NERRS Research and Monitoring Initiatives

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ABSTRACT


The National Estuarine Research Reserve System (NERRS), consisting of a network of 26 protected estuarine reserves in the conterminous US, Alaska, and Puerto Rico, generates comprehensive research and monitoring databases in support of coastal resource-management programs. Integrated water-quality, nutrient, and biological monitoring protocols conducted by the NERRS program have been valuable for identifying and tracking short-term variability and long-term changes in the integrity and biodiversity of estuarine systems nationwide. Four areas of biological monitoring in the NERRS program form the foundation for detailed research initiatives; these include (1) submerged aquatic vegetation (SAV) and emergent vegetation (marsh plants), (2) benthos (benthic invertebrates and benthic algae), (3) plankton (specifically larvae), and (4) nekton (fish, decapod crustaceans, and other swimming animals). Watershed and land-use/land-cover characterizations, benthic habitat mapping, and benthic community surveys comprise other high-priority initiatives of the NERRS program. The articles in this volume provide results of both system-wide investigations and site-specific case studies of the NERRS research and monitoring initiatives.

ADDITIONAL INDEX WORDS: System-Wide Monitoring Program, priority initiatives, water-quality monitoring, biomonitoring, land-use/land-cover characterizations.

INTRODUCTION

Research and monitoring are critical functions of the National Estuarine Research Reserve System (NERRS), an integrated network of 26 protected and coordinated estuarine reserve sites in 21 states and one territory (Puerto Rico) (Table 1). Covering more than half a million hectares of estuarine habitat, adjoining wetlands, and uplands, these 26 reserve sites encompass 15 biogeographical regions along the Atlantic, Gulf of Mexico, and Pacific coasts, as well as the Caribbean Sea and Great Lakes. Over the past three decades, NERRS sites have collected large volumes of research and monitoring data that have been valuable in characterizing a wide range of estuarine conditions and addressing an array of resource-management concerns, such as the loss and alteration of essential habitat, degraded water quality, impacted fisheries, invasive species, and declining biodiversity. By generating extensive databases that can be used to formulate sound resource-management decisions, the NERRS plays an integral role in improving the nation’s coastal environments.

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The Estuarine Reserves Division of the National Oceanic and Atmospheric Administration (NOAA), in Silver Spring, Maryland, oversees management of the NERRS program by setting operating standards, supporting general activities, and facilitating decision-making efforts at all levels.

Scientific investigations at the NERRS sites are generally designed to assess the natural and anthropogenic processes that govern stability and change in the system (GREENE and TRUEBLOOD, 1999; NERRS, 2002a). To effectively track short-term variability and long-term changes in estuarine conditions at the reserve sites, the NERRS established the System-Wide Monitoring Program (SWMP) in 1994. The SWMP consists of three major elements: (1) water-quality monitoring, (2) biomonitoring, and (3) watershed and land-use/land-cover characterizations. As an ecosystem-based monitoring network of national significance, the SWMP serves as an excellent platform to develop quantitative databases for measuring and delineating changes in physical, chemical, and biological conditions and ecological processes of estuarine systems (SANGER et al., 2002; WENNER et al., 2001). A primary functional strength of the SWMP is the standardization of sampling protocols, which...
allows accurate data comparisons among reserve sites, thereby focusing attention on estuarine environmental trends of regional and national scale, as well as of local concern.

