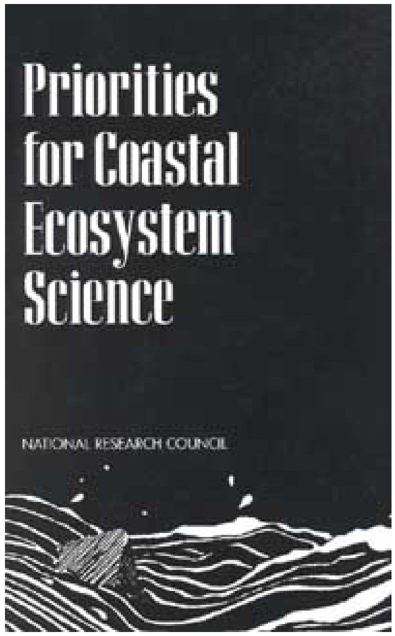



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# Priorities for Coastal Ecosystem Science

Committee to Identify High-Priority Science to Meet National Coastal Needs
Ocean Studies Board
Commission on Geosciences, Environment, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sci- ences, the National Academy of Engineering, and the Institute of Medicine.

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## COMMITTEE TO IDENTIFY HIGH-PRIORITY SCIENCE TO MEET NATIONAL COASTAL NEEDS

DONALD F. BOESCH, *Chair*, University of Maryland, Cambridge

MARY G. ALTALO, Scripps Institution of Oceanography, La Jolla, California

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MICHAEL J. DAGG, Louisiana Universities Marine Consortium, Chauvin

JOHN MARK DEAN, University of South Carolina, Columbia

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JOAN OLTMAN-SHAY, Northwest Research Associates, Inc., Bellevue, Washington

THOMAS C. ROYER, University of Alaska, Fairbanks

*Staff*

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LaVONCYÉ MALLORY, *Project Assistant*

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## Executive Summary

Coastal environments are under increasing pressure as a result of their increasing human populations. Coastal areas, including estuaries, bays, shorelines, continental shelves, and the Great Lakes, are used intensively and receive the byproducts of inland human activities, from rivers and atmospheric deposition. Because of concerns about environmental quality, habitat conservation, living and nonliving resources, and protection of life and property, a number of U.S. federal agencies conduct or sponsor scientific activities in coastal areas, spending an estimated $227 million in FY 1993. Coastal science activities conducted over the past several decades have significantly improved our knowledge of the coastal environment and human impacts on it. This knowledge has been applied to decrease environmental impacts and manage living resources. Important challenges remain or have recently emerged; these will require unprecedented coordination and cooperation among state and federal agencies, in conjunction with the scientific community. New approaches, such as comparisons among coastal systems, will be needed to make efficient use of coastal research resources.

The Committee on Environment and Natural Resources Research (CENR), one of nine National Science and Technology Council (NSTC) committees, is developing national research and development strategies on issues such as global change, biodiversity and ecosystem dynamics, resource use and management, air quality, toxic substances, natural disasters, and water resources and aquatic environments, as well as social and economic sciences, technology, and risk assessment. One of CENR's subcommittees, the Water Resources and Coastal and Marine Environments Research Subcommittee, is responsible for developing a

national research and development strategy and implementation plan for aquatic environments. This subcommittee, referred to herein as the Water Subcommittee, is building on a recently completed assessment of freshwater research priorities (*The Freshwater Imperative*; Naiman et al., in press) and a previously developed interagency framework for coastal science (*Setting a New Course for U.S. Coastal Ocean Science*; SUSCOS, 1993a,b). To provide review by the broader nonfederal scientific community for coastal environments, the Water Subcommittee requested that the Ocean Studies Board of the National Research Council (NRC) conduct this study. The Water Subcommittee requested that the committee provide an integrated assessment of research priorities based on previous NRC studies, using *Setting a New Course for U.S. Coastal Ocean Science* as a framework and the present Water Subcommittee strategy as a context (see Appendix A). The recommendations of this report should be widely applicable to decisionmakers and scientists in government, academia, and industry, but they are specifically directed to the Water Subcommittee.

The NRC Committee to Identify High-Priority Science to Meet National Coastal Needs had the broad charge of conducting an independent assessment of priorities for coastal science related to two principal issues being addressed by the Water Subcommittee: (1) water quantity and allocation and (2) ecosystem integrity. Thus, this assessment is limited to priorities for natural science related to the maintenance of coastal ecosystem integrity and the use of water resources consistent with this goal. It does not specifically address scientific priorities related to other CENR subcommittees and NSTC committees, except as they relate to issues of importance to the Water Subcommittee.

## Major Coastal Environmental Issues

As a basis for determining scientific priorities, the committee identified the following issues as posing significant threats to the integrity of coastal ecosystems.

- Eutrophication
- Habitat modification
- Hydrologic and hydrodynamic disruption
- Exploitation of resources
- Toxic effects
- Introduction of nonindigenous species
- Global climate change and variability
- Shoreline erosion and hazardous storms
- Pathogens and toxins affecting human health

Problems associated with changes in the quantity and quality of inputs to coastal environments from runoff and atmospheric deposition are particularly

important. These include increases in nutrient loading from agriculture and fossil fuel combustion, habitat losses from eutrophication, widespread contamination by toxic materials, changes in the supply of riverborne sediment, and alteration of coastal hydrodynamics. Furthermore, concern is shifting from issues amenable to single-factor risk assessment approaches to those involving multiple-stressors (e.g., combined effects of chemical contaminants and low oxygen) and indirect, cascading, and scale-related effects that require an ecosystem approach. These complex, large-scale problems pose different challenges to environmental policy, management, and science than problems now subject to regulation, such as point-source discharges, coastal land use, direct habitat destruction, and oil spills.

## Scientific Priorities Relevant To The Water Subcommittee

The committee developed priorities for science activities to address coastal environmental issues, based on the seriousness of the problem involved, the relevance to Water Subcommittee goals, the opportunity for significant progress in scientific understanding or application, and the potential for linkage of science across the land-sea interface. These recommendations are organized under five priority research areas that are now being used in the Water Subcommittee framework: Integrated Monitoring, Water Availability and Flow, Water Quality and Aquatic Ecosystem Functions, Ecological Restoration and Rehabilitation, and Predictive Systems Management. An overarching recommendation is that an integrated scientific framework should be established, that (1) facilitates systematic application of research results from individual studies in specific coastal regions to address resource management problems occurring in other regions, (2) encourages cooperative interagency activities, and (3) is based on a strong commitment to fundamental science, initiated by individual investigators or collaborators. The latter point is important because the issues set forth in Chapter 2 and the research priorities described in Chapter 3 cannot be addressed without a foundation of fundamental research. Many research programs and applications that have been planned and initiated in the past 15 years are still appropriate today and should form a basis for new interagency cooperative activities.

### *Integrated Monitoring*

To develop and implement observation systems that focus on interactions among atmosphere, land, and water dynamics at relevant time and space scales, federal agencies should:

Measure diffuse inputs, particularly of nutrients and toxic chemicals entering the coastal zone from rivers and the atmosphere.

Develop indicators of biological status and processes that can be used more effectively than existing indicators for ecosystem monitoring, including indicators of eutrophication, sublethal effects, and bioavailablity of toxic materials.
Deploy improved *in situ* and remote sensing systems to allow monitoring of physical, chemical, and biological processes spanning a wide range of spatial and temporal scales.
Link regional and national monitoring to improve the comparability and utility of local, regional, and national monitoring programs.
Improve monitoring management systems by designing monitoring that is appropriate to the problem being addressed and integrated more fully with management decisionmaking, research, and modeling.

*Water Availability and Flow*

To improve understanding of the natural patterns and processes associated with hydrological flow and develop methodologies to assess and predict cumulative effects of watershed alteration, federal agencies should:
Study the coupling of watershed hydrology and material fluxes through application of remote sensing and improved geographic information data bases, research on land-use management and investigation of material fluxes and controls of nitrogen and phosphorus export.
Develop atmosphere-watershed-coastal models to synthesize findings, guide research, and serve as management tools, including models that relate freshwater flows and the transport and transformation of materials; couple physical and biological processes; link ecosystem processes and population dynamics; provide a framework for comparing ecosystems; and assimilate observational data. Models should be shaped and corrected by observations.
Increase understanding of physical forcing processes from the head of estuaries to the edge of the continental shelf.

*Water Quality and Aquatic Ecosystem Functions*

To develop a predictive understanding of the linkages between water quality and aquatic ecosystem functions, federal agencies should:
Relate nutrient flux to ecosystem dynamics, including the regulation of primary productivity, stimulation of harmful algal blooms, deposition of organic matter, transformation and recycling of materials, controls by filter feeders and grazers, the structure of food chains, changes in habitats, and consequences on fisheries.
Conduct strategic assessments of toxic effects, by focusing on particu-

lar compounds of continuing or emerging concern, using realistic exposure conditions and applying experimental determinations of sublethal, ecosystem-level, and cumulative effects.

Investigate the role of sediment in coastal ecosystems, including its influence on particle-reactive materials, light limitation, and wetland soil building.

Relate resource use to ecosystem sustainability through increased understanding of ecosystem controls on resource species, the causes of variability of ecosystems and stocks, and the effects of resource harvest on ecosystems.

Assess the impact of multiple stressors on a variety of scales by linking both short- and long-term observations with experimental and theoretical studies.

Promote comparative coastal ecosystem science by supporting interregional collaboration, comparative analyses, and development of general conceptual models for comparison of ecological processes.

*Ecological Restoration and Rehabilitation*

To improve understanding of baseline and altered aquatic systems and develop restoration methodologies and evaluation criteria, federal agencies should:

Determine effects of habitat loss and degradation on biodiversity and productivity, by supporting research on habitat condition, requirements of specific species and communities, and vulnerability to invasion by nonindigenous species.

Advance restoration science and engineering through studies of the relationships between habitat structure and function, sediment processes, nutrient dynamics, population and community development, physical restoration techniques and restoration performance criteria, and economic and ecologic valuation.

Guide the remediation of toxic contamination through studies of the fate and transport of toxic materials mobilized from sediments and of *in situ* and other remediation technologies.

*Predictive Systems Management*

To develop the understanding, tools, methods, and models necessary to support water systems and ecosystem management for competing demands, federal agencies should:

Implement observation and prediction systems founded on near realtime measurement of physical properties and processes in selected coastal envi-

ronments that lead to environmental forecasts useful for ecosystem protection, resource management, and human safety.
Develop and employ ecosystem models as management tools by adapting scientifically-based models that couple atmospheric, watershed, and coastal process models and other more limited ecosystem models.
Advance adaptive ecosystem management, by learning from experimental management approaches and more active involvement of scientists in developing management alternatives.
Stimulate interactions between science and management by supporting exchanges of scientists and managers, and traineeships in science and technology transfer for scientists and managers.

## Regional, National, And International Scientific Programs

Regional marine research plans, recently developed for nine coastal areas of the United States, identify a number of scientific priorities consistent with the recommendations of this report, including science related to (1) indicators of ecosystem health; (2) eutrophication; (3) the fate and effect of selected toxicants, particularly in sediments; and (4) the effects of physical modification of habitats and the restoration of these habitats. In addition, themes similar to those developed in this report are evident in the scientific priorities identified in *The Freshwater Imperative* (Naiman et al., in press), including (1) the importance of modifications of water flows and associated materials fluxes and transformations, (2) the need for effective biological indicators of ecosystem function and integrity, (3) effects of physical phenomena on ecosystem structure and function, (4) the emerging science of ecosystem restoration and rehabilitation, and (5) the development of science-based predictive management aided by the use of coupled physical-chemical-biological models.

The increasing emphasis on location-specific (i.e., *place-based*) approaches for ecosystem management will increase the demand for and support of regional scientific activities serving specific ecosystem management programs. Geographically targeted, strategic researchcomprehensive enough to address ecosystem-level questionsshould be promoted to serve place-based management in those cases. But comparative knowledge of other coastal ecosystems will also be important in extending results among regions.

The committee believes that U.S. federal agencies and the national scientific community have an obligation to contribute to the advancement and application of coastal science worldwide. This obligation stems from U.S. leadership in coastal research and education, and from international commitments. U.S. involvement in international coastal science also provides opportunities to gain comparative knowledge that can be applied to maintain healthy coastal ecosystems in the United States. Therefore, the committee recommends that the Water

Subcommittee identify mechanisms to promote intellectual exchange and scientific coordination with relevant international coastal science efforts, such as the Land-Ocean Interactions in the Coastal Zone initiative and the Global Ocean Observing System.

## Interfaces With Other Cenr Subcommittees And Nstc Committees

The goals of the Water Subcommittee focus on the management of water resources and the maintenance of healthy coastal ecosystems. Additional coastal science priorities are being considered by other CENR subcommittees and NSTC committees, including those on global change; biodiversity and ecosystem dynamics; resource use and management; natural disasters; social and economic sciences; national security; health, safety, and food; and fundamental science. Although the integrated consideration of freshwater resources and coastal marine environments under the aegis of the Water Subcommittee encourages the timely development of a larger view of interacting ecosystems across the land-ocean boundary, there remains the need to plan and coordinate scientific activities in coastal waters across all relevant committees and subcommittees within NSTC. The Water Subcommittee should interact with these other NSTC components to understand how they will treat watershed and coastal research issues and to develop comprehensive coastal research activities across the NSTC.

# 1
# Introduction

*The overall importance of the coastal ocean extends far beyond its relatively small areal extent. An environment of remarkably high biological productivity, this transition zone between land and open ocean is of considerable importance for recreation, waste disposal and mineral exploitation. Such societal issues as pollution (in its many forms), bioremediation, waste disposal, and risk assessment cannot be addressed adequately until we make substantial advances in our basic understanding of the coastal ocean. A holistic approach to the coastal ocean system, blending marine meteorology with biological, chemical, geological, and physical oceanography, should enable us to progress sufficiently so that we will be better prepared to make the technical and policy decisions facing us over the next decades*. (NRC, 1992d)

Coastal areas are situated at the interface between the land and water; therefore, they are influenced by both terrestrial and oceanic/lake processes and events. The vast majority of all U.S. inland waters drain into coastal areas, extending the influence of most of the U.S. population to the coastal ocean and Great Lakes through influences on the quantity and quality of fresh water discharged. More directly, coastal counties of the United States account for half of the nation's population (SUSCOS, 1993a), and the population density in coastal counties is increasing at a faster rate than for the nation as a whole (LMER Coordinating Committee, 1992). Coastal and inland citizens enjoy benefits from coastal areas, including places for habitation and for the location and operation of certain industries, transportation, recreation, harvest and utilization of living and nonliving resources, and aesthetic qualities. Multiple uses of coastal areas and conflicts among these uses have increased public and governmental interest

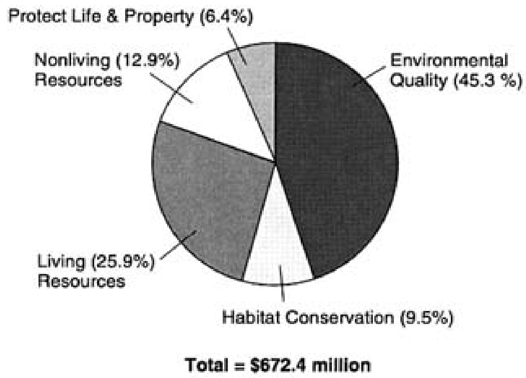
in understanding processes, mitigating impacts (both natural and human-induced), and providing a basis for sustainable resource use.

Concern about environmental quality issues, including coastal environmental quality issues, was stimulated during the 1960s by such events as the publication of *Silent Spring* by Rachel Carson (NRC, 1986; Marco et al., 1987), the Santa Barbara oil spill following on the heels of the *Torrey Canyon* oil spill (NRC, 1985), and the discovery of polychlorinated biphenyls as chemicals of environmental concern. Garrett Hardin articulated a powerful message of "the tragedy of the commons" (Hardin, 1968). These and other indications of widespread environmental degradation culminated in the first Earth Day on April 22, 1970a significant demonstration of public concern about the environment.

The *Workshop on the Critical Problems of the Coastal Zone* (Ketchum, 1972) was convened in 1972 to assess the state of knowledge about the coastal zone at that time and set forth challenges for the future. Several of the key issues identified then still confront us today, while there has been progress in several areas of endeavor. More recently, public concern over the health and vitality of the coastal ocean and its resources heightened as a result of widely publicized degradation of some coastal waters, repeated closures of beaches and shellfish beds, outbreaks of illness from contaminated shellfish and seawater, and oil spills. Partially as a result, federal agencies intensified their coastal ocean and Great Lakes research efforts and new research initiatives continue to be formed.

One (albeit imperfect) measure of the importance of coastal areas to the government and the public is the amount of funding devoted by the federal government to study these areas. For example, the U.S. government spent $672 million directly on coastal science in FY1991-1993 (SUSCOS, 1993a) (see Figure 1). The Department of Defense, through the Office of Naval Research and the U.S. Army Corps of Engineers, also made significant contributions to coastal science that are not included in this estimate of expenditures. State and local governments, universities, private nonprofit institutions, and industrial organizations spend an additional large, but unquantified, sum annually for activities that support coastal science.

Several environmental issues have, in the past, been addressed within a national scientific and regulatory framework (e.g., discharges of highly concentrated toxic chemicals, excess heat and entrainment of organisms associated with power plants, high organic loading of bodies of water with limited flushing, phosphates in detergents, pesticides, and artificial radionuclides). But, presently, research addressing threats such as widespread overenrichment and habitat deterioration has not been guided within a comprehensive national framework that could assess scientific priorities related to the most serious problems and optimize cooperation and coordination among federal agencies, states, local communities, and the academic community. Although there have been significant advances in scientific understanding of coastal ecosystems generated from numerous studies in specific systems during the past four decades, our resulting



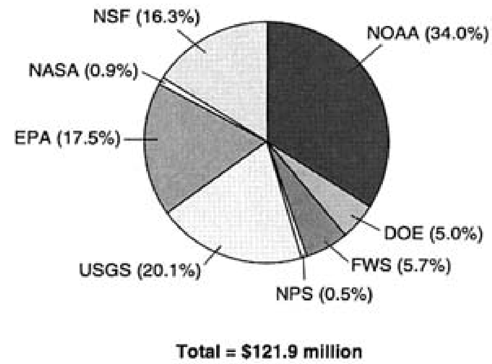




FIGURE 1 Expenditures by federal agencies for coastal research. (a) Total coastal research expenditures by national concern (FY 1991-1993); (b) environmental quality and habitat conservation expenditures by agency (FY 1992). From SUSCOS (1993a). Abbreviations: DOE, Department of Energy; EPA, Environmental Protection Agency; FWS, Fish and Wildlife Service; NASA, National Aeronautics and Space Administration; NOAA, National Oceanic and Atmospheric Administration; NPS, National Park Service; NSF, National Science Foundation; USGS, U.S. Geological Survey.

knowledge of the fundamental properties and processes of this nation's coastal ecosystems suffers from the fragmented regional nature of these studies. Unlike the open ocean, which is a contiguous body of water connected by a global circulation system, continental shelf waters, bays, estuaries, and inland seas of our nation's coastal zone are relatively isolated from each other, occur in widely varying sizes and configurations, and are driven by different combinations of physical forces (e.g., tides, river flow, wind).

What is needed now to advance coastal environmental science and to manage our coastal resources more efficiently is an integrated understanding of fundamental physical, chemical, and biological processes based on site-specific comparative studies of coastal ecosystems. Using such a comprehensive framework, knowledge derived from studies in specific regions could be applied to address the environmental problems in other coastal systems that have been the focus of less scientific research.

In 1992, 13 federal agencies began efforts to enhance coordination of their coastal science programs and to develop an integrated U.S. coastal science program that fulfills the missions of participating agencies with a minimum of overlap. As part of an initiative of the Committee on Earth and Environmental Sciences of the Federal Coordinating Council for Science, Engineering, and Technology, the Subcommittee on U.S. Coastal Ocean Science (SUSCOS) was formed. SUSCOS continued its work through the change in administration in 1993 and produced two documents that present an inventory and framework of federal agency programs, *Setting a New Course for U.S. Coastal Ocean Science, Phase I* and *Phase II* (SUSCOS, 1993a,b).

In November 1993 President Clinton established the National Science and Technology Council (NSTC), a cabinet-level entity, to elevate science and technology to the same level of consideration as national security, domestic policy, and the economy. The Committee on Environment and Natural Resources Research (CENR), one of nine committees of the NSTC (see Figure 2), has been developing a comprehensive national research and development strategy for the federal government on environmental and natural resource issues. CENR subcommittees encompass all areas of research on the environment and natural resources, including global change, biodiversity and ecosystem dynamics, resource use and management, air quality, toxic substances, natural disasters, and aquatic environments, as well as social and economic sciences, technology, and risk assessment. This research and development strategy is being used to guide budget priorities starting with FY1996.

