

7 National Estuaries

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Chapter Structure

7.1 Background and History

Describes the origins of the National Estuary Program (NEP), its focus on watershed-based and stakeholder-oriented resource management, and the formative factors that shaped its mission and goals

7.2 Current Status of Management System

Reviews existing system stressors, the web of legislation and management practices currently used to address stakeholder's varying demands on the system, and how system goals may be affected by climate change

7.3 Adapting to Climate Change

Discusses approaches to adaptation for planning and management in the context of climate change

7.4 Case Study: The Albemarle-Pamlico Estuarine System

Explores methods for and challenges to incorporating climate change into the management activities and plans of the Albemarle-Pamlico National Estuary Program

7.5 Conclusions

1

1 **7.1 Background and History**

2 **7.1.1 Historical Context and Enabling Legislation**

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

12
13 There are 28 national estuaries that comprise the U.S. National Estuarine Program, which
14 is administered by the U.S. Environmental Protection Agency (Fig. 7.1). These estuaries
15 span the full spectrum of estuarine ecosystem types and encompass the diversity of
16 estuarine ecosystem services across the country. Estuaries are sometimes defined as those
17 places where fresh and salt water meet and mix, thereby potentially excluding some
18 largely enclosed coastal features such as marine lagoons and including, for some
19 vigorous rivers like the Mississippi, extensive excursions into the coastal ocean. So as to
20 match common characteristics of the 28 national estuaries, we choose an alternative,
21 geomorphologically based definition of an estuary as a semi-enclosed body of water on
22 the sea coast in which fresh and salt water mix (adapted from Pritchard, 1967). Such a
23 definition includes not only those water bodies that are largely perpendicular to the
24 coastline where rivers approach the sea, but also marine lagoons, which are largely
25 parallel to the shoreline and experience only occasional fresh water inflow, thereby
26 retaining high salinities most of the time. In the landward direction, we include the
27 intertidal and supratidal shorezone to be part of the estuary and thus include marshes,
28 swamps and mangroves, (*e.g.*, the coastal wetlands).

29
30
31
32 **Figure 7.1.** Organization of the NEP system (U.S. Environmental Protection
33 Agency, 2007b).

34
35 Estuaries are notoriously idiosyncratic because of intrinsic differences among them in
36 physical, geological, chemical, and biological conditions (Wolfe, 1986). There can also
37 be considerable variation within an estuary. This variation exists over wide spectra of
38 time and space (Remane and Schlieper, 1971). This high level of environmental
39 variability in estuaries places physiological constraints on the organisms that can occupy
40 them, generally requiring broad tolerances for varying salinity, but also for temperature
41 and other factors. Consequently, the organisms of estuaries represent a biota that may
42 have unusually high intrinsic capability for species-level physiological adaptation to
43 changing salinity, temperature, and other naturally varying aspects of historic climate

1 change. The challenge is to predict how these species will respond to accelerated rates of
2 change and how species interactions will alter communities and ecosystems.

3
4 Estuaries possess several features that render them unusually valuable for their ecosystem
5 services, both to nature and to humans. The biological productivity of estuaries is
6 generally high, with substantial contributions from vascular plants of historically
7 extensive tidal marshes and coastal wetlands as well as from seagrasses and other
8 submerged aquatic vegetation. A large fraction of the fisheries of the coastal ocean
9 depend on estuaries to provide nursery or even adult habitat necessary to complete the
10 life cycle of the fish or shellfish. Similarly, many species of coastal wildlife including
11 terrestrial and marine mammals and coastal birds depend on estuaries as essential feeding
12 and breeding grounds. Although depicting the ecosystem services of only one estuarine
13 habitat, the wetlands and marshes, the Millennium Ecosystem Assessment (2005)
14 provides a table of ecosystem services that helps indicate the types and range of natural
15 and human values that are vested in estuarine ecosystems more broadly (Box 7.1). Partly
16 in recognition of the value of estuaries and the threats to their health, the National Estuary
17 Program (NEP) was established by Congress in 1987 and housed within EPA (U.S.
18 Congress, 1987) (see Fig. 7.1). After the establishment of this program, the 28 national
19 estuaries were added over a ten-year period (Fig. 7.2).

20
21
22
23 **Figure 7.2.** Timeline of National Estuaries Program formation (U.S.
24 Environmental Protection Agency, 2007a).

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

1 **7.1.2 Interpretation of National Estuary Program Goals**

2 Under the goals of Section 320 of the Clean Water Act, each National Estuary¹ is
3 required to develop a Comprehensive Conservation and Management Plan (CCMP).
4 Many national estuaries have watersheds found within a single state, and therefore their
5 CCMP is contained within one state. Other estuarine watersheds are trans-boundary and
6 more than one state participates. Emphasis is on “integrated, watershed-based,
7 stakeholder-oriented water resource management” (U.S. Environmental Protection
8 Agency, 2006). These plans are produced by a full range of stakeholders within each
9 National Estuary through a process involving (1) assessments of trends in water quality,
10 natural resources, and uses of the estuary, (2) evaluation of appropriate data, and (3)
11 development of pollutant loading relationships to watershed and estuarine condition. The
12 final CCMP is approved by the governors of the states in the study area and the EPA
13 administrator. The programs are then obligated to implement the CCMPs and monitor
14 effectiveness of actions (U.S. Congress, 2002). Each National Estuary prepares an annual
15 plan, approved by EPA, to guide implementation of its CCMP.

16
17 The national estuaries represent a wide variety of sizes, geomorphologies, and watershed
18 characteristics. For example Santa Monica Bay is a relatively small open embayment or
19 coastal lagoon, the Maryland Coastal Bays are a group of more closed lagoons, and the
20 Albemarle-Pamlico Sound is a complex of drowned river valleys emptying into largely
21 closed coastal lagoons. The Columbia River Estuary and the Delaware Estuary are the
22 more traditional drowned river valleys. This diversity has largely prevented classification,
23 grouping, and synthetic assessment of the constituent national estuaries. There is
24 geographic separation into four regions: West Coast (six sites), Gulf of Mexico (seven
25 sites), South Atlantic (six sites, including San Juan Bay, Puerto Rico), and Northeast
26 (nine sites). Although the estuaries do not share easily identified geomorphic
27 characteristics, they are recognized to share common stressors (Bricker *et al.*, 1999;
28 Worm *et al.*, 2006; Lotze *et al.*, 2006). These stressors include “eutrophication,
29 contamination from toxic substances and pathogens, habitat loss, altered freshwater
30 inflows, and endangered and invasive species” (Bearden, 2001). This particular list
31 ignores direct and indirect fishing impacts, which are important and included in many
32 CCMPs. Even more importantly, this list fails to include the direct and indirect effects of
33 climate change, particularly the threats posed by sea level rise.

34
35 A hallmark of the NEP is that it is largely a local program with federal support. While
36 federal grants provide a critical source of base funding, most national estuaries have
37 successfully raised significant local and state support, primarily to finance specific
38 projects or activities. The individual national estuaries lack regulatory authority; thus,
39 they depend on voluntary cooperation using various incentives plus existing federal,
40 state, tribal, and local legislation and regulation. Their purpose is to coordinate these local
41 efforts and promote the mechanisms to develop, implement, and monitor the CCMPs.
42 The NEP was designed to provide funding and guidance for the 28 estuaries around the

¹ 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 document uses the term National Estuaries to refer to the individual programs.

1 country to work in a bottom-up science-based way within the complex policy-making
2 landscape of federal, state, and local regulations. Non-regulatory strategies must
3 complement the limited federal and even state authority or regulations. Lessons learned
4 about how monitoring, research, communication, education, coordination, and advocacy
5 work to achieve goals are transferable to all estuaries, not just NEP members.

6
7 The overarching areas of concern in national estuaries can be classified as water quality,
8 fisheries, habitat, wildlife, introduced species, biodiversity, human values, and freshwater
9 quantity. More specifically the goals include “protection of public water supplies and the
10 protection and propagation of a balanced, indigenous population of shellfish, fish, and
11 wildlife, and [allowing] recreational activities, in and on water, [and requiring]...control
12 of point and nonpoint sources of pollution to supplement existing controls of pollution”
13 (U.S. Congress, 1987). Thus, overwhelmingly the interest has been on anthropogenic
14 impacts and their management (Kennish, 1999).

15
16 Within recent years, each National Estuary has developed or begun to develop system-
17 specific ecosystem status indicators. These indicators allow ongoing assessments of the
18 success of management activities resulting from the CCMPs. However, mention of
19 climate change is missing from almost all CCMPs and only one National Estuary (Puget
20 Sound) has completed a planning process to assess implications of climate change for the
21 perpetuation of ecosystem services in its system (Snover *et al.*, 2005). Managers may fail
22 to account for the effects of climate change on the estuaries if the choices of indicators
23 are not reconsidered in the context of changing climate. Perhaps more importantly,
24 climate change may confound the interpretation of the indicator trend results and thus the
25 interpretation of the effectiveness of the CCMPs.

26 **7.2 Current Status of Management Systems**

27 **7.2.1 Key Ecosystem Characteristics on Which Goals Depend**

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

35
36 Next in scale is the airshed. This is the area capable of influencing the estuary through the
37 contribution of quantitatively significant pollutants, especially nitrogen oxides (NO_x). For
38 the Chesapeake Bay, this area includes Midwestern states, the source of nutrients from
39 industrial and transportation activities. Estuaries on the Gulf and East coasts are likely to
40 have different dependencies on their airsheds for nutrient enrichment than their western
41 counterparts. Western estuaries are affected more by fog banks emanating from coastal
42 waters. Climate drivers that change wind, ultraviolet radiation, and precipitation patterns
43 are particularly important at this scale.

1
2 Next in hierarchical context is the watershed. Central to the NEP is the watershed
3 perspective to management. Land and watershed use, population density, and regulatory
4 effectiveness combine to determine the potential loading of pollutants, extraction of
5 freshwater and resources, and transformation of habitat and coastline. Climate change can
6 influence each of these factors. Changes in temperature, sea level, storminess,
7 precipitation, and evapotranspiration patterns can alter human settlement and migration,
8 agricultural and fisheries practices, and energy and resource use. These responses are
9 likely to be long-term and large-scale, although their influence on estuarine dynamics
10 may be exhibited on shorter time scales. For example, seasonal nutrient loading varies as
11 a result of changes in tourism or crop choice. These factors largely affect the
12 concentration of nutrients, while changes in runoff and river flow affect the discharge
13 component of loading.

14
15 At the opposite end of the estuary is the marine environment, which also serves as an
16 intermixing boundary susceptible to climate change. The oceans and coastal marine
17 waters have responded or are expected to respond to climate change by changes in sea
18 level, circulation patterns, storm intensity, salinity, temperature, and pH. Some of these
19 factors may change little over the large scale but may be altered locally outside the
20 mouths of estuaries. All of these factors influence the biota, with all but pH exerting
21 additional indirect effects by modifying estuarine hydrodynamics.

22
23 Susceptibility of individual estuaries to climate change depends on a number of
24 characteristics that act at a variety of spatial and temporal scales. All of the previously
25 mentioned climate drivers can affect estuaries. How they do so depends on physical
26 features such as estuarine depth, size, and balance between ocean water circulation and
27 fresh-water inflows. Furthermore, the geomorphology and direction of longest fetch set
28 conditions for susceptibility to storms. All of these features help determine the biological
29 communities that reside within the estuary and how they might respond to the various
30 components of climate change.

31
32 The way in which a specific estuary responds to climate change depends on the
33 anthropogenic stressors acting on it. These stressors include both those that pollute and
34 contaminate the system and those that remove or disrupt estuarine resources. Pollutants
35 include nutrients, metals, pathogens, sediments, and organic toxicants. Invasive species
36 are additions that disrupt communities. Extractions include uses of fresh and brackish
37 water, sediments, and living resources within the ecosystem. Disruption of a variety of
38 biological communities occurs through fishing, habitat destruction, damming, boat
39 traffic, and shoreline conversion and stabilization activities.

40
41 Finally, there are the social, political, and economic contexts for susceptibility. Some of
42 these contexts play out in ways already mentioned. But it is clear that stakeholder
43 attitudes about estuaries and their perceptions about climate change are critical to wise
44 management for climate change. Each stakeholder group, indeed each individual, uses
45 estuaries in different ways and places different importance on specific ecosystem
46 services. One aim of this report is to provide a common body of knowledge to

1 stakeholders and to managers at higher levels (local, state, tribal, and federal
2 governments) to inform their choices.

3 **7.2.2 Current Stressors of Concern**

4 Estuaries are generally stressful environments because of their strong and naturally
5 variable gradients of salinity, temperature, and other parameters. However, estuaries are
6 also essential feeding and reproduction grounds, and provide refuge for a wide variety of
7 seasonal and permanent inhabitants. Throughout history, estuaries have been focal points
8 of human settlement and resource use, and humans have added multiple stressors to
9 estuarine ecosystems (Lotze *et al.*, 2006). We define a stressor as an anthropogenic or
10 naturally occurring environmental factor that adversely affects individual physiology,
11 population performance, or ecosystem function when it extends beyond its typical range
12 of variation (Vinebrooke *et al.*, 2004). This document focuses specifically on those
13 stressors that significantly affect the services that estuaries are managed to provide. The
14 major stressors currently imposed on estuaries are listed in Table 7.1. Almost all current
15 efforts to manage estuarine resources are focused on these stressors (Kennish, 1999 and
16 the various CCMPs).

17
18 Several stressors result from modified rates of loading of naturally occurring energy and
19 materials. Nutrient loading is perhaps the most studied and important material addition.
20 Although essential to the primary production of any open ecosystem, too much nutrient
21 loading can cause eutrophication, the subject of considerable concern for estuaries and
22 the target for much management action (Nixon, 1995; Bricker *et al.*, 1999). Nutrient
23 (especially nitrogen N) loading comes from diverse point- and non-point sources
24 including agriculture, aquaculture, and industrial and municipal discharges, and can lead
25 to harmful and nuisance algal blooms, loss of perennial vegetation, bottom-water
26 hypoxia, and fish kills. Sediment delivery has also been altered by human activities.
27 Again, sediments are important to estuarine ecosystems as a material source for the
28 geomorphological balance in the face of sea level rise and for nutrients (especially
29 phosphorus P) for primary production. However, land clearing, agriculture, and urban
30 land use can increase sediment load (Howarth, Fruci, and Sherman, 1991; Cooper and
31 Brush, 1993; Syvitski *et al.*, 2005), while dams may greatly restrict delivery and promote
32 deltaic erosion (Syvitski *et al.*, 2005). Historically, sediment loading has increased on
33 average 25-fold and nitrogen and phosphorus loading almost 10-fold in estuaries since
34 1700 (Lotze *et al.*, 2006). Because riverine loading of both nutrients and sediments
35 depends on their concentration and river flow, modifications of river flow will further
36 alter the amount and timing of material delivery. River flow also contributes to the
37 energy budget through mechanical energy. River flow may be a major determinant of
38 flushing times, salinity regime, and stratification, and thus determine community
39 structure and resource use patterns. Modifications in river flow come from dam
40 management decisions, land development, loss of riparian wetlands, extraction of
41 freshwater, and surface and ground water consumption. Thermal pollution, largely from
42 power plants, is a direct enhancement of energy with resultant local changes in metabolic
43 rates, community structure, and species interactions.

44

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

21
22 Use and development in and around estuaries alter wetland and subtidal habitats directly.
23 Wetland destruction has occurred during much of human history as a result of the
24 perceptions of wetlands as wastelands and the value of waterfront land. For example, 12
25 estuaries around the world have lost an average of more than 65% of wetland area (with a
26 range of 20–95%) over the last 300 years (Lotze *et al.*, 2006). Wetland habitat loss from
27 development continues despite changes in perceptions about wetland value and
28 regulations intended to protect wetlands. Coastal wetlands represent a diverse assortment
29 of hydromorphic classes (Brinson, 1993; Christian *et al.*, 2000), both sea-level
30 controlled (*e.g.*, marshes and mangroves), non-sea-level controlled (*e.g.*, swamps, fens,
31 bogs, and pocosins) and subtidal (*e.g.*, submerged aquatic vegetation (SAV), seagrass,
32 and macroalgal) habitats. Supratidal and intertidal wetlands are subject to land use
33 change, dredging and filling, and changes in water quality. Subtidal habitats are
34 particularly susceptible to not only these impacts but also activities within the water. For
35 example, SAV loss also occurs from bottom-disturbing fishing practices and
36 eutrophication. Oyster reef habitat destruction occurs from direct exploitation and bottom
37 disturbance from fishing practices (*e.g.*, trawling). For 12 study sites around the world,
38 both seagrass meadows and oyster reefs have experienced substantial losses over the last
39 300 years (about >65% and 80%, respectively) (Lotze *et al.*, 2006). Together with the
40 loss of wetlands, these changes have resulted in great reductions of essential nursery
41 habitats, important filtering functions (nutrient cycling and storage), as well as coastal
42 protection (barriers and floodplains) in estuaries (Worm *et al.*, 2006; Lotze *et al.*, 2006).

43
44 Another important anthropogenic stressor in estuaries is the extraction of living and non-
45 living material that alters estuarine ecosystem structure and functioning. Historically,
46 estuaries provided a wide variety of resources used and valued by humans as sources of

1 food, fur, feathers, fertilizer, and other purposes (Lotze *et al.*, 2006). Since the 19th
2 century, however, the ecological service of estuaries receiving greatest management
3 attention has been their support of fisheries. Pollution, damming, and habitat destruction
4 affect fisheries. Recently more emphasis has been placed on overfishing as a negative
5 impact, not only on the target species but also on the community and food web structure
6 (*e.g.*, Dayton, Thrush, and Coleman, 2002). Large apex predators have been greatly
7 reduced from many if not most estuarine and coastal ecosystems (Lotze *et al.*, 2006). The
8 absence of these large consumers (including marine mammals, birds, reptiles, and larger
9 fish) translates through the food web, creating ecosystem states that are distinct from
10 those of the past (*e.g.*, Jackson *et al.*, 2001; Lotze *et al.*, 2006; Myers *et al.*, 2007).
11 Ongoing fishing pressure targets species lower and lower in the food chain, including
12 detritivorous and herbivorous invertebrates and marine plants, further altering ecosystem
13 structure and functioning and undermining habitat integrity and filtering functions (Pauly
14 *et al.*, 1998; Worm *et al.*, 2006; Lotze *et al.*, 2006). Management goals to stabilize current
15 or restore former ecosystem states are jeopardized if large consumers are not also
16 recovered (Jackson *et al.*, 2001).

17
18 It is rare that an estuary is subject to only one of these stressors. Management decisions
19 must consider not only stressors acting independently but also interacting with each other
20 (Breitburg, Seitzinger, and Sanders, 1999; Lotze *et al.*, 2006). Multiple stressors can
21 interact and cause responses that cannot be anticipated from our understanding of each
22 one separately. For example, Lenihan and Peterson (1998) demonstrate that habitat
23 damage from oyster dredging and the stress of bottom-water hypoxia interact to affect
24 oyster survival. Tall oyster reefs, both those that remain and those that have been rebuilt,
25 project above hypoxic bottom waters and therefore allow oyster survival in the upper
26 wind-mixed layers even as water quality further deteriorates. Unfortunately, management
27 of fisheries and water quality is done by different agencies, inhibiting the integrated
28 approach that such interacting stressors demand.

29
30 Interactive effects of multiple stressors are likely to be common and important because of
31 both the interdependence of physiological rate processes within individuals and the
32 interdependence of ecological interactions within communities and ecosystems
33 (Breitburg and Riedel, 2005). Individual stressors fundamentally change the playing field
34 upon which additional stressors act by selecting for tolerant species while also changing
35 the abundance, distribution, or interactions of predators, prey, parasites, hosts, and
36 structural foundation species (*e.g.*, organisms such as bivalves and corals that create
37 physical structures upon which other species depend). These direct and indirect effects
38 can be common when stressors occur simultaneously, but they also occur from exposure
39 to stressors in sequence. Across hierarchical levels from individuals through ecosystems,
40 the recovery period from a particular stressor can extend beyond the period of exposure,
41 thus influencing responses to subsequent stressors. For example, Peterson and Black
42 (1988) demonstrated that bivalves that were already stressed from living under crowded
43 conditions exhibited higher mortality rates after experimental application of the stress of
44 sedimentation. Moreover, effects of stressors on indirect interactions within populations
45 and communities can extend the spatial scale of stressor effects and delay recovery
46 (Peterson *et al.*, 2003), increasing the potential for interactions with additional stressors.

1 For example, years after the Exxon Valdez oil spill, female harlequin ducks (1) exposed
2 to lingering oil during feeding on benthic invertebrates in contaminated sediments and (2)
3 exhibiting activation of detoxification enzymes suffered lower survivorship over winter.
4 Winter is a period of energetic stress to these small-bodied ducks (Peterson *et al.*, 2003).
5 On longer time scales, heritable adaptations that increase tolerance to one class of
6 stressors may enhance susceptibility to others (Meyer and Di Giulio, 2003).

7
8 One hallmark of the NEP is the recognition that management actions need to take account
9 of the complexity of the larger watershed and the potentially diverse socioeconomic
10 demands and objectives within them. The NEP tracks habitat restoration and protection
11 efforts with annual updates from the component estuaries (U.S. Environmental Protection
12 Agency, 2007c).

13 **7.2.3 Legislative Mandates Guiding Management of Stressors**

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

21
22 The presentation here of applicable federal legislative acts is long, yet incomplete, and
23 does not attempt to list state and local laws. One motivation in providing this spectrum of
24 applicable legislation is to illustrate the challenges involved for estuaries in the
25 integration of management authorities that is urged under the umbrella of ecosystem-
26 based management by the U.S. Commission on Ocean Policy.

27 **7.2.3.1 Basin-Wide Management of Water Quality**

28 As one of the tools to meet the goal of “restoration and maintenance of the chemical,
29 physical, and biological integrity of the Nation’s waters” under §402 of the Federal Water
30 Pollution Control Act (U.S. Congress, 2002), any entity that discharges pollutants into a
31 navigable body of water must possess an National Pollutant Discharge Elimination
32 System (NPDES) permit. This includes public facilities such as wastewater treatment
33 plants, public and private industrial facilities, and all other point sources. While EPA was
34 the original administrator of the program, many states have now assumed this function.
35 All states have approved State NPDES Permit Programs except Alaska, The District of
36 Columbia, Idaho, Massachusetts, New Hampshire, New Mexico, and the territories and
37 trusts (American Samoa, Guam, Johnston Atoll, Midway Island, Northern Marianas,
38 Puerto Rico, the Trust Territories and Wake Island). All those without approved State
39 NPDES Permit Programs are administered directly by EPA. The only unapproved states
40 with estuaries (disregarding the trusts and territories) are then the District of Columbia,
41 Massachusetts and New Hampshire. As of 1987, NPDES permits were also required for
42 some storm water discharges, beginning with larger urbanized entities and recently

1 extending to some medium-sized units of government who own or operate municipal
2 storm water discharge facilities.

3
4 Although the content, style, and length of any given NPDES permit for point-source
5 discharge will be slightly different depending on where and when it is written, all permits
6 contain certain core components mandated by the Clean Water Act, including testing,
7 monitoring, and self reporting. NPDES permits are renewed every five years, and
8 monitoring and/or reporting requirements may change. These changes are determined by
9 the local Regional Water Quality Control Boards or the State Water Resources Control
10 Board through their research and monitoring efforts.

11 **7.2.3.2 Habitat Conservation under Federal (Essential Fish Habitat) and State Fishery** 12 **Management Plans**

13 As administered under NOAA, the Magnuson Fishery Conservation and Management
14 Act of 1976 (amended as the Sustainable Fisheries Act (SFA) in 1996 [P.L. 94-265] and
15 reauthorized as Magnuson-Stevens Fishery Conservation and Management
16 Reauthorization Act (MSA) of 2006 [P.L. 109-479]) established eight regional fishery
17 management councils that are responsible for managing fishery resources within the
18 federal 200-mile zone bordering coastal states. Management is implemented through the
19 establishment and regulation of Fishery Management Plans (FMPs). In addition to
20 “conservation and management of the fishery resources of the United States...to prevent
21 overfishing, rebuild overfished stocks and insure conservation,” the Act also mandates
22 the facilitation of long-term protection of *essential fish habitats*, which are defined as
23 “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth
24 to maturity” (U.S. Congress, 1996). The Act states “One of the greatest long-term threats
25 to the viability of commercial and recreational fisheries is the continuing loss of marine,
26 estuarine, and other aquatic habitats.” It emphasizes that habitat considerations “should
27 receive increased attention for the conservation and management of fishery resources of
28 the United States” (U.S. Congress, 1996) and “to promote the protection of essential fish
29 habitat in the review of projects conducted under Federal permits, licenses, or other
30 authorities that affect or have the potential to affect such habitat” (U.S. Congress, 1996).

