accurate topography of ground and seabed	• High cost • General data is not readily available
GIS	Computer-based method of recording, analyzing, combining, and displaying geographic information	• Maps geographic and statistical information • Allows for interactive data analysis • Highly accessible	• Data is not always available for a specific project or area • Hard to get detailed information on a single map for a large area
Bioclimatic envelope model	Models species distribution under various climate scenarios	Useful for analyses of single species reactions to specific climate variables	Does not consider reactions with in species or more complex scenarios
Hydrodynamic model	• Analyzes the water cycle • Different models are available, including Hydrologic Simulation Program – Fortain (HPSF) andPrecipitation-Runoff Modeling System (PRMS)	Can model the water cycle for a number of purposes with climate changes taken into consideration	• Data needed for an accurate model may not be available • Hard to get detailed information for a large area since hydrologic models are useful for large areas but are not as detailed, while hydraulics models give detailed information but for much smaller areas
Storm water management model	Storm Water Management Model (SWMM) simulates the quantity and pollutant load of runoff	To analyze urban area's pollutant discharge which can relate to water quality within the watershed	• Not useful for analyses of normal to low precipitation events • Non-point sources are harder to model than point sources
Inundation model	Projects areas that will be vulnerable to inundation	Adapt various patterns of inundation (sea-level rise and increase of stream flow)	Accuracy is still limited

Wetland Restoration: The restoration of ecosystems can increase an area's natural resilience to rapid climate change. For example, many wetlands that have been historically drained for agriculture can be reestablished. Wetland hydrology can be restored by terminating any deliberate drainage and re-establishing water flow into the wetland basin. Soil saturation will encourage the growth of wetland plants. However, wetland restoration efforts have less chance for success in areas where water supply is low due to reductions in surface runoff, precipitation, or groundwater recharge (Hartig et al., 1997).

Photography by Bill Silliker Jr.

Dam Removal: Removing existing dams on rivers can be an effective way to enhance aquatic species' ability to migrate and maintain natural hydrologic regimes as climates change. Dams impede the mobility of species such as migratory fish that move from marine to riverine areas to spawn, and will obstruct their ability to find a more habitable climate. Dam removals can face environmental and societal obstacles. Disposal or release of contaminated sediment that may exist behind dams over time can be a significant issue. Dam removal is also counter to increasing interest in the use of dams for hydroelectric power generation as a carbon-free, renewable source of energy. However, dam removal may be more feasible for obsolete and relic dams and for dams that produce little or no hydroelectric power.

Sustainable Dam Management: For dams that continue to meet current needs for water supply, hydropower, flood control and recreation, sustainable dam management can improve conditions and therefore resiliency compared to existing conditions. Practices such as flow management and fish passage can allow for more optimal flow and mobility.

Stream Flow Protection: Hydrologic regimes are affected by many activities beyond dams, including impervious surfaces, water withdrawals, and modifications to channels and riparian areas. Developing local and state policies that protects water resources at levels needed for maintenance of ecosystem function and services is an important tool to protect the hydrologic regime of freshwater and estuarine systems. This type of policy may become more important as precipitation patterns change and droughts become more frequent as a way to balance needs of various human uses and the needs of freshwater and coastal ecosystems.

Fishery Harvest Management: Many fish populations, particularly in coastal areas, are already overexploited from commercial and recreational fishing (Combes, 2005). Limiting the catch would maintain a higher population of species, increasing the resilience to harmful climate change impacts.

Water Conservation: Freshwater ecosystems may already be threatened by excessive residential, commercial and industrial water uses. Heightened competition between users and changing climate conditions are likely to put further pressure on these ecosystems. Water conservation policies can help manage human demand for these resources. Identification of important or endangered ecosystems can help inform decisions to withdraw water from other, less threatened sources (US EPA, n.d.).

Artificial Aeration: Summer fish kill in lakes due to low dissolved oxygen, as a result of altered timing and temperature of seasons can be addressed with artificial aeration. These methods act to increase oxygen levels in the water. "Bubblers" function with a deep-water intake that produces rising bubbles of air. Mechanical surface aerators, known as "splashers," float on the surface of the water and spray droplets of water in a radial pattern. Ecological consequences that should be considered with the use of these devices involve the disturbance of bottom sediments, ice cover, and vertical density stratification (McCord, Schladow, Miller 2000).

Dam Removal in Augusta, Maine

In 1999, the Edwards Dam in Augusta, Maine was removed allowing the Kennebec River to flow freely from the town of Waterville to the sea. For 160 years, the dam had blocked migratory fish from moving from the ocean to freshwater ecosystems for spawning. In 1997, the Federal Energy Regulatory Commission voted not to reissue the operating license for the Edwards Dam and ordered that the dam be removed. The Edwards Dam was the first hydroelectric dam in the country to be removed by the federal government for environmental reasons.

Ten species of migratory fish including the shortnose sturgeon, alewives, Atlantic salmon, striped bass, shad, and several species of river herring blocked by the small hydroelectric dam are now able to make their way upstream for the first time since 1837. In the first two years, more than two million fish have returned to the Kennebec River (PBS, n.d.; MSPO, n.d.).

Land Management

Protected Areas: The purchase, or other means, of setting aside land and water for conservation purposes is an effective way to protect it from human-caused stressors such as development that may weaken ecosystem health and lower its resiliency to changes in climate. By protecting natural communities and surrounding areas, these ecosystems and their component species, will be better suited to adapt or migrate naturally, enhancing chances for survival. In coastal waters, conservation may take the form of marine protected areas which are set aside from some or all harvesting and other activities in order to maintain habitats for feeding and reproduction of fish and other species.

Conservation Easements: A conservation easement is a transfer of usage and/or development rights whereby a property owner sells or donates these rights in order that they are held for conservation by a land trust or similar organization. This tool can be a cost effective and socially accepted method as such agreements are generally entered into on a voluntary basis and because landowners retain ownership and some uses of the property.

Easements can be targeted to address specific issues and/or on specific areas of properties. For example, easements focused on shoreline adaptation can specify erosion-prone areas as the sections of the property restricted from development. Restrictions can either prevent all development and shoreline hardening measures, or can specify density of development as well as type of shoreline stabilization methods used (such as ‘soft' protection measures rather than seawalls). The easement can also restrict removal of erosion-preventing vegetation in the area and/or restrict any other land use or activity that may either contribute to erosion or impair natural shoreline processes (NOAA, n.d.).

Migration Corridors: Species have some natural abilities to adapt to changes in their environment, including changes in climate. In particular, poleward migration is expected as species move to find cooler temperatures. This natural migration may be significantly obstructed by human development, especially urban settlement and transportation networks. The creation of protected migration corridors can help ensure that species have a safe path to reach the new habitat, particularly between existing areas of protected open space and remaining intact areas. Studies cite the removal of dams or fences or the provision of bridges and tunnels as ways to enhance species mobility (Burton, 1996).