The CENR Water Resources and Coastal and Marine Environments Research Subcommittee (referred to hereafter as the Water Subcommittee) is responsible for developing a national research and development strategy and implementation plan for aquatic environments (CENR, 1994b). The goal of the Water Subcommittee's strategic plan (CENR, 1994c) is to manage water resources and provide healthy Great Lakes, estuarine, and marine ecosystems by

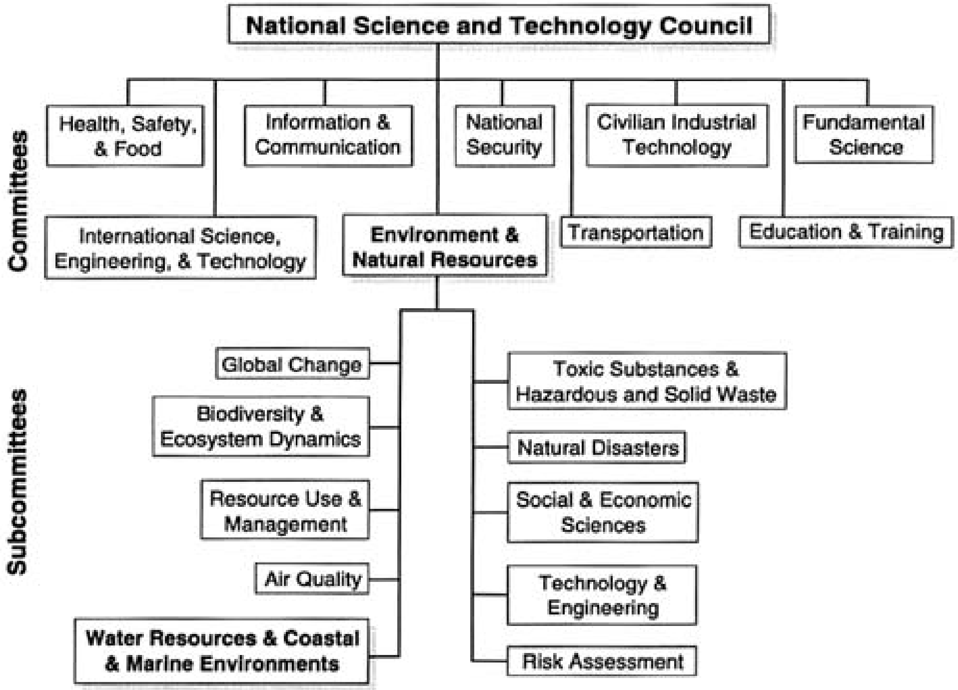



FIGURE 2 Placement of the Committee on Environment and Natural Resources Research (CENR) within the National Science and Tecnology Council and of the Subcommittee on Water Resources and Coastal and Marine Environments within CENR.

balancing two closely related environmental values: (1) water quantity and allocation and (2) ecosystem integrity (including the productivity, diversity, and vitality of aquatic ecosystems and their watersheds). During FY1991-1993, 55 percent of federal coastal science expenditures were related to environmental quality and habitat conservation. Figure 1 shows the federal budget breakdowns, by agencies, in these two science areas for one fiscal year, FY1992.

The Water Subcommittee used a recent external identification of freshwater issues and research priorities, *The Freshwater Imperative* (Naiman et al., in press), in the development of its initial plans (CENR, 1994a,c). *Setting a New Course for U.S. Coastal Ocean Science* provided a partial foundation for the Great Lakes, estuarine, and marine research aspects of the Water Subcommittee's plan. The Water Subcommittee is seeking to study a series of specific coastal ecosystems of national concern and, more generally, to identify scientific needs within five national priority research areas:

Integrated Monitoring
Water Availability and Flow
Water Quality and Aquatic Ecosystem Functions
Ecological Restoration and Rehabilitation
Predictive Systems Management

Because the Water Subcommittee's plan had not had formal input or review by the nonfederal scientific community, Douglas K. Hall, Deputy Administrator of the National Oceanic and Atmospheric Administration and Chair of the Water Subcommittee, requested that the Ocean Studies Board (OSB) of the National Research Council (NRC) provide a review regarding coastal research priorities (see request letter in Appendix A). To be useful for FY1996 budget planning, Mr. Hall requested that the study be completed by the end of 1994. This project is the latest in a series of OSB "fast-track" studies, which have included reviews of the Ocean Drilling Program, the National Sea Grant College Program, and U.S. planning for a global ocean observing system, as well as a scientific assessment of Atlantic bluefin tuna.

The NRC formed a committee to respond to the request from the Water Subcommittee (see Appendix B for biographies of committee members). To provide information in time to be considered in the development of the Water Subcommittee's strategy and implementation plan, the committee assembled this report based on a review of planning documents, one three-day meeting of the committee, and subsequent correspondence. The limited time available for the study made it imperative that the committee focus on existing documents, including CENR, agency, regional, and academic science plans (see References for full listing and Appendix C for highlights of these documents). The committee used this material as background to identify research priorities not presently being addressed and to identify the environmental issues most important for

action by the Water Subcommittee. Information in this report will contribute to the Water Subcommittee plan as it relates to the coastal environment; this report also attempts to integrate coastal science with freshwater science and water resource management, consistent with Water Subcommittee goals.

By request of the agency sponsors, this assessment was limited to priorities for the natural sciences, and the committee was constituted to reflect this focus. Social and economic science considerations are to be incorporated in the Water Subcommittee plans through some other means and will be considered more generally by the CENR Social and Economic Sciences Research Subcommittee (Figure 2). The committee recognizes that social and economic factors are often critical to the approval, authorization, funding, and acceptance of environmental protection and restoration and strongly recommends the development of federal interagency strategies to coordinate and support appropriate social and economic research, monitoring, modeling, and assessment in the coastal zone.

Chapter 2 of this report sets the stage for defining scientific priorities by describing major environmental issues confronting coastal ecosystems. Chapter 3 identifies scientific priorities to address these issues within each of the five priority areas of the Water Subcommittee's strategic framework. Chapter 4 discusses the regional and international dimensions of a national strategy for coastal ecosystem science. Chapter 5 discusses the relationships of scientific priorities defined by the committee to the issues being considered by other CENR subcommittees and NSTC committees and the need for another level of coordination of coastal science planning among these entities. Finally, Chapter 6 summarizes the committee's conclusions and recommendations.

# 2
# Major Coastal Environmental Issues

The committee began its work by identifying the most significant issues confronting coastal environments. This assessment was based on the collective experience of committee members as well as perspectives gained from background documents. The recently completed Regional Marine Research Plans (see Appendix C) provided the views of scientists and environmental managers from the major coastal regions of the United States. Also, the Group of Experts on the Scientific Aspects of Marine Pollution listed the most serious problems affecting the marine environment around the world (GESAMP, 1990). Some of the issues highlighted in the committee's list have been recognized for decades. The committee believes that achieving further significant progress in addressing these issues will require joint agency efforts spanning terrestrial and coastal systems. Such efforts are needed urgently and are now possible under the aegis of the Water Subcommittee.

The committee chose issues that are characterized by their wide geographic scope (e.g., are shared by many regions of the country) and that address the problems of (1) sustainable use of resources, (2) reversibility of effects, and (3) anthropogenically mediated deterioration of coastal systems:

- eutrophication,
- habitat modification,
- hydrologic and hydrodynamic disruption,
- exploitation of resources,
- toxic effects,
- introduction of nonindigenous species,

- global climate change and variability,
- shoreline erosion and hazardous storms, and
- pathogens and toxins affecting human health.

In this chapter the importance of each of the nine categories is described, examples are offered, and references are provided. These categories provide themes for the specific recommendations in Chapter 3 for high-priority scientific activities related to the goals of the Water Subcommittee. The committee chose to list issues overlapping those addressed by other National Science and Technology Council (NSTC) subcommittees for the sake of completeness and to highlight their relevance to improving coastal environmental quality.

Although the committee did not rank the nine categories, there was consensus among committee members that the problems associated with changes in the quantity and quality of freshwater inputs and atmospheric deposition of materials to coastal environments are of fundamental importance and are particularly relevant to the Water Subcommittee. These problems result from increases in nutrient loading from agriculture and other land-use practices, waste disposal, and fossil fuel combustion; widespread contamination by toxic materials; and changes in the delivery of freshwater and sediment to the coast.

Recommendations for high-priority science required to address these complex environmental problems should have broad applicability. For example, in the past decade, significant impacts of diffuse pollutant sources and their indirect ecosystem-level effects on coastal environmental health have been demonstrated (NRC, 1993a). This has enormous implications not only for environmental management priorities but also for how science is conducted and used to support effective management. Bearing responsibility for both water resource and coastal environmental issues, the Water Subcommittee has the opportunity to stimulate an integrated scientific approach to processes that span the land-ocean interface. Although the recommendations in this report are widely applicable, they are specifically directed to the Committee on Environment and Natural Resources Research's Water Subcommittee.

## Eutrophication

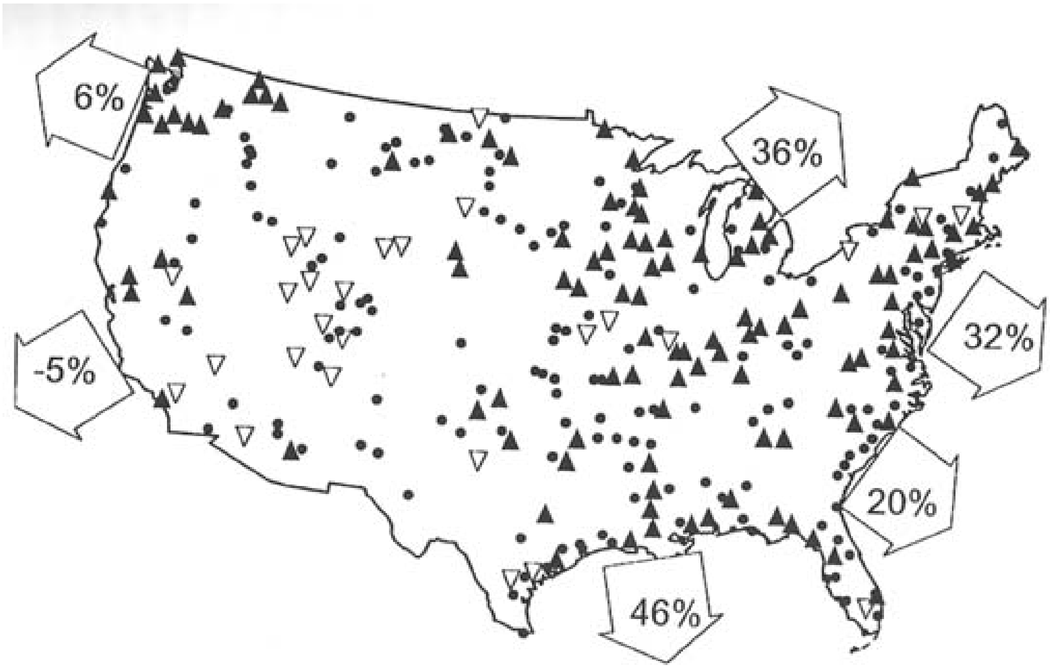



FIGURE 3 Nitrate concentrations have greatly increased in many U.S. rivers, resulting in increased loadings to coastal waters. Solid, upright triangles depict water quality monitoring sites at which concentrations of nitrate significantly increased between 1974 and 1981; open, inverted triangles depict sites where there was a significant decrease; and dots show sites where there was no statistically significant trend. The resulting percentage increase or decrease in mass flux of nitrate to coastal waters is shown for each major coastal region (Smith et al., 1987). Reprinted with permission from Smith, R.A., R.B. Alexander, and M.G. Wolman. 1987. Water-quality trends in the nation's rivers. *Science* 235:1607-1615. Copyright 1987 American Association for the Advancement of Science.

nitrogen loading to the Chesapeake Bay increased an estimated 6- to 8-fold since the pre-colonial period, while nitrogen concentrations in the lower Mississippi River increased approximately 3-fold since the early 1960s, commensurate with increases in the use of chemical fertilizers. For both the Susquehanna (the largest river entering Chesapeake Bay) and the Mississippi rivers, there is some indication that nitrogen concentrations leveled off or declined slightly in the late 1980s, perhaps as a result of a decline in fertilizer use. Organic enrichment (*eutrophication*), results from an influx of excess nutrients (particularly nitrogen in the coastal zone) and their subsequent distribution and transformation (Nixon et al., 1986). Moderate inputs of nutrients can have beneficial effects because they stimulate plant production, which can lead to enhanced productivity of living resources. However, many coastal ecosystems receive excessive nutrient inputs, leading to harmful or noxious algal blooms; shifts in food chains; increased sedimentation of organic particles; and, ultimately, depletion of dissolved oxygen, particularly in bottom waters.

Eutrophication has caused oxygen depletion (*hypoxia*) and even elimination of oxygen (*anoxia*) in such places as the Chespaeake Bay (Officer et al., 1984; D'Elia, 1987), Long Island Sound (Parker and O'Reilly, 1991), and the northern Gulf of Mexico (Rabalais et al., 1994). In addition, eutrophication can cause other undesirable impacts on marine ecosystems. Seagrass populations may decline because phytoplankton and epiphytic algae reduce the light available to seagrasses growing on the seafloor (Kemp et al., 1983; Twilley et al., 1985). Excess nutrients may increase the prevalence of algal blooms responsible for red and brown tides that are harmful to marine organisms, as well as toxic algal blooms that can injure organisms higher in the food chain, such as fish and humans (Anderson, 1989; Smayda, 1989). Also, the organic enrichment of sediments as a result of greater unconsumed primary production can cause long-term changes in benthic habitats, populations, and community structure. Changes in the biotic composition of planktonic and benthic communities as a result of nutrient enrichment and death of organisms from lack of oxygen could have important effects on biogeochemical cycles, living resources, and biodiversity.

Eutrophication has increased in many coastal regions around the world as a result of increasing inputs of nutrients from agriculture, municipal wastewater, and atmospheric deposition of fossil fuel combustion products (Nixon et al., 1986). A recent National Research Council report, *Managing Wastewater in Coastal Urban Areas* (NRC, 1993a), noted that more comprehensive controls of nutrient emissions, beyond urban wastewater treatment, are needed. The geographic extent and changing severity of eutrophication, the relative susceptibility of different coastal ecosystems, and the most effective nutrient control strategies are highly uncertain because appropriate monitoring and supporting research are lacking. A key factor necessary for understanding eutrophication is the ability to detect subtle interannual changes in water quality and its effect on ecosystem

structure and function. This requires long-term monitoring and research programs.

### Habitat Modification

Physical modifications of habitats by either natural forces or human influence pose serious threats to coastal ecosystem integrity and these modifications are often difficult to reverse. Such modification may result from filling of intertidal or subtidal habitat; loss of tidal wetlands; submerged aquatic vegetation or coral reefs due to a decline in water quality or changes in sedimentation; or from changes in the hydrodynamics of coastal systems (discussed later in this chapter). More subtle changes, such as the increasing plastic burden on the ocean floor (Goldberg, 1994a) can also damage coastal habitats. While some of these modifications are reversible over time if the offending conditions are ameliorated (e.g., revegetation by submerged aquatic vegetation or restoration of salinity conditions), the likelihood of recovery for many modified habitats is uncertain. Modification of shallow water habitats, including coral and other reefs, wetlands, and seagrass beds, pose perhaps the greatest threat to the biological diversity of marine (NRC, in press) and other aquatic organisms and can have significant consequences on the production of resource species that depend on these habitats for shelter or food at critical life stages. Because of widespread degradation of coastal ecosystems and the extensive modification of coastal habitats, active restoration or rehabilitation may be required (NRC, 1992c).

### Hydrologic And Hydrodynamic Disruption

Changes in water circulation to and within coastal ecosystems have created poorly understood, but perhaps important, consequences in some coastal systems. The hydrology of watersheds draining to the coast has been significantly altered as a result of landscape changes, channelization and damming, consumptive water uses, and diversion to other drainage basins. Reductions in freshwater flow due to increased use or diversion have caused problems in coastal areas of the United States (see Box 1). Conversely, increased freshwater flow or higher peak flows can result because of the increase in impervious surfaces, deforestation, and channelization of flows within flood plains.

Hydrological changes can affect not only salinity patterns and circulation within coastal systems but also the delivery of nutrients, toxicants, and sediment to the coast. The consequences of such changes in delivery rates may be profound. For example, the midwest floods of 1993 increased the dispersal of nutrients, leading to eutrophication and a major expansion of the hypoxic zone in the northern Gulf of Mexico (Rabalais et al., 1994). Reductions in sediment supply from rivers may result in increased shoreline erosion (Inman, 1976; NRC, 1990d) or deprive subsiding coastal wetlands of material needed for soil accre-

tion (Boesch et al., 1994). Conversely, an increase in the supply of fluvial sediments as a result of land clearing (e.g., Maser and Sedell, 1994) or agricultural practices may cause decreased light availability and the smothering or shoaling of benthic habitats.

Geomorphological modifications of shallow coastal systems may significantly affect the hydrodynamics of the coastal regime (Inman, 1976), affecting the influence of the coastal ocean on estuaries as well as the movement of materials from rivers to the sea. Such modifications may result from dredging of navigation channels, shoreline development and filling, shoreline protection (e.g., breakwaters and groins), and channelization of tidal wetlands. For example, dredging channels to facilitate shipping provides a pathway for the transport of relatively salty oceanic water into bays and estuaries and can change salinity structure, circulation, flushing, and residence times of these semi-enclosed coastal systems. Such changes can have dramatic effects on biological productivity and ecosystem structure and function (U.S. Army Corps of Engineers, 1979).

Box 1
Many Major Coastal Environmental Problems Are Linked
to Inland Water Resources

Coastal environments of the United States and many other parts of the world face unprecedented changes as a result of the use and degradation of water resources. Far-reaching consequences of changes in quantity and quality of fresh water flowing to Florida Bay, San Francisco Bay, the Mississippi Delta, the Columbia River estuary, and Chesapeake Bay illustrate the problems.

Florida Bay, at the tip of the Florida peninsula, has undergone devastating changes during the last decade, including the loss of much of its submerged aquatic vegetation and the proliferation of algal blooms, some of which cause extensive mortalities of animals (Rabalais et al., 1994). Although the exact causes of ecosystem decline are unknown, they seem to be related primarily to reductions of freshwater inflow and, possibly, to nutrient enrichment of the remaining flow. This is the ultimate result of a cascade of effects of water use and drainage on the ecosystems of south Florida (including the Everglades) and Florida Bay that may, in turn, affect the coral reefs of the Florida Keys offshore.

San Francisco Bay has been greatly altered by human activity, including the filling of most of its wetlands and the introduction of many nonindigenous species (see e.g., Nichols et al., 1990). The present quality of the bay and its future are, however, influenced considerably by the decreased allocations of freshwater inflows to the bay because of increased agricultural and urban uses. This lack of foresight about the salinity requirements of the estuarine ecosystem has resulted in endangering fish species that use the delta as a spawning or nursery habitat and may have created conditions amenable to invasions by nonindigenous organisms.

Louisiana has lost over 1,500 square miles of its coastal wetlands since the 1940s as a result of extensive channelization, hydrological modification, and reduction of the freshwater and sediment flow from the Mississippi River into the

subsiding delta (Boesch et al., 1994). Confinement of the flood plains has resulted in higher peak river flows, heightening flood peaks. The protection and restoration of this important ecosystem will require "reengineering" of freshwater and sediment flows in the delta. At the same time, increases in the flux of nutrients, particularly nitrogen, from the Mississippi River (from agricultural fertilizers and atmospheric deposition) have contributed to serious oxygen depletion over a large (3,000 square miles) area of the continental shelf in the northern Gulf of Mexico (Turner and Rabalais, 1991). "Plumbing" decisions made far upstream for flood control or wetland restoration have consequences extending into the Gulf of Mexico.

The Columbia River estuary has been dramatically altered by an extensive hydropower and irrigation system that includes 21 major dams on the Columbia and Snake rivers and over 150 dams on smaller tributaries. Flow regulations and water withdrawals have led to suppression of annual floods, and channelization of the lower river and filling of wetlands have further changed circulation in the estuary (Sherwood et al., 1990). These have affected the timing and strength of salinity intrusion and caused sedimentation along the margins of the estuary. Many native species, such as salmonids which cannot traverse the multiple dams, have declined dramatically, while introduced species, such as American shad, have increased.

Watershed management for coastal environmental restoration is perhaps most advanced in the 64,000-square-mile Chesapeake Bay watershed. This bay suffers nutrient overenrichment from nonpoint sources (agriculture, urban development, and atmospheric sources), which causes oxygen depletion, increased turbidity, and consequent loss of submerged vegetation (D'Elia, 1987) and associated living resources. A goal of 40 percent reduction of nitrogen and phosphorous inputs is being approached by dividing this large watershed into more manageable units and through the use of sophisticated hydrodynamic, ecosystem, and landscape models that simulate the effects of changes in land management on estuarine conditions.

## Exploitation Of Resources

ecosystem has been drastically altered by overexploitation of filter-feeding oysters that once were widely abundant, leading to increased turbidity and decreased survival of submerged aquatic vegetation, replacement of oysters by less desirable invertebrate species, and increasing anoxia in the bay (Newell, 1988). Fishing activities such as bottom trawling also can change the physical habitat and biological structure of ecosystems significantly. Trawl fishing, for example for shrimp in the Gulf of Mexico and groundfish in the Gulf of Maine, can change the physical character of the seafloor and increase turbidity, altering the ability of native organisms to prosper in these environments (Smith and Howell, 1987; Mayer et al., 1991).

