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Chapter

Lessons Learned from 30 Years of Assessing U.S. Coastal Water

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Abstract

The 1972 Clean Water Act (CWA) established goals and regulations regarding water quality in the U.S. water resources, including coastal waters. The U.S. Environmental Protection Agency (EPA) was charged with implementing the CWA's goals and with helping states, and tribes meet their mandate to periodically monitor and assess water quality in their jurisdictions. In response, the EPA initiated the Environmental Monitoring and Assessment Program (EMAP) to develop and test effective methods of assessing water quality in lakes, rivers and streams, and estuaries at state and national scales. EMAP-Estuaries commenced in 1990, devising sampling designs and protocols for estuaries, testing potential indicators, establishing assessment, and reporting methods. Estuarine research and development efforts continued in a series of subsequent programs, each adapting and adopting the best practices of earlier programs, each becoming more national in scale, and each integrating state and tribal participation to a greater degree. Recent surveys have included an assessment of coastal Great Lakes waters. This chapter recounts the history of assessments in coastal waters, emphasizing the current approach while highlighting examples of lessons learned over the 30-year development period leading to the National Coastal Condition Assessment.

Keywords: coastal assessment, EMAP, NCA, NCCA, NARS, indicators

1. Introduction

The 1960s were a decade of growing awareness and concern regarding the declining quality of the surface waters of the U.S., most dramatically exemplified when the Cuyahoga River, Ohio caught fire in the summer of 1969. In response, the U.S. Congress passed the Clean Water Act (CWA) in 1972 [1], establishing goals and regulations governing the restoration and maintenance of the nation's water resources, including coastal regions. The CWA also specifically addressed the need for monitoring water quality. Section 305b of the CWA required states and tribes to survey and periodically report on the overall condition of their surface waters, including coastal waters. In addition to the state programs, numerous other water quality monitoring and research programs were initiated in major estuarine systems, such as Chesapeake Bay, Narragansett Bay, Tampa Bay, and Puget Sound.

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However, for the first two decades of the Act, reviewers consistently highlighted the fact that the approaches used by the states and tribes to monitor conditions were not nationally consistent and the information they reported could not be consolidated into a single assessment of the Nation's waters [2–7]. Despite substantial expenditures, regulators were unable to judge the effectiveness of pollution-control legislation [8]. In response to these limitations, the EPA initiated the Environmental Monitoring and Assessment Program (EMAP), a research effort that spanned 17 years. These EMAP efforts would eventually evolve into what is now known as EPA's National Aquatic Resource Surveys (NARS) which continues to optimize approaches to conducting large-scale water quality assessments in lake, river, stream, estuarine and wetland resources across the U.S. This chapter focuses on the estuarine components of the EMAP and NARS assessments. An overview of EPA's efforts to assess coastal waters is presented in **Figure 1**. The timeline can be divided into three phases.

Beginning in 1990 and continuing for a decade, a series of regional assessments were executed in the major U.S. coastal ecological provinces. These EMAP-Estuaries programs explored innovative methods of conducting coastal assessments and established several of the defining features of EPA's assessment approach. For instance, EMAP planners adopted probabilistically-derived survey designs that minimized sampling bias, and designated sites that were appropriately weighted to estimate—with confidence intervals—the percentage of a region in good, fair, or poor condition. The early programs also developed a common core of indicators that could be used regionally or nationally to characterize conditions in key components of estuarine ecosystems—the water column, sediment, and benthic and fish communities. The lessons of these efforts were reported in many technical statistical summaries and summary reports, e.g., [9–14], but relatively few of the accounts were prepared with the public reader in mind. This research and developmental phase was led by EPA's Office of Research and Development (ORD) in partnership

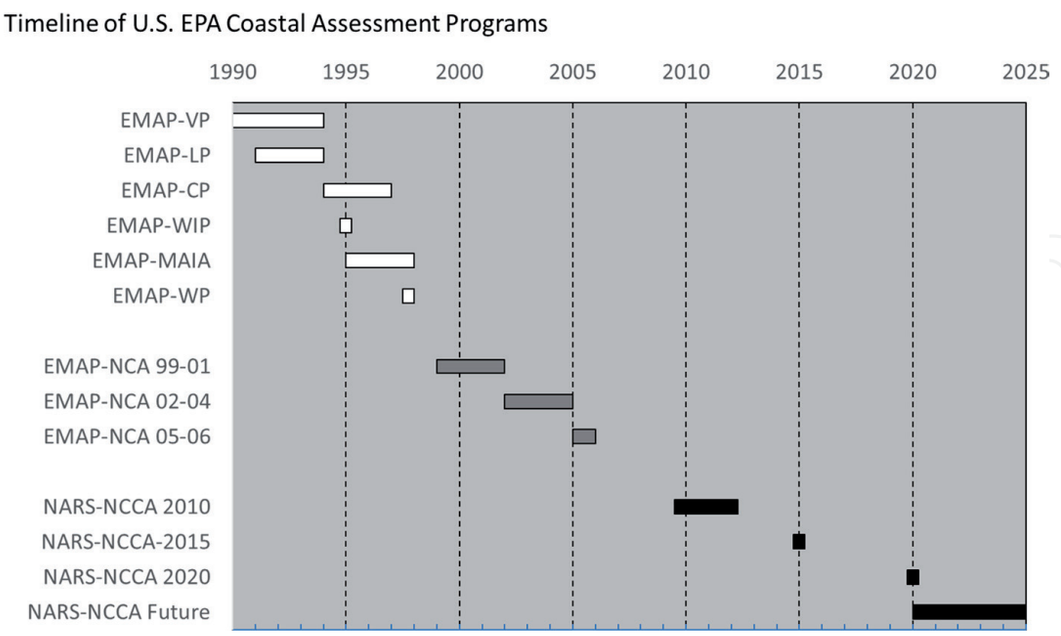


Figure 1.
EPA coastal assessment programs—Development and implementation phases. EMAP, Environmental Mapping and Assessment Program; Regional development: VP, Virginian Province (U.S. NE Atlantic coast); LP, Louisianian Province (Gulf of Mexico coast); CP, Carolinian Province (U.S. SE Atlantic coast); WIP, West Indian Province (South Florida coast); MAIA, Mid-Atlantic Integrated Assessment (Chesapeake, Delaware & Albemarle-Pamlico bays); WP, Western pilot (U.S. Pacific coast); NCA, National Coastal Assessment; Nationwide development phase NCCA, National Coastal Condition Assessment; Nationwide implementation phase.

with other federal agencies, especially the National Oceanic and Atmospheric Agency (NOAA) and U.S. Fish and Wildlife Service (FWS), and with some participation of state environmental agencies and academic institutions.

In the second phase, the EMAP-Estuaries program expanded nationally into the National Coastal Assessment, NCA 1999–2006. The NCA was also an EMAP research program, with primary goals of adopting and refining the best techniques developed in the regional studies and applying them to conduct coastal assessments at both national and regional scales [15]. The NCA evaluations continued the approach of assessing four key aspects of estuarine ecosystems, i.e., water quality, sediment quality, and the ecological condition of benthic and fish communities. Of equal importance, the NCA worked to more fully engage the states and tribes in the assessment process; thereby facilitating compliance with Section 305b of the Clean Water Act. As information accrued, the NCA also experimented with ways of analyzing and reporting how coastal conditions changed over time. Four National Coastal Condition Reports (NCCR I–IV) resulted from these efforts [16–19]. Particular attention was paid to explaining the assessment process and results to the general public.

After 16 years of research, development, and stakeholder feedback, the coastal monitoring approach was deemed ready for routine deployment, and responsibility for implementation was passed from EPA's ORD to EPA's Office of Water (OW). Now renamed as the National Coastal Condition Assessment (NCCA), surveys were executed in 2010 and 2015, and plans are underway to conduct assessments in 2020 and beyond. Beginning with the 2010 survey, the coastal waters of the Great Lakes were included as part of the NCCA program despite the substantial differences in the freshwater and estuarine realms [20]. The NCCA, together with the National Lakes Assessment (NLA), the National Rivers and Streams Assessment (NRSA), and the National Wetlands Condition Assessment (NWCA), form the EPA National Aquatic Resources Surveys (NARS) program [21]. The goals of NARS are (i) to conduct routine surveys of all surface-water resources of the U.S. on a regular schedule; (ii) issue reports on assessments of each resource; and (iii) establish a joint database useful for conducting assessments and modeling investigations concerning all components of the surface-water systems.