Rolling easements: In areas vulnerable to climate change, this type of easement restricts how a property owner can respond to a changing coast or shoreline and has a boundary that changes as the shoreline changes. As the sea advances, the easement automatically moves or "rolls" landward. Generally these easements prevent the use of hard shoreline stabilization structures and therefore are designed to preserve tidal, wetland and other shoreline habitats and processes. As developed in South Carolina, rolling easements do not restrict other types of development. They allow the landowner to build anywhere on their property with the agreement that they will not be able to prevent shoreline erosion by armoring the shore. If erosion threatens the structure, the owner will have to relocate the building or allow it to succumb to the encroaching sea (NOAA n.d).

Restrictive Covenants: Restrictive covenants are another method of regulating development and shoreline stabilization measures on private property. Restrictive covenants are restrictions written into a deed or title to a property. For example, a covenant can be written into the deeds of waterfront developments to limit owners to the types and locations of shoreline stabilization structures that can be used. Because property boundaries do not necessarily follow natural boundaries, and the inability to ensure all property owners agree to such covenants, this approach may not ensure consistent protection along shorelines.

Setbacks: A setback is a boundary created by a regulatory agency or local government to prevent development within a certain distance of a shoreline or other resource area. Setbacks are often used in areas of high erosion, such as shorelines or steep slopes, to prevent or minimize development in these areas. A challenge associated with establishing setbacks is having adequate scientific information to draw the appropriate boundary (NOAA, n.d.). If sea level rise is more severe than projections indicate, the setback may be inadequate to minimize damage to resources or structures. In such a case, landowners outside of the setback area may retain their right to protect their property using shore armoring, such as seawalls (Titus, 1998). In addition, some setbacks may sufficiently limit property owners' ability to develop their land that it may lead to 'takings' claims.[1]

Zoning Overlay Districts: Another land use regulation available to local governments are zoning overlays. This type of zoning ordinance can be an "overlay" in addition to existing land use regulations and is designed to place restrictions on or limit development in vulnerable areas, such as erosion-prone shorelines or water recharge areas. This type of regulation can dictate development densities and shoreline stabilization methods, restrict removal of vegetation, and expand setback boundaries. Overlays represent a holistic approach to shoreline management, as opposed to the lot-by-lot approach of easements. However, zoning overlays face similar difficulties as other methods, such as having enough scientific information to establish protective provisions and the unpopularity of implementing regulations that restrict development rights of property owners (NOAA, n.d.).

Physical Protection Measures

A physical protection measure is designed to act as a physical barrier to protect an area from threats of a changing climate such as floods, storm surges and sea level rise. These measures are often classified as either "hard" or "soft" protection. Soft protections are generally considered less environmentally damaging and more likely to function with and as part of natural processes. Such soft measures are often less expensive and more visually appealing. Soft protection measures involve the placement of plants, plant materials, rocks, soil and sand to mimic erosion control methods that exist in nature and create natural barriers between the sea and inland ecosystems. Most importantly, they minimize environmental impacts and create additional benefits as they are designed to allow natural processes to continue. However, some methods are more beneficial than others, and some can be quite controversial.

Hard protection measures include sea walls, rip-rap and groins built to armor the shoreline or stream channel or trap sand and sediment. Shoreline armoring is often cited for its negative impacts on the environment as it blocks natural processes. While construction of hard protection structures may not often be the focus of conservation efforts, it is important to anticipate the ways in which humans will adapt to climate change because methods such as shoreline armoring will, in turn, affect aquatic ecosystems.

Bioengineering and Living Shorelines: Bioengineering is a restoration approach that seeks to use natural materials and project design based on ecosystem functions to restore degraded areas. Often this involves the strategic placement of organic materials to help control riverbank erosion. In the Chesapeake Bay region, this approach is known broadly as Living Shorelines. Rocks

[1] The Takings clause of the U.S. Constitution grants government the ability to take land from private owners for meeting a public good or need as long as there is payment of just compensation. In general the courts have found that as long as a regulation does not take all uses and value of the property the restrictions are not considered a taking.

Rolling Easements in South Carolina

The South Carolina Beach Front Management Act of 1988 established a setback line leading some property owners to lose development rights. One owner, David Lucas, sued the Coastal Council for compensation. The trial court for the landmark shoreline management case, Lucas vs. the South Carolina Coastal Council found that the setback line resulted in a “takings”. The state then had to compensate Lucas for the lost use of his property.

The Lucas decision prompted the legislature to amend the Beach Front Management Act in 1990 to allow for a rolling easement on any lot seaward of the setback line to avoid the need for “takings” compensations. As a result, properties seaward of the setback line can be developed but no hard shoreline stabilization structures can be used to protect the property. However, some “soft” erosion control methods can be used including beach nourishment, building up artificial dunes, and temporarily placing small sandbags around a home. If homes are damaged or destroyed during a storm, they are allowed to rebuild as long as high ground still exists. If the lot is submerged during high tide, rebuilding/repairing is no longer allowed.

Photography by Alan Eckert

and plant roots hold up against waves from boats and storms while simultaneously providing habitat for water species such as crabs and fish, enhancing the productivity of the shoreline ecosystem (Maryland DNP, n.d.).

Wetland and Marsh Creation: A variety of techniques fall into this category, including restoration of natural hydrology and the planting of vegetation to help maintain marsh levels by trapping and stabilizing sediments (Sorensen, 1984). This method can revitalize marsh areas damaged by human activities. In addition to the benefit of creating an ecosystem for intertidal species, marshes provide some protection for estuarine areas from mild wave activity.

Dune Creation: Dunes are hills of sand that occur naturally in many coastal areas. Dunes can act as natural dikes, preventing seawater from inundating the land beyond while also supplying sand to replenish what is eroded away by wave and storm activity. Dunes can be artificially restored or created by bringing in additional sand. Fences and native vegetation can be used to maintain the shape of the dune (Sorensen, 1984). Potential problems can occur regarding the source of sand for replenishment. When extracted faster than the rate of natural replenishment, sand supplies are vulnerable to overexploitation, disrupting ecosystems at the supply site. In some cases, dredged materials have been used to replenish sand supplies, but there have been occurrences where materials contained chemical contaminants (Hedrick, 2000).

Oyster Reef Restoration: The restoration of oyster reefs is a technique that restores habitat and provides coastal protection from wave energy. Restoration involves the strategic placement of oyster shells and other organic materials on footprints of historic oyster reefs (VA Institute of Marine Science). Oyster reefs can also act as a breakwater, to help slow wave and storm energy and sand transport. Reefs can help to moderate damage from intensified weather events and sea-level rise predicted from climate change.

