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Science and Integrated Drainage Basin Coastal Management

Chesapeake Bay and Mississippi Delta

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ABSTRACT

Modern precepts of coastal management involve three challenging dimensions: integration, sustainability, and adaptation. The extent to which management addresses these dimensions is examined for two large coastal ecosystems heavily influenced by extensive continental drainage basins: the Chesapeake Bay and the Mississippi delta. The Chesapeake Bay, the largest estuary in the U.S.A., has been affected by eutrophication, habitat loss, and overfishing. Its biggest challenges are the control of diffuse sources of nutrient inputs from agriculture and expanding urban–suburban development and the physical restoration of once plentiful oyster habitats. The Mississippi delta is experiencing rapid loss of coastal wetlands and eutrophication of the adjacent Gulf of Mexico. River controls for navigation and flood protection and the world's most intense industrial agriculture in the upper basin affect this ecosystem greatly. Although assessments and models of nutrient dynamics in the watershed and coastal waters provide a foundation for intermedia and interdisciplinary integration, the management of both systems is not yet well integrated among sectors (e.g., fishing, transportation, and agriculture) and issues (e.g., eutrophication, overfishing, and habitat restoration). While the development of management goals is further advanced in the Chesapeake, even there a scientifically realistic vision of a sustainable future has not been developed. Management of the Chesapeake Bay is adaptive in the long term, but lacks the tight connections between models and outcomes needed for highly responsive adaptive management. Science could better serve integrated coastal management in these regions if it included: interdisciplinary and strategic research targeted to the coastal ecosystem and its watershed; more predictive approaches involving historical reconstruction, models, and experiments; more effective integration of modeling, monitoring, and research; and institutional and individual commitment to civic science.

Science and Integrated Coastal Management
Edited by B. von Bodungen and R.K. Turner

INTRODUCTION

In many regions of the world, coastal ecosystems are greatly influenced not only by anthropogenic activities in the coastal zone proper, but also by activities throughout large river drainage basins, extending hundreds or even thousands of kilometers from the coast. This is particularly true for large estuaries and river–delta ecosystems. Management of coastal environments and resources thus requires not only integration among coastal resource users and among the marine natural and social sciences, but also among resource users and sciences on continental scales (Boesch 1996). Typically, this requires integration and coordination across many political and scientific boundaries.

The large scales, socioeconomic complexity, and need to link atmospheric, landscape, aquatic, marine, and human components make the modern challenges of coastal management of such ecosystems especially steep. Three dimensions of these challenges are particularly prominent and interrelated: integration, sustainability, and adaptation.

Integration as used by the management and policy science community, as in integrated coastal management (ICM), generally implies collective consideration of the uses of products and services provided by the coastal zone to determine an "optimal mix" (Bower and Turner 1998). As Knecht and Archer (1993) point out, the integration required is itself multidimensional: intergovernmental, intermedia (land–water interface in a shoreline area from their perspective, but on larger scales from the present perspective), intersectoral (among users), and interdisciplinary.

From the natural sciences community has emerged the notion of ecosystem management (Christensen et al. 1996), which is not really different from integrated management, but provides greater emphasis on biophysical features and processes. Concepts of ecosystem management address ecosystem integrity as a critical goal; scale and boundaries; the complexity, connectedness, and dynamic nature of ecosystems that limit the predictions that can be made; and ecological principles and models. At the same time, ecosystem management acknowledges, but pays less attention to, societal needs and collaboration and consensus building among sectoral interests. Nonetheless, ecosystem management has numerous social science and governance implications (Hennessey and Soden 1999).

Sustainability has long been a concept embedded in ICM but has become a more explicit requirement in the post-UNCED era (Cicin-Sain 1993). "Sustainable" is a word that is often used, but seldom defined. In the context of sustainable development, it implies the economic development needed to sustain and improve the quality of life of human populations (i.e., sustainable economically and socially) that is environmentally sustainable, equitable among groups in society and nations, and does not foreclose options of future generations. This is a tall order. Sustainability is also listed as a goal of the natural scientists' view of ecosystem management (Christensen et al. 1996), but perhaps with a greater emphasis on environmental sustainability and less emphasis on the imperative of economic development of current populations.

