7 National Estuaries

Authors

Lead Author
Charles H. Peterson, University of North Carolina

Contributing Authors
Richard T. Barber, Duke University
Kathryn L. Cottingham, Dartmouth College
Heike K. Lotze, Dalhousie University
Charles A. Simenstad, University of Washington
Robert R. Christian, East Carolina University
Michael F. Piehler, University of North Carolina
John Wilson, U.S. Environmental Protection Agency

Chapter Contents

7.1 Summary

National estuaries comprise a group of 28 estuaries, distributed around the United States and its protectorates and territories, that form the U.S. Environmental Protection Agency's National Estuary Program (NEP). The NEP mandates and supports the grass-roots development of estuary-specific Comprehensive Conservation and Management Plans (CCMPs), which, because national estuaries have no regulatory authority, rely on voluntary commitments to targets and on a wide suite of existing federal, state, and local authorities for implementation. The CCMPs hold several management goals in common: maintaining water quality; sustaining fish and wildlife populations, preserving habitat, protecting human values, and fulfilling water quantity needs.

Maintaining the status quo of estuarine management would guarantee growing failures in meeting all of these management goals under progressive climate change. This chapter thus reviews the suite of management adaptations that might accommodate effects of climate change in ways that could preserve the ecosystem services of estuaries. On time scales of a few decades, management strategies exist that may build resilience sufficiently to minimize ecosystem service losses from estuaries. However, over longer time scales, despite these actions to enhance resilience, dramatic net losses in ecosystem services will arise, requiring trade-offs to be made among which services to preserve and which to sacrifice.

Key Findings

In the short time frame of a few decades, negative consequences of climate change may be avoided or minimized by enhanced efforts in managing traditional stressors of estuarine ecosystems through existing best management practices (BMPs). For example, climate change will enhance eutrophication in many estuaries by increasing stratification of the water column, elevating biological oxygen demand by increasing temperatures, elevating nutrient loading as wetland buffers are inundated and eroded with sea level rise, and increasing organic loading in runoff from more frequent intense storms. Thus, traditional BMPs to minimize eutrophication are appropriate to expand so as to protect against the climate change enhancement of eutrophication. Protection and restoration of wetland buffers along riverine and estuarine shores should emphasize those shorelines where no barriers exist to prevent wetland transgression to higher ground as sea level rises. This strategy may require modification of present priorities in policy for protection and restoration of riparian wetlands. BMPs that remove non-native invasive species, and maintain and restore native genetic, species, and landscape diversity in estuarine habitats may build resilience to changing climate, although this ecological concept needs further testing to confirm its practical value.

Many management adaptations to climate change can be achieved at modest expense by strategic shifts in existing practices. Reviews of federal, tribal, state, and local environmental programs could be used to assess the degree to which climate change is being addressed by management activities. Such reviews would identify barriers to and opportunities for management adaptation. One major form of adaptation involves recognition of the projected consequences of sea level rise and then application of policies that create buffers to anticipate them. An important example would be redefining riverine flood hazard zones to match the projected expansion of flooding frequency and extent. Other management adaptations could be designed to build resilience of ecological and social systems. These adaptations could include choosing only those sites for shoreline habitat restoration that allow natural recession landward, and thus provide resilience to sea level rise.

The appropriate time scale for both planning and implementing new management adaptations requires considering and balancing multiple factors. Management adaptations to climate change can occur on three different time scales: (a) reactive measures taken in response to observed negative impacts; (b) immediate development of plans for management adaptation to be implemented later, either when an indicator signals that delay can no longer occur without risking serious consequences, or in the wake of a disaster that provides a window of socially feasible opportunity; or (c) immediate implementation of proactive policies. The factors determining which of these time frames is appropriate for any given management adaptation include balancing expenditures associated with implementation against the magnitude of risks of injurious consequences under the status quo of management; the degree of reversibility of negative consequences of climate change; recognition and understanding of the problem by managers and the public; the uncertainty associated with the projected consequences of climate change; the time table on which change is anticipated; and the extent of political, institutional, and financial impediments.

To minimize negative consequences of climate change beyond a few decades, planning for some future management adaptations and implementing other present management adaptations is necessary now. For estuaries, the most critical management challenge to sustain ecosystem services over longer time frames is to implement actions now that will allow orderly retreat of development from shorelines at high risk of erosion and flooding, or to preclude development of undeveloped shorelines at high risk. Such proactive management actions have been inhibited in the past by: (a) uncertainty over climate change and its implications; (b) failures to include true economic, social, and environmental costs of present policies allowing and subsidizing such risky development; and (c) legal tenets of private property rights. One possible proactive management option would be to establish and enforce “rolling easements” along largely undeveloped estuarine shorelines as sea level continues to rise, thereby sustaining the public ownership of tide lands yet allowing private property use to continue. Another proactive management action could be developing and implementing effective ecosystem-based management (EBM). This requires collaboration that crosses traditionally separate levels of management (*e.g.*, state and federal) and management authorities (*e.g.*, water quality and land-use planning) to coordinate and focus actions of all agencies with responsibilities to manage and influence stressors that affect estuarine organisms and ecosystems.

Even with sufficient long-term planning and enhancing short-term resilience by instituting BMPs, dramatic long-term losses in ecosystem services are inevitable and will require tradeoffs among services to protect and preserve. The most serious conflict arises between sustaining public trust values and private property. This is because current policies allowing shoreline armoring to protect private property from damaging erosion imply escalating losses of public tidewater lands, especially including tidal wetlands, as sea level continues to rise and the frequency of intense storms increases. In regions where relative sea level is rising most rapidly, coastal wetlands and other shoreline habitats that maintain water quality and support fish and wildlife production can be sustained only where transgression of tidal marshes and other shoreline habitats to higher ground can occur: such transgression is incompatible with bulkheading and other types of shoreline armoring that protect development from erosion. One possible management adaptation for maximizing natural ecosystem services of estuaries with minimal loss of shoreline development involves establishment of rolling easements to achieve orderly retreat, perhaps only politically feasible where estuarine shoreline development is slight.

Establishing baselines and monitoring ecosystem state and key processes related to climate change and other environmental stressors is an essential part of any adaptive approach to management. Going back into the past to identify baselines from historic environmental, agency, and ecological records, and from paleoecological reconstructions, is critical so as to enhance our understanding of estuarine responses to historic climate change and thereby improve our models of the future. A key goal of monitoring is to establish and follow indicators that signal an approach toward an ecosystem threshold that—once passed—implies passage of the system into an alternative state from which conversion back is difficult. Avoiding conversion into such alternative states, often maintained by positive feedbacks, is one major motivation for implementing proactive management adaptation. This is especially critical if the transition is irreversible, or very difficult and costly to reverse, and if the altered state delivers dramatically fewer ecosystem services. One example of such ecosystem conversions involves nitrogen-induced conversion from an estuary dominated by submersed benthic grasses to an alternative dominated by seaweeds and planktonic microalgae. Detecting ecosystem responses to climate change plays an integral role in management adaptation, because it can trigger implementation of planned but delayed management responses and because such monitoring serves to test the accuracy, and reduce the uncertainty, of the models that guide our management actions. This is the essence of agency learning and adapting management accordingly. Various federal programs for global and national observing systems are currently in development, but they need to include more focus on estuaries and more biological targets to accompany the physical parameters that dominate the current plans.

The nature and scope of many anticipated consequences of climate change are not widely recognized by policy makers, managers, and the public because they involve interactions among stressors. Consequently, an effective class of management adaptation involves reducing levels of those existing stressors to minimize the risks and magnitudes of interactive consequences of climate change. These interactions and their potential significance also imply a need for more substantive rather than superficial evaluations of interacting effects of climate change in environmental impact and environmental assessments conducted in response to the National Environmental Policy Act and its state analogs. Interactions of climate change with other stressors leads to a management priority for including consideration of climate change sensitivity, resilience, and adaptation responses in all relevant federal and state funding programs. In the absence of such actions, for example, climate impacts on estuarine wetlands will likely violate the "no net loss of wetlands" policy, which underlies the Clean Water Act, in two ways: (a) wetland losses resulting from sea level rise and increasing frequency of intense storms will compound the continuing loss of wetlands from small development projects with inadequate mitigation; and (b) measures used to protect human developments and infrastructure from climate change impacts will inhibit wetland adaptation to climate change. Management adaptations taken in response to the importance of potential interactions between climate change and existing stressors could include ending direct and indirect public subsidies that now support risky development on coastal barriers and estuarine shores at high risk of flooding and storm damage.

7.2 Background and History

7.2.1 Historical Context and Enabling Legislation

This chapter focuses on meeting the challenges of managing national estuaries and estuarine ecosystem services under influence of changing climate. Our contribution is distinguished from previous reviews of estuarine responses to climate change (*e.g.*, National Coastal Assessment Group, 2000; National Assessment Synthesis Team, 2000; Scavia *et al.*, 2002; Kennedy *et al.*, 2002; Harley and Hughes, 2006) by its focus on developing adaptive management options and analyzing the characteristics of human and ecological systems that facilitate or inhibit management adaptation. The chapter is thus written mostly for an audience of natural resource and environmental managers and policy makers.

A summary of federal legislation for the protection and restoration of estuaries is presented in the Appendix (section 7.10). There are 28 national estuaries in the U.S. National Estuarine Program, which is administered by the U.S. Environmental Protection Agency (Fig. 7.1). These estuaries span the full spectrum of estuarine ecosystem types and encompass the diversity of estuarine ecosystem services across the country. Estuaries are sometimes defined as those places where fresh and salt water meet and mix, thereby potentially excluding some largely enclosed coastal features such as marine lagoons and including, for some vigorous rivers like the Mississippi, extensive excursions into the coastal ocean. So as to match common characteristics of the 28 national estuaries, we choose an alternative, geomorphologically based definition of an estuary as a semi-enclosed body of water on the seacoast in which fresh and salt water mix (adapted from Pritchard, 1967). Such a definition includes not only those water bodies that are largely perpendicular to the coastline where rivers approach the sea, but also marine lagoons, which are largely parallel to the shoreline and experience only occasional fresh water inflow, thereby retaining high salinities most of the time. In the landward direction, we include the intertidal and supratidal shore zone to be part of the estuary and thus include marshes, swamps and mangroves (*i.e.*, the coastal wetlands).

Figure 7.1. Organization of the NEP System.[1]

Estuaries are notoriously idiosyncratic because of intrinsic differences among them in physical, geological, chemical, and biological conditions (Wolfe, 1986). There can also be considerable variation within an estuary. This variation exists over wide spectra of time and space (Remane and Schlieper, 1971). This high level of environmental variability in estuaries places physiological constraints on the organisms that can occupy them, generally requiring broad tolerances for varying salinity but also for temperature and other factors. Consequently, the organisms of estuaries represent a biota that may

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[1] **U.S. Environmental Protection Agency**, 2007: Office of Water organizational chart. EPA Website, http://www.epa.gov/water/org_chart/index.htm, accessed on 5-30-2007.

have unusually high intrinsic capability for species-level physiological adaptation to changing salinity, temperature, and other naturally varying aspects of historic climate change. The challenge is to predict how these species will respond to accelerated rates of change and how species interactions will alter communities and ecosystems.

Estuaries possess several features that render them unusually valuable for their ecosystem services, both to nature and to humans. The biological productivity of estuaries is generally high, with substantial contributions from vascular plants of historically extensive tidal marshes and coastal wetlands as well as from sea grasses and other submerged aquatic vegetation. A large fraction of the fisheries of the coastal ocean depend on estuaries to provide nursery or even adult habitat necessary to complete the life cycle of the fish or shellfish. Similarly, many species of coastal wildlife, including terrestrial and marine mammals and coastal birds, depend on estuaries as essential feeding and breeding grounds. Although depicting the ecosystem services of only one estuarine habitat, the wetlands and marshes, the Millennium Ecosystem Assessment (2005) provides a table of ecosystem services that helps indicate the types and range of natural and human values that are vested in estuarine ecosystems more broadly (Box 7.1). Partly in recognition of the value of estuaries and the threats to their health, the National Estuary Program (NEP) was established by Congress in 1987 and housed within EPA (Fig. 7.1).[2] After the establishment of this program, the 28 national estuaries were added over a 10-year period (Fig. 7.2).

Figure 7.2. Timeline of National Estuaries Program Formation.[3]

Estuaries represent the collection point past which runoff from the entire watershed must flow. The health and functioning of estuaries are at risk from pollutants that are discharged and released over the entire catchment area and reach these collection points. Degradation of estuarine habitats, water quality, and function is traceable to human modification of watersheds, with substantial cumulative consequences worldwide (Jackson *et al.*, 2001; Worm *et al.*, 2006; Lotze *et al.*, 2006). More recently, threats to estuaries have arisen from sources even closer to estuarine waters as human population migration and growth have targeted the coasts, especially waterfront property. Although more than half of the U.S. population now lives on the 17% of lands considered coastal, within the next 25 years human populations on the coast are expected to increase by 25% (National Coastal Assessment Group, 2000). Thus, the threats to estuarine ecosystems are not only widespread, requiring a basin-wide scope for management, but increasingly local as more people choose to occupy habitats of higher risk. The growing human occupation of estuarine shores increases the challenge of managing for climate change, because estuarine services are placed at growing risk from both direct impacts of changing climate as well as indirect consequences of human responses to personal and property risks from climate change.

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[2] 33 U.S.C. 1251-1387 P.L. 100-4

[3] **U.S. Environmental Protection Agency**, 2007: National Estuary Program: program profiles. EPA Website, http://www.epa.gov/owow/estuaries/list.htm, accessed on 5-30-2007.

7.2.2 Interpretation of National Estuary Program Goals

Under the goals of Section 320 of the Clean Water Act, each national estuary[4] is required to develop a Comprehensive Conservation and Management Plan (CCMP). Many national estuaries have watersheds found within a single state, and therefore their CCMP is contained within one state. Other estuarine watersheds are trans-boundary and more than one state participates. Emphasis is on "integrated, watershed-based, stakeholder-oriented water resource management."[5] These plans are produced by a full range of stakeholders within each national estuary through a process involving (1) assessments of trends in water quality, natural resources, and uses of the estuary; (2) evaluation of appropriate data; and (3) development of pollutant loading relationships to watershed and estuarine condition. The final CCMP is approved by the governors of the states in the study area and the EPA administrator. The programs are then obligated to implement the CCMPs and monitor effectiveness of actions.[6] Each national estuary prepares an annual plan, approved by EPA, to guide implementation of its CCMP.

The national estuaries represent a wide variety of sizes, geomorphologies, and watershed characteristics. For example Santa Monica Bay is a relatively small, open embayment or coastal lagoon; the Maryland Coastal Bays are a group of more closed lagoons; and the Albemarle-Pamlico Sound is a complex of drowned river valleys emptying into largely closed coastal lagoons. The Columbia River Estuary and the Delaware Estuary are the more traditional drowned river valleys. This diversity has largely prevented classification, grouping, and synthetic assessment of the constituent national estuaries. The NEP separates national estuaries into four geographic regions: West Coast (six sites), Gulf of Mexico (seven sites), South Atlantic (six sites, including San Juan Bay, Puerto Rico), and Northeast (nine sites). Although the estuaries do not share easily identified geomorphic characteristics, they are recognized to share common stressors (Bricker *et al.*, 1999; Worm *et al.*, 2006; Lotze *et al.*, 2006). These stressors include "eutrophication, contamination from toxic substances and pathogens, habitat loss, altered freshwater inflows, and endangered and invasive species" (Bearden, 2001). This particular list ignores direct and indirect fishing impacts, which are important and included in many CCMPs. Even more importantly, this list fails to include the direct and indirect effects of climate change, particularly the threats posed by sea level rise.

A hallmark of the NEP is that it is largely a local program with federal support. While federal grants provide a critical source of base funding, most national estuaries have successfully raised significant local and state support, primarily to finance specific projects or activities. The individual national estuaries lack regulatory authority; thus they depend on voluntary cooperation using various incentives, plus existing federal, state, tribal, and local legislation and regulation. Their purpose is to coordinate these local

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[4] In the National Estuary Program, individual national estuaries are referred to as National Estuary Programs. To avoid confusion between individual estuary programs and the umbrella program, this chapter uses the term "national estuaries" to refer to the individual programs.

[5] **U.S. Environmental Protection Agency**, 2006: The National Estuary Program: a Ten Year Perspective. U.S. Environmental Protection Agency Website, http://www.epa.gov/owow/estuaries/aniv.htm, accessed on 4-6-2007.

[6] 33 U.S.C. 1251-1387 § 320

efforts and promote the mechanisms to develop, implement, and monitor the CCMPs. The NEP was designed to provide funding and guidance for the 28 estuaries around the country to work in a bottom-up science-based way within the complex policy-making landscape of federal, state, and local regulations. Non-regulatory strategies must complement the limited federal and even state authority or regulations. Lessons learned about how monitoring, research, communication, education, coordination, and advocacy work to achieve goals are transferable to all estuaries, not just NEP members.

The overarching areas of concern in national estuaries can be classified as water quality, fisheries, habitat, wildlife, introduced species, biodiversity, human values, and freshwater quantity. More specifically the goals include "protection of public water supplies and the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife, and [allowing] recreational activities, in and on water, [and requiring]…control of point and nonpoint sources of pollution to supplement existing controls of pollution."[2] Thus, overwhelmingly, the interest has been on anthropogenic impacts and their management (Kennish, 1999).

Within recent years, each national estuary has developed or begun to develop system-specific ecosystem status indicators. These indicators allow ongoing assessments of the success of management activities resulting from the CCMPs. However, almost none of the CCMPs mention climate change, and only one national estuary (Puget Sound) has completed a planning process to assess implications of climate change for the perpetuation of ecosystem services in its system (Snover *et al.*, 2005). Managers may fail to account for the effects of climate change on the estuaries if the choices of indicators are not reconsidered in the context of changing climate. Perhaps more importantly, climate change may confound the interpretation of the indicator trend results and thus the interpretation of the effectiveness of the CCMPs.

7.3 Current Status of Management Systems

7.3.1 Key Ecosystem Characteristics on Which Goals Depend

To understand how climate drivers might affect individual national estuaries, it is useful to identify the susceptibility of characteristics of the entire management system. At a large scale, the location of the estuary on Earth (*i.e.,* its latitude and longitude) determines its susceptibility. Climate varies over the globe, and expectations for change likewise differ geographically on a global scale. Expected temperature and precipitation changes and range shifts can be estimated from global-scale geographic position quite well, whereas local variation of these and other variables (*e.g.,* winds) of climate change are less predictable.

Next in scale is the airshed. This is the area capable of influencing the estuary through the contribution of quantitatively significant pollutants, especially nitrogen oxides (NO_x). For the Chesapeake Bay, this area includes Midwestern states, the source of nutrients from industrial and transportation activities. Estuaries on the Gulf and East coasts are likely to have different dependencies on their airsheds for nutrient enrichment than their western counterparts. Western estuaries are affected more by fog banks emanating from coastal waters. Climate drivers that change wind, ultraviolet radiation, and precipitation patterns are particularly important at this scale.

Next in hierarchical context is the watershed. The NEP takes a watershed perspective to management. Land and watershed use, population density, and regulatory effectiveness combine to determine the potential loading of pollutants, extraction of freshwater and resources, and transformation of habitat and coastline. Climate change can influence each of these factors. Changes in temperature, sea level, storminess, precipitation, and evapotranspiration patterns can alter human settlement and migration, agricultural and fisheries practices, and energy and resource use. These responses are likely to be long-term and large-scale, although their influence on estuarine dynamics may be exhibited on shorter time scales. For example, seasonal nutrient loading varies as a result of changes in tourism or crop choice. These factors largely affect the concentration of nutrients, while changes in runoff and river flow affect the discharge component of loading.

At the opposite end of the estuary is the marine environment, which also serves as an intermixing boundary susceptible to climate change. The oceans and coastal marine waters have responded—or are expected to respond—to climate change by changes in sea level, circulation patterns, storm intensity, salinity, temperature, and pH. Some of these factors may change little over the large scale, but may be altered locally outside the mouths of estuaries. All of these factors influence the biota, with all but pH exerting additional indirect effects by modifying estuarine hydrodynamics.

Susceptibility of individual estuaries to climate change depends on a number of characteristics that act at a variety of spatial and temporal scales. All of the previously mentioned climate drivers can affect estuaries. How they do so depends on physical features such as estuarine depth, size, and balance between ocean water circulation and fresh-water inflows. Furthermore, the geomorphology and direction of longest fetch set conditions for susceptibility to storms. All of these features help determine the biological communities that reside within the estuary and how they might respond to the various components of climate change.

The way in which a specific estuary responds to climate change depends on the anthropogenic stressors acting on it. These stressors include those that pollute and contaminate the system, as well as those that remove or disrupt estuarine resources. Pollutants include nutrients, metals, pathogens, sediments, and organic toxicants. Extractions include uses of fresh and brackish water, sediments, and living resources within the ecosystem. Disruption of a variety of biological communities occurs through overfishing, introduction of invasive species, habitat destruction, damming, boat traffic, and shoreline conversion and stabilization activities.

Finally, there are the social, political, and economic contexts for susceptibility. Some of these contexts play out in ways already mentioned. But it is clear that stakeholder attitudes about estuaries and their perceptions about climate change are critical to wise management for climate change. Each stakeholder group, indeed each individual, uses estuaries in different ways and places different importance on specific ecosystem services. One aim of this report is to provide a common body of knowledge to stakeholders and to managers at higher levels (local, state, tribal, and federal governments) to inform their choices.

7.3.2 Current Stressors of Concern

Estuaries are generally stressful environments because of their strong and naturally variable gradients of salinity, temperature, and other parameters. However, estuaries are also essential feeding and reproduction grounds, and provide refuge for a wide variety of seasonal and permanent inhabitants. Throughout history, estuaries have been focal points of human settlement and resource use, and humans have added multiple stressors to estuarine ecosystems (Lotze *et al.*, 2006). A stressor is any physical, chemical, or biological entity that can induce an adverse response (U.S. Environmental Protection Agency, 2000). This document focuses specifically on those stressors that significantly affect the services that estuaries are managed to provide. The major stressors currently imposed on estuaries are listed in Table 7.1. Almost all current efforts to manage estuarine resources are focused on these stressors (Kennish, 1999 and the various CCMPs).

Several stressors result from modified rates of loading of naturally occurring energy and materials. Nutrient loading is perhaps the most studied and important material addition. Although essential to the primary production of any open ecosystem, too much nutrient loading can cause eutrophication, the subject of considerable concern for estuaries and the target for much management action (Nixon, 1995; Bricker *et al.*, 1999). Nutrient (especially nitrogen) loading comes from diverse point- and non-point sources, including agriculture, aquaculture, and industrial and municipal discharges, and can lead to harmful and nuisance algal blooms, loss of perennial vegetation, bottom-water hypoxia, and fish kills.

Sediment delivery has also been altered by human activities. Again, sediments are important to estuarine ecosystems as a material source for the geomorphological balance in the face of sea level rise, and for nutrients (especially phosphorus) for primary production. However, land clearing, agriculture, and urban land use can increase sediment load (Howarth, Fruci, and Sherman, 1991; Cooper and Brush, 1993; Syvitski *et al.*, 2005), while dams may greatly restrict delivery and promote deltaic erosion (Syvitski *et al.*, 2005). Historically, sediment loading has increased on average 25-fold, and nitrogen and phosphorus loading almost 10-fold, in estuaries since 1700 (Lotze *et al.*, 2006). Because riverine loading of both nutrients and sediments depends on their concentration and river flow, modifications of river flow will further alter the amount and timing of material delivery. River flow also contributes to the energy budget through mechanical energy. River flow may be a major determinant of flushing times, salinity regime, and stratification, and thus determine community structure and resource use patterns. Modifications in river flow come from dam management decisions, land development, loss of riparian wetlands, extraction of freshwater, and surface and ground water consumption. Thermal pollution, largely from power plants, is a direct enhancement of energy with resultant local changes in metabolic rates, community structure, and species interactions.

Human activities also cause or enhance the delivery of materials and organisms that are not normally part of the natural systems. Pathogen loading compromises the use of estuarine resources, causing shellfish bed closures and beach closures (*e.g.*, Health Ecological and Economic Dimensions of Global Change Program, 1998), human health advisories, and diseases to estuarine organisms themselves. Other anthropogenic contributions include the discharge and ongoing legacy of organic wastes and persistent organic pollutants (*e.g.*, DDT, dioxin, PCBs, petroleum) (Kennish, 1999). The toxicity of some of the persistent organic pollutants has been recognized for decades, dating to the publication of *Silent Spring* by Rachel Carson (1962). More recently, the potential importance of other endocrine-disrupting chemicals is causing concern (Cropper, 2005). Added to these organic pollutants are metals entering estuaries from direct dumping, riverine waters, sediments, and atmospheric deposition. Moreover, biodegradable organic wastes contribute to eutrophication and dissolved oxygen deficits (Nixon, 1995). Finally, the introduction and spread of non-indigenous species are enhanced by globalization and shipping, intentional decisions for commerce or other human use, and unintentional actions (Mooney and Hobbs, 2000). For those locations that have been surveyed, the known number of resident non-indigenous species ranges from about 60 to about 200 species per estuary in the United States (Ruiz *et al.*, 1997; Lotze *et al.*, 2006), likely the result of an increasing rate of invasions over the last 300 years (Lotze *et al.*, 2006).

