CHAPTER 3

Classification of Estuarine and Coastal Waters

3.1 INTRODUCTION

Purpose and Background

Classification is an important step in addressing the problem of degradation, especially because of nutrient overenrichment. There are too many nutrient-degraded estuaries in the United States for the Nation to conduct comprehensive ecosystem studies of all those affected by overenrichment. Where possible, similar estuaries, tributaries, or coastal reaches should be equated through physical classification to reduce the magnitude of the criteria development problem and to enhance predictability of management responses. To be useful, classification should reduce variability of ecosystem-related measures (e.g., water quality factors) within identified classes and maximize interclass variability. This is important because managers need to understand how different types of estuaries and coastal waters, as well as important habitat differences within these systems, respond to nutrient overenrichment in order to plan effective management strategies.

The ecosystem processes that regulate nutrient dynamics, discussed in Chapter 2, should provide the elements for initial development of a useful classification system. Although predicting susceptibility of estuarine and coastal waters to nutrient overenrichment is in a primitive state, several approaches are reviewed because they have some utility even if they are only marginally adequate for prediction of nutrient effects. The general approach is also appropriate for coastal systems.

General trends relate N loading with chlorophyll and primary productivity; however, these trends are seldom usefully predictive for individual systems or for all classes of coastal systems (Kelly in press). Progress has been especially slow in predicting many of the secondary, but societally important, effects of nutrient overenrichment, e.g., bottom water dissolved oxygen (DO) deficiency, harmful algal blooms (HABs) or species-specific HABs, formation of macroalgal mats, fisheries productivity, and species composition. For many cross-system comparisons, N loading and SAV decline have become more predictive than for other indirect effects (Duarte 1995; Dennison et al. 1993), but even here the predictions may be confounded by highly variable ecosystem factors. A major impedance to effective understanding is limited comparative studies designed to test hypotheses regarding estuarine susceptibility to nutrient enrichment (Turner 2001). Post hoc comparative approaches and assessment of disparate studies have been useful but clearly inadequate (Livingston 2001b).

Post hoc statistical approaches have helped explain some of the variability in eutrophication, but have not captured the actual mechanisms and their interactions controlling eutrophication across estuaries and coastal waters (NRC 2000). The ability to explain the mechanisms in a predictive manner is clearly a critical national and global research need, as nutrient overenrichment of coastal ecosystems extends far beyond the shores of the United States. For site-specific criteria, several approaches are available, including empirical regression and mechanistic simulation models. The large effort typically required to calibrate and verify mechanistic models is an indicator of the difficulty in understanding the many potential confounding factors of ecosystem-level prediction. A basic premise of this manual is that knowledge of the physical setting and the minimally disturbed ecosystem reference condition must underpin monitoring and management efforts to protect and restore coastal systems impaired by nutrient overenrichment.

Only in approximately the past two decades have comparative studies of nutrient dynamics among two or more relatively large estuaries been published (e.g., Fisher et al. 1988; Malone et al. 1999; Pennock et al. 1994). Comparative analysis of the Delaware and Chesapeake Bays has provided insights regarding processes that control expression of nutrient enrichment (Chapter 2). For example, both systems are drowned river mouth coastal plain estuaries and are located adjacent to each other along the coast, but have very different responses to nutrient loading. Delaware Bay has a somewhat larger nutrient load than the Chesapeake, but has few of the nutrient enrichment symptoms well chronicled for the Chesapeake Bay (Flemer et al. 1983, Sharp et al. 1994, Chesapeake Bay Program Periodic Status Reports). Similar insights have been provided by comparing nutrient processes between Delaware and Mobile Bays (Pennock et al. 1994). Susceptibility appears to be largely explained by differences in the physics of flushing, including bathymetry and related physical habitat differences.

Defining the Resource of Concern

As a first step in classification, defining the resource of concern is important. Resources of concern are estuaries and coastal waters located in the contiguous States or within authorized Tribal lands. Managers must decide which waterbodies to include in the population to which criteria will be applicable. A lake classification may exempt small ponds that might be excluded because of their size and man-made nature, whereas tidal creeks, although small, still have a functional connection to the larger estuary and might not be excluded because of size. Many estuaries and coastal waters share multiple political boundaries, and for the sake of consistency all involved jurisdictions should jointly decide on the scale of inclusiveness. For open coastal waters, a State or authorized Tribe's legal authority may extend for a relatively short distance on the continental shelf, e.g., 3 nautical miles. However, coastal oceanographic processes seaward of the statutory limit likely influence nutrient overenrichment processes and exacerbate the difficulty of diagnosing the anthropogenic contribution to nutrient problems.

3.2 MAJOR FACTORS INFLUENCING ESTUARINE SUSCEPTIBILITY TO NUTRIENT OVERENRICHMENT

The NRC (2000) publication summarized approximately a dozen factors deemed important to characterize the susceptibility of estuaries to nutrient loading. A short list is provided; however, it is expected that the following list will be modified and refined as more is learned about the subject:

1. System dilution and water residence time or flushing rate
2. Ratio of nutrient load per unit area of estuary
3. Vertical mixing and stratification
4. Algal biomass (e.g., chlorophyll *a*, and chlorophyll *a* corrected for nonchlorophyll *a* light attenuation over seagrass/SAV beds and macroalgal biomass as AFDW)
5. Wave exposure (especially relevant to seagrass potential habitat)
6. Depth distribution (bathymetry and hypsographic profiles)
7. Ratio of side embayment (s) volume to open estuary volume or other measures of embayment influence on flushing.