Beach Nourishment: Also known as beach fill, beach nourishment is the replacement of sand on beaches that are vulnerable to erosion. This common method can help stabilize shorelines and protect inland areas from inundation. However, this method of coastal zone management has many shortcomings. Beach fill can be highly expensive and the benefits can be short term, as sand may need to be replaced quite frequently. Concerns regarding sand sources are similar to those involved in dune creation. The method is also controversial because the movement of sand from one habitat to

North Carolina Setback Requirements

North Carolina's Administrative Code for Ocean Hazard Areas (15A NCAC 7H .0306) establishes a tiered approach for setbacks based on the size and type of the structure. For the most part, setback lines are measured from the first stable natural vegetation, and are based on the annual erosion rates. Small structures (less than 5,000 square feet and five units) and single-family homes must be set back thirty times the average annual erosion rate. Larger structures, such as hotels and condominiums, must meet additional setback requirements due to the technical, financial and legal problems that can arise when these structures need to be relocated. For buildings 5,000 square feet or more, the setback line is sixty times the average annual erosion rate or at least 120 feet landward of the vegetation line. If the erosion rate is greater than 3.5 feet per year, these larger structures must be setback thirty times the erosion rate plus 105 feet. Existing structures seaward of the setback line are grandfathered in. However, if they are damaged or destroyed and the cost to repair would be more than 50 percent of the physical value of the structure, the owner must obtain a permit and meet all current setback requirements before repair or rebuilding is allowed.

another can create various disturbances. For instance, the placement of new sand can bury intertidal species and disturb the feeding and nesting habitats of coastal species (Hedrick, 2000).

Tidal Hydrology Restoration: Restrictions on natural tidal flow can be removed to restore the hydrological conditions necessary to maintain ecosystem function in wetlands and marshes. Roads, bridges, and rail lines disrupt sediment transfer and natural hydrodynamics. Removing obstructive infrastructure can restore these processes and, thus, boost ecosystem health and resiliency to changes in climate. Moreover, the restoration of sediment transport can enhance a wetlands' ability to accrete, an adaptive capacity that may prove necessary in the face of rising sea levels.

However, the rate and extent of sea-level rise may influence the efficacy of this method. Removing restrictions to full tidal flush may eventually leave ecosystems vulnerable to levels of inundation that are higher than can be tolerated by the marsh. Data gathering regarding marsh and wetland elevation and projected tidal influence can help identify which wetlands may be more or less susceptible to this threat.

Retreat Measures

Retreat is the abandonment of an area in order to avoid a direct impact. Retreat involves avoiding risk in order to eliminate a direct impact. With this strategy, no attempts are made to protect areas. Instead, some human uses of the land are abandoned or not developed in the first place.

SCORE - South Carolina Oyster Restoration and Enhancement Program

The Marine Resources Division of South Carolina Department of Natural Resources has initiated a program to restore and enhance South Carolina oyster habitats. This program is a community-based restoration effort to involve citizens in habitat enhancement. Scientists and citizen volunteers build oyster reefs using recycled shells. After the reefs are constructed, volunteers are trained to monitor water quality, reef development, and reef/shoreline interactions. 121 oyster reefs have been constructed at 29 sites as part of the SCORE program since May 2001. The sites span 200 miles of coastline from Murrell's Inlet to Hilton Head, South Carolina. SCORE received the Coastal America Partnership Award in 2004 (SCORE, n.d.).

Tidal Hydrology Restoration in Bridge Creek, Barnstable, Massachusetts

Bridge Creek, in the coastal town of Barnstable, MA, has been crossed by state Route 6A and an adjacent rail line for over a hundred years. Culverts were built in the attempt to allow for tidal flow; however, the culverts built were too small to allow sufficient tidal flows. The two crossings effectively restricted the natural tidal flow to upstream tidal marshes, inhibiting the hydrological conditions necessary to maintain these ecosystems.


Photography by Mark Godfrey

The Bridge Creek salt marsh was one of six priority sites selected from the 1996 Army Corps of Engineers "Cape Cod Wetlands Investigation," leading to a restoration project headed by the Wetlands Restoration Program (WRP) of the Massachusetts Office of Coastal Zone Management. The project involved the collaboration of the Town of Barnstable, 5 federal agencies, 8 state agencies, 10 corporate partners, and 6 non-profit organizations. The project replaced the undersized original drains with 10 x 10 foot concrete box culverts. WRP reports, "…the replacement of the culverts has restored the dynamic tidal hydrology and water chemistry needed to bring back healthy salt marsh habitats and functions, along with the fish and wildlife they support. The rail replacement of the project restored tidal flow to…a total of 40 acres of salt marsh." (MCZM, n.d.)

Relocation of Infrastructure: Retreat often means removing human impediments to shoreline or species migration or removing structures that are in harm's way. This includes the relocation of roads, railroads and other structures, removal of dams and other structurs that have the potential to block the migration of species and communities. In particular, this may be an important strategy to allow for the migration of coastal shorelands, wetlands and marshes. In many cases, these systems might be able to survive sea-level rise through accretion or landward movement of dunes, beaches and barrier islands.

Assisted Species Migration: One of the more controversial techniques is that of assisted migration, which is the deliberate relocation of species to a new habitat with the goal of establishing a population there. The strongest argument for helping species migrate as the climate changes is that natural migration may be hindered by human development. However, the value of this technique is complicated by unknowns such as which species to save, the ability of the species to adapt to a new ecosystem, and the possibility that the species may become invasive to existing species in the new habitat (Zimmer, 2007).

Table 7. Adaptation Techniques - Accommodation - Resource Management Measures

Policy Measure	Description	Benefits	Limitations
Freshwater Buffer Zones	Protection of area immediately surrounding a body of water	• Absorb water in times of inundation • Allow vegetative communities to shift in reaction to wetter or drier periods	Often conflicts with existing development or plans for future development
Dam Removal	Physical removal and breaching of dams that impede migratory ability of ambulatory species	Restore the ability of ambulatory species to migrate to refuge or northward as climate changes	• Ecological consequences arise with disposal of sediment deposits • Local opposition to removing the dam
Sustainable Dam Management	Enhancement of flow management and improving fish passage, i.e. fish ladders, slots	Allow for more optimum flow and mobility	Usually cannot mimic spring flood this way so will not replace natural flooding
Stream Flow Protection	Developing local and state policies to protect natural hydrologic regimes	Maintain ecosystem functions by maintaining and restoring physical and ecological processes	Changing current water uses and allocations can be difficult
Fisheries Harvest	• Regulate fishing practices • Create marine protected areas	Alleviate already stressed and overexploited fisheries to increase resilience to climate change impacts	Implementation and regulation is difficult
Water Conservation and Drought Management	Improve efficiency in human water uses	Reduce competing demand for water supply in face of low flow	Conflict with human demand, may be unpopular
Artificial Aeration	Mechanical aeration systems installed in lakes such as point-source bubblers and mechanical surface aerators	Maintain mixing and dissolved oxygen levels necessary for lake ecosystem function	Disturbance of bottom sediments, ice cover, and vertical density stratification, energy use