Adaptation is a dimension necessitated by the inherent uncertainty in our predictions about the natural world, socioeconomic developments, and the consequences of management actions. The concept of adaptive management has been developed and applied principally in North America (Lee 1993; Hennessey and Soden 1999) but is implicit in the ICM policy cycle envisioned by the GESAMP (1996) (see also von Bodungen and Turner, this volume, and

Olsen, this volume) as a moving feedback loop through assessment, implementation, evaluation, and reassessment. Adaptive management involves implicitly learning by doing and treating management programs as experiments, with a great emphasis on accounting for outcomes.

In this chapter, I examine the status and challenges for science in advancing these three dimensions of integrated management of the two most prominent drainage basin–coastal systems in the United States: the Chesapeake Bay and its watershed, and the Mississippi delta (including the coastal environments of the delta and the nearby waters of the northern Gulf of Mexico) and its vast drainage basin. Although physiographically different, these two ecosystems share many similar issues, including eutrophication and other consequences of landscape changes within their catchments, habitat losses, fishery declines, toxic contamination, and navigation access. The management programs to address these issues and the science to support them are, in general, more advanced for the Chesapeake Bay than for the Mississippi delta, offering some instructive contrasts.

THE ECOSYSTEMS

Chesapeake Bay and Watershed

The Chesapeake Bay is the largest estuary in the United States and one of the largest in the world. Its main stem is 332 km long; the estuary has a surface area of 11,400 km^2 with 12,870 km of shoreline; and its drainage basin covers 166,000 km^2 in six states. The bay is relatively shallow (mean depth 6.5 m); therefore, the area of its drainage basin is large with respect to the estuarine volume. This, coupled with its modest tidal exchange, makes the bay very susceptible to inputs of fresh water, sediments, and dissolved materials from its catchment (Matuszeski 1996).

Approximately 15 million people live in the Chesapeake basin, with the largest concentrations at the tidal headwaters of estuarine tributaries around the Washington, D.C., Baltimore, Richmond, and Norfolk metropolitan areas. The bay includes important commercial and military ports and is an important recreational resource. Although a number of the historically important fisheries (particularly oysters) have declined, the bay supports commercial fisheries worth approximately U.S. $1 billion per year. The estuary is also heavily used for domestic and industrial waste disposal, with about 5,000 point-source discharges into the estuary or drainage basin.

The sediments laid down in the deeper parts of the Chesapeake Bay yield a chronicle of the many anthropogenic changes in the estuarine ecosystem since colonization of the region by Europeans almost 400 years ago (Boesch 1996; Boesch et al. 2001). The rate of sedimentation increased rapidly beginning in the mid-1700s as a result of erosion from land clearing to grow tobacco for export and grains to support growing populations. More plant nutrients — forms of nitrogen and phosphorus that the native forests efficiently retained — began to wash down into the bay, subtly altering its natural food web, during this agrarian period.

The industrialization that began during the late 1800s left a clear record of increased contamination by trace metals. Steam technology provided the mechanical means to overexploit the abundant oysters, effectively strip-mining the extensive reefs that gave the bay its aboriginal name, Chesapeake or "great shellfish bay." The mid-1900s brought on the petrochemical period of the bay's history. Manufactured organic chemicals, such as pesticides, and petroleum by-products appear prominently in the sediment record. More importantly, microfossil and biochemical indicators in the bay's sediments reveal a profound change in the ecosystem. Over a relatively short time during the 20th century, the estuary changed from a relatively clear-water ecosystem, characterized by abundant plant growth in the shallows, to a turbid ecosystem dominated by super-abundant microscopic plants in the water column and stressful low-oxygen conditions during the summer.

This state shift was largely due to the dramatic increase in nutrient inputs in the form of wastes from the growing population and runoff of agricultural fertilizers manufactured from petrochemicals. In addition, the burning of fossil fuels in power plants and automobiles releases nitrogen oxides into the atmosphere, which rain back down on the bay and its catchment. In all, it has been estimated that the Chesapeake Bay now receives, from land and air, about seven times more nitrogen and 16 times more phosphorus than it received when English colonists arrived (Boesch et al. 2001). In addition, the drastic depletion of the once-prodigious oyster populations has reduced by 90% or more the capacity of these and other organisms to clean the bay's waters through filter feeding. Meanwhile, humans eliminated more than half of the wetlands in the Chesapeake watershed — wetlands that served as sinks for nutrients and sediments — and built dams on rivers that prevent the upstream migration of shad and other anadromous fishes.