Human use and development in and around estuaries alter wetland and subtidal habitats directly. Wetland destruction has occurred during much of human history as a result of the perceptions of wetlands as wastelands and the value of waterfront land. For example, 12 estuaries around the world have lost an average of more than 65% of their wetland area (with a range of 20–95%) over the last 300 years (Lotze *et al.*, 2006). Wetland habitat loss from development continues, despite changes in perceptions about wetland value and regulations intended to protect wetlands. Coastal wetlands represent a diverse assortment of hydrogeomorphic classes (Brinson, 1993; Christian *et al.*, 2000), both sea-level controlled (*e.g.*, marshes and mangroves), non-sea-level controlled (*e.g.*, swamps, fens, bogs, and pocosins) and subtidal (*e.g.*, submerged aquatic vegetation (SAV), seagrass, and macroalgal) habitats. Supratidal and intertidal wetlands are subject to land use change, dredging and filling, and changes in water quality. Subtidal habitats are particularly susceptible to not only these impacts but also activities within the water. For example, SAV loss also occurs from bottom-disturbing fishing practices and eutrophication. Oyster reef habitat destruction occurs from direct exploitation and bottom disturbance from fishing practices (*e.g.*, trawling). For 12 study sites around the world, both seagrass meadows and oyster reefs have experienced substantial losses over the last 300 years (>65% and about 80%, respectively) (Lotze *et al.*, 2006). Together with the loss of wetlands, these changes have resulted in great reductions of essential nursery habitats, important filtering functions (nutrient cycling and storage), and coastal protection (barriers and floodplains) in estuaries (Worm *et al.*, 2006; Lotze *et al.*, 2006).

Another important anthropogenic stressor in estuaries is the extraction of living and non-living material that alters estuarine ecosystem structure and functioning. Historically, estuaries provided a wide variety of resources used and valued by humans as sources of food, fur, feathers, fertilizer, and other materials (Lotze *et al.*, 2006). Since the 19th century, however, the ecological service of estuaries receiving greatest management attention has been their support of fisheries. Pollution, damming, and habitat destruction affect fisheries. Recently, more emphasis has been placed on overfishing as a negative impact, not only on target species but also on the community and food web structure (*e.g.*, Dayton, Thrush, and Coleman, 2002). Large apex predators have been greatly reduced from many, if not most, estuarine and coastal ecosystems (Lotze *et al.*, 2006). The absence of these large consumers (including marine mammals, birds, reptiles, and larger fish) translates through the food web, creating ecosystem states that are distinct from those of the past (*e.g.*, Jackson *et al.*, 2001; Lotze *et al.*, 2006; Myers *et al.*, 2007). Ongoing fishing pressure targets species lower and lower in the food chain, affecting detritivorous and herbivorous invertebrates and marine plants; consequences can include further alteration of ecosystem structure and functioning and negative effects on habitat integrity and filtering functions (Pauly *et al.*, 1998; Worm *et al.*, 2006; Lotze *et al.*, 2006). Management goals to stabilize current or restore former ecosystem states are jeopardized if large consumers are not also recovered (Jackson *et al.*, 2001).

It is rare that an estuary is subject to only one of these stressors. Management decisions must consider not only stressors acting independently but also interacting with each other (Breitburg, Seitzinger, and Sanders, 1999; Lotze *et al.*, 2006). Multiple stressors can interact and cause responses that cannot be anticipated from our understanding of each one separately. For example, Lenihan and Peterson (1998) demonstrate that habitat damage from oyster dredging and the stress of bottom-water hypoxia interact to affect oyster survival. Tall oyster reefs, both those that remain and those that have been rebuilt, project above hypoxic bottom waters and therefore allow oyster survival in the upper wind-mixed layers even as water quality further deteriorates. Unfortunately, management of fisheries and water quality is done by different agencies, inhibiting the integrated approach that such interacting stressors demand.

Interactive effects of multiple stressors are likely to be common and important because of both the interdependence of physiological rate processes within individuals and the interdependence of ecological interactions within communities and ecosystems (Breitburg and Riedel, 2005). Individual stressors fundamentally change the playing field upon which additional stressors act, by selecting for tolerant species while also changing the abundance, distribution, or interactions of predators, prey, parasites, hosts, and structural foundation species (*e.g.*, organisms such as bivalves and corals that create physical structures upon which other species depend). These direct and indirect effects can be common when stressors occur simultaneously, but they also occur from exposure to stressors in sequence. Across hierarchical levels from individuals through ecosystems, the recovery period from a particular stressor can extend beyond the period of exposure, thus influencing responses to subsequent stressors. For example, Peterson and Black (1988) demonstrated that bivalves that were already stressed from living under crowded conditions exhibited higher mortality rates after experimental application of the stress of sedimentation. Moreover, effects of stressors on indirect interactions within populations and communities can extend the spatial scale of stressor effects and delay recovery (Peterson *et al.*, 2003), increasing the potential for interactions with additional stressors.

For example, years after the Exxon Valdez oil spill, female harlequin ducks exposed to lingering oil during feeding on benthic invertebrates in contaminated sediments, and exhibiting activation of detoxification enzymes, suffered lower survivorship over winter. Winter is a period of energetic stress to these small-bodied ducks (Peterson *et al.*, 2003). On longer time scales, heritable adaptations that increase tolerance to one class of stressors may enhance susceptibility to others (Meyer and Di Giulio, 2003).

One hallmark of the NEP is the recognition that management actions need to take account of the complexity of the larger watershed and the potentially diverse socioeconomic demands and objectives within them. The NEP tracks habitat restoration and protection efforts with annual updates from the component estuaries.[7] The reality of interacting stressors has important implications for estuarine management. Specifically, because climate change affects some pre-existing stressors, and the magnitude of such interactive effects typically increases with the intensity of each stressor, more effective management of the pre-existing stressor can help reduce climate change consequences.

7.3.3 Legislative Mandates Guiding Management of Stressors

Because of the intrinsically wide range of estuarine resources and diversity of human activities that influence them, management of estuarine services is achieved via numerous legislative acts at the federal level. Many of these acts possess state counterparts, and local laws—especially land use planning and zoning—also play roles in management of estuarine services. This web of legal authorities and guiding legislation is a historical legacy, reflective of prevailing management that compartmentalized responsibilities into multiple agencies and programs.

The presentation here of applicable federal legislative acts is long, yet incomplete, and does not attempt to list state and local laws. One motivation in providing this spectrum of applicable legislation is to illustrate the challenges involved for estuaries in the integration of management authorities that is urged under the umbrella of ecosystem-based management by the U.S. Commission on Ocean Policy.

7.3.3.1 Basin-Wide Management of Water Quality

As one of the tools to meet the goal of "restoration and maintenance of the chemical, physical, and biological integrity of the Nation's waters" under §402 of the Federal Water Pollution Control Act, any entity that discharges pollutants into a navigable body of water must possess a National Pollutant Discharge Elimination System (NPDES) permit.[8] This requirement applies to public facilities such as wastewater treatment plants, public and private industrial facilities, and all other point sources. While EPA was the original administrator of the program, many states have now assumed the administrative function. All states have approved State NPDES Permit Programs except Alaska, the District of Columbia, Idaho, Massachusetts, New Hampshire, New Mexico, and the territories and trusts (American Samoa, Guam, Johnston Atoll, Midway Island, Northern Marianas,

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[7] **U.S. Environmental Protection Agency**, 2007: Performance indicators visualization and outreach tool introduction. EPA Website, www.epa.gov/owow/estuaries/habitat/index.html, accessed on 7-25-2007.

[8] 33 U.S.C. 1251-1387 § 420

Puerto Rico, the Trust Territories and Wake Island). EPA directly administers NPDES permitting in states without approved State NPDES Permit Programs. The only unapproved states with estuaries (disregarding the trusts and territories) are the District of Columbia, Massachusetts, and New Hampshire. As of 1987, NPDES permits were also required for some stormwater discharges, beginning with larger urbanized entities and recently extending to some medium-sized units of government that own or operate municipal stormwater discharge facilities.

Although the content, style, and length of any given NPDES permit for point-source discharge will be slightly different depending on where and when it is written, all permits contain certain core components mandated by the Clean Water Act, including testing, monitoring, and self reporting. NPDES permits are renewed every five years, and monitoring and/or reporting requirements may change. These changes are determined by the local Regional Water Quality Control Boards or the State Water Resources Control Board through their research and monitoring efforts.

In addition to traditional NPDES permitting for point sources, states are required by the Clean Water Act of 1972 (modified in 1977, 1981, and 1987) to manage and protect water quality on a basin-wide scale. This involves assessing the assimilative capacity of the water body for wastes of various sorts and managing loads from all sources to prevent water quality violations in any of the key water quality standards used to indicate degradation. The inputs of most concern for estuaries are nutrient loading, sedimentation, BOD, and fecal coliform bacteria. EPA has developed several technical guidance manuals to assist the states in their basin-wide planning, including those for nutrients, sediments, and biocriteria of estuarine health. When chronic water quality violations persist, then TMDLs (total maximum daily loads) are mandated by EPA and must be developed to cap loading and restore water quality. TMDLs are also now triggered by inclusion of any water body on the 304(d) list of impaired waters, which the states are obligated to provide annually to EPA. In the 2000s, EPA has expanded the scope of the NPDES program to include permits for municipal stormwater discharges, thereby bringing a traditionally non-point source of water pollution under the NPDES permitting program. Non-point sources must also be considered in any basin-wide plans, including establishment of TMDLs and allocation of loads among constituent sources to achieve the necessary loading caps. Climate change has great potential to influence the success of basin-wide water quality management and the effectiveness of TMDLs through possible changes in rainfall amounts and patterns, flooding effects, stratification of waters, salt penetration and intrusion, and acidification.

7.3.3.2 Habitat Conservation under Federal (Essential Fish Habitat) and State Fishery Management Plans

As administered under NOAA, the Magnuson Fishery Conservation and Management Act of 1976 (amended as the Sustainable Fisheries Act (SFA) in 1996[9] and reauthorized as Magnuson-Stevens Fishery Conservation and Management Reauthorization Act

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[9] P.L. 94-265

(MSA) of 2006[10] established eight regional fishery management councils that are responsible for managing fishery resources within the federal 200-mile zone bordering coastal states. Management is implemented through the establishment and regulation of Fishery Management Plans (FMPs). In addition to "conservation and management of the fishery resources of the United States…to prevent overfishing, rebuild overfished stocks and insure conservation," the Act also mandates the facilitation of long-term protection of *essential fish habitats*, which are defined as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." The Act states "One of the greatest long-term threats to the viability of commercial and recreational fisheries is the continuing loss of marine, estuarine, and other aquatic habitats." It emphasizes that habitat considerations "should receive increased attention for the conservation and management of fishery resources of the United States" and "to promote the protection of essential fish habitat in the review of projects conducted under Federal permits, licenses, or other authorities that affect or have the potential to affect such habitat."

FMPs prepared by the councils (or by the Secretary of Commerce/NOAA) must describe and identify essential fish habitat to minimize adverse effects on such habitat caused by fishing. In addition, they must identify other actions to encourage the conservation and enhancement of essential fish habitat, and include management measures in the plan to conserve habitats, "considering the variety of ecological factors affecting fishery populations."[2]

Because managed species use a variety of estuarine/coastal habitats throughout their life histories, few are considered to be "dependent" on a single, specific habitat type (except, for example, larger juvenile and adult snappers and groupers on ocean hard bottoms) or region. As a result, federal FMPs do not comprehensively cover species' habitats that are not specifically targeted within their region. In addition, the only estuarine-dependent fish stocks under federal management authority are migratory stocks, such as red drum and shrimp, so estuarine habitats are not a key focus for essential fish habitat. However, many states also have FMPs in place or in preparation for target fisheries under their jurisdiction (the non-migratory inshore species) and participate with the regional councils under the SFA/MSA.

Thus, threats to marshes and other estuarine systems that constitute essential fish habitat or state-protected fisheries habitat should include all potential stressors, whether natural or anthropogenic, such as climate change and sea level rise. Although essential fish habitats have been codified for many fisheries, and science and management studies have focused on the status and trends of fisheries-habitat interactions, most management consideration has targeted stresses caused by different types of fishing gear. Because few fisheries take place in emergent marshes, the essential fish habitat efforts have not provided much protection to this important habitat. Seagrass and oyster reef habitats have been targeted for additional management concern because of the federal essential fish habitat provisions. State protections of fishery habitat vary, but generally include salt marsh and other habitats. Nearly two decades ago, EPA projected extensive loss of coastal marshes and wetlands from sea level rise by 2100, with an elimination of 6,441

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[10] P.L. 109-479

square miles (65%) of marshes in the continental United States associated with a probable rise of 1m (Park *et al.*, 1989).

7.3.3.3 Estuarine Ecosystem Restoration Programs

While comprehensive planning of coastal restoration is inconsistent at the national level, a number of national, regional, and local programs are coordinated to the extent that stressors are either the target of restoration or addressed as constraints to restoration. These programs tend to be oriented toward rehabilitation of injuries done by individual stressors, such as eutrophication or contaminants, or toward restoration of ecosystems that have not been so extensively modified that their loss or degradation is not irreversible. Federal programs that authorize restoration of estuaries include:

Estuary Restoration Act of 2000 (P.L. 106-457, Title I)

Probably the most prominent federal program that involves non-regulatory restoration in the nation's estuaries is the Estuary Restoration Act of 2000 (ERA). The ERA promotes estuarine habitat restoration through coordinating federal and non-federal restoration activities and more efficient financing of restoration projects. It authorizes a program under which the Secretary of the Army, through the Corps of Engineers (USACE), may carry out projects and provide technical assistance to meet the restoration goal. The purpose of the Act is to promote the restoration of estuarine habitat; to develop a national Estuary Habitat Restoration Strategy for creating and maintaining effective partnerships within the federal government and with the private sector; to provide federal assistance for and promote efficient financing of estuary habitat restoration projects; and to develop and enhance monitoring, data sharing, and research capabilities. Guidance provided by an Estuary Habitat Restoration Council, consisting of representatives of NOAA, EPA, USFWS, and USACE, includes soliciting, evaluating, reviewing, and recommending project proposals for funding; developing the national strategy; reviewing the effectiveness of the strategy; and providing advice on development of databases, monitoring standards, and reports required under the Act. The Interagency Council implementing the ERA published a strategy in December of 2002 with the goal of restoring one million acres of estuarine habitat by the year 2010. Progress toward the goal is being tracked via NOAA's National Estuaries Restoration Inventory.

Although the guiding principles that contributed to the development of this legislation argued for the "need to learn more about the effects of sea level rise, sedimentation, and a host of other variables to help set appropriate goals and success indicators for restoration projects in their dynamic natural environments," climate change is not explicitly addressed in the ERA. Similarly, the Council's Estuarine Habitat Restoration Strategy, published in 2002, neglects to explicitly mention climate change or sea level rise.

National Estuary Program and National Monitoring Program (EPA)

The National Estuary Program (NEP), administered under Section 320 of the 1987 amended Clean Water Act, focuses on point- and non-point source pollution in targeted, high-priority estuarine waters. Under the NEP, EPA assists state, regional, and local governments, landowners, and community organizations in developing a Comprehensive Conservation and Management Plan (CCMP) for each estuary. The CCMP characterizes the resources in the watershed and estuary and identifies specific actions to restore water quality, habitats, and other designated beneficial uses. Each of the 28 national estuaries has developed a CCMP to meet the goals of Section 320. Because the primary goal of the NEP is maintenance or restoration of water quality in estuaries, the CCMPs tend to focus on source control or treatment of pollution. NEP tracks estuarine habitat restoration and protection, with annual updates using information provided by the constituent national estuaries.[7] While climate change is not considered a direct stressor, it is gradually being addressed in individual CCMPs in the context of potential increased nutrient loading from watersheds under future increased precipitation. For instance, the Hudson River Estuary Program has initiated with other partners an ongoing dialogue about how climate change constitutes a future stressor of concern to the estuary and its communities.[11] The Puget Sound and Sarasota Bay Estuary Programs have been the most proactive relative to anticipating a range of climate change challenges, although their assessments have been completed only recently.

7.3.3.4 National Coastal Zone Management Act and its Authorized State Programs

The federal Coastal Zone Management Act of 1972 (CZMA) provides grants to states to develop and implement federally approved coastal zone management plans. Approval of the state plan then allows that state to participate in reviews of federal actions and determine whether they are consistent with the approved state plan. In addition, CZMA authorized establishment of the National Estuarine Research Reserve System (NERRS). Individual states have responded by creating various governmental structures, legislation, commissions, and processes for developing and implementing the coastal planning process. Planning extends down to the local level as local communities take responsibility for local Land Use Plans, which are then reviewed for approval by the state authority. Thus, this process has substantial capacity for responding to and adapting to climate change. CZMA explicitly identifies planning for climate change as one of its mandates: "Because global warming may result in a substantial sea level rise with serious adverse effects in the coastal zone, coastal states must anticipate and plan for such an occurrence."[12] The act calls for balancing of the many uses of the coastal zone with protection of natural resources.

The Coastal States Organization, an organization established in 1970 to represent the governors of the 35 coastal states, commonwealths, and territories on policy issues related to management of coastal and ocean resources, released a recent report reviewing how the states are using their Coastal Program under the CZMA to anticipate climate change and practice adaptive management.[13] This report identifies the very same suite of climate change impacts that we emphasize and address here. The report used surveys, to which 18 state programs responded, to develop information on how the state Coastal Management Programs are currently addressing climate change and the new challenges

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[11] **New York State Department of Environmental Conservation**, 2006: Hudson Valley climate change conference, December 4, 2006. New York State Department of Environmental Conservation, http://www.dec.state.ny.us/website/hudson/hvcc.html, accessed on 3-23-2007.

[12] 16 U.S.C. 1451-1456 P.L. 92-583

[13] **CSO Climate Change Work Group**, 2007: *The Role of Coastal Zone Management Programs in Adaptation to Climate Change*. Coastal States Organization.

posed by accelerating rates of sea level rise, enhanced frequencies of intense storms, and rainfall and flood risk changes.[13] Several states are actively examining climate change impacts to their coastal zone planning, often through interagency commissions. New policies are being considered and developed in response to rising rates of sea level rise and enhanced storm and flood risk to reconsider siting of public infrastructure, site-level project planning, wetland conservation and restoration, shoreline building setbacks, building elevations, and alternatives to shoreline "armoring" to counteract erosion.

The NOAA NERRS Program authorized by CZMA now includes 27 constituent estuaries from around the country. This program uses a local grassroots process to help monitor and create public awareness of the resources, threats, and values of constituent estuaries. Clearly, the goals of NERRS are compatible with the goals of the National Estuary Program and CZMA, implying need for cross-agency and federal-state partnerships to develop integrated management adaptations to climate change.

7.3.3.5 State Sedimentation and Erosion Control, Shoreline Buffers, and Other Shoreline Management Programs Involving Public Trust Management of Tidelands and Submerged Lands

Protection from shoreline erosion has a long legal history, as far back as the tenets of property law established under the court of Roman Emperor Justinian.[14] In general, property law protection of tidelands held in public trust (most of the U.S. coastline) is conveyed either as the *law of erosion* (public ownership migrates inland when shores erode) or the *public trust doctrine* (the state holds tidelands in trust for the people unless it decides otherwise). Shoreline planners in many states (*e.g.*, Texas, Rhode Island, South Carolina, and Massachusetts) use these laws to plan for natural shoreline dynamics, including policies and tools such as "rolling easements" (*i.e.*, as the sea rises, the public's easement "rolls" inland; owners are obligated to remove structures if and when they are threatened by an advancing shoreline), setbacks (*i.e.*, prohibitions against development of certain areas at a set distance from the shoreward property line), prohibition of future shoreline armoring, and direct purchase of land that will allow wetlands or beaches to shift naturally (IPCC, 2001).[14] Some states are beginning to prohibit new structures in areas likely to be eroded in the next 30–60 years (*e.g.*, North Carolina through its Coastal Resources Commission).

7.3.3.6 Species Recovery under Federal Endangered Species Act

Recovery plans for aquatic species that are threatened or endangered under the Endangered Species Act (ESA)[15] may be contingent on implicit assumptions about habitat conditions in the coastal zone. However, explicit accounting for impacts and strategic designing of recovery efforts to consider climate variability and change is rare. A recent analysis of current ESA recovery plans indicates that of 101 plans that mention climate change, global warming, or related terms, only 60 actually discuss these topics, and only 47 identify climate change or its effects as a threat, possible threat, or factor in

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[14] **Spyres**, J., 1999: Rising tide: global warming accelerates coastal erosion. Erosion Control, http://www.forester.net/ec_9909_rising_tide.html, accessed on 3-22-2007.

[15] 16 U.S.C. 1531-1544, 87 Stat. 884

the species' decline.[16] Strategies and approaches that specifically address climate include monitoring for metapopulation variability that could link climate variation to extinction/recolonization probabilities or to unpredictable changes in existing or proposed future habitat. For example, the NOAA recovery plan for the Hawaiian monk seal (*Monachus schauinslandi*) suggests that habitat loss that has already been observed could be exacerbated by "…sea level rise over the longer term [that] may threaten a large portion of the resting and pupping habitat…" (National Marine Fisheries Service, 2006).

Climate variability and change will undoubtedly involve an even more consequential response by diadromous fishes and macroinvertebrates that require extensive, high-quality juvenile or adult transitional habitats during migrations between ocean and estuarine or freshwater aquatic systems. For example, in the Pacific Northwest and Alaska, sea level rise and shifts in timing and magnitude of snowmelt-derived riverine runoff may be particularly exacerbated by climate variability and change. Consequently, the recovery plans for threatened or endangered Pacific salmon (*e.g.,* juvenile, "ocean-type" Chinook [*Oncorhynchus tshawytscha*] and summer chum [*O. keta*] salmon) may need to account for their extreme sensitivity to climate-induced changes in environmental conditions of their estuarine wetland habitats during different life stages of the fish.

7.3.3.7 Wetland Protection Rules Requiring Avoidance, Minimization, and Mitigation for Unavoidable Impacts

Federal jurisdiction of waters of the United States began in 1899 with the Rivers and Harbors Act of 1899, and wetlands were included in that definition with the passing of the Clean Water Act of 1977 (CWA). This jurisdiction does not extend beyond the wetland/upland boundary. However, many state environmental laws, such as those of New York[17] and New Jersey, require permits for alterations in adjacent upland areas in addition to protecting the wetland itself. While not originally intended for the purpose of increasing climate change preparedness, many of these regulations could facilitate adaptation to sea level rise (Tartig *et al.*, 2000).

The U.S. Army Corps of Engineers regulates dredging, the discharge of dredged or fill material, and construction of structures in waterways and wetlands through Section 404 of the CWA,[18] the provisions of which have been amended progressively through 1987. Although not explicitly required within the language of the amended law, the CWA provides the Corps with the implicit authority to require that dredge or fill activities avoid or minimize wetland impacts (Committee on Mitigating Wetland Losses, National Research Council, 2001). The Corps and EPA developed criteria (Section 404(b)(1) guidelines) that over the years (latest, 1980) have defined mitigation as both minimization of wetland impacts and compensation for wetland losses. Thus, mitigation has been loosely interpreted to include a range of actions from wetland restoration and enhancement to creation of wetlands where they have never occurred. However, a 1990 memorandum of agreement between the Corps and EPA established that mitigation must

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[16] **Jimerfield**, S., M. Waage, and W. Snape, 2007: Global Warming Threats and Conservation Actions in Endangered Species Recovery Plans: a Preliminary Analysis. Center for Biological Diversity.

[17] **New York State**, 1992: Tidal wetlands - land use regulations. **6 NYCRR Part 661**.

[18] Codified generally as 33 U.S.C. §1251; 1977.

be applied sequentially. In other words, an applicant must first avoid wetland impacts to the extent practicable, then minimize unavoidable impacts, and finally—only after these two options are reasonably rejected—compensate for any remaining impacts through restoration, enhancement, creation, or in exceptional cases, preservation (Committee on Mitigating Wetland Losses, National Research Council, 2001). The Corps now grants permits for shoreline development that include armoring of the present shoreline, which guarantees future loss of wetlands as sea level rises, thereby violating the requirement for mitigation in the application of this authority (Titus, 2000).

