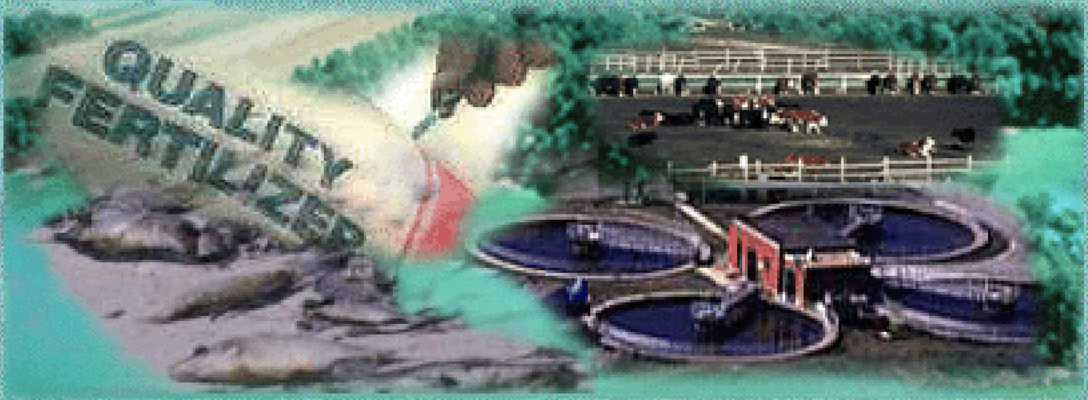
EUTROPHIC CONDITIONS IN ESTUARINE WATERS



High expressions of eutrophic conditions are exhibited in 44 estuaries of the coterminous United States, representing approximately 40% of the national estuarine surface area. An additional 40 estuaries exhibit moderate conditions. When considered together, the estuaries with moderate to high eutrophic conditions represent approximately 65% of the nation's estuarine surface area. High conditions, determined by assessing the extent of primary and secondary symptoms of eutrophication, occur in estuaries along all coasts, but are most prevalent in estuaries along the Gulf of Mexico and Middle Atlantic coasts. A high level of human influence is associated with 36 of the 44 estuaries with high eutrophic conditions. While high levels of primary symptoms, such as elevated levels of chlorophyll a, are strong indicators of the onset of eutrophication, secondary symptoms such as depleted dissolved oxygen, indicate more serious or highly developed eutrophication. Moderate to high expressions of at least one of the secondary symptoms are exhibited in 82 estuaries, representing 67% of the estuarine surface area studied.

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INTRODUCTION

Eutrophication is a natural process in which there is "an increase in the rate of supply of organic matter" to a water body (Nixon 1995). This usually refers to an increase in the rate of algal production which, under natural conditions, is influenced by a gradual buildup of plant nutrients in ecosystems over long periods of time, and generally leads to productive and healthy estuarine and marine environments. However, in recent years, human activities have substantially increased the rate of delivery of plant nutrients to many estuarine and marine areas (National Research Council 2000, Peierls et al. 1991, Turner and Rabalais 1991). As a result, algal production in many estuaries has increased much faster than would occur under natural circumstances. This accelerated algal production is referred to as "cultural" or "anthropogenic" eutrophication, and often results in a host of undesirable conditions in estuarine and marine environments.

These conditions, which include low dissolved oxygen concentrations, declining sea grasses, and harmful algal blooms, may impact the uses of estuarine and coastal resources by reducing the success of commercial and sport fisheries, fouling swimming beaches, and causing odor problems from the decay of excess amounts of algae (National Research Council 2000, Duda 1982). Despite much research, however, the link between coastal eutrophication and effects on living marine resources and fisheries is not well understood or quantified (National Research Council 2000, Boesch et. al. 2001).

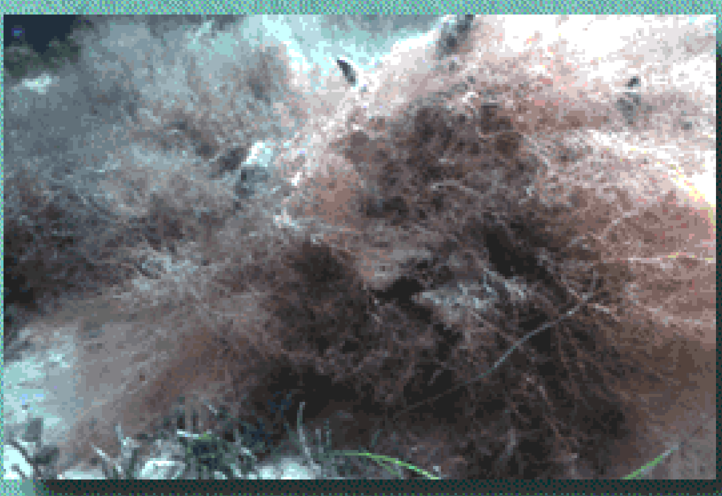

Photo 1. Accelerated growth of nuisance algae, as shown here, can be stimulated by high levels of plant nutrients and leads to undesirable conditions, such as low dissolved oxygen.

Photo 2. Fish kills are symptoms of highly eutrophic conditions. They can result from low dissolved oxygen caused by the decomposition of excess amounts of algae.

Assessing Symptoms of Eutrophication

Between 1992 and 1998, NOAA conducted a survey and series of regional workshops to synthesize the best available information on eutrophication-related symptoms in 138 estuaries, comprising over 90 percent of the estuarine surface area of the coterminous United States. The Mississippi River Plume in the Gulf of Mexico was also assessed; while "the plume" is not an estuary, it is an important offshore marine area that experiences eutrophic conditions. The information, collected from more than 300 scientists and environmental managers, was organized in a common spatial framework (salinity zones representing tidal fresh, mixing, and saltwater environments), and predefined data categories were used to consistently characterize the information so that comparisons could be made among all of the estuaries. The data characterize the spatial domain, severity, duration, frequency and past trends of 16 eutrophication-related symptoms in estuaries of the coterminous United States (Figure 1) (NOAA 1996, 1997a, 1997b, 1997c, 1998).

To help interpret the eutrophication survey results, a simple eutrophication model was employed (Figure 2). Of the 16 symptoms, survey data for three primary symptoms (chlorophyll a, epiphyte abundance, and macroalgal abundance) and for three secondary symptoms (depleted dissolved oxygen, decline of submerged aquatic vegetation, and nuisance/toxic algal blooms) were used to make an overall assessment of the expression of eutrophic conditions.

In order to understand the overall extent of eutrophic conditions in a given estuary, a determination was made of the "level of expression" of each symptom based primarily on the concentration, spatial coverage, and frequency of occurrence. A single value for each of the primary symptoms and secondary symptoms was then determined. The primary and secondary values were then compared in a matrix to assign an overall level of expression of eutrophic conditions in each estuary (Figure 3).). For instance, estuaries having high scores for both primary and secondary symptoms were considered to have an overall "high" level of expression of eutrophic conditions. Conversely, estuaries with low primary and secondary values were assigned an overall "low" level of eutrophication.

Due to many factors, susceptibility to nutrient inputs varies widely from estuary to estuary. In some estuaries, large quantities of nutrient inputs have seemingly little effect, while in others, only moderate inputs appear to cause extensive expressions of eutrophic conditions. Furthermore, the expression of symptoms does not necessarily result from nutrient inputs; many other factors may be involved. In an effort to determine the level of human influence on the expression of eutrophic conditions, the overall eutrophic condition was considered with respect to the level of nutrient inputs and an estuary's susceptibility to retain nutrients. Nitrogen values were used as the primary estimates of nutrient inputs, while information on population density and land use was used as a general indicator of nutrient pressure to help account for the presence of phosphorus and to corroborate the nitrogen estimates. Nitrogen input estimates were based on watershed monitoring data from the U.S. Geological Survey, as produced by the SPARROW model (Smith et al. 1997). While the human influence assessment was not as rigorously performed as the Eutrophication Survey, it provides valuable insight into the role that human activities play in the expression of eutrophic conditions in estuaries.

Photo 3. Livestock feedlots are among the numerous sources of excess nutrients to estuarine waters.

Following the data collection and preliminary assessment, NOAA conducted a National Eutrophication Assessment Workshop in which experts analyzed and interpreted the preliminary conditions and human influences, finalized the assessments, and assigned confidence ratings to each assessment. These final national assessment results provide a snapshot of eutrophic conditions (circa 1995) and are the primary source of information for this essay (Bricker et al, 1999).

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NATIONAL PICTURE

Status of Eutrophic Conditions

The National Eutrophication Assessment Workshop participants concluded that the expression of overall eutrophic conditions ranked as high in 44 estuaries, representing 40% of the total estuarine surface area studied. In these estuaries, one or more symptoms generally occurred at problem levels every year, or persistently, across a major part of the estuary. These estuaries are concentrated in the Gulf of Mexico and Middle Atlantic regions; however, all regions contained estuaries with high eutrophic conditions. An additional 40 estuaries exhibited moderate eutrophic conditions. When considered together, the 84 estuaries with moderate to high conditions represent 65% of the estuarine surface area studied. The remaining 38 estuaries exhibited low levels of eutrophic conditions, meaning that symptoms were not observed at problem levels or that problem conditions occurred infrequently or only under specific and unusual circumstances. About half of these latter estuaries were located in the South Atlantic and Pacific regions. Figure 4 and Figure 5 summarize the national picture of overall eutrophic conditions. Appendix A lists all of the estuaries in the Eutrophication Survey and Assessment and their eutrophic conditions.

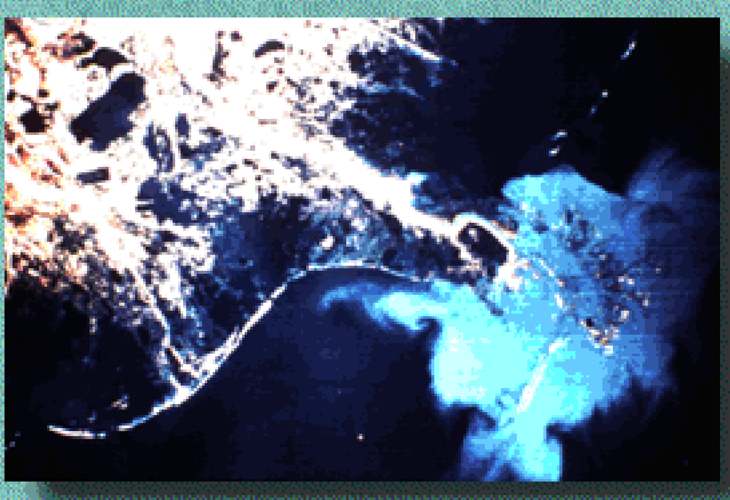

Photo 4. The Mississippi River plume (above right) was assessed for eutrophic conditions in addition to 138 estuaries. The Plume exhibits high eutrophic conditions with the symptoms of low dissolved oxygen, high chlorophyll *a* concentrations, and nuisance algae blooms.

In more than 80 percent of estuaries with high and moderate levels of eutrophic conditions, the assessment confidence was high; conversely, confidence was high in fewer than half of the systems assessed as having low eutrophic conditions. Most of the estuaries with low confidence are located in the Pacific and South Atlantic regions. Despite all of the monitoring and research done to date, information and knowledge is still inadequate in 48 of the nation's 138 best known estuaries (low confidence or inadequate data for assessment). These estuaries represent approximately 25% of the estuarine surface area studied. The data for 17 estuaries were too sparse to provide even a speculative overall view of eutrophic conditions, although limited data existed for certain symptoms in some of the estuaries.

Symptoms: Common Signs of Eutrophication

Primary Symptoms. The primary symptoms of increased nutrient inputs to estuarine waters are high levels of chlorophyll a, epiphytes, and/or macroalgae. It is thought that once primary symptoms are observed at high levels, an estuary is in the first stages of displaying undesirable eutrophic conditions.

High expressions of chlorophyll a, macroalgal abundance, and epiphyte abundance occurred in 39, 24, and 11 estuaries, respectively. Overall, at least one of these primary symptoms was expressed at high levels in 58 estuaries. This finding indicates that 40 percent of the estuaries studied are probably in the first stages of developing problems associated with eutrophication. Figure 6 summarizes the number of estuaries with primary symptoms.

Photo 5. An algae bloom on the tidal Potomac River, a major tributary of the Chesapeake Bay.

Secondary Symptoms. While high levels of primary symptoms are strong indicators of the onset of eutrophic problems, the secondary symptoms, which include low dissolved oxygen concentrations, the loss of submerged aquatic vegetation, and the occurrence of nuisance and toxic blooms, indicate more serious problems, even at moderate levels. While there is a direct causative link between nutrients and primary symptoms, there are many other factors, both natural and human-related, that might contribute to the occurrence of secondary symptoms.