31
32 FMPs prepared by the councils (or by the Secretary of Commerce/NOAA) must describe
33 and identify essential fish habitat to minimize adverse effects on such habitat caused by
34 fishing. In addition, they must identify other actions to encourage the conservation and
35 enhancement of essential fish habitat and include management measures in the plan to
36 conserve habitats, “considering the variety of ecological factors affecting fishery
37 populations” (U.S. Congress, 1987).

38
39 Because managed species use a variety of estuarine/coastal habitats throughout their life
40 histories, few are considered to be “dependent” on a single, specific habitat type (except,
41 for example, larger juvenile and adult snappers and groupers on ocean hard bottoms) or
42 region. As a result, federal FMPs do not comprehensively cover species’ habitats that are
43 not specifically targeted within their region. In addition, the only estuarine-dependent fish
44 stocks under federal management authority are migratory stocks, such as red drum and
45 shrimp, so estuarine habitats are not a key focus for essential fish habitat. However, many

1 states also have FMPs in place or in preparation for target fisheries under their
2 jurisdiction (the non-migratory inshore species) and participate with the regional councils
3 under the SFA/MSA.
4

5 Thus, threats to marshes and other estuarine systems that constitute essential fish habitat
6 or state-protected fisheries habitat should include all potential stressors, whether natural
7 or anthropogenic, such as climate change and sea level rise. Although essential fish
8 habitats have been codified for many fisheries, and science and management studies have
9 focused on the status and trends of fisheries-habitat interactions, most management
10 consideration has targeted stresses caused by different types of fishing gear. Because few
11 fisheries take place in emergent marshes, the essential fish habitat efforts have not
12 provided much protection to this important habitat. Seagrass and oyster reef habitats have
13 been targeted for additional management concern because of the federal essential fish
14 habitat provisions. State protections of fishery habitat vary, but generally include salt
15 marsh and other habitats. Nearly two decades ago, EPA projected extensive loss of
16 coastal marshes and wetlands from sea level rise by 2100, with an elimination of 6,441
17 square miles (65%) of marshes in the continental United States associated with a
18 probable rise of 1m (Park *et al.*, 1989).

19 **7.2.3.3 Estuarine Ecosystem Restoration Programs**

20 While comprehensive planning of coastal restoration is inconsistent at the national level,
21 a number of national, regional, and local programs are coordinated to the extent that
22 stressors are either the target of restoration or addressed as constraints to restoration.
23 These programs tend to be oriented toward rehabilitation of injuries done by individual
24 stressors, such as eutrophication or contaminants, or toward restoration of ecosystems
25 that have not been so extensively modified that their loss or degradation is not
26 irreversible. Federal programs that authorize restoration of estuaries include:
27

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

29 Probably the most prominent federal program that involves non-regulatory restoration in
30 the nation's estuaries is the Estuary Restoration Act of 2000 (ERA). The ERA promotes
31 estuarine habitat restoration through coordinating federal and non-federal restoration
32 activities and more efficient financing of restoration projects. It authorizes a program
33 under which the Secretary of the Army through the Corps of Engineers (USACE) may
34 carry out projects and provide technical assistance to meet the restoration goal. The
35 purpose of the Act is to promote the restoration of estuarine habitat; to develop a national
36 Estuary Habitat Restoration Strategy for creating and maintaining effective partnerships
37 within the federal government and with the private sector; to provide federal assistance
38 for and promote efficient financing of estuary habitat restoration projects; and to develop
39 and enhance monitoring, data sharing, and research capabilities. Guidance provided by an
40 Estuary Habitat Restoration Council consisting of representatives of NOAA, EPA,
41 USFWS, and USACE includes soliciting, evaluating, reviewing, and recommending
42 project proposals for funding; developing the national strategy; reviewing the
43 effectiveness of the strategy; and providing advice on development of databases,
44 monitoring standards, and reports required under the Act. The Interagency Council
45 implementing the ERA published a strategy in December of 2002 with the goal of

1 restoring one million acres of estuarine habitat by the year 2010. Progress toward the goal
2 is being tracked via NOAA’s National Estuaries Restoration Inventory.

3
4 Although the guiding principles that contributed to the development of this legislation
5 argued for the “need to learn more about the effects of sea level rise, sedimentation, and a
6 host of other variables to help set appropriate goals and success indicators for restoration
7 projects in their dynamic natural environments,” climate change is not explicitly
8 addressed in the ERA (U.S. Congress, 2000). Similarly, the Council’s Estuarine Habitat
9 Restoration Strategy, published in 2002, neglects to explicitly mention climate change or
10 sea level rise.

11 **National Estuary Program and National Monitoring Program (EPA)**

12 The National Estuary Program (NEP), administered under Section 320 of the 1987
13 amended Clean Water Act, focuses on point- and non-point source pollution in targeted,
14 high-priority estuarine waters. Under the NEP, EPA assists state, regional, and local
15 governments, landowners, and community organizations in developing a Comprehensive
16 Conservation and Management Plan (CCMP) for each estuary. The CCMP characterizes
17 the resources in the watershed and estuary and identifies specific actions to restore water
18 quality, habitats, and other designated beneficial uses. Each of the 28 national estuaries
19 has developed a CCMP to meet the goals of Section 320. Because the primary goal of the
20 National Estuary Program is maintenance or restoration of water quality in estuaries, the
21 CCMPs tend to focus on source control or treatment of pollution. Estuarine habitat
22 restoration and protection is tracked by EPA’s National Estuaries Program, with annual
23 updates using information provided by the constituent national estuaries (U.S.
24 Environmental Protection Agency, 2007c). While climate change is not considered a
25 direct stressor, it is gradually being addressed in individual CCMPs in the context of
26 potential increased nutrient loading from watersheds under future increased precipitation.
27 For instance, the Hudson River Estuary Program has initiated with other partners an
28 ongoing dialogue about how climate change constitutes a future stressor of concern to the
29 estuary and its communities (New York State Department of Environmental
30 Conservation, 2006). The Puget Sound and Sarasota Bay Estuary Programs have been the
31 most proactive relative to anticipating a range of climate change challenges, although
32 these assessments have been completed only recently.

34 **7.2.3.4 State Sedimentation and Erosion Control, Shoreline Buffers, and Other Shoreline** 35 **Management Programs Involving Public Trust Management of Tidelands and** 36 **Submerged Lands**

37 Protection from shoreline erosion has a long legal history, as far back as the tenets of
38 property law established under the court of Roman Emperor Justinian (Spyres, 1999). In
39 general, property law protection of tidelands held in public trust (most of the U.S.
40 coastline) is conveyed either as the *law of erosion* (public ownership migrates inland
41 when shores erode) or the *public trust doctrine* (the state holds tidelands in trust for the
42 people unless it decides otherwise). Shoreline planners in many states (*e.g.*, Texas,
43 Maine, Rhode Island, South Carolina, and Massachusetts) use these laws to plan for
44 natural shoreline dynamics, including policies and tools such as “rolling easements” (*i.e.*,
45 as the sea rises, the public’s easement “rolls” inland; owners are obligated to remove

1 structures if and when they are threatened by an advancing shoreline), setbacks (*i.e.*,
2 prohibitions against development of certain areas at a set distance from the shoreward
3 property line), prohibition of future shoreline armoring, and direct purchase of land that
4 will allow wetlands or beaches to shift naturally (Spyres, 1999; IPCC, 2001). Some states
5 are beginning to prohibit new structures in areas likely to be eroded in the next 30-60
6 years (*e.g.*, North Carolina through its Coastal Resources Commission).

7 **7.2.3.5 Species Recovery under Federal Endangered Species Act**

8 Recovery plans for aquatic species that are threatened or endangered under the
9 Endangered Species Act (ESA) (U.S. Congress, 1973) may be contingent on implicit
10 assumptions about habitat conditions in the coastal zone. However, explicit accounting
11 for impacts and strategic designing of recovery efforts to consider climate variability and
12 change is rare. A recent analysis of current ESA recovery plans indicates that of 101
13 plans that mention climate change, global warming, or related terms, only 60 actually
14 discuss these topics, and only 47 identify climate change or its effects as a threat, possible
15 threat, or factor in the species' decline (Jimerfield, Waage, and Snape, 2007). Strategies
16 and approaches that specifically address climate include monitoring for metapopulation
17 variability that could link climate variation to extinction/recolonization probabilities or to
18 unpredictable changes in existing or proposed future habitat. For example, the NOAA
19 recovery plan for the Hawaiian monk seal (*Monachus schauinslandi*) suggests that
20 habitat loss that has already been observed could be exacerbated by "...sea level rise over
21 the longer term [that] may threaten a large portion of the resting and pupping habitat..."
22 (National Marine Fisheries Service, 2006).

23
24 Climate variability and change will undoubtedly involve an even more consequential
25 response by diadromous fishes and macroinvertebrates that require extensive, high-
26 quality juvenile or adult transitional habitats during migrations between ocean and
27 estuarine or freshwater aquatic systems. For example, in the Pacific Northwest and
28 Alaska, sea level rise and shifts in timing and magnitude of snowmelt-derived riverine
29 runoff may be particularly exacerbated by climate variability and change. Consequently,
30 the recovery plans for threatened or endangered Pacific salmon (*e.g.*, juvenile, "ocean-
31 type" Chinook [*Oncorhynchus tshawytscha*] and summer chum [*O. keta*] salmon) may
32 need to account for their extreme sensitivity to climate-induced changes in environmental
33 conditions of their estuarine wetland habitats during different life stages of the fish.

34 **7.2.3.6 Wetland Protection Rules Requiring Avoidance, Minimization, and Mitigation for** 35 **Unavoidable Impacts**

36 Federal jurisdiction of waters of the United States began in 1899 with the Rivers and
37 Harbors Act of 1899 and wetlands were included in that definition with the passing of the
38 Clean Water Act of 1977 (CWA). This jurisdiction does not extend beyond the
39 wetland/upland boundary. However, many state environmental laws, such as those of
40 New York (*e.g.*, New York State, 1992) and New Jersey, require permits for alterations
41 in adjacent upland areas in addition to protecting the wetland itself. While not originally
42 intended for the purpose of increasing climate change preparedness, many of these
43 regulations could facilitate adaptation to sea level rise (Tartig *et al.*, 2000).

1
2 The U.S. Army Corps of Engineers regulates dredging, the discharge of dredged or fill
3 material, and construction of structures in waterways and wetlands through Section 404
4 of the CWA (codified generally as 33 U.S.C. §1251; 1977), the provisions of which have
5 been amended progressively through 1987. Although not explicitly required within the
6 language of the amended law, the CWA provides the Corps with the implicit authority to
7 require that dredge or fill activities avoid or minimize wetland impacts (Committee on
8 Mitigating Wetland Losses, National Research Council, 2001). The Corps and EPA
9 developed criteria (Section 404(b)(1) guidelines) that over the years (latest, 1980) have
10 defined mitigation as both minimization of wetland impacts and compensation for
11 wetland losses. Thus, mitigation has been loosely interpreted to include a range of actions
12 from wetland restoration and enhancement to creation of wetlands where they have never
13 occurred (U.S. Congress, 1980). However, a 1990 memorandum of agreement (MOA)
14 between the Corps and EPA established that mitigation must be applied sequentially. In
15 other words, an applicant must first avoid wetland impacts to the extent practicable, then
16 minimize unavoidable impacts, and finally—only after these two options are reasonably
17 rejected—compensate for any remaining impacts through restoration, enhancement,
18 creation, or in exceptional cases, preservation (Committee on Mitigating Wetland Losses,
19 National Research Council, 2001). The Corps now grants permits for shoreline
20 development that include armoring of the present shoreline, which guarantees future loss
21 of wetlands as sea level rises, thereby violating the requirement for mitigation in the
22 application of this authority (Titus, 2000).

23 **7.2.3.7 Compensatory Restoration Requirements for Habitat and Natural Resource**
24 **Injuries from Oil Spills or Discharges of Pollutants**

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

40 **7.2.3.8 Federal Legislation Controlling Location of Ballast Water Release to Limit**
41 **Introduction of Non-Indigenous Marine and Estuarine Species**

42 One of the more troubling implications of climate change for estuaries is the probability
43 of expanded distributions of non-indigenous species with the potential of progressively

1 warmer waters in temperate zones. Ballast water discharged from ships in harbors after
2 transiting from foreign ports (and domestic estuaries with extensive species invasions,
3 such as San Francisco Bay) is one of the major sources of aquatic nuisance species. The
4 primary federal legislation regulating ballast water discharge of invasive species is the
5 National Invasive Species Act of 1996, which required the Coast Guard to establish
6 national voluntary ballast water management guidelines. Because of a lack of compliance
7 under the initial nationwide self-policing program that began in 1998, the voluntary
8 program became mandatory in 2004. All vessels equipped with ballast water tanks that
9 enter or operate within U.S. waters must now adhere to a national mandatory ballast
10 water management program and maintain a ballast water management plan. Ballast water
11 discharge may fall under the scope of the Clean Water Act, which adjudication may
12 resolve.

13 **7.2.3.9 Flood Zone Regulations**

14 Tidal flood surge plains will likely be the estuarine regions most susceptible to climate
15 change forcings, with consequent effects on human infrastructure, especially as
16 development pressures continue to increase along the nation’s coastal zone. Before the
17 more recent projections of (higher) sea level rise rates, the Federal Emergency
18 Management Agency (Federal Emergency Management Agency, 1991) estimated that
19 existing development in the U.S. Coastal Zone would experience a 36%–58% increase in
20 annual damages for a 0.3-meter rise in sea level, and a 102%–200% percent increase for a
21 1-meter rise. While state and local governments regulate building and other human
22 activities in existing flood hazard zones, FEMA provides planning assistance by
23 designating Special Flood Hazard Areas and establishing federal flood insurance rates
24 according to the risk level.

25 **7.2.3.10 Native American Treaty Rights**

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

40
41 Where climate variability and change intersect with resource management of shared
42 natural resources, Natives’ treaty status may provide them with additional responsibility
43 and influence. For example, on the basis of the “Boldt II decision,” treaty tribes in

1 Washington State have treaty-based environmental rights that make them legal
2 participants in natural resource and environmental decision making, including salmon
3 and shellfish habitat protection and restoration (Brown, 1993; 1994).

4 **7.2.4 Sensitivity of Management Goals to Climate Change**

5 **7.2.4.1 Climate Change and Changing Stressors of Estuarine Ecosystems**

6 Many estuarine properties are expected to be altered by climate change. Global-scale
7 modeling has rarely focused on explicit predictions for estuaries because realistic
8 estuarine modeling would require very high spatial and temporal resolution. It is,
9 however, reasonable to assume that estuaries will be forced by the same climate forcing
10 that affects the coastal and marginal oceans. With increases in atmospheric CO₂, models
11 project increases in oceanic temperature and stratification, decreases in convective
12 overturning, decreases in salinity in mid- and high latitudes, longer growing seasons in
13 mid- and high latitudes, and increases in cloud cover (Table 7.2). Such changes will
14 necessarily force significant alterations in the physics, chemistry, and biology of
15 estuaries. In particular, climate change may have significant impacts on those factors that
16 are included in the definition of an estuary (Box 7.2). For example, climate-driven
17 alterations to geomorphology will affect every physical, chemical, biological, and social
18 function of estuaries.

19
20 The 2007 IPCC report provides a summary of the results of multiple credible models of
21 climate change, providing various ranges of estimated change by year 2100. Whereas
22 these predictions carry varying degrees of uncertainty and in some cases fail to include
23 processes of likely significance in the modeling because of high scientific uncertainty,
24 these predictions of rates of change over the next century help ground our scenario
25 building for consequences of climate change on estuarine dynamics and on ability to
26 attain management goals. The best estimates of average global temperature rise in the
27 surface atmosphere vary from a low scenario of 1.1–2.9°C and a high scenario of 2.4–
28 6.4°C. Scenarios of sea level rise range from a low prediction of 0.18–0.38 m to a high
29 prediction of 0.26–0.59 m by 2100. The modeled sea level does not, however, include
30 enhanced contributions from shifts of the Greenland and Antarctic ice shelves and could
31 therefore be a serious underestimate. The future temperatures for Greenland reach levels
32 inferred to have existed in the last interglacial period 125,000 years ago, when
33 paleoclimate information suggests reductions of polar ice extent and a 4–6 m rise in sea
34 level. The IPCC projects growing acidification of the ocean with reductions in pH of
35 between 0.14 and 0.35 units over the next century. In our report, so as to standardize our
36 framework for climate change across responses, we discuss a short term of two to three
37 decades and also project the consequences of a 1 m rise in sea level. This increase may
38 not occur within the next century, but if ice sheet shifts add to the present rate of sea level
39 rise, a 1 m increase may occur sooner than the IPCC (2007) projections.

40
41 Climate change may also modify existing stressors (described in Section 7.2.2) and create
42 new ones not discussed above. For example, the nutrient, sediment, pathogen, and
43 contaminant stressors usually carried downstream with freshwater runoff will change in
44 proportion to that runoff. If runoff increases, it can be expected to deliver more

1 deleterious material to estuaries, leading to increased eutrophication via nutrients,
2 smothering of benthic fauna via sediment loading, decreased photosynthesis via sediment
3 turbidity, decreased health and reproductive success via a wide spectrum of toxins, and
4 increased disease via pathogens. In contrast, “novel” stressors created by climate change
5 include increased temperatures, shifts in the timing of seasonal warming and cooling, and
6 the acidification caused by increased CO₂ (Box 7.3).

7
8 Importantly, there are likely to be interactions among existing and novel stressors,
9 between those factors that define estuaries and stressors, and between stressors and
10 existing management strategies. As noted above (Section 7.2.2), interactions among the
11 multiple stressors posed by climate change are likely to pose considerable challenges.
12 Nonetheless, it is important for successful natural resource management and conservation
13 that managers, researchers, and policy makers consider the myriad stressors to which
14 natural systems are exposed. Importantly, interactions among multiple stressors can
15 change not only the magnitude of stressor effects, but also the patterns of variability and
16 predictability on which management strategies rely (Breitburg *et al.*, 1998; Breitburg *et al.*
17 *et al.*, 1999; Worm *et al.*, 2006). Enhancing ecosystem resilience by establishing better
18 controls on current stressors would limit the strength of interactions with climate change.

19 **7.2.4.2 Impacts to and Responses of the Ecosystem**

20 **7.2.4.2.1 Temperature Effects on Species Distributions**

21 Because species distributions are determined in part by physiological tolerances of
22 climatic extremes, ecologists expect that species will respond to climate warming by
23 shifting distributions towards the poles so long as dispersal and resources allow such
24 shifts (Walther *et al.*, 2002). In fact, a wide array of species is already responding to
25 climate warming worldwide (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*,
26 2003; Parmesan and Galbraith, 2004; Parmesan, 2006). Global meta-analyses of 99
27 species of birds, butterflies, and alpine herbs demonstrate that terrestrial species are
28 migrating poleward at a rate of 6.1 km per decade (Parmesan and Yohe, 2003).
29 Moreover, 81% of 920 species from a variety of habitats showed distributional changes
30 consistent with recent climate warming (Parmesan and Yohe, 2003). In marine systems,
31 warm water species of zooplankton, intertidal invertebrates, and fish have migrated into
32 areas previously too ‘cool’ to support growth (Barry *et al.*, 1995; Southward, Hawkins,
33 and Burrows, 1995; Walther *et al.*, 2002; Southward *et al.*, 2004). Some copepod species
34 have shifted hundreds to 1,000 kilometers northward (Beaugrand *et al.*, 2002), and the
35 range of the oyster parasite *Perkinsus marinus* expands in warm years and contracts in
36 response to cold winters (Mydlarz, Jones, and Harvell, 2006). Its range expanded 500
37 kilometers from Chesapeake Bay to Maine during one year—1991—in response to
38 above-average winter temperatures (Ford, 1996).

39
40 It is important to keep in mind that each species responds individualistically to warming:
41 ecological communities do not move poleward as a unit (Parmesan and Yohe, 2003;
42 Parmesan, 2006). This pattern was first demonstrated by paleoecological studies tracking
43 the poleward expansions of individual species of plants following Pleistocene glaciation
44 (*e.g.*, Davis, 1983; Guenette, Lauck, and Clark, 1998) and has since been extended to
45 animals in phylogeographic studies (*e.g.*, Turgeon *et al.*, 2005). Climate warming is

1 therefore likely to create new mixes of foundation species, predators, prey, and
2 competitors. For example, “invading” species may move poleward faster than “resident”
3 species retreat, potentially creating short-term increases in species richness (Walther *et*
4 *al.*, 2002). Competitive, plant-herbivore, predator-prey, and parasite-host interactions can
5 be disrupted by shifts in the distribution, abundance, or phenology of one or more of the
6 interacting species (Walther *et al.*, 2002; Parmesan, 2006). Not surprisingly, therefore, it
7 is difficult, if not impossible, to predict how community dynamics and ecosystem
8 functioning will change in response to species shifts (Walther *et al.*, 2002).

9
10 Evidence from studies that have monitored changes in marine biota over the last three
11 decades has shown that in coastal waters, the response of annual temperature cycles to
12 climate change is both seasonally and regionally asymmetric. Along the mid-Atlantic
13 East Coast, maximal summer temperatures are close to 30°C. When greenhouse gas
14 forcing provides more heat to the surface waters in summer, they do not get warmer;
15 instead the additional heat increases evaporation and is transferred to the atmosphere as a
16 latent heat flux. Consequently maximum summer temperatures have not changed in the
17 mid-Atlantic regions, but the minimum winter temperatures are now dramatically higher,
18 by as much as 1-6°C (Parker Jr. and Dixon, 1998). In the reef fish community off North
19 Carolina, the reduction over 30 years in winter kill during the coldest months made it
20 possible for two new (to the area) families and 29 new species of tropical fishes to
21 become permanent residents on the reef (Parker Jr. and Dixon, 1998). In addition, the 28
22 species of tropical reef fishes that have been present on the site for the entire three
23 decades increased in abundance. An increase in fish-cleaning symbiosis was especially
24 noticeable. Over the 30-year study period, no new temperate species became permanent
25 residents and, while no temperate species dropped out of the community, the temperate
26 species that was most abundant at the start of the study decreased in abundance by a
27 factor of 22. This kind of seasonal asymmetry in temperature change expands the range
28 of tropical species to the north, but so far has not changed the southern limit of temperate
29 species—although it has reduced the biomass of temperate species that were previously
30 abundant.

31
32 On the West Coast, changes in the species composition of a rocky intertidal community
33 showed that between the 1930s and 1990s most species’ ranges shifted poleward (Barry
34 *et al.*, 1995). The abundance of eight of nine southern species increased and the
35 abundance of five of eight northern species decreased. Annual mean ocean temperatures
36 at the central California coastal site increased by 0.75°C during the past 60 years, but
37 more importantly the monthly mean maximum temperatures during the warmest month of
38 year were 2.2°C warmer. On the West Coast, summer conditions are relatively cool and
39 foggy due to strong coastal upwelling that produces water temperatures from 15–20°C.
40 For intertidal organisms adapted to these relatively cool summer temperatures a 2°C
41 increase in monthly mean temperature during the warmest month of the year was enough
42 to decrease survival of northern species and increase the survival of southern species. It is
43 clear that climate change has already altered the species composition and abundance of
44 marine fauna, but is equally clear that the physical and biological response of organisms
45 to warming in marine waters is extremely complex.

