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Classifying Coastal Waters: Current Necessity and Historical Perspective

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ABSTRACT: Coastal ecosystems are ecologically and commercially valuable, productive habitats that are experiencing escalating compromises of their structural and functional integrity. The Clean Water Act (USC 1972) requires identification of impaired water bodies and determination of the causes of impairment. Classification simplifies these determinations, because estuaries within a class are more likely to respond similarly to particular stressors. We reviewed existing classification systems for their applicability to grouping coastal marine and Great Lakes water bodies based on their responses to aquatic stressors, including nutrients, toxic substances, suspended sediments, habitat alteration, and combinations of stressors. Classification research historically addressed terrestrial and freshwater habitats rather than coastal habitats. Few efforts focused on stressor response, although many well-researched classification frameworks provide information pertinent to stressor response. Early coastal classifications relied on physical and hydrological properties, including geomorphology, general circulation patterns, and salinity. More recent classifications sort ecosystems into a few broad types and may integrate physical and biological factors. Among current efforts are those designed for conservation of sensitive habitats based on ecological processes that support patterns of biological diversity. Physical factors, including freshwater inflow, residence time, and flushing rates, affect sensitivity to stressors. Biological factors, such as primary production, grazing rates, and mineral cycling, also need to be considered in classification. We evaluate each existing classification system with respect to objectives, defining factors, extent of spatial and temporal applicability, existing sources of data, and relevance to aquatic stressors. We also consider classification methods in a generic sense and discuss their strengths and weaknesses for our purposes. Although few existing classifications are based on responses to stressors, many well-researched paradigms provide important information for improving our capabilities for classification as an investigative and predictive management tool.

Introduction

Coastal environments are characterized by high biological production and diversity and are subject to escalating environmental pressures due to population growth (Hobbie 2000). Scientists and managers need classification frameworks to understand, protect, and manage coastal resources. Such frameworks are useful tools for describing and inventorying near-coastal communities and habitat types, identifying and prioritizing conservation efforts, managing ecosystem resources, guiding research, and increasing our understanding of differences and similarities among hundreds of semidiscrete units. A classification system organizes data about ecological systems within a logical scientific framework in a manner that characterizes the systems based on their properties, e.g., hydrology, chemistry, geology, and biology (Jay et al. 2000).

The general criterion for the usefulness of classification systems is that they identify coherent groups with similar properties that inform or simplify a management question. Many organizations have developed coastal classification systems for their own unique purposes (Allee et al. 2000; Beck and Odaya 2001; Groves et al. 2002). The key to the usefulness of a classification system to improve the management of coastal systems under the Clean Water Act of 1972 sections 303(d) and 305(b) (USC 1972) is that the identified classes must respond differently to the influence of one or more stressors. Three results are possible for any particular pollutant: systems respond as individuals (classification is not useful and research proceeds no further); all systems respond similarly under the influence of stressors (classification is not informa-

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tive); or groups of systems have coherent and distinctly different responses under the influence of stressors (the classification system is informative and has utility for diagnosis or prediction).

In light of these possible outcomes and within the context of our need to develop a classification for coastal marine and Great Lakes ecosystems based on their susceptibility to stress, we reviewed existing classifications to determine the important elements of successful classification strategies. Classification approaches from Australia, South America, Europe, and the United States are included. Our objectives were to examine existing classification systems for their ability to group coastal marine and Great Lakes systems for a defined purpose; identify key factors or forcing functions that could group systems with similar properties, such as sensitivity or response to aquatic stressors, e.g., nutrients, altered habitat, toxic compounds, suspended sediments, and combinations of stressors; and consider how classification systems might facilitate environmental management.

Early Coastal Classification Systems

Kennish (1986) reviewed the coastal and estuarine classification systems that had been proposed up to that time. He identified five classification themes: geomorphology and physiography, hydrography (water circulation, mixing, and stratification), salinity and tidal characteristics, sedimentation, and ecosystem energetics. Pritchard (1967) placed estuaries into four geomorphic classes: drowned river valleys (e.g., Chesapeake and Delaware Bays), fjord-type (e.g., Puget Sound), lagoon-type or bar built (e.g., Laguna Madre and Pamlico Sound), and those produced by tectonic processes (e.g., San Francisco Bay). Other classifications grouped estuaries based on stratification and circulation. Stommel and Farmer (1952) divided estuaries into four types based on stratification: well mixed, partially mixed, fjord-like, and salt wedge. This simple typology was the basis for numerous modifications (Ippen and Harlemann 1961; Simpson and Hunter 1974; Fischer 1976; Prandle 1986; Nunes Vaz and Lennon 1991). In addition to geomorphic classes, Pritchard (1967) placed estuaries into four classes based on circulation regime: type A or salt wedge, type B or partially mixed (moderately stratified), type C or vertically homogenous with a lateral salinity gradient, and type D or sectionally homogenous with a longitudinal salinity gradient. Hansen and Rattray (1966) devised a classification based on two dimensionless parameters expressing stratification due to the relative salinity difference between surface and bottom water, and circulation, as the ratio of net longitudinal surface flow velocity to the mean cross-sectional velocity of freshwater discharge. Estuaries were grouped into Types 1–3 in increasing magnitude of the circulation parameter, with subtypes *a* (well mixed) and *b* (partially stratified). Highly stratified estuaries with little circulation were designated Type 4. These classification systems lack consideration of some important forcing functions (wind, multiple freshwater discharges) that influence circulation and stratification in estuarine systems, and do not express complex dynamic patterns, such as three-layered or reverse estuarine circulation, that occur episodically in some estuaries.

Estuaries have been classified as positive, negative, or neutral based on their salinity regimes (Pritchard 1967). The volume of freshwater inflow and the relationship between evaporation and precipitation determine these salinity classes. Salinity also has been used to divide estuaries into sections based on the average salinity in a section. In the Venice system, suggested at a symposium on the classification of brackish waters in 1959 (Venice system 1959), six distinct zones were recognized: limnetic or freshwater (< 0.5‰), oligohaline (0.5–5‰), mesohaline (5–18‰), polyhaline (18–30‰), euhaline (30–40‰), and hyperhaline (> 40‰). Tidal range also has been proposed as a way to distinguish three classes of estuaries based on tidal height: microtidal (0–2 m), mesotidal (2–4 m), and macrotidal (> 4 m; Carriker 1967).

A hierarchical, functional description of coastal ecosystems based on dominant forcing functions was developed by Odum and Copeland (1974). They used characteristic energy sources, storage, and flows of estuaries and coastal ecosystems, including wetlands, to define six major classes of systems: natural stressed systems of wide latitudinal range, natural tropical systems of high diversity, natural temperate ecosystems with seasonal programming, natural Arctic systems with sea ice stress, emerging new systems associated with man, and migrating subsystems that organize extensive areas. The last of these classes does not refer to the subsystems themselves migrating, but rather to the strong connections between subsystems effected by migrating organisms, as in the huge seasonal influxes of juvenile fish and invertebrates from coastal oceanic spawning areas to estuaries. This classification was semihierarchical, in that most of the classes were divided into several more specific subclasses. The stated purpose of Odum and Copeland's (1974, p. 5) work was to develop a classification system. ". . . that groups together estuaries with similar responses to disturbance, planning, or management." This work presages our present need to develop a stressor-based (disturbance) classification system for managing coastal ecosystems.