Depleted dissolved oxygen was expressed at moderate to high levels in 42 estuaries. Twenty-seven estuaries had moderate to high levels of submerged aquatic vegetation loss, and 51 estuaries exhibited moderate to high expressions of nuisance/toxic algal blooms. Overall, moderate or high levels of at least one secondary symptom were observed in 82 estuaries, representing 67% of the nation's estuarine surface area. Figure 6 summarizes the number of estuaries with secondary symptoms. Appendix A lists all of the estuaries and their expressions of primary and secondary symptoms of eutrophication.

Influencing Factors

Figure 7 shows the nitrogen input data and the estuarine susceptibility data, which together provide a rough estimate of the level of human influence on the overall expression of eutrophic conditions in the study.

Of the 44 estuaries with high expressions of eutrophic conditions, 36 appear to be highly influenced by human activities, despite relatively low to moderate nutrient inputs (only six had high-level nitrogen inputs). Most of these 44 estuaries (86 %) also had a moderate to high susceptibility to retaining nutrient inputs; that is, their physical characteristics made them vulnerable to developing the symptoms of eutrophication. For instance, estuaries with very low tidal exchange or low dilution with fresh water tend to retain nutrients, and thus, are more susceptible to developing eutrophic conditions. It follows that susceptibility is an important factor in the expression of high eutrophic conditions, especially when nutrient inputs are not extremely high. Furthermore, of the 38 estuaries with a low expression of eutrophic conditions, 10 had high susceptibility for retaining nutrients. Appendix B lists all of the estuaries in the Eutrophication Survey and Assessment and estimates of the levels of human influence on the expression of eutrophic conditions.

Photo 6. The nutrient-laden waters often discharged by sewage treatment plants can be a significant factor in the expression of eutrophic conditions in estuaries.

Six estuaries (mostly in the North Atlantic) with high levels of eutrophic conditions had low human influence. The overall eutrophic conditions in these estuaries were assessed as high generally because of toxic algal blooms, which are believed to originate naturally offshore and drift into the estuaries. However, the role of land-based nutrients in maintaining or enhancing these blooms in the estuaries is not entirely clear.

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REGIONAL CONTRASTS

Estuaries exhibiting high expressions of eutrophic conditions were concentrated mainly in the Gulf of Mexico and Middle Atlantic regions; however, all regions included at least a few estuaries with high expressions of eutrophic conditions (Figure 8). About 45 percent of the estuaries in both the Gulf of Mexico and Middle Atlantic regions exhibit a high level of eutrophic conditions. In contrast, high levels of eutrophic conditions are exhibited in about 18 percent of both South Atlantic and Pacific estuaries. About 33 percent of North Atlantic estuaries exhibited high expressions of eutrophic conditions; however, the level of human influence attributed to these conditions was estimated primarily as low. About half of the estuaries with low eutrophic conditions were located in the South Atlantic and Pacific regions. The Gulf of Mexico and Middle Atlantic had the largest percentages of estuaries with high eutrophic conditions and concurrent high levels of human influence, 45% and 35%, respectively. In the Pacific, 18% of estuaries had these conditions, while in the North Atlantic and South Atlantic, very few had them. Although every region includes estuaries for which conditions are predicted to worsen, the Pacific and Gulf of Mexico regions contain the largest numbers of estuaries with negative outlooks, primarily due to estimates of increasing population and related nutrient supplies. Most of the estuaries with low confidence in the assessment of eutrophic conditions are located in the Pacific and South Atlantic regions.

North Atlantic

The North Atlantic region (Figure 9), which extends from the St. Croix River near the Canadian border south through Cape Cod Bay, includes 18 estuarine systems, encompassing roughly 2,000 square miles of water surface area. In the northern part of the region, the coastal shoreline consists mainly of drowned river valleys characterized by numerous small embayments, rocky shorelines, wave-cut cliffs, and large, rocky islands. The southern part of the region contains more cobble, gravel, and sand beaches, and tidal marshes are more extensive. A high degree of tidal flushing and relatively low freshwater input are characteristic of many of these systems. Major population centers, including Portland and Boston, are located in the southern portion.

Photo 7. Cobscook Bay, on the border between Maine and Canada, shows high levels eutrophic conditions primarily due to toxic algal blooms and the overabundance of macroalgae. As with many North Atlantic estuaries, the degree of human influence here on the expression of eutrophic conditions is low.

Overall Conditions. Moderate or higher levels of eutrophic conditions occurred in more than half of the 18 estuarine systems, with six in the high category. Estuaries with these conditions were located along the length of the coast, and were interspersed with the five estuaries exhibiting low eutrophic conditions.

Expression of Symptoms. Close to half of the estuaries exhibited at least one of the six primary or secondary symptoms at high levels. Chlorophyll *a* was expressed at moderate levels in a majority of estuaries. Macroalgal abundance problems occurred in almost half of the systems, but epiphyte problems were minimal. With regard to secondary symptoms, moderate to high levels of nuisance or toxic blooms occurred in more than half of the systems; depleted dissolved oxygen occurred at low levels in more than half; and losses of submerged aquatic vegetation were minimal.

In general, for those systems with high eutrophic conditions, nuisance or toxic algal blooms and overabundance of macroalgae were the principal symptoms contributing to the observed overall condition. Moderate expressions of chlorophyll *a* and low expressions of depleted dissolved oxygen were also observed in most of the systems with high eutrophic conditions, although these symptoms tended to occur regardless of overall eutrophic condition.

Photo 9. Ten of the 22 estuaries in the Middle Atlantic, including the Chesapeake Bay (above center), exhibit high levels of eutrophic conditions. Seven, including Delaware Bay (top right), exhibit low conditions.

Photo 8. Toxic algal blooms such as red tides are thought to be caused primarily by natural conditions. This one (at left) in coastal Maine occurred after heavy rains following a very dry summer. The same area is shown (at right) six days later after the red tide has cleared.

Influencing Factors. Nutrient inputs from human sources are low in all but three North Atlantic estuarine systems, primarily because freshwater inflow in the region is generally low and drains from watersheds with sparse populations. Susceptibility to nutrient inputs is low in most systems because tidal flushing is very effective in this region. As a result of the low nutrient inputs and low susceptibility, human influence is generally low in the region.

Of the six estuaries exhibiting high eutrophic conditions, only one, Boston Harbor, also had a high level of human influence. Furthermore, according to expert consensus at the National and Regional Assessment Workshops, offshore coastal waters are the major nutrient source for most estuarine systems in this region. Consequently, certain eutrophic symptoms, such as toxic algal blooms, are thought to be primarily reflective of natural conditions. Human-related nutrient inputs may or may not exacerbate these natural conditions.

Middle Atlantic

The Middle Atlantic region (Figure 10), which extends from Buzzards Bay, MA through Chesapeake Bay, includes 22 estuarine systems encompassing more than 7,790 square miles of water surface area. Coastal areas are characterized by irregular shorelines, wide, sandy beaches, numerous barrier island formations, and extensive salt marshes. Tides range from one to six feet but generally fall within the lower part of the range. Tidal flushing is more important in the northern part of the region, while freshwater inflow is more important in the Chesapeake Bay systems. Land use is characterized by large urban tracts and extensive agricultural areas. Major population centers include Providence, Hartford, New York City, Philadelphia, Baltimore, Washington, D.C., and Richmond.

Overall Conditions. Estuaries with moderate to high eutrophic conditions were widespread and evenly spaced throughout the region. Close to half of the 22 estuarine systems exhibit high levels of eutrophic conditions, with an additional five exhibiting moderate conditions. Seven estuaries in the region exhibited low eutrophic conditions.

Expression of Symptoms. Well over half of the estuaries exhibited at least one of the six eutrophic symptoms at high levels. Of the primary symptoms, chlorophyll a had the most pronounced expression, with high levels in half of the estuaries and moderate levels in the rest. Macroalgal abundance problems occurred in 10 estuaries, and in five of these at moderate to high levels. Epiphyte abundance problems occurred in more than one-quarter of the estuaries. Extensive expressions of secondary symptoms were also noted in the region. Depleted dissolved oxygen occurred in every estuary, although it tended to be expressed at low levels. Both submerged aquatic vegetation loss and nuisance or toxic algal blooms were problems in more than half of the estuaries, generally occurring at moderate to high levels.

There did not appear to be a single symptom dominating the overall expression of high eutrophic conditions. Rather, there was a wide and varied array of symptoms contributing to the overall conditions observed. The 10 estuaries exhibiting high eutrophic conditions had varying combinations of low dissolved oxygen, submerged aquatic vegetation loss, and nuisance or toxic algal blooms. In most of these estuaries, secondary symptoms coincided with high expressions of primary symptoms. The five estuaries exhibiting moderate eutrophic conditions displayed similar symptoms, except that the secondary symptoms were somewhat less severe.

Photo 10. Nonpoint sources of nutrients from fertilizer applications are a significant human influence on the expression of eutrophic conditions in estuaries.

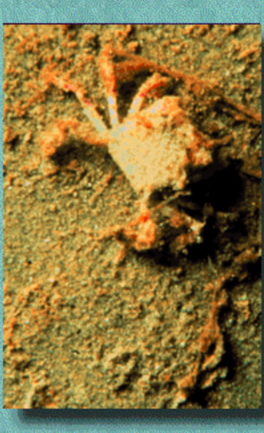

Photo 12. Low dissolved oxygen and toxic algal blooms, two symptoms of eutrophication, often result in mortalities for fish and shellfish.

Influencing Factors. The expression of severe eutrophic conditions was more pervasive in enclosed or river-dominated estuaries, such as the Chesapeake Bay and its tributaries and the Delaware Inland Bays. Ocean-influenced systems, such as Buzzards Bay and Delaware Bay, exhibited fewer impacts (although these systems had small, more localized areas of high symptoms). Nitrogen inputs were moderate to high in 15 estuaries, and susceptibility was moderate to high in all systems. Accordingly, human influence was considered strong in this region. Of the 15 estuaries with moderate to high eutrophic conditions, 12 also exhibited high human influence.

Conversely, several systems displayed minimal eutrophic conditions despite a substantial level of human influence. It is possible that some of these systems are close to developing full-scale eutrophic symptoms.

South Atlantic

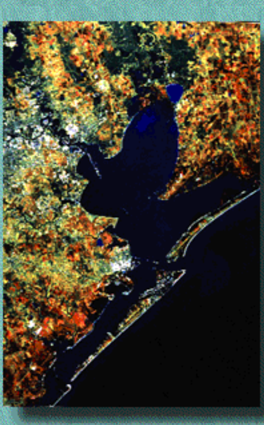

Photo 13. Galveston Bay (above) has moderate levels of nutrient inputs and is moderately susceptible to retaining them. Despite this, it ranks high in eutrophic conditions.

The South Atlantic region (Figure 11) includes 22 estuaries, encompassing more than 4,440 square miles of water surface area. The region, which extends from the Outer Banks in North Carolina south through Biscayne Bay in Florida, is comprised of extensive barrier and sea islands that parallel the shoreline. The coastal environment consists of shallow lagoonal estuaries, extensive tidal marshes and drowned river valleys. Estuarine circulation patterns are dominated mainly by wind and seasonal freshwater inflow in North Carolina, and mainly by freshwater inflow and tides in South Carolina and Georgia. Estuarine circulation along the Florida coast is dominated by wind forcing and human engineering. Tidal range throughout the region is moderately low to high (1.5-7.0 feet) and influences mixing in the water column, primarily near the inlets. The predominant land uses are agriculture and industry, and, to a lesser extent, forestry. Major population centers include Miami, Jacksonville, and Savannah.

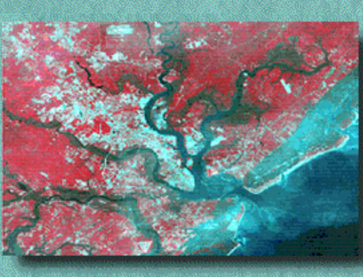

Photo 11. Satellite view of Charleston Harbor estuary in South Carolina. This estuary exhibits moderate eutrophic conditions.

Photo 14. Substantially high levels of human influence are associated with many estuaries in the Gulf of Mexico.

Overall Conditions. The South Atlantic region contains only four estuarine systems with high overall levels of expression of eutrophic conditions: the Neuse River, Pamlico/Pungo Rivers, and New River of North Carolina, and the St. John's River in northern Florida. Five additional systems exhibited moderate levels of eutrophic conditions. The other 13 systems, mostly in South Carolina and Georgia, are relatively unaffected by eutrophic symptoms.

Expression of Symptoms. In five estuaries, at least one of the six eutrophic symptoms was expressed at high levels. Of the primary symptoms, chlorophyll *a* had the most pronounced expression in five estuaries located in North Carolina and Florida. Of the secondary symptoms, depleted dissolved oxygen was considered high in only one North Carolina system, the Neuse River. Nuisance/toxic algal blooms occurred at high to moderate levels in the Pamlico/Pungo Rivers of North Carolina. The loss of submerged aquatic vegetation was a problem in almost half of the estuaries, but mainly at low to moderate levels.