Several terms listed above are briefly discussed because their significance often is not adequately appreciated.

Dilution

The volume of an estuary affects its ability to dilute inflowing nutrients. Thus, the loading rate of nutrient per unit volume of the estuary is a better indicator of the potential for exceeding the assimilative capacity of the estuary as a whole than is the absolute loading rate. This ratio may not express the potential for local effects near the point of entry into the estuary, as nutrients there are diluted by only a fraction of the total estuary volume. The potential for such local effects is reduced if mixing into the main body of the estuary is rapid.

Water Residence Time

Estuaries that flush rapidly (i.e., have a short residence time) will export nutrients more rapidly than those that flush more slowly, resulting in lower nutrient concentrations in the estuary. Dettmann (in press) has derived a theoretical relationship between the mean residence time of freshwater in an estuary and the increase in the average annual concentration of total nitrogen in the estuary as a result of inputs from the watershed and atmosphere. In addition, estuaries with residence times shorter than the doubling time of algal cells will inhibit formation of algal blooms. Residence time or flushing rate is discussed in more detail in Appendix C.

Stratification

Highly stratified systems are more prone to hypoxia than are vertically mixed systems. Stratification not only limits downward transport of oxygen from atmospheric reaeration, it also retains nutrients in the photic zone, making them more available to phytoplankton. In stratified systems, it may be more appropriate to estimate the dilution potential of the estuary using the volume above the pycnocline rather than the entire volume of the estuary.

It is expected that the shortened list will be revised and modified as more is learned about factors important in estuarine and coastal waters classification. Some of these factors will apply to estuaries and others to coastal waters.

3.3 EXAMPLES OF COASTAL CLASSIFICATION

Scientists and resource managers have used various classification schemes for many years to organize information about ecological systems. As discussed earlier, estuaries and coastal water systems are characterized by a suite of factors (e.g., river flow, tidal range, basin morphology, circulation, and biological productivity) that are ultimately controlled largely by geology and climate. A review of Chapter 6 in the NRC (2000) publication provides useful descriptions of the various approaches to estuarine classification, and some pertinent features are highlighted below.

Geomorphic Classification

Geomorphic classification schemes provide some insight into the circulation structure and are a first-order estimate of water residence time or flushing characteristics. Such classifications may not in themselves be predictive of susceptibility to nutrient enrichment, but they are a useful place to begin a first-order assessment of susceptibility. Knowledge of deep channels, however, identifies potential areas subject to hypoxia, and the extent of shallow waters and associated factors (e.g., wind fetch) often provides insights into potential seagrass habitat.

Estuaries can be divided geomorphically into four main groups (Pritchard 1955, 1967; Dyer 1973): (1) coastal plain estuaries, (2) lagoonal or bar-built estuaries, (3) fjords, and (4) tectonically caused estuaries. This classification frequently appears in textbooks, and only some important features relative to nutrient susceptibility are described.

Coastal Plain Estuaries: Classical and Salt Marsh

Both subclasses are characterized by well-developed longitudinal salinity gradients that influence development of biological communities. Examples of the classical type include the Chesapeake Bay (the largest estuary of this type), Delaware Bay, and Charleston Harbor, SC. Vertically stratified systems with relatively long residence times (e.g., Chesapeake Bay) tend to be susceptible to hypoxia formation. Pritchard (1955) further classified drowned river valley estuaries into four types (A-D) depending on the advection-diffusion equation for salt (Table 3-1). Type C estuaries are less sensitive to algal bloom formation and hypoxia because of mixing features.

The salt marsh estuary lacks a major river source and is characterized by a well-defined tidal drainage network, dendritically intersecting the extensive coastal salt marshes (Day et al. 1989). Exchange with the ocean occurs through narrow tidal inlets, which are subject to closure and migration following major storms (e.g., Outer Banks, NC). Consequently, salt marsh estuarine circulation is dominated by freshwater inflow, especially groundwater, and tides. The drainage channels, which seldom exceed a depth of 10 m, usually constitute less than 20% of the estuary, with the majority consisting of subaerial and intertidal salt marsh. These systems are a common feature of the Atlantic coast, particularly between Cape Fear, NC, and Cape Canaveral, FL. Mangrove estuaries occur from around Cape Canaveral south on Florida’s east coast and on Florida’s west coast from around Tarpon Springs south. Nutrient dynamics, primary production, and system respiration that occur within emergent marshes may greatly affect water quality in the estuarine channels (Cai et al. 1999).