Current Applications for Classification

During the 1980s, efforts to classify ecosystems were driven by the need to identify wetlands that could be drained for human use (Mitch and Gosselink 1986). More recent efforts have conservation of sensitive habitats as a focus. The Nature Conservancy has been developing a framework for conservation planning based on endangered species data coupled with data on the underlying ecological processes that support patterns of biological diversity at multiple spatial scales and levels of biological organization (Groves et al. 2002). Once the problem definition and data development phases are accomplished, conservation efforts will focus on particular species that need protecting, in combination with important ecological processes, to define conservation areas or sensitive habitats. Past conservation efforts by The Nature Conservancy focused on threatened or endangered species or those species considered to be commercially or ecologically important. In recent years, there has been a shift in emphasis within this organization toward conserving biodiversity, which can best be preserved by considering natural communities rather than specific species. Habitat preservation requires consideration of ecosystem function at the landscape scale (Allee et al. 2000).

The Water Framework Directive (WFD) was developed by the European Union, European Commission, and Norway in 2000 (Anon 2002). This framework was developed for the protection of all waters, including surface waters, transitional waters, coastal waters, and groundwater. A workgroup (COAST) had developed guidelines specific to transitional and coastal waters (Anon 2003). The goal of the directive is to achieve good water quality for all water resources. One of the key guidelines to implementing the framework requires member states to characterize all water bodies or develop a typology. The purpose of the typology is to provide a foundation for determining reference conditions for each water body type or to assist in comparing like systems. This typology is developed on the basis of physical and chemical factors that determine the structure or composition of the resident biological communities. The guidance goes further to require assessment of the ecological status of water bodies based on comparison to high status reference conditions. This process is referred to as a classification of ecological status. The WFD system identifies coherent groups with similar properties in two different ways. The typology characterizes systems based on their physical similarities, while the classification describes systems based on their condition or ecological status.

In compliance with the WFD, European Union members have promulgated several typologies in the region of the Baltic Sea, which is designated as one ecoregion (Schernewski and Wielgat 2004). This effort reflects a spatial integration of river basins and coastal waters and focuses on conditions of the biological communities in these ecosystems. Specific typologies were developed for Poland, Denmark, and Lithuania.

New Zealand researchers conducted a review of the seventeen classification systems that had been developed for their country (Froude and Beanland 1999). Classification systems addressed wetlands, freshwater ecosystems landforms, vegetation cover, indigenous forests, terrestrial ecosystems, threatened species, uncommon plants, and soils.

Environmental managers in the United States need to classify aquatic systems to support goals established under the Clean Water Act: set water quality standards and criteria, establish reference conditions (Robertson et al. 2001; Omernik et al. 2002), diagnose impairment, determine causes of impairment, and predict changes in environmental condition, either restorative or detrimental. The Clean Water Act section 305b requires states and tribes to assess and report water quality conditions and status of water bodies. Section 303d requires states to submit listings of specific water bodies that violate water quality standards or fail to meet water quality criteria or biocriteria. Reference conditions are used in establishing biological and some chemical criteria, when expectations are defined by the natural or least impaired condition. Water bodies in violation of water quality standards are determined to be impaired and states identify or diagnose suspected causes of impairment under section 303d. Grouping of systems by class should simplify the problem of determining causes of observed ecological effects that indicate impairment of a water body and improve prediction of changes in coastal ecosystem condition. Ideally, classes would differ in the forcing functions that influence system dynamics and in the effects of stressors on ecological condition.

A specific case where classification can assist environmental managers in meeting water quality standards emerges from the Total Maximum Daily Load (TMDL) program initiated as part of the Clean Water Act (USC 1972). The TMDL is the load of a pollutant that will result in compliance with a water quality standard. For water bodies determined to be impaired under section 303d, states must prioritize and develop plans for preparing TMDLs that will result in attainment of water quality standards. Of the 40,000 water bodies currently identified in the U.S., 21,000 river segments, lakes, and estuaries have been identified as being in

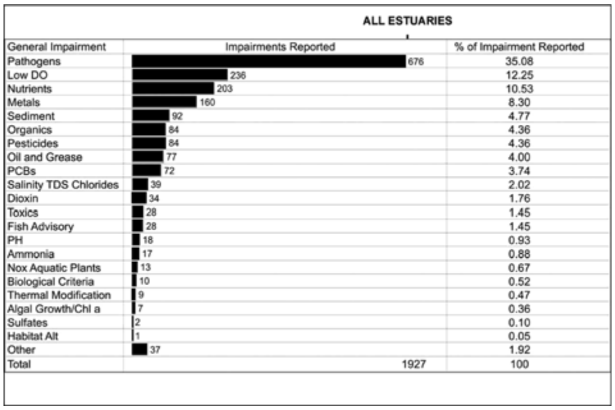

Fig. 1. Impairments reported for U.S. estuaries under section 303d of the Clean Water Act.

violation of one or more standards (NRC 2001). Of this 21,000, 937 are identified as estuaries, bays, bayous and lagoons, with 25 states reporting impaired estuaries (USEPA 2004). Of the 87,369 square miles determined to be estuarine, 31,072 or 36% have been assessed for impairment by respective states (USEPA 2000). States often report more than one stressor as the cause of impairment for a single estuarine water body. For the 937 estuaries identified as impaired, 1,927 causes of impairment are reported, each requiring TMDL development. These causes of impairment and their frequency of occurrence are provided in Fig. 1. The most frequently cited causes of impairment in estuaries were pathogens (35.08%), low dissolved oxygen levels (12.25%), excess nutrient loading (10.5%), and metal contamination (8.3%). When all estuarine areas have been assessed, the number of impairments for which TMDLs are required may well rise over 5,000.

The TMDL process requires a scientific diagnosis to determine which stressor or stressors are responsible for water body impairment, along with the total load of the stressor from point and nonpoint sources. Determining the stressors responsible for impairment of thousands of estuaries will be simplified if we can develop robust classification schemes that identify groups of water bodies that behave similarly in the presence of a stressor. A useful classification would provide regional, state, and tribal regulatory authorities with a tool to collapse the thousands of water bodies needing TMDLs into a manageable number of classes, each composed of individual water bodies with common, stressor-sensitive characteristics. Estuaries with slower turnover times should be more susceptible to nutrient loading and may form one logical class. With defined water body classes, a TMDL template or plan for remediating the impairment could be created that could be applied to all of the water bodies within the class with minor adjustments on a case-by-case basis. This process would eliminate the need for thousands of unique TMDLs.

Classification systems can guide current and future research. In building a database for classification, data gaps may readily become apparent, pointing to opportunities for empirical studies to fill in missing data. Analysis of classification databases may reveal important correlations between physical, biogeochemical, and ecological processes. Studies employing numerical models may be a useful approach for better understanding these interactions and may also address important issues of spatial and temporal variation (Geyer et al. 2000). Research comparing observed loads with responses among coastal ecosystem classes, combined with modeling approaches, will advance our ability to make responsible decisions to protect coastal ecosystems.