Influencing Factors. The overall level of human influence was low in half of the region's estuaries, especially in South Carolina and Georgia, and moderate in most of the remaining estuaries. Human influence was most pronounced in the North Carolina estuaries of Pamlico/Pungo Rivers, the Neuse River, and the New River.

Many factors influence the expression of eutrophic conditions in South Atlantic estuaries. The limited number of systems in which eutrophic conditions were high generally had restricted circulation, low tidal exchange, and moderate to high nitrogen inputs. In most of the other estuaries, which were relatively unaffected by eutrophication, the influence of tidal marshes (which act as a nutrient filtering mechanism), strong tides, and low nitrogen inputs combined to keep eutrophic conditions at low levels.

Gulf of Mexico

The Gulf of Mexico region (Figure 12) includes 37 estuaries, covering 11,000 square miles of water surface area. The region also contains the Mississippi River Plume, an offshore area stretching from Louisiana to Texas. The plume roughly encompasses an additional 12,000 square miles of water surface area. The region is comprised of a gently sloping, lowland area as part of the Gulf Coastal Plain. Estuarine and coastal environments are highly diverse, consisting of unrestricted open bays, semi-enclosed lagoons, tidal marshes and delta complexes. The fresh water that flows naturally into estuaries can fluctuate greatly in the Gulf, and depends on seasonal rainfall patterns. Estuarine circulation patterns are generally wind driven, and coastal waters are usually warmer than in other regions due to the subtropical climate. Estuaries have fairly low tidal energy (0.5-3.5 ft. tide range), and water depths are typically shallow as compared to estuaries in other regions. Land-use activity in the watersheds is typically dominated by agricultural practices. Major population centers include Houston, New Orleans and Tampa.

Overall Conditions. The Gulf of Mexico was significantly affected by elevated expressions of eutrophication. Almost half of the 37 estuaries in the region had high levels of eutrophic conditions. Estuaries noted as having the highest-level conditions were Florida Bay, Lake Pontchartrain, Calcasieu Lake, Corpus Christi Bay and the Laguna Madre system. The Mississippi River Plume off the coast also was noted to have very high overall expressions of eutrophic conditions. Fourteen estuaries had moderate levels of eutrophic conditions, and only six had low levels.

Expression of Symptoms. In 20 estuaries, at least one of the six individual symptoms was expressed at high levels. Of the primary symptoms, chlorophyll a was expressed at high levels in 12 estuaries, which were located mainly on the coasts of western Florida, Louisiana and lower Texas. In eight estuaries, epiphytes were considered moderate to high; in seven estuaries, magroalgal abundance was considered moderate to high. Of the secondary symptoms, depleted dissolved oxygen was expressed at high levels in four estuaries, mainly along the Florida coast and in the Mississippi River Plume. The loss of submerged aquatic vegetation was a problem in almost half of the estuaries, but usually at low to moderate levels. Nuisance or toxic algal blooms also tended to be pervasive, occurring in 28 estuaries, eight of which exhibited high levels of expression.

In the systems with high overall eutrophic conditions, the symptoms that generally contributed the most to the observed overall eutrophic condition were the loss of submerged aquatic vegetation, high expressions of chlorophyll a concentration, and depleted dissolved oxygen concentrations. Moderate to high levels of nuisance or toxic algal blooms and epiphyte abundance were also major factors in systems with pronounced expressions of eutrophication.

Overall Human Influence. The overall level of human influence was high in more than half of all Gulf systems and corresponded well with high levels of eutrophic conditions. Human influence was considered prominent in the Mississippi River Plume, Lake Pontchartrain, Upper and Lower Laguna Madre, and Baffin Bay. Noted for having relatively low human influence were Rookery Bay, Suwannee River, Apalachee Bay, and Breton/Chandeleur Sounds.

Many factors influenced the expression of eutrophication in Gulf estuaries. The following factors were generally associated with moderate to pronounced levels of expression: low tidal energy, low flushing rates with high nutrient inputs, and low dissolved oxygen levels, generally due to warmer waters and a long growing season. These factors, coupled with substantial levels of human influence in many Gulf estuaries, resulted in pronounced eutrophic conditions, even though nitrogen inputs were generally moderate. For example, although population density was relatively low in the Baffin Bay and Upper Laguna Madre watersheds, human influence was magnified due to high estuarine susceptibility.

Pacific Coast

The Pacific region (Figure 13) includes 39 estuaries, encompassing more than 2,750 square miles of water surface area. The region consists of a relatively straight and uninterrupted shoreline with rocky shores, sandy beaches and occasional river outlets. Limited areas of flat, lowland environments support estuaries, bays and lagoons. Estuaries are typically small and separated by large distances. Estuarine circulation patterns are dominated mainly by seasonal freshwater inflow in Southern California and by freshwater inflow and tides in the larger estuaries of central California and Washington state. The tidal range is moderately high (5.0-7.5 feet). Forestry, agriculture and industry are the predominant land uses in the region's watersheds. Some of the major population centers include Los Angeles, San Diego, San Francisco, Portland, and Seattle.

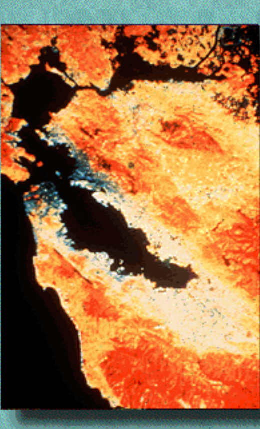

Photo 15. Very high levels of chlorophyll and nuisance algae plus loss of submerged aquatic vegetation, give San Francisco Bay a high overall eutrophic condition.

Overall Conditions. High levels of expression of overall eutrophic conditions occurred in seven estuaries, mainly in the northern and southern sections of the region. Among these were Tijuana Estuary, Newport Bay, and San Francisco Bay. Eleven estuaries were characterized as in the moderate range; these were interspersed throughout California and the Pacific Northwest. Nine estuaries appeared relatively unaffected by eutrophic conditions. There was insufficient data to determine eutrophic conditions in the remaining 12 estuaries.

Expression of Symptoms. In 19 estuaries, at least one of the six individual eutrophic symptoms was expressed at high levels. Of the primary symptoms, chlorophyll *a* was expressed at high levels in 11 systems, most of them in Southern California and northern Washington. Macroalgal abundance was observed at moderate to high levels in 13 estuaries, most of them also in Southern California and Washington. Epiphyte abundance was minimal. Eight estuaries exhibited losses in submerged aquatic vegetation, two at high levels. Nuisance or toxic algal blooms occurred in 21 estuaries, 12 of which were in the moderate to high range.

In general, the symptoms contributing most to high eutrophic conditions were elevated levels of chlorophyll *a*, coupled with various combinations of macroalgal abundance, nuisance or toxic algal blooms, and low dissolved oxygen concentrations. High chlorophyll *a* concentrations were also a common natural condition in some North Pacific estuaries due to tidal import of seasonal algal blooms.

Photo 16. An algal bloom in estuarine waters of Washington.

Overall Human Influence. In general, estuaries with high-level eutrophic conditions also had high levels of human influence. Human influence on the expression of eutrophic symptoms was most pronounced in the Tijuana Estuary, Newport Bay, San Pedro Bay, Anaheim Bay and San Francisco Bay. Three of these –Newport, Newport, Anaheim and San Pedro–are are among the top 10 U.S. estuaries with respect to watershed population density. The Tijuana Estuary is also notable because three-quarters of the watershed is located in Mexico, making management an international challenge. The Tijuana River is the primary source of fresh water to the estuary; it is also a source of untreated sewage from the city of Tijuana. In general, restricted circulation and moderate to high levels of nutrient inputs were noted as the principal factors contributing to elevated eutrophic symptoms in Pacific Coast systems.

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CASE STUDIES

Chesapeake Bay: The Classic Case of Estuarine Eutrophication

The largest estuarine system in the U.S., the Chesapeake Bay, is perhaps the best known example of human activities leading to accelerated estuarine eutrophication and its associated negative affects. During the last 50 to 100 years, nutrient additions to the Chesapeake accelerated rapidly as chemical fertilizers came into widespread use. Also, the population density of the watershed continually increased, creating the need for numerous wastewater treatment plants and generating increasing emissions of nitrogen oxides from automobiles. Human activities, such as the filling in of wetlands and deforestation for agricultural and urban development, concurrently reduced the ability of natural ecosystem processes to remove or trap nutrients, thereby further accelerating nutrient delivery to the bay. In addition, natural diseases and over harvesting led to a dramatic decline of the once highly abundant eastern oyster, seriously reducing the natural filtering of algae and other organic matter from the water column. As a result, eutrophic symptoms intensified greatly in the Chesapeake from the mid-1950s to the mid-1980s. The most apparent symptoms were the extremely high production of algae, increasingly turbid water, major declines in submerged aquatic vegetation abundance and species, and increasingly worsening anoxia and hypoxia (Boesch et. al. 2001).

Photo 17. Underwater beds of *Ruppia maritima,* known commonly as widgeon grass, and other submerged aquatic grasses were once found extensively throughout Chesapeake Bay. Excessive concentrations of algae in the water column and on the leaves of the grass itself, as well as in suspended sediments, reduce the amount of light needed for these grasses to thrive.

Photo 18. Sediment particles, particularly from agricultural fields, can carry phosphorus, a nutrient that stimulates the growth of nuisance algae in parts of some estuaries. Groundwater is the primary source of the nutrient nitrogen.

Concentrations of chlorophyll a in the surface mixed layer have increased tenfold in the seaward regions of the bay and one-and-one-half- to twofold elsewhere, paralleling estimates of increased loading of nitrogen and phosphorus to the bay since 1945 (Harding and Perry 1997).

Submerged aquatic vegetation (SAV) began to decline as a result of nutrient enrichment during the mid-1960s, disappearing entirely from the Patuxent and lower Potomac Rivers. By 1980, many areas of the bay that once contained abundant SAV beds had none or only very small remnants left (Orth and Moore 1984). Research indicated that the major driving factor in the decline of SAV was nutrient enrichment, which was causing excessive growth of algae in the water column and on SAV leaf blades (epiphytic algae). This algal growth decreased light availability to the submerged plants to the point that they simply could not survive (Kemp et. al. 1983, Twilley et. al. 1985).

Seasonal hypoxia (very low dissolved oxygen) has been a feature of the Chesapeake Bay since deforestation during the colonial period (Cooper and Brush, 1991), but evidence suggests an aggravation of the problem in more recent decades (Taft et al. 1980, Officer et al. 1984, Malone 1991). The annual cycle of oxygen depletion in the Chesapeake Bay begins as the water starts to warm and accelerates during and following the spring freshet. The spring accumulation of algal biomass is more than sufficient to create conditions for oxygen depletion and summer anoxia (Malone 1991, 1992). Hypoxia and anoxia generally occur from May through September, with the most severe conditions observed in mid-summer (see the Oxygen Depletion in Coastal Waters essay for a more detailed description).

The Chesapeake Bay is the object of an ambitious nutrient management program. In 1983, the U.S. Environmental Protection Agency, District of Columbia, and states of Virginia, Maryland, and Pennsylvania signed the first Chesapeake Bay Agreement, which established the Chesapeake Bay Program--a voluntary government partnership that directs and manages bay cleanup efforts. An executive council was established to assess and oversee the implementation of coordinated plans to improve and protect the bay's water quality and living resources. Scientific findings from the program led to the signing of the second Chesapeake Bay Agreement in 1987, in which it was agreed to reduce by 40% the nitrogen and phosphorus entering the Chesapeake Bay by the year 2000.

The Chesapeake Bay Program has continued to push for meeting the overall nutrient-reduction goal by implementing several strategies, including tributary nutrient goals, living resources restoration (e.g., SAV replanting and oyster bar restoration), and riparian forest buffer restoration. Point source reductions have been most successful, especially for phosphorus. Between 1985 and 1996, phosphorus point sources were reduced by 58% and nitrogen by 15%. Nonpoint source reductions have been slower, and have proven more difficult to control. Nonpoint sources of nitrogen and phosphorus have been reduced by only 7% and 9%, respectively. Challenges to the effective reduction of nonpoint source nutrients include the adoption of better agricultural practices, the reduction of atmospheric nitrogen deposition, enhancement of wetlands and other nutrient sinks, and the control of urban sprawl (Boesch et al. 2001)

Tampa Bay: Reversing Anthropogenic Eutrophication

Prior to the 1930s, seagrass meadows covered about 31,000 hectares of Tampa Bay. However, the area's growing population and subsequent development resulted in increased nitrogen loading, high chlorophyll concentrations, and the subsequent loss of seagrasses. By 1982, only 8,800 hectares of seagrass remained, a loss of 72%. Since the early 1990s, however, seagrass coverage has been increasing due to effective management actions.