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

4 **7.2.4.2.2 Temperature Effects on Risks of Disease and Parasitism**

5 Not only will species' distributions change, but scientists expect that higher temperatures
6 are likely to lead to increased risks of parasitism and disease, due to changes in parasites
7 and pathogens as well as host responses (Harvell *et al.*, 2002; Hakalahti, Karvonen, and
8 Valtonen, 2006). For example, temperature has the potential to alter parasite survival and
9 development rates (Harvell *et al.*, 2002), geographic ranges (Harvell *et al.*, 2002; Poulin,
10 2005; Parmesan, 2006), transmission among hosts (Harvell *et al.*, 2002; Poulin, 2005),
11 and local abundances (Poulin, 2005). In particular, shortened or less-severe winters are
12 expected to increase potential parasite population growth rates (Hakalahti, Karvonen, and
13 Valtonen, 2006). On the host side, increased temperatures can alter host susceptibility
14 (Harvell *et al.*, 2002) by compromising physiological functioning and host immunity
15 (Mydlarz, Jones, and Harvell, 2006). Animals engaged in partnerships with obligate algal
16 symbionts, such as anemones, sponges, and corals, are at particular risk for problems if
17 temperatures alter the relationship between partners (Mydlarz, Jones, and Harvell, 2006).

18
19 Reports of marine diseases in corals, turtles, mollusks, marine mammals, and
20 echinoderms have increased sharply over the past three decades, especially in the
21 Caribbean (Harvell *et al.*, 2002; Ward and Lafferty, 2004). For example, temperature-
22 dependent growth of opportunistic microbes has been documented in corals (Ritchie,
23 2006). Poulin and Mouritsen (2006) documented a striking increase in cercarial
24 production by trematodes in response to increased temperature, with potentially large
25 effects on the intertidal community (Poulin and Mouritsen, 2006). Geographic range
26 expansion of pathogens with broad host ranges is of particular concern because of the
27 potential to affect a broad array of host species (Dobson and Foufopoulos, 2001; Lafferty
28 and Gerber, 2002).

29
30 Importantly, however, we cannot predict the effects of climate change on disease and
31 parasitism based solely on temperature (Lafferty, Porter, and Ford, 2004). Temperature is
32 likely to interact with a variety of other stressors to affect parasitism and disease rates
33 (Lafferty, Porter, and Ford, 2004), including excess nutrients (Harvell *et al.*, 2004),
34 chemical pollutants such as metals and organochlorines (Harvell *et al.*, 2004; Mydlarz,
35 Jones, and Harvell, 2006), and hypoxia (Mydlarz, Jones, and Harvell, 2006). For
36 example, the 2002 die-off of corals and sponges in Florida Bay co-occurred with a red
37 tide (*Karenia brevis*) driven by high nutrient conditions (Harvell *et al.*, 2004). Moreover,
38 not all parasites will respond positively to increased temperature; some may decline
39 (Harvell *et al.*, 2002; Roy, Guesewell, and Harte, 2004) and others may be kept in check
40 by other factors (Harvell *et al.*, 2002; Hall *et al.*, 2006). This suggests that generalizations
41 may not always be possible; idiosyncratic species responses may require that we consider
42 effects on a species-by-species, or place-by-place basis, as with the species distributions
43 discussed earlier.

44

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

4 **7.2.4.2.3 Effects of Shoreline Stabilization on Estuaries and their Services**

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

18
19 Surprisingly little is known about the effects of estuarine shoreline stabilization structures
20 on adjacent habitats (Committee on Mitigating Shore Erosion along Sheltered Coasts,
21 National Research Council, 2006). Marsh communities at similar elevations with and
22 without bulkheads behind them were found to be indistinguishable in a study in Great
23 Bay Estuary in New Hampshire (Bozek and Burdick, 2005). However, this study also
24 reported that bulkheads eliminated the up-slope vegetative transition zone. This loss is
25 relevant for both current function of the marsh and also future ability of the marsh to
26 respond to rising sea level. In several systems within Chesapeake Bay, Seitz and
27 colleagues (2006) identified a link between the hardening of estuarine shorelines with
28 bulkheads or rip-rap and the presence of infaunal prey and predators. This study
29 illustrated the indirect effects that can result from shoreline stabilization, and found them
30 to be on par with some of the obvious direct effects. Loss of ecological function in the
31 estuarine land-water margin as a result of shoreline stabilization is a critical concern.
32 However, the complete loss of the structured habitats (SAV, salt marsh) seaward of
33 shoreline stabilization structures as sea level rises is a more dire threat. In addition, the
34 intertidal sand and mud flats, which provide important foraging grounds for shorebirds
35 and nektonic fishes and crustaceans, will be readily eliminated as sea level rises and
36 bulkheads and other engineered shoreline stabilization structures prevent the landward
37 migration of the shoreline habitats. Absent the ability to migrate landward, even habitats
38 such as marshes, which can induce accretion by organic production and sediment
39 trapping, appear to have reduced opportunity to sustain themselves as water level rises
40 (Titus, 1998).

41
42 These effects of shoreline stabilization interacting with sea level rise will influence salt
43 marsh and other intertidal and shallow-water estuarine habitats, with consequences for
44 water quality, fish and wildlife production, and human values, inducing need for
45 management adaptation.

1 **7.2.4.2.4 Effects of Climate Change on Marsh Trapping of Sediments and**
2 **Geomorphologic Resiliency**

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

22
23 Thus, changes in sediment and nutrient delivery and eustatic sea level rise are likely to be
24 the key factors affecting geomorphic resiliency of coastal wetlands. Sediment delivery
25 may be the critical factor: estuaries and coastal zones that presently have high rates of
26 sediment loading, such as those on the southeast and northwest coasts, may be able to
27 persist up to thresholds of 1.2 cm per year that are optimal for marsh primary production
28 (Morris *et al.*, 2002). If sea level rise exceeds that rate, then marsh surface elevation
29 decreases below the optimum for primary production. However, increased precipitation
30 and storm intensities commensurate with many future climate scenarios (*e.g.*, in the
31 Pacific Northwest) would also likely increase sediment delivery but also erode sediments
32 where flows are intensified. The large-scale responses to changes in sediment delivery to
33 estuarine and coastal marshes have not been effectively addressed by most hydrodynamic
34 models incorporating sediment transport. SAP 4.1 elucidates potential impacts by
35 providing maps depicting the wetland losses in the mid-Atlantic states that are anticipated
36 under various rates of sea level rise (U.S. Climate Change Science Program; In Press).
37 Such changes in sediment and nutrient delivery to the estuary will threaten the
38 geomorphologic resilience of salt marsh habitat, thereby altering water quality and fish
39 and wildlife production; these changes imply the need for management adaptation.

40 **7.2.4.2.5 Effects of Sea Level Rise and Storm Disturbance on Coastal Barrier**
41 **Deconstruction**

42 Two important consequences of climate change are accelerated sea level rise and
43 increased frequency of high-intensity storms. Sea level rise and intense storms work
44 alone and in combination to alter the hydrogeomorphology of coastal ecosystems and
45 their resultant services. Furthermore, the extent to which they act on ecosystems is
46 dependent on human alterations to these ecosystems. Perhaps the best known example of

1 the current interaction of sea level rise, storm intensity, and human activity is the coast of
2 the Gulf of Mexico around the Mississippi River. Relative sea level rise of the Louisiana
3 coast is one of the highest in the world, in large part as a result of human activities, and
4 this has caused significant losses of wetlands (Boesch, 1994; González and Törnqvist,
5 2006; Day, Jr. *et al.*, 2007). The consequences of intense storms (*i.e.*, Hurricanes Katrina
6 and Rita) on coastal ecosystems of the Gulf of Mexico, human dominated and natural, are
7 now legend (Kates *et al.*, 2006). New Orleans and other cities were devastated by these
8 storms. Wetland loss was dramatic with sharp alterations to community structure (Turner
9 *et al.*, 2006; U.S. Geological Survey, 2007). Barrier islands were eroded, overwashed,
10 and breached with severe impacts to both human lives and infrastructure. The impacts of
11 these storms are linked to the damaged conditions and decreased area of the wetlands and
12 their historical loss (Day, Jr. *et al.*, 2007). Now reconstruction of New Orleans and other
13 cities has begun and plans are being offered for the replenishment and protection of
14 wetlands and barrier islands (U.S. Army Corps of Engineers, In Press; Day, Jr. *et al.*,
15 2007; Coastal Protection and Restoration Authority of Louisiana, 2007).

16
17 Although the impacts of the hurricanes of 2005 and the influence of relative sea level rise
18 on their impacts were the most costly to the United States, they are not the only examples
19 of how storms and sea level rise influence hydrogeomorphology. Sea level rise and
20 erosion, fostered by storms, have caused estuarine islands to disappear and led to
21 significant changes in shorelines (Hayden *et al.*, 1995; Riggs and Ames, 2003). Barrier
22 island shape and position are dynamic, dependent on these two processes. These
23 processes are natural and have occurred throughout the Holocene; what is relatively new
24 are the ways in which human values are in conflict with these processes and how humans
25 either promote or inhibit them.

26
27 Wetlands can maintain themselves in the face of sea level rise by accretion. This
28 accretion is supported by both sedimentation and organic matter accumulation (Chmura
29 *et al.*, 2003). The ability to accrete makes it difficult to assess the true consequences of
30 sea level rise on landscape pattern and resultant area of wetlands, especially over large
31 areas (Titus and Richman, 2001). We do not know exactly the potential accretion and
32 subsidence rates of most wetlands and the thresholds at which relative sea level rise
33 exceeds net elevation change, causing increased inundation and ultimately wetland loss.
34 Based on the experiences of Louisiana, we can estimate that the maximum accretion rate
35 may be less than 10 mm per year, but applicability to other systems is undetermined. Two
36 things are clear: First, the limits depend on the source of material for accretion (*i.e.*,
37 sediment or organic matter) and hence the rates of processes that introduce and remove
38 the materials. Second, the rates of these processes will differ with location both locally
39 within the coastal landscape and regionally due to climate, community, and
40 hydrogeomorphic conditions.

41
42 Sea level rise and storm disturbance have not only severe consequences as described, but
43 they are important drivers of the natural progression of coastal ecosystems. One can
44 consider the coastal landscape as having a sequence of ecosystem states, each dependent
45 upon a particular hydroperiod and tidal inundation regime (Brinson, Christian, and Blum,
46 1995; Hayden *et al.*, 1995; Christian *et al.*, 2000). For example in the mid-Atlantic states,

1 coastal upland, which is rarely flooded, would be replaced by high salt marsh as sea level
2 rises. High marsh is replaced by low marsh, and low marsh is replaced by intertidal flats.
3 While sea level rise alone may effect these changes in state, they are promoted by
4 disturbances that either kill vegetation (*e.g.*, salt intrusion from storms killing trees) or
5 change elevation and hence hydroperiod (*e.g.*, erosion of sediment). It is unclear how
6 accelerated sea level rise and frequency of severe storms will alter the balance of this
7 sequence.

8
9 Normally one considers that disturbances would be local, such as salt water intrusion or
10 wrack deposition. But these state changes can actually result from regional impacts of
11 disturbance. For example, *Juncus roemerianus* is a rush species commonly found in high
12 marshes along the coasts of mid-Atlantic, southern Atlantic, and Gulf of Mexico regions
13 of the United States. It is less common where astronomical tidal signals are strong
14 (Woerner and Hackney, 1997; Brinson and Christian, 1999), and it is replaced by
15 *Spartina alterniflora* or perhaps other species. Any disturbance that increases the strength
16 of astronomical tides promotes this shift. Such a disturbance could be the breaching of
17 barrier islands in which increased flow through new inlets may foster more dominant
18 astronomical tides and the ecosystem state change. The predicted disintegration of barrier
19 islands as a consequence of intense storm damage acting from a higher base sea level has
20 catastrophic implications (Riggs and Ames, 2003). Coastal barriers function to protect
21 mainland shorelines from tidal energy, storm surge, and wave forces, such that loss of the
22 protections implies catastrophic inundation, erosion, and loss of wetlands and other
23 coastal habitats on mainland shores as well as back-barrier shores.

24
25 Sea level rise and increased frequency of intense storms will influence salt marsh and
26 other wetland habitats by erosion and salt water intrusion, thereby influencing fish and
27 wildlife production, available quantity of fresh water, and provision of human values,
28 with consequences for management.

29 **7.2.4.2.6 Joint Effects of Increasing Temperature and Carbon Dioxide**

30 As a consequence of increasing global temperatures, the limits of climate-adapted
31 habitats are expected to shift longitudinally. Temperate herbaceous species that dominate
32 the tidal wetlands throughout many U.S. estuaries may be replaced by more tropical
33 species such as mangroves (Harris and Cropper Jr., 1992). Salt marshes and mangroves
34 are not interchangeable, despite the fact that both provide structure to support productive
35 ecosystems and perform many of the same ecosystem functions. Mangroves store up to
36 80% of their biomass in woody tissue whereas salt marshes lose 100% of their
37 aboveground biomass through litterfall each year (Mitsch and Gosselink, 2000).
38 Production of litter facilitates detrital foodwebs and supports many ecological processes
39 in wetlands, so this distinction has implications for materials cycling such as carbon
40 sequestration (Chmura *et al.*, 2003). There are significant differences in structural
41 complexity and biological diversity between these wetland systems. These differences
42 will affect the capacity of the wetlands to assimilate upland runoff, maintain their vertical
43 position and provide flood control. Temperature-driven species redistribution will be
44 further complicated as sea level increases and vegetation is forced landward.

45

1 Since pre-industrial times, the atmospheric concentration of carbon dioxide (CO₂) has
2 risen by 35% to 379 ppm in 2005 (IPCC, 2007). Ice cores have proven that this
3 concentration is significantly greater than the natural range over the last 650,000 years
4 (180–300 ppm). In addition, the annual average growth rate in CO₂ concentrations over
5 the last 10 years is larger than the average growth rate since the beginning of continuous
6 direct atmospheric measurements: 1.9 ppm per year average from 1995–2005 compared
7 with 1.4 ppm per year average from 1960 to 2005 (IPCC, 2007). Because CO₂ is required
8 for photosynthesis, these changes may have implications for estuarine vegetation. Plants
9 can be divided based on the way in which they assimilate CO₂. C3 plants include the vast
10 majority of plants on earth (~95%) and C4 plants, which include crop plants and some
11 grasses, comprise most of the rest. Early in the process of CO₂ assimilation, C3 plants
12 form a pair of three carbon molecules whereas C4 plants form four carbon molecules.
13 The distinction between C3 and C4 species at elevated atmospheric CO₂ content is that
14 C3 species increase photosynthesis with higher CO₂ levels and C4 species generally do
15 not (Drake *et al.*, 1995). In wetland systems dominated by C3 plants (*e.g.*, mangroves,
16 many tidal fresh marshes), elevated CO₂ will increase photosynthetic potential and may
17 increase the related delivery of ecosystems services from these systems (Drake *et al.*,
18 2005). Ongoing research is examining the potential for shifts in wetland community
19 composition driven by elevated CO₂. Data from one of these efforts indicate that despite
20 the advantage afforded to C3 species at higher CO₂ levels, CO₂ increases alone are
21 unlikely to cause black mangrove to replace cordgrass in Louisiana marshes (U.S.
22 Geological Survey, 2006). However, many important estuarine ecosystem effects from
23 elevated CO₂ levels have been documented, including increases in fluxes of CO₂ and
24 methane (Marsh *et al.*, 2005), augmented nitrogen fixation by associated microbial
25 communities (Dakora and Drake, 2000), increased methanogenesis (Dacey, Drake, and
26 Klug, 1994) and changes in the quantity and composition of root material (Curtis *et al.*,
27 1990).

28
29 The joint effects of rising temperature and increased CO₂ concentrations will influence
30 composition and production of shoreline plants that are critical habitat providers and
31 contributors to detrital food chains, thereby also affecting fish and wildlife production
32 and provision of human values and inducing need for management adaptations.

33 **7.2.4.2.7 Effects of Increased CO₂ on Acidification of Estuaries**

34 Ocean acidification is the process of lowering the pH of the oceans by the uptake of CO₂
35 from the atmosphere. As atmospheric CO₂ increases, more CO₂ is partitioned into the
36 surface layer of the ocean (Feely *et al.*, 2004). Since the industrial revolution began to
37 increase atmospheric CO₂ significantly, the pH of ocean surface waters has decreased by
38 about 0.1 units and it is estimated that it will decrease by another 0.3–0.4 units by 2100 as
39 the atmospheric concentration continues to increase (Caldeira and Wickett, 2003). The
40 resulting decrease in pH will affect all calcifying organisms because as pH decreases, the
41 concentration of carbonate decreases, and when carbonate becomes under-saturated,
42 structures made of calcium carbonate begin to dissolve. However, dissolution of existing
43 biological calcium carbonate structures is only one aspect of the threat of acidification;
44 another threat is that as pH falls and carbonate becomes undersaturated it requires more
45 and more metabolic energy for an organism to deposit calcium carbonate. The present

1 lowered pH is estimated to have reduced the growth of reef-building by about 20%
2 (Raven, 2005). While corals get the most attention regarding acidification, a wide
3 spectrum of ocean and estuarine organisms are affected, including coralline algae;
4 echinoderms such as sea urchins, sand dollars, and starfish; as well as coccolithophores,
5 foraminifera, crustaceans, and molluscan taxa with shells, of which pteropods are
6 particularly important (Orr *et al.*, 2005). The full ecological consequences of the
7 reduction in calcification by marine calcifiers are uncertain, but it is likely that the
8 biological integrity of ocean and estuarine ecosystems will be seriously affected (Kleypas
9 *et al.*, 2006).

10
11 Effects of climate change on estuarine acidification will influence water quality,
12 provision of some biogenic habitat like coral reefs, fish and wildlife production, and
13 human values, thus implying need for management adaptation.

14 **7.2.4.2.8 Effects of Climate Change on Hypoxia**

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

32
33 Various scenarios predict that climate change will influence the vulnerability of estuaries
34 to hypoxia through changes in stratification caused by alterations in freshwater runoff,
35 changes in water temperature, increases in sea level, and altered exchanges with the
36 coastal ocean (Peterson *et al.*, 1995; Scavia *et al.*, 2002). Additionally, warmer
37 temperatures should increase metabolism by the water-column and benthic microbial
38 communities, whose activity drives the depletion of DO. Many of the factors that have
39 been found to contribute to the formation of hypoxia (Borsuk *et al.*, 2001; Buzzelli *et al.*,
40 2002) will be affected by one or more predicted changes in climate (Table 7.3). Because
41 hypoxia affects valued resources, such as fish and wildlife production, reductions in
42 hypoxia are a management target for many estuaries, and adaptations will be required as
43 a consequence of climate change.

1

2 **7.2.4.2.9 Effects of Changing Freshwater Delivery**

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

17
18 The potential physical and chemical consequences of altered freshwater flows to estuaries
19 include changes in salinity and stratification regimes, loadings of nutrients and sediments,
20 water residence times, and tidal importance (reviewed in Alber, 2002). Potential
21 biological consequences include changes in species composition, distribution and
22 abundance, as well as primary and secondary productivity, in response to the altered
23 availability of light, nutrients, and organic matter (Cloern *et al.*, 1983; Howarth *et al.*,
24 2000; Alber, 2002).

25
26 Increases in the delivery of freshwater to estuaries may enhance estuarine circulation and
27 salt wedge penetration up the estuary (Gedney *et al.*, 2006), resulting in stronger vertical
28 stratification. For individual estuaries there is the potential for increased freshwater
29 inflow to shift the degree of mixing along the gradient from the fully mixed toward the
30 stratified state. Those estuaries that receive increased supplies of organic matter and
31 nutrients and exhibit enhanced stratification may be particularly susceptible to enhanced
32 hypoxia and the negative effects described in the previous section. However, at some
33 level, increased freshwater delivery will reduce residence time and thus reduce the
34 potential for hypoxia. This threshold will be specific to individual estuaries and difficult
35 to predict in a generic sense.

36
37 In some estuaries, climate change may also lead to a reduction in freshwater inflow that
38 will generally increase salinity. This could lead to more salt-water intrusion upstream,
39 negatively affecting species intolerant of marine conditions (Copeland, 1966; Alber,
40 2002) and/or lengthening the estuary by extending the distance along the freshwater to
41 full seawater gradient (Alber, 2002). Water residence times within the estuary will likely
42 increase with reduced freshwater inflow, potentially allowing enhanced stratification
43 (both in temperature and salinity) and therefore creating a more stable system in which
44 phytoplankton can grow and reproduce (Cloern *et al.*, 1983; Howarth *et al.*, 2000). Thus,
45 one might expect a greater response to nutrients—*i.e.*, greater primary productivity and/or

1 larger phytoplankton populations (Mallin *et al.*, 1993)—than under baseline rates of
2 freshwater discharge. This may be especially true for estuaries that are currently
3 somewhat “protected” from eutrophication symptoms by high freshwater flow, such as
4 the Hudson River (Howarth *et al.*, 2000). However, reduced flushing times will also keep
5 water in the estuary longer, potentially increasing the risks posed by pollutants and
6 pathogens (Alber and Sheldon, 1999; Sheldon and Alber, 2002).

7
8 Other biological consequences of changing freshwater delivery include alterations in
9 secondary productivity (the directions of which are difficult to predict), the distributions
10 of plants and sessile invertebrates (Alber, 2002), and cues for mobile organisms such as
11 fish, especially migratory taxa with complex life histories (Whitfield, 1994; Whitfield,
12 2005). Not surprisingly, therefore, a whole branch of management is developing around
13 the need to determine the optimal freshwater flows required to maintain desired
14 ecosystem services (*e.g.*, Robins *et al.*, 2005; Rozas *et al.*, 2005).

15
16 Changes in freshwater delivery to the estuary will affect freshwater quantity, water
17 quality, stratification, bottom habitats, fish and wildlife production, and human values,
18 inducing needs for management adaptation.

19 **7.2.4.2.10 Phenology Modifications and Match/Mismatch**

20 Estuaries are characterized by high temporal variability on multiple time scales and
21 spatial variability, which includes sharp environmental gradients with distance upstream
22 and vertically in the water column (Remane and Schlieper, 1971). One mode of
23 adaptation that many free-living estuarine species use to exploit the many resources of
24 estuaries is to move in and out of the estuary, as well as upstream and downstream within
25 the estuary, on a complex temporal schedule. A study in North Carolina found that the
26 most abundant fish species in small tributaries of the upper estuary differed in 10 of the
27 12 months of the year (Kuenzler *et al.*, 1977). Ten different species were dominant
28 during the 12 months of the year. To accomplish such movements many estuarine species
29 have evolved behavior that uses various sensory cues to control the timing of their
30 activities (Sims *et al.*, 2004). The timing of behavior cued by environment information is
31 referred to as “phenology” (Mullins and Marks, 1987; Costello, Sullivan, and Gifford,
32 2006). The best understood type of phenology that occurs in estuaries involves matching
33 critical feeding stages with the timing of primary productivity blooms (Scavia *et al.*,
34 2002). As many estuarine stressors are altered by climate change we can expect that
35 phenology will be one of the first biological processes to be seriously disrupted.

36
37 Changing phenology has large implications for fish and wildlife production because
38 trophic coupling of important species in the food chain can be disrupted, thereby
39 presenting a need for management adaptation.

40 **7.2.4.2.11 River Discharge and Sea Level Impacts on Anadromous Fishes**

41 Anadromous fishes, such as Pacific salmon, are an important economic and cultural
42 resource that may be particularly vulnerable to significant shifts in coastal climates in the
43 Pacific Northwest and Alaska. The combined effect of shifts in seasonal precipitation,
44 storm events, riverine discharge, and snowmelt (Salathé, 2006; Mote, 2006) are likely to

1 change a broad suite of environmental conditions in coastal wetlands upon which salmon
2 depend at several periods in their life histories. The University of Washington’s Climate
3 Impacts Group (UW-CIG) has summarized current climate change in the Pacific
4 Northwest to include region-wide warming of ~0.8°C in 100 years, increased
5 precipitation, a decline in snowpack, especially at lower elevations, and an earlier spring
6 (Climate Impacts Group, University of Washington, 2007). The UW-CIG predictions for
7 future climate change in the region include an increase in average temperatures on the
8 order of 0.1–0.6°C (best estimate = 0.3°C) per decade throughout the coming century,
9 with the warming occurring during all seasons but with the largest increases in the
10 summer. Precipitation is also likely to increase in winter and decrease in summer, but
11 with no net change in annual mean precipitation. As a consequence, the mountain
12 snowpack will diminish and rivers that derive some of their flow from snowmelt will
13 likely demonstrate reduced summer flow, increased winter flow, and earlier peak flow.
14 Lower-elevation rivers that are fed mostly by rain may also experience increased
15 wintertime flow due to increases in winter precipitation. Summer river flows in the
16 Pacific Northwest are estimated to decline by as much as 30% and droughts would
17 become more common (Leung and Qian, 2003), implying significant changes in estuarine
18 salinity distribution that has not yet been examined in any detail. Chapter 6, Wild and
19 Scenic Rivers, provides an expanded discussion of these and other climate change effects
20 on rivers in the United States.