Table 8. Adaptation Techniques - Accommodation - Land Use Conservation Measures

Policy Measure	Description	Benefits	Limitations
Protected Areas	Purchase or other means of protecting land and water for conservation purposes to protect it from human stressors	Provides permanent protection of areas included	• Can be expensive • Desired areas may not be available for protection
Conservation Easements	• Purchase of development rights • Can be focused on sensitive areas of property	• More flexible and less chance of legal takings claims • Can allow other uses, such as agriculture, forestry, and recreation to continue	May not completely prevent harmful activities or development near habitat
Migration Corridors	Strategic protection of lands to provide connectivity between existing protected areas	Allow for species migration from one protected area to another	• Acquiring land can be expensive • Finding appropriate corridors may be limited by existing development
Rolling Easements	• Protects shoreline as it changes • Prevents hardening of shorelines	Allows natural shoreline and riparian processes to continue	Existing and new structures at risk as shores erode or move
Restrictive Covenants	Development and management restrictions written into a property deed or title	Provide shoreline protection measures	Development boundaries may not follow natural ones
Setbacks	A legal or zoning boundary along a shoreline within which development is restricted or prohibited	Effective way of prohibiting development	• Usually requires good scientific data • May not fully account for uncertainties such as sea-level rise
Zoning Overlays	Type of zoning ordinance 'laid over' existing land use regulations to limit development in vulnerable areas	Effective way to manage development and type of shoreline protection measures used	• Usually requires good scientific data • May not fully account for uncertainties such as sea-level rise

Table 9. Adaptation Techniques - Protection and Retreat

Adaptation Technique	Description	Appropriate for	Benefits	Limitations
PHYSICAL PROTECTION				
Bio-Engineering and Living shorelines	Placement of organic materials to prevent river-bank and shoreline erosion	Coastal areas and riverbanks	Natural rocks and plants act as buffer against boat and storm waves; provides habitat for aquatic species	Only works in sheltered areas; not appropriate on open coast; susceptible to sea-level rise
Marsh Creation	Using materials to replenish marsh elevation	Marshes, estuaries	Enhances resiliency to sea level rise; restores marsh habitats while providing protection for estuaries against wave energy	Creation not always successful; may conflict with development, etc.; other stressors may prove too great
Dune Creation	Deliberate restoration or creation of sand hills	Beaches	Can prevent inundation of inland areas; can act as sand reservoir to replenish beach during storms	Sand sources
Oyster Reef Restoration	Strategic placement of oyster shells and other organic materials on footprints of historic oyster reefs	Bays	Restores habitat while providing shoreline protection from wave and storm energy and slows sand transport	Most successful only where footprints of historic oyster reefs are available
Beach Nourishment	Replacement of eroded beach sand	Beaches	Shoreline stabilization; protect inland areas from flooding	Sand sources; introducing sand can interrupt tidal ecosystems
Tidal Hydrology Restoration	Removal or mitigation of human infrastructure restrictions on natural tidal flow	Coastal marshes and wetlands	Restore natural hydrodynamics which increases resiliency; restoration of sediment transport can enhance wetlands' ability to accrete	In rapid sea-level rise, removing restrictions to full tidal flush may eventually leave ecosystems vulnerable to inundation
RETREAT MEASURES				
Assisted Migration of Species	Deliberate relocation of species to a new habitat with the goal of establishing new populations	Threatened species	Assist species to move to more favorable climates whose natural migration is impeded by human development	Many uncertainties regarding species' ability to adapt once moved; possibility of becoming invasive
Remove Human impediments to Migration	Removal of impediments to migration and colonization such as dam or road systems; remove fences or provide bridges/tunnels	Areas that connect current and possible future habitats	Allow species to naturally migrate	Acquiring land; may be developed or exist as private property

CHAPTER

5

Recommendations and Conclusions

These recommendations provide action steps for incorporating climate change into aquatic ecosystem protection and restoration efforts. The inclusion of climate change impacts is imperative if conservation practices are to have the longevity needed to be viable in the future. Aquatic ecosystems are already being altered and thus the potential for continued change must be considered during the design and implementation of all protective measures.

Recommendations are made in two parts. The first part lays out short-term, long-term and big picture recommendations for conservation organizations, natural resource agencies and land managers to effectively analyze and protect aquatic ecosystems in a holistic manner in the face of climate change. The second part addresses each ecosystem in light of the major climate driven changes that affect them and suggests potential technological tools and adaptation methods.

Courtesy of the Nature Conservancy

Short Term Recommendations

Include climate change considerations in all levels of decision-making. Given the magnitude of changes, climate change should be considered in all types of decisions, including resource allocation, conservation planning, and strategic implementation decisions.

Land protection organizations should develop methods for evaluating individual freshwater and coastal properties based on climate change concerns. This evaluation should include all tools and information available: various types of modeling and mapping, climate change predictions, an assessment of the existing stressors to the property; a survey of the near-by and abutting development and structures, etc. After factoring these elements the property would then receive a score reflecting the vulnerability and resiliency of each ecosystem to assist the organization in determining whether to proceed with strategies to conserve or purchase the site.

Develop a long-term property management plan. Such a system could also be used to help guide long-term management of existing preserves or protected areas, assisting managers to analyze the benefits and limitations of potential protection measures. Areas which seem highly likely to lose much of their conservation value due to climate change should be considered, if possible, for transfer to non-conservation uses to allow for stronger investment of resources in sites and ecosystems which have greater resiliency and adaptation potential.

Develop a "Climate Endangered Ecosystem" list. Develop a list of ecosystems and representative places that are particularly at risk from impacts associated with climate change to focus appropriate adaptation strategies on these systems. They should be monitored in light of climatic changes to better track long-term health.

Foster collaboration between climate specialists and habitat specialists. There appears to be 'disconnect' between climate experts and habitat experts. For example, in two instances, freshwater experts interviewed for this report felt that they were unable to contribute as their research had never considered climate change.

Foster Future Research:

Encourage scientists to incorporate climate change considerations into their research so that there is a heightened awareness of how ecosystems might respond to all stressors, present and future. Encourage more research projects that focus specifically on aquatic ecosystems and their predicted responses to climate change. Identify topic areas which would benefit most from research, such as species' adaptation to low flow scenarios and the potential for assisted migration of ambulatory and less mobile aquatic species.

A general gap in research exists pertaining to freshwater ecosystems and climate change. As these ecosystems are not directly affected by sea-level rise, it seems that fewer studies have investigated how climate-driven changes will affect them. More work in this area could foster understanding of the connection between the timing and sensitivity of species' life cycles to climate change and on adaptation techniques for effectively preserving freshwater systems as they respond to climate change.