7.3.3.8 Compensatory Restoration Requirements for Habitat and Natural Resource Injuries from Oil Spills or Discharges of Pollutants

Federal legislation requires compensatory restoration of estuarine habitats and natural resources after environmental incidents such as spills of oil or other toxicants (*e.g.*, Fonseca, Julius, and Kenworthy, 2000). For example, the Oil Pollution Act of 1990 specifies the procedures that federal agencies are required to follow to assess injury from pollution events and to conduct quantitatively matching restoration actions so the responsible parties replace the lost ecosystem services. Similar federal legislation, such as the Comprehensive Environmental Response, Compensation, and Liability Act, also specifies formation of natural resource trustees composed equally of state and federal agencies to oversee the injury assessments, pursue funding from the responsible party(ies) sufficient to achieve restoration, and then design and implement the restoration. The process of restoration typically involves rehabilitation of biogenic habitats such as salt marshes, seagrass beds, or oyster reefs. The modeling done to insure that the restoration will provide ecosystem services equal to the injuries may need to be modified to reflect impacts of climate change, because services from habitat restorations are assumed to extend for years and even decades in these computations.

7.3.3.9 Federal Legislation Controlling Location of Ballast Water Release to Limit Introduction of Non-Indigenous Marine and Estuarine Species

One of the more troubling implications of climate change for estuaries is the probability of expanded distributions of non-indigenous species with the potential of progressively warmer waters in temperate zones. Ballast water discharged from ships in harbors after transiting from foreign ports (and domestic estuaries with extensive species invasions, such as San Francisco Bay) is one of the major sources of aquatic nuisance species. The primary federal legislation regulating ballast water discharge of invasive species is the National Invasive Species Act of 1996, which required the Coast Guard to establish national voluntary ballast water management guidelines. Because of a lack of compliance under the initial nationwide self-policing program that began in 1998, the voluntary program became mandatory in 2004. All vessels equipped with ballast water tanks that enter or operate within U.S. waters must now adhere to a national mandatory ballast water management program and maintain a ballast water management plan. Ballast water discharge may fall under the scope of the Clean Water Act, which adjudication may resolve.

7.3.3.10 Flood Zone Regulations

Tidal flood surge plains will likely be the estuarine regions most susceptible to climate change forcings, with consequent effects on human infrastructure, especially as development pressures continue to increase along the nation's coastal zone. Before the more recent projections of (higher) sea level rise rates, the Federal Emergency Management Agency (Federal Emergency Management Agency, 1991) estimated that existing development in the U.S. Coastal Zone would experience a 36%–58% increase in annual damages for a 0.3-meter rise in sea level, and a 102%–200% percent increase for a 1-meter rise. While state and local governments regulate building and other human activities in existing flood hazard zones, FEMA provides planning assistance by designating Special Flood Hazard Areas and establishing federal flood insurance rates according to the risk level.

7.3.3.11 Native American Treaty Rights

More than 565 federally recognized governments of American Indian and other indigenous peoples of Alaska, Hawaii, and the Pacific and Caribbean islands carry unique status as "domestic dependent nations" through treaties, Executive Orders, tribal legislation, acts of Congress, and decisions of the federal courts (National Assessment Synthesis Team, 2000). While climate variability and change are likely to impinge on all of these tribal entities, the impacts will perhaps be most strongly felt on the large coastal Native reservations, which are integrally linked to tourism, human health, rights to water and other natural resources, subsistence economies, and cultural resources. While these Native peoples have persisted through thousands of years of changes in their local environment, including minor ice ages, externally driven climate change will likely be more disruptive of their long, intimate association with their environments. In some cases, climatic changes are already affecting Natives such as those in Alaska who are experiencing melting of permafrost and the dissolution of marginal sea ice, altering their traditional subsistence-based economies and culture.

Where climate variability and change intersect with resource management of shared natural resources, Natives' treaty status may provide them with additional responsibility and influence. For example, on the basis of the "Boldt II decision," treaty tribes in Washington State have treaty-based environmental rights that make them legal participants in natural resource and environmental decision making, including salmon and shellfish habitat protection and restoration (Brown, 1993; 1994).

7.3.4 Sensitivity of Management Goals to Climate Change

7.3.4.1 Climate Change and Changing Stressors of Estuarine Ecosystems

Many estuarine properties are expected to be altered by climate change. Global-scale modeling has rarely focused on explicit predictions for estuaries because realistic estuarine modeling would require very high spatial and temporal resolution. It is, however, reasonable to assume that estuaries will be affected by the same climate forcing that affects the coastal and marginal oceans. With increases in atmospheric CO_2, models project increases in oceanic temperature and stratification, decreases in convective overturning, decreases in salinity in mid- and high latitudes, longer growing seasons in mid- and high latitudes, and increases in cloud cover (Table 7.2). Such changes will necessarily force significant alterations in the physics, chemistry, and biology of estuaries. In particular, climate change may have significant impacts on those factors that are included in the definition of an estuary (Box 7.2). For example, climate-driven alterations to geomorphology will affect every physical, chemical, biological, and social function of estuaries.

The 2007 report of the Intergovernmental Panel on Climate Change (IPCC, 2007) summarizes the results of multiple credible models of climate change, providing various ranges of estimated change by year 2100. Whereas these projections carry varying degrees of uncertainty, and in some cases fail to include processes of likely significance in the modeling due to high scientific uncertainty, these projections of rates of change over the next century help ground our scenario building for consequences of climate change on estuarine dynamics and on ability to attain management goals. The best estimates of average global temperature rise in the surface atmosphere vary from a low scenario of 1.1–2.9°C and a high scenario of 2.4–6.4°C by 2100. Scenarios of sea level rise range from a low projection of 0.18–0.38 meters to a high projection of 0.26–0.59 meters by 2100. The modeled sea level does not, however, include enhanced contributions from shifts of the Greenland and Antarctic ice shelves and could therefore be a serious underestimate. The future temperatures projected for Greenland reach levels inferred to have existed in the last interglacial period 125,000 years ago, when paleoclimate information suggests reductions of polar ice extent and a 4–6-meter rise in sea level. The IPCC projects growing acidification of the ocean, with reductions in pH of between 0.14 and 0.35 units over the next century. In our report, so as to standardize our framework for climate change across responses, we discuss a short term of two to three decades, and also project the consequences of a 1-meter rise in sea level. This increase may not occur within the next century, but if ice sheet shifts add to the present rate of sea level rise, a 1-meter increase may occur sooner than the IPCC projects.

Climate change may also modify existing stressors (described in Section 7.2.2) and create new ones not discussed above. For example, the nutrient, sediment, pathogen, and contaminant stressors usually carried downstream with freshwater runoff will change in proportion to that runoff. If runoff increases, it can be expected to deliver more deleterious material to estuaries, leading to increased eutrophication via nutrients, smothering of benthic fauna via sediment loading, decreased photosynthesis via sediment turbidity, decreased health and reproductive success via a wide spectrum of toxins, and increased disease via pathogens. In contrast, “novel” stressors created by climate change include increased temperatures, shifts in the timing of seasonal warming and cooling, and the acidification caused by increased CO_2 (Box 7.3). The most important emerging and enhanced stressors related to climate change have largely negative consequences for the ecosystem services and management goals of the Nation’s estuaries (Table 7.3).

Importantly, there are likely to be interactions among existing and novel stressors, between those factors that define estuaries and stressors, and between stressors and existing management strategies. As noted above (Section 7.2.2), interactions among the multiple stressors related to climate change are likely to pose considerable challenges. Nonetheless, it is important for successful natural resource management and conservation that managers, researchers, and policy makers consider the myriad stressors to which natural systems are exposed. Importantly, interactions among multiple stressors can change not only the magnitude of stressor effects, but also the patterns of variability and predictability on which management strategies rely (Breitburg *et al.*, 1998; Breitburg *et al.*, 1999; Vinebrooke *et al.*, 2004; Worm *et al.*, 2006). Enhancing ecosystem resilience by establishing better controls on current stressors would limit the strength of interactions with climate change.

7.3.4.2 Impacts to and Responses of the Ecosystem

7.3.4.2.1 Temperature Effects on Species Distributions

Because species distributions are determined in part by physiological tolerances of climatic extremes, ecologists expect that species will respond to climate warming by shifting distributions towards the poles—so long as dispersal and resources allow such shifts (Walther *et al.*, 2002). In fact, a wide array of species is already responding to climate warming worldwide (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003; Parmesan and Galbraith, 2004; Parmesan, 2006). Global meta-analyses of 99 species of birds, butterflies, and alpine herbs demonstrate that terrestrial species are migrating poleward at a rate of 6.1 km per decade (Parmesan and Yohe, 2003). Moreover, 81% of 920 species from a variety of habitats showed distributional changes consistent with recent climate warming (Parmesan and Yohe, 2003). In marine systems, warm water species of zooplankton, intertidal invertebrates, and fish have migrated into areas previously too “cool” to support growth (Barry *et al.*, 1995; Southward, Hawkins, and Burrows, 1995; Walther *et al.*, 2002; Southward *et al.*, 2004). Some copepod species have shifted hundreds to 1,000 kilometers northward (Beaugrand *et al.*, 2002), and the range of the oyster parasite *Perkinsus marinus* expands in warm years and contracts in response to cold winters (Mydlarz, Jones, and Harvell, 2006). Its range expanded 500 kilometers from Chesapeake Bay to Maine during one year—1991—in response to above-average winter temperatures (Ford, 1996) .

It is important to keep in mind that each species responds individualistically to warming: ecological communities do not move poleward as a unit (Parmesan and Yohe, 2003; Parmesan, 2006). This pattern was first demonstrated by paleoecological studies tracking the poleward expansions of individual species of plants following Pleistocene glaciation (*e.g.*, Davis, 1983; Guenette, Lauck, and Clark, 1998) and has since been extended to animals in phylogeographic studies (*e.g.*, Turgeon *et al.*, 2005). Climate warming is therefore likely to create new mixes of foundation species, predators, prey, and competitors. For example, “invading” species may move poleward faster than “resident” species retreat, potentially creating short-term increases in species richness (Walther *et al.*, 2002). Competitive, plant-herbivore, predator-prey, and parasite-host interactions can be disrupted by shifts in the distribution, abundance, or phenology of one or more of the interacting species (Walther *et al.*, 2002; Parmesan, 2006). Not surprisingly, therefore, it is difficult, if not impossible, to predict how community dynamics and ecosystem functioning will change in response to species shifts (Walther *et al.*, 2002).

Evidence from studies that have monitored changes in marine biota over the last three decades has shown that in coastal waters, the response of annual temperature cycles to climate change is both seasonally and regionally asymmetric. Along the mid-Atlantic East Coast, maximal summer temperatures are close to 30°C. When greenhouse gas forcing provides more heat to the surface waters in summer, they do not get warmer; instead the additional heat increases evaporation and is transferred to the atmosphere as a latent heat flux. Consequently maximum summer temperatures have not changed in the mid-Atlantic regions, but the minimum winter temperatures are now dramatically higher, by as much as 1–6°C (Parker Jr. and Dixon, 1998). In the reef fish community off North Carolina, the reduction over 30 years in winter kill during the coldest months made it possible for two new (to the area) families and 29 new species of tropical fishes to become permanent residents on the reef (Parker Jr. and Dixon, 1998). In addition, the 28 species of tropical reef fishes that have been present on the site for the entire three decades increased in abundance. An increase in fish-cleaning symbiosis was especially noticeable. Over the 30-year study period, no new temperate species became permanent residents and, while no temperate species dropped out of the community, the temperate species that was most abundant at the start of the study decreased in abundance by a factor of 22. This kind of seasonal asymmetry in temperature change expands the range of tropical species to the north, but so far has not changed the southern limit of temperate species—although it has reduced the biomass of temperate species that were previously abundant.

On the West Coast, changes in the species composition of a rocky intertidal community showed that between the 1930s and 1990s most species' ranges shifted poleward (Barry *et al.*, 1995). The abundance of eight of nine southern species increased and the abundance of five of eight northern species decreased. Annual mean ocean temperatures at the central California coastal site increased by 0.75°C during the past 60 years, but more importantly the monthly mean maximum temperatures during the warmest month of year were 2.2°C warmer. On the West Coast, summer conditions are relatively cool and foggy due to strong coastal upwelling that produces water temperatures from 15–20°C. For intertidal organisms adapted to these relatively cool summer temperatures, a 2°C increase in monthly mean temperature during the warmest month of the year was enough to decrease survival of northern species and increase the survival of southern species. It is clear that climate change has already altered the species composition and abundance of marine fauna, but is equally clear that the physical and biological response of organisms to warming in marine waters is extremely complex.

These effects of temperature on species distributions have influenced and will continue to influence fish and wildlife populations, and will modify habitat provided by organisms such as mangroves, requiring many site-specific adaptive modifications in management.

7.3.4.2.2 Temperature Effects on Risks of Disease and Parasitism

Not only will species' distributions change, but scientists expect that higher temperatures are likely to lead to increased risks of parasitism and disease, due to changes in parasites and pathogens as well as host responses (Harvell *et al.*, 2002; Hakalahti, Karvonen, and Valtonen, 2006). For example, temperature has the potential to alter parasite survival and development rates (Harvell *et al.*, 2002), geographic ranges (Harvell *et al.*, 2002; Poulin, 2005; Parmesan, 2006), transmission among hosts (Harvell *et al.*, 2002; Poulin, 2005), and local abundances (Poulin, 2005). In particular, shortened or less-severe winters are expected to increase potential parasite population growth rates (Hakalahti, Karvonen, and Valtonen, 2006). On the host side, higher temperatures can alter host susceptibility (Harvell *et al.*, 2002) by compromising physiological functioning and host immunity (Mydlarz, Jones, and Harvell, 2006). Animals engaged in partnerships with obligate algal symbionts, such as anemones, sponges, and corals, are at particular risk for problems if temperatures alter the relationship between partners (Mydlarz, Jones, and Harvell, 2006).

Reports of marine diseases in corals, turtles, mollusks, marine mammals, and echinoderms have increased sharply over the past three decades, especially in the Caribbean (Harvell *et al.*, 2002; Ward and Lafferty, 2004). For example, temperature-dependent growth of opportunistic microbes has been documented in corals (Ritchie, 2006). Poulin and Mouritsen (2006) documented a striking increase in cercarial production by trematodes in response to increased temperature, with potentially large effects on the intertidal community (Poulin and Mouritsen, 2006). Geographic range expansion of pathogens with broad host ranges is of particular concern because of the potential to affect a broad array of host species (Dobson and Foufopoulos, 2001; Lafferty and Gerber, 2002).

Importantly, however, we cannot predict the effects of climate change on disease and parasitism based solely on temperature (Lafferty, Porter, and Ford, 2004). Temperature is likely to interact with a variety of other stressors to affect parasitism and disease rates (Lafferty, Porter, and Ford, 2004), including excess nutrients (Harvell *et al.*, 2004), chemical pollutants such as metals and organochlorines (Harvell *et al.*, 2004; Mydlarz, Jones, and Harvell, 2006), and hypoxia (Mydlarz, Jones, and Harvell, 2006). For example, the 2002 die-off of corals and sponges in Florida Bay co-occurred with a red tide (*Karenia brevis)* driven by high nutrient conditions (Harvell *et al.*, 2004). Moreover, not all parasites will respond positively to increased temperature; some may decline (Harvell *et al.*, 2002; Roy, Guesewell, and Harte, 2004) and others may be kept in check by other factors (Harvell *et al.*, 2002; Hall *et al.*, 2006). This suggests that generalizations may not always be possible; idiosyncratic species responses may require that we consider effects on a species-by-species, or place-by-place basis, as with the species distributions discussed earlier.

Such changes in risk of parasitism and disease will influence populations of fish and wildlife, and can affect habitat that is provided by organisms like corals, thereby affecting management.

7.3.4.2.3 Effects of Shoreline Stabilization on Estuaries and their Services

Estuarine shorelines along much of the U.S. coast have been affected by human activities. These activities have exacerbated both water- and land-based stressors on the estuarine land-water interface. Real and perceived threats from global sea level rise, increased intensity of tropical storms, waves from boat wakes, and changes in delivery of and erosion by stream flows have contributed to greater numbers of actions taken to stabilize estuarine shorelines using a variety of techniques. Shoreline stabilization can affect the physical (bathymetry, wave environment, light regime, sediment dynamics) and ecological (habitat, primary production, food web support, filtration capacity) attributes of the land-water interface in estuaries. Collectively, these physical and ecological attributes determine the degree to which ecosystem services are delivered by these systems (Levin *et al.*, 2001). Shoreline stabilization on the estuarine shoreline has only recently begun to receive significant attention (Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2006).

Surprisingly little is known about the effects of estuarine shoreline stabilization structures on adjacent habitats (Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2006). Marsh communities at similar elevations with and without bulkheads behind them were found to be indistinguishable in a study in Great Bay Estuary in New Hampshire (Bozek and Burdick, 2005). However, this study also reported that bulkheads eliminated the up-slope vegetative transition zone. This loss is relevant for both current function of the marsh and also future ability of the marsh to respond to rising sea level. In several systems within Chesapeake Bay, Seitz and colleagues (2006) identified a link between the hardening of estuarine shorelines with bulkheads or rip-rap and the presence of infaunal prey and predators. This study illustrated the indirect effects that can result from shoreline stabilization, and found them to be on par with some of the obvious direct effects. Loss of ecological function in the estuarine land-water margin as a result of shoreline stabilization is a critical concern. However, the complete loss of the structured habitats (SAV, salt marsh) seaward of shoreline stabilization structures as sea level rises is a more dire threat. In addition, the intertidal sand and mud flats, which provide important foraging grounds for shorebirds and nektonic fishes and crustaceans, will be readily eliminated as sea level rises and bulkheads and other engineered shoreline stabilization structures prevent the landward migration of the shoreline habitats. Absent the ability to migrate landward, even habitats such as marshes, which can induce accretion by organic production and sediment trapping, appear to have reduced opportunity to sustain themselves as water level rises (Titus, 1998).

These effects of shoreline stabilization interacting with sea level rise will influence salt marsh and other intertidal and shallow-water estuarine habitats, with consequences for water quality, fish and wildlife production, and human values, inducing need for management adaptation.

7.3.4.2.4 Effects of Climate Change on Marsh Trapping of Sediments and Geomorphologic Resiliency

Coastal wetlands have been relatively sustained, and even expanded, under historic eustatic sea level rise. Marsh surfaces naturally subside due to soil compaction, other geologic (subsidence) processes, and anthropogenic extraction of fluids such as groundwater and oil. However, marsh surfaces (marsh plain) also build vertically due to the combined effect of surface sediment deposition and subsurface accumulation of live and dead plant roots and decaying plant roots and rhizomes. Both of these processes are controlled by tidal-fluvial hydrology that controls delivery of sediments, nutrients, and organic matter to the marsh, as well as the oxygen content of the soil. Local landscape setting (wave energy) and disturbance regime (storm frequency and intensity) are also factors over the long term. Thus, the relative sea level (the simultaneous effect of eustatic sea level rise and local marsh subsidence) can be relatively stable under a moderate rate of sea level rise, because marsh elevation increases at the same rate as the sea level is rising (*e.g.*, Reed, 1995; Callaway, Nyman, and DeLaune, 1996; Morris *et al.*, 2002). Whether a marsh can maintain this equilibrium with mean sea level and sustain characteristic vegetation and associated attributes and functions is uncertain. It will depend on the interaction of complex factors, including sediment pore space, mineral matter deposition, initial elevation, rate of sea level rise, delivery rates of sediments in stream and tidal flows, and the production rate of below-ground organic matter (U.S. Climate Change Science Program, in press).

Thus, changes in sediment and nutrient delivery and eustatic sea level rise are likely to be the key factors affecting geomorphic resiliency of coastal wetlands. Sediment delivery may be the critical factor: estuaries and coastal zones that currently have high rates of sediment loading, such as those on the southeast and northwest coasts, may be able to persist up to thresholds of 1.2 cm per year that are optimal for marsh primary production (Morris *et al.*, 2002). If sea level rise exceeds that rate, then marsh surface elevation decreases below the optimum for primary production. Increased precipitation and storm intensities commensurate with many future climate scenarios (*e.g.*, in the Pacific Northwest) would likely increase sediment delivery, but also would erode sediments where flows are intensified. The large-scale responses to changes in sediment delivery to estuarine and coastal marshes have not been effectively addressed by most hydrodynamic models incorporating sediment transport. SAP 4.1 elucidates potential impacts by providing maps depicting the wetland losses in the mid-Atlantic states that are anticipated under various rates of sea level rise (U.S. Climate Change Science Program, in press). Such changes in sediment and nutrient delivery to the estuary will threaten the geomorphologic resilience of salt marsh habitat, thereby altering water quality and fish and wildlife production; these changes imply the need for management adaptation.

7.3.4.2.5 Effects of Sea Level Rise and Storm Disturbance on Coastal Barrier Deconstruction

Two important consequences of climate change are accelerated sea level rise and increased frequency of high-intensity storms. Sea level rise and intense storms work alone and in combination to alter the hydrogeomorphology of coastal ecosystems and their resultant services. Furthermore, the extent to which they act on ecosystems is dependent on human alterations to these ecosystems. Perhaps the best known example of the current interaction of sea level rise, storm intensity, and human activity is the coast of the Gulf of Mexico around the Mississippi River. Relative sea level rise of the Louisiana coast is one of the highest in the world, in large part as a result of human activities, and this has caused significant losses of wetlands (Boesch *et al.*, 1994; González and Törnqvist, 2006; Day, Jr. *et al.*, 2007). The consequences of intense storms (*e.g.*, Hurricanes Katrina and Rita) on coastal ecosystems of the Gulf of Mexico, human-dominated and natural, are now legend (Kates *et al.*, 2006). New Orleans and other cities were devastated by these storms. Wetland loss was dramatic, with sharp alterations to community structure (Turner *et al.*, 2006).[19] Barrier islands were eroded, overwashed,

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[19] **U.S. Geological Survey**, 2007: Hurricanes Katrina and Rita. USGS, http://www.nwrc.usgs.gov/hurricane/katrina.htm, accessed on 3-23-2007.

and breached, with severe impacts to both human lives and infrastructure. The impacts of these storms are linked to the damaged conditions and decreased area of the wetlands and their historical loss (Day, Jr. *et al.*, 2007). Reconstruction of New Orleans and other affected cities has begun, and plans are being offered for the replenishment and protection of wetlands and barrier islands (U.S. Army Corps of Engineers, in press; Day, Jr. *et al.*, 2007; Coastal Protection and Restoration Authority of Louisiana, 2007).

Although the impacts of the hurricanes of 2005 and the influence of relative sea level rise on their impacts were the most costly to the United States, they are not the only examples of how storms and sea level rise influence hydrogeomorphology. Sea level rise and erosion, fostered by storms, have caused estuarine islands to disappear and led to significant changes in shorelines (Hayden *et al.*, 1995; Riggs and Ames, 2003). Barrier island shape and position are dynamic, dependent on these two processes. These processes are natural and have occurred throughout the Holocene; what is relatively new are the ways in which human values are in conflict with these processes and how humans either promote or inhibit them.

Wetlands can maintain themselves in the face of sea level rise by accretion. This accretion is supported by both sedimentation and organic matter accumulation (Chmura *et al.*, 2003). The ability to accrete makes it difficult to assess the true consequences of sea level rise on landscape pattern and resultant area of wetlands, especially over large areas (Titus and Richman, 2001). We do not know exactly the potential accretion and subsidence rates of most wetlands and the thresholds at which relative sea level rise exceeds net elevation change, causing increased inundation and ultimately wetland loss. Based on the experiences of Louisiana, we can estimate that the maximum accretion rate may be less than 10 mm per year, but applicability to other systems is undetermined. Two things are clear: First, the limits depend on the source of material for accretion (*i.e.*, sediment or organic matter) and hence the rates of processes that introduce and remove the materials. Second, the rates of these processes will differ with location both locally within the coastal landscape and regionally due to climate, community, and hydrogeomorphic conditions.

Sea level rise and storm disturbance have not only severe consequences as described, but also are important drivers of the natural progression of coastal ecosystems. One can consider the coastal landscape as having a sequence of ecosystem states, each dependent upon a particular hydroperiod and tidal inundation regime (Brinson, Christian, and Blum, 1995; Hayden *et al.*, 1995; Christian *et al.*, 2000). For example in the mid-Atlantic states, coastal upland, which is rarely flooded, would be replaced by high salt marsh as sea level rises. High marsh is replaced by low marsh, and low marsh is replaced by intertidal flats. While sea level rise alone may effect these changes in state, they are promoted by disturbances that either kill vegetation (*e.g.*, salt intrusion from storms killing trees) or change elevation and hence hydroperiod (*e.g.*, erosion of sediment). It is unclear how accelerated sea level rise and frequency of severe storms will alter the balance of this sequence.