Photo 19. The recovery of seagrasses in Tampa Bay is attributed to management efforts in the watershed, including a nearly 50% reduction in nitrogen loading from domestic wastewater treatment plants since the early 1980s.

Monitoring programs in Tampa Bay show that, since 1985, chlorophyll concentrations have returned to levels observed in 1950, and since 1988, the trend of seagrass loss has been reversed. Bay-wide seagrass coverage in 1996 was estimated at 10,930 hectares, a 25% increase since 1982. Recovery is attributed to a nearly 50% reduction in nitrogen loading from domestic wastewater treatment plants since the early 1980s.

To maintain these improvements, the Tampa Bay National Estuary Program adopted nitrogen loading targets based on the water quality requirements to restore turtle grass, a type of sea grass. A nitrogen management consortium consisting of a local electric utility, industries, agricultural interests, local governments, and regulatory agencies, was established to develop and implement a plan to reduce nitrogen loads by 140 tons per year by the year 2000. The results in Tampa Bay demonstrate that eutrophication impacts can be reduced and reversed (Greening et al. 1997, Johansson and Greening, in press, Tomasko and Ries 1997).

Honokowai, Hawaii: Eutrophic Symptoms in a Coral Reef System

In 1988, corals of Honokowai were healthy and abundant. At that time, Honokowai was rated among the top snorkeling spots on the island of Maui. A garden of low coral growth extended all along the coastline from Honokowai Park up to the S-Bend at a depth of about 17 feet. Today, large sections of these coral garden are dead or degraded, due, in large measure, to massive algal blooms and sedimentation. Concrete erosion-control channels without catch basins deliver runoff to this coastal area from adjacent agricultural areas and from sewage treatment plants.

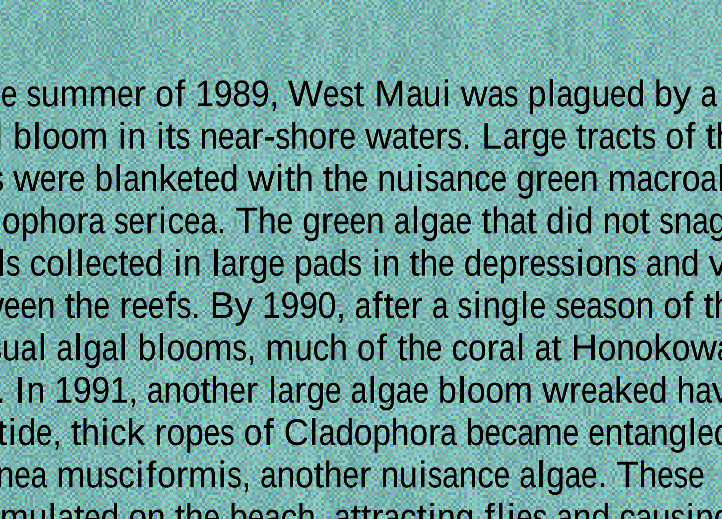

Photo 20. Nuisance algae blanketing coral.

In the summer of 1989, West Maui was plagued by a massive algal bloom in its near-shore waters. Large tracts of the coral reefs were blanketed with the nuisance green macroalgae, Cladophora sericea. The green algae that did not snag on the corals collected in large pads in the depressions and valleys between the reefs. By 1990, after a single season of these unusual algal blooms, much of the coral at Honokowai had died. In 1991, another large algae bloom wreaked havoc. At low tide, thick ropes of Cladophora became entangled with Hypnea musciformis, another nuisance algae. These accumulated on the beach, attracting flies and causing unpleasant odors of decay. Again, pads of Cladophora up to 3 feet deep collected in the depressions between reefs, and huge "rafts" of the algae drifted on the surface. By 1992, various macroalgae--primarily red Hypnea--had become a permanent feature of the area.

In July 1993, Tropical Storm Dora, a hundred-year storm, struck West Maui. Heavy runoff flowed from the West Maui mountains and pineapple fields. Silt-laden fresh water flowed through the two concrete channels at Honokowai. Red soils from upland were directly flushed into the shallows of the reef. The red silt covered corals and rubble, mixed with the sand, and even coated the backs of sea turtles. In deeper waters (33-50 feet), red silt piled up four inches thick and accumulated between reefs. Then, yet another (unidentified) species of algae bloomed in 1994 and 1995, growing throughout the sandy bottom. In the summer of 1995, red Hypnea once again plagued the area. The Cladophora and other nuisance algal blooms have continued yearly at varying intensities through the summer of 1999 (Bennett and Bennett 1999 on-line).

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STATE OF THE COASTAL ENVIRONMENT

EUTROPHIC CONDITIONS IN ESTUARINE WATERS

EXPERT INTERPRETATION

The individuals below are experts in the topic of eutrophic conditions in estuarine waters. Here they voice their opinions on two questions relevant to that topic.

Question 1. Given the difficulty in establishing clear and quantifiable linkages between eutrophic conditions and degradation of estuarine resources (e.g. commercial fishery declines), should eutrophication be as high of a management priority as over-harvesting, invasive species, and other more tangible problems? What steps should be taken to elevate eutrophication into a priority problem in the public eye?

Question 2. The NOAA assessment predicts serious future degradation of water quality for the nation over the next 20 years, based on estuarine susceptibility and expected population growth in the coastal zone. Is this a fair assessment of future conditions, or are there other important factors to consider? What should be done to reduce, mitigate, or prevent nutrient enrichment and its associated effects on the nation's estuaries, and will the costs and effort associated with these actions benefit the nation in the long run?

Experts

Tom Malone | Holly Greening | Jan Newton | Michael Mallin

Thomas Malone

Director
Center for Environmental Science
Horn Point Laboratory
University of Maryland

Dr. Thomas Malone is the Director of the University of Maryland's Center for Environmental Science Horn Point Laboratory on the Chesapeake Bay. His research expertise centers on the dynamics of coastal ecosystems, phytoplankton ecology and coastal eutrophication. He has held numerous positions on government and university panels and commissions related to ocean and coastal environmental quality and monitoring and has published extensively in the scientific literature.

Response to Question 1

Response to Question 2

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Question 1. Given the difficulty in establishing clear and quantifiable linkages between eutrophic conditions and degradation of estuarine resources (e.g. commercial fishery declines), should eutrophication be as high of a management priority as over-harvesting, invasive species, and other more tangible problems? What steps should be taken to elevate eutrophication into a priority problem in the public eye?

No audio response is availalbe.

Given the concentration of resources in coastal ecosystems, the rapid increase in the number of people living, working and playing in the coastal zone should not come as a surprise. The pressures on these ecosystems to provide living space, resources, recreation, and commerce and to receive, process, and dilute the effluents of human society will continue to grow. At the same time, coastal ecosystems are experiencing unprecedented changes that affect their capacity to provide these services and support valuable resources. The resulting conflicts between these uses will become increasingly contentious, politically charged, and expensive.

Environmental changes in coastal ecosystems include habitat loss (coral reefs, sea grass beds, tidal wetlands), loss of biodiversity, oxygen depletion of bottom waters (hypoxia), harmful algal events, fish kills, declining fish stocks, and beach closures. These are occurring despite antipollution laws that have greatly reduced discharges of toxic substances into coastal waters over the last 40 years. At the same time, nutrient loading to coastal waters has increased dramatically from both point and diffuse (line) sources as the number of people living, working and playing in the coastal zone has increased. This has resulted in the loss of critical habitat and increases in the extent of hypoxia in the nation's coastal waters. There is also evidence that nutrient over-enrichment increases the probability of harmful algal events and associated fish kills and may be related to losses of biodiversity and declining fish stocks. Given the systemic effects of nutrient enrichment, high priority must be placed on controlling both point and diffuse sources of nitrogen and phosphorus into coastal aquatic ecosystems.
(top)

Question 2. The NOAA assessment predicts serious future degradation of water quality for the nation over the next 20 years, based on estuarine susceptibility and expected population growth in the coastal zone. Is this a fair assessment of future conditions, or are there other important factors to consider? What should be done to reduce, mitigate, or prevent nutrient enrichment and its associated effects on the nation's estuaries, and will the costs and effort associated with these actions benefit the nation in the long run?

No audio response is availalbe.

Over 60% of coastal rivers, estuaries and bays are moderately to severely degraded by over-enrichment, a problem that is particularly acute in the mid-Atlantic, the southeast, and the northern Gulf of Mexico. Given the susceptibility of these ecosystems and projected human demographics, their capacity to provide services and support valuable resources is likely to continue to deteriorate rapidly in the absence of a major commitment to control nutrient inputs. As called for by a recent NRC report, the minimum goal should be a 10% reduction in the number of degraded coastal ecosystems by 2010 and a 25% reduction by 2020. No systems that are currently categorized as "healthy" should be allowed to develop the symptoms of over-enrichment. Highest priority should be placed on tertiary sewage treatment (to remove nitrogen) for those coastal watershed subject to rapid population growth, to the control of diffuse inputs from animal wastes and fertilizers, and to the control of nitrogenemissions from the combustion of fossil fuels. The costs of taking immediate action control inputs pale in the face of the costs of mitigation and restoration once the damage is done.
(top)

Holly S. Greening

Senior Scientist
Tampa Bay Estuary Program
St. Petersburg, Florida

Ms. Greening is a senior scientist with the Tampa Bay National Estuary Program where she designs, conducts, and manages projects related to aquatic ecology, watershed management, water quality, information management, and atmospheric deposition and toxic materials management. Her academic training involved extensive food web studies in North Florida estuaries. She has an M.S. in Marine Ecology from Florida State University in 1980. Ms. Greening recently served as a member of the National Academy of Sciences, National Research Council's Committee on the Causes and Management of Coastal Eutrophication.

Response to Question 1

Response to Question 2

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Question 1. Given the difficulty in establishing clear and quantifiable linkages between eutrophic conditions and degradation of estuarine resources (e.g. commercial fishery declines), should eutrophication be as high of a management priority as over-harvesting, invasive species, and other more tangible problems? What steps should be taken to elevate eutrophication into a priority problem in the public eye?

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The National Research Council established the Committee on the Causes and Management of Coastal Eutrophication (*Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*; NRC 2000) to provide broad advice on effective control of nutrient pollution and eutrophication. Eutrophication can lead to excess, and sometimes toxic, production of algal biomass (including red and brown tides); loss of important nearshore habitat such as seagrass beds (caused by light reduction); changes in marine biodiversity and species distribution; increased sedimentation of organic particles; and depletion of dissolved oxygen (hypoxia and anoxia). Recognizing eutrophication as a significant coastal problem and high management priority, the committee concluded that one of the first steps needed to spark improved nutrient management is setting challenging but attainable goals. It recommended the following as national goals to address coastal eutrophication (measured in relation to the benchmarks determined by NOAA's National Estuarine Eutrophication Assessment (Bricker et al. 1999)):

- •Reduce the number of coastal water bodies demonstrating severe impacts of nutrient over-enrichment by at least 10 percent by 2010 (5 estuaries);
- •Further reduce the number of coastal water bodies demonstrating severe impacts of nutrient over-enrichment by at least 25 percent by 2020 (11 estuaries); and
- •Ensure that no coastal area now ranked as "healthy" (showing no or low/infrequent nutrient-related symptoms) develop symptoms related to nutrient over-enrichment over the next 20 years.

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Question 2. The NOAA assessment predicts serious future degradation of water quality for the nation over the next 20 years, based on estuarine susceptibility and expected population growth in the coastal zone. Is this a fair assessment of future conditions, or are there other important factors to consider? What should be done to reduce, mitigate, or prevent nutrient enrichment and its associated effects on the nation's estuaries, and will the costs and effort associated with these actions benefit the nation in the long run?

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Although U.S. coastal counties account for only 17 percent of the U.S. landmass, population in these counties exceeds 141 million. This means that over half of the U.S. population lives in less than one fifth of its total area, and this pattern is expected to continue. Nearly 14,000 housing units are built in coastal counties every week. With this pattern of increased population in coastal areas comes additional nutrient loading to coastal waters. The National Research Council committee found that the key to addressing coastal nutrient problems is understanding that nutrient inputs to coastal waters are affected directly and significantly by activities in the watersheds and airsheds that feed coastal streams and rivers, and building this recognition into planning as well as implementation of management solutions. It recommended that a national coastal nutrient management strategy be developed and implemented by local, state, and federal entities, working with academia and the private sector to provide information and assistance with the development and implementation of effective management at all levels, as a means for meeting the goals listed in response to the first question (NRC 2000).