Factors Determining Sensitivity to Common Stressors

Both biological and physical factors can influence estuarine susceptibility to nutrients (NRC 2000). Important physical factors include physiography, dilution due to area or volume and mixing processes, water residence time and flushing rate, and stratification (NOAA 1989; Bricker et al. 1999). These factors are important for other stressors as well. Estuaries most susceptible to pollution are slow to dilute or flush sediments, toxic substances, and dissolved material (NOAA 1989). Hypsography, or the relative areal extent of sea bottom surface within elevation or depth contours, can also influence susceptibility; it determines the areas of benthic habitat where limitation by light or dissolved oxygen can greatly alter biogeochemical processes, such as primary production, respiration, and nutrient cycling.

Biological factors determining estuarine responses to stressors such as nutrient overenrichment include primary production, grazing rates, and denitrification (NRC 2000). Estuaries dominated by marshes or benthic algae are likely to be shallow with short residence times, whereas plankton-dominated systems may be deeper with longer residence times. Changes in trophic dynamics at any level, from microbial activity to zooplankton grazing on phytoplankton to top-level predation, may result in changes in food webs, altering system function and sensitivity to stressors. Denitrification, sulfate reduction, and methane generation are all biologically mediated biogeochemical processes that are important in the remineralization or transformation of substrates discharged to and generated within coastal ecosystems. These processes are important to elemental cycling in coastal systems and are likely to be factors effecting sensitivity to pollutants. Biological factors are less well-characterized than physical factors, and may be targets for future investigations to improve classification and modeling efforts.

Properties and Limitations of Existing Classification Systems

Past efforts to develop ecological classification systems or frameworks have focused principally on terrestrial and freshwater systems and have been undertaken for entire nations, as well as for specific regions and habitat types. Some coastal systems and their watersheds have been well studied, but broad-scale classification efforts have not often been expanded to include coastal and estuarine ecosystems, even though these systems are among the most productive and anthropogenically-affected ecosystems known (Edgar et al. 2000). Even fewer studies have been conducted to compare susceptibility or responses to stressors among or across coastal ecosystems.

Although none of the 26 classification systems we reviewed (Table 1) specifically defined a coastal classification based on susceptibility to multiple stressors, each provided pertinent information or approaches for meeting our objectives. Table 1 is a list of each classification system we reviewed, the purpose or objective for development of the system, and the factors that were considered in defining different classes. Our assessment of the pertinence of each classification system to different aquatic stressors is specified, along with our determination of the extent of spatial and temporal coverage offered by the effort. We evaluated the classification systems in light of existing sources of data that may be applicable to each classification approach (as opposed to sources of data that were originally used by the developers) and described limitations as well as testing that has been conducted or modifications that have been made by other researchers.

Geographic Mapping Frameworks

Geographic mapping frameworks have been developed and applied nationwide. Three of these divide the U.S. into regions with common features based on overlays of existing landscape and climatic data (Bailey 1976; Omernik 1987; Keys et al. 1995). These mapping frameworks aggregate areas (wetlands, surface waters, forests, and agricultural areas) based on spatial covariance in vegetation type, climate, and geology. They define different regions based on physical and biological components that influence ecological relationships.

Bailey (1976, 1995, 1998) combined U.S. Department of Agriculture's system of land resource areas based on soil characteristics with the U.S. Forest Service database on climate, solar radiation, moisture patterns, landforms, and potential natural vegetation to yield a hierarchical framework. Bailey's ecoregions focused on terrestrial systems, whereas other ecoregional systems (Omernik 1987) and ecological units (Keys et al. 1995) focused on terrestrial characteristics as they were expected to affect aquatic systems. Ecological units were developed in an hierarchical fashion, with different forcing functions associated with natural features operating at different scales. Finer classifications down to the valley segment and channel reach scale were suggested within the ecological unit framework (Maxwell et al. 1995). Omernik's (1987) ecoregion framework mixed land use with natural landscape features and combined factors to classify systems at a single level.

Omernik's ecoregions have been used by a number of states to develop biological criteria, set water quality standards, and set lake management goals (Detenbeck 2001). Some entities have chosen to refine the spatial resolution of Omernik's ecoregional boundaries for managing aquatic resources (e.g., USEPA's Region 3 and Florida 2004). Bailey's (1976, 1995, 1998) ecoregions, with a focus on terrestrial variables assumed to have major influence on the distribution of species, have been used extensively by The Nature Conservancy in planning for species and ecosystem conservation (Grossman et al. 1998; Beck and Odaya 2001; Groves et al. 2002; TNC 2004). Geographic (ecoregional) classifications are useful in environmental management and efforts to inventory and define natural resources for conservation purposes. Although comprehensive, these systems have not been tested for their relevance to wetlands or to coastal systems and result in an impractical number of classes for our purposes.

Habitat Inventories

Wetland-based classifications predate geographic frameworks. They have similarities to the geographic maps in that both consider plant community composition and soil characteristics, but wetland classifications are more often hierarchical in structure and were designed for inventory and management of wetlands (Shaw and Fredine 1956; Cowardin et al. 1979; Day et al. 1988; Chow-Fraser and Albert 1998; Detenbeck 2001). In the early 1950s, the U.S. Fish and Wildlife Service recognized the need for a national wetlands inventory and proposed a classification known as Circular 39 (Shaw and Fredine 1956). Twenty types of wetlands were described in four major categories: inland fresh,

TABLE 1. Comparison of classification designs and their pertinence to assessing multiple stressor effects. NWI—National Wetlands Inventory (USFWS 1998–1992), GLEI—Great Lakes Environmental Indicators Project, STATSGO database—State Soil Geographic Database (USDA 1994, 2001), MRLC—national land-use database, NWSD—National Watershed Boundary Database, USFS-EU—U.S. Forest Service-Ecological Units, USGS—Regional USGS peak flow prediction equations (USGS 2003), NOAA CA&DS—National Oceanic and Atmospheric Administration, Coastal Assessment & Data Synthesis System (NOAA 2003a), LMER—Land Margin Ecosystem Research Program, and BASINS—Better Assessment Science Integrating Point and Nonpoint Sources (USEPA 2003).