21
22 Contemporary estimates of eustatic sea level rise associated with trends in climate change
23 have ranged from 34–50 cm per century (Church, 2001). More recent estimates that have
24 taken into account measurements of continental glacier movement, such as in Greenland,
25 project increased rates from 75–100 cm per century (Meehl *et al.*, 2005) to 2.2–3.4 m by
26 2100 (Overpeck *et al.*, 2006; Otto-Bliesner *et al.*, 2006). However, relative sea level rise
27 will differ considerably on regional and local scales due to variability in isostatic
28 rebound, local extractions of subsurface fluids like ground water and hydrocarbons, and
29 rapid tectonic events like earthquakes and vulcanism.

30
31 Because different anadromous species occupy estuarine wetlands according to their
32 divergent life history strategies, impacts of these climate changes vary between and
33 within species. In the case of Pacific salmon, the “ocean-type” species and life history
34 types would be the most vulnerable because they occupy transitional estuarine waters
35 significantly longer than “stream-type” salmon. For instance, juvenile Chinook and chum
36 salmon representing this “ocean-type” life history strategy may occupy estuarine
37 wetlands for over 90 days (Simenstad, Fresh, and Salo, 1982), seeking (1) refugia from
38 predation at their small size, (2) time to achieve physiological adaptation from freshwater
39 to marine salinities, and (3) high densities of appropriate prey organisms. Based on our
40 knowledge of the habitat requirements and landscape transitions of migrating juvenile
41 ocean-type salmon (Simenstad *et al.*, 2000; Parson *et al.*, 2001; Mote *et al.*, 2003), as sea
42 water penetrates further up the estuary, the present spatial coincidence will change of
43 necessary physical habitats like marsh platforms and tidal creeks with the appropriate
44 salinity regime. This would have potentially large impacts on the ocean-type salmon
45 performance.

1 In the Pacific Northwest, shifts from snowmelt runoff to more winter storm precipitation
2 will potentially disrupt the migration timing and residence of juvenile salmon in estuarine
3 wetlands. For example, juvenile Chinook salmon in many watersheds migrate to estuaries
4 coincident with the spring freshet of snowmelt and occupy the extensive brackish
5 marshes available to them during that period. This opportunity often diminishes as water
6 temperatures increase and approach physiologically marginal limits (*e.g.*, 19–20°C) with
7 the decline of snowmelt and flows in early summer. Under the current climate
8 change/variability scenarios, much of the precipitation events will now be focused in the
9 winter, providing less brackish habitat opportunities during the expected juvenile salmon
10 migration and even more limiting temperatures during even lower summer flows.
11 Whether migration and other life history patterns of salmon could adapt to these climate
12 shifts are unknown.

13
14 The sustainability of estuarine wetlands under recent sea level rise scenarios is also of
15 concern if estuarine habitat utilization by anadromous fish is density-dependent. Estuaries
16 that are positioned in a physiographic setting allowing transgressive inundation, such as
17 much of the coastal plain of the southeastern and Gulf of Mexico coasts, have a buffer
18 that will potentially allow more inland development of estuarine wetlands. Other coasts,
19 such as those of New England and the Pacific Northwest, have more limited opportunities
20 for transgressive development of estuarine wetlands, and many estuaries are already
21 confined by upland agricultural or urban development that would prevent further inland
22 flooding (Brinson, Christian, and Blum, 1995). For one example, Hood (Hood, 2007)
23 found that a 45-cm sea level rise over the next century would result in a 12% loss, and an
24 80-cm rise would eliminate 22%, of the tidal marshes in the Skagit River delta (Puget
25 Sound, Washington), which could be translated to an estimated reduction in estuarine
26 rearing capacity for juvenile Chinook salmon of 211,000 to 530,000 fish, respectively.
27 These estimates are based entirely on the direct inundation effects on vegetation and do
28 not incorporate the potential response of existing marshes to compensate for the increased
29 rate of sea level rise, which can include increased sediment accretion and maintenance of
30 marsh plain elevation or increased marsh progradation due to higher sediment loads from
31 the river (see section 7.2.4.2.15 below). Nor do these estimates take into account
32 increased marsh erosion from greater winter storm activity or changes in salinity
33 distribution due to declining summer river flows. Court cases have already overturned
34 general permits for shoreline armoring where salmon (an endangered species under ESA)
35 would be harmed and with projected rises in sea level, the needs of salmon may come
36 even more often into conflict with management policies that generally permit bulkheads
37 and other shoreline armoring to protect private property.

38
39 Salmon represent such an iconic fish of great importance to fisheries, wildlife,
40 subsistence uses, and human culture that climate-related impacts on salmon populations
41 would require management adaptation.

42 **7.2.4.2.12 Effects of Climate Change on Estuarine State Changes**

43 The many direct and indirect influences of climate change may combine to cause
44 fundamental shifts in ecosystem structure and functioning. Some shifts, such as those
45 associated with transgression of wetlands, can be considered part of the normal responses

1 to sea-level rise (Brinson, Christian, and Blum, 1995; Christian *et al.*, 2000). Of
2 particular concern is the potential for ecosystems to cross a threshold beyond which there
3 is a rapid transition into a fundamentally different state that is not part of a natural
4 progression. Ecosystems typically do not respond to gradual change in key forcing
5 variables in a smooth, linear fashion. Instead, there are abrupt, discontinuous, non-linear
6 shifts to a new state (or “regime”) when a threshold is crossed (Scheffer *et al.*, 2001;
7 Scheffer and Carpenter, 2003; Burkett *et al.*, 2005). Particularly relevant here is the
8 hypothesis that gradual changes in “slow” variables that operate over long time scales can
9 cause threshold-crossing when they alter interactions among “fast” variables whose
10 dynamics happen on short temporal scales (Carpenter, Ludwig, and Brock, 1999; Rinaldi
11 and Scheffer, 2000). We anticipate that some climate changes will fall into this category,
12 such as gradual increases in temperature. The diversity of additional stressors arising
13 from consequences of climate change greatly enhances the likelihood of important
14 stressor interactions. Thus, in estuaries, where so many stressors operate simultaneously,
15 there is great potential for interactions among stressors to drive the system into an
16 alternative state.

17
18 Regime shifts can sometimes be catastrophic and surprising (Holling, 1972; Scheffer and
19 Carpenter, 2003; Foley *et al.*, 2005), and reversals of these changes may be difficult,
20 expensive, or even impossible (Carpenter, Ludwig, and Brock, 1999). Moreover, the
21 social and economic effects of discontinuous changes in ecosystem state can be
22 devastating when accompanied by the interruption or cessation of essential ecosystem
23 services (Scheffer *et al.*, 2001; *e.g.*, Foley *et al.*, 2005). Recognizing and understanding
24 the drivers of regime change and the inherent nonlinearities of biological responses to
25 such change is a fundamental challenge to effective ecosystem management in the face of
26 global climate change (Burkett *et al.*, 2005; Groffman *et al.*, 2006).

27
28 All the potential regime shifts described below have large implications for sustaining
29 biogenic habitat, provision of fish and wildlife, and many human values, thereby
30 implying need for management adaptation.

31 **7.2.4.2.13 Climate Change Effects on Suspension-Feeding Grazers and Algal Blooms**

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

45

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

16 **7.2.4.2.14 N-Driven Shift from Vascular Plants to Planktonic Micro- and Benthic**
17 **Macroalgae**

18 Seagrasses are believed to be in the midst of a global crisis in which human activities are
19 leading to large scale losses (Orth *et al.*, 2006). Human and natural impacts have had
20 demonstrable detrimental effects on SAV (Short and Wyllie-Echeverria, 1996). Enhanced
21 loading of nutrients to coastal waters has been found to alter primary producer
22 communities through shifts toward species with faster growth nutrient uptake rates
23 (Duarte, 1991). The shift is often toward phytoplankton, which reduces light availability
24 and can lead to losses of other benthic primary producers such as seagrasses. The
25 disappearance of seagrass below critical light levels is dramatic (Duarte, 1991), and has
26 been linked to nutrient loading in some systems (Short and Burdick, 1996). In Waquoit
27 Bay, Massachusetts, replacement of SAV by macroalgae has also been observed and was
28 primarily attributed to shading (Hauxwell *et al.*, 2001). Increases in macroalgal biomass,
29 macroalgal canopy height and decreases in SAV biomass were linked to N loading rate
30 using a space-for-time substitution (Hauxwell *et al.*, 2001). It is essential to understand
31 the potential for thresholds in water quality parameters that may lead to loss of SAV
32 through a state change. SAV is sensitive to environmental change and thus may serve as
33 “coastal canaries,” providing an early warning of deteriorating conditions (Orth *et al.*,
34 2006). SAV also provides significant ecological services (Williams and Heck Jr., 2001)
35 and its loss would have appreciable effects on overall estuarine function.

36 **7.2.4.2.15 Non-linear Marsh Accretion with Sea Level Rise**

37 Coastal inundation is projected to lead to land loss and expansion of the sub-tidal regions
38 along estuarine shorelines (Riggs, 2002). Intertidal habitats that do not accrete or migrate
39 landward proportionally to relative sea level rise are susceptible to inundation. Wetlands
40 are often present in these areas and have shown the ability to keep up with increases in
41 sea level in some systems (Morris *et al.*, 2002). However, the ability to maintain their
42 vertical position is uncertain, and depends on a suite of factors (Moorhead and Brinson,
43 1995). Recent work in the Venice Lagoon found a bimodal distribution of marsh (higher
44 elevation) and flat (lower elevation) intertidal habitats, with few habitats at intermediate

1 intertidal elevations (Fagherazzi *et al.*, 2006). The findings indicate that there may be an
2 abrupt transition from one habitat type to another. Should this model hold true for a broad
3 range of coastal systems, there are clearly significant implications for coastal
4 geomorphology and the ecological services provided by the different habitat types.

5 **7.3 Adapting to Climate Change**

6 Biologists have traditionally used the term “adaptation” to apply to intrinsic biological
7 responses to physical or biological changes that may serve to perpetuate the species,
8 community, or ecosystem. This definition includes behavioral, physiological, and
9 evolutionary adaptation of species. This question therefore arises: Can biological
10 adaptation be relied upon to sustain ecosystem services from national estuaries under
11 conditions of present and future climate change? In the short term of one or two decades,
12 the capability of estuarine organisms to migrate further toward the poles in response to
13 warming temperatures and further up the shore in response to rising water levels has
14 potential to maintain estuarine ecosystem processes and functioning that do not differ
15 greatly from today’s conditions. However, over longer time frames of perhaps 20 or 30
16 years or more, depending on the magnitude of climate changes, estuarine ecosystems may
17 not be able to adapt biologically and thereby retain high similarity to present systems.
18 The scope and pace of current and anticipated future climate change are too great to
19 assume that management goals will be sustained by intrinsic biological adjustments
20 without also requiring management adaptation (Parmesan and Galbraith, 2004; Parmesan,
21 2006; Pielke *et al.*, 2007).

22
23 The extremely high natural variability of estuarine environments has already selected for
24 organisms, communities, and ecosystems with high capacity for natural physiological,
25 behavioral, and perhaps also evolutionary adaptation (Remane and Schlieper, 1971;
26 Wolfe, 1986). Nevertheless, the present rates of change in many variables like
27 temperature and the absolute levels of key environmental variables like CO₂
28 concentration that may ultimately be reached could fall outside the historical evolutionary
29 experience of estuarine organisms. The historical experience with environmental
30 variability may not help much to achieve biological adaptation. While behavioral (*e.g.*,
31 migration) adaptation of individual species may take place to some degree, the dramatic
32 suite of projected changes in estuarine environments and stressors that we summarized
33 earlier poses complex challenges to individual species, even those of estuaries, on a
34 timetable that is inconsistent with the capacity for evolutionary change to keep up (Pielke
35 *et al.*, 2007). Even if evolutionary change could proceed at a rapid pace, the diversity of
36 environmental changes implies that conflicting demands may be placed on selection such
37 that adaptation to all change may be compromised. The success of individual species in
38 adapting to climate change does not lead to intrinsic resilience at the community and
39 ecosystems levels of organization. Because virtually all ecosystem processes involve
40 some form of interaction between or among species, biological adaptation by individual
41 species to the climate-driven changes is not a process that will protect functioning
42 estuarine ecosystems because species adapt and migrate at differing rates (Sims *et al.*,
43 2004; Parmesan, 2006).

1 Among the most important species of the estuary that dictate overall community
2 composition and ecosystem dynamics are the structural foundation species, namely
3 intertidal marsh plant and subtidal seagrass (SAV) vegetation. Donnelly and Bertness
4 (2001) have assembled ecological evidence that, starting in the late 1990s, the low marsh
5 plant *Spartina alterniflora* has begun to move upslope and invade the higher marsh of
6 New England that are typically occupied by a more diverse mix of *Juncus gerardi*,
7 *Distichlis spicata*, and *Spartina patens*. Their paleontological assessment revealed that in
8 times of rapid sea level rise in the late 19th and early 20th centuries *Spartina alterniflora*
9 similarly grew upwards and dominated the high marsh. Such replacement of species and
10 structural diversity of foundation species is likely to modify the functioning of the salt
11 marsh ecosystem and affect its capacity to deliver traditional goods and services.
12 Similarly, among SAV species, some like *Halodule wrightii* are known to be better
13 colonizers with greater ability to colonize and spread into disturbed patches than other
14 seagrasses like *Thalassia testudinum* (Stephan, Peuser, and Fonseca, 2001). In general,
15 seagrasses that recolonize by seed set can move into newly opened areas more readily
16 than those that largely employ vegetative spread. Analogous to the marsh changes, if
17 storm disturbance and rising water levels favor more opportunistic seagrass species, then
18 the new SAV community may differ from the present one and provide different
19 ecosystem services. Vascular plants of both intertidal and shallow subtidal estuaries
20 possess characteristically few species relative to terrestrial habitats (Day, Jr. *et al.*, 1989;
21 Orth *et al.*, 2006), so these differences in behavior of important foundation species in the
22 marsh and in SAV beds will have disproportionately large influences on function. Thus,
23 the web of interactions among biotic and abiotic components of the estuarine ecosystem
24 cannot be expected to be preserved through intrinsic biological adaptation alone, which
25 cannot regulate the physical changes. Management adaptations must be considered to
26 sustain ecosystem services of national estuaries. Examples of specific adaptation options
27 are presented in Box 7.4 and elaborated further throughout the sections that follow.

28 **7.3.1 Potential for Adjustment of Traditional Management Approaches to** 29 **Achieve Adaptation to Climate Change**

30 Three different time frames of management adaptation can be distinguished: (1)
31 avoidance of any advance adaptation strategy (leading to *ad hoc* reactive responses); (2)
32 only planning for management responses to climate change and its consequences (leading
33 to coordinated, planned responses initiated either after indicators reveal the urgency or
34 after emergence of impacts); and (3) taking proactive measures to preserve valuable
35 services in anticipation of consequences of climate change. Rational grounds for
36 choosing among these three options involve consideration of the risks and reversibility of
37 predicted negative consequences and the costs of planning and acting now as opposed to
38 employing retroactive measures. Political impediments and lack of effective governance
39 structures may lead to inaction even if planning for intervention or initiating proactive
40 intervention represents the optimal strategy. For example, the partitioning of authority for
41 environmental and natural resource management in the United States among multiple
42 federal and state agencies inhibits effective implementation of ecosystem-based
43 management of our estuarine and ocean resources (Peterson and Estes, 2001; Pew Center
44 on Global Climate Change, 2003; U.S. Commission on Ocean Policy, 2004; Titus, 2004).
45

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

23
24 A decision to postpone implementation of adaptation actions may rely on continuing
25 scientific monitoring of reliable indicators and modeling. Based on inputs from evolving
26 ocean observing systems, model predictions could provide comfort that necessary
27 actions, although delayed, may still be timely. Other important prospective management
28 actions may be postponed because they are not politically feasible until an event alters
29 public opinion sufficiently to allow their implementation. Such adaptations are best
30 planned in advance to anticipate the moment when they could be successfully triggered.
31 Other management actions may involve responding to events and therefore only have
32 relevance in a retrospective context. Catastrophic events provide opportunities for
33 changes that increase ecological and human community resilience, by addressing long-
34 standing problems such as overbuilding in floodplains or degradation of coastal wetlands
35 (Box 7.5) (H. John Heinz III Center for Science, Economics, and the Environment,
36 2002). However, pressures to expediently restore conditions to their familiar pre-disaster
37 state often lead to the loss of these opportunities (Mileti, 1999). Therefore, decisions
38 about whether and where to rebuild after damage from major floods and storms should be
39 carefully examined and planned in advance in order to avoid making poorer judgments
40 during chaotic conditions that follow these types of incidents. This strategy becomes
41 more valuable as flood damages increase.

42
43 Proactive intervention in anticipation of consequences of climate change represents
44 rational management under several conditions. These conditions include irreversibility of
45 undesirable ecosystem changes, substantially higher costs to repair damages than to
46 prevent them, risk of losing important and significant ecosystem services, and high levels

1 of scientific certainty about the anticipated change and its ecological consequences
2 (Titus, 1998; 2000). Avoiding dramatic structural (“phase”) shifts in estuarine ecosystem
3 state may represent a compelling motivation for proactive management because such
4 shifts threaten continuing delivery of many traditional ecosystem services and are
5 typically difficult or exceedingly expensive to reverse (Groffman *et al.*, 2006).
6 Reversibility is especially at issue in cases of potential transitioning to an alternative
7 stable state because positive feedbacks maintain the new state and resist reversal
8 (Petraitis and Dudgeon, 2004). For example, the loss of SAV increases the near-bottom
9 currents because of loss of a baffle to flow, such that seagrass seeds are less likely to be
10 deposited and seedlings more likely to be eroded; this feedback makes reestablishment of
11 lost beds much more difficult. With adequate knowledge of the critical tipping point and
12 ongoing monitoring of telling indicators, proactive intervention could in some cases be
13 postponed and still be completed in time to prevent climate change from pushing the
14 system over the threshold into a new phase. Nevertheless, many processes involved in
15 ecosystem change possess substantial inertia such that even after adjusting levels of
16 drivers, a memory of past stress will continue to modify the system, making
17 postponement of action inadvisable. Climate change itself falls into this class of
18 processes in that if greenhouse gas emissions were capped today, the Earth would
19 continue to warm for decades (IPCC, 2007).

20
21 Financial costs of climate change may be minimized by some types of proactive
22 management. For example, enacting legislation that prohibits bulkheads and other
23 engineered structures and requires rolling easements could preserve or at least delay loss
24 of important shallow-water habitats, such as salt marsh, by allowing them to migrate
25 inland as sea level rises (Box 7.6) (Titus, 1998). Such laws to require rolling easements is
26 not likely to be ruled a taking, especially if enacted before the property is developed
27 because “the law of erosion has long held that the public tidelands migrate inland as sea
28 level rises, legislation saying that this law will apply in the future takes nothing” (Titus,
29 1998). However, absent such a law and this interpretation of it, the costs of loss of habitat
30 and associated ecosystem services may exceed the value of property losses that would
31 occur if property owners could not protect their investment. Some other proactive steps
32 that enhance adaptation to climate change are likely to cost very little and deserve
33 immediate inclusion in policy and management plans. For example, the simple
34 incorporation of climate change consequences in management plans for natural and
35 environmental resources will trigger inclusion of forward-looking modifications that
36 might provide resistance to climate change, build resiliency of ecological and socio-
37 economic systems and avoid interventions incompatible with anticipated change and
38 sustained ecosystem services (Titus, 2000). Principles for environmental planning could
39 be adopted that (1) prohibit actions that will exacerbate negative consequences of climate
40 change, (2) allow actions that are climate-change neutral, and (3) promote actions that
41 provide enhanced ecosystem resilience to climate change. Such principles may lead to
42 many low-cost modifications of existing management plans that could be initiated today.

43
44 The scientific basis for predicting climate change and its ecosystem consequences must
45 be especially compelling to justify any costly decisions to take proactive steps to enhance
46 adaptation to climate change. Willingness to take costly actions should vary with the

1 magnitude of predicted consequences, the uncertainty associated with the predictions, and
2 the timing of the effects. The scientific basis for the predictions must also be transparent,
3 honest, and effectively communicated not just to managers but also to the general public
4 who ultimately must support adaptation interventions. Thus, there is an urgent need to
5 continue to refine the scientific research on climate change and its ecosystem
6 consequences to reduce uncertainty over all processes that contribute to climate change
7 and sea level rise so that future projections and GCM (General Circulation Models)
8 scenarios are more complete and more precise. Because of the tremendous publicity
9 associated with the release of each IPCC report, this process of periodic re-evaluation of
10 the science and publication of the consensus report plays an integral role in public
11 education. Scientific uncertainty about the magnitudes and timetables of potentially
12 important processes, such as melting of the Greenland ice sheet (Dowdeswell, 2006;
13 Rignot and Kanagaratnam, 2006), leads to their exclusion from IPCC projections. Further
14 scientific research will allow inclusion of such now uncertain contributions to change.

15 **7.3.2 Management Adaptations to Sustain Estuarine Services**

16 **7.3.2.1 Protecting Water Quality**

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

29
30 Perhaps the greatest threat to estuarine water quality from climate change derives from
31 the loss of water treatment of diffuse nutrient pollution by constricted tidal marsh and
32 wetland buffers (Box 7.7). These vegetated buffers are threatened by the joint effects of
33 sea level rise and increasingly intense storms interacting with hardening of estuarine
34 shorelines through installation of bulkheads, dikes, and other engineered structures
35 (Titus, 1998). Such structures are now readily permitted along estuarine shorelines to
36 protect private property and public infrastructure from shoreline erosion; however, by
37 preventing orderly retreat of intertidal and shallow subtidal habitats shoreward as sea
38 level rises (Schwimmer and Pizzuto, 2000), marsh will be lost and its functions
39 eliminated over extensive portions of estuarine shorelines (Titus, 2000; Reed, 2002;
40 Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research
41 Council, 2006). The loss of salt marsh on coastal barriers is further facilitated by beach
42 nourishment, which prevents natural processes of coastal barrier recession through
43 overwash. Overwash of sediments to the estuarine shoreline is a process that extends and
44 revitalizes salt marsh on the protected side of coastal barriers.

1
2 Estuarine shorelines differ in their susceptibility to erosion and recession under rising sea
3 levels (U.S. Environmental Protection Agency, 1989) . Relative sea level is rising at very
4 different rates around the country and the globe. The subsiding shores of the Louisiana
5 Gulf Coast represent the region of the country where the salt marsh loss induced by sea
6 level rise is greatest (U.S. Environmental Protection Agency, 1989). These marsh losses
7 on the Mississippi River Delta are enhanced by modification of river flows in ways that
8 inhibit sediment delivery to the marshes and by extraction of subsurface fluids (oil and
9 gas). Extraction of groundwater from shallow aquifers also induces subsidence and
10 enhances relative sea level rise along the shores of some estuaries like San Francisco
11 Bay. For many estuaries, salt marsh does not currently face increased flooding and
12 erosion from rising sea levels, either because relative sea level is not rising rapidly in
13 these regions or because the accumulation of organic peat and trapping and deposition of
14 largely inorganic sediments by emergent marsh plants is elevating the land surface at a
15 rate sufficient to keep up with sea level rise (Reed, 2002). Despite the capability of salt
16 marsh to rise with sea level, this gradual process produces a marsh on an elevated
17 platform where the estuarine shore is increasingly more steeply sloped. The consequently
18 deeper water does not dissipate wave energy as readily as the previously shallow slope,
19 leading to increased risk of shoreline and marsh erosion at the margin (Committee on
20 Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2006).
21 Therefore, even marsh shores that today are maintaining elevation and position as sea
22 level rises are at risk of greater erosion at their seaward margin in the future.
23 Nevertheless, substantial geographic variation exists in erosion risk and susceptibility to
24 marsh loss (U.S. Environmental Protection Agency, 1989).