Normally one considers that disturbances would be local, such as salt water intrusion or wrack deposition. But these state changes can actually result from regional impacts of disturbance. For example, *Juncus roemerianus* is a rush species commonly found in high marshes along the mid-Atlantic, southern Atlantic, and Gulf of Mexico coasts of the United States. It is less common where astronomical tidal signals are strong (Woerner and Hackney, 1997; Brinson and Christian, 1999), and it is replaced by *Spartina alterniflora* or perhaps other species. Any disturbance that increases the strength of astronomical tides promotes this shift. Such a disturbance could be the breaching of barrier islands in which increased flow through new inlets may foster more dominant astronomical tides and the ecosystem state change. The projected disintegration of barrier islands as a consequence of intense storm damage acting from a higher base sea level has catastrophic implications (Riggs and Ames, 2003). Coastal barriers function to protect mainland shorelines from tidal energy, storm surge, and wave forces, such that loss of the protections implies catastrophic inundation, erosion, and loss of wetlands and other coastal habitats on mainland shores as well as back-barrier shores.

Sea level rise and increased frequency of intense storms will influence salt marsh and other wetland habitats by erosion and salt water intrusion, thereby influencing fish and wildlife production, available quantity of fresh water, and provision of human values, with consequences for management.

7.3.4.2.6 Joint Effects of Increasing Temperature and Carbon Dioxide

As a consequence of increasing global temperatures, the limits of climate-adapted habitats are expected to shift latitudinally. Temperate herbaceous species that dominate tidal wetlands throughout many southern U.S. estuaries may be replaced by more tropical species such as mangroves (Harris and Cropper Jr., 1992). Salt marshes and mangroves are not interchangeable, despite the fact that both provide structure to support productive ecosystems and perform many of the same ecosystem functions. Mangroves store up to 80% of their biomass in woody tissue, whereas salt marshes lose 100% of their aboveground biomass through litterfall each year (Mitsch and Gosselink, 2000). Production of litter facilitates detrital foodwebs and supports many ecological processes in wetlands, so this distinction has implications for materials cycling such as carbon sequestration (Chmura *et al.*, 2003). There are significant differences in structural complexity and biological diversity between these wetland systems. These differences will affect the capacity of the wetlands to assimilate upland runoff, maintain their vertical position, and provide flood control. Temperature-driven species redistribution will be further complicated as sea level increases and vegetation is forced landward.

Since pre-industrial times, the atmospheric concentration of carbon dioxide (CO_2) has risen by 35% to 379 ppm in 2005 (IPCC, 2007). Ice cores have proven that this concentration is significantly greater than the natural range over the last 650,000 years (180–300 ppm). In addition, the annual average growth rate in CO_2 concentrations over the last 10 years is larger than the average growth rate since the beginning of continuous direct atmospheric measurements: an average of 1.9 ppm per year from 1995–2005 compared with an average of 1.4 ppm per year from 1960–2005 (IPCC, 2007). Because CO_2 is required for photosynthesis, these changes may have implications for estuarine vegetation. Plants can be divided into two groups based on the way in which they assimilate CO_2. C3 plants include the vast majority of plants on earth (~95%) and C4 plants, which include crop plants and some grasses, comprise most of the rest. Early in the process of CO_2 assimilation, C3 plants form a pair of three carbon molecules whereas C4 plants form four carbon molecules. The distinction between C3 and C4 species at higher atmospheric CO_2 concentrations is that C3 species increase photosynthesis with higher CO_2 levels, while C4 species generally do not (Drake *et al.*, 1995). In wetland systems dominated by C3 plants (*e.g.*, mangroves, many tidal fresh marshes), elevated CO_2 will increase photosynthetic potential and may increase the related delivery of ecosystems services from these systems (Drake *et al.*, 2005). Ongoing research is examining the potential for shifts in wetland community composition driven by elevated CO_2. Data from one of these efforts indicate that despite the advantage afforded to C3 species at higher CO_2 levels, CO_2 increases alone are unlikely to cause black mangrove to replace cordgrass in Louisiana marshes.[20] However, many important estuarine ecosystem effects from elevated CO_2 levels have been documented, including increases in fluxes of CO_2 and methane (Marsh *et al.*, 2005), augmented nitrogen fixation by associated microbial communities (Dakora and Drake, 2000), increased methanogenesis (Dacey, Drake, and Klug, 1994) and changes in the quantity and composition of root material (Curtis *et al.*, 1990).

The joint effects of rising temperature and increased CO_2 concentrations will influence composition and production of shoreline plants that are critical habitat providers and contributors to detrital food chains, thereby also affecting fish and wildlife production and provision of human values, and inducing need for management adaptations.

7.3.4.2.7 Effects of Increased CO_2 on Acidification of Estuaries

Ocean acidification is the process of lowering the pH of the oceans by the uptake of CO_2 from the atmosphere. As atmospheric CO_2 increases, more CO_2 is partitioned into the surface layer of the ocean (Feely *et al.*, 2004). Since the industrial revolution began to increase atmospheric CO_2 significantly, the pH of ocean surface waters has deceased by about 0.1 units and it is estimated that it will decrease by another 0.3–0.4 units by 2100 as the atmospheric concentration continues to increase (Caldeira and Wickett, 2003). The resulting decrease in pH will affect all calcifying organisms because as pH decreases, the concentration of carbonate decreases, and when carbonate becomes under-saturated, structures made of calcium carbonate begin to dissolve. However, dissolution of existing biological calcium carbonate structures is only one aspect of the threat of acidification; another threat is that as pH falls and carbonate becomes undersaturated it requires more and more metabolic energy for an organism to deposit calcium carbonate. The present lowered pH is estimated to have reduced the growth of reef-building by about 20% (Raven, 2005). While corals get the most attention regarding acidification, a wide spectrum of ocean and estuarine organisms are affected, including coraline algae; echinoderms such as sea urchins, sand dollars, and starfish; as well as coccolithophores, foraminifera, crustaceans, and molluscan taxa with shells, of which pteropods are particularly important (Orr *et al.*, 2005). The full ecological consequences of the reduction in calcification by marine calcifiers are uncertain, but it is likely that the

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[20] **U.S. Geological Survey**, 2006: Potential effects of elevated atmospheric carbon dioxide (CO_2) on coastal wetlands. USGS, http://www.nwrc.usgs.gov/factshts/2006-3074/2006-3074.htm, accessed on 4-1-2006.

biological integrity of ocean and estuarine ecosystems will be seriously affected (Kleypas *et al.*, 2006).

Effects of climate change on estuarine acidification will influence water quality, provision of some biogenic habitat like coral reefs, fish and wildlife production, and human values, thus implying need for management adaptation.

7.3.4.2.8 Effects of Climate Change on Hypoxia

Low dissolved oxygen (DO) is a problematic environmental condition observed in many U.S. estuaries (Bricker *et al.*, 1999). Although a natural summer feature in some systems, the frequency and extent of hypoxia have increased in Chesapeake Bay, Long Island Sound, the Neuse River Estuary, and the Gulf of Mexico over the past several decades (Cooper and Brush, 1993; Paerl *et al.*, 1998; Anderson and Taylor, 2001; Rabalais, Turner, and Scavia, 2002; Cooper *et al.*, 2004; Hagy *et al.*, 2004; Scavia, Kelly, and Hagy, 2006). Persistent bottom water hypoxia (*e.g.*, DO concentration < 2.0 mg per L) results from interactions among meteorology and climate, the amounts and temporal patterns of riverine inflows, estuarine circulation, and biogeochemical cycling of allochthonous and autochthonous organic matter (Kemp *et al.*, 1992; Boicourt, 1992; Buzzelli *et al.*, 2002; Conley *et al.*, 2002). Over time, the repeated bottom water hypoxia can alter biogeochemical cycling, trophic transfers, and estuarine production at higher trophic levels (Baird *et al.*, 2004). Ecological and economic consequences of fish kills, bottom habitat degradation, and reduced production at the highest trophic levels in response to low DO have provided significant motivation to understand and manage hypoxia (Tenore, 1970; Officer *et al.*, 1984; Turner, Schroeder, and Wiseman, 1987; Diaz and Rosenberg, 1995; Hagy *et al.*, 2004).

Various scenarios predict that climate change will influence the vulnerability of estuaries to hypoxia through changes in stratification caused by alterations in freshwater runoff, changes in water temperature, increases in sea level, and altered exchanges with the coastal ocean (Peterson *et al.*, 1995; Scavia *et al.*, 2002). Additionally, warmer temperatures should increase metabolism by the water-column and benthic microbial communities, whose activity drives the depletion of DO. Many of the factors that have been found to contribute to the formation of hypoxia (Borsuk *et al.*, 2001; Buzzelli *et al.*, 2002) will be affected by one or more predicted changes in climate (Table 7.4). Because hypoxia affects valued resources, such as fish and wildlife production, reductions in hypoxia are a management target for many estuaries, and adaptations will be required as a consequence of climate change.

7.3.4.2.9 Effects of Changing Freshwater Delivery

Climate change is predicted to affect the quality, rate, magnitude, and timing of the freshwater delivered to estuaries (Alber, 2002), potentially exacerbating existing human modifications of these flows, as described by Sklar and Browder (1998). However, the exact nature of these changes is difficult to predict for a particular estuary, in part because there is not clear agreement among general circulation models (GCMs) on precipitation changes over drainage basins (National Assessment Synthesis Team, 2000). There does seem to be agreement among models that increases in frequencies of extreme rainfall will occur (Scavia *et al.*, 2002), suggesting that there will be changes in potential freshwater inflow amounts and patterns (hydrographs). These inflows will then be subjected to human modifications that differ across estuaries. For example, where dams are used in flood regulation, there is reduced variability within and among seasons, damping, for example, normally peak flows at snowmelt in temperate regions (Poff *et al.*, 1997; Alber, 2002). In some watersheds, increased reuse of wastewater in agriculture, municipalities, and industry may offset changes in supply by reducing demand for "clean" freshwater.

The potential physical and chemical consequences of altered freshwater flows to estuaries include changes in salinity and stratification regimes, loadings of nutrients and sediments, water residence times, and tidal importance (reviewed in Alber, 2002). Potential biological consequences include changes in species composition, distribution, abundance, and primary and secondary productivity, all in response to the altered availability of light, nutrients, and organic matter (Cloern *et al.*, 1983; Howarth *et al.*, 2000; Alber, 2002).

Increases in the delivery of freshwater to estuaries may enhance estuarine circulation and salt wedge penetration up the estuary (Gedney *et al.*, 2006), resulting in stronger vertical stratification. For individual estuaries there is the potential for increased freshwater inflow to shift the degree of mixing along the gradient from the fully mixed toward the stratified state. Those estuaries that receive increased supplies of organic matter and nutrients and exhibit enhanced stratification may be particularly susceptible to enhanced hypoxia and the negative effects described in the previous section. However, at some level, increased freshwater delivery will reduce residence time and thus reduce the potential for hypoxia. This threshold will be specific to individual estuaries and difficult to predict in a generic sense.

In some estuaries, climate change may also lead to a reduction in freshwater inflow, which will generally increase salinity. This could lead to more salt-water intrusion upstream, negatively affecting species intolerant of marine conditions (Copeland, 1966; Alber, 2002) and/or lengthening the estuary by extending the distance along the freshwater-to-full-seawater gradient (Alber, 2002). Water residence times within the estuary will likely increase with reduced freshwater inflow, potentially creating a more stable system in which phytoplankton can grow and reproduce (Cloern *et al.*, 1983; Howarth *et al.*, 2000). Thus, one might expect a greater response to nutrients—*i.e.*, greater primary productivity and/or larger phytoplankton populations (Mallin *et al.*, 1993)—than under baseline rates of freshwater discharge. This may be especially true for estuaries that are currently somewhat "protected" from eutrophication symptoms by high freshwater flow, such as the Hudson River (Howarth *et al.*, 2000). However, reduced flushing times will also keep water in the estuary longer, potentially increasing the risks posed by pollutants and pathogens (Alber and Sheldon, 1999; Sheldon and Alber, 2002).

Other biological consequences of changing freshwater delivery include alterations in secondary productivity (the directions of which are difficult to predict), the distributions of plants and sessile invertebrates (Alber, 2002), and cues for mobile organisms such as fish, especially migratory taxa with complex life histories (Whitfield, 1994; Whitfield, 2005). Not surprisingly, therefore, a whole branch of management is developing around the need to determine the optimal freshwater flows required to maintain desired ecosystem services (*e.g.*, Robins *et al.*, 2005; Rozas *et al.*, 2005).

Changes in freshwater delivery to the estuary will affect freshwater quantity, water quality, stratification, bottom habitats, fish and wildlife production, and human values, inducing needs for management adaptation.

7.3.4.2.10 Phenology Modifications and Match/Mismatch

Estuaries are characterized by high temporal variability, on multiple time scales, and spatial variability, which includes sharp environmental gradients with distance upstream and vertically in the water column (Remane and Schlieper, 1971). One mode of adaptation that many free-living estuarine species use to exploit the many resources of estuaries is to move in and out of the estuary, as well as upstream and downstream within the estuary, on a complex temporal schedule. A study in North Carolina found that the most abundant fish species in small tributaries of the upper estuary differed in 10 of the 12 months of the year (Kuenzler *et al.*, 1977). Ten different species were dominant during the 12 months of the year. To accomplish such movements, many estuarine species have evolved behavior that uses various sensory cues to control the timing of their activities (Sims *et al.*, 2004). The timing of behavior cued by environment information is referred to as "phenology" (Mullins and Marks, 1987; Costello, Sullivan, and Gifford, 2006). The best understood type of phenology that occurs in estuaries involves matching critical feeding stages with the timing of primary productivity blooms (Scavia *et al.*, 2002). As many estuarine stressors are altered by climate change, we can expect that phenology will be one of the first biological processes to be seriously disrupted.

Changing phenology has large implications for fish and wildlife production because trophic coupling of important species in the food chain can be disrupted, thereby presenting a need for management adaptation.

7.3.4.2.11 River Discharge and Sea Level Impacts on Anadromous Fishes

Anadromous fishes, such as Pacific salmon, are an important economic and cultural resource that may be particularly vulnerable to significant shifts in coastal climates in the Pacific Northwest and Alaska. The combined effect of shifts in seasonal precipitation, storm events, riverine discharge, and snowmelt (Salathé, 2006; Mote, 2006) are likely to change a broad suite of environmental conditions in coastal wetlands upon which salmon depend at several periods in their life histories. The University of Washington's Climate Impacts Group (UW-CIG) has summarized current climate change in the Pacific Northwest to include region-wide warming of ~0.8ºC in 100 years, increased precipitation, a decline in snowpack, especially at lower elevations, and an earlier spring.[21] The UW-CIG predictions for future climate change in the region include an increase in average temperatures on the order of 0.1–0.6ºC (best estimate = 0.3ºC) per decade throughout the coming century, with the warming occurring during all seasons but with the largest increases in the summer. Precipitation is also likely to increase in winter

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[21] **Climate Impacts Group**, University of Washington, 2007: Climate Change. University of Washington, http://www.cses.washington.edu/cig/pnwc/cc.shtml, accessed on 3-23-2007.

and decrease in summer, but with no net change in annual mean precipitation. As a consequence, the mountain snowpack will diminish and rivers that derive some of their flow from snowmelt will likely demonstrate reduced summer flow, increased winter flow, and earlier peak flow. Lower-elevation rivers that are fed mostly by rain may also experience increased wintertime flow due to increases in winter precipitation. Summer river flows in the Pacific Northwest are projected to decline by as much as 30% and droughts would become more common (Leung and Qian, 2003), implying significant changes in estuarine salinity distribution that has not yet been examined in any detail. Chapter 6, Wild and Scenic Rivers, provides an expanded discussion of these and other climate change effects on rivers in the United States.

Contemporary estimates of eustatic sea level rise associated with trends in climate change have ranged from 34–50 cm per century (Church, 2001). More recent estimates that have taken into account measurements of continental glacier movement, such as in Greenland, project increased rates from 75–100 cm per century (Meehl *et al.*, 2005) to 2.2–3.4 m by 2100 (Overpeck *et al.*, 2006; Otto-Bliesner *et al.*, 2006). However, relative sea level rise will differ considerably on regional and local scales due to variability in isostatic rebound, local extractions of subsurface fluids such as ground water and hydrocarbons, and rapid tectonic events such as earthquakes and vulcanism.

Because different anadromous species occupy estuarine wetlands according to their divergent life history strategies, impacts of these climate changes vary among and within species. In the case of Pacific salmon, the “ocean-type” species and life history types would be the most vulnerable because they occupy transitional estuarine waters significantly longer than “stream-type” salmon. For instance, juvenile Chinook and chum salmon representing this “ocean-type” life history strategy may occupy estuarine wetlands for more than 90 days (Simenstad, Fresh, and Salo, 1982), seeking (1) refugia from predation at their small size, (2) time to achieve physiological adaptation from freshwater to marine salinities, and (3) high densities of appropriate prey organisms. Based on our knowledge of the habitat requirements and landscape transitions of migrating juvenile ocean-type salmon (Simenstad *et al.*, 2000; Parson *et al.*, 2001; Mote *et al.*, 2003), the present spatial coincidence of necessary physical habitats, such as marsh platforms and tidal creeks, will change with the appropriate salinity regime as sea water penetrates further up the estuary. This would have potentially large impacts on the ocean-type salmon performance.

In the Pacific Northwest, shifts from snowmelt runoff to more winter storm precipitation will potentially disrupt the migration timing and residence of juvenile salmon in estuarine wetlands. For example, juvenile Chinook salmon in many watersheds migrate to estuaries coincident with the spring freshet of snowmelt, and occupy the extensive brackish marshes available to them during that period. This opportunity often diminishes as water temperatures increase and approach physiologically marginal limits (*e.g.*, 19–20ºC) with the decline of snowmelt and flows in early summer. Under current climate change/variability scenarios, much of the precipitation events will now be focused in the winter, providing less brackish habitat opportunities during the expected juvenile salmon migration and even more limiting temperatures during even lower summer flows.

Whether migration and other life history patterns of salmon could adapt to these climate shifts are unknown.

The sustainability of estuarine wetlands under recent sea level rise scenarios is also of concern if estuarine habitat utilization by anadromous fish is density-dependent. Estuaries that are positioned in a physiographic setting allowing transgressive inundation, such as much of the coastal plain of the southeastern and Gulf of Mexico coasts, have a buffer that will potentially allow more inland development of estuarine wetlands. Other coasts, such as those of New England and the Pacific Northwest, have more limited opportunities for transgressive development of estuarine wetlands, and many estuaries are already confined by upland agricultural or urban development that would prevent further inland flooding (Brinson, Christian, and Blum, 1995). For one example, Hood[22] found that a 45-cm sea level rise over the next century would result in a 12% loss, and an 80-cm rise would eliminate 22%, of the tidal marshes in the Skagit River delta (Puget Sound, Washington), which could be translated to an estimated reduction in estuarine rearing capacity for juvenile Chinook salmon of 211,000–530,000 fish, respectively. These estimates are based entirely on the direct inundation effects on vegetation and do not incorporate the potential response of existing marshes to compensate for the increased rate of sea level rise, which can include increased sediment accretion and maintenance of marsh plain elevation or increased marsh progradation due to higher sediment loads from the river (see section 7.2.4.2.15 below). Nor do these estimates take into account increased marsh erosion from greater winter storm activity or changes in salinity distribution due to declining summer river flows. Court cases have already overturned general permits for shoreline armoring where salmon (an endangered species under ESA) would be harmed. With projected rises in sea level, the needs of salmon may come even more often into conflict with management policies that generally permit bulkheads and other shoreline armoring to protect private property.

Salmon represent such an iconic fish of great importance to fisheries, wildlife, subsistence uses, and human culture that climate-related impacts on salmon populations would require management adaptation.

7.3.4.2.12 Effects of Climate Change on Estuarine State Changes

The many direct and indirect influences of climate change may combine to cause fundamental shifts in ecosystem structure and functioning. Some shifts, such as those associated with transgression of wetlands, can be considered part of the normal responses to sea-level rise (Brinson, Christian, and Blum, 1995; Christian *et al.*, 2000). Of particular concern is the potential for ecosystems to cross a threshold beyond which there is a rapid transition into a fundamentally different state that is not part of a natural progression. Ecosystems typically do not respond to gradual change in key forcing variables in a smooth, linear fashion. Instead, there are abrupt, discontinuous, non-linear shifts to a new state (or "regime") when a threshold is crossed (Scheffer *et al.*, 2001; Scheffer and Carpenter, 2003; Burkett *et al.*, 2005). Particularly relevant here is the hypothesis that gradual changes in "slow" variables that operate over long time scales can

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[22] **Hood**, W.G., Unpublished: Possible sea-level rise impacts on the Skagit River tidal marshes. Skagit River System Cooperative.

cause threshold-crossing when they alter interactions among “fast” variables whose dynamics happen on short temporal scales (Carpenter, Ludwig, and Brock, 1999; Rinaldi and Scheffer, 2000). We anticipate that some climate changes will fall into this category, such as gradual increases in temperature. The diversity of additional stressors arising from consequences of climate change greatly enhances the likelihood of important stressor interactions. Thus, in estuaries, where so many stressors operate simultaneously, there is great potential for interactions among stressors to drive the system into an alternative state.

Regime shifts can sometimes be catastrophic and surprising (Holling, 1972; Scheffer and Carpenter, 2003; Foley *et al.*, 2005), and reversals of these changes may be difficult, expensive, or even impossible (Carpenter, Ludwig, and Brock, 1999). Moreover, the social and economic effects of discontinuous changes in ecosystem state can be devastating when accompanied by the interruption or cessation of essential ecosystem services (Scheffer *et al.*, 2001; *e.g.*, Foley *et al.*, 2005). Recognizing and understanding the drivers of regime change and the inherent nonlinearities of biological responses to such change is a fundamental challenge to effective ecosystem management in the face of global climate change (Burkett *et al.*, 2005; Groffman *et al.*, 2006).

All the potential regime shifts described below have large implications for sustaining biogenic habitat, provision of fish and wildlife, and many human values, thereby implying need for management adaptation.

7.3.4.2.13 Climate Change Effects on Suspension-Feeding Grazers and Algal Blooms

The Eastern oyster (*Crassostrea virginica*) is a historically dominant species in estuaries along the Atlantic and Gulf of Mexico coasts of the United States. At high abundances, oysters play major roles in the filtration of particles from the water column, biodeposition of materials to the benthos, nutrient cycling, and the creation of hard substrate habitat in otherwise soft-bottom systems (Kennedy, 1996; Coen, Luckenbach, and Breitburg, 1999; Newell and Ott, 1999; Newell, Cornwell, and Owens, 2002). Dominant consumers (*e.g.*, the schyphomedusan sea nettle, *Chrysaora quinquecirrha*) are dependent on oysters for habitat for sessile stages, and large numbers of estuarine fish species benefit either directly or indirectly from habitat and secondary production of oyster reefs (Coen, Luckenbach, and Breitburg, 1999; Breitburg *et al.*, 2000). Oysters are structural as well as biological ecological engineers (Jones, Lawton, and Shachak, 1994), and have been shown to reduce shoreline erosion (Meyer, Townsend, and Thayer, 1997) and facilitate regrowth of submerged aquatic vegetation by reducing nearshore wave action.

Oyster abundances in Atlantic Coast estuaries have declined sharply during the past century, with a precipitous decline in some systems during the past two to three decades. The primary stressors causing the recent decline are likely overfishing and two pathogens: *Haplosporidium nelsoni*—the non-native protist that causes MSX—and *Perkinsus marinus*, a protistan that causes Dermo and is native to the United States but has undergone a recent range expansion and possible increase in virulence (Rothschild *et al.*, 1994; National Research Council, 2004). Both overfishing and disease cause responses in the relatively slow-responding (*i.e.*, years to decades) adult oysters and oyster reefs, making recovery to the oyster-dominant regime quite difficult. High sediment loading (Cooper and Brush, 1993), eutrophication (Boynton *et al.*, 1995), and blooms of ctenophores (Purcell *et al.*, 1991) may further contribute to oyster decline or prevent recovery to the high-oyster state. These factors—all of which are likely to increase with changes in climate—appear to act most strongly on the larval and newly settled juvenile stages, raising the possibility that this system will at best exhibit hysteretic recovery to the high-oyster state.

7.3.4.2.14 N-Driven Shift from Vascular Plants to Planktonic Micro- and Benthic Macroalgae

Seagrasses are believed to be in the midst of a global crisis in which human activities are leading to large scale losses (Orth *et al.*, 2006). Human and natural impacts have had demonstrable detrimental effects on SAV (Short and Wyllie-Echeverria, 1996). Enhanced loading of nutrients to coastal waters has been found to alter primary producer communities, through shifts toward species with faster growth-nutrient uptake rates (Duarte, 1991). The shift is often toward phytoplankton, which reduces light availability and can lead to losses of other benthic primary producers such as seagrasses. The disappearance of seagrass below critical light levels is dramatic (Duarte, 1991), and has been linked to nutrient loading in some systems (Short and Burdick, 1996). In Waquoit Bay, Massachusetts, replacement of SAV by macroalgae has also been observed and was primarily attributed to shading (Hauxwell *et al.*, 2001). Increases in macroalgal biomass, macroalgal canopy height and decreases in SAV biomass were linked to nitrogen loading rate using a space-for-time substitution (Hauxwell *et al.*, 2001). It is essential to understand the potential for thresholds in water quality parameters that may lead to loss of SAV through a state change. SAV is sensitive to environmental change, and thus may serve as a “coastal canary,” providing an early warning of deteriorating conditions (Orth *et al.*, 2006). SAV also provides significant ecological services (Williams and Heck Jr., 2001) and its loss would have appreciable effects on overall estuarine function.