Classification system	Objective	Classification factors considered	Stressor pertinence	Extent, spatial and temporal variability	Data availability, gaps	Status of testing/modifications
Ecoregions of the U.S. (Bailey 1976)	Map: Develop hierarchical framework of terrestrial habitats	Land use, soil types, landform, climax, vegetation, and temperature	Habitat alteration	U.S. Spatial	Nationwide	Terrestrial focus, does not include hydrology. Used by The Nature Conservancy, but not tested for wetlands
Ecological units of the eastern U.S. (Keys et al. 1995; Maxwell et al. 1995)	Map ecological units: Based on physical and biological components that influence ecological relationships, processes, and potentials	Geomorphology, geology, human use, soil types, climate, surface water characteristics, growing season, vegetation potential, and temperature	Habitat alteration, nutrients, suspended sediments, and thermal regime	U.S. Spatial	Eastern U.S., digital. Gaps include areas other than eastern U.S. and some portions of western U.S.	Terrestrial focus, does not include hydrology. Case studies have demonstrated watersheds to group by these ecological units (Detenbeck et al. 2000; Jensen et al. 2001)
Ecoregions of the conterminous U.S. (Omernik 1987)	Map ecosystem regionalities: Define regions and explore the processes and effects of human activities	Land use, geology, climate, physiography, soil types, hydrology, and vegetation	Habitat alteration, nutrients, suspended sediments, and flow regime	U.S. Spatial	Maps, local databases are available to support some reference condition locations	Terrestrial focus. Used by a number of states to develop biological criteria and to set water quality standards and lake management goals but not tested for most wetlands
Circular 39 (Shaw and Fredine 1956)	Wetlands: Inventory the distribution, extent, and quality of wetlands along with their value as wildlife habitat	Water depth, flooding regime, salinity, and vegetation type	Habitat alteration and hydrologic regime	U.S. Spatial	Gaps in mapping	Served as a simple but effective basis for later efforts
Classification of wetlands and deepwater habitats of the U.S. (Cowardin et al. 1979)	Wetlands: Inventory status and trends in coverage and deepwater habitat types	Ecosystem type, relative elevation, substrate type, pH, soil type, flooding regime, water regime, water chemistry, and vegetation	Habitat alteration	U.S. Spatial	Gaps in digitization	Widely used, extensive number of classes may be impractical. Gibbs (1993) case study, but stressor sensitivity aspects (density, spatial configuration, temporal variability) need to be tested. Modified by McKee et al. (1992) and for marine systems (Dethier 1992).
Riverine marsh disturbance gradients (Day et al. 1988)	Wetlands: Identify vegetation community response types	Hydrologic regime, disturbance regime, and vegetative composition	Nutrients and habitat alteration	U.S. coastal and riverine wetlands	NWI, state inventories, extension to other regions necessary based on species composition and traits	Untested for stressor sensitivity applications
Coastal wetland ecosystems (Chow-Fraser and Albert 1998)	Wetlands: Identify habitats of biodiversity for conservation	Geomorphology and vegetation types	Not directly linked with stressor susceptibility	Great Lakes	NWI inventoried wetlands only	Extensive number of classes may be impractical

TABLE 1. Continued.

Classification system	Objective	Classification factors considered	Stressor pertinence	Extent, spatial and temporal variability	Data availability, gaps	Status of testing/modifications
Coastal wetlands of the Great Lakes (Keough et al. 1999)	Wetlands: Classify by functional groups	Hydrogeomorphic types: open coast, drowned-river mouth, flooded delta, and protected	Not directly linked with stressor susceptibility, but hydrogeomorphic types may differ in retention time and settling efficiency	Great Lakes	Existing NWI state inventories, GLEI	Some difficulty with separation of classes in practice
Great Lakes Wetlands Consortium (Great Lakes Wetlands Commission 2003)	Wetland habitats: Refine inventories for tracking areal status and trends and stratify types for monitoring programs	Hydrology, geomorphology, shoreline processes, resuspension, and residence time	Nutrients, suspended sediments, toxics, and hydrologic regime	Great Lakes	NWI, state wetlands inventories under assessment, point and areal coverages need matching	Untested for stressor sensitivity applications
Fluvial classification (Montgomery and Buffington 1993)	Fluvial: Apply hierarchical geomorphic classification to predict risk of sediment input and transport	Geology, climate, hydrology, and sediment transport	Not linked with stressor susceptibility per se but influenced by sediment loading	U.S. fluvial systems	State inventories	Modified by Jay et al. 2000 for estuaries
Channel types (Rosgen 1994)	Streams: Predict direction and magnitude of changes due to natural and human disturbances	Geomorphology, channel slope, substrate type, instream sediment sources and sinks, and climate	Suspended sediments and sediment-associated pollutants	U.S. fluvial systems Temporal Spatial	Not mapped	Riverine only, instream channel form focus. See also Hawkins et al. 1993
Flow regimes (Poff and Allan 1995)	Fluvial: Classify hydrologic regime by flooding or drought magnitude, frequency, and predictability and relate to biological community types	Hydrology	Nutrients, suspended sediments, toxics, and hydrologic regime	U.S. Temporal	Nationwide	Untested for stressor sensitivity applications
Hydrologic landscape regions of the U.S. (USGS 2003)	Watersheds: Group according to similarities in landscape and climate characteristics to assist with water quality assessments	Land-surface form, geologic texture (soil and bedrock permeability), and climate variables	Not linked with stressor susceptibility	43,931 small watersheds (200 km^2) in the U.S.	STATSGO USGS National Atlas databases	Parameters are assumed to affect hydrologic processes and so may relate to retention time predictions
Comparative watershed framework (Detenbeck et al. 2000)	Freshwater lotic systems: Predict susceptibility of biota, habitat, and water quality to non-point stressors mediated by changes in hydrology	Hydrogeomorphic region, watershed storage (retention time), land use, and thresholds relative to hydrologic regime	Habitat alteration, nutrients, suspended and bedded sediments, toxics, thermal regime, and hydrologic regime	U.S.: Humid regions, runoff-dominated urban regions Temporal	MRLC, NWI, NWSD, USFS-EU, USGS. Gaps in NWI-digital coverage (storage calculations) and NWBD flow thresholds	Arid regions, groundwater-dominated systems not covered. Tested in Lake Superior and Michigan Basins
Hydrodynamic, single parameter (Stommel and Farmer 1952)	Estuarine: Describe types based on stratification	Hydrology, river flow, stratification, and tidal currents	Nutrients, toxics, and suspended sediments	Narrow estuaries	NOAA CA&DS	Focuses on narrow estuaries. Modified by Ippen and Harlemann 1961, Prandle 1986, Fischer 1976, Simpson and Hunter 1974, and Nunes Vaz and Lennon 1991

TABLE 1. Continued.