In short, the EPA and its partners have devised an ambitious and unique approach of conducting multi-scale ecological assessments of the nation's coastal waters. NCCA and NARS reflect the results of concerted research and a pragmatic willingness to modify techniques and protocols based on lessons learned. Although logistically challenging, incorporating states and tribes in all aspects of the surveys has proved to be a clear success, both by enhancing the assessments and, more importantly, by helping build capacity of the states and tribes to conduct surveys on their own. Finally, the programs provide useful metrics by which environmental managers and legislators could judge the effectiveness of implemented policies. The remainder of this chapter further describes EPA's approach to assessing coastal waters, focusing primarily on the methods employed in the recent NCCA 2010 and 2015 surveys, which are the most thoroughly documented programs. Significant differences from earlier or later surveys are highlighted to emphasize how evolution shaped EPA's assessment process. Furthermore, where assessment approaches are similar in estuaries and the Great Lakes, we focus on the estuarine methodology in deference to brevity. Full documentation, data, and reports concerning both estuarine and Great Lakes assessments are available at [22]. The intended audiences for this chapter are knowledgeable scientists and environmental managers interested in reviewing the unique coastal assessment methods developed over 30 years of experimentation.

2. Key features of EPA's coastal assessments

During the summer of 2010, nearly 50 field crews visited 1104 pre-selected sampling stations in U.S. estuaries and Great Lakes coastal waters. Onsite, the crews collected environmental data and sampled the water column, sediments, and benthic and fish communities. Preserved samples were shipped to a dozen or so laboratories for analysis, and laboratory and field data were ultimately compiled into databases for analysis and reporting. In the following sub-sections, we outline the NCCA procedures used to select sampling stations, collect samples and information onsite, and assess and report ecological conditions at various scales. Further details regarding the implementation and evolution of assessment methods are described in Section 3.

2.1 Selecting sites

The NCCA employed a rigorous design process to meet several key assessment goals. First, the coastal waters to be assessed—the *target population*—was precisely specified. The target population was carefully defined as: (i) all estuarine waters in the conterminous U.S. from the "head-of-salt" (landward extent of waters with salinity greater than 0.5 ppm) to the boundary with the open ocean and (ii) Great Lakes of the U.S nearshore coastal waters located within 5 km of shore and less than 30 m in depth. EMAP included some inland river sections, river mouths, tidal streams and ponds, and sections of the continental shelf. However, NCCA excluded such waters as tidal streams and deep central channels of major rivers and bays, non-estuarine shorelines to better accommodate state needs. A GIS file specifying the areal coverage of the study regions—the *sample frame*—was compiled for subsequent use in selecting sampling sites. The sample frame for the 2010 NCCA comprised an area of 91,700 sq. km of coastal marine and fresh water.

Next, sampling sites were selected using a probabilistic, stratified survey design. That is, the target region was divided into *strata*—multiple nested assessment units that fairly represented the nation and various subregions designated for evaluation [23]. The largest domains were the five reporting regions: (1) The Atlantic coast of the northeastern U.S. from Maine through Virginia (including Chesapeake Bay); (2) the Atlantic coast of the southeastern U.S. from North Carolina through Biscayne Bay in south Florida; (3) the Gulf of Mexico coast of the U.S. from Biscayne Bay through Texas; (4) the Pacific coast of the western U.S. from Washington through California; and (5) the U.S. coasts of the Great Lakes. These strata were subdivided to delineate the coastal waters of the 21 ocean states and the five Great Lakes, and some larger units were in turn further subdivided to highlight important water bodies or regions designated for special study. The 2010 NCCA sampling design recognized a total of 64 distinct strata, which could be combined as needed for analysis or reporting at multiple spatial scales. Survey planners specified the number of sites allotted to each stratum based on cost effectiveness and survey priorities. The five primary reporting regions and the distribution of sampling sites in the 2010 NCCA survey are shown in **Figure 2**.

Sample sites were then selected probabilistically, but not randomly, using a process termed the Generalized Random Tessellation Survey (GRTS) design [23]. The GRTS method employs an intricate algorithm that ensures uniform and unbiased station placement, thereby minimizing clumping that may result if sites were selected using a purely randomized approach. A weighting factor, called the *inclusion probability*, was provided for each site. The factor was calculated as the stratum area divided by the number of sites in the stratum and was used during the analysis stage to estimate regional condition (see Section 2.3).

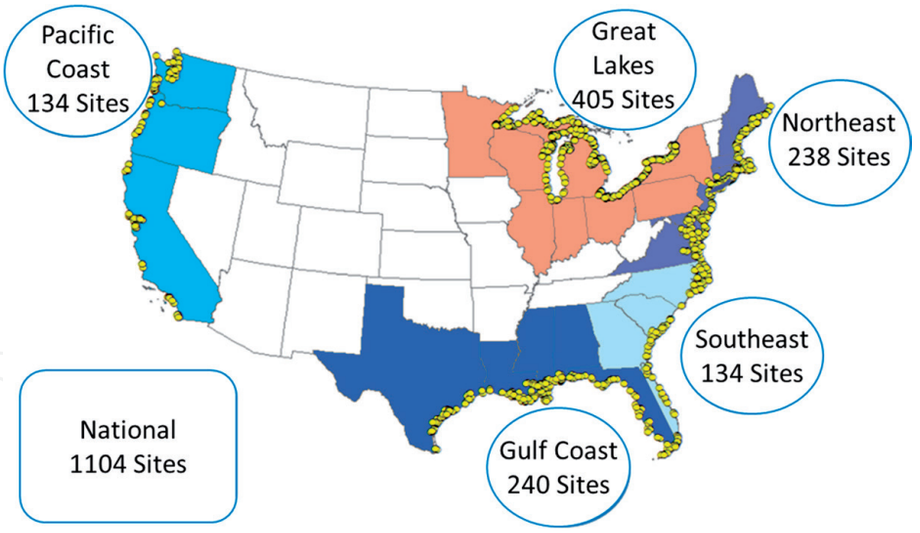


Figure 2.
Location of the 1104 sites sampled in the 2010 NCCA survey, by reporting region.

Finally, the survey design procedure identified both "base" and "oversample" locations. Sampling was mandatory at the base sites, and oversample sites were designated as replacements for inaccessible base sites or to be used by states in other regional assessments or enhancements. At least 50 base sites were allocated to each of the five reporting regions and to strata receiving an enhanced assessment. A sample size of 50 sites was considered adequate to yield results with reasonable statistical confidence [23]. Ten percent of the base sites were designated as "revisit sites", to be sampled twice during the same summer period in order to estimate intra-site variability. Additionally, 25% of sites were identified as "return sites"—stations to be repeatedly reassessed over the course of four subsequent NCCA surveys. These return sites increase the ability to quantify temporal variance and to aid in detecting change over time [24]. Further details of the entire NCCA site selection process is available in a non-technical overview of monitoring design topics provided online [25].

2.2 Implementing coastal surveys

The 2010 NCCA survey was a highly orchestrated campaign mounted to assess the nation's coastal waters. Implementation included training field crews, documenting sampling and analysis methods, collecting information and physical samples onsite, coordinating sample analysis, building databases, and performing quality assurance (QA) reviews.

Nearly 50 field crews composed of state, tribal, EPA personnel, and contractor staff, were deployed to collect samples and information during a summer *index sampling period*—June through September. Prior to the field season, the crews were rigorously trained by EPA trainers regarding NCCA protocols stipulated in the Site Evaluation Manual, Field Operations Manual, and Quality Assurance Project Plan [22]. During time on station, field crews would (i) record field conditions, including Secchi depth, vertical profiles of temperature, salinity, pH, dissolved oxygen, and photosynthetically active radiation (PAR) intensity; (ii) collect surface water samples for lab analysis of nutrients, chlorophyll, and human health indicators; (iii) collect grab sediment samples for analysis of contaminant concentrations, grain size, toxicity, and total organic carbon; (iv) collect and preserve separate sediment samples for characterization of the benthic macroinvertebrate community; and (v) collect fin-fish from within a proscribed distance from the site to characterize the local fish community and provide tissue for analysis of lipid and contaminant content (**Table 1**).