7.3.4.2.15 Non-linear Marsh Accretion with Sea Level Rise

Coastal inundation is projected to lead to land loss and expansion of the sub-tidal regions along estuarine shorelines (Riggs, 2002). Intertidal habitats that do not accrete or migrate landward proportionally to relative sea level rise are susceptible to inundation. Wetlands are often present in these areas, and have shown the ability to keep up with increases in sea level in some systems (Morris *et al.*, 2002). However, the ability to maintain their vertical position is uncertain, and depends on a suite of factors (Moorhead and Brinson, 1995). Recent work in the Venice Lagoon found a bimodal distribution of marsh (higher elevation) and flat (lower elevation) intertidal habitats, with few habitats at intermediate intertidal elevations (Fagherazzi *et al.*, 2006). The findings indicate that there may be an abrupt transition from one habitat type to another. Should this model hold true for a broad range of coastal systems, there are clearly significant implications for coastal geomorphology and the ecological services provided by the different habitat types.

7.4 Adapting to Climate Change

Biologists have traditionally used the term “adaptation” to apply to intrinsic biological responses to physical or biological changes that may serve to perpetuate the species, with implications for the community and ecosystem. This definition includes behavioral, physiological, and evolutionary adaptation of species. This question therefore arises: Can biological adaptation be relied upon to sustain ecosystem services from national estuaries under conditions of present and future climate change? In the short term of a few decades, the capability of estuarine organisms to migrate farther toward the poles in response to warming temperatures and farther up the shore in response to rising water levels has potential to maintain estuarine ecosystem processes and functioning that do not differ greatly from today's conditions. However, over longer time frames, depending on the realized magnitude of climate changes, estuarine ecosystems may not be able to adapt biologically and thereby retain high similarity to present systems. The scope and pace of current and anticipated future climate change are too great to assume that management goals will be sustained by intrinsic biological adjustments, without also requiring management adaptation (Parmesan and Galbraith, 2004; Parmesan, 2006; Pielke *et al.*, 2007).

The extremely high natural variability of estuarine environments has already selected for organisms, communities, and ecosystems with high capacity for natural physiological, behavioral, and perhaps also evolutionary adaptation (Remane and Schlieper, 1971; Wolfe, 1986). Nevertheless, the current rapid rates of change in many variables, such as temperature, and the absolute levels of key environmental variables, such as CO_2 concentration, that ultimately may be reached, could fall outside the historical evolutionary experience of estuarine organisms. The historical experience with environmental variability may not help much to achieve effective biological adaptation under these novel rates of change and conditions. While behavioral (*e.g.*, migration, dispersal) adaptation of individual species may take place to some degree, the dramatic suite of projected changes in estuarine environments and stressors that we summarized earlier poses complex challenges to individual species, including those of estuaries, on a timetable that is inconsistent with the capacity for evolutionary change to keep up (Pielke *et al.*, 2007). Even if evolutionary change could proceed at a rapid pace, the diversity of environmental changes implies that conflicting demands may be placed on selection such that adaptation to the full suite of changes may be compromised. The success of individual species in adapting to climate change does not lead to intrinsic resilience at the community and ecosystems levels of organization. Because virtually all ecosystem processes involve some form of interaction between or among species, biological adaptation by individual species to climate-driven changes is not a process that will protect functioning estuarine ecosystems, because species adapt and migrate at differing rates (Sims *et al.*, 2004; Parmesan, 2006).

Among the most important estuarine species that dictate overall community composition and ecosystem dynamics are the structural foundation species, namely intertidal marsh plant and subtidal seagrass (SAV) vegetation. Donnelly and Bertness (2001) have assembled ecological evidence that, starting in the late 1990s, the low marsh plant *Spartina alterniflora* has begun to move upslope and invade the higher marshes of New England that are typically occupied by a more diverse mix of *Juncus gerardi*, *Distichlis spicata*, and *Spartina patens*. Their paleontological assessment revealed that in times of rapid sea level rise in the late 19th and early 20th centuries, *Spartina alterniflora* similarly grew upwards and dominated the high marsh. Such replacement of species and structural diversity of foundation species is likely to modify the functioning of the salt marsh ecosystem and affect its capacity to deliver traditional goods and services. Similarly, among SAV species, some like *Halodule wrightii* are known to be better colonizers with greater ability to colonize and spread into disturbed patches than other seagrasses like *Thalassia testudinum* (Stephan, Peuser, and Fonseca, 2001). In general, seagrasses that recolonize by seed set can move into newly opened areas more readily than those that largely employ vegetative spread. Analogous to the marsh changes, if storm disturbance and rising water levels favor more opportunistic seagrass species, then the new SAV community may differ from the present one and provide different ecosystem services. Vascular plants of both intertidal and shallow subtidal estuaries possess characteristically few species relative to terrestrial habitats (Day, Jr. *et al.*, 1989; Orth *et al.*, 2006), so these differences in behavior of important foundation species in the marsh and in SAV beds will have disproportionately large influences on function. Thus, the web of interactions among biotic and abiotic components of the estuarine ecosystem cannot be expected to be preserved through intrinsic biological adaptation alone, which cannot regulate the physical changes. Management adaptations must be considered to sustain ecosystem services of national estuaries. Examples of specific adaptation options are presented in Box 7.4 and elaborated further throughout the sections that follow.

7.4.1 Potential for Adjustment of Traditional Management Approaches to Achieve Adaptation to Climate Change

Three different time frames of management adaptation can be distinguished: (1) avoidance of any advance adaptation strategy (leading to *ad hoc* reactive responses); (2) planning only for management responses to climate change and its consequences (leading to coordinated, planned responses initiated either after indicators reveal the urgency or after emergence of impacts); and (3) taking proactive measures to preserve valuable services in anticipation of consequences of climate change. Rational grounds for choosing among these three options involve consideration of the risks and reversibility of predicted negative consequences, and the expenditures associated with planning and acting now as opposed to employing retroactive measures. Political impediments and lack of effective governance structures may lead to inaction, even if planning for intervention or initiating proactive intervention represents the optimal strategy. For example, the partitioning of authority for environmental and natural resource management in the United States among multiple federal and state agencies inhibits effective implementation of ecosystem-based management of our estuarine and ocean resources (Peterson and Estes, 2001; Pew Center on Global Climate Change, 2003; U.S. Commission on Ocean Policy, 2004; Titus, 2004). Even if governance structures were developed that allow cooperation among agencies and among levels of government, successful application of ecosystem-based management of estuaries may not be a realistic expectation for estuarine management because of the intrinsic conflicts of interest among stakeholders, which include land users across the entire watershed and airshed as well as coastal interests.

Planning for adaptation to climate change, without immediate implementation, may represent the most prudent response to uncertainty over timing and/or intensity of negative consequences of global change on estuarine ecosystem services, provided that advance actions are not required to avoid irreversible damage. Issues of expense also deserve attention in deciding whether to delay management actions. An ounce of prevention may be worth a pound of cure. For example, by postponing repairs and vertical extensions of levees around New Orleans, the estimated expenditures for retroactive repair and all necessary restorations of about $54 billion following Hurricanes Katrina and Rita greatly exceed what proactive levee reconstruction would have cost (Kates *et al.*, 2006). On the other hand, the protections provided against natural disasters are typically designed to handle more frequent events, such as storms and floods occurring more frequently than once a century, but inadequate to defend against major disasters like the direct hit by a category 5 hurricane. Such management protections even enhance losses and restoration costs by promoting development under the false sense of security that is based on success in the face of more frequent, smaller storm events (Kates *et al.*, 2006). This example has direct relevance to adaptation management in estuaries, because there is broad consensus that climate change is increasing sea levels and increasing the frequency of intense hurricanes (IPCC, 2007). Engineered dikes for estuarine shorelines may represent one possible management adaptation, protective of some human values but injurious to natural resources. Thus, the need for understanding the effectiveness and consequences of alternative management policies relating to dikes, levees, and other such structural defenses makes the New Orleans experience relevant.

A decision to postpone implementation of adaptation actions may rely on continuing scientific monitoring of reliable indicators and modeling. Based on inputs from evolving ocean observing systems, model predictions could provide comfort that necessary actions, although delayed, may still be timely. Other important prospective management actions may be postponed because they are not politically feasible until an event alters public opinion sufficiently to allow their implementation. Such adaptations are best planned in advance to anticipate the moment when they could be successfully triggered. Other management actions may involve responding to events and therefore only have relevance in a retrospective context. Catastrophic events provide opportunities for changes that increase ecological and human community resilience, by addressing long-standing problems such as overbuilding in floodplains or degradation of coastal wetlands (Box 7.5).[23] However, pressures to expediently restore conditions to their familiar pre-disaster state often lead to the loss of these opportunities (Mileti, 1999). Therefore, decisions about whether and where to rebuild after damage from major floods and storms should be carefully examined and planned in advance in order to avoid making poorer judgments during chaotic conditions that follow these types of incidents. This strategy becomes more relevant as storm intensity and flood damages increase.

Proactive intervention in anticipation of consequences of climate change represents rational management under several conditions. These conditions include irreversibility of undesirable ecosystem changes, substantially higher costs to repair damages than to prevent them, risk of losing important and significant ecosystem services, and high levels of scientific certainty about the anticipated change and its ecological consequences (Titus, 1998; 2000). Avoiding dramatic structural (“phase”) shifts in estuarine ecosystem state may represent a compelling motivation for proactive management, because such

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[23] **H. John Heinz III Center for Science, Economics, and the Environment**, 2002: *Human Links to Coastal Disasters*. Washington, DC.

shifts threaten continuing delivery of many traditional ecosystem services and are typically difficult or exceedingly expensive to reverse (Groffman *et al.*, 2006). Reversibility is especially at issue in cases of potential transitioning to an alternative stable state, because positive feedbacks maintain the new state and resist reversal (Petraitis and Dudgeon, 2004). For example, the loss of SAV removes a baffle to water flow, thus increasing near-bottom currents. The faster currents in turn mean that seagrass seeds are less likely to be deposited, and seedlings are more likely to be uprooted by erosion; this feedback makes reestablishment of lost beds much more difficult.

With adequate knowledge of the critical tipping point and ongoing monitoring of telling indicators, proactive intervention could in some cases be postponed and still be completed in time to prevent climate change from pushing the system over the threshold into a new phase. Nevertheless, many processes involved in ecosystem change possess substantial inertia such that even after adjusting levels of drivers, a memory of past stress will continue to modify the system, making postponement of action inadvisable. Climate change itself falls into this class of processes, in that if greenhouse gas emissions were capped today, the Earth would continue to warm for decades (IPCC, 2007).

Financial costs of climate change may be minimized by some types of proactive management. For example, enacting legislation that prohibits bulkheads and other engineered structures and requires rolling easements along currently undeveloped estuarine shores could preserve or at least delay loss of important shallow-water habitats, such as salt marsh, by allowing them to migrate inland as sea level rises (Box 7.6) (Titus, 1998). A law to require rolling easements is not likely to be ruled as a taking, especially if enacted before property is developed, because “the law of erosion has long held that the public tidelands migrate inland as sea level rises, legislation saying that this law will apply in the future takes nothing” (Titus, 1998). However, absent such a law and this interpretation of it, the value of habitat and associated ecosystem services may exceed the value of property losses that would occur if property owners could not protect their investment. Some other proactive steps that enhance adaptation to climate change are likely to come at very little expense, and deserve immediate inclusion in policy and management plans. For example, the simple incorporation of climate change consequences in management plans for natural and environmental resources will trigger inclusion of forward-looking modifications that might provide resistance to climate change, build resiliency of ecological and socioeconomic systems, and avoid interventions incompatible with anticipated change and sustained ecosystem services (Titus, 2000). Principles for environmental planning could be adopted that (1) prohibit actions that will exacerbate negative consequences of climate change, (2) allow actions that are climate-change neutral, and (3) promote actions that provide enhanced ecosystem resilience to climate change. Such principles may lead to many low-cost modifications of existing management plans that could be initiated today.

The scientific basis for predicting climate change and its ecosystem consequences must be especially compelling in order to justify any costly decisions to take proactive steps to enhance adaptation to climate change. Willingness to take costly actions should vary with the magnitude of predicted consequences, the confidence associated with the predictions, and the timing of the effects. The scientific basis for the predictions must also be transparent, honest, and effectively communicated, not just to managers but also to the general public, who ultimately must support adaptation interventions. Thus, there is an urgent need to continue to refine the scientific research on climate change and its ecosystem consequences to reduce uncertainty over all processes that contribute to climate change and sea level rise, so that future projections and GCM scenarios are more complete and more precise. Because of the tremendous publicity associated with the release of each IPCC report, this process of periodic re-evaluation of the science and publication of the consensus report plays an integral role in public education. Scientific uncertainty about the magnitudes and timetables of potentially important processes, such as melting of the Greenland ice sheet (Dowdeswell, 2006; Rignot and Kanagaratnam, 2006), leads to their exclusion from IPCC projections. Further scientific research will allow inclusion of such now uncertain contributions to change.

7.4.2 Management Adaptations to Sustain Estuarine Services

7.4.2.1 Protecting Water Quality

All national estuaries, and estuaries more generally, include water quality as a priority management target. The federal Clean Water Act serves to identify explicit targets for estuarine water quality nationwide, but state and local programs can also include other numeric standards for explicit parameters. Some CCMPs specify explicit, sometimes numeric, targets for specific member estuaries. Parameters with federally mandated standards include chlorophyll concentration; turbidity; dissolved oxygen; fecal coliform bacteria; nutrient loading where TMDLs apply; and conditions for NPDES discharge permits that maintain balanced and indigenous communities of fish, shellfish, and wildlife. In addition, coastal marsh and other riparian wetland buffers serve to treat non-point-source storm waters before they enter the open waters of estuaries, so preserving marsh extent and functionality is an important management target relating to water quality (Mitsch and Day Jr, 2006).

Perhaps the greatest threat to estuarine water quality from climate change derives from the loss of water treatment of diffuse nutrient pollution by constricted tidal marsh and wetland buffers (Box 7.7). These vegetated buffers are threatened by the joint effects of sea level rise and increasingly intense storms interacting with hardening of estuarine shorelines through installation of bulkheads, dikes, and other engineered structures (Titus, 1998). Such structures are now readily permitted along estuarine shorelines to protect private property and public infrastructure from shoreline erosion; however, by preventing orderly retreat of intertidal and shallow subtidal habitats shoreward as sea level rises (Schwimmer and Pizzuto, 2000), marsh will be lost and its functions eliminated over extensive portions of estuarine shorelines (Titus, 2000; Reed, 2002; Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2006). The loss of salt marsh on coastal barriers is further facilitated by beach nourishment, which prevents natural processes of coastal barrier recession through overwash. Overwash of sediments to the estuarine shoreline is a process that extends and revitalizes salt marsh on the protected side of coastal barriers.

Estuarine shorelines differ in their susceptibility to erosion and recession under rising sea levels (U.S. Environmental Protection Agency, 1989) . Relative sea level is rising at very different rates around the country and the globe. The subsiding shores of the Louisiana Gulf Coast are losing more salt marsh to sea level rise than any other region of the United States (U.S. Environmental Protection Agency, 1989). Marsh losses on the Mississippi River Delta are enhanced by modification of river flows in ways that inhibit sediment delivery to the marshes, and by extraction of subsurface fluids (oil and gas). Extraction of groundwater from shallow aquifers also induces subsidence and enhances relative sea level rise along the shores of some estuaries, such as San Francisco Bay. For many estuaries, salt marsh does not currently face increased flooding and erosion from rising sea levels, either because relative sea level is not rising rapidly in these regions or because the accumulation of organic peat, along with the trapping and deposition of largely inorganic sediments by emergent marsh plants, is elevating the land surface at a rate sufficient to keep up with sea level rise (Reed, 2002). Despite the capability of salt marsh to rise with sea level, this gradual process produces a marsh on an elevated platform where the estuarine shore is increasingly more steeply sloped. The consequently deeper water does not dissipate wave energy as readily as the previously shallow slope, leading to increased risk of shoreline and marsh erosion at the margin (Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2006). Therefore, even marsh shores that today are maintaining elevation and position as sea level rises are at risk of greater erosion at their seaward margin in the future. Nevertheless, substantial geographic variation exists in erosion risk and susceptibility to marsh loss (U.S. Environmental Protection Agency, 1989).

Maintaining present management policy allowing bulkheads will likely lead to the loss of marshes, and the development of walled estuaries composed only of subtidal habitats, wherever development exists on the shoreline. Only on undeveloped estuarine shorelines can marshes recede landward. But with the ongoing dramatic expansion of coastal human communities, little undeveloped estuarine shoreline is likely to remain except in public parks, reserves, and sanctuaries. Along estuarine salinity gradients, much more development takes place toward the ocean end and less up-estuary. Therefore, as sea level rises, an increasing fraction of remaining marsh habitat will be found along these undefended, up-estuary shores (see maps in SAP 4.1; U.S. Climate Change Science Program, in press). All specific water quality parameters for which standards exist will suffer under this scenario of current management without adaptation. Reactive management holds little promise of reversing impacts, because it would require dismantling or moving structures and infrastructure, which is expensive, unpopular, and increasingly infeasible as coastal land becomes increasingly developed. Reactive marsh restoration would require removals of at least some portion of the engineered walls protecting estuarine shoreline property, so as to allow flooding of the proper elevations supporting salt marsh restoration. Implementing any public policy that would lead directly to widespread private property loss represents a large challenge under the prevailing property rights laws, but one that should be decided in favor of retaining the estuarine habitats, if done in a way that can involve rolling easements to preserve the public tidelands (Titus, 1998).

The process of retreat achieved by rolling easements or by some other administrative construct has been discussed in the United States for at least two decades. Retreat has an advantage over establishment of fixed buffer zones, because the abandonment need not be anticipated and shoreline use modified until sea level has risen enough to require action (Titus, 1998). An analogous proactive response to global climate change and sea level rise, known as "managed alignment," is being actively considered in the United Kingdom and European Union.[24] Managed alignment refers to deliberately realigning engineering structures affecting rivers, estuaries, and the coastline. The process could involve retreating to higher ground, constructing set-back levees, shortening the length of levees and seawalls, reducing levee heights, and widening river floodplains. The goals of managed realignment may be to:

(1) reduce engineering costs by shortening the overall length of levees and seawalls that require maintenance;
(2) increase the efficiency and long-term sustainability of flood and coastal levees by recreating river, estuary, or coastal wetlands, and using their flood and storm buffering capacity;
(3) provide other environmental benefits through re-creation of natural wetlands; or
(4) construct replacement coastal wetlands in or adjacent to a designated European site, to compensate for wetland losses resulting from reclamation or coastal squeeze.

Under this UK/EU perspective, the goods and services provided by wetland coastal defenses against sea level rise appear to outweigh anticipated costs under some scenarios.

Locally in the United States, proactive management to protect tidal marshes, on which water quality of estuaries so strongly depends, may have some notable success in the short term of a few decades, although prospects of longer-term success are less promising. Only Rhode Island and parts of Massachusetts have regulations in place that recognize the need to allow wetlands the capacity to migrate inland as sea level rises, and thereby provide long-term protection (Titus, 2000).

An alternative to bulkheading is using natural breakwaters of native oysters, in quiescent waters of Atlantic and Gulf Coast estuaries, to dissipate wave action and thus help inhibit shoreline and marsh erosion inshore of the reef. Rock sills (so-called "living shorelines" as developed and permitted in Maryland)[13] can be installed in front of tidal marshes along more energetic estuarine shores, where oysters would not survive (Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2006). Such natural and artificial breakwaters can induce sediment deposition behind them, and thereby may help sediments rise and marshes persist with growing sea levels. As sea level rises, oyster reefs can also grow taller and rock sills can be artificially elevated, thereby keeping up protection by the breakwaters. Oysters are active suspension feeders

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[24] **Department for Environment, Food and Rural Affairs (DEFRA) and the UK Environment Agency**, 2002: *Managed Realignment Review - Project Report*. Policy Research Project FD 2008, DEFRA, Cambridge, UK.

and help reduce turbidity of estuarine waters. Rock breakwaters in the estuary are also often colonized by oysters and other suspension-feeding invertebrates. Restoration of oyster reefs as breakwaters, and even installation of rock breakwaters, contribute to water quality through the oysters' feeding and through protection of salt marshes by these alternatives to bulkheads and dikes. This proactive adaptation to sea level rise and risk of damaging storms will probably fail to be sustainable over longer time frames, because such breakwaters are not likely to provide reliable protection against shoreline erosion in major storms as sea level continues to rise. Ultimately, the owners of valuable estuarine shoreline may not be satisfied with breakwaters as their only defense against the rising waters, and may demand permission to install levees, bulkheads, or alternative forms of shoreline armoring. This could lead to erosion of all intertidal habitats along the shoreline and consequent loss of the tidal marsh in developed areas. Some of these losses of marsh acreage would be replaced by progressive drowning of river mouths and inundation of flood plains up-estuary as sea level rises, followed by transgression and spread of wetlands into those newly flooded areas. The most promising suite of management adaptations on highly developed shorelines down-estuary is likely a combination of rolling easements, setbacks, density restrictions, and building codes (Titus, 1998). Political resistance may preclude local implementation of this adaptation, but financial costs of implementation are reasonable, if done before the shoreline is developed (Titus, 2000).

Given the political barriers to implementing these management adaptations to protect coastal wetlands, globally instituted mitigation of climate change may be the only means in the longer term (several decades to centuries) of avoiding large losses of tidal marsh and its water treatment functions. Losses will be nearly total along estuarine shorelines where development is most intense, especially in the zone of high hurricane risk from Texas to New York (see SAP 4.1; U.S. Climate Change Science Program, in press). Although rapid global capping of greenhouse gas emissions would still result in decades of rising global temperatures and consequent physical climatic changes (IPCC, 2007), it may be possible in the short term (years to a few decades) to partially alleviate damage to tidal marshes and diminution of their water treatment role on developed shores by local management adaptations, such as installation of natural and artificial breakwaters. On undeveloped estuarine shorelines, implementation of rolling easements is a critical need before development renders this approach too politically and financially costly. However, much public education will be necessary for this management adaptation to be accepted.

Estuarine water quality is also threatened by a combination of rising temperature, increased pulsing and, in many regions such as the East Coast, growing quantities of freshwater riverine discharge and more energetic upstream wedging of sea waters with rising sea level (Scavia *et al.*, 2002). Temperature increases drive faster biochemical rates, including greater rates of microbial decomposition and animal metabolism, which inflate oxygen demand. When increased fresh water discharges into the estuary, this less-dense fresh water at the surface, when combined with stronger salt water wedging on the bottom, will enhance water column stability because of greater density stratification. Such conditions are the physical precursor to development of estuarine bottom water hypoxia and anoxia in warm seasons, because oxygen-rich surface waters are too light to be readily mixed to depth (Paerl *et al.*, 1998). This water quality problem leads to persistent hypoxia and anoxia, creating dead zones on the bottoms of estuaries, one of the most serious symptoms of eutrophication (Paerl *et al.*, 1998; Bricker *et al.*, 1999). Under higher water temperatures and extended warm seasons, high oxygen demand is likely to extend for longer periods of the year while greater stratification further decreases dissolved oxygen in bottom waters. Erosion of riparian marshes from rising water levels also adds previously sequestered organic carbon to the estuary, further increasing oxygen demand for its microbial decomposition. In regions such as the Pacific Northwest, where summertime droughts are predicted rather than summer increases in storm-driven pulses of rain, this scenario of greater water-column stability and higher oxygen demand at elevated temperature will not apply. Nevertheless, negative consequences of summertime drought also are likely.

Failing to act in advance of increases in incidence, scope, and duration of bottom water hypoxia implies widespread climate-related modifications of many estuaries, inconsistent with maintaining a balanced indigenous population of fish, shellfish, and wildlife. Nutrient reduction in the watershed and airshed could limit algal blooms, and thereby reduce organic loading and oxygen demand (Conley *et al.*, 2002). However, discharge limits for point sources are already close to what is technically feasible in many rivers. From an economic standpoint, further limiting atmospheric nitrogen deposition would affect many activities, such as electric power generation, industrial operations, and automobile use. It is possible that wetland restoration over the drainage basin could be greatly enhanced to reduce the fraction of diffuse nutrient loading that reaches the estuary, and to help counteract the increased estuarine stratification and warming temperatures that drive higher microbial decomposition and oxygen demand (Mitsch and Day Jr, 2006). Thus, integrated management of nutrient sources and wetland treatment of nutrients can play a role in management to limit eutrophication and hypoxia.