Watershed-specific sources (such as urban stormwater runoff or excess nutrients from farms) can be addressed most effectively at the local or state level. Federal leadership is essential to support and coordinate the research and development needed to provide new approaches and technologies that can be used by local and state agencies charged with reducing and reversing the effects of nutrient over-enrichment. Federal leadership is also critical for dealing with nutrient sources in large watersheds that span multiple states or sources distant from the coast, particularly atmospheric sources. Costs are unknown (no doubt large on a national level), but several examples (e.g., Tampa Bay) show reversal of eutrophication symptoms with reduction in nutrient loading, where multiple benefits have been realized.
(top)

Jan Newton

Senior Oceanographer
Washington State Department of Ecology and
Affiliate Assistant Professor
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Dr. Newton has a Ph.D. in Oceanography (1989) and has focused her research on understanding marine systems, including the dynamics of phytoplankton blooms and global carbon cycle fluxes. Since 1994, she has focused on assessing water quality of Puget Sound and Pacific Coast estuaries. This entails deciphering human impacts, the role of climate variation, and natural variability. Dr. Newton is on the board of the Estuarine Research Federation and is president of the Pacific Estuarine Research Society.

Response to Question 1

Response to Question 2

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Question 1. Given the difficulty in establishing clear and quantifiable linkages between eutrophic conditions and degradation of estuarine resources (e.g. commercial fishery declines), should eutrophication be as high of a management priority as over-harvesting, invasive species, and other more tangible problems? What steps should be taken to elevate eutrophication into a priority problem in the public eye?

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Certainly, I do think eutrophication should be a high priority management issue. Just because a problem is not straightforward does not mean we can ignore it. The difficulty is that our "eutrophication indicators" are found in aquatic systems naturally. For instance, chlorophyll is high when phytoplankton bloom seasonally, oxygen can be low when productive waters have naturally slow flushing rates, and nutrient concentrations can be high from intrusions of deep ocean water. So you cannot simply measure a high or low concentration of these indicators and know that it is bad or good, like you can with many toxic or contaminant chemicals. Thus, the eutrophication indicator data must be interpreted relative to the region, to typical or historical values, and in consideration of climate variation. Assessing the degree of eutrophication being affected by humans in a particular area can be very difficult unless you have good documentation of historical conditions, which clearly does not exist for much of the country.

Although assessing eutrophication is difficult, its consequences, if unchecked, are profound. Impacts of eutrophication are pervasive, not just on commercial fisheries. Eutrophication to the point where oxygen is depleted is essentially like strangling an aquatic ecosystem. Species shifts and alteration of habitat can result. Both of these have far-reaching implications for ecosystem integrity.

Because the impacts from eutrophication are serious, it must be a management priority. Establishing good scientific procedures for assessing eutrophication and for collecting time-series data are important. But the key to bringing this awareness to the public eye is education. And this education must be aimed at all levels of our citizenry: in schools, in media, on the web. Eutrophication, the process, is relatively easy to explain. Although the eutrophication status of a given area may be difficult to assess, with good presentation of the important factors and considerations, the public can grasp the issue. It is not that different from other familiar environmental problems. We need to help people better realize that what goes down their drains and sewers and runs off of their lawns reaches the coastal waters. I think our society is very unaware of where its wastes go and what these substances can do.

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Question 2. The NOAA assessment predicts serious future degradation of water quality for the nation over the next 20 years, based on estuarine susceptibility and expected population growth in the coastal zone. Is this a fair assessment of future conditions, or are there other important factors to consider? What should be done to reduce, mitigate, or prevent nutrient enrichment and its associated effects on the nation's estuaries, and will the costs and effort associated with these actions benefit the nation in the long run?

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Regarding future conditions, I think there are some truths that we must be aware of. First, some systems respond to nutrient enrichment, some do not. NOAA asked the local scientists for help in determining these. Next, the capacity of an estuary to absorb nitrogen is a fixed number. It cannot increase with time. Finally, the amount of nitrogen delivered to an estuary by humans will increase as human and livestock populations increase, unless significant efforts are made to reduce the loads. So, accepting these, it follows that as human populations and development increase and nitrogen loads are delivered to coastal waters unchecked, eventually some estuaries will have eutrophication problems. I think that point is inarguable. What we can argue over is where and when this will or will not occur. However, as a national problem, it certainly does need focus.

The regional approach NOAA took is exactly right. Estuarine systems of the East coast, Gulf coast, Pacific coast are all different naturally in terms of nutrient loads, responses, and mechanisms. I think there should be nationally mandated attention that is implemented by local regions and sub-regions on how to best focus on what makes the most sense for nutrient over-enrichment control. First, we need a clear understanding of the systems' sensitivity (not cheap or easy to assess, in some cases), then effective measures to best control the nutrient-enrichment impact (also not cheap or easy). Both steps need to be conducted in scientifically rigorous and publicly open forums. Ignoring this is not a viable option if coastal ecosystem health and sustainability are of societal importance.

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Michael E. Mallin

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Wilmington, North Carolina

Dr. Michael Mallin is an aquatic ecologist at the University of North Carolina at Wilmington where he has worked since1992. He oversees several comprehensive water quality programs in urban and rural watersheds. His research interests include the impacts of nutrient loading on estuaries and streams, environmental effects of catastrophic weather events, impact analysis of land use practices on water quality, and water quality management issues. He has authored or co-authored over one hundred publications on the ecology and pollution of freshwater, estuarine, and coastal marine systems.

Response to Question 1

Response to Question 2

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Question 1. Given the difficulty in establishing clear and quantifiable linkages between eutrophic conditions and degradation of estuarine resources (e.g. commercial fishery declines), should eutrophication be as high of a management priority as over-harvesting, invasive species, and other more tangible problems? What steps should be taken to elevate eutrophication into a priority problem in the public eye?

Click here for audio response

There are clear and quantifiable linkages between eutrophic conditions and degradation of aquatic resources. Numerous field and experimental studies have demonstrated that nutrient loading causes phytoplankton and macroalgal blooms. Both nitrogen and phosphorus have been shown to be important in causing estuarine eutrophication, with nitrogen the most problematic during summer and phosphorus in spring. Also, in some systems phosphorus impacts are most notable in upper estuarine areas in lower salinity waters, while nitrogen becomes the most critical nutrient in mid-estuarine to marine conditions. Nutrient-caused algal blooms eventually die, causing increased biochemical oxygen demand (BOD), which leads to bottom water hypoxia or anoxia. These conditions result in habitat loss for finfish and shellfish, and occasionally death to less mobile bottom fauna. It has also been demonstrated that nitrogen loading through the coastal eutrophication process can cause physiological disruption and death to seagrass, which is important fish and shellfish habitat. Phosphorus loading has recently been shown to directly cause increased BOD concentrations in coastal plain blackwater streams, leading to reduced dissolved oxygen in these abundant ecosystems. Eutrophication also causes the increase of certain toxic dinoflagellates including Pfiesteria, which has caused large-scale fish kills along the U.S. eastern seaboard, and more recently, overseas. Levels of nutrients causing the above problems have been experimentally quantified; thus, the results can, in many instances, be predicted. Eutrophication leads to outright fish death, loss of habitat for fish and shellfish, disruption of food chains, and occasionally human health problems. Clearly, control of eutrophication should be a high priority management effort.

Question 2. The NOAA assessment predicts serious future degradation of water quality for the nation over the next 20 years, based on estuarine susceptibility and expected population growth in the coastal zone. Is this a fair assessment of future conditions, or are there other important factors to consider? What should be done to reduce, mitigate, or prevent nutrient enrichment and its associated effects on the nation's estuaries, and will the costs and effort associated with these actions benefit the nation in the long run?

Click here for audio response

Population growth is an important factor that increases eutrophication of coastal waters. Population growth leads to urbanization, which is the conversion of natural or rural landscapes to heavy use areas such as subdivisions and commercial areas. Urbanization leads to dramatic increases in impervious surface coverage (roads, parking lots, rooftops, driveways, and sidewalks) at the expense of undeveloped natural landscapes, or "green space". Green space naturally cleanses rainfall-driven runoff of pollutants that cause eutrophication and other environmental problems, because pollutants are absorbed or adsorbed to soil particles or taken up by vegetation. In contrast, impervious surfaces concentrate nutrients, bacteria, metals, pesticides, and other pollutants. When it rains, the runoff flushes the accumulated pollutants into the nearest stream, creek, canal or lake, often without the benefit of any kind of treatment.

Strong evidence links impervious surface coverage with increased flooding, degraded fisheries, impairment of the benthic community, and bacterial contamination of shellfishing beds. To avoid these problems, advance planning to minimize impervious surface coverage and maximize green space is essential. Another useful technique is to require streamside buffer zones consisting of a mixture of grass, shrubs, and trees to adsorb surface and subsurface nutrients and other pollutants associated with runoff. Above all, natural wetlands should be protected and new wetlands created where possible. In some circumstances wetlands can be incorporated into the runoff treatment process. By utilizing these techniques to prevent inputs of pollutants to coastal waters it saves much cost and effort later when agencies and municipalities try to repair already-damaged aquatic resources. The most cost-effective means of reducing estuarine eutrophication is to prevent it in the first place.

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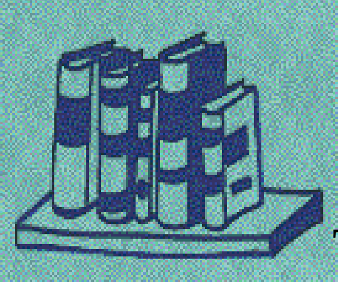

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A feature article in *Scientific American* on-line. This in-depth article explores the history, causes, and consequences of estuarine eutrophication.

Special Projects Office, NOAA. CADS Make a Map and Digital Data.

http://cads.nos.noaa.gov/

Provides access to all National Estuarine Eutrophication Assessment data. The Publications link provides access to PDF files of the five regional reports and the national report.

Symptoms of Eutrophication

Submerged Aquatic Vegetation (SAV) Loss
Virginia Institute of Marine Science. SAV in Chesapeake Bay.

http://www.vims.edu/bio/sav/index.html

Includes a brief primer on SAV in Chesapeake Bay, recent and historical SAV distribution information with continual updating, and a full bibliography of papers published about SAV in Chesapeake Bay.

US Fish and Wildlife Service, Chesapeake Bay Field Office. Submerged Aquatic Vegetation: Where have all the grasses gone?

http://www.fws.gov/r5cbfo/CBSAV.HTM

Explains the role SAV plays in the Chesapeake Bay ecosystems, describes the nature and causes of widespread decline of bay grasses, and what is being done to restore them. Includes photographs of common bay SAV.

Maryland Department of Natural Resources. Chesapeake Bay Grasses.

http://www.dnr.state.md.us/bay/sav/

Comprehensive site provides information on past and present distribution, the importance of SAV, factors affecting growth, and SAV varieties and identification, and detailed information on restoration efforts. Also includes information on bay grass regulations in Maryland.

Chesapeake Bay Program. Bay Grasses.

http://www.chesapeakebay.net/info/baygras.cfm

Provides information on the ecological role of SAV, SAV Species and Distribution, SAV decline in the Chesapeake, SAV as habitat, SAV habitat requirements, and restoration of Chesapeake Bay grasses.

Nuisance/Toxic Algal Blooms
Woods Hole Oceanographic Institution. The Harmful Algae Page.

http://habserv1.whoi.edu/hab/

Contains maps of current HAB locations and trends. Also provides information on HAB's including introductory material on what algal blooms are and how they form, characteristics of different harmful species, and the adverse impacts of blooms. Recent news coverage about current HAB outbreaks is also included.

Low Dissolved Oxygen
U.S. Environmental Protection Agency. Long Island Sound Study.

http://www.epa.gov/region01/eco/lis/hypox.html

Describes the extent of hypoxic conditions and explains the chemical, physical, and biological synergisms leading to hypoxic conditions in Long Island Sound. Also, documents how two- and three-dimensional models of the Sound's dynamics are being used to better understand the causes of, and solutions to, hypoxia. Presents efforts by The Management Conference to ameliorate the current effects of human activities on the Sound and future plans to continue improvements.

Case Studies

Chesapeake Bay Program. Overview of the Bay Program.

http://www.chesapeakebay.net/overview.htm

Provides information about the bay program, including PDF files of the 1983 and 1985 Chesapeake Bay Agreement documents and the 1992 Amendments. The site also provides a wealth of information pertaining to nutrient enrichment and eutrophication of the Chesapeake Bay.

Tampa Bay Estuary Program. The State of the Bay: Special Report! Making Strides in Saving Tampa Bay.

http://www.tbep.org/baystate/progress899.html

Outlines management efforts underway to further improve nitrogen management and submerged aquatic vegetation in Tampa Bay.

Ursula Keuper-Bennett and Peter Bennett. An Underwater History of Honokowai (1988-1995), Algae Blooms, Coral Heads, and Sea Turtles. Turtle Trax.

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A chronology of the condition of algal blooms, corals and sea turtles in nearshore Hawaiian waters between 1988 and 1995.