National Coastal Condition Assessment Indicators	
Physical habitat parameters	**Ecological contaminants in sediments and fish tissue**[a]
Physical habitat parameters Temperature (°C) Salinity (ppt) Dissolved oxygen—DO (mg/L) pH Secchi depth (m) Total organic carbon—TOC (%) % Silt/clay (grainsize) **Water-quality parameters** Chlorophyll *a* (μg/L) Ammonium (mg N/L) Nitrate plus nitrite (mg N/L) Nitrite (mg N/L) Dissolved inorganic nitrogen—DIN (mg N/L) Total nitrogen—TN (mg N/L) Dissolved inorganic phosphate—DIP (mg P/L) Total phosphorus—TP (mg P/L) **Sediment toxicity** Amphipod survival bioassay Estuarine test organisms: *Leptocheirus plumulosus* *Eohaustorius estuarius* Great Lakes test organism: *Hyalella azteca*	**Metals (μg/g)**: Ag, Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, Sn, Tl, Zn **PAHs (ng/g)**: acenaphthene, acenaphthylene, anthracene, benz(a) anthracene, benz(a,e)pyrene, benzo(b,k,b+k)flouranthene, benzo(g,h,i)perylene, biphenyl, chrysene, dibenz(a,h) anthracene, fluoranthene, fluorene, indeo(1,2,3-c,d)pyrene, naphthalene, 1-methylnaphthalene, 2-methyl naphthalene, 2,6-dimethylnaphthalene, 2,3,5-trimethylnaphthalene, perylene, phenanthrene, 1-methylphenanthrene, pyrene, total PAHs **PCB congeners (ng/g)**: 8, 18, 28, 29, 44, 52, 66, 87, 101, 105, 118, 128, 138, 153, 170, 180, 187, 195, 201, 206, 209, total PCBs **Pesticides (ng/g)**: aldrin, chlordane (alpha-, gamma-, oxy-), dieldrin, dibenzothiophene, DDD (2,4'; 4,4'), DDE (2,4'; 4,4'), DDT (2,4'; 4,4'), endosulfan I & II, endrin, heptachlor, heptachlor epoxide, hexachlorobenzene, hexachlorohexane (alpha-, beta-, delta-), lindane, mirex, trans-nonachlor
Biotic conditions Diversity and abundance of benthic macroinvertebrates Diversity and abundance of fish	
Human health indicators	
Mercury in fish plugs; algal toxins (microcystin and cylindrospermopsin) and enterococcus in water	
PCBs, PBDEs and PFCs in fish tissue (Great Lakes only)	

[a] *National Oceanic and Atmospheric Administration National Status and Trends Program analytes. Concentrations reported as dry weight of sediments and wet weight of tissue.*

Table 1.
Indicators measured in the National Coastal Condition Assessment (NCCA) surveys.

The field data were submitted as either physical or electronic data sheets to NCCA headquarters for compilation. Preserved water, sediment, and fish samples were shipped to approve national or state laboratories for analysis and results were submitted to NCCA headquarters. Each site generated hundreds of field and laboratory data values that were organized into files by type (e.g., field data, water quality data, benthic census data, etc.), and maintained as "raw files" in a centralized database by information management specialists. The raw files were then subjected to a stringent two-phase QA review process, first checking for basic compliance with submission requirements (e.g., proper units, range checks, and conformity with standard taxonomic terminology). Any revisions to the raw files were carefully documented, and finalized files were made available at the NCCA public website [26].

One of the hallmarks of the NCCA, and the NCA which preceded it, has been the emphasis on the cooperation and participation of the states and tribes in planning and conducting the assessment within their respective jurisdictions. Not only are states and tribes key to survey implementation, they are the entities responsible

under the Clean Water Act (CWA), Section 305b, to report to Congress regarding the extent to which the nation's waters support the CWA goals. From the research and development phase to the current operational program, numerous workshops and training sessions have been held to build technical expertise regarding monitoring design, sampling, data analysis, and interpretation of results. Through this technical transfer, numerous organizations have modified their local monitoring efforts to incorporate NCCA methods and approaches to assessing the condition of coastal resources. State and tribal partners have been active participants in the ongoing assessments of the performance of current indicators, and in the selection and testing of developmental indicators needed to respond to emerging environmental issues.

2.3 Assessing status and trends

Following the lead of earlier EPA coastal surveys, the NCCA approach had two primary goals regarding assessment: (1) evaluate the *status* of four major components of coastal ecosystems—the water column, sediment, and benthic and fish communities, and (2) ascertain how conditions *change over time (i.e., trends)*. For each of the key assessment components, conditions were evaluated based on a suite of core indicators and indices constructed from them. For instance, water quality was assessed using five measured indicators (concentrations of nutrients, chlorophyll, and dissolved oxygen, and water clarity) and a water quality index was then crafted from the five components. The assessment process first evaluated conditions at each site, rating each indicator and index as good, fair, or poor based on regionally determined assessment thresholds. Details regarding the indicators, indices, and thresholds used in assessments are presented in Section 3 of this chapter.

Once sites were evaluated, regional and national conditions were calculated. Recall that the survey design process had assigned each site a weighting factor equal to the area represented by the station. Regional assessments were then expressed as the percent of the region in good, fair, poor, or unassessed condition. For instance, the percent area of the Pacific coast in good condition was simply calculated as the sum of weighting factors associated with Pacific sites rated as good, divided by the total area of the Pacific coastal region (sum of all Pacific site weights). Assessments were calculated for the nation, for the five primary reporting regions (**Figure 2**), and for any state or designated research area containing a statistically-sufficient number of sites.

The survey design procedure further provided a measure of the uncertainty in the condition estimates, expressed as the 95th percentile confidence interval (CI), which was calculated as the binomial proportion confidence interval adjusted for possible spatial gradients in indicator measurements [23, 27]. Operationally, the confidence intervals were calculated using a complex computer-intensive algorithm, coded in the R-programing language, available at EPA's Aquatic Resource Monitoring website [25].

As the number of surveys conducted increases, the NCCA documents change over time. Typically, trends have been evaluated by analyzing what happens at an individual location, much as a physician monitors trends in the weight of an individual patient. In contrast, trends for NCCA were evaluated at the population level, i.e., trends in the proportion of sites in good condition. These population level trends were evaluated by noting statistically significant changes, i.e., condition estimates displaying non-overlapping CIs, determined over a series of comparable surveys. Since the early 1990s, coastal survey methods have evolved significantly over time. In some cases, new analyses can be applied to old data. In other cases, methodological differences have precluded trend analyses over the entire 30-year period. Eventually, trends in national assessments will reflect only NCCA surveys conducted from 2010 onward.

2.4 Communicating results

The approaches used to communicate survey results in summary reports reflect how the coastal survey approach evolved and innovated. Early regional EMAP surveys were essentially data reports prepared for a technical audience of monitoring practitioners. These terse reports emphasized methodology and reported results in tables, weighted-CDF plots, and bar plots e.g., [11]. While invaluable to technical staff and managers, these statistical summary reports attracted little public attention. In contrast, the national reports summarizing the EMAP-NCA surveys—the National Coastal Condition Reports NCCR I–IV [16–19]—were primarily prepared to be informative and understandable to the general public. These attractive and sizable documents were organized by region, featured highlights about local issues and showcased abundant photos and illustrations, as well as were available in hardcopy. In particular, NCCR-II and NCCR-III presented maps with site conditions portrayed by color-coded symbols. The NCCR reports' use of pie charts conveyed assessment results concisely and intuitively, but without adequate expression of uncertainty.