In the 1970s the scientific community began to understand and document the pervasive changes in the ecosystem that had taken place and to identify their causes. This led to a growing awareness by the public and political leaders, which in turn resulted in the evolution of regional management structures and restoration objectives (Hennessey 1994; Boesch et al. 2001). Through the legally established Chesapeake Bay Program, the three primary states in the region, the national capital, and the federal government have developed a series of directives and agreements related to reductions of nutrient and toxicant loadings, habitat restoration, living resource management, and landscape management. Although the bay and its drainage basin fall entirely within the United States, the commitments among the parties are quite similar to the declarations of multinational conferences and commissions for the management of European seas (Elmgren and Larsson; Mee, both this volume) because in the U.S.A., most of the responsibilities for land use and water quality fall under the jurisdiction of the states.

Because eutrophication was seen as the most pervasive and consequential human impact, the keystone agreement of the Chesapeake Bay Program called for a 40% reduction of controllable sources of nitrogen and phosphorus entering the bay by the year 2000. Large expenditures of public and private funds have already been made to reduce these inputs both from point sources (treated sewage discharges) and nonpoint sources (especially those from agriculture) or to trap the nutrients in the watershed by wetland and riparian zone restoration. As the target date for this goal approached,extensive efforts were made to assess progress and to determine the next generation of restoration goals. The assessment process relied both on the highly detailed and linked watershed and estuarine hydrodynamic models, and on an extensive water quality monitoring program. Because of the significant interannual variation in freshwater discharge and delivery of nutrients to the bay and the time lags in delivery of nutrients from nonpoint sources, it is not an easy matter to measure or predict the effects of the actual reductions. However, it appears that the 40% goal was nearly met for phosphorus;

nitrogen loadings, although reduced, did not achieved this goal. As in the Baltic Sea (Jansson and Dahlberg 1999; Elmgren and Larsson, this volume), reductions of nonpoint sources of nitrogen, particularly from agriculture, have been difficult to achieve.

On other fronts, the progress in restoring the Chesapeake Bay ecosystem has been mixed. The concentrations of a number of potentially toxic substances (some trace metals and chlorinated hydrocarbons) in sediments and organisms have declined as a result of source controls and waste treatment. Yet, the industrialized harbors in the bay remain heavily contaminated, and other subregions show elevated concentrations of toxicants or evidence of biological effects. Seagrasses have returned in some regions but cover only a small portion of the habitat occupied in the 1950s. Oyster (*Crassostrea virginica*) populations have not recovered because of the degraded reef habitat and ravages of two microbial pathogens. Populations of several anadromous fishes have increased modestly as a result of removal of barriers to upstream migration. Perhaps the most dramatic recovery has been for populations of striped bass (*Morone saxatilis*), which greatly increased as a result of a multiyear moratorium on harvest and subsequent, more conservative management of stocks.

Mississippi Delta and Basin

The coastal ecosystem associated with the Mississippi River delta is equally large as, but less well defined than, the Chesapeake Bay. It includes the Mississippi deltaic plain (Boesch et al. 1994), consisting of the mostly inactive distributaries of the river and extensive tidal wetlands, swamps, and lagoons lying between the distributaries or enclosed by fringing barrier islands. However, a large portion of the river-influenced continental shelf, which has estuary-like salinity gradients and stratified water masses, should be included as part of this coastal ecosystem. While 70% of the flow of the Mississippi River flows through its well-recognized birdsfoot delta, projecting into the Gulf of Mexico, the remaining 30% (regulated by law) flows down the only other distributary presently active, the Atchafalaya River, which enters the Gulf of Mexico 230 km to the west. This expansive wetland–estuarine–shelf ecosystem supports one of the richest fisheries in the U.S.A. and the substantial majority of the coastal and offshore oil and gas production. It is one of the most economically important coastal regions of the country — and one of the most threatened.