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Appendix A. Expression of Eutrophic Condition and Symptoms in the Nation's Estuaries

Appendix B. Overall Human Influence on Expression of Eutrophic Conditions in the Nation's Estuaries

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GLOSSARY

algae: a diverse group of chiefly aquatic plants (e.g., seaweed, pond scum, stonewort) that contain chlorophyll but lack roots, stems, leaves, and vascular tissues, and may passively drift, weakly swim, grow on a substrate, or take root in a water body. See also epiphytes, macroalgae, nuisance algae, toxic algae.

anoxia: the absense of dissolved oxygen. May occur as a result of large algal blooms that sink to the bottom of the water column where bacteria break down the algae, using oxygen during the process.

chlorophyll *a*: a pigment found in microscopic algae, called phytoplankton. Measurements of chlorophyll a levels are used to indicate the amount of phytoplankton growing in a water body. High concentrations are indicative of problems related to the overproduction of algae.

epiphytes: algae that grow on the surfaces of plants or other objects. They can cause losses of submerged aquatic vegetation by encrusting leaf surfaces and thereby reducing the light available to the plant leaves.

eutrophication: a process in which the addition of nutrients (primarily nitrogen and phosphorus) to water bodies stimulates algal growth. This is a natural process, but it can be greatly accelerated by human activities.

hypoxia: very low dissolved oxygen concentrations, usually ranging between 0 and 2 milligrams per liter. May occur as a result of large algal blooms that sink to the bottom of the water column where bacteria break down the algae, using oxygen during the process.

macroalgae: are large algae, commonly referred to as "sea-weed." Blooms can cause losses of submerged aquatic vegetation by blocking sunlight. Additionally, blooms may also smother immobile shellfish, corals, or other habitat. The unsightly nature of some blooms may impact tourism due to the declining value of swimming, fishing, and boating opportunities.

nuisance algae: any type of algae that bloom in sufficient quantity to cause low dissolved oxygen (anoxia or hypoxia), create unaesthetic conditions (unsightly blooms and/or foul odors), or other undesirable conditions. Nuisance and toxic algal blooms are often reffered to as harmful algal blooms (HABs).

nutrient enrichment: an increase in the amount of nutrients added to an ecosystem, above normal (naturally expected) levels.

submerged aquatic vegetation (SAV): rooted plants that grow entirely underwater, often in large beds or meadows. Loss of SAV is indicative of accelerated eutrophication. SAV beds serve as important habitat in many estuaries. Also called seagrasses and submerged macrophytes.

toxic algae: algae that produce toxins that are considered harmful because they are capable of causing fish kills and may also be hazardous to avians and mammals. Related human-health problems are caused by the consumption of seafood that has accumulated algal toxins, or from the inhalation of airborne toxins. Nuisance and toxic algal blooms are often reffered to as harmful algal blooms (HABs).

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CREDITS

Acknowledgments

We would like to thank all of the estuarine research scientists and coastal resource managers whose contributions of data, information, and expertise were the key to making this report possible. Special thanks go to Daniel J. Basta, Director of the Special Projects Office at the National Ocean Service (NOS), for his vision and unflagging support. We also thank our other NOS colleagues, Charles Alexander and C. John Klein for technical advice; Alison Hammer, John Hayes, Percy Pacheco, and Scot Frew for invaluable support provided for the National Estuarine Eutrophication Assessment; and Pam Rubin for reviewing and editing the manuscript.

Thanks also to Gregory McMurray, Oregon Department of Environmental Quality and Walter Boynton, University of Maryland Chesapeake Biological Laboratory, for providing critical reviews of the draft document.
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Photo 7. Cobscook Bay Resource Center Web Site
Photo 8. Maureen Keller, Bigelow Laboratory for Ocean Sciences
Photo 17. Chesapeake Bay Program Web Site
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About the Authors

Christopher Clement is a physical scientist with the Special Projects Office in NOAA's National Ocean Service where he has worked since 1990. He has a BS in Natural Resources Management from the University of Maryland and a Masters degree in Environmental Science and Policy from Johns Hopkins University. Mr. Clement has been actively involved in conducting the national estuarine eutophication survey and assessment since the start of the survey in 1992. He has also worked on assessments of classified shellfish growing waters, and developed information management systems for projects such as the Sustainable Seas Expeditions in the nation's marine sanctuaries.

Suzanne B. Bricker is a Physical Scientist at NOAA's Special Projects Office where she has been since 1990. She earned a Ph.D. in Oceanography from the University of Rhode Island's Graduate School of Oceanography in 1990 and a B.A. in Biology from Northwestern University in 1981. Dr. Bricker is the Project Manager for NOAA's National Estuarine Eutrophication Assessment, an 8 year effort completed in 1999, to characterize the extent and severity of nutrient pollution and eutrophication-related impacts on the nation's coastal waters including hypoxia, occurrences of harmful and toxic algal blooms, and losses of submerged aquatic vegetation. Her research interests include the cause and effect linkages between land-based contaminants and water quality degradation and the role of physical processes within estuaries, the role of wetlands in mitigating the effects of land-based contaminant sources, and the atmospheric contribution to eutrophication.

Douglas Pirhalla is an environmental scientist with the Center for Coastal Monitoring and Assessment in NOAA's National Ocean Service where he has worked since 1990. He has a Masters degree in Environmental Science and Policy from Johns Hopkins University and a BS degree from Frostburg State University in Geography. Mr. Pirhalla has been actively involved in conducting the National Estuarine Eutrophication Survey and Assessment since its inception in 1992. He has also worked on numerous NOAA supported remote sensing studies classifying benthic habitats in coastal waters, and has been intimately involved in watershed-based biological assessment and monitoring activities supported by Maryland's Department of Natural Resources.

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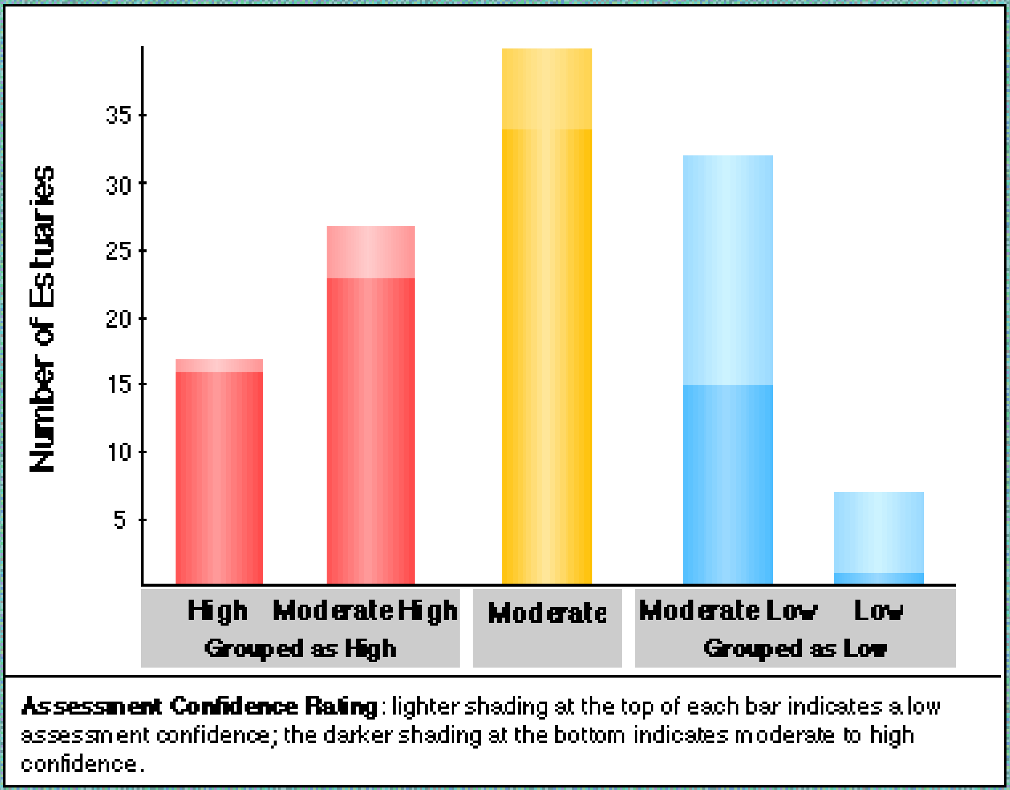

Figure 4. National summary of eutrophic condition in 138 estuaries and the Mississippi River Plume.

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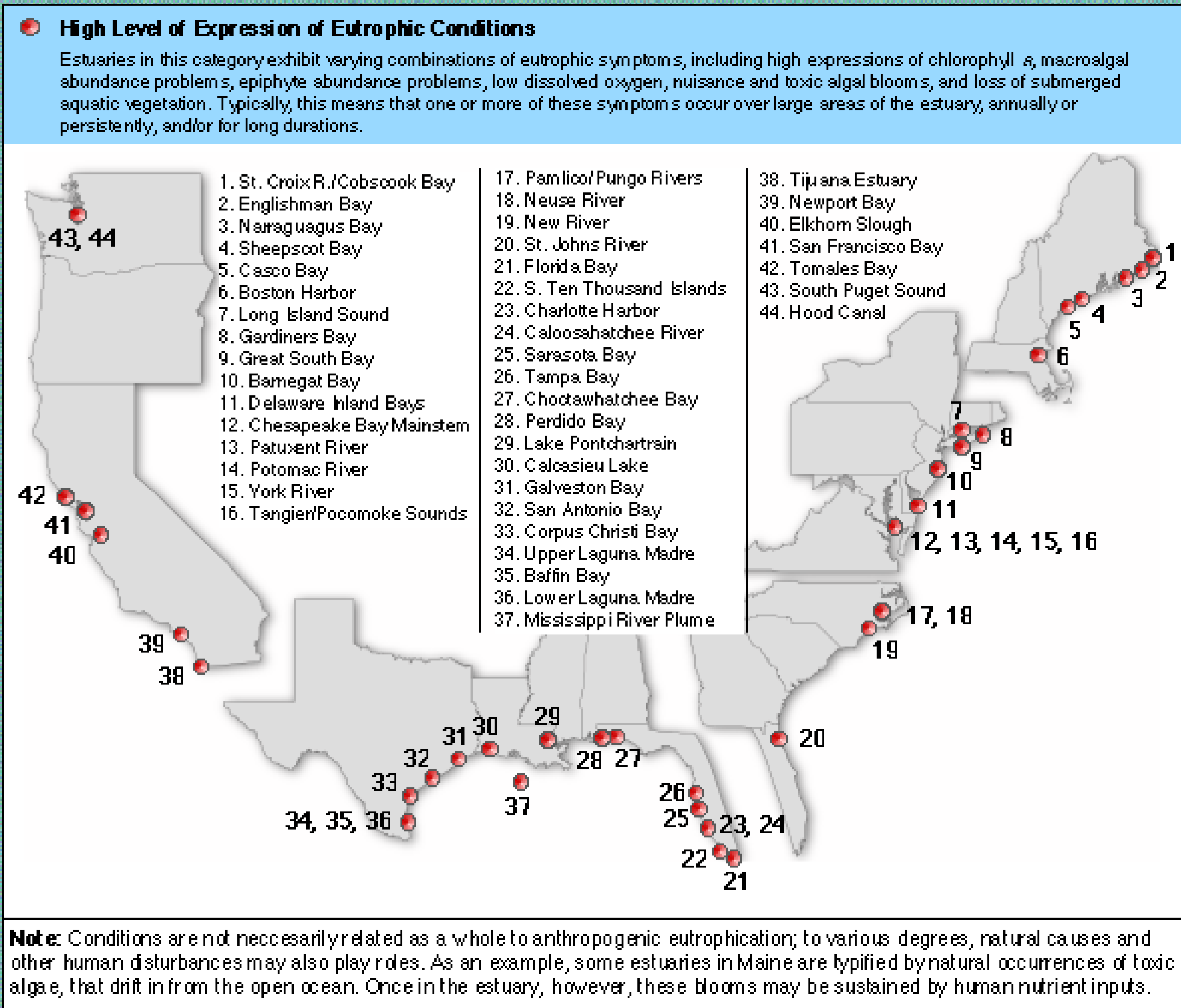

Figure 5. Estuaries with a high level of eutrophic conditions.