25
26 Maintaining present management policy allowing bulkheads will likely lead to a scenario
27 of ultimate loss of marsh and a walled estuary wherever development exists on the
28 shoreline. Only on undeveloped estuarine shorelines can marshes recede landward, but
29 with such dramatic expansion of coastal human communities, little undeveloped estuarine
30 shoreline is likely to remain except in public parks, reserves, and sanctuaries. Along
31 estuarine salinity gradients, much more development takes place toward the ocean end
32 and less up-estuary. Therefore, as sea level rises, an increasing fraction of remaining
33 marsh habitat will be found along these undefended, up-estuary shores (see maps in SAP
34 4.1; U.S. Climate Change Science Program, 2007). All specific water quality parameters
35 for which standards exist will suffer under this scenario of current management without
36 adaptation, and reactive management holds little promise of reversal of impacts. Reactive
37 marsh restoration would require removals of at least some portion of the engineered walls
38 protecting estuarine shoreline property so as to allow flooding of the proper elevations
39 supporting salt marsh restoration. Implementing any public policy that would lead
40 directly to widespread private property loss represents a large challenge under the
41 prevailing property rights laws, but one that should be decided in favor of retaining the
42 estuarine habitats if done in a way that involves rolling easements to preserve the public
43 tidelands (Titus, 1998).

44
45 The process of retreat achieved by rolling easements or by some other administrative
46 construct has been discussed in the U.S. for at least two decades. Retreat has an

1 advantage over establishment of fixed buffer zones because the abandonment need not be
2 anticipated and shoreline use modified until sea level has risen enough to require action
3 (Titus, 1998). An analogous proactive response to global climate change and sea level
4 rise is being actively considered in the United Kingdom and European Union and is
5 known as “managed alignment” (Department for Environment, Food and Rural Affairs
6 (DEFRA) and Department of the Environment, 2002). Managed alignment refers to
7 deliberately realigning engineering structures affecting rivers, estuaries, and the coastline.
8 The process could involve retreating to higher ground, constructing set-back levees,
9 shortening the length of levees and seawalls, reducing levee heights, and widening a river
10 flood plain. The goals of managed realignment may be to:

- 11
- 12 (1) reduce engineering costs by shortening the overall length of levees and
- 13 seawalls that require maintenance;
- 14 (2) increase the efficiency and long-term sustainability of flood and coastal levees
- 15 by recreating river, estuary, or coastal wetlands and using their flood and
- 16 storm buffering capacity;
- 17 (3) provide other environmental benefits through re-creation of natural wetlands;
- 18 or
- 19 (4) construct replacement coastal wetlands in or adjacent to a designated
- 20 European site to compensate for wetland losses resulting from reclamation or
- 21 coastal squeeze.
- 22

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

25

26 Locally in the U.S., proactive management to protect tidal marshes, on which water
27 quality of estuaries so strongly depends, may have some notable success in the short
28 term, although prospects of longer-term success are less promising. Only Maine, Rhode
29 Island, and Massachusetts have regulations in place that recognize the need to allow
30 wetlands the capacity to migrate inland as sea level rises and thereby provide long-term
31 protection (Titus, 2000). An alternative to bulkheading is using natural breakwaters of
32 oysters in quiescent waters of Atlantic and Gulf Coast estuaries to dissipate wave action
33 and thus help inhibit shoreline and marsh erosion inshore of the reef. Rock sills can be
34 installed in front of tidal marshes along more energetic estuarine shores where oysters
35 would not survive (Committee on Mitigating Shore Erosion along Sheltered Coasts,
36 National Research Council, 2006). Such natural and artificial breakwaters can induce
37 sediment deposition behind them and thereby can help sediments rise and marshes persist
38 with growing sea levels. As sea level rises, oyster reefs can also grow taller and rock sills
39 can be elevated, thereby keeping up protection by the breakwaters. Oysters are active
40 suspension feeders and help reduce turbidity of estuarine waters. Rock breakwaters in the
41 estuary are also often colonized by oysters and other suspension feeding invertebrates.
42 Restoration of oyster reefs as breakwaters and even installation of rock breakwaters
43 contribute to water quality through the oysters’ feeding and through protection of salt
44 marshes by these alternatives to bulkheads and dikes. This proactive adaptation to sea
45 level rise and risk of damaging storms will probably fail to be sustainable over longer
46 time frames because such breakwaters are not likely to provide reliable protection against

1 shoreline erosion in major storms as sea level continues to rise. Ultimately, the owners of
2 valuable estuarine shoreline may not be satisfied with breakwaters as their only defense
3 against the rising waters and may demand permission to install levees, bulkheads, or
4 alternative forms of shoreline armoring. This could lead to erosion of all intertidal
5 habitats along the shoreline and consequent loss of the tidal marsh in developed areas.
6 Some of these losses of marsh acreage would be replaced by progressive drowning of
7 river mouths and inundation of flood plains up-estuary as sea level rises. The most
8 promising suite of management adaptations on those highly developed shorelines down-
9 estuary is likely a combination of rolling easements, setbacks, density restrictions, and
10 building codes (Titus, 1998). Political resistance may preclude local implementation of
11 this adaptation, but financial costs of implementation are reasonable, if done before the
12 shoreline is developed (Titus, 2000).

13
14 Given the political barriers to implementing these management adaptations to protect
15 coastal wetlands, globally instituted mitigation of climate change may be the only means
16 in the longer term of several decades to centuries of avoiding large losses of tidal marsh
17 and its water treatment functions. Losses will be nearly total along estuarine shorelines
18 where development is most intense, especially in the zone of high hurricane risk from
19 Texas to New York (see SAP 4.1; U.S. Climate Change Science Program, 2007).

20 Although rapid global capping of greenhouse gas emissions would still result in decades
21 of rising global temperatures and consequent physical climatic changes (IPCC, 2007), it
22 may be possible in the short term (years to a few decades) to partially alleviate damage to
23 tidal marshes and diminution of their water treatment role on developed shores by local
24 management adaptations, such as installation of natural and artificial breakwaters. On
25 undeveloped estuarine shorelines, implementation of rolling easements is a critical need
26 before development renders this approach too politically and financially costly. However,
27 much public education will be necessary for this management adaptation to be accepted.

28
29 Estuarine water quality is also threatened by a combination of rising temperature,
30 increased pulsing and, in many regions like the east coast, growing quantities of
31 freshwater riverine discharge, and more energetic upstream wedging of sea waters with
32 rising sea level (Scavia *et al.*, 2002). Temperature increases drive faster biochemical
33 rates, including greater rates of microbial decomposition and animal metabolism, which
34 inflate oxygen demand. When increased fresh water discharges into the estuary, this less-
35 dense fresh water at the surface, when combined with stronger salt water wedging on the
36 bottom, will enhance water column stability because of greater density stratification.
37 Such conditions are the physical precursor to development of estuarine bottom water
38 hypoxia and anoxia in warm seasons because oxygen-rich surface waters are too light to
39 be readily mixed to depth (Paerl *et al.*, 1998). This water quality problem leads to
40 persistent hypoxia and anoxia, creating dead zones on the bottoms of estuaries, one of the
41 most serious symptoms of eutrophication (Paerl *et al.*, 1998; Bricker *et al.*, 1999). Under
42 higher water temperatures and extended warm seasons, high oxygen demand is likely to
43 extend for longer periods of the year while greater stratification further decreases
44 dissolved oxygen in bottom waters. Erosion of riparian marshes from rising water levels
45 also adds previously sequestered organic carbon to the estuary, further increasing oxygen
46 demand for its microbial decomposition. In regions such as the Pacific Northwest, where

1 summertime droughts are predicted rather than summer increases in storm-driven pulses
2 of rain, this scenario of greater water-column stability and higher oxygen demand at
3 elevated temperature will not apply. Nevertheless, negative consequences of summertime
4 drought are likely also.

5
6 Failing to act in advance of increases in incidence, scope, and duration of bottom water
7 hypoxia implies widespread climate-related modifications of many estuaries, inconsistent
8 with maintaining a balanced indigenous population of fish, shellfish, and wildlife.
9 Nutrient reduction in the watershed and airshed could limit algal blooms and thereby
10 reduce organic loading and oxygen demand (Conley *et al.*, 2002). However, discharge
11 limits for point sources are already close to what is technically feasible in many rivers.
12 From an economic standpoint, further limiting atmospheric nitrogen deposition would
13 affect many activities, such as electric power generation, industrial operations, and
14 automobile use. It is possible that wetland restoration over the drainage basin could be
15 greatly enhanced to reduce the fraction of diffuse nutrient loading that reaches the estuary
16 and help counteract the increased estuarine stratification and warming temperatures that
17 drive higher microbial decomposition and oxygen demand (Mitsch and Day Jr, 2006).
18 Thus, integrated management of nutrient sources and wetland treatment of nutrients can
19 play a role in management to limit eutrophication and hypoxia.

20
21 At state levels of management, recognition of the likelihood of climate change and
22 anticipation of its consequences could lead to important proactive steps, some with
23 potentially minimal costs. Regulatory change represents one major example of an
24 institutional approach at this level. Maine, Rhode Island, and Massachusetts deserve
25 praise for appropriately responding to risk of wetland loss under sea level rise by
26 instituting regulations to allow landward migration of these habitats (Titus, 2000).
27 Examination of state laws, agency rules, and various management documents in North
28 Carolina, on the other hand, suggests that climate change is rarely mentioned and almost
29 never considered. One example of how rule changes could provide proactive protection
30 of water quality would be to anticipate changes in sea level rise and storm intensity by
31 modifying riparian buffer zones accordingly to maintain water quality. Permitting rules
32 that constrain locations for construction of landfills, hazardous waste dumps, mine
33 tailings, and facilities that store toxic chemicals could be modified to insure that even
34 under anticipated future conditions of sea level rise, shoreline recession, and intense
35 storms, these facilities would remain not only outside today's floodplains but also outside
36 the likely floodplains of the future. Riverine floodplain maps and publicly run flood
37 insurance coverage could be redrafted to reflect expectations of flooding frequency and
38 extent under changing rainfall amounts and increasing flashiness of rainfall as it is
39 delivered in more intense discrete storms. Such changes in floodplain maps would have
40 numerous cascading impacts on development activities along the river edges in the entire
41 watershed, many of which would help protect water quality during floods. Water quality
42 degradation associated with consequences of floods from major storms like hurricanes
43 can persist for many months in estuaries (Paerl and Bales, 2001). Thus, if climate change
44 leads to increases in storm intensity, proactive protection of riparian floodplains could
45 help reduce the levels of pollutants that are delivered during those floods. Acting now to
46 address this stressor helps enhance ecosystem resiliency to impacts of climate change on

1 eutrophication and pollution by toxicants. Floodplains may offer some of the last
2 remaining undeveloped components of our coastal landscape over which transgressive
3 expansion of sea level might occur with minimal human impact, so expanding protected
4 areas of floodplains also helps build resilience of the socioeconomic system. Even during
5 the past two decades, many estuarine watersheds have experienced multiple storms that
6 exceeded standards for “100-year floods,” implying that recomputation and remapping of
7 those hazardous riverine floodplains is already necessary.

8 **7.3.2.2 Sustaining Fisheries and Wildlife Populations**

9 Sustaining fish production and wildlife populations represent important management
10 goals of most national estuaries and essentially all estuaries nationwide. Fisheries are
11 likely to suffer large declines from both of the major processes that affect water quality:
12 (1) loss of tidal marshes associated with rising sea levels and enhanced incidence of
13 intense storms as these drivers interact with hardened shorelines; and (2) increased
14 frequency, scope, and duration of bottom-water hypoxia arising from stronger
15 stratification of the estuarine water column and greater microbial oxygen demand at
16 higher temperatures. Marshes and other wetlands perform many valuable ecosystem
17 services (Millennium Ecosystem Assessment, 2005), several of which lead to enhanced
18 fish production. Numerous studies have demonstrated the high use of salt marshes by
19 killifish, grass shrimps, and crabs, which are important prey for larger commercially
20 important fishes and for wading birds at higher trophic levels. Salt marsh habitat supports
21 several endemic species of birds, such as some rails, and small mammals, some of which
22 are on federal or state threatened and endangered lists (Greenberg *et al.*, 2006). The
23 combination of high primary production and structural protection makes the marsh
24 significant as a contributor to important detrital-based food webs based on export of
25 vascular plant detritus from the marsh, and also means that the marsh plays a valuable
26 role as nursery habitat for small fishes and crustaceans (Peterson *et al.*, In Press).
27 Zimmerman, Minello, and Rozas (2000) demonstrated that penaeid shrimp production in
28 bays along the Gulf of Mexico varies directly with the surface area of the salt marsh
29 within the bay. Maintaining complexity of salt marsh landscapes can also be an important
30 determinant of fish, shellfish, and wildlife production, especially preserving marsh edge
31 environments (*e.g.*, Peterson and Turner, 1994). Thus, marsh loss and modification in
32 estuaries are expected to translate directly into lost production of fish and wildlife.

33
34 The climate-driven enhancement of bottom water hypoxia and anoxia will result in
35 further killing of oysters and other sessile bottom invertebrates (Lenihan and Peterson,
36 1998), thereby affecting the oyster fishery directly and other fisheries for crabs, shrimp,
37 and demersal fishes indirectly (Lenihan *et al.*, 2001). These demersal consumers prey
38 upon the benthic invertebrates of the estuary during their nursery use of the system in the
39 warm season of the year. When the benthic invertebrates are killed by lack of oxygen and
40 resulting deadly hydrogen sulfide, fish production declines as energy produced by
41 phytoplankton enters microbial loops and is thereby diverted from passing up the food
42 chain to higher trophic levels (Baird *et al.*, 2004). This enhanced diversion of energy away
43 from pathways leading to higher trophic levels will not only affect demersal fish
44 production but also diminish populations of sea birds and marine mammals, such as
45 bottle-nosed dolphins and killer whales. Because estuaries contribute so greatly to

1 production of coastal fisheries generally, such reductions in fish and wildlife transcend
2 the boundaries of the estuary itself.

3
4 Fish and wildlife suffer additional risks from climate change beyond those associated
5 with loss of marsh and other shoreline habitats and those associated with enhanced
6 hypoxia. Higher temperatures are already having and will likely have additional direct
7 effects on estuarine species. Increased temperature is associated with lower bioenergetic
8 efficiency and greater risk of disease and parasitism. As temperatures increase, species
9 will not move at equal rates pole-ward (Parmesan, 2006), so new combinations will
10 emerge with likely community reorganization, elevating abundances of some fishes and
11 crustaceans while suppressing others. Locally novel native species will appear through
12 natural range expansion as water warms, adding to the potential for community
13 reorganization. In addition, introductions of non-native species may occur at faster rates
14 because disturbed communities appear more susceptible to invasion. Finally, the changes
15 in riverine flows—both amounts and temporal patterns—may change estuarine physical
16 circulation in ways that affect transport of larval and juvenile life stages, altering
17 recruitment of fish and valuable invertebrates.

18
19 The challenges of adapting management to address impacts of climate change on fish and
20 wildlife thus include all those already presented for water quality, because the goals of
21 preventing loss of tidal marsh and other shallow shoreline habitats and of avoiding
22 expansion of hypoxic bottom areas are held in common. However, additional approaches
23 may be available or necessary to respond to risks of declines in fish and wildlife. For
24 example, fisheries management at federal and state levels is committed to the principle of
25 sustainability, which is usually defined as maintaining harvest levels at some fixed
26 amount or within some fixed range. With climate-driven changes in estuarine
27 ecosystems, sustainable fisheries management will itself need to become an adaptive
28 process as changes in estuarine carrying capacity for target stocks occur through direct
29 responses to warming and other physical factors and indirect responses to changes in
30 biotic interactions. Independent of any fishing impacts, there will be a moving target for
31 many fish, shellfish, and wildlife populations, needing adaptive definitions of what is
32 sustainable. This goal calls for advance planning for management responses to climate
33 change but not implementation until the ecosystem changes have begun. Absent any
34 advance planning, stasis of management could conceivably induce stock collapses by
35 inadvertent overfishing of a stock in decline from climate modifications.

36
37 Extermination of injurious non-native species after their introduction into estuarine
38 systems has not proved feasible. However, one proactive type of management adaptation
39 in contemplation of possible enhancement of success of introduced species into climate-
40 disrupted estuarine ecosystems may be to strengthen rules that prevent the introductions
41 themselves. This action would be especially timely as applied to the aquarium fish trade,
42 which is now a likely vector of non-native fish introductions (*e.g.*, National Ocean
43 Service, 2005). Local removals of invasive non-natives combined with restoration of the
44 native species may be a locally viable reactive management response to improve marsh
45 characteristics that promote propagation and production of fish and wildlife. This type of
46 action may best be applied to vascular plants of the salt marsh. Such actions taken now to

1 reduce impacts of current stressors represent means of enhancing ecosystem resilience to
2 impacts of climate change on fish and wildlife.

3 **7.3.2.3 Preserving Habitat Extent and Functionality**

4 All national estuaries and managers of estuarine assets nationwide identify preservation
5 of habitat as a fundamental management goal. The greatest threat to estuarine habitat
6 extent and function from climate change arises as sea level rise and enhanced incidence
7 of intense storms interacts with the presence of structural defenses against shoreline
8 erosion. As explained in our description of threats to water quality and fisheries, barriers
9 that prevent horizontal migration of tidal marshes inland will result in loss of tidal marsh
10 and other intertidal and then shallow subtidal habitats. This process will include losses to
11 seagrass beds and other submerged aquatic vegetation down-shore of bulkheads, because
12 if the grass cannot migrate up-slope, the lower margin will die back from light limitation
13 (Dennison *et al.*, 1993; Short and Wyllie-Echeverria, 1996) as water levels rise. The
14 presence of bulkheads enhances the rate of erosion below them because wave energy is
15 directed downwards after striking a hard wall, excavating and lowering the sediment
16 elevation faster than if no bulkhead were present (Tait and Griggs, 1990). As shoreline
17 erosion below bulkheads continues along with rising water levels, all presently intertidal
18 habitat will become covered by water even at low tide, removing those habitats that are
19 most productive, critical for sustaining fish and wildlife, and important to maintaining
20 water quality. Galbraith *et al.* (2002) modeled this process for installation of dikes on
21 Galveston Island and concluded that intertidal habitat for shorebirds would decline by
22 20%. The enhancement of bottom water hypoxia through induction of more intense water
23 column stratification and greater microbial degradation rates at higher temperatures will
24 not eliminate the deeper subtidal habitat of estuaries but will degrade its functions over
25 wider areas of “dead zones” of the nation’s estuaries as climate change proceeds.

26
27 The challenges of adapting management to address impacts of climate change on
28 estuarine habitat extent and function thus include all those already presented for water
29 quality, because the most important goals of preventing loss of marsh and ultimately
30 other shallow shoreline habitats and of avoiding expansion of hypoxic bottom areas are
31 held in common. However, additional approaches may be available or necessary to
32 respond to risks of areal and functional declines in estuarine habitats. At local levels,
33 expanding the planning horizons of land use planning to incorporate the predictions of
34 consequences of global change over at least a few decades would represent a rational
35 proactive process. Such a longer view could inhibit risky development and
36 simultaneously provide protections for important estuarine habitats, especially salt
37 marshes and mangroves at risk from barriers that inhibit recession. Land use plans
38 themselves rarely incorporate hard prohibitions against development close to sensitive
39 habitats and have limited durability over time, as local political pressure for development
40 and desires for protection of environmental assets wax and wane. Nevertheless, requiring
41 planners to take a longer-term view could have only positive consequences in educating
42 local decision makers about what lies ahead under alternative development scenarios.
43 States run ecosystem restoration programs, largely targeted toward riparian wetlands and
44 tidal marshes. The choice of sites for such restoration activities can be improved by
45 strategically selecting only those where the restored wetland can move a sufficient

1 distance up-slope as sea level rises. Thus, planning and decision making for ecosystem
2 restoration may require purchase of upland development rights or property to insure
3 transgression potential, unless that upland is already publicly owned and managed to
4 prevent construction of any impediment to orderly movement. This consideration of
5 building in resilience to future climate change is necessary for compensatory habitat
6 restorations that must mitigate for past losses for any restoration project that is projected
7 to last long enough that recession would occur. In areas that are presently largely
8 undeveloped, legislation requiring establishment of rolling easements represents a more
9 far-reaching solution to preventing erection of permanent barriers to inland migration of
10 tidelands. Rolling easements do not require predictions about the degree and rate of sea
11 level rise and shoreline erosion. Purchasing development rights has the disadvantage that
12 the uncertainty about rate of sea level rise injects uncertainty over whether enough
13 property has been protected. In addition, rolling easements allow use of waterfront
14 property until the water levels rise enough to require retreat and thus represent a lower
15 cost (Titus, 2000). Implementation of either solution should not be delayed because delay
16 will risk development of the very zone that requires protection.

17
18 At state and federal levels, environmental impact statements and assessments of
19 consequences of beach nourishment do not sufficiently incorporate consideration of
20 climate change and its impacts. Similarly, management policies at state and local levels
21 for responding to the joint risks posed by sea level rise and increased frequencies or
22 intensities of storms, including hurricanes, have not recognized the magnitude of growth
23 in costs of present shoreline protection responses as global change continues. Most state
24 coastal management programs discourage hardening of shorelines such as installation of
25 sea walls, groins, and jetties, because they result in adverse effects on the extent of the
26 public beach (Pilkey and Wright III, 1988). Beach nourishment, a practice involving
27 repeated use of fill to temporarily elevate and extend the width of the intertidal beach, is
28 the prevailing (Titus, 2000), rapidly escalating, and increasingly expensive alternative.
29 On average, the fill sands last three to five years (Leonard, Clayton, and Pilkey, 1990)
30 before eroding away, requiring ongoing nourishment activities indefinitely. As sea level
31 rises, more sand is needed to restore the desired shoreline position at escalating cost. The
32 public debate over environmental impacts of and funding for beach nourishment will
33 change as longer-term consequences are considered. Because beach nourishment on
34 coastal barriers inhibits overwash of sediments during storms and the consequent
35 landward retreat of the coastal barrier, erosion of the estuarine shoreline is intensified
36 without this source of additional sediments. Continually elevating the shore of barrier
37 land masses above their natural level relative to depth on the continental shelf implies
38 that wave energy will not be as readily dissipated by bottom friction as the waves
39 progress towards shore. This process brings more and more wave energy to the beach and
40 increases risk of storm erosion and substantial damage to the land mass in major storms.
41 Within less than a century, the rising sea may induce geomorphological changes
42 historically typical of geological time scales (Riggs and Ames, 2003). These changes
43 include predicted fragmentation of coastal barriers by new inlets and even disintegration
44 and loss of many coastal barriers (Riggs and Ames, 2003). Such changes would cause
45 dramatic modifications of the estuaries lying now in protected waters behind the coastal
46 barriers and would shift inland the mixing zone of fresh and salt waters. As climate

1 change progresses and sea level continues to rise, accompanied by higher frequencies of
2 hurricanes and other storms, the beach nourishment widely practiced today on ocean
3 beaches (Titus, 2000) may become too expensive to sustain nationwide (Titus *et al.*,
4 1991; Yohe *et al.*, 1996), especially if the federal government succeeds in withdrawing
5 from current funding commitments. Miami Beach and other densely developed ocean
6 beaches are likely to generate tax dollars sufficient to continue beach nourishment with
7 state and local funding. Demand for groins, geotubes, sand bags, and other structural
8 interventions will likely continue to grow as oceanfront property owners seek protection
9 of their investment. These come at a price of loss of beach, which is the public trust
10 resource that attracts most people to such areas. Retreat from and abandonment of coastal
11 barriers affected by high relative rates of sea level rise and incidence of intense storms
12 does not seem to represent a politically viable management adaptation.