There may also be undesirable effects on ecosystems by exploitation of nonliving resources of coastal waters, including development of oil and gas resources, and the recovery of sand, gravel, and other minerals. As we now strive toward sustainable use of resources, key questions pertain not only to how natural resources can be exploited on a sustainable basis but also how the ecosystems that support these resources can be sustained in the midst of resource recovery activities.

## Toxic Effects

The inputs of some toxic materials [e.g., heavy metals and dichlorodiphenyltrichloroethane (DDT)] to the coastal ocean and Great Lakes have been reduced by the United States and several developed nations, and these decreased contaminant loadings are evident in declining concentrations in organisms and the environment (O'Connor et al., 1994). However, the inputs of some other toxicants remain the same or have increased. Concerns continue regarding the bioaccumulation and ecological and human health effects of such widespread contaminants as mercury, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) (NRC, 1993a). In addition, it is now becoming clear that extremely low concentrations (nanomolar or less) of some organic compounds may inhibit reproductive processes in aquatic organisms by disrupting endocrine biochemistry (see Box 2). The disruption of the endocrine system of aquatic organisms extends beyond reproductive processes. Receptor binding and enzyme induction affect development, sexual maturation, gender distributions, behavior, and immune function.

It has been recognized for at least two decades that there can be synergistic and antagonistic interactions among multiple chemicals acting on aquatic organisms. For example, PAHs and PCBs can act in concert to affect marine organisms adversely (e.g., Dawe, 1991). Although research on the effects of individual chemicals can lay a foundation for understanding, the effects of multiple toxic chemicals are barely being addressed. Yet even more complex interactions among multiple stressors occur in coastal ecosystems, for example, combined effects of low oxygen concentrations, habitat changes, and the variety of toxic

Box 2
Emerging Concerns About Reproductive Process Inhibitors

There are a large number of anthropogenic compounds, many organic, that accumulate in the waters and sediments of the coastal zone and can inhibit reproductive processes of aquatic organisms. They fall in the general category of endocrine-disrupting chemicals (Colborn et al., 1993) that can interfere with reproduction and can also have effects in the early developmental stages of organisms at extremely low concentrations, nanomolar and less.

The first problems with reproductive process inhibitors in the marine environment involved the DDT family of compounds, which nearly decimated some bird populations in the 1960s and 1970s. Tributyltin (TBT) provides a more recent example of reproductive process inhibitors. TBT is probably the most effective antifouling agent that has ever been developed. However, after extensive use on pleasure craft in marinas of the Bay of Archachon in France, the substance nearly wiped out the oyster industry in the mid-1980s (Goldberg, 1986). TBT leached from painted ships into the marina waters where it quickly came into contact with oysters cultured nearby. Later, the causal relationship between body burden of TBT and oyster morbidity was well established. TBT has also been shown to cause female gastropods to develop male sexual organs and become effectively sterile. TBT affected a variety of other marine organisms, so that marinas with large numbers of recreational craft suffered dramatic losses of indigenous flora and fauna.

chemicals. Understanding these interactions poses an urgent challenge for science to improve coastal environmental quality.

Thus, despite the reductions in risks from some toxic chemicals, the effects of other compounds, which have not been reduced or which induce toxic effects at extremely low levels, remain of concern. In addition, even though water column concentrations of toxicants are low, contaminated sediments in many coastal areas can continue to release toxic chemicals to the overlying water column due to natural resuspension or dredging (NRC, 1989), affecting organisms living in or near the sediments (Dawe, 1991).

### Introduction Of Nonindigenous Species

In some coastal environments, nonindigenous species have been introduced by human activities and have established populations that have had major ecological consequences. The proliferation of the zebra mussel in the Great Lakes (Nalepa and Schloesser, 1993) has received the most attention, but other introductions have produced similar consequences. For example, most of the dominant species of benthic invertebrates in San Francisco Bay are nonindigenous (Nichols, 1979), and the filter-feeding activities of the Chinese clam *Potamocor-*

*bula amurensis* have eliminated summer phytoplankton blooms in the northern portions of the bay (Warner and Hollibaugh, 1993). Diseases that are ravaging populations of oysters in Chesapeake Bay may have been introduced with oysters transplanted from other regions; likewise, organisms transported for aquaculture and recreational fishing purposes in the past have been the source of many species introductions. Transport of organisms in the ballast water of ships is a major and growing source of introductions of nonindigenous species (Carlton and Geller, 1993). Consequences to coastal ecosystems include loss of biodiversity by elimination of indigenous species (NRC, in press), alteration of trophic dynamics, degradation of habitats, and diminution of fisheries productivity.

## Global Climate Change And Variability

Of all the potential effects of global climate change on coastal environments, the effects of sea level rise have received perhaps the most attention, but other effects of climate change may be even more important. These include the potential for increased tropical storm intensity and frequency; changes in precipitation patterns and river flow; changes in seawater temperature range and seasonality; alteration of coastal currents and upwelling (Bakun, 1990; van Geen et al., 1992), which affect temperature, nutrient supply, and larval transport; and modification of intermediate-scale weather patterns that affect winds, currents, and rainfall. The effects of decadal-scale climate variations on biotic communities and ecosystem productivity produced by the El Niño-Southern Oscillation along the Southern California coast (Tegner and Dayton, 1987) and on estuarine salinity and the prevalence of oyster diseases in the Gulf of Mexico (Powell et al., 1992) demonstrate the potential significance of long-term climate changes.

## Shoreline Erosion And Hazardous Storms

The coastal zone presents risks as well as benefits to those who populate or visit the shore and those who work or recreate in coastal areas. Although weather forecasting and public education now prevent the massive loss of life that previously occurred as a result of hurricanes and other coastal storms, more accurate and reliable forecasting and reporting of present conditions would help

prevent continuing loss of life and property and reduce adverse effects on coastal economies. Beaches buffer coastal land and habitats from assault by the ocean and lakes, providing the most effective means of preventing coastal erosion and habitat destruction. The principal source of sediment to the coastline is from rivers and streams (Komar, 1976); thus, changes in land use and stream hydrology can affect the supply of sediments to beaches and, consequently, shoreline erosion (Inman, 1976; Kuhn and Shepard, 1983).

Shoreline erosion is also influenced by coastal processes resulting in offshore and alongshore transport of sediments. Changing patterns in coastal storm climate can change the direction of sediment transport by altering the intensity and direction of waves incident to a beach. For example, over the last century the alongshore direction of net sediment transport in the Southern California Bight has been southwest because of the prevailing wave approach from the northwest as a result of storms off Alaska (Inman and Frautshy, 1966). The coastal storm climate was much different in the early 1880s, however, with a prevailing wave approach from the southwest from storms off Baja California (Dana, 1969). This change has altered sediment movement and the resulting nature of the coastline (Shepard and Kuhn, 1983). Shoreline erosion and hazardous storms are affected in a complex manner by land-use decisions and climate change and, conversely, can greatly affect coastal environmental quality. Studies of global climate change and improvements in the predictability of climate variability (see previous section) are crucial for predicting and mitigating the impacts of shoreline erosion and hazardous storms.

## Pathogens And Toxins Affecting Human Health

There are few national, state, or local monitoring programs for pathogens or toxic materials, particularly to maintain human health. Although use of the fecal coliform test to judge the suitability of coastal waters for swimming and shellfish harvest has provided a significant level of protection (i.e., there have been few serious outbreaks of waterborne diseases), illness and an occasional death still result from human pathogens in coastal waters. For example, the Norwalk virus is responsible for one-half of the epidemic occurrences of nonbacterial gastroenteritis in the United States (Goldberg, 1994b).

In the case of toxic phytoplankton, coastal monitoring occurs on a local basis, often by local health departments, as well as by the Food and Drug Administration. Seafood safety is an issue emerging as a significant concern to the nation (IOM, 1991). Paralytic, diarrhetic, neurotoxic, and amnesic shellfish poisonings are all caused by biotoxins accumulated from algae. Outbreaks of poisoning due to domoic acid and various neurotoxins accumulated by shellfish and fish have occurred several times in the past few years, possibly due to the increasing incidence of harmful algal blooms (Anderson, 1989; Hallegraff, 1993).

## The Ecosystem Perspective

# 3
# Scientific Priorities Relevant to the Water Subcommittee

In order to provide advice that can be applied easily within the Water Subcommittee's planning framework (that transcends freshwater resources and coastal marine environments), recommendations of high-priority science are organized under the five priority research areas being used by the Water Subcommittee: Integrated Monitoring, Water Availability and Flow, Water Quality and Aquatic Ecosystem Functions, Ecological Restoration and Rehabilitation, and Predictive Systems Management. This was difficult in many cases because many of the environmental problems discussed in Chapter 2 should be considered in more than one of the five priority areas. Scientific approaches such as observation and prediction systems, process-oriented ecosystem research, and modeling can also be relevant to more than one of the five areas.

For the purposes of this evaluation, the committee considered the contributions of science to include not only research activities but also monitoring, modeling, and assessment. The committee determined the scientific priorities on the basis of the following criteria:

- seriousness of the environmental problems to which the science is relevant;
- relevance to the Water Subcommittee's goals within the broader framework of the National Science and Technology Council (NSTC);
- opportunity for significant advancement in scientific understanding and/or application of scientific knowledge and information, and
- potential for linkage of science across the land-sea interface.

To maximize the results of the research recommended below, integration will need to occur across scientific disciplines, across government agencies at various levels, and between science and management.

## Integrated Monitoring

Monitoring of coastal environments is conducted for a range of purposes, including ensuring compliance with discharge and construction permits, long-term measurement of environmental status and trends, verification of predictive models, and determination of the effects of ecosystem restoration or rehabilitation (NRC, 1990a). There are widely held concerns, however, about the degree to which monitoring programs are effectively designed; relationships to research and modeling; whether the most appropriate ecosystem properties and processes are being monitored; the extent to which results are actually used in environmental management; and the degree of integration among local, regional, and national monitoring efforts (NRC, 1990a).

The need for effective monitoring of toxic chemicals in coastal waters has been documented extensively (NRC, 1990a). Prototype national programs such as the Environmental Protection Agency's (EPA) Mussel Watch Program led to the National Status and Trends (NS&T) program conducted by the National Oceanic and Atmospheric Administration (NOAA) (O'Connor and Ehler, 1991). This program has assessed a suite of chemical contaminants in bivalves, fish, and surface sediments at about 100 locations around the U.S. coast at approximately one-year intervals for the past six to seven years. There are numerous local and state programs that also measure chemical contaminants for a variety of reasons (NRC, 1990a,b). Some of these programs include assessments of the biological effects of toxicants on individual populations. Results have shown that several of the standard metal and organic contaminants monitored have declined in concentration in the tissues of organisms as a result of reductions in the sources of these contaminants (e.g., phasing out of lead additives in gasoline, discontinuation of the use of some organochloride pesticides, and improved waste treatment).

More recently, the EPA has developed and conducted pilot studies for the estuarine component of its Environmental Monitoring and Assessment Program (EMAP). EMAP-Estuaries includes measurement of contaminants in the environment and in coastal marine organisms, as well as activities that assess the

condition of benthic and fish communities and relate this to other environmental variables, including salinity, sediments, and dissolved oxygen. Because both the NS&T program and EMAP sample infrequently and depend primarily on relatively static properties, these national programs, and indeed most local and regional programs, are not able to conduct adequate monitoring of the trends and effects of eutrophication, which is a problem widely recognized by many coastal scientists as the most important marine pollution problem. Monitoring programs have demonstrated that contamination by at least some toxic compounds is declining, presumably as a result of regulatory activities, while contamination by other toxic chemicals remained the same over the period of 1986 to 1990 (O'Connor et al., 1994). Monitoring programs must be designed to answer specific questions and the use of the data must be determined before it is collected. Different monitoring programs may be needed, depending on the questions posed. Multiple programs should be coordinated, but not necessarily combined, if their purposes differ.

A high-priority science need is to establish a linked regional-national monitoring program to evaluate the present extent of eutrophication and to observe future trends. Because the environmental indicators and effects of eutrophication are variable over time, such a monitoring program poses significant challenges with regard to measurements of biological and functional indicators (which may consist of measurements of rates rather than absolute properties). The sections below describe important aspects of monitoring, such as measuring diffuse inputs, developing indicators of biological status and processes, and employing *in situ* and remote sensing. Monitoring of diffuse inputs and development of new indicators are necessary for studying both eutrophication and toxic effects.

*Measure Diffuse Inputs*

There is a need for long-term and uniform monitoring of inputs, particularly of nutrients, to coastal waters from rivers and the atmosphere. This is particularly true in regions where coastal eutrophication may be a problem, such as sensitive areas on the continental shelf (such as the New York Bight), offshore the Mississippi Delta, and in selected estuaries. Although data on material fluxes into coastal waters are collected by federal, state, and local agencies, few (if any) data sets include total inputs of such critically important nutrients as nitrogen (see Box 3), phosphorus, and silicon. Usually, only inorganic nutrients are measured, requiring tenuous extrapolation to estimate total (inorganic plus organic) nutrient fluxes (Meybeck, 1982, 1988; Turner and Rabalais, 1991; Howarth et al., in press). The use of widely accepted standardized techniques (including quality control and quality assurance methods) should be promoted to enable comparisons among regions. Coastal measurement programs should be linked with surface and groundwater monitoring programs conducted

Box 3
The Flux of Nitrogen

Nitrogen is thought to be the element most responsible for eutrophication of temperate coastal waters (NRC, 1993a). There are numerous controls on nitrogen fluxes through the landscape. Many aspects of human activity (e.g., human and animal wastes, nitrogen fertilizer, atmospheric pollution, destruction of wetlands) increase nitrogen inputs to estuaries and coastal waters, but some activities (e.g., impoundment of rivers by dams and forestry practices that keep forests in fastest-growth stages) may lower nitrogen inputs (Howarth et al., in press). Some human activities produce paradoxical results, as when improvement of sewage plants to secondary treatment increases the oxygen concentration of local receiving waters, resulting in less denitrification and greater long-range fluxes of nitrate (Chesterikoff et al., 1992; NRC, 1993a). On the other hand, decreased oxygen in bottom waters of Chesapeake Bay, attributable to eutrophication, have resulted in lower rates of nitrification and associated denitrification in this estuary (Kemp, 1990).

In very few cases are the sources of nitrogen to the estuaries and coastal waters of the United States well characterized. For some estuaries, such as south San Francisco Bay, sewage inputs dominate, but more typically nonpoint sources of nitrogen make up half or more of the flux, even to such human-impacted estuaries as the Chesapeake Bay, Delaware Bay, and Narragansett Bay (NRC, 1993a).

Mass balance studies of watersheds of mixed land use (Fisher and Oppenheimer, 1991; Jaworski et al., 1992) have required estimating one or more critical fluxes by difference, rather than directly. Also, a true understanding of the relative importance of nonpoint nutrient fluxes requires an evaluation of nutrient processing within watersheds. The downstream leakage of nitrogen from terrestrial ecosystems is often a small percentage of the inputs to that system.

Research progress is being made on the large-scale controls on nitrogen fluxes, and a variety of recent studies have produced intriguing results. For instance, nitrogen concentrations in large rivers of the world are correlated with human population density in watersheds (Peierls et al., 1991); increases in nitrate fluxes in t he Mississippi River from 1960 to 1980 are correlated with increases in the national average use of nitrogen fertilizers over that time (Turner and Rabalais, 1991); and nitrogen fluxes from large regions into the North Atlantic Ocean are correlated with atmospheric deposition onto these regions (Howarth et al., in press).

Globally, and at the scale of large coastal regions, the controls on nitrogen inputs to coastal waters and the effect of human activity on nitrogen fluxes are extremely uncertain (Meybeck, 1982, 1988; GESAMP, 1987; Howarth et al., in press). A better understanding is required for improved evaluations of the role of estuaries and coastal waters as sinks of atmospheric carbon from primary production (Ocean Margins Program, 1994).

inland. Many data that are presently available may be adequate for discerning relative changes compared with other measurements made by the same program, but cannot be compared with data collected by other monitoring programs.

Trends in diffuse inputs (i.e., nonpoint source inputs) and ecosystem responses may also be inferred retrospectively from geochemical and paleonto-

logical analyses of sediment cores (Cooper and Brush, 1991; Turner and Rabalais, 1994; Eadie et al., in press). Such analyses should be expanded and used to complement the monitoring of contemporary inputs.

*Develop Indicators of Biological Status and Processes*

Indicators of biological effects and ecosystem functions are not well developed for use in monitoring programs, but are essential for understanding how ecosystems respond to a variety of factors (NRC, 1994d). In the past, benthic communities have been monitored because they represent stationary, relatively long-lived sentinels. However, benthic species integrate all the environmental stresses to which they are subject, so that the relationship of observed changes to a specific environmental stressor is not always clear (Howarth, 1991). EMAP-Estuaries relies heavily on indices of benthic community integrity, but it is difficult to apply a universal index over a broad array of environments. And, the effects of environmental stresses may not be evident until conditions become severely stressful to the indicator organisms. Clearly, more sensitive biological indicators are required to monitor the effects of environmental factors before they become extreme, to monitor water column as well as benthic communities, and to monitor incremental ecosystem recovery. Further development of indicators involving benthic macroalgae (Fujita, 1985; McGlathery, 1992) is also needed. The proper selection of indicators requires some understanding of material flow and species composition within an ecosystem and indicators may differ among different environmental stressors (e.g., between eutrophication and toxic contaminants). Thus, the selected indicator must be indicative of the ecosystem or process being studied.

Another important priority for improving monitoring of eutrophication effects is the development of spectrophotometric, molecular, and remotesensing techniques that reflect trends in phytoplankton communities. Rate measurements of important biological and biogeochemical processes show promise for use in monitoring because they may be sensitive to changes in the input of nutrients. Regular observations of the rates of biological and biogeochemical processes could also be useful for research and ecosystem water quality modeling purposes.

There is also a need for development of indicators that (1) detect short-term sublethal effects of toxic substances, as well as manifestations of longer-term chronic lethal effects, and (2) measure and predict biological availability of toxic chemicals in water and sediments. The focus should be on toxic substances that may alter reproductive processes at nanomolar concentrations; are of growing, rather than declining, prevalence in the environment; or are the target of hazardous waste remediation. Such measurements are technically feasible, although their cost would suit them for research purposes

and monthly or annual monitoring, rather than monitoring at more frequent time intervals.

*Deploy Improved In Situ and Remote Sensing Systems*

Environmental responses to natural and human influences must be monitored at the appropriate space and time scales, developing monitoring instruments and systems based on indicators such as those recommended in the previous section. For eutrophication phenomena, relevant time scales range from hours to decades. Nutrient and oxygen concentrations and plankton biomass and metabolism can vary greatly over short time frames as a result of daily cycles, winds, and tides, whereas changes in community structure may only be evident over several decades. To improve understanding of many of the large-scale issues described in Chapter 2, the relevant spatial scales for monitoring, research, and modeling may extend over hundreds of kilometers. In order to monitor over short time scales *and* large areas, cost-effective means need to be developed for near-continuous *in situ* sensing and for remote sensing. This will require further development of reliable *in situ* autonomous and towed sensors of variables such as dissolved oxygen, temperature, salinity, nutrient and toxic substance concentrations, uptake rates, and measures of phytoplankton concentrations, activity, and general taxonomy, through the application of such meth-

Box 4
Platforms for Coastal Science

A recent report from a University-National Oceanographic Laboratory System (UNOLS) workshop (Wright et al., 1994) points out the need for moored *in situ* instruments and real-time telemetry for coastal ocean research. In addition, the UNOLS workshop report identified opportunities for use of satellite remote sensing, including radiometry and color sensing, as well as applications for aircraft, autonomous underwater vehicles, and seafloor observing systems.

Future requirements for coastal research vessels have received little attention, but the UNOLS report notes that modifications of existing large and intermediate oceanographic research vessels, including improved wireline gear handling, shallow water sampling techniques, three-point anchoring capabilities, and ship-to-shore communications, could make them more useful for continental shelf studies. Furthermore, a need was identified for new, more limited endurance coastal vessels with a large capacity for scientists, activities, gear, and equipment storage; shallow draft in order to operate effectively at depths of 5 to 10 meters; sea keeping and stability to allow sampling in all seasons and during episodic events; good station-keeping abilities; capabilities for multiwire operations, launching autonomous and remote vehicles, buoys, moorings, and observing systems; and towing devices through undisturbed water.

The report also observes that state and federal partnerships are required for supporting and using the UNOLS fleet for coastal research and monitoring.

ods as photometrics, acoustics, molecular biology, and fiber optics (NRC, 1993e). Improvements of platforms for coastal science will also be needed (see Box 4).

*Link Regional and National Monitoring*

A major recommendation of the National Research Council's (NRC) (1990a) assessment of marine environmental monitoring is that effective coordination and linkages should be established among the national marine environmental monitoring programs (particularly NS&T and EMAP-Estuaries). These programs aim to provide a national assessment of environmental conditions and trends through regional monitoring, as well as location-specific assessments, for use in environmental protection, restoration, and resource management. Although there has been some progress in coordinating NS&T and EMAP, much remains to be accomplished to achieve the goal of fully integrated monitoring. EMAP-Estuaries has not been able to follow the timetable originally planned. Thus far, pilot studies have been conducted only in the Virginian (Mid-Atlantic) and Louisianan (Gulf of Mexico) provinces. Most monitoring programs of this type have been implemented at less than their full designed scope, due to funding limitations. Unfortunately, scaled-back programs may not meet the original objectives. Controversies have raged within the scientific and management communities about EMAP's design, measurements, interpretation, sustained effort, and relevance.