Beginning with the NARS-NCCA 2010, the reporting strategy changed substantially to accommodate the approach of conducting relatively standardized assessments on a regular schedule. The reports focused on delivering assessment results

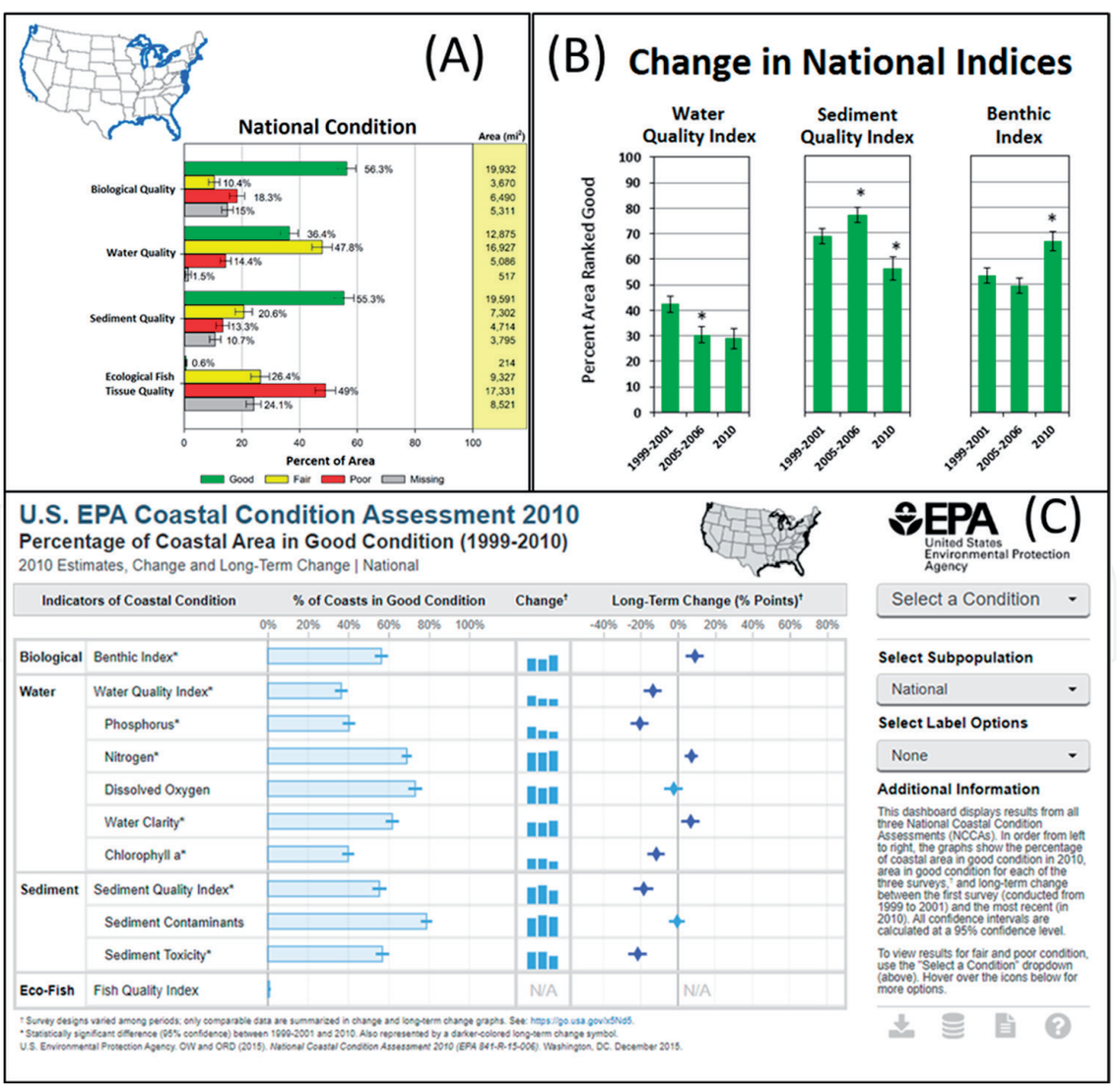


Figure 3.
Examples of coastal survey summary graphics from NCCA national reports highlighting national status in 2010 (A), trends 1999 to 2010 (B), and "dashboard" approach of reporting results (C).

concisely and quickly, primarily tailored for a technical audience of environmental managers. The reports are only accessible online and include fewer highlight-sections or explanatory graphics but continue to present material intuitively for public viewing. Graphics prominently display estimates of uncertainty and express change over time (**Figure 3**). The online 2015 NCCA report (in preparation) notably features an interactive "dashboard" graphic that allows the viewer to select the results in summary form as well as to access the data associated with the display. Importantly, the coastal reporting format is evolving in concert with the reporting approaches of other NARS surveys, thereby facilitating cross-resource assessment and modeling efforts.

3. NCCA method highlights

In this section we take a closer look at the methods used to assess the major components of coastal ecosystems—the water column, sediment, and benthic and fish communities. One issue was recognized early in the NCA program when national-scale surveys were undertaken—the U.S. coastal regions are extraordinarily diverse. The northeastern states reflect relatively late deglaciation, featuring minimal run-off from small watersheds into well-mixed coastal waters. Large drowned-river estuaries dominate the mid-Atlantic states, where environmental conditions are heavily influenced by the densely populated coastal communities. Estuaries along the southeastern states and the Gulf of Mexico reflect interaction with large, flat watersheds; these regions are subject to distinct sub-tropical biophysical processes. In contrast, there are far fewer estuaries along the Pacific coast because of the absence of a coastal plain, and coastal processes there are uniquely affected by strong ocean currents and upwelling of cold, nutrient-rich water. How should surveys account for such diversity and differentiate natural from anthropogenic sources and responses?

In response to these challenges, survey planners initially relied on the advice of regional estuarine experts convened to suggest assessment indicators and provide benchmark values used to distinguish good, fair, and poor conditions. In reports we emphasized that these cut-points were appropriate for the surveys only, and generally distinct from regulatory thresholds. For each component assessment, several indicators of condition were evaluated separately and then combined into an overall index. In some cases, as is described below, the initial suite of indicators, indices, and benchmark values were modified and refined based on lessons learned. For instance, local benthic indices were replaced with a single index applicable nationwide; the fish community index was refashioned to better reflect ecological rather than human health conditions; and several human-health indicators were introduced. In the following sections, we describe the indicators and thresholds currently specifically employed in the NCCA surveys while highlight lessons learned from 30 years of experimenting and refining techniques.

3.1 Assessing water quality

The water column is a notoriously dynamic environment. Physical and biological process interact to create rapid and highly localized interactions of light, nutrients, algal growth and predation, and a host of quickly changing abiotic factors. Despite these challenges, deepening concerns regarding cultural eutrophication in coastal waters motivated survey planners to devise a strategy for assessing coastal water quality. Cultural eutrophication is the detrimental degradation of water quality often associated with nutrient over-enrichment [28, 29]. The NCCA assessment

approach consisted of employing indicators that measure eutrophication-related symptoms and problems such as nutrient over-enrichment, excessive algal blooms, hypoxia or anoxia, low water transparency, etc. To moderate the inherent variability of such measures, the indicators were then combined into an index that is less dynamic than the individual components.

Table 2 lists the five core indicators and thresholds used in recent NCCA surveys to assess water quality in estuaries and the Great Lakes. Nutrient and chlorophyll concentrations were measured in surface water, dissolved oxygen levels were determined in bottom water, and water clarity was established at each site. These measures were then combined into a water quality index (WQI) that captured conditions likely to be indicative of problematic eutrophication regardless of when in summer sampling occurred [17]. For instance, the WQI might record excessive dissolved nutrients in early season, excessive algal production and poor water clarity in mid-season or hypoxic, turbid conditions in late season. Essentially, the WQI reflects a "preponderance of evidence"; the index is a more robust indicator of problematic eutrophication symptoms than the core indicators.

Thresholds generally varied by region. For instance, less stringent nutrient thresholds were specified for the West coast region, which experiences natural upwelling in summer [30], and more conservative guidelines were applied when assessing the tropical waters of southern Florida to protect submerged aquatic vegetation (SAV) beds. Assessment methods differed slightly when evaluating nutrients and water clarity in estuaries and the Great Lakes, recognizing the distinct ecologies and assessment histories in these environments. See details of the coastal water quality approach at pp. 11–15 of reference [19].