At state levels of management, recognition of the likelihood of climate change and anticipation of its consequences could lead to important proactive steps, some with potentially minimal financial costs. Regulatory change represents one major example of an institutional approach at this level. Rhode Island and Massachusetts deserve praise for appropriately responding to risk of wetland loss under sea level rise by instituting regulations to allow landward migration of these habitats (Titus, 2000). Examination of state laws, agency rules, and various management documents in North Carolina, on the other hand, suggests that climate change is rarely mentioned and almost never considered. One example of how changes in rules could provide proactive protection of water quality would be to anticipate changes in sea level rise and storm intensity by modifying riparian buffer zones to maintain water quality. Permitting rules that constrain locations for construction of landfills, hazardous waste dumps, mine tailings, and facilities that store toxic chemicals could be modified to insure that, even under anticipated future conditions of sea level rise, shoreline recession, and intense storms, these facilities would remain not only outside today’s floodplains but also outside the likely floodplains of the future. Riverine floodplain maps and publicly run flood insurance coverage could be redrafted to reflect expectations of flooding frequency and extent under changing rainfall amounts and increasing flashiness of rainfall as it is delivered in more intense discrete storms. Such changes in floodplain maps would have numerous cascading impacts on development activities along the river edges in the entire watershed, many of which would help protect water quality during floods. Water quality degradation associated with consequences of floods from major storms such as hurricanes can persist for many months in estuaries (Paerl and Bales, 2001). Thus, if climate change leads to increases in storm intensity, proactive protection of riparian floodplains could help reduce the levels of pollutants that are delivered during those floods. Acting now to address this stressor helps enhance ecosystem resistance to impacts of climate change on eutrophication and pollution by toxicants. Floodplains may offer some of the last remaining undeveloped components of our coastal landscape over which transgressive expansion of sea level might occur with minimal human impact, so expanding protected areas of floodplains also helps build resilience of the socioeconomic system. Even during the past two decades, many estuarine watersheds have experienced multiple storms that exceeded standards for “100-year floods,” implying that recomputation and remapping of those hazardous riverine floodplains is already necessary.

7.4.2.2 Sustaining Fisheries and Wildlife Populations

Sustaining fish production and wildlife populations represent important management goals of most national estuaries and essentially all estuaries nationwide. Fisheries are likely to suffer large declines from both of the major processes that affect water quality: (1) loss of tidal marshes associated with rising sea levels, and enhanced incidence of intense storms as these drivers interact with hardened shorelines; and (2) increased frequency, scope, and duration of bottom-water hypoxia arising from stronger stratification of the estuarine water column and greater microbial oxygen demand at higher temperatures.

Marshes and other wetlands perform many valuable ecosystem services (Box 7.1) (Millennium Ecosystem Assessment, 2005), several of which lead to enhanced fish production. Numerous studies have demonstrated the high use of salt marshes by killifish, grass shrimps, and crabs, which are important prey for larger commercially important fishes, and for wading birds at higher trophic levels. Salt marsh habitat supports several endemic species of birds, such as some rails, and small mammals, some of which are on federal or state threatened and endangered lists (Greenberg *et al.*, 2006). The combination of high primary production and structural protection makes the marsh significant as a contributor to important detrital-based food webs based on export of vascular plant detritus from the marsh, and also means that the marsh plays a valuable role as nursery habitat for small fishes and crustaceans. Zimmerman, Minello, and Rozas (2000) demonstrated that penaeid shrimp production in bays along the Gulf of Mexico varies directly with the surface area of the salt marsh within the bay. Maintaining complexity of salt marsh landscapes can also be an important determinant of fish, shellfish, and wildlife production, especially preserving marsh edge environments (*e.g.*, Peterson and Turner, 1994). Thus, marsh loss and modification in estuaries are expected to translate directly into lost production of fish and wildlife.

The climate-driven enhancement of bottom water hypoxia and anoxia will result in further killing of oysters and other sessile bottom invertebrates (Lenihan and Peterson, 1998), thereby affecting the oyster fishery directly and other fisheries for crabs, shrimp, and demersal fishes indirectly (Lenihan *et al.*, 2001). These demersal consumers prey upon the benthic invertebrates of the estuary during their nursery use of the system, in the warm season of the year. When the benthic invertebrates are killed by lack of oxygen and resulting deadly hydrogen sulfide, fish production declines as energy produced by phytoplankton enters microbial loops and is thereby diverted from passing up the food chain to higher tropic levels (Baird *et al.*, 2004). This enhanced diversion of energy away from pathways leading to higher trophic levels will not only affect demersal fish production, but also diminish populations of sea birds and marine mammals, such as bottle-nosed dolphins. Because estuaries contribute so greatly to production of coastal fisheries generally, such reductions in fish and wildlife transcend the boundaries of the estuary itself.

Fish and wildlife suffer additional risks from climate change, beyond those associated with loss of marsh and other shoreline habitats and those associated with enhanced hypoxia. Higher temperatures are already having and will likely have additional direct effects on estuarine species. Increased temperature is associated with lower bioenergetic efficiency, and greater risk of disease and parasitism. As temperatures increase, species will not move poleward at equal rates (Parmesan, 2006), so new combinations will emerge with likely community reorganization, elevating abundances of some fishes and crustaceans while suppressing others. Locally novel native species will appear through natural range expansion as water warms, adding to the potential for community reorganization. In addition, introductions of non-native species may occur at faster rates, because disturbed communities appear more susceptible to invasion. Finally, the changes in riverine flows—both amounts and temporal patterns—may change estuarine physical circulation in ways that affect transport of larval and juvenile life stages, altering recruitment of fish and valuable invertebrates.

The challenges of adapting management to address impacts of climate change on fish and wildlife thus include all those already presented for water quality, because the goals of preventing loss of tidal marsh and other shallow shoreline habitats and of avoiding expansion of hypoxic bottom areas are held in common. However, additional approaches may be available or necessary to respond to risks of declines in fish and wildlife. For example, fisheries management at federal and state levels is committed to the principle of sustainability, which is usually defined as maintaining harvest levels at some fixed amount or within some fixed range. With climate-driven changes in estuarine ecosystems, sustainable fisheries management will itself need to become an adaptive process as changes in estuarine carrying capacity for target stocks occur through direct responses to warming and other physical factors, and indirect responses to changes in biotic interactions. Independent of any fishing impacts, there will be a moving target for many fish, shellfish, and wildlife populations, necessitating adaptive definitions of what is sustainable. This goal calls for advance planning for management responses to climate change, but not implementation until the ecosystem changes have begun. Absent any advance planning, stasis of management could conceivably induce stock collapses by inadvertent overfishing of a stock in decline from climate modifications.

Extermination of injurious non-native species after their introduction into estuarine systems has not proved feasible. However, one proactive type of management adaptation in contemplation of possible enhancement of success of introduced species into climate-disrupted estuarine ecosystems may be to strengthen rules that prevent the introductions themselves. This action would be especially timely as applied to the aquarium fish trade, which is now a likely vector of non-native fish introductions.[25] Local removals of invasive non-natives, combined with restoration of the native species, may be a locally viable reactive management response to improve marsh characteristics that promote propagation and production of fish and wildlife. This type of action may best be applied to vascular plants of the salt marsh. Such actions taken now to reduce impacts of current stressors represent means of enhancing ecosystem resilience to impacts of climate change on fish and wildlife.

7.4.2.3 Preserving Habitat Extent and Functionality

All national estuaries and managers of estuarine assets nationwide identify preservation of habitat as a fundamental management goal. The greatest threat to estuarine habitat extent and function from climate change arises as sea level rise and enhanced incidence of intense storms interact with the presence of structural defenses against shoreline erosion. As explained earlier in the description of threats to water quality and fisheries, barriers that prevent horizontal migration of tidal marshes inland will result in loss of tidal marsh and other intertidal and then shallow subtidal habitats. This process will include losses to seagrass beds and other submerged aquatic vegetation down-shore of bulkheads, because if the grass cannot migrate upslope, the lower margin will die back from light limitation (Dennison *et al.*, 1993; Short and Wyllie-Echeverria, 1996) as water levels rise. The presence of bulkheads enhances the rate of erosion below them because wave energy is directed downwards after striking a hard wall, excavating and lowering the sediment elevation faster than if no bulkhead were present (Tait and Griggs, 1990). As shoreline erosion below bulkheads continues along with rising water levels, all currently intertidal habitat will become covered by water even at low tide, removing those habitats that are most productive, critical for sustaining fish and wildlife, and important to maintaining water quality (Box 7.6). Galbraith *et al*. (2002) modeled this process for installation of dikes on Galveston Island, and concluded that intertidal habitat for shorebirds would decline by 20%. The enhancement of bottom water hypoxia through induction of more intense water column stratification and greater microbial degradation rates at higher temperatures will not eliminate the deeper subtidal habitat of estuaries, but will degrade its functions over wider areas of “dead zones” of the nation’s estuaries as climate change proceeds.

Adaptations to address impacts of climate change on estuarine habitat extent and function face the same challenges as those already presented for water quality, due to common goals of preventing loss of marsh and other shallow shoreline habitats and avoiding expansion of hypoxic bottom areas. However, there may also be additional approaches available or necessary to respond to risks of areal and functional declines in estuarine

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[25] See, for example, **National Ocean Service**, 2005: Lionfish discovery story. NOAA Website, www.oceanservice.noaa.gov/education/stories/lionfish/lion03_blame.html, accessed on 7-25-2007.

habitats. At local levels, expanding the planning horizons of land use planning created in response to the federal Coastal Zone Management Act to incorporate the predictions of consequences of global change over at least a few decades would represent a rational proactive process. Such a longer view could inhibit risky development and simultaneously provide protections for important estuarine habitats, especially salt marshes and mangroves at risk from barriers that inhibit recession. Land use plans themselves rarely incorporate hard prohibitions against development close to sensitive habitats. They also have limited durability over time, as local political pressure for development and desires for protection of environmental assets wax and wane. Nevertheless, requiring planners to take a longer-term view could have only positive consequences in educating local decision makers about what lies ahead under alternative development scenarios. States run ecosystem restoration programs, largely targeted toward riparian wetlands and tidal marshes. The choice of sites for such restoration activities can be improved by strategically selecting only those where the restored wetland can move up-slope as sea level rises. Thus, planning and decision-making for ecosystem restoration may require purchase of upland development rights or property to insure transgression potential, unless that upland is already publicly owned and managed to prevent construction of any impediment to orderly movement. This consideration of building in resilience to future climate change is necessary for compensatory habitat restorations that must mitigate for past losses for any restoration project that is projected to last long enough that recession would occur. In areas that are currently largely undeveloped, legislation requiring establishment of rolling easements represents a more far-reaching solution to preventing erection of permanent barriers to inland migration of tidelands. Rolling easements do not require predictions about the degree and rate of sea level rise and shoreline erosion. Purchasing development rights has the disadvantage that the uncertainty about rate of sea level rise injects uncertainty over whether enough property has been protected. In addition, rolling easements allow use of waterfront property until the water levels rise enough to require retreat, and thus represent a lower cost (Titus, 2000). Implementation of either solution should not be delayed, because delay will risk development of the very zone that requires protection.

At state and federal levels, environmental impact statements and assessments of consequences of beach nourishment do not sufficiently incorporate consideration of climate change and its impacts. Similarly, management policies at state and local levels for responding to the joint risks posed by sea level rise and increased frequencies or intensities of storms, including hurricanes, have not recognized the magnitude of growth in expenditures of present shoreline protection responses as climate change continues. Most state coastal management programs discourage hardening of shorelines, such as installation of sea walls, groins, and jetties, because they result in adverse effects on the extent of the public beach (Pilkey and Wright III, 1988). Beach nourishment, a practice involving repeated use of fill to temporarily elevate and extend the width of the intertidal beach, is the prevailing (Titus, 2000), rapidly escalating, and increasingly expensive alternative. On average, the fill sands last three to five years (Leonard, Clayton, and Pilkey, 1990) before eroding away, requiring ongoing nourishment activities indefinitely. As sea level rises, more sand is needed to restore the desired shoreline position, at escalating cost. The public debate over environmental impacts of and funding for beach nourishment will change as longer-term consequences are considered. Because beach nourishment on coastal barriers inhibits overwash of sediments during storms and the consequent landward retreat of the coastal barrier, erosion of the estuarine shoreline is intensified without this source of additional sediments. Continually elevating the shore of barrier land masses, above their natural level relative to depth on the continental shelf, implies that wave energy will not be as readily dissipated by bottom friction as the waves progress towards shore. This process brings more and more wave energy to the beach, and increases risk of storm erosion and substantial damage to the land mass in major storms.

Within less than a century, the rising sea may induce geomorphological changes historically typical of geological time scales (Riggs and Ames, 2003). These changes include predicted fragmentation of coastal barriers by new inlets, and even disintegration and loss of many coastal barriers (Riggs and Ames, 2003). Such changes would cause dramatic modifications of the estuaries lying now in protected waters behind the coastal barriers, and would shift inland the mixing zone of fresh and salt waters. As climate change progresses and sea level continues to rise, accompanied by more intense hurricanes and other storms, the beach nourishment widely practiced today on ocean beaches (Titus, 2000) may become too expensive to sustain nationwide (Titus *et al.*, 1991; Yohe *et al.*, 1996), especially if the federal government succeeds in withdrawing from current funding commitments. Miami Beach and other densely developed ocean beaches are likely to generate tax dollars sufficient to continue beach nourishment with state and local funding. Demand for groins, geotubes, sand bags, and other structural interventions will likely continue to grow as oceanfront property owners seek protection of their investment. These come at a price of loss of beach, which is the public trust resource that attracts most people to such areas. Retreat from and abandonment of coastal barriers affected by high relative rates of sea level rise and incidence of intense storms does not seem to represent a politically viable management adaptation.

7.4.2.4 Preserving Human Values

All national estuaries recognize that estuaries provide diverse ecosystem services to people living in close proximity and to others who benefit from the estuaries' resources and functions, even passively. This category of human values relies on so many functions that the CCMPs vary widely in terms of the services they highlight and target for special management protection or restoration. Various consequences of climate change will modify these human values, and a complete assessment of how and by how much for each of the diverse values would be extensive. Nevertheless, it is clear that implications of many predictable climate-induced changes in the estuarine ecosystems are serious. Humans have a public trust stake in all other major management targets of the national estuaries, including water quality, fish and wildlife, and habitat, so to that extent we already address issues of perhaps the most importance to human interests in the estuary. However, other human values not expressly included deserve comment. Conflicts between private values of people living on estuarine shores and the public trust values are already evident, but will become increasingly prominent as sea level rises.

Probably the most serious effects of climate change on private human values associated with estuaries are those arising from climate-change-driven increases in shoreline erosion, flooding, and storm damage. Rising sea level and increased incidence of intense storms brings higher risk of extensive loss of real estate, houses, infrastructure, and even lives on estuarine shores. The houses and properties at greatest risk are those on coastal barriers lying between the ocean and outer estuary, because development on such coastal barriers is exposed during major storms to large waves in addition to storm surge and high winds. Economic and social costs of major storm events under conditions of elevated sea level may be staggeringly high, as illustrated by hurricane damage during the past decade. The management of such risks can already be considered proactive: on ocean beaches, nourishment is practiced to widen and elevate the beach, and bulkheads are widely installed on estuarine shorelines. However, each of these defenses is largely ineffective against major storms, and climate change models project more such storms developing on a continually warming Earth. Additional proactive management in the future may involve construction of dikes and levees, designed to withstand major storms and capable of vertical extension as sea level increases. Such intervention into natural processes on ocean and estuarine shores is technically feasible, but probably affordable only where development is intense enough to have created very high aggregate real estate values. It sacrifices public trust values for private values. Long-term sustainability of such barriers is questionable. In places experiencing rapid erosion but lacking dense and expensive development, shoreline erosion is likely to be accepted; retreat and abandonment will occur. Even before extensive further storm-related losses of houses, businesses, and infrastructure on ocean and estuarine shores, property values may deflate as sea level and risks of storm and flood damage increase. Many property insurers are already cancelling coverage and discontinuing underwriting activities along wide swaths of the coast in the areas most at risk to hurricanes, from Texas through New York. State governments are stepping into that void, but policy coverage is far more costly. Availability of mortgage loans may be the next economic blow to coastal development. As losses from storms mount further, the financial risks of home ownership on estuarine shorelines may create decreased demand for property and thus cause declines in real estate demand and values.

Comprehensive planning could be initiated now at federal, tribal, state, and local levels to act proactively, or opportunistically after major storm events, to modify rules or change policies to restructure development along coastal barrier and estuarine shorelines to avoid future loss of life and property, and at the same time protect many environmental assets and ecosystem services in the interest of the public trust. For example, up-front planning to prevent rebuilding in hazardous areas of high flood risk and storm damage may be feasible. Establishing setbacks from the water and buffer widths, based on the new realities of shoreline erosion and on reliable predictions of shoreline position into the future, may be possible if advance planning is complete so that rules or policies can be rapidly implemented after natural disasters. Many programs, such as federal flood insurance and infrastructure development grants, subsidize development. For undeveloped coastal barriers, such subsidies were prohibited by the Coastal Barriers Resources Act, and these prohibitions could be extended to other estuarine and coastal shorelines now at high and escalating risk. Local land use plans could be modified to influence redevelopment after storms and direct it into less risky areas. Nevertheless, such plans would result in financial losses to property owners who cannot make full use of their land. Land trusts and programs to protect water quality, habitat, and fisheries may provide funding to purchase the most risky shorelines of high resource value.

7.4.2.5 Water Quantity

Many national estuaries, especially those on the Pacific coast where snowmelt is a large determinant of the hydroperiod, identify water quantity issues among their management priorities. These issues will become growing concerns directly and indirectly for all estuaries as climate continues to change. Projected climate changes include modifications in rainfall amount and temporal patterns of delivery, in processes that influence how much of that rain falling over the watershed reaches the estuary, and in how much salt intrusion occurs from altered river flows and rising sea levels penetrating into the estuary. These climate changes interact strongly with human modifications of the land and waterways, as well as with patterns of water use and consumption. The models predicting effects of climate change on rainfall amount are not all in agreement, complicating adoption of proactive management measures. Thus, complex questions of adaptive management arise that would help smooth the transition into the predictably different rainfall future, whose direction of change is uncertain. Many of these questions will have site (basin)-specific conditions and solutions; however a generic overview is possible.

As freshwater delivery patterns change and salt water penetration increases in the estuaries, many processes that affect important biological and human values will be affected. Where annual freshwater delivery to the estuary is reduced, and in cases where only seasonal reductions occur, salt water intrusion into groundwater will influence the potable yield of aquifers. In the Pacific Northwest, predicted patterns of precipitation change imply that increased salt water penetration up-estuary will be a summertime phenomenon when droughts are likely. Fresh water is already a limiting resource globally (Postel, 1992), and is a growing issue in the United States even in the absence of climate change. Failure to develop proactive management responses will have serious consequences on human welfare and economic activity. Proaction includes establishing or broadening “use containment areas” (where withdrawal is allocated and capped) in the managed allocation of aquifer yields, so that uses are sustainable even under predicted climate-related changes in recharge rates and salt water infiltration. This may result in the need to develop reverse osmosis plants to produce potable water and replace ground water sources currently tapped to supply communities around estuaries. Further actions may be needed to modify permitting procedures for affected development, plan for growing salt water intrusion as sea level rises, and maintain aquifer productivities. Proactive planning measures for water shortage can include much greater water reuse and conservation.

The enhanced flashiness of runoff from seasonal rainfall events, as they come in discrete, more intense storms, and fall upon more impervious surface area in the drainage basin, will have several consequences on human values and on natural resources of management priority. Greater pulsing of rain runoff reaching the rivers will lead to much higher frequency and extent of floods after intense storms. The resulting faster downstream flows will erode sediment from estuarine shorelines, and thus reduce the area of shallow habitats along the shores. In the Pacific Northwest, rain-on-snow events are major sources of flood waters (Marks *et al.*, 1998; Mote *et al.*, 2003) and are likely to become more frequent and intense under current climate change scenarios. These events have economic, health and safety, and social consequences for humans living or working in the newly enlarged flood plain. Bank stability and riparian habitats are threatened by increased water velocities in flood flows, which would affect water quality and ultimately fish and wildlife. When these pulses of water reach the estuary, they bring pollutants from land as well as nutrient and organic loading that have negative effects on estuarine functions for relatively long periods of time—on the order of a year or more. In estuaries where freshwater runoff is increased by global climate change, and in all estuaries where salt water has penetrated further upstream as sea level rises, the specific locations of important zones of biogeochemical processes and biotic use will shift in location. These shifts may have the effects of moving those zones, such as the turbidity maximum zone, which could influence the performance of anadromous fishes that make use of different portions of the rivers and estuaries for completing different life history stages and processes. Accurate modeling of such position changes in estuaries could allow proactive management to protect fish and wildlife habitats along the rivers and estuaries that will become critical for propagation of important fish stocks as positional shifts occur.

7.4.3 New Approaches to Management in the Context of Climate Change

Historically, little attention has been paid to preserving and enhancing ecosystem resilience in the management of estuaries and estuarine resources. Resilience refers to the amount of disturbance that can be tolerated by a socioecological system (*e.g.,* an estuary plus the social system interacting with it) before it undergoes a fundamental shift in its structure and functioning (Holling, 1972; Carpenter *et al.*, 2001; Gunderson *et al.*, 2002; Carpenter and Kinne, 2003). The ability of a system to maintain itself despite gradual changes in its controlling variables or its disturbance regimes is of particular concern for those interested in predicting responses to climate change. Importantly, resilience of a socioecological system results in part from appropriate management strategies. Human behaviors can reduce resilience in a variety of ways, including increasing flows of nutrients and pollutants; removing individual species, whole functional groups (*e.g.,* seagrasses, bivalves), or whole trophic levels (*e.g.,* top predators); and altering the magnitude, frequency, and duration of disturbance regimes (Carpenter *et al.*, 2001; Folke *et al.*, 2004). Importantly, climate change has the potential to exacerbate poor management and exploitation choices and cause undesirable regime shifts in ecosystems, as seen in the North Sea cod fishery and recent declines in coral reefs (Walther *et al.*, 2002). It is critical that we pursue wise and active adaptive management in order to prevent undesirable regime changes in response to climate change.

In recent years, basic research has dramatically improved our understanding of the ecosystem characteristics that help promote resilience. For example, the study of the roles of biodiversity in ecosystem dynamics has demonstrated several examples where productivity (Tilman and Downing, 1994; Naeem, 2002), biogeochemical functioning (Solan *et al.*, 2004), and community composition (Duffy, 2002; Bruno *et al.*, 2005) are stabilized under external stresses if biodiversity is high. Worm *et al.* (2006) likewise demonstrated that many services of marine ecosystems, including fisheries production, and ecosystem properties, such as resilience, are greater in more diverse systems. Some evidence exists to suggest that proliferation of non-native species can be suppressed by ecosystem biodiversity (*e.g.*, Stachowicz, Whitlatch, and Osman, 1999; but see Bruno *et al.*, 2004). These research results have not yet been directly translated into management of estuarine systems. This represents a potential approach to the goal of enhancing adaptation in contemplation of climate change. However, acting on the knowledge that higher biodiversity implies higher resilience represents a challenge for estuaries, where application of this concept is not necessarily appropriate and where any effectiveness may last only for a few decades given accelerating sea level rise.

Absent system-specific knowledge, some management actions are likely to preserve or enhance biodiversity (genetic, species, and landscape) and thus may support resilience, based upon current theory and some empirical evidence. Maintaining high genetic diversity provides high potential for evolutionary adaptation of species, and provides short-term resilience against fluctuating environmental conditions (Hughes and Stachowicz, 2004). This goal may be achieved by establishing diversity refuges, which in aggregate protect each of a suite of genotypes. Implementing this proactive management concept depends on knowledge of genetic diversity and spatial patterns of its genotypic distribution—a task most readily achieved for structural habitat providers, such as marsh and sea grasses and mangroves. Maintaining or restoring habitat and ecosystem diversity and spatial heterogeneity is another viable management goal, again most applicable to the important plants that provide habitat structure. Preserving or restoring landscapes of the full mix of different systems, and including structural corridors among landscape elements otherwise fragmented or isolated, can be predicted to enhance resilience by establishing replication of systems that can enable migrations to sustain biodiversity across the landscape (Micheli and Peterson, 1999). Structural complexity of vegetation has been related to its suitability for use of some (endangered) species (Zedler, 1993), so preserving or restoring the vegetational layering and structure of tidal marshes, seagrass meadows, and mangroves has potential to stabilize estuary function in the face of climate perturbations. In addition to salt marshes, oyster reefs have been the target of much active restoration. Success is mixed, with many reefs failing the test of sustainability because of insufficient oyster recruitment and early death of adult oysters from disease. Lenihan et al. (2001) demonstrated experimentally that the concept of representation applies well to enhance the resiliency of restored oyster reefs. They constructed more than 100 new oyster reefs along a depth gradient in the Neuse River Estuary, and showed that when persistent bottom-water hypoxia developed during summer, reef fishes were able to feed on reef-associated crustacean prey and survive the widespread mortality on reefs in deeper water by moving to shallow-water reefs, which were within the surface mixed layer. Thus, the creation of a system of reefs with representation in different environmental conditions protected against catastrophic loss of mobile fishes when eutrophication caused mass mortality of oysters and other benthic invertebrates in deeper waters.