Table 3-1. General drowned river valley estuarine characteristics

Estuarine type[a]	Dominant mixing force	Mixing energy	Width/depth ratio	Salinity gradient	Mixing index[b]	Turbidity	Bottom stability	Biological productivity	Example
A	River flow	Low	Low	Longitudinal vertical	≥ 1	V. high	Poor	Low	Southwest Pass Mississippi River
B	River flow, tide	Moderate	Moderate	Longitudinal vertical	<1/10	Moderate	Good	V. high	Chesapeake Bay
C	Tide, wind	High	High	Longitudinal lateral	<1/20	High	Fair	High	Delaware Bay
D	Tide, wind	V. high	V. High	Longitudinal	?	High	Poor	Moderate	?

[a]Follows Pritchard's advection-diffusion classification scheme.
[b]Follows Schubel's definition: MI = equation here▸ (vol. freshwater discharge on ½ tidal period) / (vol. tidal prism).
Source: Neilson and Cronin, 1981.

Lagoons
Lagoons are characterized by narrow tidal inlets and are uniformly shallow (i.e., less than 2 m deep) open-water areas. The shallow nature enhances sediment–water nutrient cycling. Flushing is typically of long duration. Most lagoonal estuaries are primarily wind-dominated and have a subaqueous drainage channel network that is not as well drained as the salt marsh estuary. Lagoons fringe the coast of the Gulf of Mexico and include the mid-Atlantic back bays; Pamlico Sound, NC; and Indian River Lagoon, FL. Although these systems are typically shallow, they may have pockets of hypoxic water subject to spatial variability because of freshwater pulsing and wind effects. Some lagoonal systems have relatively strong vertical stratifications near the freshwater river mouth and may be subject to hypoxia formation (e.g., Perdido Bay, AL/FL; Livingston 2001a).

Fjords and Fjordlike Estuaries
Classical fjords typically are several hundred meters deep and have a sill at their mouth that greatly impedes flushing. Hypoxia/anoxia is often a natural feature but anthropogenic nutrient loading can severely exacerbate the problem. Examples of classical fjords on the North American continent can be found in Alaska and Washington State (Puget Sound). Some other estuaries were also formed by glacial scouring of the coast, but in regions with less spectacular continental relief and more extensive continental shelves. Examples of these much shallower, fjordlike estuaries can be found along the Maine coast.

Tectonically Caused Estuaries
Tectonically caused estuaries were created by faulting, graben formation (i.e., bottom block-faults downward), landslide, or volcanic eruption. They are highly variable and may resemble coastal plain estuaries, lagoons, or fjords. San Francisco Bay is the most studied estuary of this type (Cloern 1996).

Man-Made Estuaries
Especially around the Gulf of Mexico, dredged bayous, canals, and salt water impoundments with weirs function as estuaries but do not fit well any of the other types presented. As a special case, especially in the Gulf of Mexico, the passes of some estuaries periodically were closed off by storms and historically remained closed until a natural event reopened them (e.g., Perdido Bay, AL/FL; R. Livingston, personal communication). In recent years, these systems typically are maintained in an open condition by dredging. Dredged inlets such as at Ocean City, MD, also fit this classification.

Physical/Hydrodynamic Factor–Based Classifications
Classification Using Stratification, Mixing, and Circulation Parameters
Estuarine circulation was a dominant consideration used in an earlier classification of the Chesapeake Bay, a coastal plain system, and major tributaries, and is largely utilized today with some modifications (Flemer et al. 1983). Coastal plain estuaries are sometimes classified by mixing type: highly stratified, partially mixed (moderately stratified), or well mixed (vertically homogeneous). The flow ratio of these estuaries (the ratio of the volume of freshwater entering the estuary during a tidal cycle to its tidal prism) is a useful index of the mixing type. If this ratio is approximately 1.0 or greater, the estuary is normally

highly stratified; for values near 0.25 the estuary is normally partially mixed; and for ratios substantially less than 0.1, it is normally well mixed (Biggs and Cronin 1981).

Stratification/Circulation Parameters

Hansen and Rattray (1966) developed a two-parameter classification scheme based on circulation and stratification of estuaries. Circulation is described by the nondimensional parameter U_s/U_f, where U_s is the net (time-averaged) longitudinal surface current and U_f is the cross-sectional average longitudinal velocity. Stratification is represented by the nondimensional parameter $\delta S/S_o$, where δS is the top-to-bottom difference in salinity and S_o is the mean salinity. Jay et al. (2000) review alternative two-parameter classification schemes involving parameters such as the ratio of tidal amplitude to mean depth, along-estuary and vertical density differences and vertical tidal excursion of isopycnals, or other factors that take into account effects of tidal flats and provide additional discussion to which the reader is referred for additional insights. They argue that the merit of the approach is its simplicity of parameters employed and the predictive ability with regard to salt transport needed to maintain salt balance in modeling.

Classification Using Water Residence Time

Water residence time, the average length of time that a parcel of water remains in an estuary, influences a wide range of biological responses to nutrient loading. The residence time of water directly affects the residence time of nutrients in estuaries, and therefore the nutrient concentration for a given loading rate, the amount of nutrient that is lost to internal processes (e.g., burial in sediments and denitrification), and the amount exported to downstream receiving waters (Dettmann in press, Nixon et al. 1996). Residence times shorter than the doubling time of algae will inhibit bloom formation because algal blooms are exported from the system before growing to significant numbers. Residence time can also influence the degree of recruitment of species reproducing within the estuary (Jay et al. 2000).