**SWMP PRIORITY INITIATIVES**

**Water-Quality Monitoring**

All 26 reserves deploy Yellow Springs Instrument Company (YSI®), Yellow Springs, Ohio, 6-series data loggers (YSI 6000 model or YSI 6600 model) at four principal, long-term SWMP stations to record six water-quality parameters (*i.e.*, temperature, salinity, dissolved oxygen, pH, turbidity, and water depth) every 30 minutes, year-round (KENNISH, 2003; NERRS, 2002a). The quality-controlled databases generated from the data logger deployments over a range of spatial scales yield accurate measurements of water-quality conditions useful for assessing the health and function of the NERRS estuaries. In addition to monitoring water quality, the NERRS SWMP collects meteorological data (*i.e.*, air temperature, wind speed and direction, short-wave radiation, barometric pressure, relative humidity, precipitation, and photosynthetically active radiation) employing a Campbell Scientific Weather Station at each reserve site. The meteorological data enable investigators to determine how estuaries in the NERRS program respond to climatic variations and anthropogenic perturbations. NERRS SWMP meteorological monitoring has established important couplings between atmospheric and water-quality conditions at the reserve sites. Atmospheric deposition plays a significant role in nutrient loading and eutrophication problems of many US estuaries (Rabalais, 2002). Faerl *et al.* (2002) showed that atmospheric deposition accounts for 10–40% of new nitrogen loading to estuaries. Hence, NERRS nutrient monitoring may reveal key linkages between human activities, watershed and airshed chemical loading, and nutrient impacts on estuarine waters that can be vital for establishing effective management controls of anthropogenically mediated nutrient inputs.

**Nutrient Monitoring**

Nutrients have been monitored at the NERRS SWMP sites since January 2002. Nutrient sampling protocols involve the collection of monthly replicate grab samples at four long-term SWMP sites. In addition, monthly diel samples are taken at 2.5-h or smaller intervals over a lunar day (24 h: 48 min) at one SWMP site using an ISCO autosampler. Mandatory nutrient sampling in the NERRS program targets a series of tier 1 parameters (*i.e.*, ammonium, nitrate, nitrite, orthophosphate, and chlorophyll *a*). Optional nutrient sampling targets an array of tier 2 parameters (*i.e.*, silica, particulate nitrogen and phosphorus, dissolved total nitrogen and phosphorus, particulate and dissolved carbon, and total suspended solids) (NERRS, 2002b, 2004).

NERRS sites are encouraged to collect additional water samples that will shed light on spatial and temporal variations in nutrient levels. Analysis of these samples may also yield data on the influence of storm events and/or ocean inputs (NERRS, 2004). Such data are particularly important for developing nutrient budgets of the reserve systems.

Because of ongoing human encroachment on the coastal zone and escalating eutrophication problems associated with it, nutrient monitoring is critical for devising effective restoration programs and other remedial actions (KENNISH, 2003). The cascading array of environmental problems cou-
pled to nutrient overenrichment and bottom-up effects poses the most serious threat to the long-term health and function of estuaries nationwide (Kennish, 2002). Included among the most deleterious effects of estuarine eutrophication are algal blooms, oxygen depletion (hypoxia and anoxia), biotic community structural and functional changes, imbalanced food webs, disruption and loss of essential habitat (e.g., seagrass and shellfish beds), impacted harvestable fisheries, diminished ecosystem resilience, and impaired human uses (Boesch et al., 2001; Cloern, 2001; Kennish, 1997, 2001; Livingston, 2000, 2003; Nixon, 1995; Paerl, 1997; Paerl et al., 1998, 2002; Rabalais, 2002; Smith et al., 1999; Valiela et al., 1997; Vitousek et al., 1997). Boesch et al. (2001) estimate that two-thirds of the surface area of estuaries and bays in the conterminous US exhibit symptoms of eutrophication. Of the 138 US estuaries assessed by the National Oceanographic and Atmospheric Administration (NOAA) in the late 1990s, 30% were categorized as highly eutrophic and another 60% as moderately to highly eutrophic (Bricker et al., 1999). These figures underscore the profound impact of human-mediated nutrient inputs to coastal ecosystems.

**Biomonitoring**

NERRS has recently initiated a biomonitoring program that focuses on four primary areas of study:

- Submerged aquatic vegetation (SAV) and emergent vegetation (marsh plants),
- Benthos (benthic invertebrates and benthic algae),
- Plankton (specifically larvae),
- Nekton (fish, decapod crustaceans, and other swimming animals).