The NCCA approach of assessing nutrient status in estuaries continues to evolve. Early surveys measured nutrients as dissolved inorganic nitrogen and phosphorus (DIN and DIP). While DIN and DIP concentrations are valid indicators of nutrient enrichment status, they are unreliable measures of nutrient availability later in the season because they are generally assimilated into algal biomass in spring and early summer [19]. This is particularly problematic for NCCA surveys, which sample throughout the summer index period. In contrast, total nitrogen and phosphorus (TN and TP) are less variable and are related to chlorophyll concentrations [31]. Consequently, TN and TP were added as core indicators beginning in 2010 and were used to evaluate nutrient status in subsequent NCCA surveys. Since regional TN and TP thresholds have not yet been established, TN and TP were treated as exploratory indicators, rated as low, moderate, high, and very high based on the 25th, 50th, and 75th quartile values of the measured 2010 TN and TP values. The water quality index (WQI) continued to be calculated with DIN and DIP as described in **Table 2**, reflecting the key role of dissolved nutrients in eutrophication processes [17, 31].

3.2 Assessing sediment quality

Contaminants from agricultural, industrial, and nonpoint sources find their way to coastal waters where they may adsorb onto suspended particles and settle to the sediment. There, metals and organic pollutants are ingested by benthic-dwelling organisms and may become concentrated throughout the food web and adversely affect fish, pelagic mammals, and human consumers of aquatic organisms. To monitor sediment contamination, all EPA coastal assessments since the 1990s followed the approach of NOAA's Status and Trends program [32] and collected sediment grab samples and measured a suite of 74 metal, PAH, PCB, and pesticide contaminants in surficial sediment samples (**Table 1**). The impacts of the pollutants on benthic organisms were evaluated against the effects-based sediment quality guidelines, ERL (effects range low) and ERM (effects range median) [33].

Water quality indicators	Estuary thresholds	Great Lakes thresholds
Nitrogen status DIN & TN in surface water DIN used to assess N status in estuaries prior to 2015; TN used thereafter. Water Quality Index (WQI) constructed with DIN in estuaries; with TN in the GL	*DIN Thresholds (mgN/L): Good/Fair, Fair/Poor* NE/SE/Gulf: 0.1, 0.5 West: 0.35, 0.5 Tropical: 0.05, 0.1 *2015 TN Interim Thresholds (mgN/L):* 25th, 50th, 75th percentiles of NCCA 2010 TN values	Nitrogen not assessed in the Great Lakes
Phosphorus status DIP & TP in surface water DIP used to assess P status in estuaries prior to 2015; TP used thereafter. Water Quality Index (WQI) constructed with DIP in estuaries; with TP in the GL	*DIP Thresholds (mgP/L): Good/Fair, Fair/Poor* NE/SE/Gulf: 0.01, 0.05 West: 0.07, 1.0 Tropical: 0.005, 0.01 *2015 TP Interim Thresholds (mgN/L):* 25th, 50th, 75th percentiles of NCCA 2010 TP values.	*TP Thresholds (mgP/L): Good/Fair, Fair/Poor*/Superior/Huron: 0.005, 0.01 Michigan: 0.007, 0.01 Saginaw/West Erie: 0.015, 0.032 Mid & East Erie/Ontario: 0.01, 0.015
Algal biomass Chlorophyll *a* in surface water	*Chla Thresholds (μg/L): Good/Fair, Fair/Poor* NE/SE/Gulf/West: 5.0, 20.0 Tropical: 0.5, 1.0	*Chla Thresholds (μg/L): Good/Fair, Fair/Poor*/Superior/Huron: 1.3, 2.6 Michigan: 1.8, 2.6 Saginaw/Erie West: 3.6, 6.0 Mid & East Erie/Ontario: 2.6, 3.6
Oxygen status Dissolved oxygen (DO) in bottom water	*DO Thresholds (mg/L): Good/Fair, Fair/Poor* All coastal regions: 5.0, 2.0	*DO Thresholds (mg/L): Good/Fair, Fair/Poor* All lakes and basins: 5.0, 2.0
Water clarity *Estuaries*: Rated by fraction of PAR transmitted through 1 m. Thresholds vary by turbidity category *Great Lakes*: Rated by Secchi depth	*Transmissivity* @ 1m(%)*: *Good/Fair, Fair/Poor* Naturally turbid waters: 10%, 5% Normally turbid waters: 20%, 10% SAV restoration priority: 40%, 20%	*Secchi Thresholds* (m): *Good/Fair, Fair/Poor*/Superior/Huron: 8.0, 5.3 Michigan: 6.7, 5.3 Saginaw/West Erie: 3.9, 2.1 Mid & East Erie/Ontario: 5.3, 3.9
Water Quality Index (WQI) Constructed based on the ratings of the measured component WQ metrics (five metrics in estuaries, including DIN & DIP; four metrics in the Great Lakes)	*Thresholds* **Good**: a maximum of one metric is rated as fair, and no metrics are rated as poor **Fair**: one metric is rated as poor, or two are rated as fair **Poor**: two or more metrics are rated as poor **Missing**: two metrics are missing, and available metrics do not suggest fair or poor ratings	*Thresholds* **Good**: a maximum of one metric is rated as fair, and no metrics are rated as poor **Fair**: one metric is rated as poor, or two are rated as fair **Poor**: two or more metrics are rated as poor **Missing**: two metrics are missing, and available metrics do not suggest fair or poor ratings

**Trans = exp(−Kd); where Kd is PAR extinction factor, calculated via regression of exponential attenuation of PAR intensity Iz/Io vs depth z, i.e., Beer's law: Iz/Io = exp(−Kd*z).*

Table 2.
Indicators and thresholds employed in the NCCA 2010 to assess water quality in estuaries and the Great Lakes.

ERL values are the concentration levels below which adverse bioeffects are unlikely, and ERM values signify the concentration above which adverse effects are likely. Sediments were also characterized by measuring grain size and total organic carbon (TOC) concentrations and were further tested for toxicity arising from either natural or anthropogenic sources by exposing amphipods to sediments in laboratory assays [34, 35].

Prior to the NCCA 2010, estuarine surveys evaluated sediment quality based on three core metrics: (1) sediment contaminants were evaluated as good, fair, or poor based on the number of ERL or ERM exceedances evident at a site; (2) toxicity was rated as good or poor if the survival rate of the amphipod *Ampelisca abdita* exceeded or was less than 80%, respectively; and (3) TOC was rated against concentration thresholds of 2 and 5%. A sediment quality index (SQI) was then calculated reflecting the ratings of the individual core components. Details are further explained in the National Coastal Condition Report IV [19].

Several modifications were introduced into NCCA surveys conducted in 2010 and later. Pollutant levels in estuaries were expressed as mean ERM quotients (mERMQ)—the ratio of a contaminant concentration to its ERM value, designated as mERMQ [36, 37]. Estuarine sediment contaminants were evaluated in a more nuanced manner, using the mERMQ and a logistic regression model approach [38] to better estimate the adverse effects of pollutants on benthic organisms. Estuarine sediment toxicity tests were primarily conducted using the amphipod species

Sediment quality indicators	Estuary thresholds	Great Lakes thresholds
Sediment contamination **Mean contaminant quotients**[a] For estuaries: calculate ERM-Q and mean ERM-Q (mERM-Q); For Great Lakes: calculate PEC-Q and mean PEC-Q (mPEC-Q). **Logistic regression model (LRM)**[b] For estuaries only: (1) calculate LRM factor for each of 36 analytes with fitting parameters; (2) select largest factor LRM_{max}; (3) calculate LRM P_{max}	**Good**: mERM-Q ≤ 0.1 & LRM P_{max} ≤ 0.05 **Fair**: mERM-Q > 0.1 & ≤ 0.5 or LRM P_{max} > 0.5 & ≤ 0.75 **Poor**: mERM-Q > 0.5 or LRM P_{max} > 0.5	**Good**: mPEC-Q ≤ 0.1 **Fair**: mPEC-Q > 0.1 and ≤ 0.6 **Poor**: mean PEC-Q > 0.6
Sediment toxicity % Survival of amphipods after 10-day exposure to site sediment, compared with survival in clean control sediment Amphipods tested for estuarine sediments: *Leptocheirus plumulosus* or *Eohaustorius estuarius*; for Great Lakes sediments: *Hyalella azteca*	**Good**: test results not significantly different from control (p > 0.05) and ≥ 80% control-corrected survival **Fair**: test results significantly different from control (p ≤ 0.05) and ≥ 80% control-corrected survival or Test not significantly different from control (p > 0.05) and < 80% control-corrected survival **Poor**: test results significantly different from control (p < 0.05) and <80% control-corrected survival	**Good**: control corrected survival ≥90% **Fair**: control corrected survival ≥75 and <90% **Poor**: ontrol corrected survival <75%
Sediment Quality Index (SQI) Constructed based on the ratings of sediment contaminant and sediment toxicity metrics The assessment criteria are the same for estuarine and Great Lakes sites	**Good**: both sediment contaminant and sediment toxicity metrics are rated good **Fair**: neither metric is rated poor and at least one metric is rated fair **Poor**: at least one metric is rated poor	**Same assessment criteria**