Promote collaboration between scientists from different specialties in order to perpetuate the concept of interconnectedness of all ecosystems and how the health of one affects the health of others. This collaboration could come in the form of workshops, conferences, and partnerships with other organizations.

Research the relationship between human related water resource management and water conservation for aquatic ecosystems. This research is especially important as a significant increase in demand for human water supplies could have serious repercussions for aquatic ecosystems.

Long Term Recommendations

Seek funding for LIDAR mapping. While this is a costly and time intensive method of mapping, it is the best way to understand the future of shoreline inundation from sea-level rise, flooding rivers and changing hydrologic regimes. Being able to predict these patterns is essential for protecting existing conservation properties and evaluating new purchases.

Photography by Harold E. Malde

Support accurate, high resolution elevation mapping for coastal wetlands. This is necessary for providing baseline data to identify wetlands which may survive inundation.

Floodplain mapping should be updated to better predict future scenarios of hydrological systems. The size and frequency of the '100 year flood' is changing as a result of climate change and current mapping may not be adequate for the expected increase in storm intensity and resultant increased flood magnitudes.

Prioritize protection over restoration of aquatic ecosystems. In the long term, it is often more cost effective to protect a resilient ecosystem than to restore one that has been degraded.

Photography by Budd Titlow

Establish long-term goals that consider mid-century and end of century climate predictions. Implement appropriate adaptation techniques on high-priority ecological areas or existing protected areas that are identified as most viable in the changing climate. Undertake planning on a 50-100 year time scale to ensure strategies (or sequence of strategies) are effective under the changing conditions.

Evaluate existing monitoring programs and implement additional programs to ensure adequate data for identifying and tracking trends. This will help to predict how ecosystems change and respond over time.

Promote the use of conservation methods which mimic natural processes, such as marsh and wetland restoration, wherever possible.

Promote the removal of existing and prevent the construction of new hard structures such as seawalls and dams to allow for species' and ecosystem mobility.

Promote migration corridors that allow for connections within and between aquatic and terrestrial ecosystems.

Pay special attention to north/south migration corridors as species are likely to seek out northern latitudes as temperatures rise.

Big Picture Recommendations

Work with federal, state and local agencies to strategically maximize the number of aquatic ecosystems that are designated as protected areas.

Promote regional planning which integrates climate change into land use and conservation strategies. Examples: Cape Cod Commission, California Commission.

Promote stricter wetland protection at all levels of government. Ensure wetlands are adequately protected and integrate expected impacts from climate change into current wetland policies and laws.

Work with local land trusts and property owners to build a vision of the future for local properties that incorporates climate change considerations. For example, give priority to protecting coastal wetlands with accretion rates that match or exceed the rates of sea-level rise, as well as the buffer zones around them.

Continue to work to reduce other anthropogenic stressors such as development, pollution, and wetland drainage. For example, promote policies that facilitate or require low-impact development, especially on properties adjacent to threatened aquatic ecosystems.

Partner with other environmental non-profits on climate change issues; the collective group will have more power than one organization acting alone.

While there is still uncertainty surrounding how climate change will play out in precise locations, there is substantial evidence that aquatic ecosystems are significantly threatened from the climate changes underway. The longer organizations and agencies wait to act, the less chance there will be for successful response.

Table 10. Recommendations: River and Stream Ecosystems

Climate Driven Change	Technology or Future Research Recommendations	Potential Adaptation Techniques
Summer low flow/ drought	• Hydrological modeling • Assess flow as conditions change • Model flood patterns of mid and end of century	• Sustainable water resource management of human water supply • Investigate in-stream policies in terms of benefits and disadvantages • Dam removal, where possible and appropriate • Maintain and improve fish ladders to facilitate up-stream mobility • Sustainable dam management
Earlier spring high flow	• Hydrological modeling • Research species' vulnerability to flood levels, severity, and timing	• Utilize land-use conservation tools to preserve riparian communities that provide erosion control • Fortify shoreline with tools such as living shorelines to prevent erosion and maintain habitat • Dam removal, where possible and appropriate • Maintain and improve fish ladders to facilitate up-stream mobility • Sustainable dam management
Increased storm intensity	• Storm-water management modeling • Hydrological modeling	• Promote storm-water management policies to reduce storm-water flooding
Increased water temperature	• Research potential water temperature models • Research conservation methods focusing on less mobile species	• Protect shoreline trees whose canopies shade rivers and help maintain lower temperatures and additional habitat • Create and protect north/south corridors so cold-water species can migrate north • Sustainable dam management • Maintain and improve fish ladders to facilitate up-stream mobility

Aquatic Ecosystem Recommendations

These recommendations are specific to each aquatic ecosystem and their individual responses to the major impacts of climate change. These recommendations represent the synthesis of the information presented in the previous chapters of this report. For each aquatic ecosystem, technological tools and adaptation methods are identified which may assist conservation organizations and land managers in promoting the protection of the ecosystem.

The recommendations made here are important steps in understanding the potential responses of aquatic ecosystems, as well as potential preservation strategies. The list can seem long and some of these projects demand a serious commitment of time and resources. However, making this commitment early will benefit both the organizations and the ecosystems that land trusts and other groups work so hard to protect. Climate change is already occurring; these recommendations will assist natural resource managers to face these changes and prepare for those that have not yet happened.

Table 11. Recommendations: Freshwater Wetland Ecosystems

Climate Driven Change	Technology or Future Research Recommendations	Potential Adaptation Techniques
Lower summer water levels	• Utilize GIS to identify location of wetlands and connecting freshwater ecosystems • Hydrological modeling • Analysis of groundwater inputs • Research ecological integrity of artificial wetlands	• Sustainable water resource management • Dam removal, where possible and appropriate • Protect intact wetlands • Promote migration corridors so that species can migrate to more optimal habitats
Decrease in precipitation falling as snow	• Hydrological modeling • Bioclimatic modeling • Research species' vulnerability to flood levels, severity, and timing	• Utilize land-use conservation tools to preserve riparian communities • Dam removal, where possible and appropriate • Sustainable dam management • Sustainable water resource management of human water supply
Increased water temperature	• Research potential water temperature models • Research conservation methods that focus on less mobile species • Research species' vital role to ecosystems and anticipate possible effects of extinction	• Protect shoreline trees whose canopies shade rivers and help maintain lower temperatures • Create and protect north/ south corridors so cold-water species can migrate north • Assess potential for assisted migration of ambulatory and less mobile species
Increased storm intensity	• Storm-water management modeling • Hydrological modeling	• Use land-use conservation tools to preserve riparian communities that provide erosion control • Promote storm-water management policies • Implement policies regulating pollution to decrease toxins entering wetlands from storm-water run-off

This report identifies the major impacts of climate change on freshwater and coastal ecosystems throughout the northeast and mid-Atlantic regions. Based on these impacts and the responses which they elicit within the ecosystems, technological tools and adaptation methods are identified and recommended which can be utilized to effectively preserve these vulnerable and valuable ecosystems in the face of climate change.