In 1992 Congress established the National Marine Monitoring Program under Title V of the NOAA Authorization Act, providing a statutory and institutional mechanism to stimulate regional marine monitoring where it would be useful and to provide incentives for these regional programs to contribute to a national marine monitoring program. However, funding to implement this program has not been appropriated. The Intergovernmental Task Force on Monitoring Water Quality (1993), which considered monitoring of inland as well as coastal waters, concluded that the lack of coordination in (1) monitoring program design, (2) selecting monitoring stations and parameters, (3) comparable sample collection and analytical methods, and (4) data-sharing formats and protocols have hindered sharing of data and the development of comprehensive information on water quality and environmental conditions. Efforts to improve comparability and utility of monitoring data among national monitoring programs and among national, regional, and local monitoring programs should be a high priority for the CENR Water Subcommittee. It is clear that, in order to be successful, the efforts will need to be based on a partnership with regional and state authorities and regulated industries and utilities. The committee is uncertain of the extent to which the federal agencies have explored the partnership issue with such entities. This is a major concern because the effort required from these partners will be substantial and cannot be assumed automatically.

*Improve Monitoring Management Systems*

The NRC (1990a) assessment of marine environmental monitoring noted that much, if not most, monitoring was conducted without a clear objective for use of the results. Data are frequently laboriously collected and stored but not synthesized or used in decisionmaking, often because the problem to be resolved has not been defined adequately. The NRC (1990a) recommended that monitoring should be considered as part of the environmental management system and designed based on rigorous criteria of sensitivity and utility. Federal and state agencies engaged in coastal science can improve the use of monitoring in management systems through support of (1) education and training in monitoring design, technologies, analysis, and implementation; (2) development of techniques to make monitoring results more understandable and useful to managers (e.g., computer visualization); (3) efforts to link research and predictive modeling with the design and interpretation of monitoring; and (4) feedback from management in an adaptive management strategy. The adequacy and usefulness of data from monitoring programs need to be assessed regularly.

A key to understanding many coastal environmental problems, including eutrophication and toxic contaminant pollution, is the ability to detect subtle inter-interannual changes in water and habitat quality and in ecosystem structure and function. Detection of long-term (decadal or more) trends in degradation of water and habitat quality requires long-term observations with frequent sampling (greater than twice per year) of key parameters of water and sediment chemistry, as well as ecological properties and processes. Furthermore, when process-oriented research is coupled with these long-term data collection programs, a deeper understanding of the fundamental mechanisms controlling ecosystem dynamics will emerge.

Water Availability And Flow

> CENR Objective: *Improve understanding of the natural patterns and processes associated with hydrological flow and develop methodologies to assess and predict the cumulative effects of watershed alteration on water availability and aquatic ecosystem health.*

As described in the CENR Water Subcommittee strategy and implementation plan, this priority research area deals with freshwater resources in surface water and groundwater and the effects of modified hydrology within watersheds (CENR, 1994c). From the coastal perspective, not only are the movement and changes of water and materials within watersheds important, but the effects of water flow within coastal ecosystems also must be considered.

Quantification of the movement of water within the watershed and its influ-

ence on the flux of important materials (nutrients, toxicants, and sediment) to coastal ecosystems is a new and timely integrating factor that is bringing together the disparate scientific and management communities working on issues addressed by the Water Subcommittee. Meteorology, atmospheric chemistry, hydrology, freshwater biology and chemistry, agricultural sciences, and the marine sciences must be involved. The growing recognition of the effects of diffuse sources of pollutants from land on coastal ecosystems, particularly in causing eutrophication, provides another important reason to understand hydrology and materials flux for entire watersheds.

To achieve an understanding of the effects of water availability and flow on ecosystem integrity, research should focus on understanding (1) the coupling between watershed hydrology and materials flux and (2) physical forcing processes within the coastal environment. Such research is the foundation for understanding how coastal ecosystems function and for the development of atmosphere-watershed-coastal ecosystem models.

*Study the Coupling of Watershed Hydrology and Material Flux*

An important goal is to develop a quantitative understanding of the dynamics of the complex basins that drain into coastal waters and to use this improved understanding to manage land use to minimize adverse impacts on coastal ecosystems. The watershed is a logical geographic unit for research and land management, primarily because components of a given watershed are linked by the natural movement of water. The hydrology of both surface water and groundwater must be understood as a unit. Often, only about 5 percent of the annual precipitation actually moves downhill on the land surface and quickly reaches the nearest stream as a brief pulse. In contrast, groundwater that percolates slowly from the uplands of the watershed can enter coastal waters directly or through streams. Groundwater may be entrained in an aquifer for weeks to centuries before discharge, depending on the geology and size of the aquifer. Therefore, movement of both surface and groundwaters must be included in estimates of water and material fluxes.

It is important also to measure atmospheric deposition, both that which occurs as the washout of pollutants during precipitation events (*wet deposition*) and that which occurs as direct deposition of gases, aerosols, and particulates between storm events (*dry deposition*). The types of pollutants and the magnitude of the discharges per unit land area differ depending on land use. Thus, an unperturbed forest usually discharges relatively little nitrate, whereas an area of intensive agriculture usually discharges high amounts of nitrate (NRC, 1993d). Even in the case of forests, however, there is a pressing need to understand if and why forests become "nitrogen saturated" as the result of large inputs of nitrate and ammonium from the atmosphere.

The output of a particular piece of land is a function of land characteristics

and use (e.g., farming practices), weather and climate conditions, urbanization, and soil characteristics. The delivery of contaminants will depend not only on land use but also on how overland storm flows and groundwater percolating from the fields interact with other habitats before discharge into the stream channel network. Thus, the positions of land-use patches on the watershed as well as their types and proportions are important. For example, riverside (*riparian*) forest buffers can remove over 80 percent of the nitrate in shallow groundwaters percolating through them from agricultural uplands to headwater stream channels (Lowrance et al., 1984; Cooper et al., 1987; Correll and Weller, 1989). In this case, the riparian forest acts as a sink for nitrate generated in upland agricultural areas. Obviously, such nitrate removal would not occur if the positions of the forest and agricultural areas were reversed. Finally, when a large watershed is composed of many streams, rivers, wetlands, and lakes, contaminants may be removed in each type of water body, and interactions among these hydrological elements must be known adequately to understand watershed-level processes.

Scientific priorities for coupling watershed hydrology with material fluxes to coastal waters include (1) high spatial resolution remote sensing; (2) improved geographic information systems, including detailed data on such factors as topography, geology, soils, land use, stream channels, aquifer recharge and discharge areas, wetlands, flow, residence, and land-use practices; (3) research on land-use management for reducing contaminant inputs to surface and groundwaters (NRC, 1993d); (4) research on the hydrological connections between surface and groundwaters; (5) investigation of material fluxes operating over scales ranging from small experimental plots to large watersheds of mixed land use; and (6) study of controls on export of nitrogen from forests, particularly as a function of atmospheric deposition and forest age.

*Develop Atmosphere-Watershed-Coastal Ecosystem Models*

Ecosystem modeling is considered in this section for coherence, but it has equal relevance to ecosystem function and habitat restoration and management, as discussed in subsequent sections. Calibrated and verified landscape and ecosystem models can be used to identify unknown ecosystem processes, synthesize research findings, and serve as management tools. These models must couple watersheds to both atmospheric and coastal ecosystem models and must integrate spatially explicit patterns with transfer, transformation, and response processes. It is especially important to develop models that can use, on an ongoing basis, data from all the important disciplines of coastal science. Present generation models often lack this capability, using data sets limited in time or in the type of variables they include. Coupled atmosphere-watershed-coastal models will need to include such a multidisciplinary data handling ability. Coupled models should not be developed as ends in themselves but as tools to organize

thoughts, identify important research questions, and quantitatively represent understanding of how complex systems work in a way that promotes more informed management decisions. Models should always be treated with some skepticism and be improved continuously and are often a critical and integral part of research and monitoring. Models must be improved to use data of many types, such as observations of the distributions of elemental and isotopic tracers and data from episodic events.

Watershed models need to be structured differently from simple hill slope or ecosystem models appropriate to one landscape patch. Appropriate models must quantitatively route water through the surface and subsurface of the watershed and accurately predict the transport and removal of pollutants along those hydrologic pathways. The models must account for the movement of water from one type of landscape patch to another along its trajectory. The models also need to include the effects of irrigation, in-stream processes, and the effects of lakes and reservoirs. Finally, the models must include the inputs to each watershed patch of contaminants from the atmosphere, point sources, and land-use practices.

At present, adequate estimates of the turnover times of many important aquifers are not available. More accurate measures of the volumes of water following various pathways through watersheds are needed, including direct and realistic measurement of evapotranspiration. It is important that the watershed models under development be calibrated with accurate and detailed data from each region. It is equally essential that these calibrated regional watershed models be verified with other data so that their transferability to other watersheds and other contaminants can be assessed.

Atmosphere-watershed models should be linked with hydrodynamic-ecosystem models of coastal receiving waters. A priority for such ecosystem modeling research is "to establish improved predictive capabilities for coastal ocean systems that link physical processes, biogeochemical cycles, and the interactions of living marine resources" (SUSCOS, 1993b). Many of the key frontiers in ecosystem modeling research are at the interfaces between existing modeling efforts. Coastal ecosystem modeling that focuses on the following topics would improve scientific understanding and management of the nation's coastal ecosystems:

1. Coupled models relating physical, biological, and biogeochemical processes in coastal environments need to be expanded and improved to include ecological feedback processes (e.g., coupling of benthic and water-column processes, nutrient recycling, top-down control from higher trophic levels), suspended sediment dynamics, and benthic biogeochemistry. Most existing models are primitive in their structures, being generally limited to: (a) simple nutrientalgal-oxygen interactions in conventional water quality models; and (b) simple phytoplankton-zooplankton-nutrient models commonly used to simulate basic processes in pelagic regions of the ocean. Special attention should be given to

the development of methods for coupling biological and physical models at time and space scales that are coherent and appropriate for simulation of fundamental biological and physical processes. It is also important for modelers to develop a clear understanding of the scale dependency of simulated ecosystem behaviors; that is, the extent to which models that use different time and space scales produce different simulations of the same processes and system scenarios.

2. Ecosystem process models should be coupled with population dynamics models, with special attention given to scale coherence. Traditionally, ecosystem process models have been used to address questions of how nutrient and other anthropogenic inputs to coastal systems affect water and habitat quality and overall ecosystem functions. Conventional population models of fish and other living resources have been used to analyze relations between fishery harvests and fish abundance. A growing recognition of key interactions between water and habitat quality and fish abundance, however, suggests that these two separate modeling approaches need to converge into an integrated framework. Moreover, the effect of physical transport processes on both recruitment into adult fish stocks and nutrient/trophic interactions reveals that these integrated process-population models should be driven by physical circulation models. Ecological feedback effects and material exchanges could be coupled between process and population models with simple seamless algorithms.
3. As a consequence of varying climate regime, geomorphology, hydrologic input, and hydrodynamic circulation, there is a great diversity of ecosystem types along the coasts of North America. Prudent cost-effective approaches to management of these ecosystems suggests the need for a systematic approach that recognizes similarities and differences among them. One component of this strategy would be to develop general conceptual models of coastal systems to facilitate cross-system comparative analyses of monitoring and ecological process data (see p. 47). These models could be modified systematically to represent different broad classes of coastal environments.
4. The development of ecosystem models capable of using data from remote and *in situ* observation systems is an important objective, particularly models that permit real-time comparisons between model predictions and observations. Techniques should be developed for using time-series data in model simulations as a diagnostic tool for model analysis and assessment to improve environmental forecasting (see pp. 54 and 55).

*Increase Understanding of Physical Forcing Processes*

As water moves from the highest headwaters to the edge of the continental shelf, there is a continuity of processes and fluxes across coastal ecosystems. The task of understanding integrated terrestrial and coastal processes is daunt-

ing. The relevant time and space scales are relatively short compared with processes that operate on a global scale. The processes are three-dimensional and vary with the site. For example, major sources of nutrients are riverine in the Gulf of Mexico, whereas the source in the Gulf of Alaska is the deep ocean. Differences in the relative importance of wind forcing, freshwater fluxes, tides, topography, currents, air-sea interactions, storm events, and longer-term forcing, such as the El Niño-Southern Oscillation, are found in different regions.

The continuum of physical flow requires the development of an integrated understanding of the physical forcing upon coastal systems from the terrestrial, oceanic, lake, and atmospheric factors mentioned above. The fluxes of salt, heat, and buoyancy through the coastal ecosystem should be studied. These fluxes can vary on time scales from minutes to decades. After acquiring sufficient observations and research results, these fluxes should be modeled on a wide variety of temporal and spatial scales. Similar to actual processes, these models should be continuous across the coastal ecosystem.

Hydrological models have been developed to study variability in riverine inputs to estuaries (Howarth et al., 1991; Naiman et al., in press), but these have not been coupled with large-scale atmospheric models to address the effects of climate on coastal systems. Such coupled models should be developed. Because atmospheric models depend on sea surface conditions offshore, these are potentially important feedback mechanisms to terrestrial hydrology.

Coastal tides and alongshore currents, because they are relatively large and observable, have been the focus of successful research and modeling efforts. Coastal ocean areas can be relatively isolated from the open ocean, particularly bays, estuaries, and regions with broad continental shelves. In such areas the fluxes of materials off the shelf tend to be smaller than along the shelf. Cross-shelf fluxes are poorly understood and the quantification of such fluxes is a central objective of both the National Science Foundation (NSF) Coastal Ocean Processes (CoOP) initiative (Brink et al., 1992) and the Department of Energy (DOE) Ocean Margins Program (Jahnke et al., 1994). Cross-shelf exchange can be strongly driven by winds, producing coastal upwelling and associated influx of nutrients to surface waters and increased primary productivity.

Atmospheric effects on the coastal ocean and Great Lakes include previously mentioned effects on inland hydrologic cycles, as well as winds and storm events (see NRC, 1992e for a description of research priorities in coastal meteorology). The contrast in temperatures between land and water that occurs in coastal areas creates a variety of atmospheric conditions that are unique to the coast and that drive physical processes in coastal waters (Brink et al., 1992). Winds can enhance the flux of momentum and gases between coastal waters and the atmosphere. Tides and currents provide a means of structuring shallow-water benthic communities and affect the distribution of food, gametes, larvae, and planktonic organisms. Finally, storm events provide episodic physical forcing that can have extreme effects on coastal ecosystems by decreasing salinity

due to increased precipitation, increasing turbidity as bottom sediments are resuspended, and even destroying habitats and organisms.

No single federal agency is responsible for studies of physical forcing in coastal systems, and better cooperation is needed among the agencies, perhaps with CoOP as an integrating and coordinating mechanism, at least for continental shelf studies. Coordination should include research, observations, data exchanges, and modeling efforts. Also, investigations should relate physical forcing to important ecosystem processes, population dynamics, organismal health and survival, and production of living resources.

## Water Quality And Aquatic Ecosystem Functions

> CENR Objective: *Support research on the predictive understanding of the linkages between water quality and aquatic ecosystem functions, emphasizing conceptual and mathematical models and the development of new paradigms.*

Inputs of nutrients, organic materials, toxic contaminants, and sediment can degrade water quality sufficiently to affect coastal ecosystem functions. These inputs may be direct waste discharges into the coastal waters or from nonpoint sources delivered from the watershed or the atmosphere. Additionally, these materials may be remobilized by human activities taking place within the coastal system itself (e.g., dredging).

Specific scientific priorities within this research area focus on (1) relating coastal nutrient fluxes to ecosystem dynamics, (2) conducting strategic scientific assessments of toxic effects, (3) understanding the role of sediments in coastal ecosystems, (4) relating resource use to ecosystem sustainability, (5) assessing the impact of multiple stressors, and (6) promoting comparative ecosystem science.

### *Relate Nutrient Flux to Ecosystem Dynamics*

The importance of understanding the flux of nutrients within and between coastal ecosystems is not only due to trends toward greater eutrophication but also to the fact that nutrients are an important regulator of normal biological activity within these systems. Understanding the transformations of nutrients and organic matter and their relationship to ecosystem dynamics would help in studies of the interactions between adjacent coastal ecosystems and provide a basis for comparing the responses of coastal ecosystems in different geographic areas.

Physical models are necessary to describe the spatial and temporal variability of these nutrient fluxes (see previous section). The potentially important time

scales of physical processes include hourly (tidal forcing), daily, seasonal, annual, and interannual. The models should begin at the head of the estuary to include the stream and riverine influences on physical, chemical, and biological parameters of the estuary and consider the retention of materials within the estuary.

The exchange of material between nearshore regions and estuaries depends on the freshwater flow rates, coastal circulation, tides, waves, winds, bottom topography, and chemical and biological transformations of materials of interest. These materials are not passive, conservative, or all transported in the same manner. Understanding of the coupling between physical, chemical, and biological fluxes requires basic research on transformations and coupling processes. Biological productivity in coastal waters leading to eutrophication depends not only on the supply of nutrients but also on the ability of organisms to remain in the euphotic zone. This ability is dependent on the vertical density structure (stratification) of the water column, which is related to the temperature and salinity structure, which, in turn are related to the fluxes of heat and salt (i.e., hydrology). Therefore, coupled models of physical, chemical, and biological processes are necessary to understand coastal nutrient dynamics and eutrophication phenomena (see p. 39). A strategy needs to be developed whereby generic models can be made specifically applicable to the wide range of coastal ecosystems across the nation.

Aspects of ecosystem dynamics that deserve attention as they relate to ecosystem nutrient fluxes include (1) the regulation of primary productivity and the algal and plant species responsible for it, (2) the relationship of nutrient enrichment to harmful algal blooms, (3) the flux of organic matter through the pycnocline and to the seabed, (4) rates of nutrient remineralization, (5) the effects of top-down control of algal and plant species by filter feeders and grazers, (6) food chain structure, and (7) the consequences of nutrient enrichment on harvested species.

There are a number of existing and planned programs that could individually make contributions to those goals, but they could make even greater contributions if they were better integrated and coordinated. NSF's Land-Margin Ecosystem Research Program (LMER; see LMER Coordinating Committee, 1992) supports investigator-initiated, multidisciplinary studies of estuaries and coastal embayments, all of which include investigations of nutrient transformations and biological responses. The CoOP program (Brink et al., 1992), which is funded primarily by NSF, has developed a plan to address the issues of cross-shelf transport of contaminants and nutrients; early projects deal with nearshore processes on a topographically simple shelf and with wind-driven currents. NOAA's Coastal Ocean Program (NOAA, 1991), through its Coastal Ecosystems Health theme, has addressed aspects of coastal eutrophication (e.g., in its Nutrient Enhanced Coastal Ocean Productivity study off the Mississippi Delta and the Atmospheric Nutrient Inputs to Coastal Areas projects). Also, DOE is

launching a comprehensive study of nutrient dynamics and offshelf transport of organic material off Cape Hatteras (Jahnke et al., 1994).

*Conduct Strategic Scientific Assessments of Toxic Effects*

Scientific research and monitoring of the coastal ocean and Great Lakes and use of this information for policy and management decisions have reduced the impacts of toxic chemicals on human health and life. In the late 1950s and early 1960s the marine scientific community undertook studies and provided assessments that informed policymakers and managers (and the general public) about the dangers associated with indiscriminate release of artificial radionuclides to coastal waters. In the late 1960s and early 1970s further losses of birds and other organisms were avoided once the widespread nature and severity of the effects of dichlorodiphenyltrichloroethane (DDT) and other chlorinated pesticides were identified.

These successes in preventing acute toxicity should not be cause for complacency. Concerns have shifted from chemical substances of immediate toxicity (within hours to days) to substances with longer-term (years to decades), more subtle, but serious, effects such as mutagenicity, carcinogenicity, and impairment of reproductive activity (see Box 2). Many of these effects are manifested through antagonistic and/or synergistic interactions among substances. Although there is clear evidence of the decrease in concentrations of some toxic synthetic chemicals and human mobilized chemicals [e.g., DDT, polychlorinated biphenyls (PCBs), lead] in organisms and sediments of many coastal areas, inputs to coastal waters of chemical contaminants of known or suspected adverse effects continue (e.g., polycyclic aromatic hydrocarbons), and there are many places where significant reservoirs of chemical contaminants (e.g., PCBs) exist in sediment. These reservoirs of past inputs and the continuing inputs of toxic chemicals pose threats to coastal ecosystems and to human health by transfer through aquatic food chains (Dawe, 1991; IOM, 1991; Hamelink et al., 1994). The fate, transformation, and bioavailability of various contaminants vary widely as a result of differences in their reactivities and uptake and incorporation into organisms (e.g., Fisher et al., 1991; Fisher and Reinfelder, 1991).

Scientific assessments should focus on the most important, strategic, components of toxic effects questions, particularly on compounds of continuing or emerging concern, realistic exposure conditions, chronic rather than acute exposures, and experimental determination of sublethal and ecosystem-level effects. Poorly quantified estimates of atmospheric and groundwater inputs of toxic chemicals should be improved. Research should be directed to improve understanding of the synergistic and antagonistic effects of toxic chemicals such as carcinogenic and mutagenic effects on aquatic organisms (Dawe, 1991; IOM, 1991; Colburn et al., 1993). Further development, application, and long-term testing of models that link physical transport processes, biogeochemical trans-

formations, biological uptake, and effects on organisms are needed for multiple toxic chemicals entering, or already present in, coastal ecosystems.