The main goal of the NERRS biomonitoring program, similar to that of the NERRS water-quality monitoring program, is to delineate the patterns of short-term variability and long-term changes in biotic components of the estuarine reserves. “Quantitative biological measures will be used to assess biotic community composition, species abundance, and species distribution. The data will yield baseline biotic conditions, characterize biotic diversity, and help to detect invasive species. The data will also be useful in investigating indicators of estuarine condition and function and enable insightful comparisons to be made among the reserve sites” (Kennish, 2003, p. 17).

All NERRS sites follow mandatory biomonitoring sampling protocols for specific projects of national interest. In addition, some NERRS sites may opt to conduct site-specific studies on local biological problems of concern (NERRS, 2002a). Consistent sampling methodology across reserve sites serves as the basis for a regional assessment of reserves as well as a national synthesis of trends that are useful for coastal resource management and decision making (Kennish, 2003).

The initial biomonitoring effort in the NERRS program commenced in May 2004 with investigations of SAV and emergent vegetation (marsh plants) at several reserve sites. These investigations entail the collection of demographic data to improve understanding of the natural variability and anthropogenic-induced change of strategically located submergent and emergent plant biotopes. Such investigations may also provide essential data for determining areas most suitable for SAV and salt marsh restoration.

**Watershed and Land-Use/Land-Cover Characterizations**

Human settlement and population growth in the coastal zone have significantly altered the landscape of estuarine watersheds via habitat destruction and fragmentation. Land-cover and land-use changes resulting from watershed development (e.g., urbanized centers, farms, and industrial complexes) have contributed to declining quality of estuaries nationwide due to increased surface-water runoff, accelerated loading of nutrients and sediments, freshwater diversions, and other factors (Kennish, 2002). The dramatic rise in impervious land cover has been especially problematic because impervious surfaces greatly facilitate non-point source pollutant transport to receiving estuarine waters. Buildout analyses and inventories of watershed habitats have been useful in identifying land-use practices most detrimental to the landscape and adjoining aquatic environments.

Various remote-sensing applications and land-cover mapping methods (e.g., aerial photography, satellite imagery, high-resolution digital land-use data, and historical maps) are effective tools for assessing long-term trends of habitat loss and alteration in coastal watersheds (Lathrop and Bognar, 2001). NOAA’s Coastal Change Analysis Program is an example of a well-organized coor-
An organized initiative that has successfully tracked the effects of human land-use activities by monitoring changes in coastal land cover at regular time intervals via satellite remote-sensing mapping and change-detection techniques (Dobson et al., 1995). A major goal of land-use/land-cover studies is to develop databases from multiple time periods to track habitat changes. Geographic Information Systems (GIS) can be applied in these studies to document even subtle changes in land use/land cover that may be attributed to either anthropogenic or natural factors. GIS applications are useful for inventorying and assessing the status and trends of coastal watersheds, as well as identifying land-use practices most damaging to watershed and estuarine habitats.

Benthic Habitat Mapping

Intertidal and subtidal habitat mapping is also a high-priority initiative of the NERRS program to define the type and extent of aquatic habitats at the reserve sites. Several methods are being used to characterize benthic habitats at NERRS sites, including the deployment of conventional grabs and cores, sediment-profile imaging systems, as well as autonomous and remotely operated vehicles (ROVs) fitted with acoustic-imaging devices. Bottom grabs and cores are perhaps the most cost-effective instruments for determining the sediment composition and distribution at spatially restricted SWMP sites. However, their use is labor intensive when collecting many samples over extensive areas; therefore, they may be of limited utility in characterizing sediment texture estuary-wide. However, these instruments are vital for conducting benthic community surveys in estuaries, which also constitute a high-priority initiative of the NERRS program.

Sediment profile imaging, employing a camera and video array that photographs the upper sediment layers and sediment-water interface of the estuarine floor, yields a wide range of data useful for classifying benthic habitats. In addition to providing information on sediment and habitat type (e.g., unvegetated bottom, seagrass and clam beds, and oyster bars), sediment profile imaging can be used to determine the bedforms, depositional and erosional regimes, and benthic communities of an area. Furthermore, natural and anthropogenic disturbance gradients may be delineated along the estuarine floor, which can be important when targeting sites for habitat restoration (Nieder et al., 2002; Rhoads and Germano, 1986).