The catchment of the Mississippi River is vast, over 3.2 million km^2, including 41% of the conterminous United States and even a small part of Canada. It encompasses all or part of thirty of the fifty United States, from the arid west toward the Rocky Mountains to the humid forests of the Appalachian Mountains to the east. The north-central part of the basin, originally prairies, forests, and wetlands, has been extensively converted to cropland that produces most of the corn, soybeans, wheat, sorghum, and livestock grown in the U.S.A.

The average annual discharge of water through the Mississippi and Atchafalaya rivers to the coastal ecosystem is 628 km^3, essentially an order of magnitude higher than freshwater discharge into the Chesapeake Bay. The hydrology of this great river system has been greatly altered by locks, dams, reservoirs, earthwork levees, channel straightening, and spillways for purposes of flood protection, navigation, and water supply. These alterations have significantly affected the transport of water, sediments, and dissolved materials (including nutrients and toxic contaminants) in ways that have major consequences to the coastal ecosystem (Boesch 1996).

Disruption of overbank flooding in the delta, widespread hydrological modifications caused by myriad canals, and high rates of subsidence (because of the huge thickness of alluvial deposits) have conspired to result in rapid loss of tidal wetlands, particularly during the last half of the 20th century. By the late 1960s, approximately 73 km^2 of vegetated wetlands were being lost per year (Boesch et al. 1994). There is an active program to protect remaining wetland and restore degraded wetland–estuarine systems by various physical management techniques, including placement of dredged sediments, water-level controls, and diversions of river flows back into the deltaic plain. Many of these programs are conducted under the federal Coastal Wetlands, Planning, Protection, and Restoration Act.

A more recently recognized problem is the extensive seasonal hypoxia in bottom waters on the continental shelf (Rabalais et al. 1996). Hypoxic (< 2 mg l^{-1}) bottom waters have extended over 10,000 to 20,000 km^2 in the summer during the 1990s (Rabalais et al. 1998). This phenomenon and other manifestations of eutrophication have been related to the increases in nutrient loading by the Mississippi–Atchafalaya river system. In particular, flux of nitrate from the Mississippi basin to the Gulf of Mexico has averaged nearly 1 million metric tons per year since 1980, about three times higher than it was thirty years ago (Goolsby et al. 2000). The majority of the increased nitrate emanates from agricultural sources in the upper Mississippi and Ohio river basins, over 1,500 km upstream from the discharge into the Gulf of Mexico.

The popular press has provided extensive coverage of the scientific documentation of the dimensions and causes of what is frequently referred to as the Gulf of Mexico "dead zone." In response, the U.S. Congress directed the government to conduct an assessment of the causes and consequences of hypoxia in the Gulf of Mexico, including analyses of the potential for reduction of nutrient sources and associated economic costs. The resulting integrated assessment (Committee on Environment and Natural Resources 2000) presents much more comprehensive evidence concerning nutrient sources, trends, and effects on oxygen depletion for the Mississippi–Atchafalaya delta system than existed at the initiation of the Chesapeake Bay Program and its commitments for nutrient reduction, approximately fifteen years prior.

Nonetheless, agricultural interests and states upstream are fiercely contesting the assessment's findings. For example, the fertilizer industry commissioned a group of scientists to prepare an alternative analysis (Carey et al. 1999), which raises uncertainties and complications such as the role of organic carbon rather than nutrient loading and the effects of climate. The state of Illinois, which according to the integrated assessment is a major source of nutrients to the river, has vehemently criticized the assessment arguing that total nitrogen loadings have actually decreased and have no relationship with agricultural practices, questioning evidence that hypoxia has increased, observing that hypoxia in the sea is a natural phenomenon, and suggesting that efforts to reduce nutrient loading risk reducing fisheries productivity in the Gulf of Mexico.