There are a number of definitions of water residence time, including freshwater residence time and estuarine residence time (Hagy et al. 2000; Miller and McPherson 1991), each with its own interpretation and utility. Freshwater residence time is the mean amount of time required for freshwater entering the estuary to exit the seaward boundary, whereas estuarine residence time is the average residence time in the estuary for all water, regardless of its origins. Because nutrient loading is generally associated with freshwater inputs, freshwater residence time is generally the most useful measure in considering estuary sensitivity to nutrient loading. Freshwater residence time of a given estuary is influenced by numerous factors, including freshwater loading rate (Pilson 1985; Asselin and Spaulding 1993; Hagy et al. 2000), tidal range, and wind forcing (Geyer 1997), and therefore varies over a range of time scales.

Residence time and volume together may be used to scale nitrogen loading to estuaries to permit calculation of nitrogen concentrations and perform cross-system comparisons. Dettmann (in press) uses a model that includes mechanistic representations of nitrogen export and loss within estuaries to show that $[N_u]$, the contribution to the annual average concentration of total nitrogen in an estuary from upland sources (watershed, direct discharges, and atmosphere), may be calculated as

$$[N_u] \quad \left(\frac{L_l \tau_{fw}}{V}\right) \frac{1}{1 \quad \alpha\tau_{fw}}$$

where L_l is the annual average loading rate (mass/month) of total nitrogen from all upland sources (watershed and atmosphere), J_{fw} is the freshwater residence time in months, *V* is the estuary volume, and " is a parameter (value = 0.3 month^{-1}) related to losses of nitrogen to processes such as denitrification and burial in sediments within the estuary.

Definitions of residence time, the methods used to measure or calculate them, variability of residence time, and other estimators of residence time are described further in Appendix C.

River Flow, Tides, and Waves

Dronkers (1988) proposed an estuarine classification that distinguished various types of estuarine ecosystems based on water exchange processes (e.g., river flow, tides, and waves) that greatly affect energy and material fluxes including mixing (Table 3-2). This classification suggests that river flow in partially mixed estuaries is essentially neutral, but its variation relative to hydrodynamic residence time can be important in interpreting property-salinity diagrams (Cifuentes et al. 1990) (Figure 3-1). River flow in the partially mixed mainstem of the Chesapeake Bay is seasonally important.

Tidal Amplitude—A Dominant Physical Factor

Tidal amplitude provides a means to broadly classify estuaries relative to their sensitivity to nutrient supplies. Monbet (1992) analyzed phytoplankton biomass in 40 estuaries and concluded that macrotidal estuaries (mean tidal range $\geq$2 m) generally exhibit a tolerance to nitrogen pollution despite high loadings originating from freshwater outflows (Figures 3-2a, b). These systems generally exhibit lower concentrations of chlorophyll *a* than do systems with lower tidal energy, even when they have comparable concentrations of nitrogen compounds. Estuaries with mean annual tidal ranges $\leq$2 m seem more sensitive to dissolved nitrogen, although some overlap occurs with macrotidal estuaries.

NOAA Scheme for Determining Estuarine Susceptibility

NOAA (Bricker et al. 1999) developed a categorical approach based on surveys and decision rules that led to a classification of estuarine nutrient export potential (e.g., dilution potential and flushing potential). From this information a susceptibility matrix was constructed. The low, moderate, and high susceptibility indices were combined with low, moderate, and high human levels of nutrient input, resulting in a final matrix of overall human influence (see Appendix D for details).

Comparative Systems Empirical Modeling Approach

The empirical regression method can be used to determine the response of estuarine systems to nutrient loading. This approach requires that the response factor be common to all systems in the analysis and assumes that any graded response among systems is due to a common form of disturbance, e.g., nutrients. The space-for-time paradigm (Pickett 1988) posits that relationships between nutrient inputs and

Table 3-2. Classification of coastal systems based on relative importance of river flow, tides, and waves to mixing

Type	River flow	Tide	Waves	Description
I		–	–	River delta
II		–		River delta (plus barriers)
III			–	Tidal river delta
IV	0		–	Coastal plain estuary
V	–			Tidal lagoon
VI	–		–	Bay
VII	–	–		Coastal lagoon

Plus and minus designations indicate relative impacts; e.g., – means that river discharge is very small relative to tidal and wave energy.
Source: Adapted from Dronkers 1988.

ecologically meaningful estuarine responses, using multiple systems, have predictive capability, at least for the systems used in the model development. This allows for a wide range in nutrient loading and estuarine types to be included. The comparative-systems empirical approach has been used to determine, for example, relationships between nutrient inputs and fish yields (Lee and Jones 1981, Nixon 1992), benthic biomass, production and abundances (Josefson and Rasmussen 2000), summer ammonia flux (Boynton et al. 1995), chlorophyll *a* concentration (Boynton et al. 1996, Boynton and Kemp 2000, Monbet 1992), primary productivity (Nixon et al. 1996), and the dominant source of primary productivity (Nixon et al. in press). In many of these cases, important environmental factors such as flushing time and depth are used to normalize the nutrient loading in a similar way as Vollenweider (Vollenweider 1976) Did for lakes to yield more precise relationships. Appendix E provides additional details.