Acoustic-imaging devices (e.g., side-scan and multibeam systems) fitted on autonomous ROVs as well as on towed fish are producing high-resolution images of the estuarine floor useful for documenting the bedforms and bottom habitats of reserve sites. For example, side-scan sonar imaging of Great Bay, New Jersey, using REMUS (Remote Environmental Monitoring Units), an autonomous, underwater vehicle (AUV), generated accurate data on the seabed morphology of this important water body of the Jacques Cousteau National Estuarine Research Reserve (see Kennish et al., 2004). Similarly, the deployment of ROVER (Remote Observation Vehicle Earth Resources), a ROV, in other systems has produced high-resolution images of seabed morphology in even shallower water areas. Both AUVs and ROVs can rapidly survey extensive stretches of estuarine floor and are capable of yielding comprehensive, coincident data sets across broad spatial scales. They thus offer a major advantage over traditional methods of benthic habitat mapping.

Other SWMP Initiatives

Habitat restoration and invasive species are two other high-priority initiatives of the NERRS program (NERRS, 2002c). Many reserve sites have initiated small- to medium-scale (0.2–180-ha) restoration projects on salt marsh, seagrass, riparian, and native habitats. These types of restoration projects are expected to increase in the NERRS program during the next decade.

Because of the serious threat of nonindigenous species invasions to biotic communities and habitats of US estuaries, the NERRS is advocating the formation of a nationally coordinated invasive-species-monitoring program (Wasson, 2002). The wide geographic distribution of the NERRS network of estuarine sites along the Atlantic, Gulf of Mexico, and Pacific coasts represents an excellent platform to conduct such a nationally significant monitoring program. Hundreds of invasive species have been identified in US estuaries. Their potential disruption of the endemic flora and fauna in these systems is a cause of concern for both scientists and resource managers. It is common for invasive species to outcompete native forms, often leading to reduced biodiversity and acute alteration of biotic community structure. Recreational and commercial fisheries may also be adversely af-
fected in the invaded estuaries. The serious problems caused by invasive species nationwide warrant the establishment of an active, well-coordinated monitoring program to detect and track species invasions in estuaries along all US coasts.

Aside from the aforementioned high-priority restoration and invasive-species efforts, the NERRS is also engaged in a number of lower priority initiatives. Two of these initiatives include chemical-contaminant monitoring and global sea-level rise. Chemical-contaminant impacts are most evident in urban industrialized estuaries, particularly among benthic communities and habitats located in hot-spot areas (Kennis, 1997, 2001). One of the goals of the NERRS is to establish a long-term contaminant-monitoring program whereby surficial bottom sediments will be sampled for contaminant loadings at 2–4 sites in each reserve (Kennis, 2003). Sampling at these sites will be conducted once every 5 years to provide status and trends of the contaminant loadings (NERRS, 2002a).

Eustatic sea level rise is of growing interest to the NERRS because of its link to global warming and the potential impact on estuarine beaches, fringing wetlands, and riparian habitats. One coastal monitoring effort being considered by the NERRS program is the assessment of sediment elevation change relative to sea-level rise. Sediment elevation data collected across reserve sites will be used to assess sea-level-induced habitat change on local, regional, and national scales.

**PLAN OF THIS VOLUME**

Since the initiation of the NERRS SWMP in 1994, comprehensive research and monitoring databases have been developed at the local reserve sites. This volume focuses on case studies of research and monitoring initiatives conducted at selected NERRS sites during the past decade, although significant physical, chemical, and biological data collected at reserve sites prior to 1994 are also considered. Broader treatments, which synthesize the SWMP water-quality databases across the majority of reserves, are likewise included.

The 15 papers that follow cover a range of research and monitoring topics; together with this paper, they comprise Special Issue 45 of the Journal of Coastal Research. The initial contribution by Porter et al. (Data management in support of environmental monitoring, research, and coastal management) examines the data and information management strategy of the NERRS SWMP. The authors cite the importance of procedures to manage the infrastructure and data protocols that support and sustain the acquisition and exchange of data in the system. The effectiveness of data management in the NERRS SWMP is evidenced by (1) the capability of the program to assimilate and provide timely delivery of appropriate data and information products to targeted end users, (2) the assurance that the data are documented appropriately, and (3) the verification that end users have ready access to high-quality data.