Political jurisdictions and economic sectors responsible for the sources of nutrient pollution in the Gulf of Mexico are remote from direct relationship with the affected coastal environments. They have a natural tendency to protect the interests of agriculture, which is very economically and culturally important in these upriver regions. Furthermore, they are demanding higher levels of proof and more evidence of significant impacts on living resources in the Gulf before taking action than was the case for the Chesapeake Bay, where the responsible political jurisdictions are located on or near the bay and public concern about the environment is high. Nonetheless, in late 2000, a task force representing basin states and the federal government agreed to take steps to reduce the extent of hypoxia and recognized that this may require a 30% reduction in nitrogen loading.

In addition to wetland loss and eutrophication, integrated coastal management of the Mississippi delta region must also address significant issues in fishery management (including overfishing of some stocks, bycatch mortalities due to shrimp trawling, commercial and recreational fishery conflicts, and endangered species concerns), flood protection, navigation, oil and gas exploration and production, and migratory waterfowl management.

DIMENSIONS OF MANAGEMENT

I now provide brief perspectives on the extent to which management of these large and important coastal ecosystems addresses the three dimensions of modern management: integration, sustainability, and adaptation. I also address the contributions of science to those dimensions.

Integration

Evaluating eutrophication that results from diffuse sources of nutrients forces one to conduct assessments across environmental media and requires contributions, if not collaboration, from diverse disciplines. The Mississippi River integrated assessment (Committee on Environment and Natural Resources 2000) involves the analysis of atmospheric inputs of nutrients from data collected to monitor acid deposition; land-use characteristics; water quality data from throughout the basin and statistical models to estimate fluxes by river segment; and box models of nutrient and carbon budgets in the Gulf of Mexico. More complex, deterministic modeling is applied for the Chesapeake Bay, including atmospheric inputs as a function of meteorological variability; land-use changes; hydrologic transfer of water, nutrients, and sediments through the watershed; and three-dimensional, hydro- and ecosystem dynamics of the estuary (Boesch et al. 2001). Such integrated assessment and modeling has helped managers and scientists alike to think across environmental media, disciplines, and sectors (e.g., agriculture, environmental quality, and living resources). While there is still a long way to go in terms of improvement of models and their predictive uses, both the Mississippi River assessment and the Chesapeake Bay models are leading examples of the power of systemic science for large system management.

There is much less integration among the multiple stressors that confront these ecosystems, including eutrophication, toxic contamination, habitat modification, fishing, species introductions, and coastal land use. Surely, many of these stressors interact in important ways. For example, trace metals and organic contaminants have been shown to affect the type of algal production in enriched waters. Conversely, eutrophication-induced oxygen stresses affect immunological responses of marine animals to toxicants and pathogens.

In the Chesapeake Bay Program, different management committees exist for nutrients, toxic materials, and living resources, with relatively little interaction (except for the linkage between eutrophication and seagrasses). The scientific community as well is organized into nutrient–plankton, chemistry–toxicology, wetlands, fisheries, and social science communities, which typically sort themselves out into different lecture rooms at scientific meetings. The Chesapeake Bay Program (2000) has recently adopted a proposed comprehensive agreement (Table 3.1) that incorporates and supersedes previous agreements and directives. It establishes specific objectives or indicates actions and timetables under each goal. The renewed agreement is comprehensive in scope and many of the goals have an integrating requirement for sustaining and enhancing the living resources of the bay. Thus, a conceptual framework, if not yet a quantitative prescription, for integrated management is provided.

While the Chesapeake Bay Program provides an umbrella management structure for dealing with multiple stressors and integrated coastal management, there is no common

Table 3.1 Goals of the proposed Chesapeake 2000 Agreement (Chesapeake Bay Program 2000). Specific objectives and actions under each goal are briefly summarized.