Conclusion

It can be difficult to determine precisely how ecosystems will respond to predicted changes. There are many factors affecting these aquatic zones and it is challenging to anticipate the outcome of their aggregate effect. Many of these systems are already stressed by anthropogenic activities. How these systems will respond as they become further stressed as a result of climate change is still uncertain. However, despite this uncertainty, there is a definitive body of research which provides well founded predictions. Overwhelmingly, these predictions indicate serious consequences for the long-term health and stability of aquatic ecosystems and the species which inhabit them.

The most significant effects of climate change on aquatic ecosystems are predicted to be the following:

Table 12. Recommendations: Lake Ecosystems

Climate Driven Change	Technology or Future Research Recommendations	Potential Adaptation Techniques
Increased summer stratification	• Monitor dissolved oxygen levels • Monitor nutrient levels throughout the water column	• Nutrient and sediment control in the watershed • Protect connecting rivers and streams to allow ambulatory species the ability to migrate • Remove obstacles that impede migration • Artificial aeration of lakes to promote mixing and increase dissolved oxygen levels
Increased water temperature	• Research species' vulnerability to temperature change	• Protect shoreline trees whose canopies shade rivers and help maintain lower temperatures as well as provide additional habitat • Promote connections between rivers and streams to allow ambulatory species the ability to migrate • Remove obstacles that impede migration
Lower summer water levels	• Hydrological modeling	• Sustainable water resource management of human water supply • Protect wetlands as they store water, maintaining water-table levels • Dam removal, where possible and appropriate • Sustainable dam management

An increase in sea-level rise will lead to the deterioration of saltwater wetlands and the inundation of coastal properties along the entire coast throughout the Eastern Region. Numerous species may be affected as they depend on these ecosystems for food, shelter, and as breeding grounds. Sea-level rise could also lead to saltwater intrusion into groundwater, negatively affecting water supplies along the eastern coast.

An increase in water temperature is predicted to have negative effects on plant and other aquatic species living in these ecosystems. Species that are mobile may be pushed further north in search of cooler waters while species which cannot migrate will be forced to adapt or perish. In addition, as increased water temperatures yield a decrease in water oxygen levels, even those species which are not adversely affected by warmer water may be threatened due to lack of oxygen.

Changing weather patterns and an altered water regime may threaten aquatic ecosystems in a number of ways. An increase in high intensity storms may increase erosion of coastal beaches and wetlands and leave inland properties unprotected. An increase in short term summer droughts may decrease freshwater levels, threatening those species which depend on freshwater. These droughts may be compounded by a decrease in precipitation falling as snow, further threatening those ecosystems which depend on an annual flood, driven by snow-melt.

In light of these anticipated changes, immediate action is imperative. Climate driven changes are already happening and it is essential to implement programs which create the conditions to allow or assist ecosystems to adapt, as they do not necessarily have the ability or the time to do so naturally.

Table 13. Recommendations: Saltwater Wetland Ecosystems

Climate Driven Change	Technology or Future Research Recommendations	Potential Adaptation Techniques
Sea-Level Rise	• LIDAR mapping • Inundation modeling • Assess the land slope adjacent to wetland ecosystems as well as existence of human development to determine potential for wetland migration • Run models at least 150 years into the future to predict wetlands response • Determine which properties will be viable in the decades to come	• Protect upland buffers • Remove hard structures impeding supply of sediment into wetlands • Promote low impact or restricted development on property abutting wetlands • Ensure adequate sediment supply into wetlands • Promote conservation oriented land-use methods and policies • Implement wetland creation conservation projects (Example: Jamaica Bay)
Increased water temperature	• Research species' tolerance to increased temperature and decreased oxygen levels • Research species' tolerance to increased water and soil salinity	• Remove hard structures to protect tidal inputs to ensure adequate mixing
Increased storm intensity	• Storm-water management modeling • Hydrological modeling	• Protect barrier beaches • Promote storm-water management policies • Implement policies regulating pollution to decrease toxins entering wetlands from storm-water run-off • Consider constructing living shoreline structures to reduce wave energy

There are a number of adaptation techniques available for promoting the conservation of these aquatic ecosystems. They are divided into three different types.

Accommodation measures attempt to temper the severity of climate-driven change through management strategies to provide for expected changes in ecosystems, such as providing migration corridors and improving water management.

Protection measures attempt to protect and restore resilient and functioning ecosystems through development of protected areas and undertaking projects to restore ecosystem functions and processes.

Retreat measures acknowledge that an area will soon become unsuitable for a species, or group of species and put people and property in harms way. Providing more room for these areas to shift and adapt to these changes will benefit species and natural communities while simultaneously taking people out of harms way.

Each adaptation tool has different benefits and limitations. It is important to carefully evaluate each ecosystem and its location in order to determine which technique would be most appropriate.

Table 14. Recommendations: Coastal Region Ecosystems

Climate Driven Change	Technology or Future Research Recommendations	Potential Adaptation Techniques
Sea-Level Rise: Inundation	• LIDAR mapping • Inundation modeling	• Allow beaches and wetlands to migrate • Promote conservation oriented land-use methods and policies • Create living shorelines where appropriate (along sheltered costs) • Assess costs and benefits of beach nourishment • Deconstruct beach stabilizing structures, such as seawalls • Remove shoreline armoring • Consider groynes where critical sand habitat exists • Dune creation
Sea-Level Rise: Increased water depth along coasts	• LIDAR mapping • Inundation modeling • Research effects of increased water depth on species	• Remove shoreline armoring • Assess development of artificial reefs to create new habitat
Sea-Level Rise: Salinity intrusion into estuaries and groundwater	• Intrusion modeling through combined hydrological and inundation modeling • Research invasive species • Assess costs and benefits of implementing hard barriers to prevent salt intrusion into the groundwater supply	• Dam removal, where possible and appropriate • Maintain and improve fish ladders to facilitate up-stream mobility • Sustainable water flow management around dams
Increased water temperature	• Species modeling to understand impacts of increased temperatures on species' survival • Identify potential northern spawning grounds for migratory fish	• Promote sustainable fishing practices • Implement marine protected areas • Limit development of coastal areas

This report documents both the vulnerability and resiliency of aquatic ecosystems. These natural areas have been under increasing stress for centuries, yet have managed to adapt and continue to thrive. Those organizations devoted to protecting ecosystems at risk have an important role to play in preparing for and reacting to climate change. By integrating climate change concerns into their operations and the evaluation of their properties, conservation organizations will be better equipped to anticipate negative changes before they occur. This will allow conservation planning to become more proactive, providing freshwater and coastal ecosystems a greater chance of survival, a critical element for the health of the natural world as a whole.