Wenner et al. (Variability in dissolved oxygen and other water-quality variables within the National Estuarine Research Reserve System) demonstrate the utility of the NERRS SWMP, analyzing water-quality data collected at 55 sites in 22 reserves over the 1995–2000 time frame. Seasonal and interannual trends for specific water-quality variables are characterized among the NERRS sites and regions. The significance of the SWMP, as evidenced by this work, is the long-term water-quality and ecological databases being developed, which differ from other existing national water-quality monitoring programs that typically provide shorter term or periodic data ranging in duration from days to weeks.

While the work of Wenner et al. deals with analysis of the NERRS system-wide water-quality data, that of Ward (Variations in physical properties and water quality in the Wachapreague estuary) focuses on water-quality parameters from the North Inlet-Winyah Bay National Estuarine Research Reserve, South Carolina. Edwards et al. (Nonparametric harmonic analysis of estuarine water-quality data: a National Estuarine Research Reserve case study), and Phlips et al. (A comparison of water quality and hydrodynamic characteristics of the Guana Tolomato Matanzas National Estuarine Research Reserve and the Indian River Lagoon of Florida) concentrate on water-quality analysis at specific NERRS sites. Ward delineates the temporal and spatial patterns of water-quality characteristics at the Wells National Estuarine Research Reserve in Maine. Buzzelli et al. investigate water-quality conditions at the North Inlet-Winyah Bay National Estuarine Research Reserve in South Carolina. Edwards et al. employ a new analytic method, nonparametric harmonic analysis, to assess water-quality data from the Sapelo Island National Estuarine Research Reserve in

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Georgia. Philips et al. document the temporal and spatial variability of physical and chemical water-quality data from the Guana Tolomato Matanzas National Estuarine Research Reserve and other Florida lagoonal systems.

Apple et al. (The effects of system-level nutrient enrichment on bacterioplankton production in a tidally-influenced estuary) detail the response of bacterioplankton in Monie Bay, Maryland, to system-level nutrient influx associated with agriculturally derived nutrient inputs and other nutrient sources. Monie Bay is a subsystem of the Chesapeake Bay and a component of the Chesapeake Bay (Maryland) National Estuarine Research Reserve. Agriculturally derived nutrients comprise a large fraction of the total nutrient inputs to the bay. Elevated rates of bacterioplankton production in the system are positively correlated with pulsed nutrient availability associated with agricultural activity in watershed areas.

In a study of experimental plots of Spartina patens on Prudence Island, Narragansett Bay National Estuarine Research Reserve, Rhode Island, Wigand et al. (Response of Spartina patens to dissolved inorganic nutrient additions in the field) compile records of demographic changes and other plant responses to enrichment of inorganic nitrogen and phosphorus. They compare the photosynthetic rates, above- and belowground biomass, shoot density and length, as well as tissue nutrient concentrations of plants in nutrient-treated plots and controls. In addition, endomycorrhizal colonization of S. patens roots is measured among treatments. Analysis of the responses of S. patens to inorganic nitrogen and phosphorus additions indicates that nutrient inputs from anthropogenic activities can have a significant effect on plant performance in salt marsh habitats.

Moore (Influence of seagrasses on water quality in shallow regions of the lower Chesapeake Bay) evaluates the effect of seagrasses (Zostera marina and Ruppia maritima) on water quality in shoal regions of the Chesapeake Bay (Virginia) National Estuarine Research Reserve. Emphasis is placed on the relationship between seagrass bed development and water-quality changes in the lower reaches of the York River. Seasonal variations in the influence of seagrass beds on water quality are conspicuous in the lower estuary. The longevity of seagrass beds here appears to be contingent on the capacity of the beds to improve water-quality conditions (i.e., nutrients and turbidity). High levels of turbidity, in particular, are detrimental to seagrasses in this region, and thus the reduction of turbidity levels by seagrass growth may be a key factor to the long-term viability of the beds.