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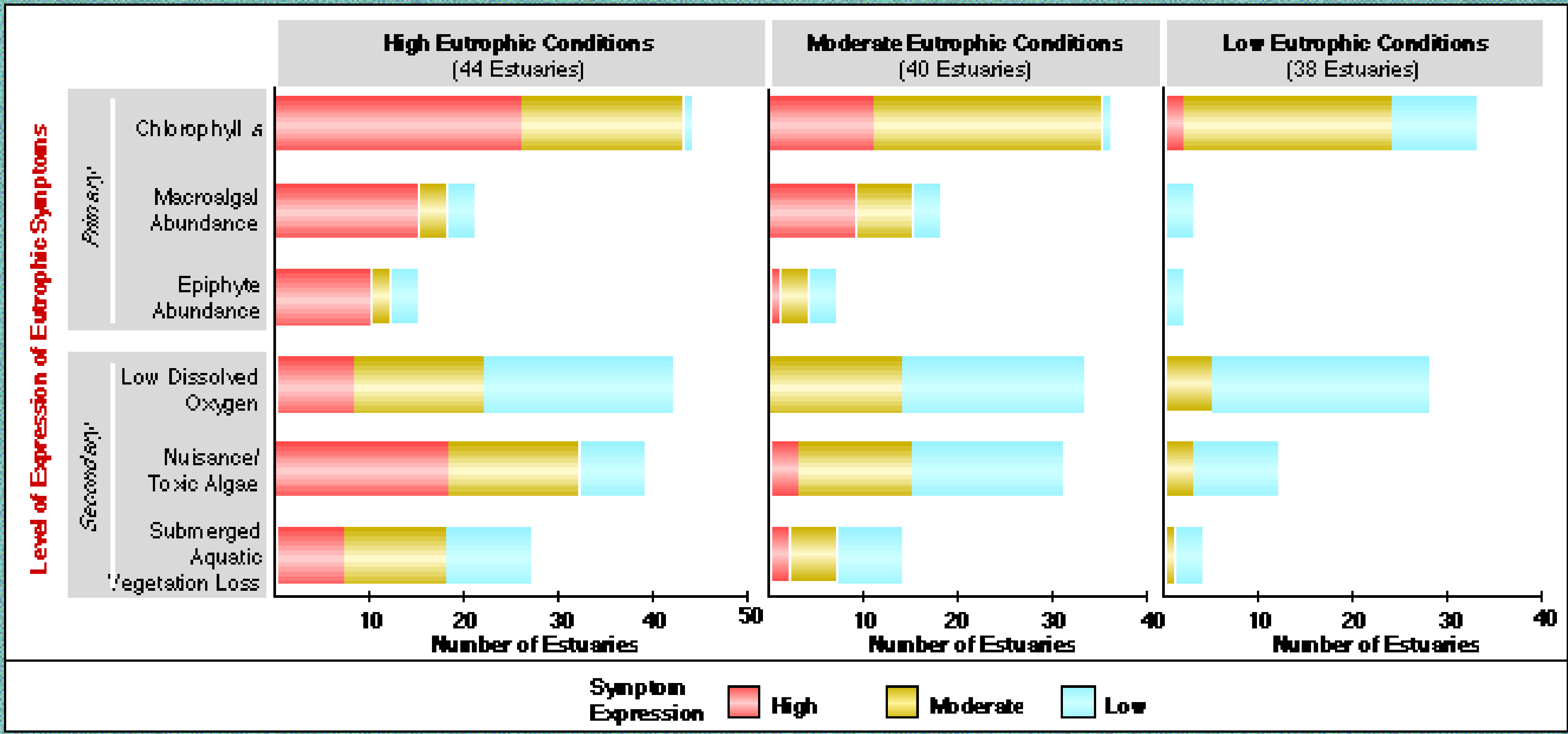

Figure 6. Number of estuaries with primary and secondary symptoms of eutrophication.

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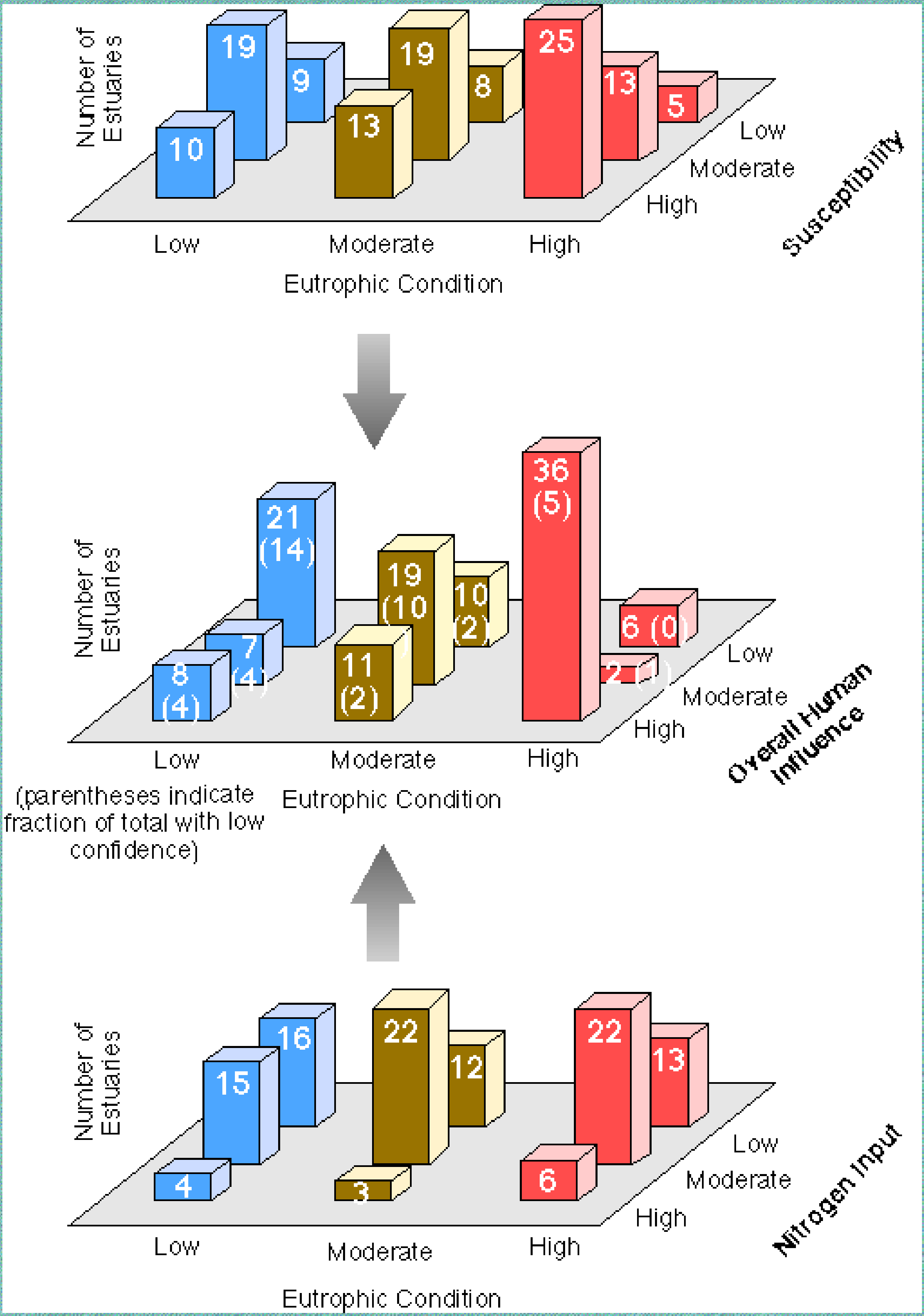

Figure 7. Nitrogen input, estuarine susceptibility, and level of human influence on the overall expression of eutrophic conditions in the nation's estuaries.

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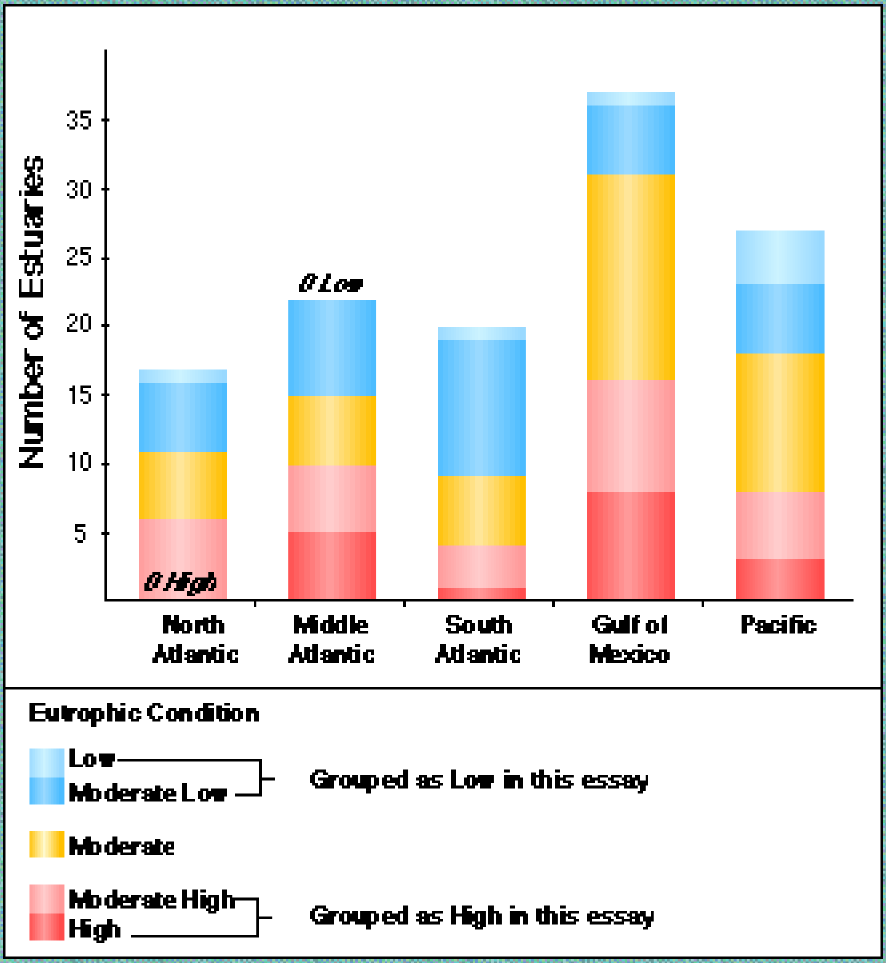

Figure 8. Regional distribution of estuaries with high, moderate, and low eutrophic conditions.

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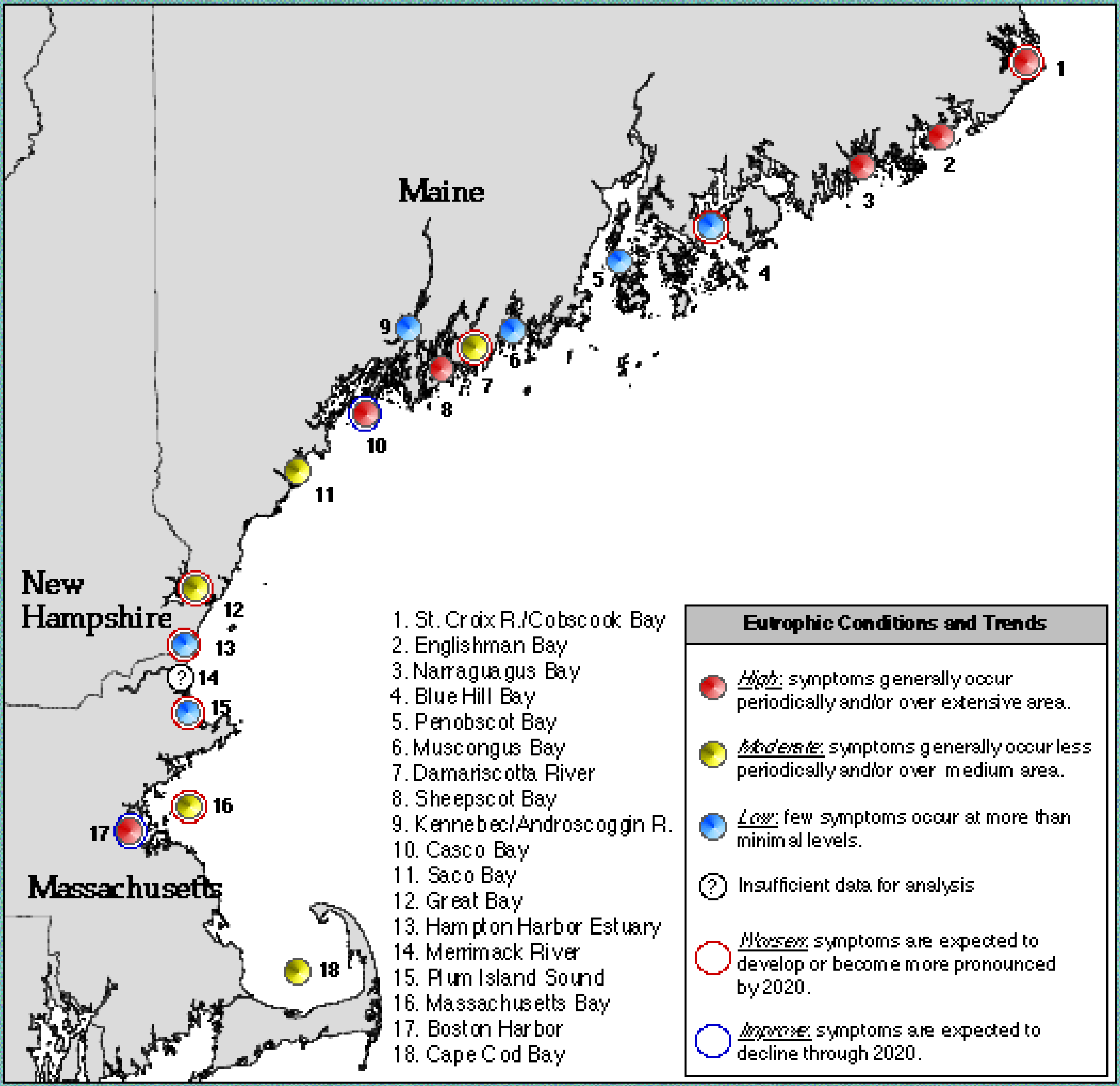

Figure 9. Summary of eutrophication and future outlook for estuaries of the North Atlantic region.