*Investigate the Role of Sediments in Coastal Ecosystems*

Coastal ecosystems differ from those in the open ocean in a number of important respects. Perhaps the most profound difference is the functional importance of the seabed and suspended sediments in coastal ecosystem processes. Not only is there a continuous supply of sediment from rivers and shoreline erosion, but coastal ecosystems are characterized by the frequent resuspension of deposited sediment and the prevalence of biologically created or modified particulates in the form of organic-mineral aggregates, calcareous or siliceous skeletons, and fecal pellets. Coastal sediments, both deposited and suspended, play a number of important roles in coastal ecosystem function. They (1) affect light availability; (2) are sites of intense activity by associated microbes; (3) greatly influence the transport and fate of chemical constituents, including organic and inorganic contaminants; (4) accumulate the ecosystem's waste products; (5) are important in the cycling of biologically important materials, including carbon, nutrients, and sulfur; and (6) determine living conditions for benthic organisms.

Scientific investigations of the processes that affect the transport, deposition, and resuspension of sediments are seldom included in studies of coastal ecosystems; such "geological" studies are generally pursued separately. Basic studies of sediment dynamics, particularly of fine sediments, in different coastal environments should be expanded and integrated with studies of ecosystem function (ASLO/ERF/SAML, 1990; USGS, 1994). To a certain degree, programs such as LMER (in which the Columbia River study focuses on the role of the turbidity maximum zone in the estuary), CoOP (Brink et al., 1992), the DOE Ocean Margins Program (Jahnke et al., 1994), and certain elements of the U.S. Geological Survey's National Marine and Coastal Geology Program (USGS, 1994) attempt to integrate sediment processes into ecosystem studies.

More concerted research is needed on such subjects as (1) particle and biogeochemical dynamics of the turbidity maximum zones, (2) soil-building processes in coastal wetlands, (3) how sediment dynamics influence biogeochemical fluxes across the sediment-water interface, and (4) sediment accumulation and mixing rates.

*Relate Resource Use to Ecosystem Sustainability*

Important questions for relating the human exploitation of living resources to the integrity of coastal ecosystems that sustain those resources concern the effects of harvesting activities on habitats and nontarget species and the effects of selective removal of the target species, which are often mid- to top-level predators in their ecosystems. For example, there is ample evidence from fresh-

Box 5
Top-Down Controls in Marine Ecosystems

The removal of reef fishes results in structural changes in coral communities because of algal growth (Hughes, 1994); in response to a strictly enforced reduction in fishing, reefs around Bermuda are recovering from algal overgrowth. The return of sea otters along the west coast of the United States has led to a reduction in sea urchin populations, with a resultant positive response in kelp production (Paine, 1993). When there are ctenophore blooms in Narragansett Bay, zooplankton populations are sufficiently grazed to allow substantial increases in phytoplankton production to occur (Kremer and Nixon, 1978). Top-down effects can also interact with nutrient availability. For instance, McGlathery (1992) demonstrated that fertilization of the tropical seagrass *Thallasia* in Bermuda could result in its disappearance; the fertilized grass increased in nutrient content, making it a more attractive food to grazing fish, which consequently ate the grass at a rate faster than its increased growth rate.

water ecosystems that modification of populations of intermediate or top predators will cause changes in the population structure of the prey organisms. There are also examples of marine ecosystem modifications that result from such top-down effects (see Box 5). The top components of marine and Great Lakes food webs have been severely modified in recent history by fishing. Examples (described in Chapter 2) include groundfish species on Georges Bank, oysters in the Chesapeake Bay, and sea otters in the Pacific Ocean. What effects have the severe depletions or effective removal of these consumers had on the structure and function of the food webs that supported them? In some cases the niches occupied by these organisms have, to some degree, been reoccupied by other species. This might suggest that there should be no significant effects at lower trophic levels. In other cases, however, there has not been an obvious replacement (e.g., for menhaden), and lower trophic levels might be modified as a consequence.

Coastal waters exhibit tremendous spatial and temporal variability, with the additional complexity that different scales are important for different processes or groups of organisms. If the effects of overexploitation on the structure and composition of coastal ecosystems are to be determined, studies will need to be planned in the context of this variability.

Research should be undertaken to determine the effects of exploitation of living resources on ecosystem structure and function. This research should strive to (1) increase understanding of ecosystem controls at the population level (see p. 40 for a discussion of the integration of population dynamics and ecosystem function) and (2) increase understanding of causes of variability.

Attempts to identify the ranges and important scales of variability have

often been made through routine monitoring. In some cases these efforts have yielded correlations that provide significant insights. For example, fisheries recruitment is often correlated with some physical or meteorological parameter, suggesting mechanisms by which recruitment may be controlled. These correlative approaches do not, however, provide understanding of the underlying causes of interannual variability of populations, which should be investigated through process-oriented research.

*Assess the Impact of Multiple Stressors*

Our approaches to understanding and managing the effects of water quality on coastal ecosystem function are too often highly reductionist (e.g., determining the effects of a single contaminant on a specific target organism under laboratory conditions that hold other variables constant) or too vaguely holistic (e.g., monitoring ecosystem health through abiotic and biotic condition indicators as is done by EMAP). To improve predictions for use in environmental management, the effects of multiple stressors must be assessed in ways that differentiate the individual and collective effects of stressors. The consequences of these effects must be applied over a range of the spatial and temporal scales. This notion is at the heart of understanding what are often called *cumulative impacts*.

Mitigation of multiple-stressor effects requires research to determine the most important factors, how they interact, and over what scales their effects act. The distribution, concentrations, bioavailability, and fate of toxic organic materials are related to the degree of eutrophication present in a coastal system. Integrated monitoring provides a means to study toxic contaminants, eutrophication, and other coastal environmental problems as they relate to one another, instead of maintaining the artificial boundaries that now exist between these problems.

Federal sponsorship for research on multiple stressors and scalesadmittedly a daunting challengehas been meager and should be increased. This high-risk, but essential, research must involve the interaction of diverse disciplines ranging from toxicology to ecology to modeling and must link observational, experimental, and theoretical studies.

*Promote Comparative Coastal Ecosystem Science*

Coastal ecosystems vary greatly in their sensitivity to nutrient enrichment, habitat modification, resource exploitation, and toxic chemical stress. Yet we lack a sound theoretical and practical basis for extending results from one location to another or even a framework for comparing ecosystem responses in a way that would enhance environmental protection and management. The increasing emphasis on place-based ecosystem management, rather than on uniform, single medium regulation (Gore, 1993) requires, ironically, more comparative ap-

proaches to coastal ecosystem science rather than fewer. We simply cannot afford to study each place with the same level of intensity and must rely on results extended from the broader base of knowledge (Cole et al., 1991).

Unfortunately, the way coastal science is supported and conducted has not been conducive to the development of comparative coastal science. Much of the support for science has been applied to regionally focused efforts. For reasons related to sponsorship as much as to logistics, coastal scientists tend to work near their home institutions. There has been relatively little support or encouragement from federal agencies for the advancement of comparative coastal science. For example, NSF has only just begun to treat the individual LMER projects in a way that should stimulate the rich opportunities, both for science and its applications, that would come from an implicitly comparative approach. The NSF Long-Term Ecosystem Research (LTER) sites have attempted integration, achieving mixed success. The committee believes that the national coastal science community has recognized this major shortcoming and is now prepared to work across parochial boundaries.

The federal agencies should promote the development of comparative ecosystem science by supporting comparative studies and synthesis and by encouraging cross-fertilization through interregional research collaboration among coastal scientists. Such efforts must be conducted over an extended period of time. Extending the results from one region to other regions requires that the principles determining ecosystem structure and function be understood. Simple characterization of a system is insufficient to provide understanding that is transportable to another system. Long-term projects such as those supported by NSF's LTER and LMER programs should be expandedwith greater emphasis on ecosystem comparisonsbecause they seek understanding of ecosystem principles (Likens, 1989).

## Ecological Restoration And Rehabilitation

> CENR Objective: *Improve understanding of baseline and altered aquatic systems, develop restoration methodologies, and identify evaluation criteria to define and assess the endpoints of restoration efforts*.

In the past, most scientific efforts directed to the protection of coastal ecosystem integrity have focused on demonstrating threats or determining the precautions needed to protect these ecosystems. However, because of widespread degradation of coastal ecosystems and the extensive modification of coastal habitats, it is now necessary or desirable in many cases to rehabilitate coastal ecosystems through active intervention. Protection against future impacts is simply not sufficient to ensure ecosystem integrity. The growing emphasis on restoration poses significant challenges to the scientific community to provide guidance for

effective restoration, as well as to environmental management, which is generally oriented toward regulatory protection rather than active restoration.

It is easier to describe what caused an ecosystem to degrade than to prescribe what should be done to restore it to a former or otherwise improved condition. Thus, recreating the original conditions may result in a different outcome than the original ecosystem. Although understanding the causes of ecosystem degradation provides some information useful for restoration, much additional knowledge is required to determine how the environment can be manipulated to accomplish the desired restoration goals.

The committee organized its assessment of science priorities for coastal ecosystem restoration and rehabilitation within three themes: (1) determining the effects of habitat loss and degradation on biodiversity and productivity, (2) advancing scientific approaches to restoration, and (3) guiding the remediation of toxic contamination.

### *Determine Effects of Habitat Loss and Degradation on Biodiversity and Productivity*

Extensive efforts over the past decade have documented the extent and rate of loss of certain important coastal habitats, such as wetlands, seagrass beds, and coral reefs. Other physical changes to habitats, such as siltation of bottom habitats and alterations to salinity and flow patterns, are less well documented. To guide restoration and rehabilitation, it is not only necessary to chart habitat loss and degradation but also to understand the effects of this degradation on living resources and biodiversity. Research agendas have been offered on this subject for biologically generated habitats such as wetlands (NRC, 1992c), seagrass beds, and reefs (NRC, 1994b). Habitat changes due to altered hydrodynamics and the introduction of nonindigenous species also must be considered. For example, diversion of fresh water increases the salinity of coastal marine ecosystems and can diminish the supply of sediment and nutrients to coastal systems (NRC, 1993c; Boesch et al., 1994)

Estuarine and coastal habitat restoration will be influenced by present and future modifications in freshwater flow into the coastal zone. In particular, salinization and sediment input have a marked influence on the type and rate of plant establishment in wetland restoration projects. Nutrient and contaminant loading levels affect subtidal habitat and submerged vegetation by increasing turbidity or toxicity. To date, most restoration efforts have been short term and are planned assuming steady-state conditions. Substantial effort is needed to understand how to restore habitats in the coastal zone under various water management scenarios through seeking improved knowledge about the interactions of hydrological changes with establishment, succession, and function of restored coastal ecosystems. Research should address restoration rates and variation in wetland functions under modified hydrological regimes such as wet-dry cycles.

altered tidal regimes, and different rates of sediment and nutrient loading. Greater emphasis is needed on how water management affects coastal habitats and on how to integrate anthropogenic changes into long-term management of coastal habitats. Research should be supported for studies of the role of water management in controlling physical, chemical, and biological processes within the coastal zone and the examination of means by which large-scale water management can be incorporated into coastal restoration.

Coupled with research that relates habitat condition to water flow, research should be conducted on species and community requirements under conditions of managed hydrology. Floral and faunal responses to managed hydrological regimes need to be understood, especially if restoration is to succeed in coastal habitats affected by highly managed watershed tributary systems. Research may also suggest appropriate management to promote habitat rehabilitation.

Restoration of coastal ecosystems may also be influenced by the presence of nonindigenous species, which can be aggressive invaders. Unfortunately, restoration projects present opportunities for the establishment of nonindigenous species, which are often adapted for colonizing disturbed habitats, and eventual displacement of the anticipated natural community. Given the long time frame over which restored communities must establish themselves, they are subject to invasion for decades after their initial creation. Some invading species alter the community structure so seriously that establishment of a native community similar to nearby mature communities may be impossible.

Restoration often involves maintaining some degree of management control. For example, subsided coastal wetlands restored to vegetated marshes are contained within levee systems or impoundments in which water levels are managed or coastal wetlands are restored within urbanized areas containing sources for nonindigenous species introduction. Restoration efforts need to focus not only on initial control but also on long-term management to reduce deleterious effects of nonindigenous species in the future. Along the east coast, control of the marsh plant *Phragmites* is a prime example of the necessity of understanding altered hydrological regimes on competition between invasive and natural plant communities.

Research is needed on the causes of vulnerability to invasion by nonindigenous species, competitive interactions with native species, human-caused changes in native communities that result in invasion, and mechanisms by which these species persist. In addition, environmentally acceptable methods to prevent and control invasive species need to be developed. Chemical and mechanical means to control nonindigenous species have often proven to be expensive or environmentally unacceptable. The use of "integrated pest management" in coastal habitats should be examined. Such an approach has been successful in freshwater environments for the control of aquatic weeds and may find applicability in coastal environments.

*Advance Restoration Science and Engineering*

Federal science agencies should encourage rapid advancement of the science and engineering of ecosystem restoration and rehabilitation as called for by two recent NRC assessments (1992c, 1994b). Mitigation, if properly designed, can provide a significant mechanism for reducing loss of habitat, whereas rehabilitation, enhancement, and restoration can actually increase our depleted natural resource base. The success of restoration and rehabilitation depends on scientifically sound design and performance criteria, effective technical implementation, and monitoring of performance. Science priorities include research to provide a firmer basis for the design of restoration projects, various modeling approaches to yield understanding from quantitative measures of design and performance, and monitoring the effectiveness of the restoration and rehabilitation.

Research, including small-scale experiments and larger pilot programs, is needed to eliminate shortcomings in our understanding of coastal habitat needs, functions, and processes. In particular, research should be directed to providing a capability for predicting the effects of hydrodynamic and other physical processes on coastal habitats, with important factors for habitats ranging from wetlands to reefs. In addition, research is needed on the following subjects:

- the relationships between habitat structure and function;
- sediment properties, transport, and accretion as they influence the physical and biological performance of habitat rehabilitation, restoration, and creation projects (see p. 45);
- the relationship between nutrient dynamics and establishment of wetlands and submerged aquatic vegetation;
- recruitment and population and community development in restored ecosystems;
- processes that regulate and control interannual variability in populations of coastal biota;
- techniques, including the use of dredged material, for coastal habitat restoration; and
- methodologies for economic evaluation of alteration and restoration of coastal habitats.

Improved physical and biological models would greatly help advance the engineering of ecosystem restoration. In environments in which wetlands or seagrasses are restored, the boundary conditions in shallow water and tidal channels present unique problems to physical and chemical modelers. Sedimentation rates and biogeochemical cycles also could be studied in conjunction with improved modeling. Biological responses such as reproduction and propagation should be modeled for the species that structure the habitat (e.g., vascular plants

or oysters) and models linked with environmental quality factors and with production of living resources. With improved information on interactions between vegetation, soil development, and organisms, models can be useful tools in predicting and designing wetlands restoration and rehabilitation.

Coastal wetlands restoration has often been labeled unsuccessful or ineffective in replacing natural ecosystems. However, few projects have been monitored sufficiently long or with enough detail to understand the rates at which restoration proceeds. Restoration sites may have similar vegetative structure and habitat values as natural wetlands in less than a decade, but the establishment of equivalent nutrient retention and transformation and biodiversity may take decades and is highly scale dependent. From a practical standpoint, information about relevant time and space scales can be used to establish appropriate monitoring programs and in setting regulatory standards for wetland use permits.

Successful project performance is the most productive, conclusive, and reliable means of demonstrating the viability of restoration technology and building public and professional confidence in its application. Structural and functional monitoring before, during, and after project implementation is crucial for determining the effectiveness of the engineering methods, technologies, and practices used and their relation to natural functions. Many coastal habitat restorations do not establish well-defined criteria to assess their performance or monitoring programs to establish or document performance relative to scientific and engineering parameters. Refinement of individual project design during implementation to meet project-specific conditions is not often included in project plans, but it is especially important when innovative approaches and emerging technologies are used.

*Guide the Remediation of Toxic Contamination*

Many toxic contaminants are widespread in the environment and occur at low concentrations. Removing these contaminants from the coastal environment is often expensive and impractical. For example, DDT is found in California coastal sediments (off Los Angeles) due to past discharges from a chemical manufacturing plant. The DDT-contaminated sediments are found at depths exceeding 300 m, and removal would be costly if not infeasible. Many harbors and estuaries also have elevated levels of contaminants in sediments. The presence of contaminated sediments and the possible remobilization of toxic contaminants during dredging and disposal or during attempts to remove these sediments from the environment raise concerns about effects on the ecosystem, contamination of coastal fishery stocks, and impacts on recreational uses (NRC, 1989).

New technologies are being developed to remove contaminants from soils on site through the use of biological agents or chemical deactivation. Although some effort has focused on microbial degradation of oil and plastics in aquatic

environments, little research has been completed on the wide array of contaminants in coastal sediments and water. In addition to processing of sediments *in situ*, procedures and technologies to use contaminated soils in offsite habitat restoration activities are needed. Low-level contaminated soils might be buried in basins that are then restored with marsh vegetation that can act as an erosion control method to retain the sediments in place.

Scientific activities needed to guide the rehabilitation of contaminated sediments include studies of the fate and transport of toxic materials in sediments, the water column, and organisms; development and demonstration of *in situ* technology to eliminate or reduce contamination in sediments; demonstration of successful habitat restoration technologies that remediate low-level contamination within the coastal environment; application of risk management; and risk communication to include the concerns of the citizens of nearby communities.

### Predictive Systems Management

> CENR Objective: *Develop the understanding, tools, methods, and models necessary to support water systems and ecosystem management for competing demands.*

Despite the long list of research needs identified earlier in this report, it must be noted that scientists have accumulated a great deal of knowledge about how coastal ecosystems work and how human activities affect them. Often, the lack of application of existing scientific knowledge to management decisions is as much a barrier to good decisions as is lack of sufficient knowledge. Good management decisions demand quantitative scientific information that can be used as a means of predicting possible and likely outcomes of these decisions. Likewise, good management decisions also require accurate and effective communication of information among scientists, policymakers, and managers. Scientists and managers should strive to make environmental science more predictive by implementing observation and prediction systems that technological advances now allow and by employing ecosystem models as management tools. However, nature can and often does defy prediction and scientists and managers are not totally objective observers of nature or users of knowledge. Thus, given the limitations associated with using ecosystem models, coastal scientists must be prepared to contribute effectively to adaptive management as a means of dealing with uncertainty. There must be sufficient cross-training of scientists and managers to allow the communication of relevant knowledge and predictions effectively. To advance predictive systems management, federal agencies should work together to implement observation and prediction systems, employ ecosystem models as management tools, advance adaptive eco-

system management, and stimulate interactions between science and management at the science-management interface.

*Implement Observation and Prediction Systems*

Rapidly developing technologies for *in situ* environmental sensing, remote sensing (see Box 6), and data management and communication are increasing our ability to observe environmental phenomena in near real time. This opens opportunities for the application of such information for a variety of purposes, including providing coastal storm warnings and marine advisories, weather forecasting, tracking oil spills, and fishing reports, as well as for use in scientific research and environmental management. Converging with these technological developments is a growing quantitative understanding of environmental processes and predictive modeling capabilities that, especially when coupled with near-real-time data, allow accurate "now-casting" and forecasting of environmental conditions.

Federal agencies should work to implement multipurpose observation and prediction systems in selected areas of the U.S. coastal ocean and Great Lakes (see also NRC, 1994d). NOAA (1993a) has developed a strategic plan for a coastal forecast system. Such a system should serve broad needs, such as those related to coastal hazards, maritime safety, and weather forecasting, in addition to serving the needs of environmental research and management. For research purposes these systems should include the kinds of observations identified by the CoOP program, including observations along "corridors"

Box 6
Observations from Space: New Opportunities

There is now or will soon be a wide array of satellite-borne sensors that provide extensive, near-real-time data that could be integrated into coastal observation and prediction systems and in the monitoring initiatives discussed in the section on integrated monitoring. These include radiometers, altimeters, scatterometers, synthetic aperture radar, and ocean color sensors. New opportunities for coastal investigations will be provided by the ocean color sensors, the Sea-Viewing Wide Field Sensor and the Japanese Advanced Earth Observing Satellite, which are scheduled to become operational in 1995. These will provide useful information about phytoplankton biomass in coastal systems with more accuracy (as a result of the development of algorithms for interpreting coastal waters), higher resolution, and more immediately than did the Coastal Zone Color Scanner (the products of which began to be appreciated only after it was no longer operational). Federal agencies should work together to make effective use of these resources in monitoring programs and in observation and prediction systems.

extending from estuaries to the shelf break (Vincent et al., 1993). The requirements of the Global Ocean Observing System should also be criteria for the design of a national ocean observing system (NRC, 1994d). In addition, these observation and prediction systems should be linked closely with regional monitoring and should employ innovative *in situ* and remote sensing, as discussed above in the Integrated Monitoring section. Finally, observation and prediction systems should be integrated with both the predictive and adaptive aspects of ecosystem management, as discussed in the next two sections.