[a]*ERM-Q, conc/ERM for estuarine sites only, for 28 analytes with ERM values; PEC-Q, conc/PEC for Great Lakes only, for 9 analytes with PEC values (As, Cd, Cr, Cu, Pb, Ni, Zn, PAHs, PCBs); mean ERM-Q, ∑ERM-Q/n; mean PEC-Q = ∑PEC-Q/n; where n = number or analytes.*
[b]*LRM factor calculated as follows, for 36 analytes with fitting factors B_0 and B_1 (Field et al., 2002).*
*LRM P_{max} = 0.11 + 0.33*LRM_{max} + 0.4*LRM_{max}^2.*

Table 3.
Indicators and thresholds employed in the NCCA 2010 to assess sediment quality in estuaries and the Great Lakes.

Leptocheirus plumulosus and *Eohaustorius estuarius* (in California), which could be cultured in the laboratory and gave more consistent results than *Ampelisca abdita*. TOC was no longer used to assess sediment quality because it could have positive and negative impacts on organisms, complicating interpretation. The sediment quality index (SQI) was constructed from the remaining two core metrics to summarize overall sediment condition. Similar to the estuarine approach, the Great Lakes sediment quality index utilizes a mean sediment quality guideline quotient method and a toxicity test. The mean Probable Effect Concentration Quotient (mPEC-Q), rather than the mERM-Q, is used in the Great Lakes [39], along with using the freshwater amphipod *Hyalella azteca* to assess toxicity (**Table 3**). Further details concerning the evolution and calculation of methods are available in the NCCA 2010 technical report [40].

3.3 Assessing benthic community condition

All EPA estuarine surveys since the 1990s collected sediment grab samples of benthic macroinvertebrate communities for assessment of ecological condition based on measures of diversity, species richness, and dominance. The benthos is a key component of estuarine ecosystems, serving as important food source for higher trophic levels and maintaining sediment and water quality. Benthic communities respond to contaminant concentrations, dissolved oxygen stress, salinity fluctuations and physical disturbance, and are relatively immobile and therefore integrate the effect of adverse conditions over months and years.

Separate regional, benthic-community condition indices were developed during the EMAP programs of the 1990s, including for the Virginian [41], Carolinian [42] and Louisianan [43, 44] biogeographic provinces. Later, an index was created for the Acadian Province (Maine through Cape Cod waters) [45]. No specific index was developed for the Pacific coast; rather, sites were assessed based on observed vs. expected species richness [30]. These benthic indices were used in estuarine assessments prior to NCCA 2015. Benthic communities in the Great Lakes were evaluated using an oligochaete trophic index (OTI) based on the classification of oligochaete species by their tolerance to organic enrichment [46, 47]. **Table 4** presents a summary of these regional benthic indices. The NCCA 2010 Technical Appendix [40] provides further detail regarding the development and calculation of the indices.

While the separate estuarine indices performed well in the region for which they were developed, they were developed using different statistical models and metrics. Because the different indices might not be comparable, combining the separate indices into a nationwide evaluation tool was problematic. In response, a national-scale index called M-AMBI (multivariate-AZTI marine biotic index) was adapted to provide a single index applicable to all U.S. estuarine waters [48, 49]. This index is based on benthic indices that were successfully deployed in Europe and elsewhere [50, 51]. AMBI is an abundance-weighted tolerance index, while M-AMBI combines AMBI, species richness and species diversity together using factor analysis calculated for a given habitat. The resulting index was shown to be comparable to several local indices [49] and was better correlated with land use variables [52]. The resulting scores are based on comparison of a sites' position along a pollution gradient [49].

3.4 Assessing fish tissue contaminants

Many aquatic organisms in coastal regions are inadvertent inheritors of a legacy of disturbances often associated with human practices. For instance, chemical pollutants from farms and cities delivered to coastal waters enter the food web

Region/province	Method	Component metrics	References
Northeast/ Acadian	Logistic regression analysis	Shannon H' (diversity) MN_ES(50)0.05 (species tolerance index) % Capitellid polychaetes (abundance)	[39]
Northeast/ Virginian	Discriminant analysis	Salinity adjusted Gleason D (diversity) Salinity adjusted % tubificid (abundance) % Spionids (abundance)	[35]
Southeast/ Carolinian	B-IBI approach	Mean abundance Mean number of taxa 100% abundance of 2 dominant taxa % Abundance of pollution sensitive taxa	[36]
Gulf/Louisianian	Discriminant analysis	% Expected diversity (Shannon H') Mean abundance of tubificids % Capitellids % Bivalves % Amphipods	[37, 38]
Pacific coast	Regression	Observed vs expected species richness	[11, 27]
Great Lakes	Abundance-weighted tolerance equation	Oligochaete tolerance scores (based on organic enrichment)	[40, 41]
National estuarine	Factor analysis	Shannon H' (diversity) Species richness AMBI (abundance-weighted pollution tolerance)	[42, 43]

The national M-AMBI index was developed for the NCCA 2015 and future surveys.

Table 4.
Summary of methods, metrics, and thresholds used to construct regional benthic indices used to evaluate assess coastal waters.

and accumulate, threatening fish and higher trophic-level communities, humans included. To assess the ecological danger to aquatic communities, EPA's coastal surveys since the 1990s have measured concentrations of metals, PCBs, PAHs, and pesticides (**Table 1**) in demersal and pelagic fish collected at sampling stations. Prior to the NCCA 2010 survey, sites were evaluated by comparing contaminant concentrations against human health fish-consumption advisory thresholds as a surrogate for ecologically-relevant benchmarks [53]. When both humans and wildlife were similarly sensitive to specific contaminant exposures, the surrogate used for the assessment was meaningful. Beginning with the NCCA 2010 survey, an *ecological* risk-based approach using wildlife endpoints was incorporated to better align with the ecosystem focus of the NCCA surveys.

The ecological risk approach assessed contaminant levels in whole-body fish tissue following the methods of EPA's ecological risk assessment [54]. The primary goal of this NCCA index, therefore, was to evaluate the potential risk that consuming contaminated fish poses to predators other than humans. Because such "wild" predators consume the entire fish, the NCCA protocol measured contaminant concentrations in the entire fish collected in the survey, rather than measuring contaminant levels in just the fillet—the protocol formerly used when human health was the focus. Operationally, the process first identified mammalian, avian, and piscivorous "receptors," i.e., predator species that consume coastal fish and could be adversely affected by contaminants in the prey-fish. **Table 5** lists the freshwater and marine receptors selected for analysis based on their diet (predominantly fish) and availability of data in the literature. The literature studies were reviewed to identify the Lowest Observed Adverse Effects Level or LOAEL for each receptor, that is,

the contaminant concentration likely to elicit toxicological effects. The minimum contaminant LOAEL found for any member of a receptor group was designated as an impairment threshold, and was used to rate survey sites as good, fair, or poor (**Table 6**). Because of the very different methods used in the human-health and ecological-risk approaches, the NCCA assessments cannot be directly compared

Avian receptors	Freshwater mammalian receptors	Marine mammalian receptors	Freshwater fish receptors	Marine fish receptors
Great Blue Heron	River Otter	Harbor Seal	Largemouth Bass	Bluefin Tuna
Osprey	Mink	Bottlenose Dolphin	Florida Gar	Yellowfin Tuna
Bald Eagle	—	Walrus	Muskellunge	Shortfin Mako
Herring Gull	—	—	Snakehead	Mackerel Tuna
Belted Kingfisher	—	—	Lake Walleye	Swordfish
Brown Pelican	—	—	—	—

Table 5.
Higher trophic-level piscivores potentially at risk from consuming contaminated prey fish.