1. Restore, enhance, and protect the finfish, shellfish, and other *living resources*, their habitats and ecological relationships to sustain all fisheries and provide for a balanced ecosystem.
    - Oysters: tenfold increase
    - Exotic species: identify and reduce introduction
    - Fish passage: restore passage in blocked rivers
    - Multispecies management: develop and revise management plans
    - Crabs: restore health of spawning population
2. Preserve, protect, and restore those *habitats* and natural areas vital to the survival and diversity of the living resources of the bay and its rivers.
    - Submerged aquatic vegetation: recommit and raise previous restoration goal
    - Wetlands: achieve net gain through regulatory protection and restoration
    - Forests: protect and restore riparian forests
    - Stream corridors: encourage local governments to improve stream health
3. Achieve and maintain the *water quality* necessary to support the aquatic living resources of the bay and its tributaries and to protect human health.
    - Nutrients: achieve and maintain 40% goal and reduce further to protect living resources
    - Sediments: reduce loading to protect living resources
    - Chemical contaminants: no toxic or bioaccumulative impacts on living resources
    - Priority urban waters: restore urban harbors
    - Air pollution: strengthen air emission pollution prevention programs
    - Boat discharges: establish "no discharge zones"
4. Develop, promote, and achieve *sound land-use practices* that protect and restore watershed resources and water quality, maintain reduced pollutant loadings for the bay and its tributaries, and restore and preserve aquatic living resources.
    - Land conservation: protect and preserve forests and agricultural lands
    - Public access: expand public access points
    - Development, redevelopment, and revitalization: reduce rate of land development
    - Transportation: coordinate with land-use planning to reduce dependence on automobiles
5. Promote *individual stewardship* and assist individuals, community-based organizations, local governments, and schools to undertake initiatives to achieve the goals and commitments of this agreement.
    - Public outreach and education: provide information about bay to schools and public
    - Community engagement: enhance small watershed and community-based actions
    - Government by example: develop and use government properties consistent with goals

management framework in which to address the two dominant issues of the Mississippi delta: coastal wetland loss and eutrophication. Yet, river diversions intended to rebuild deteriorating deltaic wetlands may also result in removal of nitrogen delivered to the Gulf of Mexico (Lane et al. 1999), although depending on their location and efficiency of nutrient removal they could also conceivably exacerbate eutrophication in inshore or shelf waters.

A major challenge in both areas is the integration of environmental and fisheries management. Although it is generally thought that environmental degradation (hypoxia and other effects of eutrophication and wetland and other habitat modification) has diminished the capacity of these ecosystems to sustain healthy fisheries, this relationship is in fact very poorly quantified or understood in both cases. Correlations, much less cause and effect relationships, are difficult to demonstrate when other factors, including climatic variations and fishing pressures, also play such a large role. Better scientific understanding is critical both because of the recognized need to manage multispecies fishery resources in an ecosystem context and because managers are seeking performance endpoints for environmental management that are closer to what is valued by society.

In these two regions, as in everywhere else in the world, environmental management cannot be conducted detached from the pressures of socioeconomic development. The economic importance of agricultural production in the upper Mississippi basin and the role of the region in the global food supply are potent forces that constrain the options for controlling nutrient inputs into the Gulf of Mexico, just as is sustaining agriculture while accommodating population growth and development in the growing information economy in the Chesapeake region. Restoration of delta wetlands has to contend with the realities of providing flood protection and navigational access. A variety of scientific approaches help illuminate these relationships, e.g., the agricultural economic modeling conducted in the Gulf of Mexico integrated assessment or the economic land-use watershed models that predict water quality changes in the Patuxent subestuary of the Chesapeake (Voinov et al. 1999). However, we remain far from the kinds of ecological–socioeconomic models needed to guide coastal management and development toward a harmonious future.

Finally, the Chesapeake Bay and Mississippi delta case studies represent different levels of development of intergovernmental integration in management — and different degrees of difficulty. To be sure, intergovernmental agreements remain challenging in the Chesapeake Bay Program as it struggles to define post-2000 goals and approaches. There are differences in the governance structure and prevailing political philosophies among the states. For the Mississippi delta, however, even though the coastal environments in question fall essentially in one state, Louisiana, the problems cannot be addressed without the involvement of distant, noncoastal states and the federal government. In the Chesapeake, as has been the case in the Mediterranean, Baltic, and North Seas, consensus among scientists across different states (or nations) has been an empowering force for management of large marine ecosystems.

Sustainability

As the American baseball legend and bard of the obvious, Yogi Berra, is reported to have said: "It's hard to make predictions, especially about the future." Defining sustainability involves making predictions about the future, including unintended consequences, not just reconstructing the past or understanding the present. This is inherently challenging. There is always high uncertainty. Moreover, important larger-scale changes, for example, sea-level rise and other manifestations of climate change or national or global economic forces, are generally beyond the perspective, much less control, of managers.