Other Considerations

Habitat Type

The presence and extent of different habitat/community types may help distinguish one or more estuaries within a region. These types may include seagrasses, mangroves, mudflats, deep channels, oyster reefs, dominance of sand versus mud bottoms, extensive emergent marshes (typically coastal plain systems), and the presence of unconsolidated versus rocky shorelines. Some of these categories may be subclassified by salinity ranges (e.g., oligohaline, mesohaline, and polyhaline). Although related more to water quality, blackwater versus turbid versus relatively clear estuaries defines a group representative of estuaries around the Gulf of Mexico.

Theoretical Considerations

Coastal zone managers may wish to consider more theoretical approaches to classification as ecosystem science develops a more in-depth understanding of ecosystem processes for estuaries under their purview. Several different approaches are described in Appendix F.

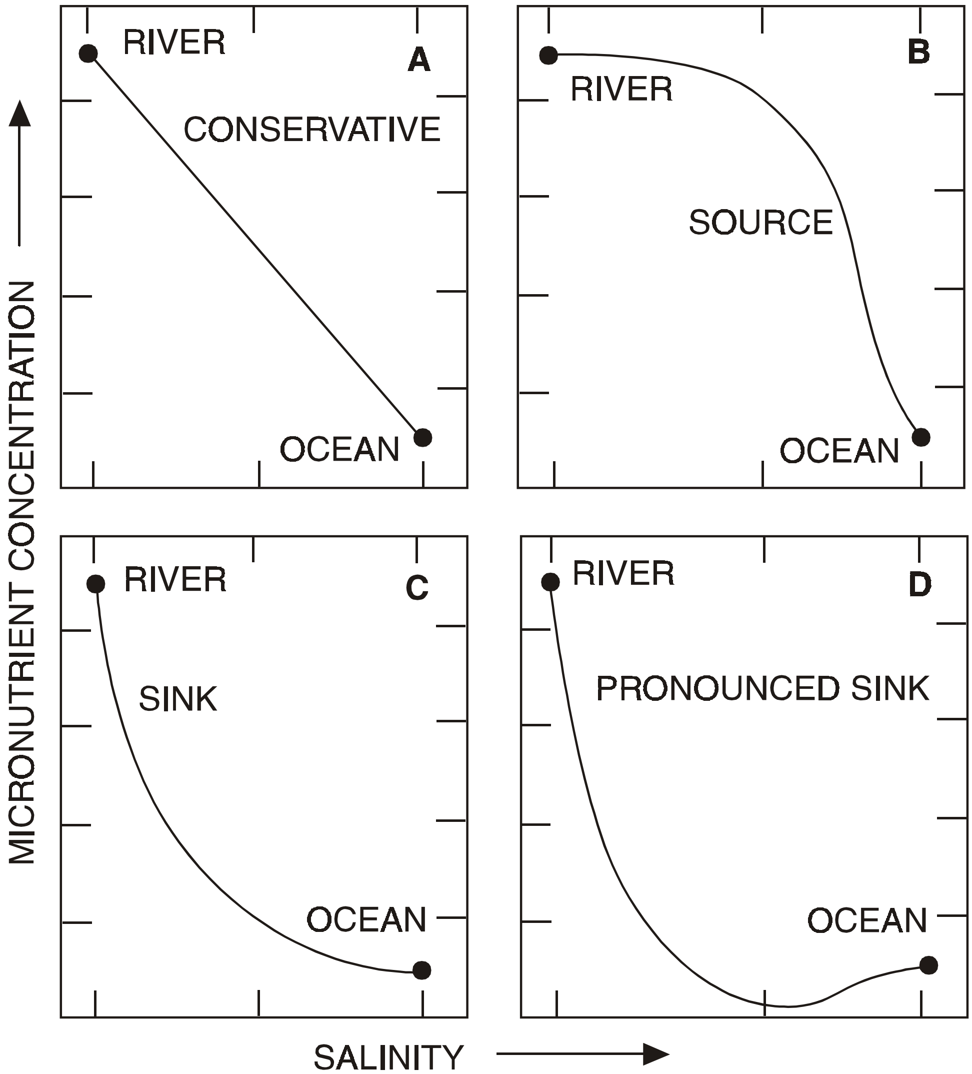

Figure 3-1. Idealized micronutrient-salinity relations showing concentration and mixing of nutrient-rich river water with nutrient-poor seawater. Source: Peterson et al. 1975. A. Expected concentration-salinity distribution of a substance behaving in a conservative manner (e.g., chloride) in an estuary. B. Expected concentration-salinity distribution of a substance for which the estuary is a source (e.g., particulate carbon). C. Expected concentration-salinity distribution of a substance for which the estuary is a sink (e.g., phosphorus). D. Expected concentration-salinity distribution of a substance for which the estuary is a pronounced sink, that is, where the concentration of the substance in the estuary is lower than the river and the ocean (e.g., Si). Source: Biggs and Cronin 1981.