*Employ Ecosystem Models as Management Tools*

A basic premise of this report is that the effectiveness of coastal ecosystem and resource management can be improved by increasing the use of high-quality science in coastal environmental decisionmaking. Scientific understanding of the complex environmental problems that confront coastal regions worldwide requires an integrated multidisciplinary approach. Ecosystem modeling is one tool that allows integration of diverse scientific information and dynamic simulation of interactions embodied in such information. In addition, ecosystem models can serve to focus scientific understanding toward resource management questions. Therefore, ecosystem models offer tools for scientific integration and for applying integrated science to improve resource management. Coastal circulation models are the basis for ecosystem models. For example, such a model is being used to predict water quality in the Massachusetts Bay-Cape Cod Bay system (Box 7).

Modeling strategies should strive to capture the key mechanisms embodied in ecosystem processes and population dynamics (see p. 40), and equations should be calibrated with the highest-quality data available. To achieve maximum credibility, uncertainties underlying model coefficients (and model formulations) need to be stated in quantitative terms and sensitivity analyses should be used to reveal the consequences of these uncertainties on model performance. Models used as research tools and for coastal resource management must also be calibrated rigorously and validated with independent data sets. Modeling activities should strive to achieve real-time comparisons between model behavior and observations from key coastal environments. Techniques need to be developed to assimilate these data into model simulations as a diagnostic tool for model analysis and in the future as means for improved forecasting.

Coastal research programs that address regional and global-scale questions tend to use models as integrative (and occasionally predictive) tools. For example, several of the LMER programs have successfully used mass balance and numerical simulation models to relate watershed and atmospheric inputs of nutrients to biological production, transport, and accumulation of organic matter in coastal environments. Models have also been used in LMER and the Joint

Box 7
Massachusetts Bay Model

The distribution of effluents (e.g., nutrients, contaminants, and sediments) to coastal systems is controlled by physical transport processes such as coastal currents, waves, tides, and internal mixing. Therefore, coastal water quality models must incorporate such factors. An example of this type of model is a three-dimensional model of the Massachusetts Bay and Cape Cod Bay system. It is based on the coastal ocean circulation model developed by Blumberg and Mellor (1980), used in conjunction with available observations. The purpose of the Massachusetts/Cape Cod bays model is "to determine the fate and transport of contaminants, nutrients, and other waterborne materials in the bays, including effluent from the proposed [Boston] outfall site" (NRC, 1994a). Comparing model results with observations under a number of conditions, scientists have demonstrated that circulation in the Massachusetts/Cape Cod bays system depends on both winds and the Maine Coastal Current and that wind-driven upwelling could channel pollutants discharged at the bottom to surface waters under certain conditions. The model makes it possible to predict the effect of the outfall, the Merrimack River, and presumably other sources under the full range of possible physical forcing factors and at different times of the year (Signell et al., 1994).

Global Ocean Flux Study to extrapolate from regional observations in estuaries and shelf areas to global estimates of oceanic carbon balance.

An example of the kind of linked atmosphere-watershed-coastal ecosystem model discussed on page 38 is one being used to guide efforts to reduce nitrogen and phosphorous inputs to the Chesapeake Bay (see Figure 4). It includes a large-scale atmospheric deposition model; a watershed model that uses inputs on meteorology, land use, soil, and geophysical characteristics; and a hydrodynamic water quality model for the mainstem of the bay. The three-dimensional mainstem model is highly sophisticated, is relatively accurate in predicting water quality (e.g., dissolved oxygen), and is being refined to predict effects on living resources. The watershed model is, however, less well developed and based on surface water flow, yet it is critical to making land-use and management practice decisions to reach environmental quality goals in the bay most efficiently. The Green Bay Mass Balance Model is another example of a coupled coastal ecosystem model. It was developed by the EPA Great Lakes National Program Office with cooperation from NOAA, USGS, the State of Wisconsin, and numerous academic institutions. This model of the fates of toxic contaminants integrates watershed, tributary, atmospheric deposition, and ecological processes. A few coastal research initiatives (LMER and the NOAA Coastal Ocean Program Ecosystem Health Theme) are attempting to develop generic simulation models that can be used for comparative analyses of ecosystem processes across a wide spectrum of coastal environments. In principle, such generic models could be-

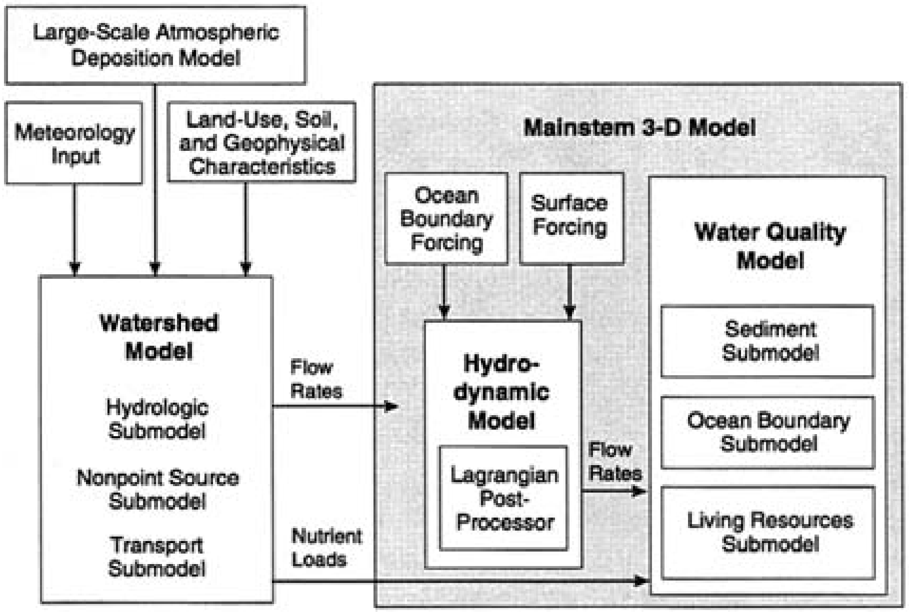



FIGURE 4 Chesapeake Bay modeling strategy. (pers. comm., Lewis Linker, EPA Chesapeake Bay Program Office, Annapolis, Md.)

come useful tools for adjusting management policies that have been used in one coastal region to similar situations in other systems although achieving compatibility of such models among a range of systems may require relatively simple models that can be tailored to individual systems.

*Advance Adaptive Ecosystem Management*

Adaptive environmental management (Walters, 1986) provides an approach to develop and use science in environmental management in the face of high uncertainty surrounding both scientific predictions and the outcomes of management decisions. It assumes that management is essentially an experimental process through which scientists can learn and managers readily accept, even encourage, alternative views of how ecosystems may respond to management actions. Adaptive management allows the exploration of a broader range of options than are typically pursued by environmental management. Science provides a "compass," but management is also steered by a "gyroscope" of bounded conflict among the stakeholders (Lee, 1993). In adaptive environmental management, scientists are significantly involved in the process of management because management depends on regular reassessment of ecosystem performance

and changes in science-based management strategies over time. Adaptive management is a dynamic process, different from most of today's environmental regulations that remain relatively static for years or decades at a time. Attitudes and tactics appropriate to adaptive management differ from those conventionally adopted (Walters, 1986). Generally, adaptive approaches require embracing alternative explanations and approaches rather than seeking narrow consensus and precise predictions.

A lack of understanding of coastal systems will impede attempts to manage them. Therefore, fundamental science must proceed in cooperation with adaptive management. New observations, research, and modeling studies will be needed as new areas of uncertainty and management failure are identified. Management strategies can evolve as new information and techniques become available. This will demand different approaches to research, more rapid reporting of results, and different modes of group interaction and communication among and between scientists and managers. Federal science agencies should provide leadership and support in involving scientists in adaptive ecosystem management.

*Stimulate Interactions Between Science and Management*

Improvements in the communication (both the transmission and reception) of scientific information and policy requirements is sorely needed to aid policy formulation and management decisionmaking that influence coastal ecosystem integrity. The development and use of science-based management models and other innovative ways to transmit meaningful information and the intense interactions between scientists and managers involved in adaptive ecosystem management will help. To make real progress, however, federal agencies involved in coastal science and/or environmental management should make a more concerted effort to improve the understanding of management issues by scientists and of science by managers. This would promote cross-sectoral literacy and a better understanding and appreciation of the different cultural perspectives and requirements of the two sectors.

Presently, interactions between scientists and managers generally take place over brief, intense periods, such as during workshops and conferences, which have inherent limitations in penetrating the science-management interface. Federal agencies could help bridge this gap by (1) supporting the exchange of scientists to management organizations and managers to research institutions, (2) supporting traineeships in science and technology transfer for scientists and managers, and (3) encouraging the education of specialists in the translation of scientific information for environmental management.

# 4
# Relationship of Regional, National, and International Scientific Programs

## Regional Marine Research Priorities

The Regional Marine Research Program (RMRP), administered by the National Oceanic and Atmospheric Administration (NOAA) under authority of the South Carolina Fish Hatchery Act (PL 101-593), includes nine regional marine research programs (see Figure 5). Each region has established an 11-person board and has developed a Regional Marine Research Plan. Only one region, the Gulf of Maine, has received research funding to implement its plan, although all regions received funding to develop their plans. Although it is uncertain whether the implementation of any other plans will be funded in the future, much effort has been expended in developing these plans, and they can serve as a valuable source of information about regional research priorities. The enabling legislation specified that the plans be focused on water quality and environmental health (Bryant, 1993). This focus is congruent with those of the Water Subcommittee and the Committee to Identify High-Priority Science to Meet National Coastal Needs, so the committee examined the nine Regional Marine Research Plans to assess whether any common themes and research priorities emerged among the regions.

RMRP research could fill a niche in the national coastal research program because of its regional, ecosystem-level focus, which brings together the capabilities and expertise of individuals and agencies from (in most cases) multistate regions. Such an emphasis is needed because much ongoing research funded by the federal government is either relatively localized or more national or global in nature, yet many environmental problems are regional in scope. The *Gulf of*


FIGURE 5 Regional marine research programs. (From "The Regional Marine Research Program (RMRP): A new approach to marine research planning, in *Coastal Management*, 1993, Vol. 21(4), p. 328, B. C. Bryant, Taylor & Francis, Inc., Washington, D.C. Reproduced with permission. All rights reserved.)

*Maine Research Plan* (Gulf of Maine Regional Marine Research Program, 1992) noted that regional marine research may also provide the boundary conditions or the context for research on smaller or larger scales.

Most plans share some common elements pertaining to how research priorities were generated. There was initially some type of survey of scientists and managers within the region regarding their ideas about what research priorities should be included in the plan. Such information was gathered through questionnaires, interviews, workshops, and other means. In some regions the RMRP board made the initial determination of research possibilities and later participants ranked these. Regardless of the process, long lists of priority research topics were produced. Regional boards applied various criteria to select a small number of appropriate research priorities that were not otherwise being addressed on a regional level and that were of sufficient societal importance within the region.

In Table 1 research priorities of the nine RMRP regions are compared in summary form to the national scientific priorities identified by the committee in Chapter 3. Some research priorities contained in the regional plans did not fall neatly within the national research priority areas identified by the Water Subcommittee. Those primarily concerned living resource utilization and management.

The priorities shared most consistently among the regional assessments and the national assessments of the committee are as follows: indicators of ecosystem health that can be used in monitoring; studies of eutrophication and the response of coastal ecosystems to nutrient inputs; assessments of the fate and effects of selected toxicants, particularly in sediments; and investigation of the effects of physical modification of habitats and the restoration of these habitats. In addition, more than one region identified understanding natural variability and population stability in ecosystems, the causes of increased incidence of biotoxins (possibly related to algal blooms), trophic dynamics, and coastal erosion as important objectives for regional research. There are also some obvious regional differences, with concerns about eutrophication being higher along the east and Gulf coasts [because of the preponderance of large watershed inputs (Figure 3), large coastal embayments, and broad continental shelves], issues related to fisheries rating more attention in Alaska and the Gulf of Mexico, and attention to coral reefs limited, of course, to the Caribbean and Insular Pacific. Differences are also related to the fact that the plans were to focus on issues that were not otherwise being addressed adequately. Interestingly, although many plans identified nutrient and toxicant inputs from diffuse sources as an issue meriting research and monitoring, only the Mid-Atlantic plan specifically addressed the effects of land use and exchanges between estuaries and the coastal ocean.

TABLE 1 Relationship of the Research Priorities Identified in the Regional Marine Research Plans to Those Identified by the Committee to Identify High-Priority Science to Meet National Coastal Needs

| National Priority Research Areas | Regional Marine Research Plan Priorities | National Priorities Identified by Committee |
|---|---|---|
| Integrated Monitoring | Indicators of water quality and ecosystem health (AK, SA); Integrated water quality and ecosystem health assessment and monitoring (IP) | Measure diffuse inputs; Develop indicators of biological status and processes; Deploy improved *in situ* and remote sensing systems; Link regional and national monitoring; Improve monitoring management systems |
| Water Availability and Flow | Effects of land use on coastal ecosystem structure and function (MA); Create numerical ocean circulation model (SA); Assessment and monitoring of nearshore physical processes (IP); Freshwater inputs, saltwater intrusion (MEX) | Couple watershed hydrology and material flux; Develop atmosphere-watershed-coastal ecosystem models; Increase understanding of physical forcing processes |
| Water Quality and Aquatic Ecosystem Functions | Natural variability, threshold of effects, detecting change and cumulative impacts (NW, SW); Catastrophic events (MEX); Nutrients and eutrophication: algal blooms, oxygen depletion, nutrient cycling (MA, ME, MEX, NY); Contaminated sediments (NY); Fates and effects of toxic contaminants (IP, ME, MEX, NW); Causes of increased incidence of biotoxins (AK, MEX); Population stability of marine organisms (MEX) | Relate nutrient flux to ecosystem dynamics; Conduct strategic scientific assessments of toxic effects; Investigate the role of sediments in coastal ecosystems; Relate resource use to ecosystem sustainability; Assess multiple stressors and scales; Promote comparative coastal ecosystem science |

| | | |
|---|---|---|
| | Trophic dynamics, linkages between pelagic and benthic food chains (AK, MEX);<br>Evaluate complete estuarine systems based on function (SA);<br>Material and biotic exchanges between estuaries and coastal ocean (MA) | |
| Ecological Restoration and Rehabilitation | Importance of natural and human-induced changes to physical environment (ME, MEX, NW);<br>Coastal erosion, sediment transfer, and climatic effects (MA, MEX);<br>Causes and effects of coral reef decline, factors affecting recovery (SA);<br>Habitat protection and management (SW);<br>Restoration of coastal marine habitats (MEX, SW);<br>Habitat use (MEX) | Determine effects of habitat loss and degradation on biodiversity and productivity;<br>Advance restoration science and engineering;<br>Guide the remediation of toxic contamination |
| Predictive Systems Management | Data-gathering and -sharing system (AK);<br>Forum for communication (AK) | Implement observation and prediction systems;<br>Employ ecosystem models as management tools;<br>Advance adaptive ecosystem management;<br>Stimulate interactions between science and management |

Abbreviations: AK, Alaska region; IP, Insular Pacific region; MA, Mid-Atlantic region; ME, Gulf of Maine region; MEX, Gulf of Mexico region; NW, Pacific Northwest region; NY, Greater New York Bight region; SA, South Atlantic and Caribbean region; SW, Southwest region (see Figure 5).

## Relationship To The Priorities Of *The Freshwater Imperative*

*The Freshwater Imperative* (Naiman et al., in press) makes a case for expanded research on the nation's freshwater environments and makes recommendations concerning institutional changes to accomplish the greatly expanded scientific effort that is recommended. Although the Committee on Environment and Natural Resources Research's (CENR) Water Subcommittee has indicated that it intends to use *The Freshwater Initiative*, it was not developed in response to a Water Subcommittee request, as is the case of the present report, and, consequently, did not specifically seek to address the five priority research areas defined by the Water Subcommittee.

The research priorities identified in *The Freshwater Imperative* are grouped under six areas (see Table 2). In general, there is considerable coherence between the scientific priorities identified for freshwater ecosystems in that report and for coastal ecosystems in this report. Only a few of the recommended research efforts for freshwater environments are not somehow embodied in the science priorities identified in this report: biodiversity inventories, quantification of aesthetic and recreational values, and biogeochemical research on enhanced ultraviolet radiation, linked cycles, and gas flux. This is largely a result of the fact that the Committee to Identify High-Priority Science to Meet National Coastal Needs addressed only those issues under consideration by the Water Subcommittee; the additional freshwater priorities given in *The Freshwater Initiative* may be more closely related to issues being addressed by other CENR subcommittees (see Chapter 5). For example, biodiversity is considered in our assessment only as it relates to water quality and habitat condition, while the CENR Biodiversity and Ecosystem Dynamics Subcommittee would logically address the need for maintaining biodiversity.

More importantly, there are similar themes in the sets of freshwater and coastal priorities that reflect both the nature of environmental problems and the present state of aquatic sciences. These serve as common goals and organizing concepts for water resource research and include (1) the importance of modifications of water flows and associated material fluxes and transformations on watershed and regional scales; (2) the need for indicators of ecosystem health and function for use in monitoring and restoration; (3) the integration of physical phenomena and ecosystem structure (i.e., populations and their interactions) and function (i.e., energetics and biogeochemical processes) in order to understand the effects of human activities on ecosystems; (4) ecosystem restoration and rehabilitation; and (5) the development of science-based predictive management through the use of coupled models.

## Geographically Targeted Strategic Research

Environmental management in the mid-1990s is moving rapidly to an eco-

TABLE 2 Research Priorities Identified in *The Freshwater Imperative* (Naiman et al., in press)

| Priority Research Area | Recommended Research Efforts |
| --- | --- |
| Ecological Restoration and Rehabilitation | Determine how specific freshwater ecosystems function; Predict environmental responses to specific restoration practices; Standardize protocols for restoration across regions and habitats; Develop evaluation capabilities for restored systems |
| Maintaining Biodiversity | Document biodiversity by surveys and inventories; Define the importance of specific species and ecological processes to human society and ecosystem structure and function; Assess the effects of biotic manipulations, exotic invasions, and abiotic manipulations on biodiversity |
| Modified Flow Patterns | Assess effects of watershed alternations on hydrological regimes; Quantify status and trends in landscape patterns within watersheds across U.S. ecoregions; Understand effects of modified hydrological regimes on biodiversity, biotic interactions, riparian and downstream ecosystems, and biogeochemical cycling of particles, nutrients, and other chemicals |
| Ecosystem Goods and Services | Determine effects of toxicants, nutrients, organic matter, and sediments on water quality and quantity; Evaluate biological productivity in terms of factors limiting heterotrophic production; biophysical transformations that affect productivity in land-water ecotones; role of food web structure; and effects of environmental lagtimes and life history controls on community structure and dynamics; Quantify aesthetic and recreational values and establish carrying capacities |
| Predictive Management | Determine how changes in frequency, intensity, and duration of disturbance events are influenced by human actions and affect freshwater ecosystems; Understand how environmental disturbances create long-term lagtimes and legacies at the watershed scale; Develop and evaluate biological indicators and integrative measures of ecosystem and biogeochemical functioning; Develop coupled physical-biological models |
| Solving Future Problems | Physical research to improve predictions over wide spatial and temporal scales; relate alteration of temperature and water availability to environmental processes; and understand how biophysical patches and boundaries affect water quality; Biogeochemical research on enhanced ultraviolet radiation, linked cycles, and gas flux with the atmosphere; Biological research on species persistence and environmental change, theory development, and sensitive landscape components |

system management approach that is place-based. This is developing because of the shortcomings of regulation on a medium-by-medium basis (e.g., air quality, water quality, wetlands health). It has become increasingly clear that these media interact and that the medium-by-medium approach has not always protected the environment. In addition, it is observed that people relate to the places in which they livetheir surrounding ecosystemsand are more willing to make commitments to ensure the quality of their environmental place and address use conflicts in that place.

One of the recommendations of *The National Performance Review* is the application of ecosystem management throughout the federal government (Gore, 1993). This would require an integrating and coordinating mechanism that has often been lacking in federal environmental science and management, for example, a framework for addressing the kinds of linkages between watersheds and coastal ecosystems that have been discussed in this report. At the same time, ecosystem management presents significant challenges, including the decentralization of both science planning and environmental regulation and the need to work across the firmly entrenched lines of agencies and scientific disciplines.

The move toward regional ecosystem management suggests that considerable opportunities for scientific progress in the future may lie largely within regional scientific or management programs. The Water Subcommittee, in addition to its development of a national scientific strategy and implementation plan, is also developing initiatives targeting specific locations in support of the federal government's efforts to develop collaborative management initiatives with federal, state, and local governments and other interested parties that integrate the ecological, economic, and social factors affecting ecosystems.

From the scientific perspective, two questions about geographically targeted research arise: (1) How will these geographically focused research initiatives avoid the tendency of being overly prescriptive and allow for the creative contributions of the scientific community? (2) How will the national and geographically focused strategies be coordinated in such a way as to advance the development and application of comparative coastal science, as recommended in Chapter 3? The committee believes that this is possible through research that is intense enough to approach ecosystem-level questions in the targeted area. Such research should rely on the creative proposals of individuals and groups of scientists that respond to clearly defined, strategic questions important to ecosystem management and that are evaluated by a rigorous peer review process. The Water Subcommittee's geographically targeted strategic research should be integrated with its overall research plan to avoid competition for funds and to ensure that local research programs contribute to Water Subcommittee goals. The focus on local issues within a national strategic framework of the National Sea Grant College Program (NRC, 1994f) offers both a model and opportunity for geographically targeted strategic research.