In the Chesapeake Bay, the commitment to reduce controllable sources of nitrogen and phosphorus by 40% also meant maintaining future nutrient loadings at or below those goals once achieved. This was a step toward sustainability, albeit with an arbitrary and limited definition, with details to follow. Mississippi delta eutrophication is obviously still in an earlier stage of consensus building, but I would predict that ultimately similar "caps" that are consistent with acceptable economic impacts on agriculture will eventually be adopted.

Goals for the permanent reduction of loadings of nutrients and other pollutants such as those adopted by the Chesapeake Bay Program, the Helsinki Commission for the Baltic Sea (Jansson and Dahlberg 1999; Elmgren and Larsson, this volume), or the Paris Commission for the North Sea (Colijn and Reise, this volume) were set based on best estimates at the time of those characteristic of some prior time, such as the 1950s. They do not necessarily correspond to those conditions necessary to restore and maintain the ecosystem to a given level of health, in the sense of its vigor, organization, and resilience (Boesch 2000). The Chesapeake 2000 Agreement takes the concept of sustainability further by linking land use, individual responsibility, and community engagement to water quality, habitats and, ultimately, living resources.

One interesting approach to a broadly based vision of environmental sustainability was produced by the Chesapeake Bay Foundation, a nongovernmental conservation organization, in its annual State-of-the-Bay Report, intended to communicate the status of the bay in a way understandable to the public (Boesch 2000). The report scores 12 factors, including those related to habitats, water quality, and living resources, on a scale of 100, with 100 representing the conditions estimated at the time of arrival of European colonists. Thus the composite index (average of all 12) for 1999 was judged to be 28, up from a low of 23 in 1983, but well below the average of 70 thought to be achievable (recognizing it is not possible to return the bay to its pristine condition).

In any case, even such a progressive and ambitious effort as the Chesapeake Bay Program, with its record of commitments extending a decade or more, has not yet developed a truly long-term, intergenerational perspective. The Chesapeake Bay Program's Scientific and Technical Advisory Committee is presently undertaking an assessment of potential outcomes for the bay 30 to 50 years into the future. This requires consideration of the natural aging of the bay; the consequences of climate change on the region (higher relative sea level, warmer temperatures, and possibly more freshwater runoff); new technologies for energy production and waste treatment; and social, economic, and land-use changes. These projections require ever more efficient treatment of wastes, in order to offset population growth (estimated to be 20% within 30 years), to maintain nutrient loading caps. Even then, ground will be lost if there is not a dramatic change in the sprawling patterns of land conversion for development.

The driving forces that will determine the sustainability of the health of coastal ecosystems of the Mississippi delta are the agricultural economy in the drainage basin and river as well as river and delta management, as influenced by considerations for flood protection and navigation. A 50-year plan for coastal wetland and estuarine protection and restoration (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1998) has been developed with the goals of (a) creating and sustaining marshes by accumulating sediment and organic matter, (b) maintaining habitat diversity by varying salinities and protecting key land forms, and (c) maintaining the exchange of energy and organisms. However, as discussed above, these have not yet been integrated with eutrophication reduction goals. Furthermore, even if this ambitious plan is fully implemented, it is not clear that it will produce a truly sustainable outcome over multiple generations (100 years and more) for an environment so susceptible to sea-level rise. Clearly, here as in the Chesapeake, science should contribute more to the definition of achievable futures and sustainable options; however, the choices ultimately belong to society.

Adaptation

Adaptive management embodies a simple imperative: policies are experiments; learn from doing them (Lee 1993). Practitioners must be explicit about what they expect, and they must collect and analyze information so that expectations can be compared with actuality. Finally, they must correct errors, improve their imperfect understanding, and change actions and plans.