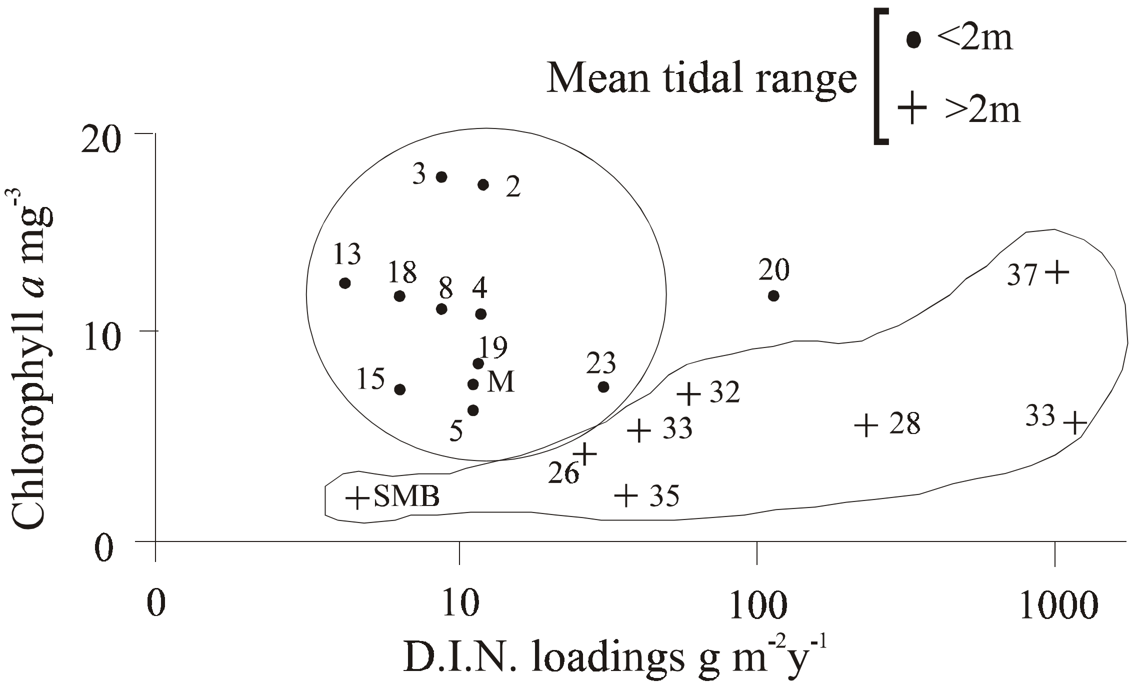

Figure 3-2a. Relationship between the mean annual loadings of dissolved inorganic nitrogen (DIN) and the mean annual concentration of chlorophyll *a* in microtidal and macrotidal estuaries.

Summary

Various ways are available to classify estuaries regarding their vulnerability to nutrient enrichment. None appear to provide all the information a resource manager may want for decisionmaking. The NOAA estuarine export potential (EXP) appears to have the current greatest utility for predictive purposes for large systems, but even this approach embodies considerable variability (e.g., see Figures 6-5 and 6-6 in NRC 2000). For embayments within a larger estuary, the comparative empirical modeling approach has been demonstrated to have considerable utility. The more theoretical models eventually may provide greater predictive power, especially as to biological sensitivities to nutrient enrichment. They are data intensive and may become more useful at a future time.

3.4 COASTAL WATERS SEAWARD OF ESTUARIES

Several approaches are available to classify coastal waters. The geomorphic focus is a good place to begin, hydrographic considerations should follow, and finally habitat and community features should be considered. Although functional considerations and theoretical indices are not described for coastal waters, they have as much relevance for these waters as they do for estuaries. Even though much of the concern for coastal waters will be within 20 nautical miles of shore, and most of that within the 3-mile limit, elements of the following large-scale classification scheme will have value to the manager and investigator.