## Regional Coordination

Federal science agencies should work to improve regional coordination of science supported by their national programs in addition to whatever coordination is accomplished as a result of regional programs such as the RMRP; the Great Lakes, Gulf of Mexico, and Chesapeake Bay programs; and EPA's National Estuary Program. Not only are there efficiencies to be gained in the sharing of ships, observation systems, data, personnel, and other resources, but there are often significant opportunities for improving understanding beyond that allowed by a single program. Often, narrow perspectives of agency mission, logistical obstacles, and restrictions posed by contracting and granting procedures limit such coordination, even when it may be in the nation's interest (see Box 8). On the other hand, some federal agencies have a long tradition of cooperatively funding oceanographic investigations. CENR should work to maximize the synergy of federal science investments when they coincide geographically.

## International Roles

The Water Subcommittee's strategy and this report (to this point) have dealt with the coastal ecosystems of the United States. But the committee believes that the U.S. government and the national scientific community also have an obligation to contribute to the advancement and application of coastal science around the world. The United States has substantial expertise in coastal science. Moreover, this nation has a tremendous training capability within its many universities engaged in research and graduate training in the coastal sciences. The problems in evidence in the United States (eutrophication, habitat destruction, and others) are also manifest throughout the rest of the world. The pressures on coastal environments and resources in the developing world as a result of projected population growth in coastal areas, and agricultural and industrial growth to sustain these populations, will almost certainly make our problems pale by comparison. Moreover, there are benefits for management of U.S. coastal environments to be gained by comparative studies of other relatively pristine and highly stressed environments around the world, expanding the range of systems that can be studied. Moreover, the United States has made international commitments to implement integrated coastal management under Agenda 21 of the United Nations Conference on Environment and Development and to maintain global biodiversity under the Biodiversity Treaty. Contributions by U.S. scientists should be an important part of meeting these commitments.

The international community of coastal scientists has been working together in the development of an initiative under the International Geosphere-Biosphere Program (IGBP). This initiative, the Land-Ocean Interactions in the Coastal Zone (LOICZ) program has identified scientific activities under four foci (see

Box 8
Opportunities: Past, Present, and Future

Agencies that sponsor coastal ocean and Great Lakes research sometimes have opportunities for coordinating their research or monitoring efforts in ways that mutually enhance their programs simply because of the geographic proximity and timing of those programs. However, coordination does not always occur, nor is it always effective.

Two large multiyear research programs were begun within the same general time frame on the continental shelf of the northwestern Gulf of Mexico. The Nutrient Enhanced Coastal Ocean Productivity (NECOP) program of NOAA assessed the effects of nutrients discharged by the Mississippi and Atchafalaya rivers on production and oxygen depletion on the shelf. The Louisiana-Texas (LATEX) Shelf Physical Oceanography study, sponsored by the Minerals Management Service (MMS), was begun shortly thereafter and included a very extensive field program of current measurements and survey cruises, coupled with physical modeling. There was very little coordination between these two programs until they were well under way, and then it was mostly accomplished through shared principal investigators. The NECOP program lacked the physical oceanographic measurements that would provide quantification of important processes affecting shelf oxygen depletion. MMS sponsored the LATEX program to help understand the impacts of oil and gas production. Important to measuring those impacts is their separation from those due to oxygen depletion and contaminants introduced by the large rivers. It too missed an opportunity to add value to its physical oceanographic studies.

Opportunities now exist for profitable coordination of the variety of federally supported studies being conducted or planned in the southern Mid-Atlantic Bight above Cape Hatteras. Fortunately, they are being coordinated. Nearshore physical and biological processes are being investigated under National Science Foundation support as the first Coastal Ocean Processes Program (CoOP) study. These are being coordinated with U.S. Army Corps of Engineers-sponsored studies off Duck, North Carolina, and with Office of Naval Research studies in the same region. The Department of Energy's Ocean Margins Program investigation of shelf transport and offshelf deposition of carbon is beginning in the same region. There are additional opportunities to link all of these efforts to those under way in the Chesapeake Bay as part of a Land-Margins Ecosystem Research (LMER) study to address the transport and transformation of nutrients and organic carbon from a major estuary, exchange with the presumably enriched inner shelf regime, and contribution to potentially globally significant offshelf deposition.

Table 3). Focus 1, dealing with the effects of changes in external forcing or boundary conditions on coastal fluxes, is very coherent with science priorities identified in this report: catchment basin (watershed) dynamics and delivery, atmospheric inputs, fluxes across coastal systems, and development of coupled land-estuarine-ocean models. In addition, the Intergovernmental Oceanographic Commission is seeking to implement the Global Ocean Observing System (GOOS), called for specifically by Agenda 21. One of the five GOOS modules

TABLE 3 Foci and Activities of the IGBP Land-Ocean Interaction in the Coastal Zone (LOICZ) Program (Holligan and de Boois, 1993)

| | |
|---|---|
| FOCUS 1: | The effects of changes in external forcing on boundary conditions on coastal fluxes |
| 1.1 | Catchment basin dynamics and delivery |
| 1.2 | Atmospheric inputs to the coastal zone |
| 1.3 | Exchange of energy and matter at the shelf edge |
| 1.4 | Factors influencing the mass balance of materials in coastal systems |
| 1.5 | Reconstructions of past changes in the coastal zone |
| 1.6 | Development of coupled land-estuarine-ocean models for coastal systems |
| FOCUS 2: | Coastal biogeomorphology and sea-level rise |
| 2.1 | Role of ecosystems in determining coastal geomorphology |
| 2.2 | Biogeomorphological responses to changes in land use, climate, and human activities in the coastal zone |
| 2.3 | Prediction of coastal geomorphology for different scenarios of relative sea level change |
| FOCUS 3: | Carbon fluxes and trace gas emissions |
| 3.1 | Cycling of organic matter within coastal systems |
| 3.2 | Estimation of net fluxes of N2O and CH4 in the coastal zone |
| 3.3 | Estimation of global coastal emissions of dimethyl disulfide |
| FOCUS 4: | Economic and social impacts of global change on coastal systems |
| 4.1 | Evolution of coastal systems under different scenarios of global change |
| 4.2 | Effects of changes to coastal systems on social and economic activities |
| 4.3 | Development of improved strategies for the management of coastal resources |

deals specifically with Monitoring of the Coastal Zone Environment and Its Changes, and other modules concerned with climate, the health of the ocean, living marine resources, and marine meteorology are also highly relevant to the objective of coastal ecosystem integrity (NRC, 1994d).

The committee recommends that the Water Subcommittee identify and develop mechanisms to promote intellectual exchange between the U.S. coastal science community and its counterparts in other nations, including scientific coordination with the LOICZ program, GOOS activities, and bilateral science programs (e.g., the U.S.-Canadian Integrated Atmospheric Deposition Network). Such exchanges will maximize the contributions of U.S. programs such as LMER, CoOP, the Department of Energy Ocean Margins Program, the Global Ocean Ecosystems Dynamics program, and national and regional monitoring.

# 5
# Interfaces with Other National Science and Technology Council Committees and Subcommittees

Federally supported science in the coastal ocean and Great Lakes is performed for many reasons other than the management of water resources and maintenance of healthy coastal ecosystems (i.e., the goals of the Water Subcommittee). Other scientific activities are conducted for reasons of national defense, natural resource management, global climate change prediction, and protection of life and property, as well as simply to advance basic science. Because this research also contributes to improving the scientific understanding of coastal ecosystems and thus to Water Subcommittee goals, it is important to recognize the importance of such research. Significant coastal science activities are included under the programs being examined by other subcommittees of the Committee on Environmental and Natural Resources Research (CENR) and committees of the National Science and Technology Council (NSTC) (see Figure 1). These will be considered briefly here to provide a more complete picture of the coastal science carried out under the sponsorship of the federal government.

## Global Change

- Global Ecosystems Dynamics Program, which is sponsored by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration and seeks to understand how populations and food chains in the sea may be affected by climate change;
- the U.S. Joint Global Ocean Flux Study, which is primarily sponsored by NSF and addresses the flux of carbon in the oceans;
- the Department of Energy's Ocean Margins Program, which aims to quantify the processes and mechanisms that affect the cycling, flux, and storage of carbon and other biogenic elements at the land-ocean interface;
- the NSF-sponsored Land-Margin Ecosystem Research program;
- Department of Interior activities, including those of the National Biological Survey on the impacts of global change on coastal lands and ecosystems, and studies of the U.S. Geological Survey that focus on biogeochemical exchanges between terrestrial systems, aquatic systems, and the atmosphere; and
- aspects of the Earth Observing System of the National Aeronautics and Space Administration.

In addition, other global change studies, such as the Global Energy and Water Experiment assessments of the energy budget and hydrological cycle of the Mississippi River watershed, have obvious implications to understanding changes in the availability and quantity of water reaching the coast.

## Biodiversity And Ecosystem Dynamics

The CENR Biodiversity and Ecosystem Dynamics Subcommittee is addressing a broad goal: "to ensure the sustainability of the ecological systems and processes that support life on Earth and provide the goods and services necessary for human life, opportunity, and well being. This includes minimizing the loss of biodiversity and degradation of ecosystems as well as the restoration of ecosystems as appropriate" (CENR, 1994b).

In a recently completed report on biological diversity in marine systems (NRC, in press), a National Research Council (NRC) committee proposes an integrated, regional-scale research strategy to pursue five fundamental objectives, all of which have implications to coastal ecosystem integrity:

- "to understand the patterns, processes, and consequences of changing marine biological diversity by focusing on critical environmental issues and their threshold effects, and to address these effects at spatial scales from local to regional and at appropriate temporal scales;
- to improve the linkages between the marine ecological and oceanographic sciences by increasing understanding of the connectivity between local, smaller-scale biodiversity patterns and processes, and regional, large-scale oceanographic patterns and processes that may directly impact local phenomena;

to strengthen and expand the field of marine taxonomy through training, the development of new methodologies, and enhanced information dissemination and to raise the standard of taxonomic competence in all marine ecological research;

to facilitate and encourage the incorporation of (1) new technological advances in sampling instrumentation, experimental techniques, and molecular genetic methods; (2) predictive models for hypothesis development, testing, and extrapolation; and (3) historical perspectives (geological, paleontological, archeological, and historical records of early explorations), in investigations of the patterns, processes, and consequences of marine biodiversity; and

to use the new understanding of the patterns, processes, and consequences of marine biodiversity derived from this regional-scale research approach to predictions of the impacts of human activities on the marine environment."

All of these objectives, except that dealing with marine taxonomy, are related in one form or another in the scientific priorities recommended in this report. Only the organization and framing of the respective recommendations differ.

### Resource Use And Management

The CENR Resource Use and Management Subcommittee has as its vision the sustainable management and use of our natural resources to provide goods and services in a manner that it is compatible with environmental goals and enhances our health, welfare, and prosperity (CENR, 1994a). Implicit in that vision is linkage among resource exploitation, environmental quality, and ecosystem integrity. At this interface are the issues of the effects of overexploitation of fishery resources, the harvesting techniques themselves, and urbanization of coastal environments. Also, oil, gas, and mineral extraction may have undesirable effects on habitats ranging from coastal wetlands to the open continental shelf.

### Natural Disasters

The CENR Natural Disasters Subcommittee has as its vision the reduction of loss of life, property damage, and economic disruption by natural hazards (CENR, 1994a). Significant among these hazards are storms that threaten coastal settlements and vessels and the longer-term erosion of land and property. As discussed in Chapter 3, improved coastal observation and prediction systems (NOAA, 1993a; NRC, 1994d) would contribute to this reduction in the loss of life and property but would also be very useful for ecosystem protection and living resource management.

## Social And Economic Sciences

The CENR Social and Economic Sciences Subcommittee seeks a better understanding of the relationships between humans and their environment and the social and economic consequences of both policies and environmental changes (CENR 1994a). This is important for predicting environmental changes more accurately, developing mitigation policies, and facilitating adaptation to environmental changes. Such social and economic science should have strong links to the natural science discussed here. For example, developing more realistic economic valuation must rely on a better understanding of the services and resources actually provided by coastal ecosystems (NRC, 1994b).

## National Security

The U.S. Navy has conducted a reappraisal of its ocean science research needs following the collapse of the Soviet naval threat and proliferation of regional conflicts. It now plans to place greater emphasis on the oceanography and meteorology of the coastal zone. This is undoubtedly a significant planning factor for the NSTC Committee on National Security.

The NRC (1993b) has identified promising coastal research topics related to physical processes that are of relevance to the Navy: upwelling fronts, bottom boundary layer dynamics, vertical turbulent mixing processes, surface wave propagation across the continental shelf; responses to cold-air outbreaks, estuary-shelf coupled circulation, circulation and morphology in the surf zone, and small-scale sediment dynamics. It also identified opportunities for model development and evaluation and for development of instrumentation, technology, and facilities. Virtually all of the physical processes identified are also of significance to the function of coastal ecosystems. As the Department of Defense seeks, at the same time, dual use of its science and technology, new prospects are emerging for partnerships embracing science that is of importance to both national security and "ecosystem security." The Navy also has a major research program regarding the environmental quality at and near its bases.

## Health, Safety, And Food

## Fundamental Science

> *Environmental responsibility requires much better understanding of the complex interrelationships among components of the biosphere and among human activities and the world around us. We must carry out the necessary fundamental research and develop appropriate technologies to detect and correct environmental problems, to manage natural resources, and to sustain the environment.* (Clinton and Gore, 1994)

A strong commitment to fundamental science, initiated by individual investigators or collaborators, must be an essential ingredient in the U.S. coastal science strategy. Fundamental studies supported by NSF have contributed greatly and directly to improved management of coastal ecosystems. Without this fundamental research, which provides an understanding of ecosystem processes, meaningful interpretation of the results of monitoring and other observational efforts cannot be made, nor can ecosystem models be constructed properly. Moreover, advancement in fundamental knowledge in such strategically important fields as landscape ecology, geochemical tracers, biodiversity, molecular approaches to assessing marine ecosystem function, and the physics of shallow water systems will be critical to the success of more directly applied scientific activities.

## Overall Coordination Of Coastal Science

Conversely, the combined consideration of freshwater resources and coastal

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marine environments under the aegis of the Water Subcommittee facilitates the development of a larger view of coastal ecosystems, that includes watershed processes and the coastal ocean. This should help bridge a chasm between scientists who specialize in freshwater and terrestrial systems and coastal scientists and provide critical synthesis needed to reduce the impacts of land-based activities and protect ecosystems. But there remains a significant need to plan and coordinate scientific activities in coastal waters across the issue sectors. The committee recommends that CENR ensure that there is effective integration and coordination of coastal science among the contributing CENR subcommittees and NSTC committees.

# 6
# Summary of Conclusions and Recommendations

Coastal environments and ecosystems (from estuaries and shorelines to the edge of the continental shelf) are increasingly likely to be modified by changes in the delivery of materials from diffuse sources via rivers and the atmosphere, widespread habitat modification resulting from human activities, and the overexploitation of living and nonliving resources. These problems pose a different set of challenges to environmental policy, management, and science than traditional concerns of point source discharge, coastal land use, and spills of hazardous materials. As a result, concern is shifting from problems amenable to single-factor risk assessment paradigms to multiple-factor risk assessment and regulatory strategies that take into account indirect, cascading, and scale-related effects that require an ecosystem perspective (e.g., eutrophication, hydrologic and hydrodynamic modifications, resource sustainability, loss of biodiversity).

Science priorities that are needed to understand the consequences of broad-scale ecosystem modifications can be cast within the strategic framework being used by the Water Resources and Coastal and Marine Environments Research Subcommittee of the Committee on Environment and Natural Resources Research: Integrated Monitoring, Water Availability and Flow, Water Quality and Aquatic Ecosystem Functions, Ecological Restoration and Rehabilitation, and Predictive Systems Management. In the view of the committee, particularly high priorities for coastal science are:

- the development of indicators of biological status and processes, reflecting ecosystem health and integrity;
- the use of advanced *in situ* observation systems coupled with the applica-

- tion of remote sensing to provide insight on ecosystem behavior on appropriate time and space scales:
- investigations of the effects of modifications of land use and water flow and associated material fluxes and transformations on watershed and coastal regional scales;
- research on the relationship of physical phenomena to ecosystem structure and function and the interaction of ecosystem structure and function;
- research, modeling, and monitoring to support effective restoration or rehabilitation of degraded habitats and sustained yield of coastal ecosystems; and
- development of models and the understanding behind them, of atmosphere-watershed-coastal ecosystem interactions for use in ecosystem management.

These priorities are generally consistent with those identified by the freshwater scientific community, with previous national assessments for coastal environments (NRC, 1990a, 1993a), and with recent research plans developed for nine coastal regions of the United States.

The application of ecosystem management in place of uniform regulatory control on a medium-specific basis requires regional as well as national strategies for science planning and implementation. Federal science agencies can help implement ecosystem management by working with various bodies engaged in research and management, including Regional Marine Research Program boards; National Estuary Program components; and Great Lakes, Chesapeake Bay, and Gulf of Mexico programs. The goal should be to optimize the contribution of national programs to ecosystem management and to foster geographically targeted, strategic research that is intense enough to address ecosystem-level questions but avoids narrow prescriptions, to allow scientific creativity and program evaluation in response to new knowledge.

The United States should show more international leadership by extending its scientific expertise in coastal science to assist other nations and address what are truly global environmental problems facing coastal ecosystems. The federal agencies should embrace this as a goal complementary to domestic goals and should support the involvement of U.S. scientists in the Land-Ocean Interactions in the Coastal Zone program, the Assessment and Prediction of the Health of the Ocean and Monitoring of the Coastal Zone Environment and Its Changes modules of the Global Ocean Observing System (NRC, 1994d), and other productive bilateral and multinational ventures.

The development by the Committee on Environment and Natural Resources Research (CENR) of a national science strategy that for the first time, comprehensively considers freshwater and coastal marine environments of the nation could catalyze the scientific synthesis needed to protect and restore our aquatic ecosystems. It is important that the further development and implementation of

this strategy continue to involve input and review by the scientific, policy, and management communities. However, CENR should also seek to integrate and coordinate scientific activities in the coastal ocean and Great Lakes that are related to global climate change, resource use, biodiversity, natural disasters, public health, and national security with those contributing and maintaining ecosystem integrity and advancing fundamental science.

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Appendixes

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Appendix A
Letter of Request

UNITED STATES DEPARTMENT OF COMMERCE
The Assistant Secretary for Oceans and Atmosphere
Washington, D.C. 20230
JUL 26 1994

Dr. William Merrell
Chairman, Ocean Studies Board
National Research Council
Commission on Geosciences, Environment and Resources
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Dr. Merrell:

Under the new National Science and Technology Council, the Water Resources and Coastal and Marine Environments Subcommittee (Water Subcommittee) of the Committee on the Environment and Natural Resources (CENR) has developed an interagency research strategy and is preparing an implementation plan for water resources and coastal and marine environments. This implementation plan is intended to help guide individual agency programs, as well as to contribute to development of an overall CENR environmental strategy. Because it is important to reflect the concerns of stakeholders outside the Federal Government, external input is being sought for water resources, freshwater ecosystems, and coastal and marine environments. Within this context, the Ocean Studies Board (OSB) is in a unique position to contribute to the development and identification of integrated coastal and marine research priorities.

A solid planning base for coastal oceans science exists. Many agencies have relied on the academic community to assist in development of agency-relevant research programs. The National Research Council has also reviewed the status, quality, and relevance of several agency programs. Each of these efforts has used academic expertise to develop or review research priorities for specific disciplines, particular agencies, or certain geographic regimes. Also, the previous Federal Coordinating Committee for Science, Engineering and Technology Subcommittee on U.S. Coastal Ocean Science (SUSCOS) has reviewed Federal coastal policy needs and research programs and formulated a framework for an integrated research strategy. It is now necessary to update and integrate all of these efforts to reflect the current direction and context of the CENR.

By using results from previous studies as a base, the SUSCOS plan as a framework, and the current CENR Water Subcommittee research strategy as a new context, the OSB is requested to analyze this array of academic advice and provide an *integrated* assessment of research priorities to the Subcommittee as it formulates its Implementation Plan.

THE DEPUTY ADMINISTRATOR

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The relevant agencies will identify the external leaders of its recent reviews and program development efforts. It is expected that the OSB will benefit from the input and advice of these individuals, as they integrate the results of their activities. The OSB is not expected to identify specific agency roles for the integrated effort.

The proposed deadlines for the effort include an interim assessment on September 15, 1994, and a completed report on November 1, 1994. My contact person for this request is Donald Scavia, Director of the National Oceanic and Atmospheric Administration Coastal Ocean Program, 1315 East-West Highway, Room 15140, Silver Spring, Maryland 20910. Dr. Scavia may be reached at (301) 713-3338.

Thank you for your efforts on behalf of this important project.