Modifications of natural estuarine ecosystems, communities, and species populations through various forms of aquaculture represent human perturbations that may affect resilience of the estuarine ecosystem to climate change. For example, the modification and frequently the reduction in genetic diversity of cultured species can modify the gene pool of wild stocks, probably reducing their capacity for biological adaptation (Goldburg and Triplett, 1997). Flooding a system with unnaturally high densities of a cultured species such as salmon in Maine and Washington, or Pacific oysters in Oregon and Washington, carries risks of promoting disease and of simplifying the natural species composition of the fish and benthic communities respectively, thereby losing the biodiversity and natural balance of the system, which may reduce resilience. On the other hand, culturing species that are currently depleted relative to natural baselines, such as oysters and other suspension-feeding bivalve mollusks, can serve to restore missing ecosystem functions and build resilience to eutrophication (Jackson *et al.*, 2001). Similarly, culturing seaweeds can result in enhanced uptake of nutrients, thereby buffering against eutrophication (Goldburg and Triplett, 1997). Impacts of aquaculture in the estuaries have not been adequately considered in the context of emerging stresses of climate change, and deserve further integration into the ecosystem context (*e.g.*, Folke and Kautsky, 1989).

Analogous need exists for enhanced understanding of factors that contribute to resilience of human communities and of human institutions in the context of better preparation for consequences of changing climate. Both social science and natural science monitoring may require expansion to track possible fragility, and to look for signs of cracks in the system, as a prelude to instigating adaptive management to prevent institutional and ecological disintegration. For example, more attention should be paid to tracking coastal property values, human population movements, demography, insurance costs, employment, unemployment, attitudes, and other critical social and economic variables, in order to indicate need for proactive interventions as climate change stresses increase. An analogous enhancement of in-depth monitoring of the natural ecosystem also has merit; this likely would require changes in indicators now monitored to be able to enhance resilience through active intervention of management when the need becomes evident. Thus, monitoring in a context of greater understanding of organizational process in socioeconomic and natural systems is one means of enhancing resilience.

Both managers and the general public need better education to raise awareness of how important management adaptation will be if negative impacts of climate change are to be averted or minimized. Surely, managers undergo continuing education almost daily as they conduct their jobs, but targeted training on expected changes within the ecosystem they are responsible for managing is an emerging necessity. Careful articulation of uncertainties about the magnitudes, timelines, and consequences of climate change will also be important. Such education is vital to induce the broad conversations necessary for public stakeholders and managers to rethink in fundamental ways how we have previously treated and managed estuaries to provide goods and services of value.

Whereas we have used the term “management adaptation” to mean taking management actions that expressly respond to or anticipate climate change, and that are intended to counteract or minimize any of its negative implications, natural resource managers and academics have developed a different process termed “adaptive management” (Walters, 1986). Adaptive management in this context (see Chapter 9, Synthesis) refers to designing and implementing regulations or other management actions as an experiment, and employing rigorous methods of assessing the impacts of the actions. Monitoring the status of the response variables provides the data against which a management action's effectiveness can be judged. This blending of experimental design into management provides perhaps the most rigorous means of testing implications of management actions. Adaptive management has the valuable characteristic that it continuously re-evaluates the basis on which predictions are made, so that as more information becomes available to reduce the uncertainties over physical and biological changes associated with climate change, the framework of adaptive management is in place to incorporate that new knowledge. Use of this approach where feasible in testing management adaptations to global climate change can provide much-needed insight in reducing uncertainty about how to modify management to preserve delivery of ecosystem services. Unfortunately, this approach is very complex and difficult to implement, in large part because of the multiple and often conflicting interests of important stakeholders.

Because its holistic nature includes the full complexity of interactions among components, the most promising new approach to adapt estuarine management to global climate change is the further development and implementation of ecosystem-based management (EBM) of estuarine ecosystem services, in a way that incorporates climate change expectations (Peterson and Estes, 2001). The concept of EBM has its origins among land managers, where it is most completely developed (Grumbine, 1994; Christensen *et al.*, 1996). EBM is an approach to management that strives for a holistic understanding of the complex of interactions among species, abiotic components, and humans in the system and evaluates this complexity in pursuit of specific management goals (Lee, 1993; Christensen *et al.*, 1996). EBM explicitly considers different scales and thus may serve to meet the challenges of estuarine management, which ranges across scales from national and state planning and regulation to local implementation actions. Practical applications of the EBM approach are now evolving for ocean ecosystems (Pikitch *et al.*, 2004) and hold promise for achieving sustainability of ecosystem services. Both the Pew Oceans Commission (2003) and the U.S. Commission on Ocean Policy (2004) have identified EBM as our greatest hope and most urgent need for preserving ecosystem services from the oceans. The dramatic potential impacts of climate change on estuarine ecosystems imply many transformations that simply developing and applying EBM cannot reverse, but development of synthetic models for management may help optimize estuarine ecosystem services in a changing world. Ecosystems are sufficiently complex that no practical management model could include all components and processes, so the more simplified representations of the estuarine system might best be used to generate hypotheses about the effectiveness of alternative management actions that are then tested through rigorous protocols of adaptive management. One widely advocated approach to implementing EBM is the use of marine protected areas, which does not require an elaborate understanding of ecosystem structure and dynamics (Halpern, 2003; Roberts *et al.*, 2003; Micheli *et al.*, 2004). This approach may be applicable to solving important management challenges in estuaries, especially where fishery exploitation and collateral habitat injury exist; clearly, these issues apply to many estuarine systems.

7.4.4 Prioritization of Management Responses

Setting priorities is important to the development of management adaptations to respond to global climate change. Because responsibilities for managing estuaries are scattered among so many different levels of government and among so many different organizations within levels of government, building the requisite integrated plan of management responses will be difficult. EBM is designed to bring these disparate groups together to achieve the integration and coordination of efforts (Peterson and Estes, 2001). However, implementing EBM for national estuaries and other estuaries may require changes in governance structures and, even then, may prove politically impractical. The State of North Carolina has made progress in bringing together diverse state agencies with management authority for aspects of estuarine fisheries habitats in its Coastal Habitat Protection Plan, which approaches an EBM plan. However, this governance method is targeted toward producing fish, rather than the complete scope of critical estuarine functions and broad suite of estuarine goods and services. This model approach also lacks a mechanism to engage the relevant federal authorities. The national estuaries bring to the table a wider range of managers and stakeholders, including those from federal, tribal, state, and local levels, as are contemplated in the genesis of an EBM plan. However, the CCMPs that arise from the national estuaries do not carry any force of regulation and often lack explicit numerical targets, instead expressing wish lists and goals for improvements that are probably unattainable without substantially more resources and powers. Perhaps the national estuaries could provide the basis for a new integrative governance structure for estuaries that could be charged with setting priorities among the many management challenges triggered by climate change.

Factors that probably would dictate priorities are numerous, including socioeconomic consequences of inaction, feasibility of effective management adaptations, the level of certainty about the projected consequence of climate change, the time frame in which action is best taken, the popular and political support for action, and the reversibility of changes that may occur in the absence of effective management response. Clearly, the processes that threaten to produce the greatest loss of both natural ecosystem services and human values are the rise of sea level and ascendancy of intense storms, with implications for land inundation, property loss, habitat loss, water quality degradation, declines in fisheries and in wildlife populations associated with shallow shoreline habitats, and salt water intrusion into aquifers. These issues attract the most attention in the media and from the public, but the global capping of greenhouse gases may not represent a feasible management response. Thus, removing and preventing engineered shoreline armoring such as bulkheads, levees, and dikes, combined with shoreline property acquisition, may be the focus of discussion if their costs are not an overwhelming impediment. Because the complexity of intermingled responsibilities for managing interacting components inhibits establishment of EBM, attention to modifying governance structures to meet this crisis would also rank high among priorities.

7.5 Conclusions

7.5.1 Management Response

(1) Maintaining the status quo in management of estuarine ecosystems would result in substantial losses of ecosystem services as climate change progresses.

(2) In the absence of effective management adaptation, climate-related failures will appear in all of the most important management goals identified in the CCMPs of national estuaries: maintaining water quality, sustaining fish and wildlife populations, preserving habitat, protecting human values and services, and fulfilling water quantity needs.

(3) Changes in the climate system would continue into the future even if global reductions in greenhouse gas emission were to be implemented today; thus, impacts of climate change and sea level rise, in particular, are inevitable. As an example, climate change impacts on sea level are already evident in the growing demand for and costs of beach nourishment.

(4) Many of the anticipated consequences of climate change occur via mechanisms involving interactions among stressors, and therefore may not be widely appreciated by policy makers, managers, stakeholders, and the public. The magnitude of such interactive effects typically declines as each stressor is better controlled, so enhanced management of traditional estuarine stressors has value as a management adaptation to climate change as well.

(5) Among the consequences of climate change that threaten estuarine ecosystem services, the most serious involve interactions between climate-dependent processes and human responses to climate change. In particular, conflicts arise between sustaining public trust values and private property, in that current policies protecting private shoreline property become increasingly injurious to public trust values as climate changes and sea level rises further.

(6) Many management adaptations to climate change to preserve estuarine services can be achieved at all levels of government at modest expense. One major form of adaptation involves recognizing the projected consequences of sea level rise and then applying policies that create buffers to anticipate associated consequences. An important example would be redefining riverine flood hazard zones to match the projected expansion of flooding frequency and extent.

(7) Other management adaptations can be designed to build resilience of ecological and social systems. These adaptations include choosing only those sites for habitat restoration that allow natural recession landward, thus providing resilience to sea level rise.

(8) Management adaptations to climate change can occur on three different time scales: (a) reactive measures taken in response to observed negative impacts; (b) immediate development of plans for management adaptation to be implemented later, either when an

indicator signals that delay can occur no longer, or in the wake of a disastrous consequence that provides a window of socially feasible opportunity; or (c) immediate implementation of proactive policies. The factors determining which of these time frames is appropriate for any given management adaptation include balancing costs of implementation with the magnitude of risks of injurious consequences under the status quo of management; the degree of reversibility of negative consequences of climate change; recognition and understanding of the problem by managers and the public; the uncertainty associated with the projected consequences of climate change; the timetable on which change is anticipated; and the extent of political, institutional, and financial impediments.

(9) A critical goal of monitoring is to establish and follow indicators that signal approach toward an ecosystem threshold that—once passed—implies passage of the system into an alternative state from which conversion back is difficult. One example of such ecosystem conversions involves nitrogen-induced conversion from an estuary dominated by submersed benthic grasses to an alternative dominated by seaweeds and planktonic microalgae. Avoiding conversion into such alternative states, often maintained by positive feedbacks, is one major motivation for implementing proactive management adaptation. This is especially critical if the transition is irreversible or very difficult and costly to reverse, and if the altered state delivers dramatically fewer ecosystem services. Work to establish environmental indicators is already being done in national estuaries, and can be used to monitor climate change impacts.

(10) One critically important management challenge is to implement actions to achieve orderly retreat of development from shorelines at high risk of erosion and flooding, or to preclude development of undeveloped shorelines at high risk. Such proactive management actions have been inhibited in the past by: (a) uncertainty over or denial of climate change and its implications; (b) failures to include true economic, social, and environmental costs of present policies allowing and subsidizing such risky development; and (c) legal tenets of private property rights. One possible proactive management option would be to establish and enforce "rolling easements" along estuarine shorelines as sea level continues to rise, thereby sustaining the public ownership of tide lands.

(11) Management adaptation to climate change may include ending public subsidies that now support risky development on coastal barrier and estuarine shores at high risk of flooding and storm damage as sea level rises further and intense storms are more common. Although the flood insurance system as a whole may be actuarially sound, current statutes provide people along the water's edge in eroding areas of highest risk with artificially low rates, subsidized by the flood insurance policies of people in relatively safe areas. Ending such subsidization of high-risk developments would represent a form of management adaptation to sea level rise. The federal Coastal Barriers Resources Act provides some guidance for eliminating such subsidies for public infrastructure and private development, although this act applies only to a list of undeveloped coastal barriers and would require extension to all barriers and to estuarine shorelines to enhance its effectiveness as an adaptation to climate change.

(12) Building upon ongoing efforts to operationalize ecosystem-based management (EBM) for oceans, analogous research is required for estuarine ecosystems. This research needs to address a major intrinsic impediment to EBM of estuarine services, which is the absence of a synthetic governance structure that unites now disparate management authorities, stakeholders, and the public. The U.S. Commission on Ocean Policy appealed for just this type of modification of governance structure to serve to implement EBM. EBM is necessary to facilitate management of interacting stressors, an almost ubiquitous condition for estuaries, because under present governance schemes management authority is partitioned among separate agencies or entities. Although national estuaries lack regulatory authority, they do unite most, if not all, stakeholders and could conceivably be reconstructed as quite different entities to develop and implement EBM. Such coordination among diverse management authorities must involve land managers in order to incorporate a major source of inputs to estuaries. Under changing climate, scales of management actions ultimately extend upward to include need for international collaboration, placing even greater challenges to implementation of EBM.

(13) Using the Albemarle-Pamlico National Estuarine Program as a case study illustrates several management challenges posed by changing climate (see Case Study Summary 7.1). Risks of rising sea level, together with increases in intense storms, pose a serious threat to the integrity of the Outer Banks and thus to the character of the Albemarle and Pamlico Sounds, which are now sheltered and brackish, possessing little astronomical tide. A state analog to EBM, the Coastal Habitat Protection Plan, unifies state agencies to provide synthetic protection for fish habitats. This provides a model on which to base further development and application of estuarine EBM. The Legislature of the State of North Carolina established a study commission to report on the consequences of climate change and to make recommendations for management responses. This procedure too can form a model for other states and the federal government through the NEP. Although the Albemarle-Pamlico National Estuary is among the estuaries most sensitive to climate change, in large part because of the huge area of low-lying wetlands along the estuarine shorelines, and has an active management planning process in place, the absence of explicit adaptive management consideration in its CCMP reflects a need for attention to this issue by all national estuaries.

(14) Include climate change sensitivity, resilience, and adaptation responses as priorities on all relevant funding programs at state and federal levels. In the absence of such actions, for example, climate impacts on estuarine wetlands will likely violate the national “no-net-loss of wetlands” policy, which underwrites the current application of the Clean Water Act, in two ways: (a) wetland loss due to climate change will increasingly compound the continuing loss of wetlands due to development and inadequate mitigation; and; (b) measures used to protect human infrastructure from climate impacts will prevent wetland adaptation to climate change.

(15) Review all federal and state environmental programs to assess whether projected consequences of climate change have been considered adequately, and whether adaptive management needs to be inserted to achieve programmatic goals. For example, Jimerfield *et al.* conclude that “There clearly needs to be [a] comprehensive approach by federal

agencies and cooperating scientists to address climate change in the endangered species recovery context. The current weak and piece-meal approach will waste precious resources and not solve the problem we are facing."[16]

7.5.2 Research Priorities

7.5.2.1 Conceptual Gaps in Understanding

(1) There is urgent need for further study of factors affecting sea level rise that may be significant, but now remain so uncertain that they cannot yet be included in IPCC projections. This especially includes enhancing our understanding of processes and rates of melting of Antarctic and Greenland ice sheets as a function of changing temperature and other coupled climatic conditions. Furthermore, it is important to resolve uncertainties about the fate of water in liquid phase released from the Greenland ice sheet, which involves the ability to project how land surface levels will respond to release from the weight of ice cover.

(2) Our understanding of processes affecting elevation change in land masses needs to be enhanced generally, so that risk of flooding, shoreline erosion, and storm damage can be better based upon geography-specific predictions of change in relative sea level, which combines rate of eustatic sea level change with land subsidence or emergence rate.

(3) Quantitative monitoring and research should be established in some model estuarine systems to develop mechanistic understanding of changes projected as consequences of climate change. Many climate change drivers (*e.g.,* CO_2 concentration, ocean temperature at the surface and with depth, sea level) are currently monitored. However, projected consequences (*e.g.,* shoreline erosion rates; estuarine physical circulation patterns; water column stratification and extent of hypoxia; species range extensions and subsequent consequences of interactions within these new combinations of predators, prey, and competitors; the incidence and impacts of disease and parasitism) require new targeted monitoring and research efforts to fill the many conceptual gaps in our understanding of these processes.

(4) Integrated, landscape-scale numerical modeling will have to become a fundamental tool to predict potential estuarine responses to the complex and often interacting stressors induced by climate change. For instance, in most cases significantly modified hydrology and sediment transport predictions will need to be linked at the estuarine interface to sea level and storm (wind/wave regime) predictions in order to evaluate the interactive effects on sediment accretion and erosion effects in estuarine marshes. Models will have to take into account complex aspects such as changes in contribution of snowmelt and rain-on-snow to timing, magnitude and hydroperiod of river discharges (*e.g.*, Mote, 2006), changes in storm tracks (*e.g.*, Salathé, 2006), changes in sediment loading to and circulation within estuaries, and how river management and regulation will be a factor (Sanchez-Arcilla and Jimenez, 1997) Ultimately, these models will need to be tied to coastal management models and other tools that allow assessment of both climate change and human response and infrastructure response.

(5) Research is needed on alternative implementation mechanisms, costs, and feasibility of achieving some form of coastal realignment, probably involving rolling easements. This would include legal, social, and cultural considerations in alternative methods of resolving or minimizing conflicts between public trust and private property values, in context of building resilience to climate change by requiring rolling easements for development in now largely undeveloped waterfront and riparian areas at risk of flooding, erosion, and storm damage.

7.5.2.2 Data Gaps

There is great need for socioeconomic research and monitoring on how social and economic variables and systems are changing, and likely to change further, in coastal regions as sea level rises. This includes developing better information on economic, social, and environmental costs of estuarine-relevant management policies under global climate change. Economic and social impacts of the growing abandonment of risky coastal areas by property insurers, and the possible future challenges in finding mortgage loans in such regions, may be important inputs into decisions on regulating development and redevelopment of such areas.

7.5.2.3 Governance Issues

(1) As stated in Management Response recommendation 12 above, a synthetic governance structure that unites now disparate management authorities, stakeholders and the public may be needed to address major impediments to EBM of estuarine services. Because of its reliance on stakeholder involvement, a restructured NEP could represent a vehicle for developing and implementing EBM.

(2) EBM of estuaries involves at minimum an approach that considers the entire drainage basin. Management plans to control estuarine water quality parameters sensitive to eutrophication, for example, must take a basin-wide approach to develop understanding of how nutrient loading at all positions along the watershed is transferred downstream to the estuary. Basin-scale management by its very nature thus prospers from uniting local governments across the entire watershed to develop partnerships that coordinate rule development and implementation strategies. Often trading programs (*e.g.*, non-point source pollution “credits”) are available that allow economies to be realized in achieving management goals. To this end of facilitating management adaptation to climate change, new ecologically based partnerships of local governments could be promoted and supported.

7.5.2.4 Tool Needs

(1) New and enhanced research funds need to be invested in development and implementation of estuarine observing systems that are currently in a planning stage, such as NEON, ORION, US IOOS, and others. These observing systems need full integration with global coastal observing programs and the Global Earth Observation System of Systems. Whereas physical and chemical parameters lend themselves to automated monitoring by remote sensing and observing system platforms, more basic technological research is also necessary to allow monitoring of key biological variables

as part of these observing systems. Furthermore, it is critical that current efforts to develop monitoring systems in coastal ocean waters be brought into estuaries and up into their watersheds, where the largest human populations concentrate and where ecosystem values are most imperiled.

(2) New, more complete, interdisciplinary models are needed to project social, economic, and cultural consequences of alternative management scenarios under projected consequences of climate change. These models include decision tools that are accessible by and applicable to managers and policy makers at all levels of government.

(3) New tools are required to enhance local capacity for developing and implementing management adaptations in response to climate change, including especially the ability to use alternative scenarios to produce more effective local land-use planning.

(4) New tools are not enough: older, well-accepted tools must be used more effectively. Government agencies responsible for monitoring the environment have been reducing their commitment to this mission because of funding cuts. Extending historical records of environmental conditions is now even more urgent as a means of detecting climate change.

7.5.2.5 Education

(1) Urgent need exists to inform policy makers, managers, stakeholders, and the public about the specific evidence of climate change and its predicted consequences on estuaries. Education on the scale necessary will require new initiatives that make use of a variety of media tools, and that provide the public with accurate and unbiased information. Effective efforts must involve diverse suites of educational media including information delivery on evolving platforms such as the internet and cell phones. The information cannot reach far enough or rapidly enough if restricted to traditional delivery in school curricula and classes, but must propagate through churches, civic organizations, and entertainment media. Such education is particularly challenging and requires creative approaches.

(2) One goal of education about implications of climate change for estuaries is to build capacity for local citizen involvement in decision making. This is particularly important because of the dramatic changes required to move from management-as-usual to adaptive management. Especially challenging is the process of reconsideration of developing and redeveloping shorelines at risk of flooding, erosion, and storm damage.

(3) Some countries and states provide periodic assessments of the state of their environment. Monitoring data from many national estuaries often now serve this goal when placed in a sufficiently long time frame that extends back before establishment of the NEP. Similar scoreboards relating the status of stressors associated with climate change and of the consequences of climate change might be valuable additions to websites for all national estuaries and for our country’s estuaries more broadly. To illustrate these aspects of climate change, longer-term records are required than those typically found in state of environment reports. One simple example would be provision

of empirical data on sea level from local recording stations. Similarly, maps of historical shoreline movement would provide the public with a visual indication of site-specific risks. Historical hurricane tracks are similarly informative and compelling.

7.6 Appendix

Federal Legislation for Protection and Restoration of Estuaries

LEGISLATION	AS IT PERTAINS TO ESTUARIES	Link
Clean Water Act (1972, 1977, 1981, 1987)	Authorizes EPA to implement pollution control programs; established the basic structure for regulating discharges of pollutants and requirements to set water quality standards for all contaminants in surface waters.	http://www.epa.gov/region5/water/cwa.htm
• Sec. 320 National Estuary Program (1987)	Authorizes EPA to develop plans for improving or maintaining water quality in estuaries of national significance including both point and nonpoint sources of pollution.	http://www.epa.gov/owow/estuaries/
• Sec. 404. Permits for Dredged or Fill Materials (1987)	Authorizes the Corps of Engineers (U.S. Army) to issue permits for the discharge of dredged or fill material into the navigable waters at specified disposal sites.	http://www.epa.gov/owow/wetlands/
• SEC. 601 State Water Pollution Control Revolving Funds (1987)	Authorizes EPA to capitalize state grants for water pollution control revolving funds for (1) for construction of public treatment facilities (2) for management program under section 319 (nonpoint source), and (3) for conservation and management plans under section 320 (NEP).	http://www.epa.gov/owm/cwfinance/
Coastal Zone Management Act (1972)	Provides grants to states that develop and implement federally approved coastal zone management plans; allows states with approved plans the right to review federal actions; authorizes the National Estuarine Research Reserve System.	http://www.legislative.noaa.gov/Legislation/czma.html

LEGISLATION	AS IT PERTAINS TO ESTUARIES	Link
National Environmental Policy Act (NEPA) (1969)	Establishes national environmental policy for the protection, maintenance, and enhancement of the environment; integrates environmental values into decision making processes; requires federal agencies to integrate environmental values into their decision making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions.	http://www.epa.gov/compliance/nepa/
Magnuson-Stevens Fishery Conservation and Management Act (1996, amended)	Provides for the conservation and management of the fishery resources; ensures conservation; facilitates long-term protection of essential fish habitats; recognizes that one of the greatest long-term threats to the viability of fisheries is the continuing loss of marine, estuarine, and other aquatic habitats; promotes increased attention to habitat considerations.	http://www.nmfs.noaa.gov/sfa/
Endangered Species Act (1973)	Provides a means for ecosystems, upon which endangered species and threatened species depend, to be conserved; applicants for permits for activities that might harm endangered species must develop a Habitat Conservation Plan, designed to offset any harmful effects of the proposed activity.	http://www.fws.gov/Endangered/
National Flood Insurance Program (1968)	Component of FEMA that makes federally backed flood insurance available to homeowners, renters, and business owners in ~20,000 communities who voluntarily adopt floodplain management ordinances to restrict development in areas subject to flooding, storm surge or coastal erosion; identifies and maps the Nation’s floodplains.	http://www.fema.gov/business/nfip/

LEGISLATION	AS IT PERTAINS TO ESTUARIES	Link
Nonindigenous Aquatic Nuisance Prevention and Control Act (1990)	Provides means to prevent and control infestations of the coastal inland waters of the United States by nonindigenous aquatic nuisance species, control of ballast water, and allows for development of voluntary State Aquatic Nuisance Species Management Plans.	http://nas.er.usgs.gov/links/control.asp
Coastal Barrier Resources Act (CBRA) (1982)	Designates various undeveloped coastal barrier islands for inclusion in the Coastal Barrier Resources System. Areas so designated are made ineligible for direct or indirect federal financial assistance that might support development, including flood insurance, except for emergency life-saving activities.	http://www.fws.gov/habitatconservation/coastal_barrier.htm

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7.8 Acknowledgements

Workshop Participants

- Mark Alderson, Sarasota Bay Project
- Carol Auer, National Oceanic and Atmospheric Administration
- Rich Batiuk, U.S. Environmental Protection Agency
- Dean E. Carpenter, Albemarle-Pamlico National Estuary Program
- Derb Carter, Southern Environmental Law Center
- Holly Greening, Tampa Bay Estuary Program
- Michael J. Kennish, Rutgers University
- Karen L. McKee, U.S. Geological Survey National Wetlands Research Center
- Doug Rader, Environmental Defense
- Curtis J. Richardson, Duke University
- Stan Riggs, East Carolina University
- Ron Shultz, Puget Sound Water Quality Action Team
- Jan Smith, Massachusetts Bays National Estuary Program
- Katrina Smith Korfmacher, University of Rochester

7.9 Boxes

Box 7.1. Ecosystem services provided by coastal wetlands, adapted from the Millennium Ecosystem Assessment (2005).