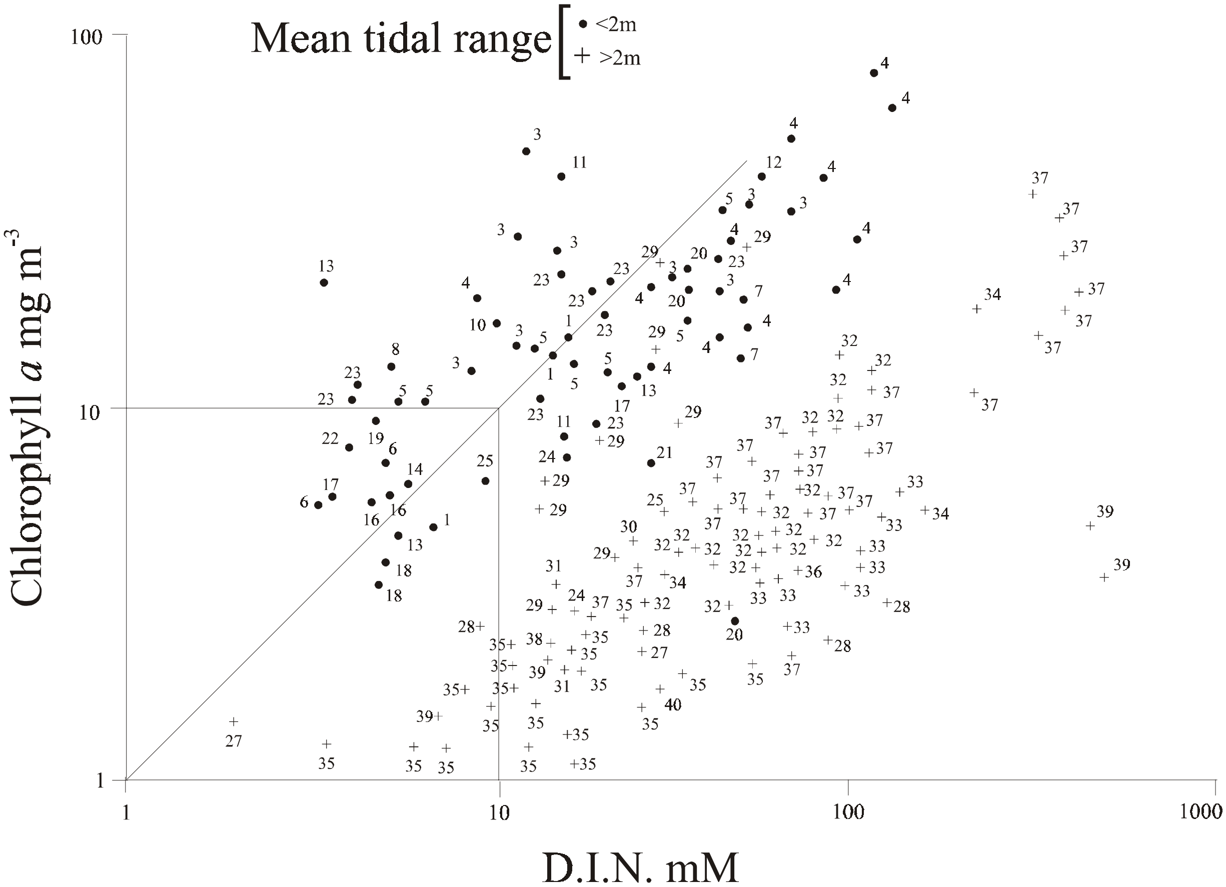

Figure 3-2b. Relationship between the mean annual concentrations of dissolved inorganic nitrogen (DIN) and chlorophyll *a* in microtidal and macrotidal estuaries. Source: Monbet 1992.

Geomorphic Classification

The flow of energy and nutrients through coastal food webs differs greatly among continental shelves, and is driven largely by differences in the form and amount of primary production (e.g., seagrasses are important in the Big Bend area of Florida and kelp forests are important habitats along much of the U.S. Pacific Coast and sections of coastal Maine). These differences in turn ultimately are determined by differences in local and ocean-scale patterns of climate (e.g., light and temperature effects), water circulation, chemistry, and shelf geomorphology (Alongi 1998). The spring bloom, especially along the U.S. Atlantic Coast, generally progresses from low to higher latitudes but with sharper seasonal peaks toward higher latitudes. Variability in the progression should be considered in any classification scheme. Because near-coastal shelf oceanographic processes usually are not limited by the jurisdiction of a single State, it is important that a similar classification approach be shared among coastal States, where that oceanography determines the sensitivity of the ecosystem to nutrient enrichment. The geographic extent of the shelf in which a State has jurisdiction is a useful place to begin classification. Here one should consider whether the shelf is wide or narrow (e.g., mid-Atlantic versus Pacific Coast). The Texas coastal shelf is very wide, with a gentle slope compared with much of the northern Gulf of Mexico. The steepness of the slope is another useful factor, as it may influence bottom sediment stability and upwelling. The degree of bottom roughness or sculpture may influence vertical mixing, which may in turn influence water column stability and depth of the euphotic zone versus mixing depth.

Nongeomorphic Classification

Walsh characterized the world's continental shelves on the basis of their location, major rivers, and rates of primary production, and included some U.S. coastal waters for comparison. The shelf proper is where oceanic and estuarine boundaries often intermingle. At the shelf edge, cold, nutrient-rich water and associated materials intrude onto the shelf. There, exchanges often are rapid, promoting conditions favorable for higher fertility than in the open ocean. Higher primary productivity is the main reason why approximately 90% of the world's fish catch is harvested on the continental shelves versus the open sea (Alongi 1998).

Water Quality Trend Detection on the Shelf

Physical mixing and advective processes may add considerable variability to water column measures. Therefore, it is important to consider detection of trends in nutrient concentrations and measures such as chlorophyll *a* based on comparisons at a reference salinity (e.g., 30 psu). Otherwise, classification schemes may incur extraneous variability. A common approach is to use "mixing diagrams" to compare measured changes in an ambient constituent among sampling periods. At mid- and higher latitudes, winter measures of DIN and DIP may provide insight into long-term trends of changes in nutrient concentrations available to drive the spring bloom. At low latitudes winter values will likely have less applicability, as primary production has a smaller seasonal signal.