Climate change is already affecting aquatic ecosystems. Therefore, immediate action is imperative.

Appendix A: Coastal Vulnerability Index

Explanation of the CVI Index

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	>0.115	0.115 – 0.055	0.055 – 0.035	0.035 –0.022	<0.022
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 3.0	3.0 – 3.4	> 3.4
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 –2.0	-1.0 – +1.0 Stable	-1.1– -2.0 Erosion	< - 2.0
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 –1.9	< 1.0
Mean wave height (m)	<0.55	0.55 – 0.85	0.85 – 1.05	1.05 –1.25	>1.25

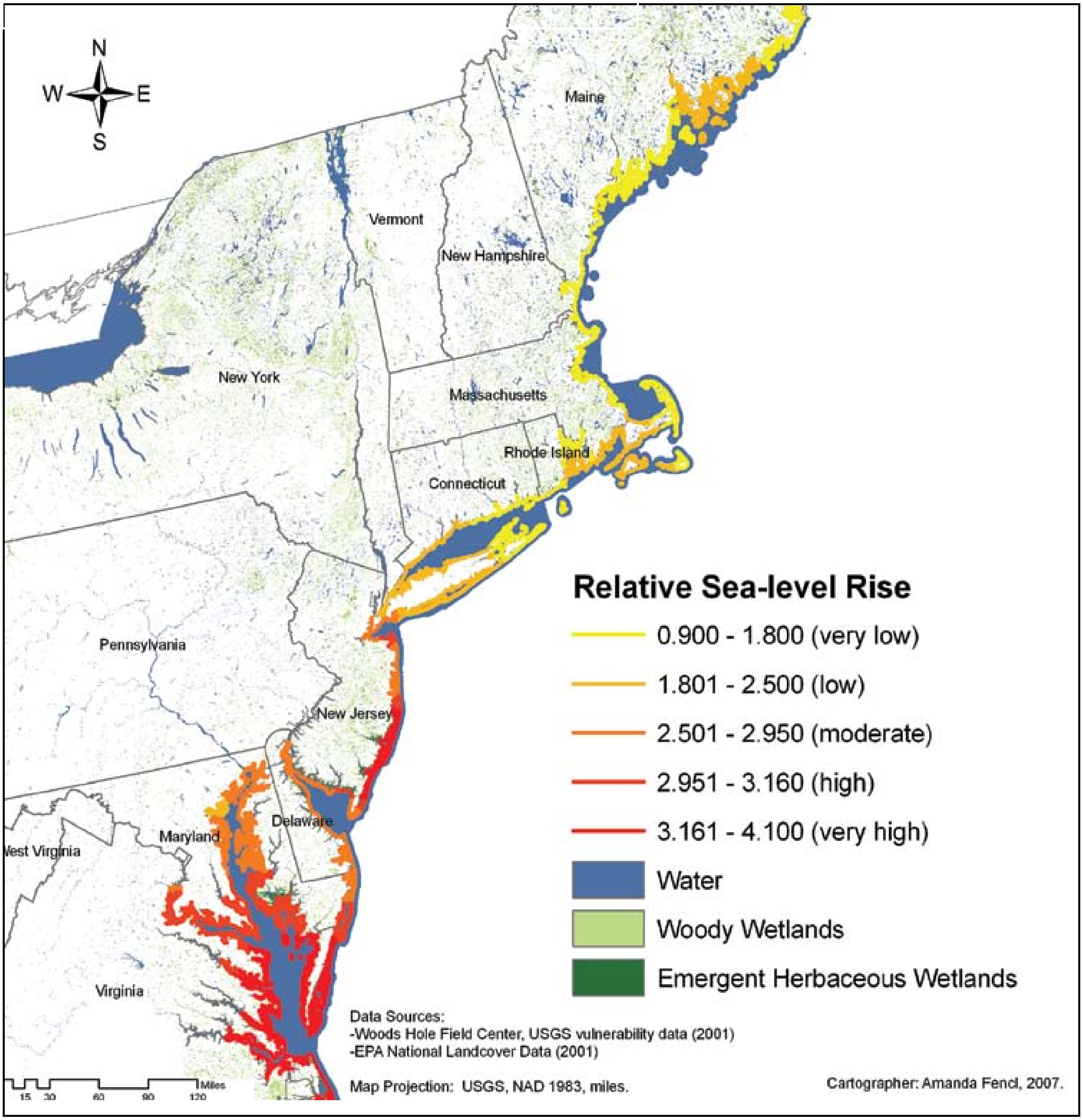
COASTAL VULNERABILITY INDEX

The coastal vulnerability index (CVI) provides insight into the relative potential of coastal change due to future sea-level rise. The maps and data presented here can be viewed in at least two ways: 1) as a base for developing a more complete inventory of variables influencing the coastal vulnerability to future sea-level rise to which other elements can be added as they become available; and 2) as an example of the potential for assessing coastal vulnerability to future sea-level rise using objective criteria.