Sincerely,

Douglas K. Hall
Chair. Subcommittee on Water Resources and Coastal and Marine Environments

## Appendix B
## Biographies of Committee Members

Donald F. Boesch earned a Ph.D. in marine science from the College of William and Mary in 1971. He is presently the president of the University of Maryland Center for Environmental and Estuarine Studies and a professor at the University of Maryland. Dr. Boesch is a member of the NRC Ocean Studies Board and the chair of its Committee on the Coastal Ocean and has served on the advisory groups of a number of state and federal agencies. His research interests focus on biological oceanography, estuarine science, marine pollution, and marine environmental management.

Mary G. Altalo earned a Ph.D. in biology from Johns Hopkins University in 1977. Dr. Altalo has worked in academic (Johns Hopkins University, University of Delaware, and Scripps Institution of Oceanography), industry (Martin Marietta), and federal agency (National Science Foundation and Office of Naval Research) settings. She presently holds the positions of deputy director for scientific affairs at the Scripps Institution of Oceanography and associate vice chancellor for marine sciences at the University of California at San Diego. Dr. Altalo's research interests focus on physical and physiological mechanisms for the formation of phytoplankton blooms in nearshore and estuarine environments.

David L. Correll earned a Ph.D. in limnology and biochemistry from Michigan State University in 1961. Dr. Correll has been employed by the Smithsonian Institution since 1962 and presently serves as director of the Smithsonian Environmental Research Center at Edgewater, Maryland. His research interests focus on watersheds, riparian forest buffers, atmospheric deposition and impacts.

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photomorphogenesis in plants, nutrient dynamics in estuaries, and phosphorous biochemistry of microorganisms.

Michael J. Dagg earned a Ph.D. in biological oceanography from the University of Washington in 1975. Dr. Dagg has been at the Louisiana Universities Marine Consortium since 1981 and served as its interim director in 1990 and 1991. He is presently a member of the Ocean Studies Board's Committee on the Coastal Ocean. Dr. Dagg's research interests include coastal and open ocean biological oceanography and zooplankton ecology.

John Mark Dean earned a Ph.D. in biological science from Purdue University in 1962. Dr. Dean has been a professor at the University of South Carolina since 1977. He is a fellow of the American Association for the Advancement of Science and has served on a number of regional and national councils and committees related to fisheries management. Dr. Dean presently serves as chair for the U.S. Advisory Committee to the International Commission for the Conservation of Atlantic Tunas. His research interests are focused on physiological ecology of estuarine fish, age and growth of fishes, and fisheries management.

John W. Farrington earned a Ph.D. in oceanography from the University of Rhode Island in 1972. Dr. Farrington has spent most of his professional career at the Woods Hole Oceanographic Institution, where he is now the associate director for education and dean of graduate studies. He has served on a number of NRC committees. His research interests include organic geochemical processes in the marine environment and environmental quality.

Edward D. Goldberg earned a Ph.D. in chemistry from the University of Chicago. Dr. Goldberg has been a professor of chemistry at the Scripps Institution of Oceanography since 1960. He was elected to the National Academy of Sciences in 1980 and presently serves on the NRC Marine Board. His interests are in marine geochemistry and geotechnology, waste management and marine pollution, and colloids in seawater.

Robert W. Howarth earned a Ph.D. in oceanography from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in 1979. Dr. Howarth was a staff scientist at the Marine Biological Laboratory (Woods Hole) for six years before joining the faculty at Cornell University in 1985. He has served on a number of NRC committees. Dr. Howarth's present research interests include controls on coastal eutrophication and the influence of land use and climate changes on the flow of nutrients from land to sea.

Michael N. Josselyn earned a Ph.D. in marine botany from the University of New Hampshire in 1978. Dr. Josselyn has been on the teaching faculty at San

Francisco State University since 1978 and is presently a professor there. He served as the director of the university's Tiburon Center for Environmental Studies from 1982 to 1989. Dr. Josselyn is presently a member of the Ocean Studies Board's Panel on the NOAA Coastal Ocean Program. His research interests include wetlands restoration, estuarine algal ecology, and tropical seagrass ecology.

William Michael Kemp earned a Ph.D. in environmental science from the University of Florida in 1976. Dr. Kemp has been a systems ecologist at the University of Maryland since 1977. His research interests focus on ecosystem modeling, productivity and nutrient dynamics of estuaries, structure of ecological trophic webs, and economics and energetics of the environment.

Joan Oltman-Shay earned a Ph.D. in oceanography from the Scripps Institution of Oceanography in 1986. She has worked in the private sector since 1990, before which she was an assistant research professor at Oregon State University. Dr. Oltman-Shay serves on the editorial board of two journals and presently holds adjunct faculty appointments at the University of Washington and Oregon State University. Her research interests focus on nearshore and inner shelf physical oceanography.

Thomas C. Royer earned a Ph.D. in physical oceanography from Texas A&M University in 1969. Dr. Royer has been a professor at the University of Alaska since 1981. He is an honorary member of Sigma Xi and a member of the Ocean Studies Board. Dr. Royer's research focuses on ocean circulation, especially the Alaska Gyre; measurements of currents, water masses and air-sea interactions; and long-period ocean waves, including tsunamis and storm surges.

# Appendix C
## Background Material Examined

To carry out this assessment, the committee examined *Setting a New Course for U.S. Coastal Ocean Science* (SUSCOS, 1993a,b), *The Freshwater Imperative* (Naiman et al., in press), various relevant National Research Council (NRC) reports, a number of agency program descriptions and plans, and other relevant research agendas developed by the scientific community from both national and regional perspectives (see References for full listing). The committee evaluated this documentation to determine how existing and developing programs can address the needs identified by the Water Subcommittee, to identify research needs not presently being addressed, and to aid in its development of scientific priorities relevant for the Water Subcommittee. Descriptions of the most important documents are given below because they provide a context for the Water Subcommittee's future activities and for discussions by the committee.

### *Setting A New Course For U.S. Coastal Ocean Science*

The fundamental goal of *Setting a New Course for U.S. Coastal Ocean Science* was "to establish improved predictive capabilities for coastal ocean systems that link physical processes, biogeochemical cycles, and the interactions of living marine resources" (SUSCOS, 1993a). An inventory of federal programs and a strategic framework developed by SUSCOS were intended to encourage cooperation among federal agencies in coastal ocean and Great Lakes science so that federal resources can be used more effectively to understand coastal systems and human impacts on them.

Phase I of the SUSCOS report (SUSCOS, 1993a) inventoried federal coastal

ocean and Great Lakes science programs and estimated direct federal expenditures for all categories and agencies to be $227 million in FY1993. Contributing activities, either research involving coastal areas outside the United States or supporting observations critical to the direct research, accounted for another $199 million.

The program and expenditure inventory was assembled as a three-way matrix of budget expenditures for coastal research according to science topics (physical processes, biogeochemical cycles, and biological interactions), environmental regimes of coastal waters (Great Lakes, shorelines, estuaries, and ocean margins), and national concerns (environmental quality, habitat conservation, living resources, nonliving resources, and protection of life and property). During FY1991-1993, 55 percent of the expenditures for scientific activities was related to environmental quality and habitat conservation (Figure 3), that is, the topics of direct importance to the Water Subcommittee. Programs and expenditures listed under other national concerns also contributed to issues related to water quality and ecosystem integrity. For example, the environmental studies program of the Minerals Management Service was listed under Nonliving Resources. Within the Environmental Quality and Habitat Conservation categories, the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), Environmental Protection Agency (EPA), and National Science Foundation (NSF) were the most significant supporters of coastal science activities (Figure 1).

Phase II of *Setting a New Course for U.S. Coastal Ocean Science*, the strategic framework, focused on four strategic priorities that would be most amenable to a coordinated multiagency approach (SUSCOS, 1993b). These are (1) restoring and protecting coastal ecosystems, (2) sustaining coastal resources, (3) protecting coastal life and property, and (4) ensuring national defense. The focus of the present report is primarily on the first priority issue because it relates most directly to the Water Subcommittee's goals; the latter three SUSCOS priority areas fall under the principal purview of other National Science and Technology Council committees and subcommittees. For each of the four strategic priorities, the SUSCOS Phase II document described four interdependent integrating approaches: prediction, information, observation, and research. The strategic framework identified several areas of process-oriented research that could be approached through multiagency efforts:

comparative coastal, estuarine, and Great Lakes ecosystems analysis and prediction;
terrestrial discharge processes;
coastal ecosystem structure;
cross-shelf exchange processes;
processes coupling the benthic and pelagic zones;
ocean and shoreline hazard reduction;

atmospheric and air-sea interaction processes;
environmental technology development; and
effects of environmental change on coastal economic and social structures.

*The Freshwater Imperative*

*The Freshwater Imperative* (Naiman, et al. in press) was written by a group of researchers; the effort was catalyzed and initiated by several concerned managers in federal agencies such as NSF, NOAA, EPA, the National Aeronautics and Space Administration, and the Tennessee Valley Authority. The document describes the results of mismanagement of fresh water and freshwater habitats in the United States, the importance of fresh water to society, how mankind is degrading freshwater systems, and the effects of such degradation. The strategic goal of *The Freshwater Imperative* is "to ensure that water resource managers and policymakers have adequate and timely scientific information to protect, utilize, and enhance the nation's water resources." It is essentially a research plan for the future of limnology, balancing and integrating management and science, and encouraging the conduct of studies with adequate duration to separate natural changes from human-induced ones and to allow the study of cumulative effects.

*The Freshwater Imperative* focuses on regional-scale and integrated watershed management, assuming that research and management are most effective at this level. Finally, it integrates freshwater research priorities with human needs. The document focuses on three societal issues related to the U.S. freshwater resources: water availability, aquatic system integrity/ecological impoverishment, and human health and safety. Six scientific and management issues are directly related to these needs: (1) restoring and rehabilitating ecosystems, (2) maintaining biodiversity, (3) understanding the effects of modified hydrologic flow patterns, (4) describing the importance of ecosystem goods and services provided by freshwater ecosystems, (5) predictive management, and (6) solving future problems. For each of these issues, specific research topics are posed. *The Freshwater Imperative* proposes that the National Biological Survey serve as a vehicle to link science and management. It is estimated that full implementation of *The Freshwater Imperative* would cost $200 million annually.

*CENR Planning Documents*

The Committee on Environment and Natural Resources Research (CENR) Water Subcommittee provided working documents that relate its developing views of the science needed for providing reliable sources of clean water and ensuring the integrity of aquatic ecological systems and watersheds. These include (1) the *Draft R&D Strategy for the Committee on Environment and Natu-*

*ral Resources*, which resulted from the National Forum (CENR, 1994a), and (2) *A National R&D Strategy and Implementation Plan for Freshwater and Marine Environments* (CENR, 1994c), which represented the Water Subcommittee's planning as of September 1994.

The Water Subcommittee is in the process of developing this research strategy, including both freshwater and marine environments (CENR, 1994b). Input from the Committee to Identify High-Priority Science to Meet National Coastal Needs will contribute to this plan to complement the input from *The Freshwater Imperative*. The scientific goal of *A National R&D Strategy for Freshwater and Marine Environments* is "to provide essential data and gain a predictive understanding of the interactive physical, geological, chemical, biological, economic, and social processes required to ensure the health and integrity of aquatic ecosystems." The plan details the current state of information and research needs. Finally, it describes federal research priorities for FY1996. These are divided into priorities within several Geographically Focused Research "Laboratories" and five national priority research areas:

Integrated Monitoring
Water Availability and Flow
Water Quality and Aquatic Ecosystem Functions
Ecological Restoration and Rehabilitation
Predictive Systems Management

*Agency And Scientific Community Science Plans*

It was neither possible nor prudent given the time constraints of this assessment to conduct a broad survey or originate a new process for developing scientific community consensus on the priorities for coastal science. Rather, the committee sought to synthesize and build upon the large number of recent workshop reports, NRC studies, community planning efforts, and agency plans. Agency strategic and program plans include those for USGS's National Marine and Coastal Geology Program (USGS, 1994), NOAA's strategic plan (NOAA, 1993b), the Department of Energy's Ocean Margins Program (Jahnke et al., 1994), and the U.S. Global Change Research Program (CENR, 1994b). Research priorities have been articulated by the U.S. scientific community for basic research on the land-sea interface (ASLO/ERF/SAML, 1990), coastal ocean processes (Brink et al., 1992), and land-margin ecosystems (LMER Coordinating Committee, 1992) and by the international scientific community for land-ocean interactions in the coastal zone (Holligan and de Boois, 1993). Recommendations of a considerable number of NRC reports are also relevant, including reports on marine environmental monitoring (NRC, 1990), environmental studies related to oil and gas development on the Outer Continental Shelf (NRC, 1990c, 1992a), managing wastewater in coastal urban areas (NRC, 1993a), coastal zone

research issues (NRC, 1994a), and restoration of habitats and ecosystems (NRC, 1992c, 1994b).

*Regional Marine Research Program Plans*

In addition to these national assessments, the committee reviewed the nine regional marine research plans that were recently completed under the authority of the Regional Marine Research Program (RMRP), authorized by the South Carolina Fish Hatchery Act of 1990 (PL 101-593). The research recommendations of these plans are summarized below.

Alaska Region

"1. Distinguish between natural and human-induced changes in the marine ecosystem of the Alaska Region.

2. Distinguish between natural and human-induced changes in water quality of the Alaska Region.

3. Stimulate the development of a data gathering and sharing system which will serve scientists from government, academia, and the private sector in dealing with water quality and ecosystem health issues in the Region.

4. Provide a forum for maintaining and enhancing communication between the marine scientific communities on issues related to maintaining the Region's water quality and ecosystem health."[1]

Greater New York Bight Region

The goal of the Greater New York Bight RMRP is "to foster regional cooperation and planning in marine research and coastal management in order to enhance the values and uses of the marine environment."[2] Planners for this region gathered information about research priorities through a questionnaire sent to more than 200 individuals and organizations in the region. Respondents were asked to identify and rank the three "most important regional marine re-

1Alaska Regional Marine Research Program, 1993, *Alaska Regional Marine Research Plan, 1992-1996*, University of Alaska, Fairbanks, pp. 13-14.

2Greater New York Bight Regional Marine Research Program, 1994, *Research Plan, 1993-1996, Volume I*. University of Rhode Island, Narragansett, p. 50.

search and information needs for the coming decade. From this list the regional board chose two issues on which to focus its attention: (1) nutrients and eutrophication and (2) contaminated sediments. Further, the program's primary objectives are "(1) to design and conduct research programs to address the priority issues and (2) to integrate existing scientific research into a framework for regional management."

Gulf of Maine Region

1. "What are the sources, pathways, fates, and effects on living marine resources of contaminants in the Gulf of Maine?"

2. "What are the causes and effects of noxious and/or excessive phytoplankton concentrations?"

3. "What is the relative importance of natural and human-induced changes to the physical environment on ecosystem structure and function?"

4. "How susceptible are various parts of the Gulf [of Maine] to dissolved oxygen depletion?"[3]

Gulf of Mexico Region

Planners for the Gulf of Mexico region divided it into three subregionseastern (primarily the west coast of Florida), central (Alabama, Louisiana, and Mississippi), and western (primarily Texas)because of the diversity of systems around the Gulf of Mexico. A workshop was held in each of the three regions to discuss and prioritize a list of 13 research topics identified by the regional board. Priorities identified in regional workshops were combined to obtain a Gulf-wide priority list.

"1. Habitat use, assessment, loss, restoration, and enhancement. To include but not limited to wetlands, seagrass beds, natural and artificial reefs, mangrove swamps, hyper- and hyposaline bays, estuaries, and nurseries.

2. Nutrient enrichment and cycling.

3. Freshwater input (riverine and watershed).

4. Modifiers such as nonpoint source contaminants (including nutrients), transport mechanisms, rates of discharge, dispersion, transformation, and fates.

3Gulf of Maine Regional Marine Research Program, 1992, *Gulf of Maine Research Plan*, The Land Grant University and Sea Grant College of Maine, Orono, p. 25.

5. Population stability of marine organisms including factors such as predator-prey relationships and reproductive and colonization success.

6. Trophic dynamics.

8. Toxic materials, anthropogenic and natural.

9. Coastal erosion, sediment transfer and loss.

10. Saltwater intrusion.

11. Catastrophic events (e.g., storms, spills, red and brown tides, etc.).

12. Global change.

13. Nuisance/exotic species."[4]

Insular Pacific Region

Research priorities for the Insular Pacific region were reviewed through a series of three workshops, covering (1) Guam and the Northern Mariana Islands, (2) American Samoa, and (3) Hawaii. One conclusion of this process is that there is little regional activity and coordination for research on marine water quality and ecosystem health. Research was defined as including "goal-oriented, cost effective sampling which is conducted for a defined period of time in order to contribute to long-term trend analyses,"[5] referred to as monitoring in the plan. Broad research priorities and topics were developed, although there is no prioritization within this list.

"I. Assessment and Monitoring

1. Development of Integrated Water Quality and Ecosystem Health Assessment and Monitoring Programs

2. Assessment and Monitoring of Nearshore Physical Oceanographic Processes

3. Assessment and Monitoring of Nearshore Marine Water Quality

4. Assessment and Monitoring of Nearshore Marine Species and Communities

5. Assessment and Monitoring of Nearshore Marine Habitats

6. Assessment and Monitoring of Coastal Development and Resource Use

II. Sources, Transport, Fate, and Effects of Contaminants

III. Effects of Coastal Development and Resource Use

IV. Analysis and Application of Research Results."[6]

4Gulf of Mexico Regional Marine Research Program, 1993, Gulf of Mexico Marine Research Plan 1992-1996, Corpus Christi, Texas, p. 60

5Insular Pacific Regional Marine Research Program, 1993, *Marine Research Plan, 1992-1996,* University of Hawaii Sea Grant College Program, Honolulu, p. 47.

6Ibid., p. 47.

Mid-Atlantic Region

The Mid-Atlantic region identified priority information needs and research priorities to meet these information needs:

"1. Data management, synthesis, and interpretation

2. Ecosystem modeling and comparative studies

3. Presentation and application of regional research to regional management

4. Economic and social considerations."[7]

To gather the information necessary to meet these information needs, the board identified the following research priorities:

"1. Historical and contemporary effects of land use on living resources in the context of ecosystem structure and function

2. Eutrophication, algal blooms and anoxia

3. Fishery yields, recruitment, and trophodynamics of the Mid-Atlantic Bight

4. Parameters of material (including nutrients, sediments and contaminants) and biotic exchanges between estuaries and the coastal ocean

5. Coastal erosion and climatic effects."[8]

Pacific Northwest Region

The Pacific Northwest region used an interview process to compile its list of possible research priorities, followed by elimination of those topics that were judged to be inappropriate for the region. Thirty-three research and information needs were obtained; all except two information needs were categorized into three priority research areas:

"1. Investigating the natural system in order to detect and understand ecosystem change," including studies of "(a) baseline conditions and natural processes and (b) effects of perturbations on the natural system.

2. Alteration of marine and estuarine habitats due to anthropogenic activities and natural phenomena.

3. Fate, effects, and transport of contaminants."[9]

7Mid-Atlantic Regional Marine Research Program, 1994, *Mid-Atlantic Research Plan*, University of Maryland, College Park, p. 21.

8Ibid., p. 25.

South Atlantic and Caribbean Region

This region's goal is "to promote regional interdisciplinary research that will help to identify, characterize, and quantify the relationships between human population and human activities associated with coastal development and habitat structure and function."10 Program planners separated the region into two subregions, the Caribbean Sea and the South Atlantic Bight and focused on human and ecosystem health. They started by identifying two ecosystems of greatest concern: (1) coral reefs and (2) estuaries and embayments. After these two ecosystems were identified, program planners elicited information from workshop participants and other experts in the region to select a small number of research needs and questions for each ecosystem. Thus, for the coral reef ecosystem, the following specific research needs were selected:

"1. Determine the mechanisms, causes, and effects of coral decline as manifest by coral disease, low coral recruitment, and decreased growth rates of individual species. Determine, thereby, factors affecting reef recovery and reef succession

2. Determine economic and sociological ramifications of reef decline

3. Develop (in coordination with the U.S. Environmental Protection Agency) tropical water quality standards and classifications for the maintenance of reef health."11

For estuaries and embayments the regional board recommended research to:

"1. Evaluate complete estuarine systems (including estuaries, embayments, marshes, and mangroves)i.e., characterize (and classify, if appropriate) based on function and functional status

2. Create numerical ocean circulation models

3. [Include] Stand-alone socioeconomic and policy-oriented research needs."12

Southwest Region

The Southwest region is unique among the nine regions in explicitly including foreign coastal waters, the Pacific coast of Baja California and the Gulf of California. This was done because relevant ecosystems (particularly the California Current) extend south of the border and because the North American Free

10South Atlantic and Caribbean Regional Marine Research Program, 1994, *South Atlantic and Caribbean Regional Marine Research Plan*, North Carolina Sea Grant College, Raleigh, p. 61.

11Ibid., p. 72.

12Ibid., p. 75.

Trade Agreement makes new arrangements possible. According to this plan, several areas of research could benefit from joint U.S.-Mexico cooperation, including biodiversity, human health and safety, transboundary water quality, fisheries management, restoration of aquatic habitats, and freshwater uses. This region will focus on three research priorities: (1) natural variability, cumulative impacts, and thresholds in biological systems; (2) habitat protection and management; and (3) restoration of coastal marine habitats. Each of these priorities was discussed in a separate workshop, to develop the research priorities in greater detail. These workshops involved participants (representatives from academic, government, and user groups) from the United States and Mexico.

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