Presence of Large Rivers

Although large rivers are included in Walsh's characterization of shelf systems, it seems useful to distinguish shelf areas based primarily on large rivers, such as the Mississippi River in the Gulf of Mexico and the Columbia River off the Washington-Oregon coast. Large rivers on the shelf dominate local ecological relationships.

Hydrographic Features

Vertical salinity differences tend to decrease toward the open ocean boundary. The principal reason is summertime thermal stratification. The thermocline tends to be deeper toward the open sea margin, except where buoyancy effects are associated with large rivers that flow onto the shelf. Coastal waters contain a variety of biotic communities, including a diverse assemblage of macroepifauna and -infauna, kelp forests, coral reefs, bottom and pelagic fishes, marine mammals, and seabirds. The relationship of these communities to physical-ordering factors can assist in classification.

Temperate and subtropical coastal waters also experience a seasonal sea-level fluctuation, whereby summer levels rise approximately 0.2 m by upper-ocean heat expansion, producing what is known as thermosteric effects (Pattulo et al. 1955, Bell and Goring 1998). This nontidal process operates in conjunction with other factors affecting apparent mean sea level (e.g., near and far-field wind effects and barometric pressure). Depending on local conditions, water levels overlying the continental shelf and in estuaries can rise from 0.1 to 0.2 m. Such a rise may seem nominal but can have a significant impact in wetlands and other low-lying areas that potentially exchange nutrients and suspended sediments with the coastal ocean.

Coastal ocean waters range from quite cold (e.g., Gulf of Maine) to quite warm (e.g., Gulf of Mexico). Where large rivers enter coastal waters, such as the Mississippi River Plume and Chesapeake Bay Plume, visual discoloration can be observed because suspended material from land runoff and relatively high plankton concentrations contrast with the predominantly blue color of the open ocean. The Columbia River and the Mississippi River form an "estuary" mostly at sea, as very little of the diluted seawater is bounded by land.

Physical gradients are dynamic and change at multiple scales. Seasonal or wet and dry periods frequently differ depending on the various shelf gradients associated with estuarine, riverine, and ocean/shelf break processes. Regional geomorphology and physical mixing processes play a pivotal role in energy flow and material cycles. For example, the Loop Current in the eastern Gulf of Mexico may show seasonal reversals and vary seasonally in its penetration onto the shelf. Along-shore drift inside the north-flowing Gulf Stream off the Mid-Atlantic Bight tends to transport materials southward toward the North Carolina coast. Further south, the Gulf Stream forms a seaward boundary that tends to significantly isolate in-shore waters from those beyond the shelf break. Local current maps are available from the National Ocean Service of NOAA (www.noaa.gov; then click on nos).

Many different types of boundaries or fronts occur in coastal seas, but no formal classification exists. Alongi (1998) lists five categories:

- Shelf-sea (tidal) fronts
- Estuarine fronts or plumes
- Shelf-break fronts
- Upwelling fronts
- Island wakes and fronts caused by other land features

Fronts provide increased physical stability at local scales, which may positively influence primary production and energy flow to higher trophic levels (see Chapter 2).

Habitat/Community Differences

Presence of Mangrove/Seagrass and Coral Communities

Along the southeastern Florida Atlantic coast exists a combination of mangrove, seagrass, and coral reef ecosystems. In some localities, each community type may dominate the others, but often they co-occur. Seagrass communities may dominate certain shelf areas along the west coast of Florida (e.g., Big Bend region). The Flower Gardens, a disjunct coral community, exist off the southern coast of Texas. Alongi (1998) devotes chapters to coral reefs and mangrove ecosystems including factors regulating primary productivity (e.g., N and P). The role of N and P enrichment versus grazing in coral reef ecosystems is still strongly debated in the scientific literature (e.g., Miller et al. 1999). A paper by Chen and Twilley (1999) discusses soil nutrient relationships and productivity in a Florida Everglades mangrove ecosystem along an estuarine gradient (see the references cited above for the most recent perspective). These distinctive ecosystems provide a basis for local coastal waters classification. Mangrove communities also occur along the lower Texas coast, and seagrasses are a dominant community in Laguna Madre, TX.

Presence of Seaweed

Seaweeds are common algal communities in rocky intertidal zones (e.g., *Fucus* spp.), attaching themselves by means of a holdfast. Seaweeds belong to three marine algal classes: *Chlorophyceae* (green algae), *Rhodophyceae* (red algae), and *Phaeophyceae* (brown algae). The kelps (*Laminariales*), members of the brown algae, live subtidally but in relatively shallow waters and can form large forests along the cooler north Atlantic and Pacific coasts. These communities also may occur in the higher salinity reaches of estuaries. Alongi (1998) provides a discussion of primary production, factors limiting growth, nutrient cycling, and grazing in these communities.