13 **7.3.2.4 Preserving Human Values**

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

28
29 Probably, the most serious effects of climate change on private human values associated
30 with estuaries are those arising from climate-driven increases in shoreline erosion,
31 flooding, and storm damage. Rising sea level and increased incidence of intense storms
32 brings higher risk of extensive loss of real estate, houses, infrastructure, and even lives on
33 estuarine shores. The houses and properties at greatest risk are those on coastal barriers
34 lying between the ocean and outer estuary because development on such coastal barriers
35 is exposed during major storms to large waves in addition to storm surge and high winds.
36 Economic and social costs of major storm events under conditions of elevated sea level
37 may be staggeringly high, as illustrated by hurricane damage during the past decade. The
38 management of such risks can already be considered proactive: on ocean beaches,
39 nourishment is practiced to widen and elevate the beach and bulkheads are widely
40 installed on estuarine shorelines. However, each of these defenses is largely ineffective
41 against major storms, and climate change predictions project more such storms
42 developing on a continually warming Earth. Additional proactive management in the
43 future may involve construction of dikes and levees designed to withstand major storms
44 and capable of vertical extension as sea level increases. Such intervention into natural
45 processes on ocean and estuarine shores is technically feasible but probably affordable

1 only where development is intense enough to have created very high aggregate real estate
2 values. It sacrifices public trust values for private values. Long-term sustainability of
3 such barriers is questionable. In places experiencing rapid erosion but lacking dense and
4 expensive development, shoreline erosion is likely to be accepted and retreat and
5 abandonment occur. Even before extensive further storm-related losses of houses,
6 businesses, and infrastructure on ocean and estuarine shores, property values may deflate
7 as sea level and risks of storm and flood damage increase. Many property insurers are
8 already cancelling coverage and discontinuing underwriting activities along wide swaths
9 of the coast in the areas most at risk to hurricanes, from Texas through New York. State
10 governments are stepping into that void, but policy coverage is far more costly.
11 Availability of mortgage loans may be the next economic blow to coastal development.
12 As losses from storms mount further, the financial risks of home ownership on estuarine
13 shorelines may create decreased demand for property and thus cause losses in real estate
14 values.

15
16 Comprehensive planning could be initiated now at federal, tribal, state, and local levels to
17 act proactively, or opportunistically after major storm events, to modify rules or change
18 policies to restructure development along coastal barrier and estuarine shorelines to avoid
19 future loss of life and property, and at the same time protect many environmental assets
20 and ecosystem services in the interest of the public trust. For example, doing up-front
21 planning to prevent rebuilding in hazardous areas of high flood risk and storm damage
22 may be feasible. Establishing setbacks from the water and buffer widths, based on the
23 new realities of shoreline erosion and on reliable predictions of shoreline position into the
24 future, may be possible if advance planning is complete so that rules or policies can be
25 rapidly implemented after natural disasters. Many programs such as federal flood
26 insurance and infrastructure development grants subsidize development. For undeveloped
27 coastal barriers, such subsidies were prohibited by the Coastal Barriers Resources Act
28 and these prohibitions could be extended to other estuarine and coastal shorelines now at
29 high and escalating risk. Local land use plans could be modified to influence
30 redevelopment after storms and direct it into less risky areas. Nevertheless, such plans
31 would result in financial losses to property owners who cannot make full use of their
32 land. Land trusts and programs to protect water quality, habitat, and fisheries may
33 provide funding to purchase the most risky shorelines of high resource value.

34 **7.3.2.5 Water Quantity**

35 Many national estuaries, especially those on the Pacific coast where snowmelt is a large
36 determinant of the hydroperiod, identify water quantity issues among their management
37 priorities. Such water quantity issues will become growing concerns directly and
38 indirectly for all estuaries as climate continues to change. Projected global climate
39 change includes modifications in rainfall amount and temporal patterns of delivery, in
40 processes that influence how much of that rain falling over the watershed reaches the
41 estuary, and in how much salt intrusion occurs from altered river flows and rising sea
42 levels penetrating into the estuary. These climate changes interact strongly with human
43 modifications of the land and waterways as well as with patterns of water use and
44 consumption. The models predicting effects of climate change on rainfall amount are not
45 all in agreement, complicating adoption of proactive management measures. Thus,

1 complex questions of adaptive management arise that would help smooth the transition
2 into the predictably different rainfall future, whose direction of change is uncertain. Many
3 of these questions will have site (basin)-specific conditions and solutions; however a
4 generic overview is possible.

5
6 As freshwater delivery patterns change and salt water penetration increases in the
7 estuaries, many processes that affect important biological and human values will be
8 affected. Where annual freshwater delivery to the estuary is reduced, and in cases where
9 only seasonal reductions occur, salt water intrusion into groundwater will influence the
10 potable yield of aquifers. In the Pacific Northwest, predicted patterns of precipitation
11 change imply that increased salt water penetration up-estuary will be a summertime
12 phenomenon when droughts are likely. Fresh water is already a limiting resource globally
13 (Postel, 1992) and is a growing issue in the United States even in the absence of climate
14 change. Failure to develop proactive management responses will have serious
15 consequences on human welfare and economic activity. Proaction includes establishing
16 or broadening “use containment areas” (where withdrawal is allocated and capped) in the
17 managed allocation of aquifer yields so that uses are sustainable even under predicted
18 climate-related changes in recharge rates and salt water infiltration. This may result in the
19 need to develop reverse osmosis plants to produce potable water and replace ground
20 water sources currently tapped to supply communities around estuaries. Further actions
21 may be needed to modify permitting procedures for affected development, plan for
22 growing salt water intrusion as sea level rises, and maintain aquifer productivities.
23 Proactive planning measures for water shortage can include much greater water re-use
24 and conservation.

25
26 The enhanced flashiness of run-off from seasonal rainfall events, as they come in
27 discrete, more intense storms and fall upon more impervious surface area in the drainage
28 basin, will have several consequences on human values and on natural resources of
29 management priority. Greater pulsing of rain runoff reaching the rivers will lead to much
30 higher frequency and extent of floods after intense storms. The resulting faster
31 downstream flows will erode sediment from estuarine shorelines and thus reduce the area
32 of shallow habitats along the shores. In the Pacific Northwest, rain-on-snow events are
33 major sources of flood waters (Marks *et al.*, 1998; Mote *et al.*, 2003) and are likely to
34 become more frequent and intense under current climate change scenarios. These events
35 have economic, health and safety, and social consequences for humans living or working
36 in the newly enlarged flood plain. Bank stability and riparian habitats are threatened by
37 increased water velocities in flood flows, which would affect water quality and ultimately
38 fish and wildlife. When these pulses of water reach the estuary, they bring pollutants
39 from land as well as nutrient and organic loading that have negative effects on estuarine
40 functions for relatively long periods of time, on the order of a year or more. In estuaries
41 where freshwater runoff is increased by global climate change, and in all estuaries where
42 salt water has penetrated further upstream as sea level rises, the specific locations of
43 important zones of biogeochemical processes and biotic use will shift in location. These
44 shifts may have the effects of moving those zones, such as the turbidity maximum zone,
45 which could influence the performance of anadromous fishes that make use of different
46 portions of the rivers and estuaries for completing different life history stages and

1 processes. Accurate modeling of such position changes in estuaries could allow proactive
2 management to protect fish and wildlife habitats along the rivers and estuaries that will
3 become critical habitats for propagation of important fish stocks as positional shifts
4 occur.

5 **7.3.3 New Approaches to Management in the Context of Climate Change**

6 Little attention has historically been paid to preserving and enhancing ecosystem
7 resilience in the management of estuaries and estuarine resources. Resilience refers to the
8 amount of disturbance that can be tolerated by a socioecological system (*e.g.*, an estuary
9 plus the social system interacting with it) before it undergoes a fundamental shift in its
10 structure and functioning (Holling, 1972; Carpenter *et al.*, 2001; Gunderson *et al.*, 2002;
11 Carpenter and Kinne, 2003). The ability of a system to maintain itself despite gradual
12 changes in its controlling variables or its disturbance regimes is of particular concern for
13 those interested in predicting responses to climate change. Importantly, resilience of a
14 socioecological system results in part from appropriate management strategies. Human
15 behaviors can reduce resilience in a variety of ways, including increasing flows of
16 nutrients and pollutants; removing individual species, whole functional groups (*e.g.*,
17 seagrasses, bivalves), or whole trophic levels (*e.g.*, top predators); and altering the
18 magnitude, frequency, and duration of disturbance regimes (Carpenter *et al.*, 2001; Folke
19 *et al.*, 2004). Importantly, climate change has the potential to exacerbate poor
20 management and exploitation choices and cause undesirable regime shifts in ecosystems,
21 as seen in the North Sea cod fishery and recent declines in coral reefs (Walther *et al.*,
22 2002). It is critical that we pursue wise and active adaptive management in order to
23 prevent undesirable regime changes in response to climate change.

24
25 In recent years, basic research has dramatically improved our understanding of the
26 ecosystem characteristics that help promote resilience. For example, the study of the roles
27 of biodiversity in ecosystem dynamics has demonstrated several examples where
28 productivity (Tilman and Downing, 1994; Naeem, 2002), biogeochemical functioning
29 (Solan *et al.*, 2004), and community composition (Duffy, 2002; Bruno *et al.*, 2005) are
30 stabilized under external stresses if biodiversity is high. Worm *et al.* (2006) likewise
31 demonstrated that many services of marine ecosystems, including fisheries production,
32 and ecosystem properties, such as resilience, are greater in more diverse systems. Some
33 evidence exists to suggest that proliferation of non-native species can be suppressed by
34 ecosystem biodiversity (*e.g.*, Stachowicz, Whitlatch, and Osman, 1999; but see Bruno *et al.*
35 *et al.*, 2004). These research results have not yet been directly translated into management
36 of estuarine systems. This represents a promising approach to the goal of enhancing
37 adaptation in contemplation of climate change. However, acting on the knowledge that
38 higher biodiversity implies higher resilience represents a challenge.

39
40 Absent system-specific knowledge, some management actions are likely to preserve or
41 enhance biodiversity (genetic, species, and landscape) and thus support resilience, based
42 upon current theory and some empirical evidence. Maintaining high genetic diversity
43 provides high potential for evolutionary adaptation of species and provides short-term
44 resilience against fluctuating environmental conditions (Hughes and Stachowicz, 2004).

1 This goal may be achieved by establishing diversity refuges, which in aggregate protect
2 each of a suite of genotypes. Implementing this proactive management concept depends
3 on knowledge of genetic diversity and spatial patterns of its genotypic distribution, a task
4 most readily achieved for structural habitat providers such as marsh and sea grasses and
5 mangroves. Maintaining or restoring habitat and ecosystem diversity and spatial
6 heterogeneity is another viable management goal, again most applicable to the important
7 plants that provide habitat structure. Preserving or creating landscapes of the full mix of
8 different systems and including structural corridors among landscape elements otherwise
9 fragmented or isolated can be predicted to enhance resilience by enabling migrations to
10 sustain biodiversity across the landscape (Micheli and Peterson, 1999). Structural
11 complexity of vegetation has been related to its suitability for use of some (endangered)
12 species (Zedler, 1993), so preserving or restoring the vegetational layering and structure
13 of tidal marshes, seagrass meadows, and mangroves has potential to stabilize estuary
14 function in the face of climate perturbations.

15
16 Analogous need exists for enhanced understanding of factors that contribute to resilience
17 of human communities and of human institutions in the context of better preparation for
18 consequences of changing climate. Both social science and natural science monitoring
19 may require expansion to track possible fragility and look for signs of cracks in the
20 system, as a prelude to instigating adaptive management to prevent institutional and
21 ecological disintegration. For example, more attention should be paid to tracking coastal
22 property values, human population movements, demography, insurance costs,
23 employment, unemployment, attitudes, and other critical social and economic variables in
24 order to indicate need for proactive interventions as climate change stresses increase. An
25 analogous enhancement of in-depth monitoring of the natural ecosystem also has merit;
26 this likely would require changes in indicators now monitored to be able to enhance
27 resilience through active intervention of management when the need becomes evident.
28 Thus, monitoring in a context of greater understanding of organizational process in socio-
29 economic and natural systems is one means of enhancing resilience.

30
31 Both managers and the general public need better education to raise awareness of how
32 important management adaptation will be if negative impacts of climate change are to be
33 averted or minimized. Surely, managers undergo continuing education almost daily as
34 they conduct their jobs, but targeted training on expected changes within the ecosystem
35 they are responsible for managing is an emerging necessity. Re-education is necessary to
36 counteract the disinformation that has recently been circulated to support agendas of
37 various interest groups. Careful articulation of uncertainties about the magnitudes,
38 timelines, and consequences of climate change will also be important. Such education is
39 vital to induce the broad conversations necessary for public stakeholders and managers to
40 rethink in fundamental ways how we have previously treated and managed estuaries to
41 provide goods and services of value.

42
43 Whereas we have used the term “management adaptation” to mean taking management
44 actions that expressly respond to or anticipate climate change and are intended to
45 counteract or minimize any of its negative implications, natural resource managers and
46 academics have developed a different process termed “adaptive management” (Walters,

1 1986). Adaptive management in this context (see Chapter 9, Synthesis) refers to
2 designing and implementing regulations or other management actions as an experiment,
3 and employing rigorous methods of assessing the impacts of the management action.
4 Monitoring the status of the response variables provides the data against which the
5 management action's effectiveness can be judged. This blending of experimental design
6 into management provides perhaps the most rigorous means of testing implications of
7 management actions. Adaptive management has the valuable characteristic that it
8 continuously re-evaluates the basis on which predictions are made, so that as more
9 information becomes available to reduce the uncertainties over physical and biological
10 changes associated with climate change, the framework of adaptive management is in
11 place to incorporate that new knowledge. Use of this approach where feasible in testing
12 management adaptations to global climate change can provide much needed insight in
13 reducing uncertainty about how to modify management to preserve delivery of ecosystem
14 services.

15
16 Because its holistic nature includes the full complexity of interactions among
17 components, the most promising new approach to adapt estuarine management to global
18 climate change is the further development and implementation of ecosystem-based
19 management (EBM) of estuarine ecosystem services in a way that incorporates climate
20 change expectations (Peterson and Estes, 2001). The concept of EBM has its origins
21 among land managers, where it is most completely developed (Grumbine, 1994;
22 Christensen *et al.*, 1996). EBM is an approach to management that strives for a holistic
23 understanding of the complex of interactions among species, abiotic components, and
24 humans in the system and evaluates this complexity in pursuit of specific management
25 goals (Lee, 1993; Christensen *et al.*, 1996). Ecosystem-based management explicitly
26 considers different scales and thus may serve to meet the challenges of estuarine
27 management, which ranges across scales from national and state planning and regulation
28 to local implementation actions. Practical applications of the EBM approach are now
29 evolving for ocean ecosystems (Pikitch *et al.*, 2004) and hold great promise for achieving
30 sustainability of ecosystem services. Both the Pew Oceans Commission (2003) and the
31 U.S. Commission on Ocean Policy (2004) have identified EBM as our greatest hope and
32 most urgent need for preserving ecosystem services from the oceans. The dramatic
33 potential impacts of climate change on estuarine ecosystems imply many transformations
34 that simply developing and applying EBM cannot reverse, but development of synthetic
35 models for management hold great promise for optimizing estuarine ecosystem services
36 in a changing world. Ecosystems are sufficiently complex that no model will include all
37 components and processes, so the more simplified representations of the estuarine system
38 might best be used to generate hypotheses about the effectiveness of alternative
39 management actions that are then tested through rigorous protocols of adaptive
40 management. One widely advocated approach to implementing EBM does not require an
41 elaborated understanding of ecosystem structure and dynamics, and may be applicable to
42 solve important management challenges in estuaries; it is the implementation of marine
43 protected areas (Halpern, 2003; Roberts *et al.*, 2003; Micheli *et al.*, 2004). This tool is
44 most applicable where fishery exploitation and collateral habitat injury exist; clearly,
45 these issues apply to many estuarine systems.

1 **7.3.4 Prioritization of Management Responses**

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

24
25 Factors that probably would dictate priorities are numerous, including socio-economic
26 consequences of inaction, feasibility of effective management adaptations, the level of
27 certainty about the projected consequence of climate change, the time frame in which
28 action is best taken, the popular and political support for action, and the reversibility of
29 changes that may occur in the absence of effective management response. Clearly, the
30 processes that threaten to produce the greatest loss of both natural ecosystem services and
31 human values is the rise of sea level and ascendancy of intense storms with implications
32 for land inundation, property loss, habitat loss, water quality degradation, declines in
33 fisheries and in wildlife populations associated with shallow shoreline habitats, and salt
34 water intrusion into aquifers. This issue attracts the most attention in the media and from
35 the public, but the global capping of greenhouse gases may not represent a feasible
36 management response. Thus, various means of removing and preventing engineered
37 shoreline armoring such as bulkheads, levees, and dikes, combined with shoreline
38 property acquisition may be the focus of discussion if their costs are not an overwhelming
39 impediment. Because the complexity of intermingled responsibilities for managing
40 interacting components inhibits establishment of ecosystem-based management, attention
41 to modifying governance structures to meet this crisis would also rank high among
42 priorities.

1 **7.4 Case Study: The Albemarle-Pamlico Estuarine System**

2 **7.4.1 Introduction**

3 We chose the Albemarle-Pamlico Estuarine System (APES) for our case study. APES
4 provides a range of ecosystem services, extending over a diversity of ecosystem types,
5 which provide the basis for the management goals of the Albemarle-Pamlico National
6 Estuary Program (APNEP). Like other estuaries, the ecosystem services of APES are
7 climate sensitive, and this sensitivity affects the ability to meet management goals. A
8 range of adaptation options exist for climate-sensitive management goals. Many of these
9 adaptation options are applicable across estuarine ecosystems generally. Furthermore,
10 because APNEP represents one of the first national estuaries, documentation of
11 management successes and failures (Korfmacher, 1998; Korfmacher, 2002) exists for its
12 20-year history. Extensive data and decision support information are available for the
13 system and are likely to continue to be gathered into the future. We highlight a few key
14 climate-related issues in this case study, including warming and altered precipitation
15 patterns, but especially accelerated sea level rise and increased frequency of intense
16 storms.

17 **7.4.2 Historical Context**

18 Like many important estuaries, the Albemarle-Pamlico ecosystem has experienced a long
19 history of human-induced changes including species depletion, habitat loss, water quality
20 degradation, and species invasion (Lotze *et al.*, 2006). About 800 years ago, indigenous
21 Native Americans initiated agriculture in the basin, and approximately 400 years ago
22 Europeans began to colonize and transform the land. Since then, the human population
23 around the estuary has increased by two orders of magnitude from that in 1700 (Lotze *et al.*,
24 2006). Before European colonization, North Carolina had about 11 million acres of
25 wetlands, of which only 5.7 million remain today. About one-third of the wetland
26 conversion, mostly to managed forests and agriculture, has occurred since the 1950s
27 (U.S. Geological Survey, 1999). Since 1850, the amount of cropland has increased 3.5-
28 fold. More recent land use patterns show that 20% of the basin area consists of
29 agricultural lands, 60% is forested, and relatively little is urbanized (Stanley, 1992). Over
30 the last three decades, the production of swine has tripled and the area of fertilized
31 cropland has almost doubled (Cooper *et al.*, 2004). These changes in land-use patterns
32 and increases in point and non-point nutrient loading have induced multiple changes in
33 water quality, with the greatest changes appearing during the last 50–60 years (Cooper *et al.*,
34 2004).

35
36 Over the last two to three centuries in the Albemarle and Pamlico Sounds,
37 overexploitation, habitat loss, and pollution have resulted in the depletion and loss of
38 many marine species that historically have been of economic or ecological importance
39 (Lotze *et al.*, 2006). Of the 44 marine mammals, birds, reptiles, fish, invertebrates, and
40 plants for which sufficient time series information exists, 24 became depleted (<50% of
41 former abundance), 19 became rare (<90%), and 1 became regionally extinct by 2000
42 (Lotze *et al.*, 2006). Great losses also occurred among the subtidal bottom habitats.
43 Historical accounts from the late 1800s indicate that bays and waterways near the

1 mainland once had extensive beds of seagrass, while today seagrass is limited to the
2 landward side of the barrier islands (Mallin *et al.*, 2000). Oyster reef acreage has been
3 diminished over the last 100 years as a consequence of overharvesting, habitat
4 disturbance, pollution, and most recently Dermo (*Perkinsus marinus*) infections (North
5 Carolina Department of Environmental and Natural Resources, 2006).

6 **7.4.3 Geomorphological and Land Use Contexts and Climate Change**

7 Climate change impacts on APES may take numerous forms. Warming in and of itself
8 can alter community and trophic structure through differential species-dependent
9 metabolic, phenological, and behavioral responses. Changes in precipitation patterns also
10 may have species-specific consequences. In combination, warming and precipitation
11 patterns affect evapotranspiration, soil moisture, groundwater use and recharge, and river
12 flow patterns. The current rate of relative rise in mean sea level in this geographic region
13 is among the highest for the Atlantic coast, with estimates commonly over 3 mm per year
14 and in at least one study as high as 4.27 mm per year (Zervas, 2001). The anticipated
15 scenario of increasing frequency of intense storms in combination with rising sea levels
16 creates a likelihood of dramatic physical and biological changes in ecosystem state for
17 APES because the very integrity of the Outer Banks that create the protected estuaries
18 behind them is at risk (Riggs and Ames, 2003; Paerl *et al.*, 2006).

19
20 APES is a large and important complex of rivers, tributary estuaries, extensive wetlands,
21 coastal lagoons and barrier islands. Its 73,445 km² watershed (Stanley, 1992) is mostly in
22 North Carolina but extends into southern Virginia (Figure 7.3). The largest water body is
23 Pamlico Sound to the southeast, with two major tributaries, the Neuse and the Tar-
24 Pamlico Rivers. Both rivers empty into drowned river estuaries, the Neuse River Estuary
25 (NRE) and the Pamlico River Estuary (PRE), which connect to Pamlico Sound.
26 Albemarle Sound is farther north with two major tributaries, the Chowan and the
27 Roanoke Rivers, and a number of local tributary estuaries. Other smaller sounds connect
28 the Albemarle and the Pamlico (Roanoke and Croatan Sounds), and the Currituck Sound
29 extends along the northeastern portion of the complex.

30
31
32

33 **Figure 7.3.** The Albermarle-Pamlico National Estuary Program region
34 (Albemarle-Pamlico National Estuary Program, 2007).

35

36 The geological framework for coastal North Carolina, including APES has recently been
37 summarized by Riggs and Ames (2003). The system represents several drowned river
38 valley estuaries that coalesce into its large coastal lagoon (Figure 7.3). The coastal plane,
39 estuaries and sounds have a very gentle slope in which Quarternary sediments are
40 underlain largely by Pliocene sediments. Much of this sediment is organic rich mud
41 arising from eroding peat of swamps and marshes (Riggs, 1996). The gentle slope has
42 allowed major shifts in position of the shoreline and barrier islands as sea level has risen
43 and fallen. Furthermore, the position and number of inlets has changed along the barrier
44 islands, promoting or limiting the exchange of fresh and seawater.

1
2 Much of the watershed is within the coastal plain with low elevations that affect land use.
3 Moorhead and Brinson (1995) estimate that 56% of the peninsula between the Albemarle
4 Sound and PRE is less than 1.5 m in elevation. Fifty-three percent of the peninsula's area
5 is composed of wetlands, and 90% contains hydric soils. Thus, this region of the
6 watershed is sparsely populated and largely rural. In contrast, other regions are more
7 highly developed. The barrier islands, the famous "Outer Banks" of North Carolina, are a
8 mosaic of highly developed lands for tourism and protected natural areas. The
9 southeastern portion of Virginia in the APES basin is highly urbanized, and the piedmont
10 origins of the Neuse and Tar Rivers in North Carolina are highly populated. Agriculture
11 and silviculture are important land uses and economic drivers in the region. Urban
12 economies dominate much of southeastern Virginia. And a relatively new trend is the
13 development of high-end and retirement subdivisions along the "Inner Banks," the
14 mainland shore zone of the complex. The watershed's population exceeds 3,000,000
15 people including Virginia. However, only about 25% are found in coastal counties of
16 North Carolina, based on estimates for 2000 (Federal Emergency Management Agency,
17 2007). A significant portion of this population is considered "vulnerable" to strong
18 storms and thus faces risks from climate change (*i.e.*, people who live in evacuation
19 zones for storm surge or who are subject to risks from high winds by living in mobile
20 homes). The low-lying lands and basic nature of services and infrastructure of the rural
21 environment pose growing risks of flood damage as sea level and storm intensities rise to
22 land uses, infrastructure (*e.g.*, water delivery from aquifers, waste water treatment
23 facilities, roads, and buildings) and even human lives.

24
25 Another characteristic of the system's geomorphology makes it uniquely susceptible to
26 climate change drivers. The exchange of water between the ocean and the sounds is
27 restricted by the few and small inlets that separate the long, thin barrier islands (Giese,
28 Wilder, and Parker, 1985; Riggs and Ames, 2003). This restricted connectivity greatly
29 dampens amplitude of astronomical tides and limits the degree to which seawater is
30 mixed with freshwater. Temperature increases may have significant impacts on the APES
31 because its shallow bays have limited exchange with ocean waters, which serve as a
32 cooling influence in summer.