Contaminant	Whole-body tissue concentration (μg/dry g) by receptor group		
	Lowest observed adverse effect level (LOAEL)		
	Mammal	Avian	Fish
Arsenic (inorganic)	3.8	9.2	0.7
Cadmium	32.1	14.0	3828
Mercury (methyl)	1.1	0.1	1.4
Selenium	2.3	0.6	33.6
Chlordane	55.4	2.9	—
DDTs	28.0	1.6	7.1
Dieldrin	1.2	0.3	1.6
Endosulfan	42.8	43.2	0.003
Endrin	5.6	0.1	3.9
Heptachlor epoxide	7.5	6.3	81.1
Hexachlorobenzene	14.0	0.6	0.04
Lindane	280	2.4	376
Mirex	4.6	0.7	9.9
Toxaphene	280	3.6	0.03
PCBs	3.9	1.3	2.0
Rating criteria for ecological fish tissue contaminant index			
Good	**Fair**		**Poor**
No contaminant concentration exceeds a LOAEL for any receptor group	At least one contaminant concentration exceeds a LOAEL for one receptor group		At least one contaminant concentration exceeds a LOAEL for two or more receptor groups

Table 6.
Whole-body tissue contaminant LOAEL concentrations (μg/dry g) by receptor group.

with earlier survey results and cannot be used to inform human consumption advisories. Refer to the NCCA 2010 technical appendix for further details [34].

3.5 Addressing human-health concerns and emerging issues

Along with evaluating the ecological condition of several major ecological compartments of coastal ecosystems, the NCCA also addressed several matters regarding human health and emerging issues. For instance, in the Great Lakes with the support of the Great Lakes Restoration Initiative (GLRI) [55], the concentrations in fish tissue of the contaminants mercury, polychlorinated biphenyls (PCBs), flame retardant polybrominated diphenyl ethers (PBDEs), and perfluorinated compounds (PFCs) were measured in the Great Lakes NCCA surveys and evaluated against human health screening values [40]. The NCCA also initiated a survey-wide monitoring program quantifying aqueous concentrations of the algal toxins microcystin and cylindrospermopsin, as well as mercury in fish muscle. Several exploratory studies were also undertaken to address important issues such as ocean acidification and the distribution of micro-plastics in coastal water. Newer assessment techniques are also under investigation, such as exploring the use of underwater cameras and environmental genetic screening to monitor the expansion of invasive organisms in the Great Lakes.

4. Conclusion

In retrospect, the mandate issued to the U.S. EPA by the Clean Water Act in 1972 to compile a national assessment of water quality was a bold and challenging directive. No blueprint was available to indicate the best approach of conducting a large-scale assessment program. Tactics regarding monitoring designs, sampling strategies, indicators, thresholds, assessment protocols, etc. all needed to be developed from scratch. The EPA adopted a pragmatic approach to assessing coastal regions, exploring and testing methodologies regionally, and then gradually building a national program based on the best practices learned over 30 years of experimentation. While the NARS-coastal surveys and assessments are not perfect, they represent the first nationally consistent effort, based on current practices, to assess the Nation's coastal waters through time. The data and results represent information available for evaluating national policy and a basis for the scientific community to evaluate coastal waters from many perspectives.

The evolution of methodologies and approaches for the NCCA is an ongoing process. Future surveys will continue the practices of adapting current methods to the latest best practices and the adaptation of new strategies, while striving to strike a balance between consistency and creative exploration. The continued importance of partnerships among federal, state and tribal agencies cannot be over-emphasized in achieving the aims of the monitoring program. Such cooperation has proven to be both efficient and productive, and the enhanced capacity of states and tribes to conduct assessments independently is particularly valuable in assuring a sustainable monitoring program. Particularly striking has been the deep commitment of many individuals, research scientists, program planners, crew members, information managers, analysts, communicators, and partners, who have offered feedback and criticism to continuously improve the coastal assessment process. Finally, the development and evolution of coastal assessment expertise described in this chapter is similarly evident in sister NARS programs that assess lakes, rivers and streams, and wetlands. Descriptions of these programs are presented elsewhere in this book.

Acknowledgements

These coastal assessments were conducted in partnership with many state and tribal agencies, the National Oceanic and Administration (NOAA), the National Park Service (NPS), as well as other federal agencies. EPA offices included the Office of Research and Development, the Office of Water, Great Lakes National Program Office, and EPA Regional Monitoring Coordinators from Regions 1, 2, 3, 4, 5, 6, 9, and 10. We note the particular efforts of EPA colleagues who contributed to the conception, administration and operation of the coastal surveys, including Kevin Summers, John Paul, Virginia Hansen, Treda Grayson, Sarah Lehmann, and Greg Colianni and many others too numerous to name. Thanks also to EPA colleagues Don Cobb, Charlie Strobel, and Hal Walker who reviewed the chapter. We especially wish to acknowledge the truly invaluable assistance of the hundreds of participants who conducted the assessments, including the field crews, biologists, taxonomists, statisticians, analysts, program administrators, regional coordinators, project managers, quality control officers, and reviewers.

Conflict of interest

The authors declare no conflict of interest.

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References

[1] U.S. EPA. Summary of the Clean Water Act. 2019. Available from: https://www.epa.gov/laws-regulations/summary-clean-water-act; and https://www.epa.gov/sites/production/files/2017-08/documents/federal-water-pollution-control-act-508full.pdf

[2] U.S. General Accounting Office. Better Monitoring Techniques Are Needed to Assess the Quality of Rivers and Streams. Volume 1. CED-81-30. Washington, DC: U.S. General Accounting Office; 1981

[3] National Research Council. Environmental Monitoring. Washington, DC: Volume IV. National Academy of Sciences; 1977

[4] U.S. Environmental Protection Agency. Surface Water Monitoring: A Framework for Change. Washington, DC: Water Office; 1987

[5] U.S. Environmental Protection Agency. Report of the National Workshop on Instream Biological Monitoring and Criteria. Corvallis, OR: Environmental Research Laboratory-Corvallis; 1987

[6] U.S. General Accounting Office. Protecting human health and the environment through improved management. GAO/RCED-88-101. Gaithersburg, MD: U.S. General Accounting Office; 1988

[7] U.S. Environmental Protection Agency. Framework for ecological risk assessment. EPA/630/R-92/001. Washington, DC: Risk Assessment Forum, USEPA; 1992

[8] Messer JJ, Linthurst RA, Overton WS. An EPA program for monitoring ecological status and trends. Environmental Monitoring and Assessment. 1991;**17**:67-78

[9] Holland AF. Near Coastal Program Plan for 1990: Estuaries. Washington, DC: Office of Research and Development; 1990. EPA 600/4-90/033

[10] Summers JK, Paul JF, Robertson A. Monitoring the ecological condition of estuaries in the United States. Toxicological and Environmental Chemistry. 1995;**49**:93-108

[11] Nelson WG, Lee H, Lamberson JO, Engle V, Harwell L, Smith LM. Condition of Estuaries of Western United States for 1999: A Statistical Summary. Washington, DC: Office of Research and Development, National Health and Environmental Effects Research Laboratory; 2004. EPA/620/R-04/200

[12] Hyland JL, Snoots TR, Balthis WL. Sediment quality of estuaries in the southeastern U.S. Environmental Monitoring and Assessment. 1998;**51**:331-343

[13] Paul JF, Gentile JH, Scott KJ, Schimmel SC, Campbell DE, Latimer RW. EMAP-Virginian Province four-year assessment (1990-93). EPA/620/R-99/004. Washington, DC: Office of Research and Development; 1999

[14] Kiddon JA, Paul JF, Buffum HW, Strobel CS, Hale SS, Cobb D, et al. Ecological condition of U.S. Mid-Atlantic estuaries, 1997-1998. Marine Pollution Bulletin. 2003;**46**:1224-1244

[15] Summers JK, Engle VD, Smith LM, Harwell LM, Macauley JM, Harvey JE. Monitoring the condition of the estuaries in the United States. In: Jordan S, editor. Estuaries: Classification, Ecology, and Human Impacts. Hauppauge, NY: Nova Science Publishers, Inc; 2012. pp. 249-268

[16] National Coastal Condition Report I. EPA-620-R-01-005. 2001.

Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development and Office of Water. Available from: https://archive.epa.gov/nheerl/arm/web/html/monit_intro.html

[17] National Coastal Condition Report II. EPA-620-R-03-003. 2004. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development and Office of Water. Available from: https://archive.epa.gov/nheerl/arm/web/html/monit_intro.htm

[18] National Coastal Condition Report III. EPA-842R-08-002. 2008. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development and Office of Water, Available from: https://archive.epa.gov/nheerl/arm/web/html/monit_intro.html

[19] National Coastal Condition Report IV. EPA-842-R-08-003. 2010. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development and Office of Water. Available from: https://archive.epa.gov/nheerl/arm/web/html/monit_intro.html

[20] National Coastal Condition Report 2010. EPA-841-R-15-006. 2015. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development and Office of Water. Available from: https://www.epa.gov/national-aquatic-resource-surveys/ncca

[21] National Aquatic Resources Surveys (NARS). Available from: https://www.epa.gov/national-aquatic-resource-surveys

[22] National Coastal Condition Assessment. Basics of the NCCA/Manuals. Available from: https://www.epa.gov/national-aquatic-resource-surveys/ncca

[23] Olsen AR, Stevens DL Jr, White D. Application of global grids in environmental sampling. Computing Science and Statistics. 1998;**30**:279-284

[24] Urquhart NS, Paulsen SG, Larsen DP. Monitoring for policy-relevant regional trends over time. Ecological Applications. 1998;**8**:246-257

[25] Aquatic Resources Monitoring (USEPA). Available from: https://archive.epa.gov/nheerl/arm/web/html/monit_intro.html

[26] Data from the National Aquatic Resources Surveys. Available from: https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys

[27] Stevens DL, Olsen AR. Variance estimation for spatially balanced samples of environmental resources. Environmetrics. 2003;**14**:593-610

[28] Paerl HW, Hall NS, Peierls BL, Rossignol KL. Estuarine and coastal eutrophication dynamics in a culturally and climatically stressed world. Estuaries and Coasts. 2014;**37**:243-258

[29] Bricker S, Longstaff B, Dennison W, Jones A, Boicourt K, Wicks C, et al. Effects of nutrient enrichment in the Nation's estuaries: A decade of change. In: NOAA Technical Memorandum NOS NCCOS Coastal Ocean Program Decision Analysis Series 26. Silver Spring, MD: National Center for Coastal Ocean Science; 2007. p. 328

[30] Nelson WG, Brown CA. Use of probability-based sampling of water-quality indicators in supporting development of quality criteria. ICES Journal of Marine Science. 2008;**65**:1421-1427

[31] Smith VH. Responses of estuarine and coastal marine phytoplankton to nitrogen and phosphorus enrichment. Limnology and Oceanography. 2006;**51**:377-384

[32] O'Connor TP, Ehler CN. Results from the NOAA National Status and trends program on distribution and

effects of chemical contamination in the coastal and estuarine United States. Environmental Monitoring and Assessment. 1991;**17**:33-41

[33] Long ER, MacDonald DD, Smith SL, Calder FD. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. 1995. Environmental Management. 1995;**19**:81-97

[34] ASTM. Guide for conducting 10-day static sediment toxicity tests with marine and estuarine amphipods. In: American Testing and Materials ASTM Standard Methods. Section 11.04, Methods Number E-1367-90. Philadelphia, PA: American Society for Testing and Materials;

[35] Strobel C, Klemm DJ, Lobring L, Eichelberger J, Alford-Stevens A, Potter B, et al. EMAP-Estuaries Laboratory Methods Manual, Volume 1—Biological and Physical Analysis. EPA/620/R-95/008. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development. 1996

[36] Long ER, Field LJ, MacDonald DD. Predicting toxicity in marine sediments with numerical sediment quality guidelines. Environmental Toxicology and Chemistry. 1998;**17**:714-727

[37] Long ER, Ingersoll CG, MacDonald DD. Calculation and uses of mean sediment quality guideline quotients: A critical review. Environmental Science & Technology. 2006;**40**:1726-1736

[38] Field LJ, Macdonald DD, Norton SB, Ingersoll CG, Severn CG, Smorong D, et al. Predicting amphipod toxicity from sediment chemistry using logistic regression models. Environmental Toxicology and Chemistry. 2002;**21**:1993-2005

[39] MacDonald DD, Ingersoll CG, Berger TA. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Archives of Environmental Contamination and Toxicology. 2000;**39**:20-31

[40] National Coastal Condition Assessment (NCCA). 2010. Technical Report. Available from: https://www.epa.gov/sites/production/files/2016-01/documents/ncca_2010_technical_report_20160127.pdf

[41] Paul JF, Scott KJ, Campbell DE, Gentile JH, Strobel CS, Valente RM, et al. Developing and applying a benthic index of estuarine condition for the Virginian Biogeographic Province. Ecological Indicators. 2001;**1**:83-99

[42] Van Dolah RF, Hyland JL, Holland AF, Rosen JS, Snoots TR. A benthic index of biological integrity for assessing habitat quality in estuaries of the southeastern USA. Marine Environmental Research. 1999;**48**:269-283

[43] Engle VD, Summers K, Gaston GR. A benthic index of environmental condition of Gulf of Mexico estuaries. Estuaries. 1994;**17**:372-384

[44] Engle VD, Summers JK. Biogeography of benthic macroinvertebrates in estuaries along the Gulf of Mexico and western Atlantic coasts. Hydrobiologia. 2000;**436**:17-33

[45] Hale SS, Heltshe JF. Signals from the benthos: Development and evaluation of a benthic index for the nearshore Gulf of Maine. Ecological Indicators. 2008;**8**:338-350

[46] Howmiller RP, Scott MA. An environmental index based on relative abundance of oligochaete species. Journal of the Water Pollution Control Federation. 1997;**49**:809-815

[47] Environmental Canada and the U.S. Environmental Protection Agency. 2014. State of the Great Lakes 2011. Cat. No. En161-3/1-2011E-PDF. EPA 950-R-13-002. Available from: https://binational.net

[48] Gillett DJ, Weisberg SB, Grayson T, et al. Effect of ecological group classification schemes on performance of the AMBI benthic index in U.S. coastal waters. Ecological Indicators. 2015;**50**:99-107

[49] Pelletier MC, Gillett DJ, Hamilton A, Grayson T, Hansen V, Leppo EW, et al. Adaptation and application of multivariate AMBI (M-AMBI) in U.S. coastal waters. Ecological Indicators. 2018;**89**:818-827

[50] Borja A et al. A marine biotic index to establish the ecological quality of soft-bottom benthos within European Estuarine and Coastal Environments. Marine Pollution Bulletin. 2000;**40**(12):1100-1114

[51] Muxika I, Borja A, Bald J. Using historical data, expert judgement and multivariate analysis in assessing reference conditions and benthic ecological status, according to the European Water Framework Directive. Marine Pollution Bulletin. 2007;**55**:16-29

[52] Pelletier MC, Gold AJ, Copeland J, Gonzalez L, August PV. Landscape structure and land use affects estuarine benthic invertebrates in the Virginian Biogeographic Province, USA. Environmental Monitoring and Assessment. 2019;**191**:252

[53] U.S. Environmental Protection Agency. Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories, Volume 2: Risk Assessment and Fish Consumption Limits. Washington, DC: U.S. Environmental Protection Agency, Office of Water; 2000. EPA-823-B00-008

[54] U.S. Environmental Protection Agency. Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments. Edison, NJ: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Environmental Response Team; 1997

[55] Great Lakes Restoration Initiative [Internet]. 2020. Available from: https://www.glri.us/ [Accessed: 03 March 2020]