Classification system	Objective	Classification factors considered	Stressor pertinence	Extent, spatial and temporal variability	Data availability, gaps	Status of testing/modifications
Circulation based (Prichard 1967)	Estuarine: Describe types based on circulation features	Circulation, salt wedge, partially mixed, moderately stratified, and sectionally stratified	Nutrients, toxics, and suspended sediments	Estuaries Spatially	NOAA CA&DS	May overgeneralize for TMDL applications
Hydrodynamic, two parameter (Hansen and Rattray 1966)	Estuarine: Describe types based on stratification and circulation	Hydrology, geomorphology, freshwater, tidal influences, and stratification	Nutrients, toxics, and suspended sediments	Narrow estuaries, fjords, and river-dominated estuaries; worldwide	NOAA CA&DS	Unsuitable for broad shallow embayments and systems subject to wind forcing or temporal variability. Modified by Fischer 1976, Officer 1976, Oey 1984, Jay and Smith 1988, Friederichs and Madsen 1992, Hearn 1998, Geyer et al. 2000
Ecological perspective on estuarine classification (Jay et al. 2000)	Estuarine: Identify environments found in different estuaries and describe their sediment transport processes	River flow, tidal flow, residence time, and forcing processes: wind, waves, and sea ice	Suspended and bedded sediments and hydrologic regime	Estuaries Spatial Temporal	LMER	Effectively oriented towards susceptibility to suspended and bedded sediments as a stressor, but untested for other aquatic stressors, i.e., does not address eutrophication
Physical classification of Australian estuaries (Digby et al. 1998)	Estuarine: Develop a framework for 780 Australian estuaries based on quantifiable, biologically important physical characteristics and transfer knowledge between estuaries with similar characteristics	Geomorphology, climactic zones, tidal range, shoreline, and intertidal proportion	Nutrients, toxics, and suspended and bedded sediments	Australia Spatial	Data available for 623 of 780 estuaries. Gaps in seagrass coverage and in accounting for temporal variability of this and other parameters	Temperate estuaries become a large category that may be amenable to subdivision based on a biological parameter, i.e., seagrass coverage or diversity of fish or macrobenthic communities
NOAA estuarine classification (NOAA 2000)	Marine and estuarine: Describe the spatial heterogeneity of marine and estuarine landscapes and link to underlying mechanisms structuring the ecosystem and biotic communities	Hydrology, geomorphology, topology, ecosystem type, substratum, climate zones, wave-wind energy, temperature, salinity, alkalinity, extreme events, and biological interactions	Habitat alteration and nutrients	U.S.: marine and estuarine Spatial	NOAA CA&DS bathymetry, topography	Leads to a large number of classes, reduction strategies may include system response factors.
Coastal provinces (Briggs 1974)	Near coastal and marine: Outline zoogeographic regions	Coastal ocean currents and distribution of marine organisms and indigenous species	Not directly linked with stressor susceptibility	Near coastal		Untested for stressor sensitivity assessment
The Nature Conservancy (e.g., Beck and Odaya 2001)	Aquatic systems: Map and inventory community and ecosystem habitats for conservation of biodiversity and target species	Physicochemical-geologic factors, system attributes, target species, habitat type, land use, road and dam density, and point source density	Habitat alteration, point sources, toxins, nutrients, suspended and bedded sediments, hydrologic regime	U.S., Central and South America Spatial	Species, aquatic system targets, conservation areas. Gaps in aquatic insect species coverage, snails, crayfish, fish, and mussels, and tidal marsh habitats	Used to select priority areas for conservation action, not tested for stressor susceptibility applications

TABLE 1. Continued.

Classification system	Objective	Classification factors considered	Stressor pertinence	Extent, spatial and temporal variability	Data availability, gaps	Status of testing/modifications
Coastal effects from freshwater flow alterations (Sklar and Browder 1998)	Near coastal: Identify potential effects of alterations to freshwater flow to the Gulf of Mexico	Freshwater flow, salinity, isohaline zone, dissolved oxygen, system geometry, discharge component, and vegetative habitat	Habitat alteration, nutrients, suspended and bedded sediments, toxics, hydrologic regime, compares individual stressor effects with multiple stressor effects	Gulf of Mexico Spatial Temporal	Data for individual systems	Currently used for indepth examination of individual systems, not tested for extrapolating across systems.
Geomorphic modeling approach (Stefan et al. 1995, 1996)	Lakes: Predict susceptibility of fish habitat to global climate change	Stratification (as a function of mean depth and area), trophic status, latitudinal gradient, and thermal regime	Habitat alteration, nutrients, suspended and bedded sediments, thermal regime, and interacting stressors	Potential for U.S. applicability Temporal Spatial	Lake morphometry and trophic status	Predictions have applicability to multiple stressors. Currently limited regionally (Minnesota lakes)
Estuarine quality index (Ferreira 2000)	Estuarine: Design a decision-support system to provide an index or score based on estuarine condition to facilitate classification	Vulnerability, water quality, sediment quality, and trophodynamics	Nutrients, toxics, and suspended and bedded sediments	U.S. and Europe	NOAA CA&DS BASINS	Benthic community, sediment quality, and fish diversity data may not be widely available.
Water Framework Directive: Transitional and coastal waters (Anon 2000, 2003)	Typology: Characterization of water bodies for establishment of and comparison to type-specific reference conditions. Classification: Determine ecological condition or status of water bodies	Latitude, longitude, tidal range, salinity, depth, turbidity, current velocity, wave exposure, water temperature, mixing features, retention time, and substratum Composition, abundance, and biomass of phytoplankton, aquatic flora, and benthic invertebrates, depth variation, bed structure, substrate, intertidal zone, current direction, wave exposure, transparency, temperature, salinity, oxygenation, nutrients, and pollutants	Aquatic stressors, nutrients, toxins, and sediments	European Union member states, Norway and the European Commission	Coastal guidelines do not include lakes, rivers, groundwater, and heavily modified water bodies. But subsequent guidelines will be/have been developed	Databases do not address the entirety of the indicators included in the guidelines. Comparable methods for sampling and analytical techniques are not entirely in place. Spatial and temporal coverage may not be consistent.
Estuarine susceptibility (NOAA 1989; Bricker et al. 1999)	Estuaries: Classify by susceptibility to nutrient overenrichment	Nutrient load, dilution, flushing, dissolved concentration potential, particle retention efficiency, and estuarine export potential	Nutrients	138 U.S. estuaries or estuarine drainage units	NOAA CA&DS Gaps in considering temperature, wind mixing, inlet configuration, estuarine plume exchange with nearshore oceanic water, and ratio of shoreline length to estuarine surface area	Effectively oriented towards nutrient susceptibility, but untested for other aquatic stressors. Prediction less useful for estuaries in Maine, small estuaries in southern California, and Puget Sound estuaries

inland saline, coastal freshwater, and coastal saline. The classes inventoried the distribution, extent, and quality of the remaining U.S. wetlands in relation to their value as wildlife habitat. Salinity was the sole chemical criterion considered.

This classification was widely used in the U.S. until 1979, when the National Wetlands Inventory classification was adopted for wetlands and deepwater habitats (Cowardin et al. 1979). The most widely used of the habitat inventories, this wetlands classification divides environments into groups in a manner similar to a taxonomic key. Broad categories of habitat types are divided successively into groups with more aspects in common, cascading in a hierarchical fashion to numerous, well-defined classes with many common features. Four broad categories of systems are defined, three of which include coastal habitats: marine, estuarine, and riverine. Wetlands and deepwater habitats within each system are classified based on the forms of vegetation present and the flooding regime. Classification at the lowest level describes water regime, salinity, pH, and soil.