33
34 Water quality has been a recurring management concern for APES and APNEP. The
35 tributary rivers generally have high concentrations of dissolved nutrients. This fosters
36 high primary productivity in tributary estuaries, but under most circumstances nutrient
37 concentrations in the sounds remain relatively low (Peierls, Christian, and Paerl, 2003;
38 Piehler *et al.*, 2004). Most nutrient loading derives from non-point sources, although
39 nitrogen loading from point sources may account for up to 60–70% in summer months
40 (Steel and Carolina, 1991). Nitrogen deposition from the atmosphere may account for an
41 additional 15–32% (Paerl, H.W., Dennis, and Whittall, 2002). Phosphorus loading to the
42 Pamlico River Estuary was greatly enhanced by phosphate mining, which accounts for
43 about half of the total point source phosphorus loadings to this estuary and officially
44 began in 1964 (Copeland and Hobbie, 1972; Stanley, 1992). Loading has decreased
45 dramatically in recent years as treatment of mine wastes has improved. High surface
46 sediment concentrations of the toxic heavy metals arsenic, chromium, copper, nickel, and

1 lead are found in the Neuse River Estuary, possibly associated with industrial and
2 military operations, while high cadmium and silver levels in Pamlico River Estuary most
3 likely result from phosphate mining discharges (Cooper *et al.*, 2004). In 1960, hypoxia
4 was first reported in the Pamlico River Estuary (Hobbie, Copeland, and Harrison, 1975).
5 Since then, hypoxic and anoxic waters in the Pamlico River Estuary and Neuse River
6 Estuary were mostly of short duration (days to weeks) but have resulted in death of
7 benthic invertebrates on the bottom and fish kills (Stanley and Nixon, 1992; Buzzelli *et*
8 *al.*, 2002; Cooper *et al.*, 2004). Nuisance and toxic algal blooms are reported periodically
9 (Burkholder *et al.*, 1992; Bricker *et al.*, 1999), and about 22 aquatic plants and 116
10 aquatic animals, of which 22 occur in marine or marine-freshwater habitats, have been
11 identified as non-indigenous species in North Carolina (U.S. Geological Survey, 2005).
12 Increases in temperatures are expected to enhance hypoxia and its negative consequences,
13 through the combined effects of increased metabolism and, to a lesser degree, decreased
14 oxygen solubility.

15
16 The interactions between relative sea level rise, shoreline morphology, and bay
17 ravinement could have significant impacts on estuarine water quality and ecosystem
18 function in the APES. Losses of wetlands to inundation could lead to a large shift in
19 function from being a nitrogen sink to being a nitrogen source. Both planktonic and
20 benthic primary producers may be affected by, and mediate, changes in water quality,
21 nutrient and material fluxes across the sediment-water interface that may result from sea
22 level rise (Figure 7.4). Changes in the water column productivity affect particle
23 composition and concentration, which in turn increases turbidity and feedback to modify
24 further the balance between water column and benthic productivity. Inundated sediments
25 will then be subject to typical estuarine stressors (*e.g.*, salinity, changes in water table,
26 isolation from atmosphere) that can lead to dissolution of particulates, desorption of
27 nutrients or organic matter, and altered redox states. These changes result in fluxes of
28 nutrients and DOC that could radically transform the proportion of productivity and
29 heterotrophic activity in the water above the sediment and in the rest of the estuary.
30 Nutrient management plans generally assume that the frequency and magnitude of
31 bottom water hypoxia will decrease by reducing watershed inputs of dissolved inorganic
32 nitrogen and organic matter that either indirectly or directly fuel water column and
33 benthic respiration (Kemp *et al.*, 1992; Conley *et al.*, 2002). However, factors such as the
34 nutrient and sediment filtration capacity of wetlands under flooded conditions of higher
35 sea levels, and the potential for a large organic matter input from erosion and
36 disintegration of now inundated wetlands, create uncertainty about progress in containing
37 eutrophication across different scales and render the determination of management targets
38 and forecasting of hypoxia extremely difficult.

39
40
41
42 **Figure 7.4.** Feedbacks between nutrient and sediment exchange and primary
43 production in the benthos and water column. A plus symbol indicates
44 enhancement and a minus symbol suppression.
45

1 Because of the large fetch of the major sounds and tributary estuaries, wind tides control
2 water levels and wave energy can be quite high. Wind tides can lead to extended flooding
3 and high erosion rates, especially within the eastern and southern parts of the complex
4 (Brinson, 1991; Riggs and Ames, 2003). Furthermore, the barrier islands are prone to
5 breaching during storms, and geological history demonstrates the fragility of this thin
6 strip of sand and reveals the locations of highest risk of breaching. Formation of
7 persistent inlets within the barrier islands would increase oceanic exchange and thereby
8 the amplitude of astronomical tides. This, in turn, could profoundly alter the ecology of
9 both aquatic and wetland ecosystems in the APES.

10
11 The size, geomorphology, and location of the APES complex make it an important source
12 of ecosystem services for the region and the nation. The largest economic contribution of
13 APES today derives from tourism and recreation. The Outer Banks attract people from
14 around the world. Populations during the prime summer season considerably exceed
15 winter populations. The Outer Banks include the most economically important acreage of
16 the complex along with ecologically important natural areas. These coastal barriers are
17 also the most sensitive to the combination of sea level rise and increased frequency of
18 intense storms. Barrier island geomorphology is constantly changing on short and long
19 time scales, increasing and decreasing in width with sand movement and both forming
20 and closing inlets during storms. Inlets have broken through the Outer Banks repeatedly
21 over the past century and paleo records from the past few thousand years demonstrate
22 dramatic movements in location and character of the barriers as sea level has changed
23 (Riggs and Ames, 2003). But human structures on the islands and human uses of the
24 barrier islands' natural resources have now changed the degree to which natural
25 geological processes occur. Construction and maintenance of Route 12 along the Outer
26 Banks has restricted washover and the movement of sand from the seaward side of the
27 islands to the sound side. Furthermore, the presence of houses, condominiums, hotels,
28 etc. produces conflicts between maintaining the natural geomorphic processes that allow
29 island migration landwards as sea level rises and protecting human infrastructure. Rising
30 sea level and increased frequency of intense storms enhances the potential beach erosion,
31 thereby increasing costs of beach nourishment, and increases risk of island disintegration,
32 leading to increased political pressure to legalize hard structures on the ocean shoreline.

33
34 Beaches are a major natural resource and drive many coastal economies. Because the
35 presence of houses, condominiums, and roads and other infrastructure leads to defense of
36 the shoreline position and prevents natural recession, beach erosion now reduces beach
37 widths as sea level is rising. North Carolina prohibits hard structures (*e.g.*, bulkheads,
38 jetties, and permanent sand bags) on the ocean shoreline. Instead, erosion is countered by
39 beach nourishment, in which sand is dredged from offshore. This is a temporary and
40 expensive solution. It also has potentially significant impacts on the living resources of
41 the beach, such as shorebirds and resident invertebrates (Peterson and Bishop, 2005;
42 Peterson *et al.*, 2006). Erosion of beaches tends to occur with the major axis parallel to
43 the islands (*i.e.*, meters or tens of meters of erosion of beach along hundreds to thousands
44 of meters along the beach face). Breaching of new inlets and overwash events penetrate
45 more into the islands. A recent breach occurred on Hatteras Island during Hurricane
46 Isabel, but it was quickly closed by the U.S. Army Corps of Engineers to permit road

1 reconstruction and automobile travel along the Outer Banks. Riggs and Ames (2003)
2 have projected that under higher stands of sea level, future hurricanes may create
3 numerous large, new inlets and break the chain of coastal barriers that forms the eastern
4 edge of the entire APES system. They mapped locations of the paleochannels along the
5 islands and identified these as the most likely locations for such breaches. Such events
6 represent the most dramatic consequences of climate change to APES. Extensive new
7 inlets would lead to an entirely new tidal, salinity, wave, and hydrodynamic regime
8 within APES, and in turn drastically change the ecology of the complex. Wise
9 management for the future must include preparation for the possibility of events such as
10 these and their consequences.

11
12 Natural areas in APES have been recognized for their significance as wildlife habitat,
13 nurseries for aquatic species, stop-over sites (flyways) for migratory birds, and important
14 spawning areas for anadromous fish. Recreational fishing and boating add to the
15 attraction of the beaches, barrier islands, and natural areas within the watershed. The
16 nursery services of the complex are also important to fisheries, both locally and along the
17 entire eastern coast of the United States. Cape Hatteras sits at the biogeographic
18 convergence of populations of northern and southern species, and many of these species
19 use the sounds during their life cycles. Thus, the location of APES makes it particularly
20 sensitive to any climate-related changes that alter migratory patterns of both birds and
21 marine organisms.

22
23 The wetlands of the Albemarle Pamlico Sound complex are largely non-tidal and subject
24 to irregular wind tides, as described above. In freshwater regions along the rivers and
25 flood plains, swamp forests dominate. Pocosins—peat-forming ombrotrophic wetlands—
26 are found in interstream divides. As sea level rises in oligohaline regions, swamp forests
27 may continue to dominate or be replaced by brackish marshes. Irregularly flooded
28 marshes, dominated by *Juncus roemerianus*, extend over much of the higher-salinity
29 areas. Back barrier island marshes are dominated by *Spartina alterniflora*. The ability of
30 these wetlands to respond to sea level rise is becoming compromised by increased human
31 infrastructure. Roads, residential and urban developments, hard structures for shoreline
32 stabilization, and agricultural ditching are preventing horizontal transgression of wetlands
33 and promoting erosion of edges throughout the complex. Furthermore, development of
34 the barrier islands has prevented natural overwash and inlet-forming processes that
35 promote salt marsh development (Christian *et al.*, 2000; Riggs and Ames, 2003).

36 **7.4.4 Current Management Issues and Climate Change**

37 The Albemarle-Pamlico Estuarine System became part of the NEP (APNEP) in 1987.
38 Initial programmatic efforts focused on assessments of the condition of the system
39 through the Albemarle-Pamlico Estuarine Study. The results of these efforts were used in
40 the stakeholder-based development of a Comprehensive Conservation and Management
41 Plan (CCMP) in 1994. The CCMP presented objectives for plans in five areas: water
42 quality, vital habitats, fisheries, stewardship, and implementation (Box 7.8) (Albemarle-
43 Pamlico National Estuary Program, 1994). For each objective, issues of concern were
44 identified and management actions proposed. None of the issues or proposed actions

1 explicitly included climate change. In 2005, NEP Headquarters conducted its most recent
2 triennial implementation review of APNEP. APNEP passed the implementation review
3 and was found eligible for funding through FY 2008.

4
5 Although no management objective explicitly identifies climate change or its
6 consequences, water quality, vital habitats, and fisheries are likely to be substantially
7 affected by changes in climate. Recent efforts by APNEP and the State of North Carolina
8 led to more direct consideration of the impacts of climate change. APNEP has identified
9 indicators of condition of the system and begun the process for implementing their use.
10 Multiple indicators assess condition of atmosphere, land, wetland, aquatic, and human
11 components of the system. While some indicators focus on short-term changes in these
12 components, many have meaning only in their long-term trends. Given a changing
13 climate and associated impacts, these indicators place APNEP in position to assess these
14 impacts for wise management. On a broader front, the legislature of North Carolina in
15 2006 established a commission on climate change to assess how climate change will
16 affect the state and to propose actions to either minimize impacts or take advantage of
17 them.

18
19 In 1987 North Carolina passed the Fisheries Reform Act, requiring both development of
20 formal species management plans for each commercially and/or recreationally harvested
21 fishery stock and the development of a Coastal Habitat Protection Plan (CHPP). The
22 CHPP development and implementation process resembles an EBM at the state level
23 because it requires consideration and integrated management of all factors that affect the
24 quality of fish habitats in a synthetic, integrative fashion. To achieve this goal, staff from
25 all appropriate state resource and environmental commissions came together to map
26 coordinated approaches to achieve sustainability of habitat quantity and quality for
27 fishery resources. This partnership among agencies, while only at the state level,
28 addresses one of the biggest goals of EBM (Peterson and Estes, 2001). Commissions and
29 agencies responsible for fisheries management (Marine Fisheries Commission), water
30 quality and wetlands (Environmental Management Commission), and coastal
31 development (Coastal Resources Commission) are the major entities, but the
32 Sedimentation Control Commission and Wildlife Resources Commission also contribute.
33 The CHPP does contemplate several aspects of climate change and human responses to
34 threats such as beach and shoreline erosion, although long-term solutions are elusive.
35 Now that a plan exists, the implementation of its short-term goals has yet to begin and
36 may become contentious.

37
38 Other innovative programs and initiatives within North Carolina are the Ecosystem
39 Enhancement Program (EEP), Clean Water Management Trust Fund (CWMTF), and the
40 designation of estuaries as nutrient sensitive. EEP is an agency that coordinates wetland
41 mitigation efforts to maximize their effectiveness. The North Carolina Department of
42 Transportation's mitigation needs are largely met through EEP. The program uses a
43 watershed approach in planning mitigation projects. This allows a broad and
44 comprehensive perspective that should be reconciled with climate change expectations.
45 The CWMTF provides financial support for activities that improve or protect water
46 quality. It offers an opportunity to link consideration of climate change to such activities,

1 although no such link has been an explicit consideration. The designation of nutrient
2 sensitivity allows enhanced controls on nutrient additions and total maximum daily
3 loadings to the Neuse and Tar-Pamlico systems. In fact, regulations have been designed
4 to not only curb expansion of nutrient enrichment but to roll it back with restrictions to
5 both point- and non-point sources.

6 **7.4.5 Recommendations for Environmental Management in the Face of Climate** 7 **Change**

8 We make three overarching recommendations for management of estuaries in the face of
9 climate change: (1) maintain an appropriate environmental observing system; (2) educate
10 a variety of audiences on long-term consequences; and (3) pursue adaptation and adaptive
11 management. Each of these is described specifically for APES but has application to
12 other estuaries in whole or part. Furthermore, each involves coordination of multiple
13 initiatives and programs. It is this coordination that should be a major focus of APNEP in
14 particular and NEP in general.

15
16 An appropriate observing system involves a network of programs that detects, attributes
17 and predicts change at multiple scales. It includes sustained monitoring, data and
18 information management, predictive model production, and communication of these
19 products to users. The users include environmental managers, policy makers, and
20 members of the public over a range of economic positions and status. Regulatory and
21 policy needs require a variety of measurements to be made in a sustained way. These
22 measurements extend to variables of physical, chemical, biological, and socioeconomic
23 attributes of APES. Many have been identified by APNEP with its indicator program.
24 These measurements must be made to respond to drivers at different time scales; while
25 these time scales include short-term variation, the most important to this report are long-
26 term trends and infrequent but intense disturbances.

27
28 There are other observing system initiatives within coastal North Carolina. These include
29 the North Carolina Coastal Ocean Observing System and Coastal Ocean Research and
30 Monitoring Program. Both have their emphases on the coastal ocean and near real-time
31 products of physical conditions. However, their efforts need to be more directed toward
32 the APES and other estuarine ecosystems to be more valuable to the people of North
33 Carolina. More effort is needed to assess and understand the physical dynamics of the
34 estuarine systems. Observations and analyses should be extended to characterize the
35 physical and geochemical processes of catchment and riverine inflows, which are likely
36 to change dramatically under changing climatic conditions. The systems also need to
37 broaden their observations to include ecological and socioeconomic measurements. These
38 measurements are less likely to be near real-time, but user needs do not require such
39 quick reporting. We recommend that the coastal observing systems be linked explicitly to
40 APNEP indicator activities.

41
42 Education is needed across the spectrum of society to produce informed stakeholders and
43 thus facilitate enlightened management adaptations. The need for K–12 education on
44 climate change is obvious, but there is also a lack of general understanding among adults.
45 Education efforts are needed for the general public, policy makers, and even

1 environmental managers. North Carolina has several significant programs that can
2 promote this general understanding. APNEP and the Commission on Climate Change
3 have been mentioned above. Public television and radio have a general mission to
4 educate and have contributed time to the topic. Two other programs are (1) the
5 Partnership for the Sounds, including the Estuarium in Washington, North Carolina, and
6 (2) the North Carolina Aquariums. The latter includes three aquaria along the coast.
7 These programs are in a unique position to teach the general public about climate change.
8 We recommend that coordination among these different programs be fostered to promote
9 education within the state.

10
11 Finally, adaptive management and adaptation strategies are essential to respond to the
12 complex implications of climate change. Adaptive management recognizes the need for
13 both sustained monitoring associated with observing systems and adaptive justification of
14 intervention plans that reflect advances in our understanding of impacts of climate change
15 and new insights on what experimental interventions are needed. Adaptive management
16 also recognizes the important role of education that promotes better appreciation of a
17 changing and uncertain world. Adaptive management is explicit within APNEP, CHPP,
18 and EEP. It also is incorporated into controls on nutrient additions to alleviate the impacts
19 of cultural eutrophication. It acknowledges the importance of the ecosystem perspective
20 and breaks the regulatory mold of being specific to an issue, species, single source of
21 pollution, etc. This enhances the ability to meet the challenges of climate change. One
22 aspect of this change is the expectation that landscape units that are controlled by sea
23 level will migrate. Beaches and wetlands will move shoreward. Regulations and policies
24 that foster the ability to retreat from these landscape migrations are part of this adaptive
25 approach. Adaptive management is an established approach in North Carolina, which can
26 serve as a successful example nationally.

27 **7.4.6 Barriers and Opportunities**

28 APNEP possesses environmental and social barriers to effective implementation of
29 management adaptation to climate change, yet at the same time various social and
30 environmental characteristics represent favorable opportunities for adaptation. Indeed,
31 APNEP was chosen for a case study because it could illustrate both significant barriers
32 and opportunities. Perhaps its greatest single barrier to successful adaptation to climate
33 change is the intractable nature of the challenge of preserving the integrity of the coastal
34 barrier complex of the Outer Banks over the long time scales of a century and longer.
35 These coastal barriers are responsible for creating the APNEP estuarine system, and a
36 major breach in the integrity would ultimately convert the estuary into a coastal ocean
37 embayment (Riggs and Ames, 2003). Current management employs beach nourishment
38 to fortify the barrier, but this method will become increasingly expensive as sea level
39 rises substantially, and thus would be politically infeasible. Construction of a seawall
40 along the entire extent of the barrier complex also does not appear to be a viable option
41 because of financial costs and loss of the beach that defines and enriches the Outer
42 Banks.

1 Special opportunities for implementation of adaptive management in APNEP include the
2 existence of the CHPP process, a legislatively mandated ecosystem-based management
3 plan for preserving and enhancing coastal fisheries. This plan involves collaborative
4 attentions by all necessary state agencies and thereby can overcome the historic
5 constraints of compartmentalization of management authorities. This plan sets an
6 admirable example for other states. Similarly, the novel state commission on effects of
7 climate change that was legislated in 2005 also provides opportunity for education and
8 participation of legislators in a process of looking forward, well beyond the usual time
9 frames of politics, to serve as an example of proactivity for other states to emulate.
10 Sparse human populations and low levels of development along much of the interior
11 mainland shoreline of the APNEP complex provide opportunities for implementation of
12 policies that protect the ability of the salt marsh and other shallow-water estuarine
13 habitats to be allowed to retreat as sea level rises. Implementing the policies required to
14 achieve this management adaptation would not be possible in places where development
15 and infrastructure are so dense that the economic and social costs of shoreline retreat are
16 high. Special funding to support purchase of rolling easements or other implementation
17 methods can come from the Clean Water Management Trust Fund and the Ecosystem
18 Enhancement Program of North Carolina, two facilitators of large coordinated projects.
19 The State of North Carolina was among the first to establish basin-scale water quality
20 management and has established novel methods of basin-wide capping of nutrient
21 delivery to estuaries, such the Neuse River Estuary, involving ecosystem-based
22 management through participation of all stakeholders. This too facilitates actions required
23 to manage consequences of climate change to preserve management goals of a national
24 estuary.

25 **7.5 Conclusions**

26 **7.5.1 Management Response**

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

29
30 (2) In the absence of effective management adaptation, climate-related failures will
31 appear in all of the most important management goals identified in the CCMPs of
32 national estuaries: maintaining water quality, sustaining fish and wildlife populations,
33 preserving habitat, protecting human values and services, and fulfilling water quantity
34 needs.

35
36 (3) Avoiding negative impacts in estuaries to either public trust or private property values
37 on shore could only be achieved by management at the global scale by capping
38 greenhouse gas emissions, a solution that, if accomplished today, would not prevent
39 decades of change because of past emissions. Consequently, impacts of climate change
40 and sea level rise, in particular, are inevitable. As an example, climate change impacts on
41 sea level are already evident in the growing demand for and costs of beach nourishment.
42

1 (4) Many of the anticipated consequences of climate change occur via mechanisms
2 involving interactions among stressors and therefore may not be widely appreciated by
3 policy makers, managers, stakeholders, and the public.
4

5 (5) Among the consequences of climate change that threaten estuarine ecosystem
6 services, the most serious involve interactions between climate-dependent processes and
7 human responses to climate change. In particular, conflicts arise between sustaining
8 public trust values and private property in that current policies protecting private
9 shoreline property become increasingly injurious to public trust values as climate changes
10 and sea level rises further.
11

12 (6) Many management adaptations to climate change to preserve estuarine services can
13 be achieved at all levels of government at modest cost. One major form of adaptation
14 involves recognition of the projected consequences of sea level rise and then application
15 of policies that create buffers to anticipate associated consequences. An important
16 example would be redefining riverine flood hazard zones to match the projected
17 expansion of flooding frequency and extent.
18

19 (7) Other management adaptations can be designed to build resilience of ecological and
20 social systems. These adaptations include choosing only those sites for habitat restoration
21 that allow natural recession landward and thus provide resilience to sea level rise.
22

23 (8) Management adaptations to climate change can occur on three different time scales:
24 (a) reactive measures taken in response to observed negative impacts; (b) immediate
25 development of plans for management adaptation to be implemented later, either when an
26 indicator signals that delay can occur no longer, or in the wake of a disastrous
27 consequence that provides a window of socially feasible opportunity; or (c) immediate
28 implementation of proactive policies. The factors determining which of these time frames
29 is appropriate for any given management adaptation include balancing costs of
30 implementation with the magnitude of risks of injurious consequences under the status
31 quo of management; the degree of reversibility of negative consequences of climate
32 change; recognition and understanding of the problem by managers and the public; the
33 uncertainty associated with the projected consequences of climate change; the time table
34 on which change is anticipated; and the extent of political, institutional, and financial
35 impediments.
36

37 (9) A critical goal of monitoring is to establish and follow indicators that signal approach
38 towards an ecosystem threshold that—once passed—implies passage of the system into
39 an alternative state from which conversion back is difficult. Avoiding conversion into
40 such alternative states, often maintained by positive feedbacks, is one major motivation
41 for implementing proactive management adaptation. That is especially critical if the
42 transition is irreversible or very difficult and costly to reverse, and if the altered state
43 delivers dramatically fewer ecosystem services. One example of such ecosystem
44 conversions involves nitrogen-induced conversion from an estuary dominated by
45 submersed benthic grasses to an alternative dominated by seaweeds and planktonic

1 microalgae. Such work to establish important environmental indicators is already being
2 done in national estuaries and can be used to monitor climate change impacts.

3
4 (10) One critically important management challenge is to implement actions to achieve
5 orderly retreat of development from shorelines at high risk of erosion and flooding and to
6 preclude development of undeveloped shorelines at high risk. Such proactive
7 management actions have been inhibited in the past by: (a) uncertainty over or denial of
8 climate change and its implications; (b) failures to include true economic, social, and
9 environmental costs of present policies allowing and subsidizing such risky development;
10 and (c) legal tenets of private property rights. One possible proactive management option
11 would be to establish and enforce “rolling easements” along estuarine shorelines as sea
12 level continues to rise, thereby sustaining the public ownership of tide lands.