Nieder et al. (Distribution and abundance of submerged aquatic vegetation and Trapa natans in the Hudson River estuary) report on the abundance, biomass, and species composition of SAV in the Hudson River from Hastings-on-Hudson north to Troy, New York. In addition, data are recorded on the occurrence and distribution of the Eurasian water chestnut (Trapa natans) in the survey area. This nonindigenous plant has shaded out SAV in some areas of the Hudson and other systems.

Bull kelp (Nereocystis luetkeana) forms important habitat in areas of Kachemak Bay, Alaska. It also supports a complex food web there. Schoch and Chenelot (The role of estuarine hydrodynamics in the distribution of kelp forests in Kachemak Bay, Alaska) discuss a 3-year (2000–2002) mapping project on bull kelp in the estuary using low-altitude aerial photography. Results of this mapping effort show that N. luetkeana is essentially confined to the outer basin of the estuary. Spatial distribution of kelp forests in the system appears to be significantly influenced by cyclonic surface circulation in the outer basin. Most notably, the restricted distribution pattern may reflect the effect of a seasonally occurring baroclinic jet that prevents broader dispersal of Nereocystis spores.

Shirley et al. (Relative abundance of stenohaline and euryhaline oyster reef crab populations as a tool for managing freshwater inflow to estuaries) propose a novel approach—the relative abundance of stenohaline (Petrolisthes armatus) to euryhaline (Eurypanopeus depressus) crab populations in estuaries of the Rookery Bay National Estuarine Research Reserve—to generate ecological performance measures to guide freshwater restoration projects as part of the Everglades Restoration Initiative. Altered quantity, quality, and timing of freshwater inflow to estuarine waters of the reserve due to the channelization of wetland sheetflow and other anthropogenic watershed modifications can significantly shift the salinity structure in the estuaries. The changing freshwater inflow and salinities may be causing substantial disruption of biotic communities by modulating species composition, primary productivity, floral and faunal biomass, and nekton abundance. Abundance ratios of stenohaline to euryhaline crab populations, therefore, appear to be an important indicator of the altered environmental conditions in the system.
Kennish et al. (Benthic macrofaunal community structure along a well-defined salinity gradient in the Mullica River-Great Bay estuary) describe the structure of estuarine benthic invertebrate assemblages in the Mullica River-Great Bay estuary, which is part of the Jacques Cousteau National Estuarine Research Reserve. Four distinct assemblages of benthic invertebrates occur along the salinity gradient of the estuary, notably river-, bay-, lower bay-, and estuary-wide forms. Of these assemblages, the estuary-wide forms consist of the most abundant species with the widest salinity tolerances. While salinity and other environmental gradients from upriver to down-bay regions play a key role in controlling the regional distribution of benthic populations in the estuary, sediment composition (especially the percentage of silt-clay) is a major factor regulating the local distribution of the organisms. The highest population abundances and species richness values are reported for the central bay region.

A complexity of seabed features serves as potential habitat for benthic organisms in the Mullica River-Great Bay estuary. Kennish et al. (Side-scan sonar imaging of subtidal benthic habitats in the Mullica River-Great Bay estuarine system) identify a variety of small-, medium-, and large-scale bedforms in side-scan sonar records of the Great Bay floor. Numerous constructive transverse bedforms (i.e., sand waves, dunes, and ripples) generated in the eastern bay by advancing tidal currents create substantial seabed roughness and protective habitat for various benthic invertebrate and demersal finfish populations. These bedforms may significantly influence the structure of benthic communities in the estuary.

The aforementioned articles provide case studies of research and monitoring projects conducted at NERRS program sites. Additional information on research and monitoring initiatives of the NERRS program is available at the 26 reserve sites. Extensive environmental databases can be obtained by accessing the web sites of these reserves. The reader is also advised to access the web site of the NOAA NERRS in Silver Spring, Maryland, for other details on the research and monitoring elements of the NERRS program.

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