Other hierarchical systems for marine and estuarine habitats include one from the Joint Nature Conservation Committee that is specific to benthic marine habitats and for Britain and Ireland (Connor et al. 2004). Habitats for benthic invertebrate communities and seaweeds are classified at 6 different hierarchical levels into 370 classes. The Baltic Marine Biotope Classification System, a hierarchical system, aims to characterize biodiversity measures of the plant and animal communities of the phytobenthic zone (Backer et al. 2004). This hierarchy uses nine main criteria, including depth, substrate, functional group, and community type, resulting in a high number of theoretical habitat classes. Considerations of synergistic natural processes within the hierarchy help to make the actual number of classes considerably smaller. One analysis resulted in 45 biotopes at the first level and 23 biotopes at level 2; 95% of the observations aggregate into the 7 most dominant biotope classes. Allee et al. (2000) developed a marine classification with a hierarchical design that is intended to be global in scope. This classification uses physical and biological information to define ecological units, which represent the biological community within a given habitat. This system is designed to allow aggregation at different levels depending on the amount of data available for a particular ecosystem. Thirteen levels of aggregation are described, the first level being the broadest or most general while the most refined level may need further refinement by modifiers, such as temperature, salinity, or biological interactions, to describe a particular location or characteristic type.

For Great Lakes coastal wetlands, McKee et al. (1992) suggested a modification of the Cowardin et al. (1979) classification system incorporating landscape position, depth zone, vegetative cover, and modifiers of ecoregions, water level regimes, fish community structure, geomorphic structure, and human alterations. More detailed habitat type classifications for both coastal and inland aquatic systems in the Great Lakes basin are being developed by the U.S. Geological Survey (USGS 2004) Gap Analysis Program (http://www.glsc.usgs.gov/GLGAP.html). Habitat types are predicted from landscape information and are related to organism presence or absence and biological community types. Early habitat-based systems worked well for inventory but lacked a quantitative component, making susceptibility to stressors difficult to measure or predict (Jay et al. 2000). Although the inclusion of biological information may improve their predictive ability at the level of refinement necessary for considering susceptibility to stressors, these systems still result in an extensive number of classes. Conceptual or empirical relationships between wetland types and susceptibility to stressors have not been established.

Freshwater and Watershed Approaches

Several additional classification frameworks focus on fluvial systems and watersheds (Montgomery and Buffington 1993; Rosgen 1994; Poff and Allan 1995; Detenbeck 2000; USGS 2003). Hierarchical geomorphic classifications predict susceptibility to sediment loadings and deposition based on valley-side slope and channel gradient (Montgomery and Buffington 1993). Rosgen's (1994) stream classification is based on valley segment, channel patterns, and processes at different temporal and spatial scales. Hawkins et al. (1993) proposed a fluvial classification system based on hierarchical ranking of linkages between geologic and climatic settings, stream habitat features, and biota. The USGS (2003) hydrologic landscape regions cluster watersheds of the U.S. based on similar geomorphic and geologic characteristics that determine hydrologic regimes, whereas the comparative watershed framework (Detenbeck et al. 2000) uses some of these characteristics to predict susceptibility to nonpoint source pollution.

These freshwater system classifications focus on hydrology and geomorphology, but also use aspects of sediment input and transport as classification parameters, enabling prediction of susceptibility to suspended and bedded sediments and associated pollutants. These systems result in a smaller number of classes and are relevant to classifying aquatic habitats for the coastal Great Lakes. They are not directly applicable to estuaries because of complex estuarine dynamics and oceanic influences, but forcing functions for upstream lotic systems may be contributing factors to estuarine responses.

Coastal Hydrologic Regimes

Early classification efforts identified estuarine groups based on elements of geomorphology, circulation, and stratification. While geomorphology is known to be important (Hume and Herdendorf 1988; Digby et al. 1998), other forcing functions are being considered, such as climate (Ryan et al. 2003), residual circulation (Jay and Smith 1988), surface heating and evaporation (Hearn 1998), tidal flat influence (Friedrichs and Madsen 1992), salinity gradients (Geyer et al. 2000), and density field to tidal process connections (Fischer 1976; Officer 1976; Oey 1984). Jay et al. (2000) proposed adding forcing functions like wind and waves in a classification system based on Montgomery and Buffington (1993). Jay's framework relates estuarine type to dominant sediment transport processes, linking geomorphic with hydrodynamic aspects through nondimensional hydrodynamic parameters associated with each sediment transport forcing mode. Six transport processes are considered: net motion of river flow, oscillatory tidal flow, internal circulation, atmospherically forced circulation, transport and resuspension by wind waves and swell, and transport by sea ice. Traditional approaches to estuarine classification based on stratification and circulation have been improved upon as researchers consider additional forcing functions and influences (which may be biological) on mixing and residence times. A quantitative framework for prediction and management of estuarine responses to stressor loading remains to be established and demonstrated (NRC 2001).

Stressor Susceptibility

A series of statistical approaches were used by Biggs et al. (1989) to separate U.S. estuaries into groups based their susceptibility to pollution. They considered population and occupational data, such as total population and the proportion of workers in various industries (e.g., agricultural and primary metal workers), along with factors related to retention time and hydrology, e.g., freshwater discharge and watershed area. These parameters were the foundation for dividing estuaries into high, medium, and low susceptibility classes (Biggs et al. 1989).

Six additional classification systems address susceptibility to stressors in a more direct way. The National Oceanic and Atmospheric Administration (NOAA) designed Environmental Sensitivity Indices for coastal marine systems (NOAA 2003) and for Great Lakes coastal systems (USEPA 2001); the indices specifically predict the sensitivity of coastal areas to spills of oil and other hazardous substances.

Quantitative indices of estuarine susceptibility to a single class of stressors, nutrient overenrichment, have been developed by the NOAA (NOAA 1989; Bricker et al. 1999). Dissolved concentration potential (DCP) integrates nutrient loads with estimates of estuarine dilution (proportional to estuarine volume) and flushing (calculated from the replacement of the freshwater component of the total system volume by river flow). The DCP provides an estimate of average nutrient concentration throughout an estuary assuming there is no biological processing. High DCP systems concentrate nutrient inputs, whereas low DCP systems can be expected to dilute nutrient inputs. In other words, estuaries most susceptible to nutrient pollution are those that have a poor ability to dilute or flush incoming nutrient loads.

These calculations assume that there is no mixing or turnover of the water column and that the water column is homogeneous as opposed to stratified (NRC 2000). Mixing of freshwater coming into the system is not considered a dilution mechanism nor is the estuary's tidal prism. Several of the deficiencies of the DCP and particle retention efficiency approaches were addressed in NOAA's classification framework (Bricker et al. 1999), which incorporated aspects of stratification and tidal prism in an Estuarine Export Potential index (EXP). The calculations and metrics employed in the EXP should classify estuaries effectively on the basis of nutrient susceptibility, but multiple stressors are not addressed.

Ferreira et al. (2000) developed a qualitative estuarine quality index that included estuarine condition and risk from multiple stressors. Four different components were aggregated to determine estuarine quality: the capacity of the system to react to change, the trophic status of the water column, the trophic status of the benthos, and the condition of higher levels of the trophic structure. This decision-support system addresses vulnerability to a range of stressors, including nutrient loading and persistent pollutants, and includes components for sediment loading. The index amalgamates quantitative data, but also relies on a degree of expert-based heuristic evaluation, yielding semiquantitative results. The final index is a score of 1–5Ca broad comparative measure based on system condition, rather than a tool for detailed management of specific systems. Parameters needed to calculate an index for a specific system include fish and benthic community diversity measures and sediment quality indicator data that may not be available for a wide range of estuaries.