1. Habitat and food web support
    - High production at base of food chain
        - Vascular plants
        - Microphytobenthos
        - Microbial decomposers
        - Benthic and phytal invertebrates (herbivores and detritivores)
    - Refuge and foraging grounds for small fishes and crustaceans
    - Feeding grounds for larger crabs and fishes during high water
    - Habitat for wildlife (birds, mammals, reptiles)
2. Buffer against storm wave damage
3. Shoreline stabilization
4. Hydrologic processing
    - Flood water storage
5. Water quality
    - Sediment trapping
    - Nutrient cycling
    - Chemical and metal retention
    - Pathogen removal
6. Biodiversity preservation
7. Carbon storage
8. Socioeconomic services to humans
    - Aesthetics
    - Natural heritage
    - Ecotourism
    - Education
    - Psychological health

Box 7.2. Estuarine properties and the climate-driven processes that affect them. The order of the properties and processes is a subjective ranking of the importance of the property and the severity of the particular process.

Semi-enclosed geomorphology is affected by:
- sea level rise – (Rahmstorf, 2007)
- storm intensity – (Emanuel, 2005)
- storm frequency – (Emanuel, 2005)
- storm duration – (Emanuel, 2005)
- sediment delivery – (Cloern *et al.*, 1983)

Fresh water inflow is affected by:
- watershed precipitation – (Arora, Chiew, and Grayson, 2000)
- system-wide evapotranspiration – (Arora, Chiew, and Grayson, 2000)
- timing of maximum runoff – (Ramus et al., 2003)
- groundwater delivery – (Wolock and McCabe, 1999)

Water column mixing is affected by:
- strength of temperature-driven stratification – (Li, Gargett, and Denman, 2000)
- strength of salinity-driven stratification – (Li, Gargett, and Denman, 2000)
- wind velocity – (Li, Gargett, and Denman, 2000)

Water temperature is affected by:
- air temperature via sensible heat flux – (Lyman, Willis, and Johnson, 2006)
- insolation via radiant heat flux – (Lyman, Willis, and Johnson, 2006)
- temperature of fresh water runoff – (Arora, Chiew, and Grayson, 2000)
- temperature of ocean seawater advected into the estuary – (Lyman, Willis, and Johnson, 2006)

Salinity is affected by:
- exchange with the ocean – (Griffin and LeBlond, 1990)
- evaporation from estuary or lagoon – (Titus, 1989)

Box 7.3. "Novel" stressors resulting from climate change, together with a listing of potential biological responses to these stressors. The most important of these changes are highlighted in the main text. Not included are increases in sea levels and modifications in geomorphology of estuarine basins (barrier island disintegration), which are of utmost importance but act through complex interactions with other factors, as explained in the text.

Temperature increases, acting through thermal physiology, may cause:
- altered species (fauna and flora) distributions, including expanding ranges for tropical species currently limited by winter temperatures and contracting ranges due to increased mortality via summer temperatures
- altered species interactions and metabolic activity
- altered reproductive and migration timing
- increased microbial metabolic rates driving increased hypoxia/anoxia
- increased desiccation lethality to intertidal organisms
- increased roles of disease and parasitism
- all of the above open niches for invasive species

Timing of seasonal temperature changes, acting through phenology, disrupts:
- predator and prey availability
- food and reproductive pulses
- runoff cycle and upstream migration
- temperature-driven behavior from photoperiod-driven behavior
- biological ocean-estuary exchanges (especially of larvae and juveniles)

CO_2 increases drive acidification (lowered pH), forcing:
- reduced carbonate deposition in marine taxa
- greatly increased coral reef dieoff
- reduced photosynthetic rates
- increased trace metal toxicity

Box 7.4. Adaptation Options for Resource Managers

- Help protect tidal marshes from erosion with oyster breakwaters and rock sills, and thus preserve their water filtration and fisheries enhancement functions.
- Preserve and restore the structural complexity and biodiversity of vegetation in tidal marshes, seagrass meadows, and mangroves.
- Adapt protections of important biogeochemical zones and critical habitats as the locations of these areas change with climate.
- Prohibit bulkheads and other engineered structures on estuarine shores to preserve or delay the loss of important shallow-water habitats, by permitting their inland migration as sea levels rise.
- Connect landscapes with corridors to enable migrations to sustain wildlife biodiversity across the landscape.
- Conduct integrated management of nutrient sources and wetland treatment of nutrients to limit hypoxia and eutrophication.
- Manage water resources to ensure sustainable use in the face of changing recharge rates and saltwater infiltration.
- Maintain high genetic diversity through strategies such as the establishment of reserves specifically for this purpose.
- Maintain landscape complexity of salt marsh landscapes, especially preserving marsh edge environments.
- Support migrating shorebirds by ensuring protection of replicated estuaries along the flyway.
- Restore important native species and remove invasive non-natives to improve marsh characteristics that promote propagation and production of fish and wildlife.
- Direct estuarine habitat restoration projects to places where the restored ecosystem has room to retreat as sea level rises.
- Restore oyster reefs in replication along a depth gradient to provide shallow water refugia for mobile species, such as fish and crustaceans, to retreat to in response to climate-induced deep water hypoxia/anoxia, or to spread the risk of losses due to other climate-related environmental disturbances.
- Develop practical approaches to apply the principle of rolling easements, to prevent engineered barriers from blocking landward retreat of coastal marshes and other shoreline habitats as sea level rises.

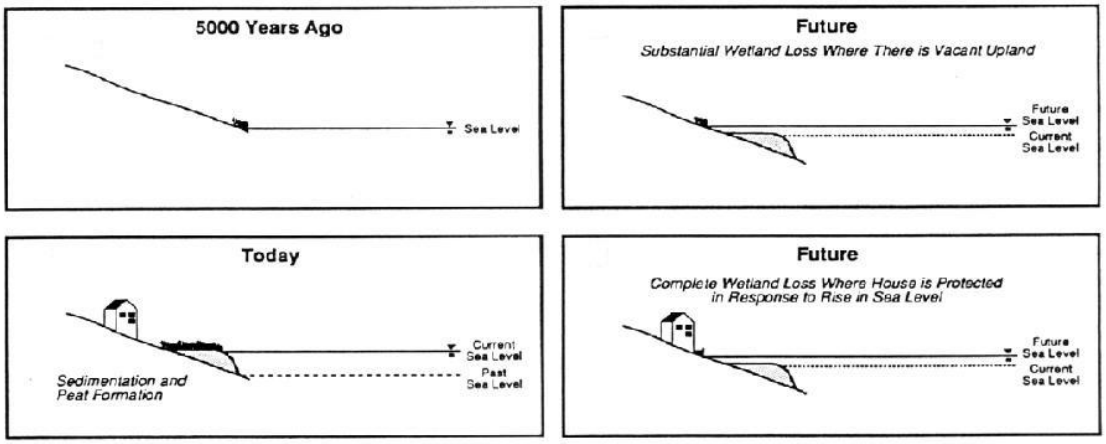
Box 7.5. Storms as Opportunities for Management Change

Catastrophic events provide management opportunities that make difficult decisions more publicly acceptable for increasing ecological and human resilience to climate change. Comprehensive planning could be initiated at federal, tribal, state, and local levels before—and applied after—major storm events to avoid future loss of life and property, and at the same time protect many environmental assets and ecosystem services in the interest of the public trust. Examples of proactive management activities include:

- Planning to prevent rebuilding in hazardous areas of high flood risk and storm damage.
- Establishing setbacks, buffer widths, and rolling easements based on reliable projections of future erosion and sea level rise, and implementing them rapidly after natural disasters.
- Prohibiting development subsidies (*e.g.*, federal flood insurance and infrastructure development grants) to estuarine and coastal shorelines at high risk.
- Modifying local land use plans to influence redevelopment after storms and direct it into less risky areas.
- Using funds from land trusts and programs designated to protect water quality, habitat, and fisheries, to purchase the most risky shorelines of high resource value.

Box 7.6 Responding to the Risk of Coastal Property Loss

The practice of protecting coastal property and infrastructure with hard engineered structures, such as bulkheads, prevents marshes and beaches from migrating inland as the sea level rises. Ultimately, many marshes and beaches seaward of bulkheads will disappear as sea level rises (Titus, 1991).



Coastal marshes have generally kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands have been inundated. If, in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract. Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas.

Beach nourishment may also contribute to the loss of salt marsh on coastal barriers, because it prevents natural processes of coastal barrier migration through overwash. Overwash of sediments to the estuarine shoreline is a process that extends and revitalizes salt marsh on the protected side of coastal barriers.

Box 7.7 Estuarine Water Quality and Climate Change

Climate change may lead to changes in estuarine water quality, which in turn would affect many of the vital ecosystem services offered by estuaries.

- Changes in nutrient concentrations and light penetration into estuarine waters may affect productivity of submerged aquatic vegetation, which provides a range of services such as nursery habitat for fish species, sediment stabilization, and nutrient uptake.
- Changes in water quality may affect oxygen demand as well as directly affecting availability of dissolved oxygen. An increase in freshwater discharge to estuaries may lead to increased frequency, scope, and duration of bottom-water hypoxia arising from stronger stratification of the estuarine water column and greater microbial oxygen demand at higher temperatures.

7.10 Case Study Summary

The summary below provides an overview of the case study prepared for this chapter. The case study is available in Annex A5.

Case Study Summary 7.1

Albemarle-Pamlico National Estuary Program, North Carolina

Southeast United States

Why this case study was chosen

The Albemarle-Pamlico National Estuary:

- Possesses more low-lying land within 1.5 m of sea level than any other national estuary;
- Is expected to lose large areas of wetlands and coastal lands to inundation, according to sea level rise projections;
- Faces projected disintegration of the protective coastal barrier of the Outer Banks of North Carolina and conversion to an oceanic bay, if the integrity of the banks is breached;
- Has a Coastal Habitat Protection Plan for fisheries enhancement (mandated under the state's Fisheries Reform Act in 1997), which provides a model opportunity for integrating climate change into an ecosystem-based plan for management adaptation.

Management context

The Albemarle-Pamlico system is a large complex of rivers, tributary estuaries, extensive wetlands, coastal lagoons, and barrier islands. It became part of the National Estuary Program in 1987. Initial efforts focused on assessments of the condition of the system through the Albemarle-Pamlico Estuarine Study. Assessment results were used in the stakeholder-based development of a Comprehensive Conservation and Management Plan (CCMP) in 1994. The CCMP presented objectives for plans in five areas: water quality, vital habitats, fisheries, stewardship, and implementation. Although long-term solutions to climate change are not specifically addressed in the Coastal Habitat Protection Plan, it does contemplate several anticipated impacts of climate change and human responses to threats.

Key climate change impacts

- Observed rise in mean sea level (current rate of relative sea level rise estimated at over 3 mm per year);
- Projected increase in interannual variability of precipitation;
- Projected increase in frequency of intense storms;
- Observed increase and projected future increase in water temperatures.

Opportunities for adaptation

- The Coastal Habitat Protection Plan ongoing process provides a means for adaptation planning across management authorities that can overcome historic constraints of compartmentalization.
- A recently established (2005) state commission on effects of climate change provides opportunity for education and participation of legislators, in a forward-looking planning process that can address issues with time frames that extend well beyond a single election cycle.
- Sparse human populations and low levels of development along much of the interior mainland shoreline of the Albemarle-Pamlico National Estuary provide openings for implementation of policies that protect the ability of the salt marsh and other shallow-water estuarine habitats to retreat as sea level rises. (Implementing the policies required to achieve this management adaptation would be extremely difficult in places where development and infrastructure are so dense that the economic and social costs of shoreline retreat are high.)

- Rolling easements and other management adaptations to climate change could be promoted by the Clean Water Management Trust Fund and the Ecosystem Enhancement Program of North Carolina.

Conclusions

Community education and continuous dialogue with stakeholders are critically important in this situation, where the most economically valuable part of the ecosystem (the coast) is also the most vulnerable to climate. In estuaries, the human interest in protecting the shoreline from change is in direct conflict with the need for the shallow marshlands to transgress. Thus, the Albemarle-Pamlico National Estuary Program's stakeholder-driven process is well suited to catalyze necessary dialog on planning issues and thereby encourage legislative or regulatory actions to adapt to climate change.

The Coastal Habitat Protection Plan process provides a model on which to base further development and application of estuarine ecosystem-based management. Similarly, the North Carolina study commission established to report on the consequences of climate change and to make recommendations for management responses can serve as a model for other states and the National Estuary Program to synthesize information on climate change impacts and adaptation measures.

Finally, even the Albemarle-Pamlico National Estuary Program, which is among the most sensitive estuaries to climate change and is equipped with an active management planning process, does not explicitly include climate change adaptation measures in its Comprehensive Conservation and Management Plan. This highlights the need for increased attention to this issue by the National Estuary Program.

7.11 Tables

Table 7.1. The major stressors currently acting on estuaries, and their expected impacts on management goals, as determined by consensus opinion of the contributing authors. Evidence is mounting that sea level rise is already having direct and indirect impacts on estuaries (*e.g.*, Galbraith *et al.*, 2002), but because this factor has not yet been widely integrated into management, we do not list it here despite its dominating significance in future decades.

Stressor	Water Quality	Fisheries	Habitat	Human Value & Welfare	Water Quantity
Excess Nutrients	negative	positive then negative	positive then negative	positive then negative	
Sediments	negative	positive **or** negative	positive **or** negative	negative	
Pathogens	negative	negative		negative	
Oyster Loss & Habitat Destruction	negative	negative	negative	negative	
Benthic Habitat Disturbance	negative	positive **or** negative	positive then negative	negative	
Wetland Habitat Loss from Development	negative	negative	negative	positive **or** negative	positive **or** negative
Toxics	negative	negative	negative	negative	
Invasive Species	positive **or** negative	positive **or** negative	positive **or** negative	positive **or** negative	
Thermal Pollution	positive then negative **or** down	positive then negative	pos then negative **or** down	positive then negative	
Biological Oxygen Demand (BOD)	negative	negative	negative	negative	

Table 7.2. Percentage change in oceanic properties or processes as a result of climate change forcing by 2050. This table is adapted from Sarmiento *et al.* (2004). Physical changes used as inputs to the biological model are the mean of six global Atmosphere-Ocean Coupled General Circulation Models (AOCGCMs) from various laboratories around the world. The AOCGCMs were all forced by the IPCC IS92a scenario, which has atmospheric CO_2 doubling by 2050.

	Percentage Change by 2050 due to Climate Change Forcing					
Domain	Mixed layer	Upwelling volume	Vertical stratification	Growing season	Chlorophyll concentration	Primary productivity
marginal ice zone	-41	-10	+17	-14	+11	+18
subpolar gyre, seasonally stratified	-22	+1	+11	+6	+10	+14
subtropical gyre, seasonally stratified	-12	-6	+13	+2	+5	+5
subtropical gyre, permanently stratified	nd*	-7	+8	0	+3	-3
low-latitude and equatorial upwelling	nd*	-6	+11	0	+6	+9

*no data

Table 7.3. Effects of emerging or enhanced stressors on estuaries arising from climate change.

Stressor	**Water Quality**	**Fisheries& Wildlife**	**Habitat**	**Human Value & Welfare**	**Water Quantity**
Sea Level Rise (shoreline armoring prevents transgression of habitats)	positive **then** negative	positive **then** negative	positive then negative	negative	negative
Increased Intensive Storms (shoreline erosion; pulsed floods and runoff)	negative	negative	negative	negative	
Temperature Increases (new species mix; disease and parasitism increase, phenology mismatch)	positive **then** negative	positive **then** negative	positive then negative	positive **then** negative	
Increased CO_2 and Acidification (CaCO3 deposition inhibited)	negative	negative	negative	negative	
Precipitation Change (stratification changes)	negative	positive **or** negative	positive **or** negative	positive **or** negative	positive **or** negative
Species Introduction (facilitated by disturbance)	unpredictable	positive **or** negative	positive **or** negative	positive **or** negative	

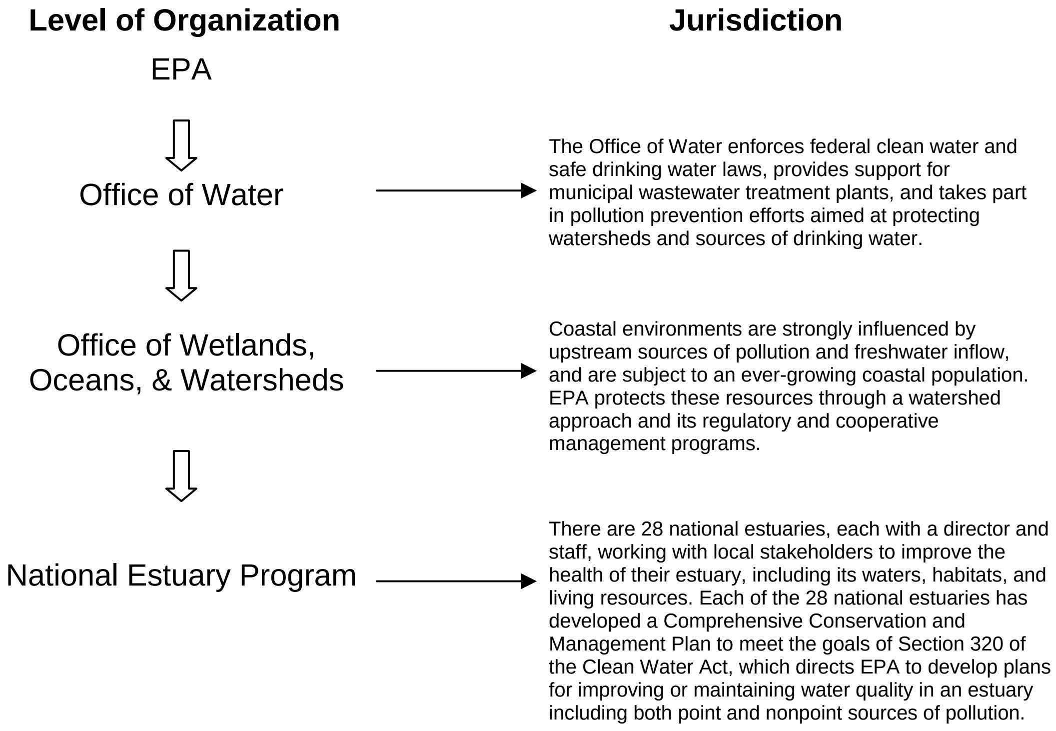
Table 7.4. Factors that control the occurrence of estuarine hypoxia and the climate change-related impacts that are likely to affect them.

Factor	Climate-Related Forcing
Water temperature	Δ T
River discharge	Δ precipitation
N&P loading	Δ T, Δ precipitation
Stratification	Δ T, Δ precipitation, Δ RSL*
Wind	Δ weather patterns, Δ tropical storms
Organic carbon source	Δ T, Δ precipitation, Δ RSL*

*RSL = relative sea level

7.12 Figures

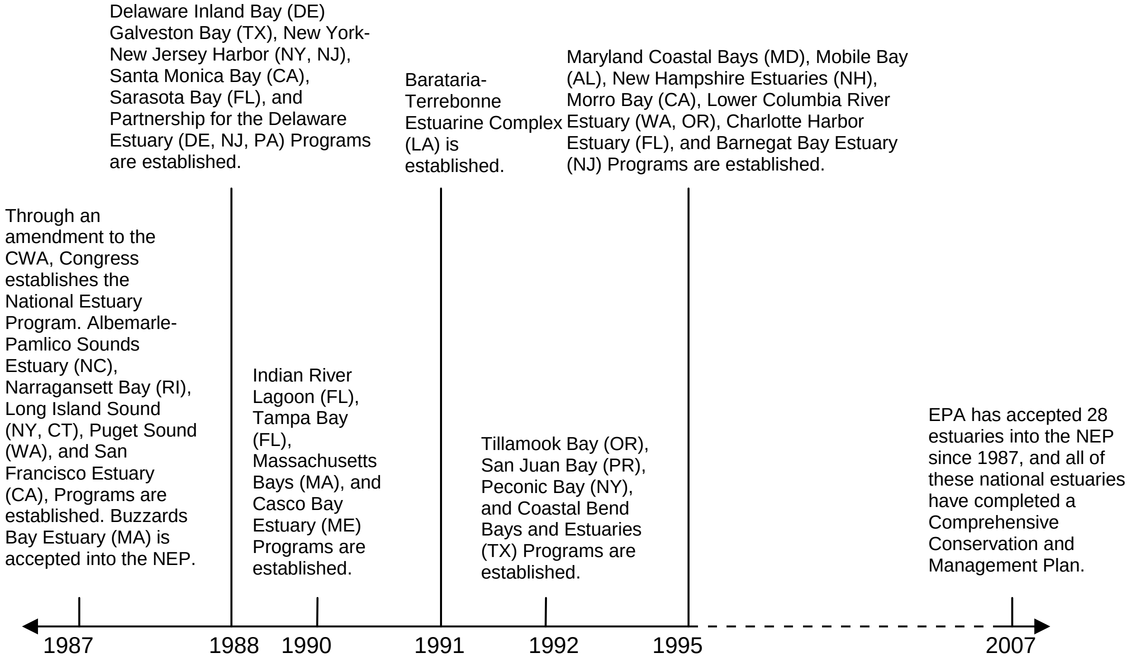
Figure 7.1. Organization of the NEP system.[1]



Level of Organization	Jurisdiction
EPA	
Office of Water	The Office of Water enforces federal clean water and safe drinking water laws, provides support for municipal wastewater treatment plants, and takes part in pollution prevention efforts aimed at protecting watersheds and sources of drinking water.
Office of Wetlands, Oceans, & Watersheds	Coastal environments are strongly influenced by upstream sources of pollution and freshwater inflow, and are subject to an ever-growing coastal population. EPA protects these resources through a watershed approach and its regulatory and cooperative management programs.
National Estuary Program	There are 28 national estuaries, each with a director and staff, working with local stakeholders to improve the health of their estuary, including its waters, habitats, and living resources. Each of the 28 national estuaries has developed a Comprehensive Conservation and Management Plan to meet the goals of Section 320 of the Clean Water Act, which directs EPA to develop plans for improving or maintaining water quality in an estuary including both point and nonpoint sources of pollution.

Adapted from http://www.epa.gov/water/org_chart/index.htm#

Figure 7.2. Timeline of National Estuaries Program formation.[3]



Through an amendment to the CWA, Congress establishes the National Estuary Program. Albemarle-Pamlico Sounds Estuary (NC), Narragansett Bay (RI), Long Island Sound (NY, CT), Puget Sound (WA), and San Francisco Estuary (CA), Programs are established. Buzzards Bay Estuary (MA) is accepted into the NEP.

Delaware Inland Bay (DE) Galveston Bay (TX), New York-New Jersey Harbor (NY, NJ), Santa Monica Bay (CA), Sarasota Bay (FL), and Partnership for the Delaware Estuary (DE, NJ, PA) Programs are established.

Indian River Lagoon (FL), Tampa Bay (FL), Massachusetts Bays (MA), and Casco Bay Estuary (ME) Programs are established.

Barataria-Terrebonne Estuarine Complex (LA) is established.

Tillamook Bay (OR), San Juan Bay (PR), Peconic Bay (NY), and Coastal Bend Bays and Estuaries (TX) Programs are established.

Maryland Coastal Bays (MD), Mobile Bay (AL), New Hampshire Estuaries (NH), Morro Bay (CA), Lower Columbia River Estuary (WA, OR), Charlotte Harbor Estuary (FL), and Barnegat Bay Estuary (NJ) Programs are established.

EPA has accepted 28 estuaries into the NEP since 1987, and all of these national estuaries have completed a Comprehensive Conservation and Management Plan.