Hennessey (1994) viewed the Chesapeake Bay Program as an excellent example of adaptive management of a large ecosystem. On the other hand, Boesch (1996) noted shortcomings in the degree of emphasis on learning and pursuit of multiple options in the face of uncertainty. The coupling among explicit expectations (from modeling), comparisons with actuality (through monitoring), and changed actions and plans is the essence of adaptive management. The program has extensive and advanced environmental and monitoring programs; however, they are relatively weakly linked in either periodic or ongoing assessments of progress (e.g., Chesapeake Bay Program 1999). In addition, the program's adaptation has been less responsive than the ideal of adaptive management would have it. This is a result of inefficiencies in the modeling–monitoring–management triad — some of which can be improved — but also because of inertia in large ecosystems (which delays the outcomes from management actions) as well as political systems (which delays policy responses).

The integrated assessment of hypoxia in the Gulf of Mexico also recommends an adaptive management framework for controlling nutrient inputs to reduce hypoxia, as does an earlier assessment of wetland protection and restoration in the delta (Boesch et al. 1994). While the emphasis on explicit expectations, collection of information for comparison with actuality, and learning provides an overall philosophical model and framework for integrating modeling, monitoring, and research, adaptive management does have its practical limits for such a large ecosystem, where many potential interventions are costly and relatively irreversible. For example, although one can certainly learn valuable lessons from monitoring the small-scale river diversions currently in place in the delta, the expense and social dislocations involved in massive river diversions require that they be considered as more than experiments, with limited degrees of control of future operations. Nonetheless, rigorous monitoring of the effects of river diversions, as they are put into place and operated at different flow rates, can provide valuable learning experiences not only for their future operations but also for planning of future diversions.

The implementation of an adaptive approach to management faces many practical challenges, including convincing the stakeholders to participate in experiments; sustaining well-supported monitoring programs in the face of waning interests and other priorities;

interpreting the ambiguous outcomes likely in complex and uncontrolled ecosystem; and resistance to changes in management approaches. Nonetheless, it is clear that our understanding, goals, and priorities do evolve over time. It stands to reason that embracing some form of formally adaptive structure would assist in the orderly and effective evolution of integrated coastal management.

TOWARD MORE EFFECTIVE SCIENCE

Among those factors limiting the effectiveness of integration, sustainability, and adaptation in coastal management are those related to the support, execution, and application of science. The following improvements in the practice of science would advance integrated coastal management:

- Development of integrated environmental and social science of large-scale problems, such as those that involve large drainage basins and coastal ecosystems. This requires the support of geographically targeted strategic research (NRC 1994), in addition to the nationally (or European Union) oriented, disciplinary research programs that now exist. Furthermore, this will also require concerted efforts within the scientific community (e.g., by scientific societies) to break down disciplinary barriers of communication and understanding of complex environmental issues. It will require similar efforts within research institutions (universities and agencies).
- Interregional comparisons that advance the general understanding of environmental phenomena and human effects and thus allow more robust extrapolation to other ecosystems. Important lessons can be learned through intercomparisons of the scientific and management experiences among the five large coastal regions treated under the topic of transboundary issues (Jickells et al., this volume). For example, what can the responses of the Danube River and Black Sea (Mee, this volume) to dramatic reduction of fertilizer application tell us with regard to nutrient management strategies in the Mississippi River basin?
- More forward-looking, predictive science based on modeling, experimentation, and reconstruction. The conservative scientific culture deters forward-looking science (with its untested hypotheses) in favor of descriptions of nature as it is or was. Support should be provided and institutional arrangements revised to foster predictive approaches to science that would enhance integrated management, which is inherently about the future.
- More effective integration of modeling, monitoring, and research (NRC 1994). Prediction, observation, and understanding are fundamental to adaptive environmental management, yet modeling, monitoring, and research are largely decoupled in program management and implementation. This leads both to doubts about model performance and unresolved discrepancies between predictions and observations.
- Advancement of civic science (*sensu* Lee 1993), in which scientists actively participate in the communication and precautionary use of science in the political process (Costanza et al. 1998; Boesch 1999). The rapidity of global and regional environmental degradation requires a new sense of urgency within the scientific community and a new social contract between science and society (Lubchenco 1998). Environmental and

social scientists and the institutions that employ them must develop mechanisms to engage in the management process on a timely basis, while preserving the standards of objective evidence required for the impartiality and long-term advancement of science.

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