The WFD classification scheme for coastal and transitional waters (Anon 2003) requires classification of ecological status based on comparison of biological, hydromorpological, and physical elements between specific water bodies and reference or high status systems that are similar in type. For coastal waters, biological elements include descriptions of phytoplankton, benthic invertebrate, and other aquatic floral communities. Morphological conditions include variations in depth and structure of the bedded substrate and intertidal zone. Tidal regime is also considered and characterized in terms of current directions and wave exposure. Physical considerations include water clarity, temperature, salinity, oxygenation, nutrient status, and presence of specific pollutants. These factors are used to designate five ecological status classes: high, good, moderate, poor, and bad. Potential problems with implementation of the guidelines include availability of data on the suite of indicators recommended and determining values for the boundaries between environmental status classes for each parameter. Areas of uncertainty include spatial and temporal variability and sampling or analytical errors.

We identified only two classification approaches that considered vulnerability to multiple stressors quantitatively. Sklar and Browder (1998) identified the potential effects of altered freshwater flow, comparing effects from individual stressors to those caused by multiple stressors. Stefan et al. (1996) used a modeling approach to predict fish habitat susceptibility to global climate change. Sklar and Browder's (1998) in-depth examination of Gulf of Mexico systems investigated both direct and indirect effects of flow alterations, the former as mediated by the influence of freshwater flow on salinity, nutrients, sediments, dissolved oxygen, and toxic contaminants. To accommodate both positive and negative effects associated with altered freshwater flow, Sklar and Browder (1998) suggested that optimal levels of freshwater inputs for maximum ecosystem productivity were intermediate, with systems becoming stressed at both very low and very high flows. Responses of estuaries to altered freshwater flow are expected to vary depending on the geometry of the systems and to be apparent as changes in response variables, such as the area of isohaline zones or the rate of sediment inflow. They proposed three alternatives for managing freshwater flows to optimize system productivity or to reduce effects. The concepts they developed have proven to be useful for in-depth examination and management of particular Gulf of Mexico systems; additional research may demonstrate broader applicability to a wider array of systems.

Modeling approaches could yield significant insights into behaviors of different aquatic systems exposed to multiple stressors. Stefan et al. (1996) used such an approach to predict the susceptibility of various fish habitat types to global climate change and tested their predictions using a database for 3,002 Minnesota lakes. Twenty-two physical variables were reduced to a set of 9 explaining 80% of the variability among lakes. Three variables (lake surface area, maximum depth, and Secchi depth) were selected from those 9 to model expected habitat changes due to variations in temperature and dissolved oxygen. Lakes were separated into 27 classes based on a $3 \times 3 \times 3$ classification scheme (3 depth ranges, 3 surface area ranges, and 3 trophic state classes with associated Secchi depths). Stefan et al. (1996) combined monitoring data sets and lake classification with modeling exercises, illustrating differential sensitivity of lake classes based on morphometry and trophic state. The models provided a way to investigate the interactive effects of climate, eutrophication, transparency (including effects of suspended solids), and available habitat across lake classes. Elegant approaches like those of Stefan and colleagues have application to classification frameworks as a whole. We might expect that estuaries in general are intermediate between lakes and streams with respect to residence time, internal versus external influences, and responses to stressors.

Discussion

In this review, we have encountered several approaches to classifying estuaries and related systems. The basic distinctions appear to be among hierarchical and nonhierarchical, data-driven and theory- or judgment-driven, functional and structural approaches. Some classifications combine two or more of these methods or combine other tools like modeling. These two tools can be applied together, e.g., a generic process-oriented simulation model that could be reparameterized for each of several classes of systems (identified by classification analysis) could be used to predict stressor-response relationships. There is no one correct method; the purpose of the classification determines the method and the types of classes that are constructed.

Several authors have partitioned maps into unique areas known variously as biomes, ecological provinces, or ecoregions, with no two areas falling into the same class. The distinctions have been based on consistent climate, geology, plant or animal communities, or combinations of these attributes within each discrete area. Such systems are not classifications by strict definition, i.e., ''the grouping of things by classes or categories'' (The American Heritage Dictionary of the English Language 2000), because the objects are not grouped,

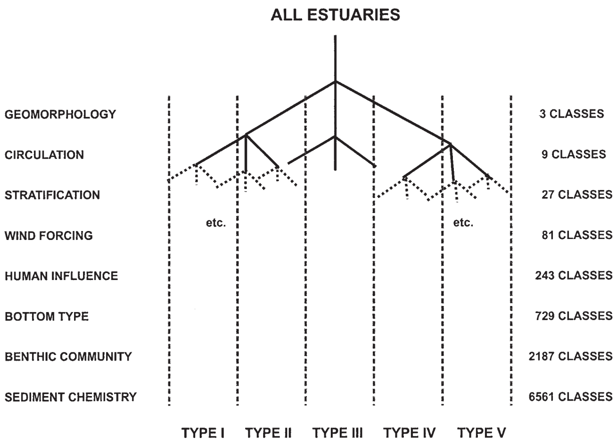

Fig. 2. Conceptual illustration of a top-down hierarchical classification system assuming three types within each major category of attributes. The dashed lines illustrate one method of aggregating into a manageable number of classes.

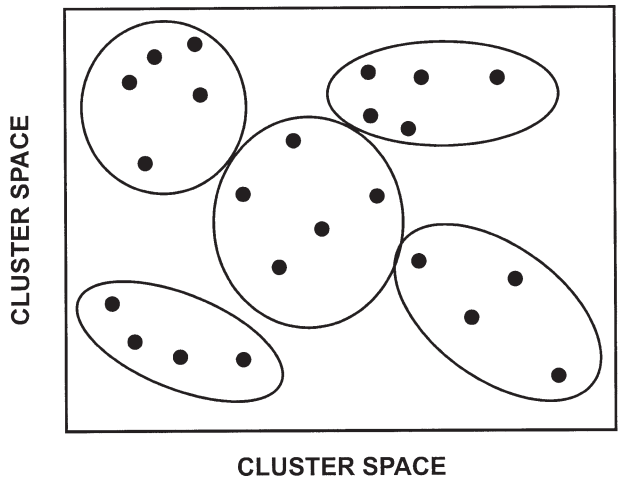

Fig. 3. Conceptual illustration of a nonhierarchical multivariate classification. Cluster space could have any number of dimensions; here they have been collapsed to two for simplicity.

rather they are given unique designations. Such regions might be used as strata for a classification system.