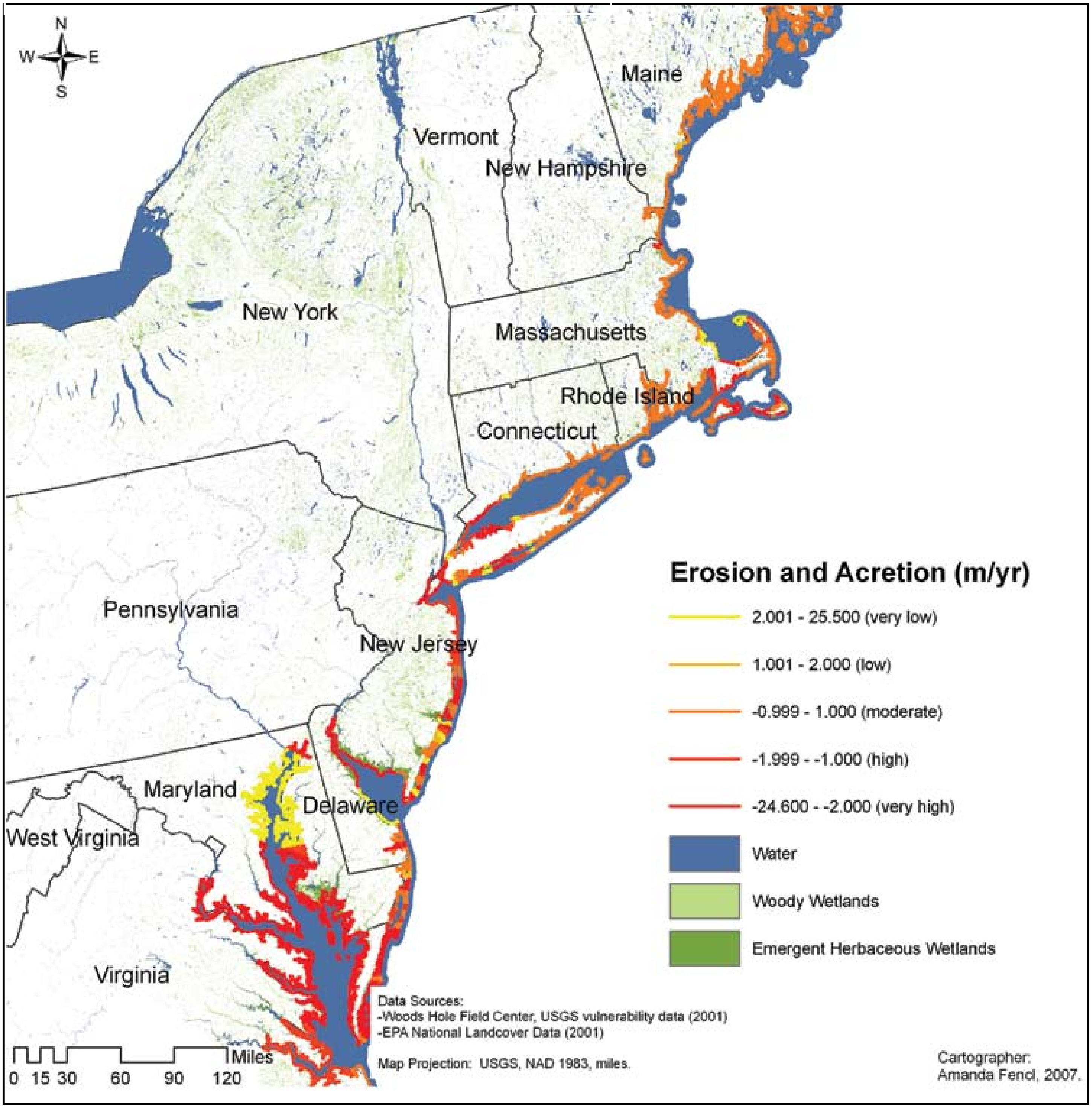
As ranked in the CVI index, coastal geomorphology is the most important variable in determining the CVI. Coastal slope, wave height, relative sea-level rise, and tide range provide large-scale variability to the coastal vulnerability index. Erosion and accretion rates contribute the greatest variability to the CVI at short (~3 km) spatial scales. The rates of shoreline change, however, are the most complex and poorly documented variable in this data set. The rates used here are based on a dated, low-resolution data set and thus far corrections have been made only on a preliminary level. To best understand where physical changes may occur, large-scale variables must be clearly and accurately mapped, and small-scale variables must be understood on a scale that takes into account their geologic, environmental, and anthropogenic influences (Theiler & Hammar-Klose, 1999).

For more information:
(http://pubs.usgs.gov/dds/dds68/reports/eastrep.pdf)

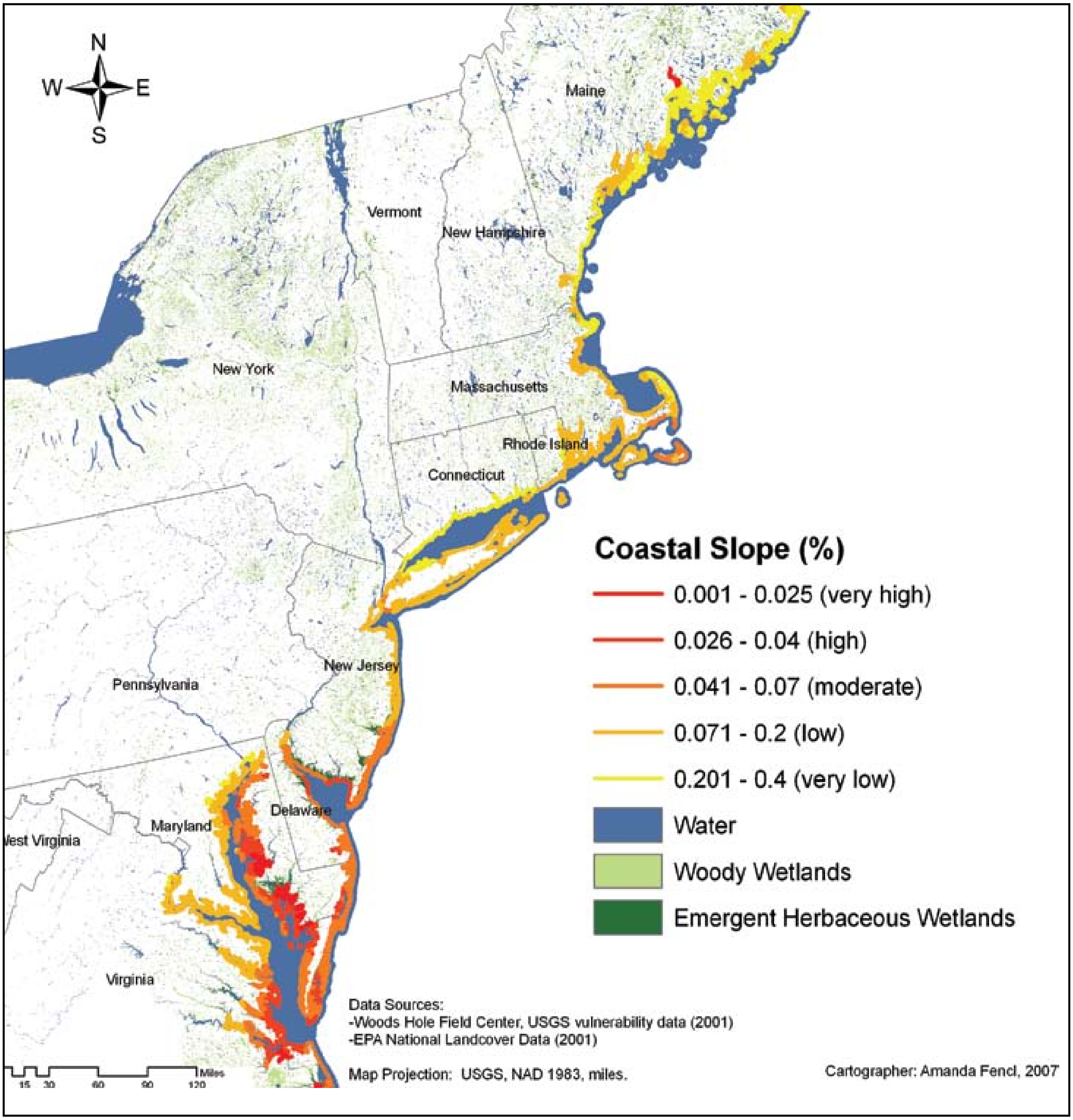
Map 2. Relative Sea Level Rise



Map 3. Erosion and Acretion



Map 4. Coastal Slope



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