13
14 (11) Management adaptation to climate change may include ending public subsidies that
15 now support risky development on coastal barrier and estuarine shores at high risk of
16 flooding and storm damage as sea level rises further and intense storms are more
17 common. Although the flood insurance system as a whole may be actuarially sound,
18 current statutes provide people along the water’s edge in eroding areas of highest risk
19 with artificially low rates, subsidized by the flood insurance policies of people in
20 relatively safe areas. Ending such subsidization of high risk developments would
21 represent a form of management adaptation to sea level rise. The federal Coastal Barriers
22 Resources Act provides some guidance for eliminating such subsidies for public
23 infrastructure and private development, although this act applies only to a list of
24 undeveloped coastal barriers and would require extension to all barriers and to estuarine
25 shorelines to enhance its effectiveness as an adaptation to climate change.

26
27 (12) Building upon ongoing efforts to operationalize EBM for oceans, analogous research
28 is required for estuarine ecosystems. This research needs to address a major intrinsic
29 impediment to EBM of estuarine services, which is the absence of a synthetic governance
30 structure that unites now disparate management authorities, stakeholders, and the public.
31 The U.S. Commission on Ocean Policy appealed for just this type of modification of
32 governance structure to serve to implement EBM. EBM is necessary to facilitate
33 management of interacting stressors, an almost ubiquitous condition for estuaries,
34 because under present governance schemes management authority is partitioned among
35 separate agencies or entities. Although national estuaries lack regulatory authority, they
36 do unite most, if not all, stakeholders and could conceivably be reconstructed as quite
37 different entities to develop and implement ecosystem-based management. Such
38 coordination among diverse management authorities must involve land managers in order
39 to incorporate a major source of inputs to estuaries.

40
41 (13) Using the Albemarle-Pamlico National Estuarine Program as a case study illustrates
42 several management challenges posed by changing climate. Risks of rising sea level
43 together with increases in intense storms pose a serious threat to the integrity of the Outer
44 Banks and thus to the character of the Albemarle and Pamlico Sounds, which are now
45 sheltered and brackish, possessing little astronomical tide. A state analog to ecosystem-
46 based management, the Coastal Habitat Protection Plan, unifies state agencies to provide

1 synthetic protection for fish habitats. This provides a model on which to base further
2 development and application of estuarine ecosystem-based management. The Legislature
3 of the State of North Carolina established a study commission to report on the
4 consequences of climate change and to make recommendations for management
5 responses. This procedure too can form a model for other states and the federal
6 government through the NEP. Although the Albemarle-Pamlico National Estuary is
7 among those most sensitive to climate change and has an active management planning
8 process in place, the absence of explicit adaptive management consideration in its CCMP
9 reflects a need for attention to this issue by NEPs.

10
11 (14) Contemplate pursuit of a Federal Executive Order on climate change analogous to
12 the Environmental Justice Executive Order to increase awareness of the potential for
13 catastrophe on our coasts. This could include requirements for substantive rather than
14 superficial evaluations of climate change impact in NEPA.

15
16 (15) Include climate change sensitivity, resilience, and adaptation responses as priorities
17 on all relevant funding programs at state and federal levels. In the absence of such
18 actions, for example, climate impacts on estuarine wetlands will likely violate the
19 national “no-net-loss of wetlands” policy, which underwrites the current application of
20 the Clean Water Act, in two ways: (a) wetland loss due to climate will increasingly
21 compound the continuing loss of wetlands due to development and inadequate mitigation;
22 and; (b) measures used to protect human infrastructure from climate impacts will prevent
23 wetland adaptation to climate change.

24
25 (16) Review all federal and state environmental programs to assess whether projected
26 consequences of climate change have been adequately considered and whether adaptive
27 management needs to be inserted to achieve programmatic goals. For example, Jimerfield
28 *et al.* (2007) conclude that “There clearly needs to be [a] comprehensive approach by
29 federal agencies and cooperating scientists to address climate change in the endangered
30 species recovery context. The current weak and piece-meal approach will waste precious
31 resources and not solve the problem we are facing.”

32 **7.5.2 Research Priorities**

33 **7.5.2.1 Conceptual Gaps in Understanding**

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

42
43 (2) Our understanding of processes affecting elevation change in land masses needs to be
44 enhanced generally so that risk of flooding, shoreline erosion, and storm damage can be

1 better based upon geography-specific predictions of change in relative sea level, which
2 combines rate of eustatic sea level change with land subsidence or emergence rate.

3
4 (3) Establish quantitative monitoring and research in some model estuarine systems to
5 develop mechanistic understanding of changes projected as consequences of climate
6 change. Many climate change drivers (*e.g.*, CO₂ concentration, ocean temperature at the
7 surface and with depth, sea level) are currently monitored. However, projected
8 consequences (*e.g.*, shoreline erosion rates; estuarine physical circulation patterns; water
9 column stratification and extent of hypoxia; species range extensions and subsequent
10 consequences of interactions within these new combinations of predators, prey, and
11 competitors; the incidence and impacts of disease and parasitism) require new targeted
12 monitoring and research efforts to fill the many conceptual gaps in our understanding of
13 these processes.

14
15 (4) Integrated, landscape-scale numerical modeling will have to become a fundamental
16 tool to predict potential estuarine responses to the complex and often interacting stressors
17 induced by climate change. For instance, in most cases significantly modified hydrology
18 and sediment transport predictions will need to be linked at the estuarine interface to sea
19 level and storm (wind/wave regime) predictions in order to evaluate the interactive
20 effects on sediment accretion and erosion effects in estuarine marshes. Models will have
21 to take into account complex aspects such as changes in contribution of snowmelt and
22 rain-on-snow to timing, magnitude and hydroperiod of river discharges (*e.g.*, Mote,
23 2006), changes in storm tracks (*e.g.*, Salathé, 2006), and changes in sediment loading to
24 and circulation within estuaries, and how river management and regulation will be a
25 factor (Sanchez-Arcilla and Jimenez, 1997) Ultimately, these models will need to be tied
26 to coastal management models and other tools that allow assessment of both climate
27 change and human response and infrastructure response.

28
29 (5) Research is needed on alternative implementation mechanisms, costs, and feasibility
30 of achieving some form of coastal realignment, probably involving rolling easements.
31 This would include legal, social, and cultural considerations in alternative methods of
32 resolving or minimizing conflicts between public trust and private property values in
33 context of building resilience to climate change by requiring rolling easements for
34 development in now largely undeveloped waterfront and riparian areas at risk of
35 flooding, erosion, and storm damage.

36 **7.5.2.2 Data Gaps**

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

1 **7.5.2.3 Governance Issues**

2 (1) As stated in Management Response recommendation 12 above, a synthetic
3 governance structure that unites now disparate management authorities, stakeholders and
4 the public may be needed to address major impediments to EBM of estuarine services.
5 NEPs could be restructured to develop and implement ecosystem-based management.
6

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

17 **7.5.2.4 Tool Needs**

18 (1) New and enhanced research funds need to be invested in development and
19 implementation of estuarine observing systems that are currently in a planning stage,
20 such as NEON, ORION, US IOOS, and others. Fully integrate these observing systems
21 with global coastal observing programs and the Global Earth Observation System.
22 Whereas physical and chemical parameters lend themselves to automated monitoring by
23 remote sensing and observing system platforms, more basic technological research is also
24 necessary to allow monitoring of key biological variables as part of these observing
25 systems. Furthermore, it is critical that current efforts to develop monitoring systems in
26 coastal ocean waters be brought into estuaries and up into their watersheds, where the
27 largest human populations concentrate and where ecosystem values are most imperiled.
28

29 (2) New, more complete, interdisciplinary models are needed projecting social,
30 economic, and cultural consequences of alternative management scenarios under
31 projected consequences of climate change. These models include decision tools that are
32 accessible by and applicable to managers and policy makers at all levels of government.
33

34 (3) New tools are required to enhance local capacity for developing and implementing
35 management adaptations in response to climate change.
36

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

1 **7.5.2.5 Education**

2 (1) Urgent need exists to inform policy makers, managers, stakeholders, and the public
3 about the specific evidence of climate change and its predicted consequences on
4 estuaries. Re-education of some audiences may require additional effort and media tools
5 to combat past and future disinformation campaigns that create confusion. Education on
6 the scale necessary will require new funding and educational initiatives. Effective efforts
7 must involve diverse suites of educational media including information delivery on
8 evolving platforms such as the internet and cell phones. The information cannot reach far
9 enough or rapidly enough if restricted to traditional delivery in school curricula and
10 classes, but must propagate through churches, civic organizations, and entertainment
11 media. Such education is particularly challenging and requires creative approaches.
12

13 (2) One goal of education about implications of climate change for estuaries is to build
14 capacity for local citizen involvement in decision making. This is particularly important
15 because of the dramatic changes required to move from management-as-usual to adaptive
16 management. Especially challenging is the process of reconsideration of developing and
17 redeveloping shorelines at risk of flooding, erosion, and storm damage.
18

19 (3) Some countries and states provide periodic assessments of the state of their
20 environment. Monitoring data from many National Estuary Programs often now serve
21 this goal when placed in a sufficiently long time frame that extends back before
22 establishment of the NEP program. Similar scoreboards relating the status of stressors
23 associated with climate change and of the consequences of climate change might be
24 valuable additions to websites for all national estuaries and for our country's estuaries
25 more broadly. To illustrate these aspects of climate change, longer-term records are
26 required than those typically found in state of environment reports. One simple example
27 would be provision of empirical data on sea level from local recording stations. Similarly,
28 maps of historical shoreline movement would provide the public with a visual indication
29 of site-specific risks. Historical hurricane tracks are similarly informative and
30 compelling.

1

2 **7.6 Appendix**

3 **7.6.1 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 |
| <ul style="list-style-type: none"> • 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/ |
| <ul style="list-style-type: none"> • 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/ |
| <ul style="list-style-type: none"> • 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.legendary.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 (HCP), 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 (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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3

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- 17 ▪ Katrina Smith Korfmacher, University of Rochester

18

1 **7.9 Boxes**

Box 7.1. Ecosystem services provided by coastal wetlands adapted by Peterson *et al.* (In Press) 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

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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)
- ground water 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)

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)

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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)

CO₂ 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

**National Estuaries Program:
Adaptation Options for Resource Managers**

- ✓ Protect the water quality of tidal marshes with oyster breakwaters and rock sills.
- ✓ Use “managed alignment” to reorient existing engineering structures affecting rivers, estuaries, and the coastlines.
- ✓ Preserve the structural complexity 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.
- ✓ Prohibit bulkheads and other engineered structures 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 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 complexity of salt marsh landscapes, especially preserving marsh edge environments.
- ✓ Restore the vegetational layering and structure of tidal marshes, seagrass meadows, and mangroves to stabilize estuary function.
- ✓ Restore native species and remove invasive non-natives to improve marsh characteristics that promote propagation and production of fish and wildlife.
- ✓ Direct restoration programs to places where the restored ecosystem has room to retreat as sea level rises.

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Box 7.5. Storms as opportunities for management change

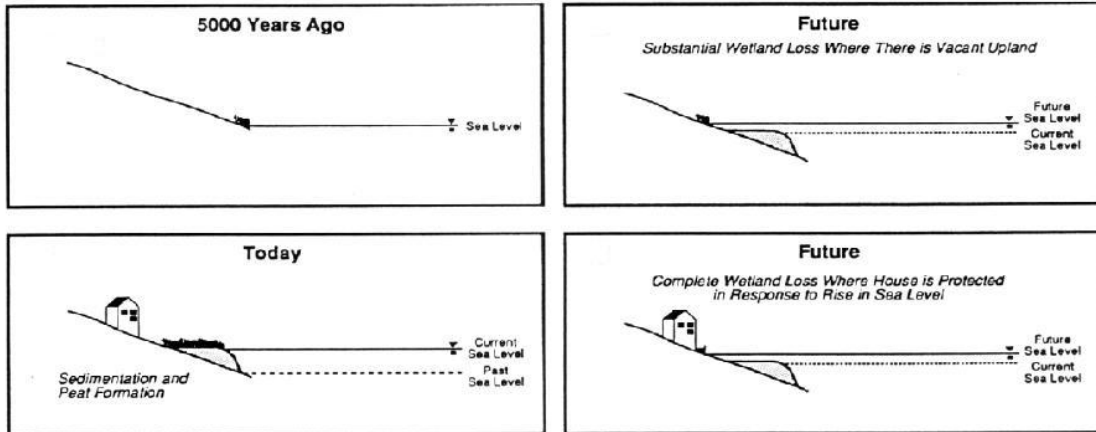
Catastrophic events provide management opportunities for increasing ecological and human resilience to climate change. Comprehensive planning could be initiated at federal, tribal, state, and local levels after major storm events to avoid future loss of life and property, and at the same time protect 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 and buffer widths 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 to protect water quality, habitat, and fisheries to purchase the most risky shorelines of high resource value.

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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 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 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.

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Box 7.7 Estuarine water quality and climate change

Climate change may lead to changes in estuarine water quality, which in turn may 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.

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Box 7.8. CCMP objectives for the Albemarle-Pamlico National Estuary Program (Albemarle-Pamlico National Estuary Program, 1994)

Water Quality Plan

GOAL: Restore, maintain or enhance water quality in the Albemarle-Pamlico region so that it is fit for fish, wildlife and recreation.

- Objective A: Implement a comprehensive basinwide approach to water quality management
- Objective B: Reduce sediments, nutrients and toxicants from nonpoint sources
- Objective C: Reduce pollution from point sources, such as wastewater treatment facilities and industry
- Objective D: Reduce the risk of toxic contamination to aquatic life and human health
- Objective E: Evaluate indicators of environmental stress in the estuary and develop new techniques to better assess water quality degradation

Vital Habitats Plan

GOAL: Conserve and Protect Vital Fish and Wildlife Habitats and Maintain the Natural Heritage of the Albemarle-Pamlico Sounds Region.

- Objective A: Promote regional planning to protect and restore the natural heritage of the A/P Sounds region
- Objective B: Promote the responsible stewardship, protection and conservation of valuable natural areas in the A/P Sounds region
- Objective C: Maintain, restore and enhance vital habitat functions to ensure the survival of wildlife and fisheries

Fisheries Plan

GOAL: Restore or Maintain Fisheries and Provide for Their Long-Term, Sustainable Use, Both Commercial and Recreational.

- Objective A: Control overfishing by developing and implementing fishery management plans for all important estuarine species
- Objective B: Promote the use of best fishing practices that reduce bycatch and impacts on fisheries habitats

Stewardship Plan

GOAL: Promote Responsible Stewardship of the Natural Resources of the Albemarle-Pamlico Sounds Region.

- Objective A: Promote local and regional planning that protects the environment and allows for economic growth
- Objective B: Increase public understanding of environmental issues and citizen involvement in environmental policy making
- Objective C: Ensure that students, particularly in grades K-5, are exposed to science and environmental education

Implementation Plan

GOAL: Implement the Comprehensive Conservation and Management Plan in a way that protects environmental quality while using the most cost-effective and equitable strategies.

- Objective A: Coordinate public agencies involved in resource management and environmental protection to implement the recommendations of the CCMP
- Objective B: Assess the progress and success of implementing CCMP recommendations and the status of environmental quality in the Albemarle-Pamlico Sounds region.

1 **7.10 Tables**

2 **Table 7.1.** The major stressors currently acting on estuaries and their expected impacts
 3 on management goals, as determined by consensus opinion of the contributing authors.
 4 Evidence is mounting that sea level rise is already having direct and indirect impacts on
 5 estuaries (*e.g.*, Galbraith *et al.*, 2002), but because this factor has not yet been widely
 6 integrated into management, we do not list it here despite its dominating significance in
 7 future decades.
 8

| 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 | |
| BOD | negative | negative | negative | negative | |

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1 **Table 7.2.** Percentage change in oceanic properties or processes as a result of climate
 2 change forcing by 2050. This table is adapted from Sarmiento *et al.* (2004). Physical
 3 changes used as inputs to the biological model are the mean of six global AOCGMs from
 4 various laboratories around the world. The AOCGMs were all forced by the IPCC IS92a
 5 scenario, which has atmospheric CO₂ doubling by 2050.
 6

| | 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 |

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Table 7.3. Factors that control the occurrence of estuarine hypoxia and the climate change-related impacts that are likely to affect them.

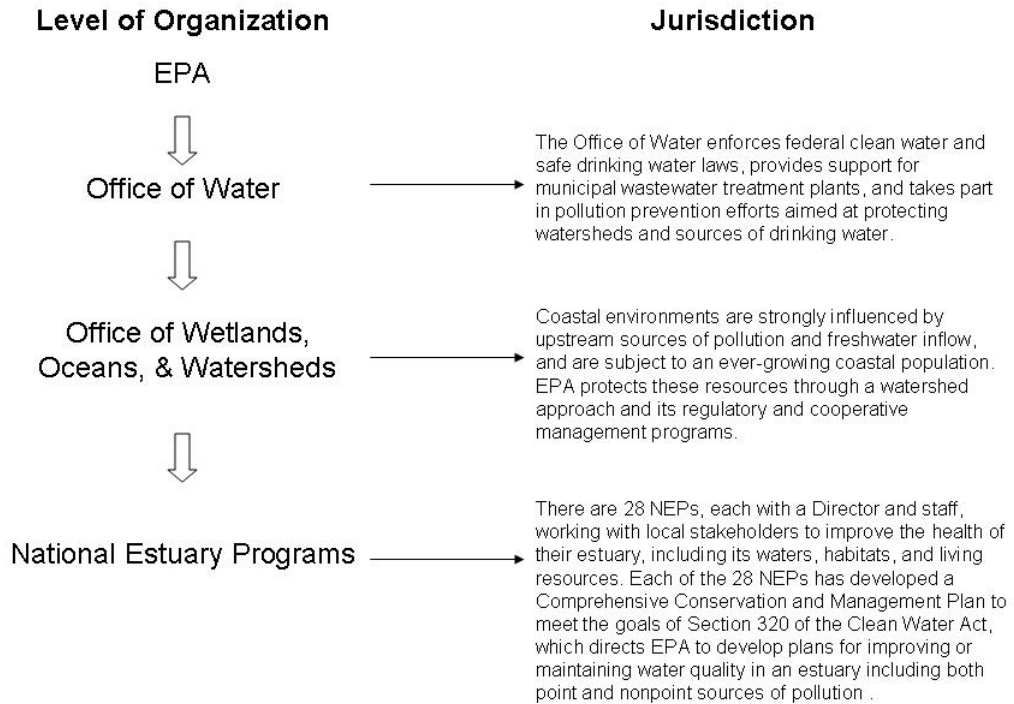
| Factor | Climate-Related Forcing |
|-----------------------|---|
| Water temperature | ΔT |
| River discharge | Δ precipitation |
| N&P loading | ΔT , Δ precipitation |
| Stratification | ΔT , Δ precipitation, Δ RSL* |
| Wind | Δ weather patterns, Δ tropical storms |
| Organic carbon source | ΔT ,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

*RSL = relative sea level

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1 **7.11 Figures**

2 **Figure 7.1.** Organization of the NEP system (U.S. Environmental Protection Agency,
3 2007b).

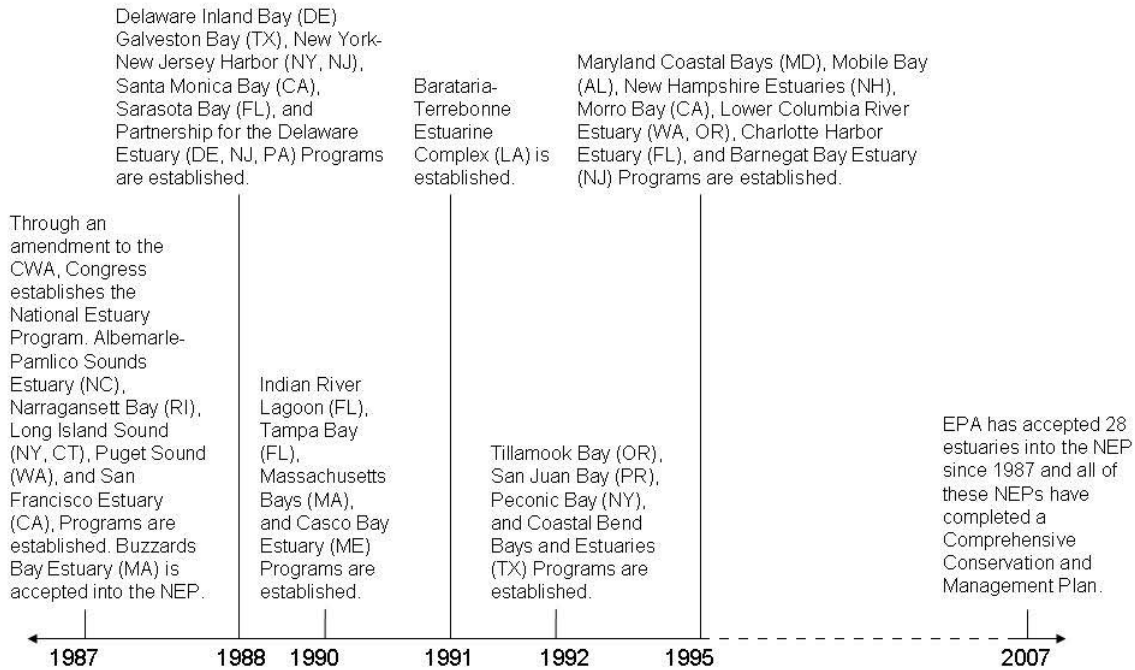


Adapted from http://www.epa.gov/water/org_chart/index.htm#

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2 **Figure 7.2. Timeline of National Estuaries Program formation (U.S. Environmental**
 3 **Protection Agency, 2007a).**



4

- 1 **Figure 7.3.** The Albermarle-Pamlico National Estuary Program region (Albemarle-Pamlico National Estuary Program, 2007).
- 2

ALBEMARLE-PAMLICO NATIONAL ESTUARY PROGRAM REGION



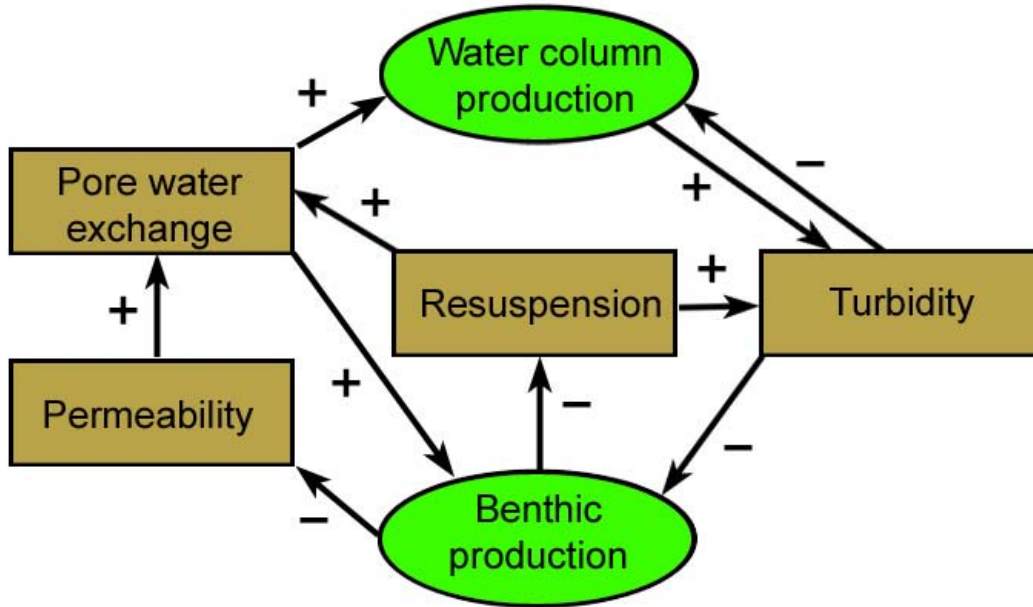
- 1 - Chowan River Basin
- 2 - Roanoke River Basin
- 3 - Currituck Sound & Pasquotank River/Albemarle Sound Drainage Basin
- 4 - Tar-Pamlico River & Pamlico Sound Drainage Basin
- 5 - Neuse River Basin & Core Sound/Bogue Sound Drainage Basin



- 3

Map prepared April 30, 1998 by the NC Center for Geographic Information & Analysis

- 1 **Figure 7.4.** Feedbacks between nutrient and sediment exchange and primary production in the benthos and water column. A plus symbol indicates enhancement and a minus symbol suppression.
- 2
- 3



- 4
- 5