Hierarchical classifications can be top-down, i.e., beginning with all objects in one group and successively splitting the groups based on sets of attributes (Fig. 2), or bottom-up, i.e., beginning with each object as a separate class and successively grouping objects into more inclusive classes. The wetlands classification system of Cowardin et al. (1979) is an example of a top-down method, from which the level of classification (with more or less detail) can be chosen to suit a particular purpose or scale of analysis. Bottom-up methods are illustrated by hierarchical cluster analysis, which results in the familiar tree (dendrogram) diagrams where objects are grouped according to similarities among multiple attributes. Hierarchical classifications may be aggregated in various ways, based upon objective or subjective criteria, the number of classes appropriate to the investigator's purposes, and the geographic scales of interest. A cluster dendrogram, for example, can be aggregated based on an objective multivariate similarity or difference statistic; all objects that meet the numerical criterion are grouped within a single class. Figure 2 illustrates the need for aggregation in cases where many attributes are considered; the number of classes grows exponentially with the number of attributes.

Nonhierarchical methods of classification typically array objects along one or more qualitative or quantitative axes. The classes are then designated by partitioning the space defined by the axes. The Hansen and Rattray (1966) estuary classification system is an example of a nonhierarchical classification with two axes based on theoretical physical properties. Nonhierarchical cluster analysis is a data-driven method of classification by which any number of structural and functional attributes can be used to generate a specified number of classes (e.g., Jordan and Vaas 2000). In a typical application, objects are randomly assigned to the specified number of classes to initiate the analysis, then resorted repeatedly to minimize within-cluster variance, maximize between cluster variance, or satisfy other criteria. Here the distinction between classification and simulation modeling becomes blurred. A hybrid approach would be to use a generic process-oriented simulation model that could be reparameterized for each of several classes of systems (identified by classification analysis) to predict stressor-response relationships. The method can be used iteratively to optimize the number of classes for a given application; it also can estimate the relative contributions of individual attributes (variables) to the classification. Figure 3 is a conceptual illustration of a nonhierarchical, multivariate classification.

What we describe as functional classifications are based on relationships among two or more properties of the system (Fig. 4). To form classes, the functional space can be divided into quadrants or diagonals as in Fig. 4 or by more complex algorithms. A functional classification of estuary sensitivity to stressors might use the relationship between relative loads of contaminants and freshwater turnover or residence time. Theoretically, estuaries with low relative loads and short residence times should be least sensitive to stressor effects, whereas systems with high loads and long residence times should be most sensitive. Classes would be defined by ranges of coordinates within the two-dimensional space. In reality, several dimensions,

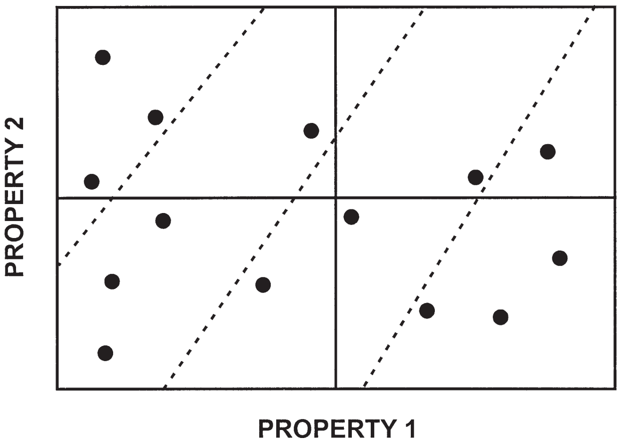

Fig. 4. Conceptual illustration of a functional classification system based on two variables. The coordinate space can be divided in various ways to generate classes, as illustrated by the solid and dashed lines within the frame.

including attributes and processes that affect the stressor-response relationship, might be necessary for a fully effective functional classification.

Our interest in classifying estuaries with respect to their sensitivity to specific stressors and groups of stressors will guide our choice of methods. Since one of our goals is to reduce the number of unique TMDLs for estuarine systems, the number of classes should be small, preferably less than 20. The attributes of each class should fall within distinct ranges that can be interpreted in terms of sensitivity to one or more stressors. Multivariate classifications always require a compromise between specificity and parsimony. With a large number of classes we retain more of the information in the original variables, but may not sufficiently satisfy the reason for classification, i.e., simplification of a complex problem. With a very small number of classes, the classification may lack the discrimination required for the intended application and is likely to be trivial, e.g., a classification into large, medium, and small estuaries. Objective statistical measures can be helpful in deciding the appropriate level of classification, but informed judgment and testing with real examples also must be employed.

A preliminary classification of U.S. estuaries (USEPA 2004) employed hierarchical cluster analysis of several physical variables and salinity. The resulting dendrogram was aggregated into 11 classes in nonalgorithmic fashion, i.e., by judgment of the investigators. Work is in progress on a second-stage classification, which will include chemical and biological variables in addition to physical attributes and salinity. The definitive method of classification has not been determined, but hierarchical and nonhierarchical cluster analyses will be conducted and compared for their applicability to the question of multiple-stressor sensitivity.

Conclusions

Classification research has cataloged, inventoried, mapped, and analyzed a variety of ecosystem types for various purposes and will continue to do so, since there is considerable need by environmental managers. Since our analysis, additional classifications have been brought to our attention. The first, a typology (TICOR: Bettencourt et al. 2003) classifies Portuguese coastal and transitional waters into seven types based on morphology. Consideration is also given to benthic and pelagic reference conditions, measures, and condition determinations by type or class. Second, a classification for conserving biodiversity has been developed in Australia. This conservation lands classification accounts for the level of management or protection in place for the areas considered, and is intended for application on an international basis (Fitzsimons and Wescott 2004). These classifications provide a useful common ground for defining concepts, terms, regions, and scales to promote understanding and uniformity in applications. The logic and structure of such frameworks facilitates compilation and analysis of data in more comprehensive and efficient ways, using application tools such as databases and models.

The information systems that result have the potential to use empirical mapping and monitoring from field studies and data from newer technologies such as satellite imagery, remote sensing, and modeling studies (Jay et al. 2000). The simpler hydrographic-geomorphic-landscape models can more readily be parameterized for broad geographic areas. Considerable bodies of data exist to populate such models, and research for classification and modeling results in data compilation and analyses that expand what we know about well-studied areas to those that are less well known. Efforts like the Land-Ocean Interactions in the Coastal Zone project of the International Geosphere Biosphere Programme result in organizing data to characterize the role of the coastal zone in fluxes of carbon, nitrogen, and phosphorus on a global scale. The project is a repository for validated, consistently expressed biogeochemical budget data on well-studied coastal areas for extrapolation to less well-studied areas determined to be similar on the basis of classification (Bartley et al. 2001).

Including biogeochemical and ecological factors in classification systems becomes more important as classification systems transcend a structural or descriptive role to a more function-based role useful for diagnosis and prediction. Data describing biological responses or effects on trophic state are not as well-developed nor do they apply to broad geographic areas. Yet much can be learned from smaller studies focused on biological responses and such studies are a logical focus for future research. The experience gained from studying a few areas in detail can be placed in a larger context to enhance our knowledge of similar but less studied areas. Information systems that successfully compile and synthesize the relevant data across many systems, encompassing broader spatial and temporal scales, will reveal similarities in the way biological populations and communities respond to stressors. Detecting similarities in response patterns will improve the predictive and proactive capability for classification frameworks and their utility as management tools.

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