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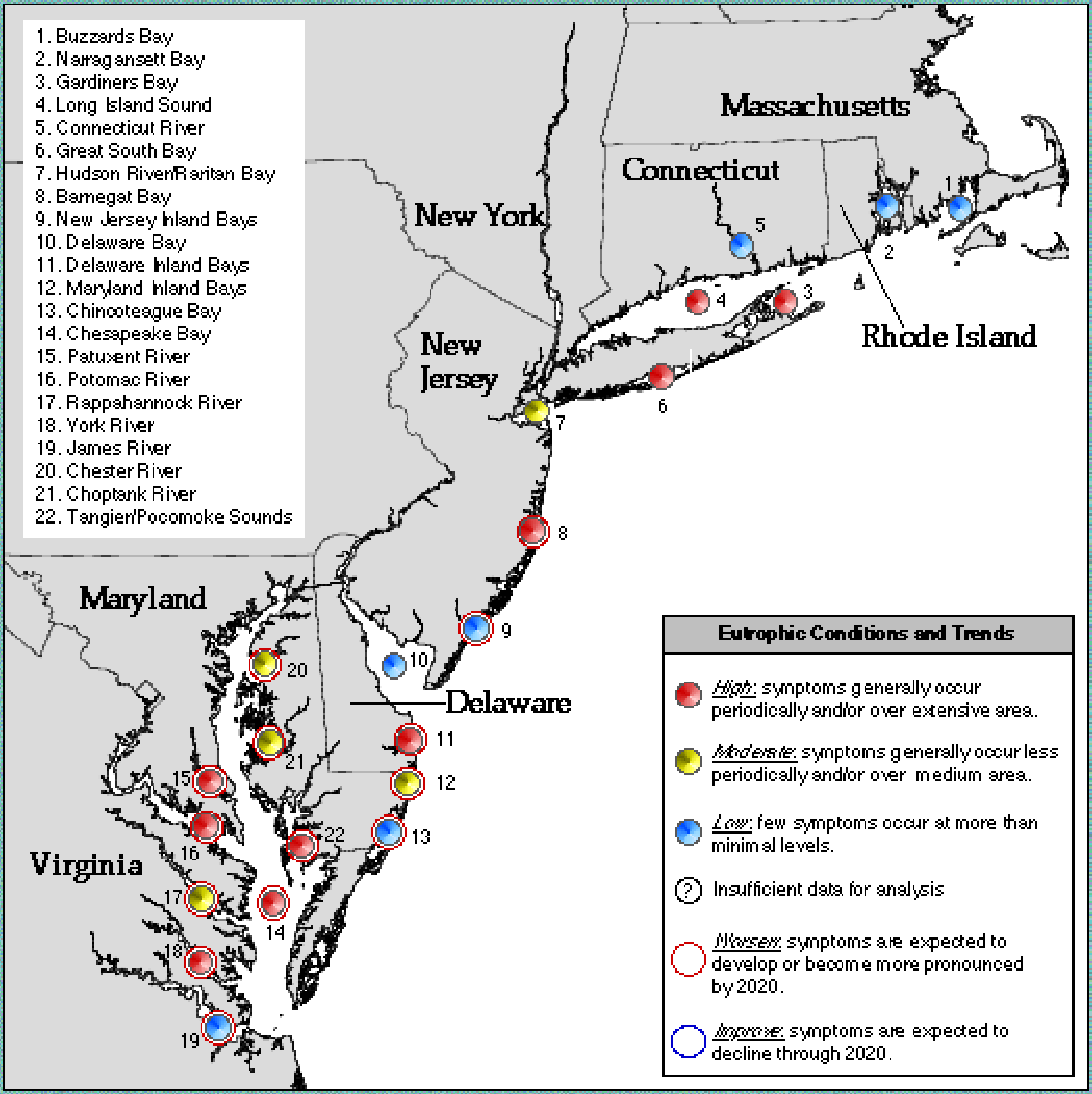

Figure 10. Summary of eutrophication and future outlook for estuaries of the Middle Atlantic region.

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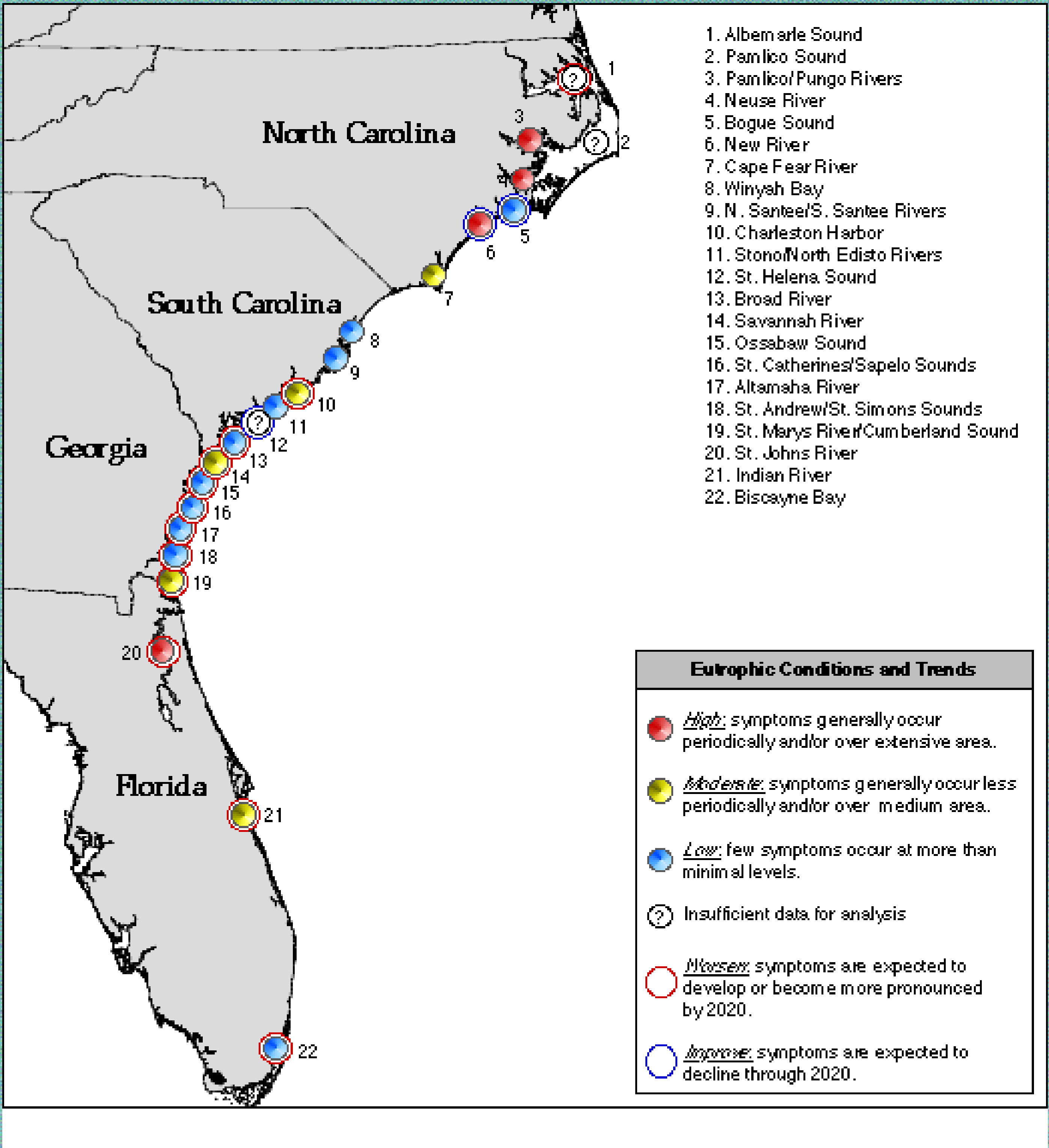

Figure 11. Summary of eutrophication and future outlook for estuaries of the South Atlantic region.

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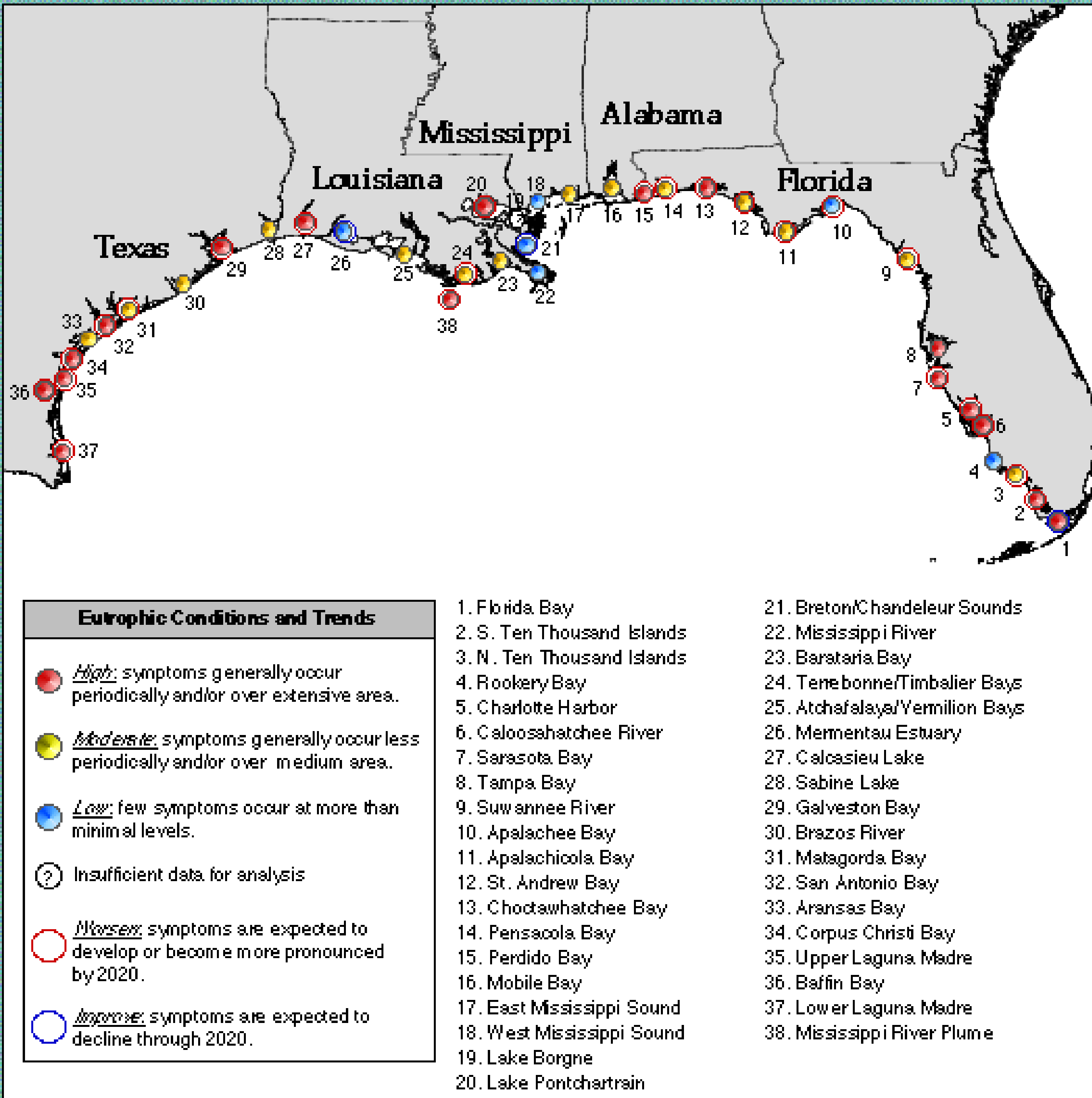

Figure 12. Summary of eutrophication and future outlook for estuaries of the Gulf of Mexico region.

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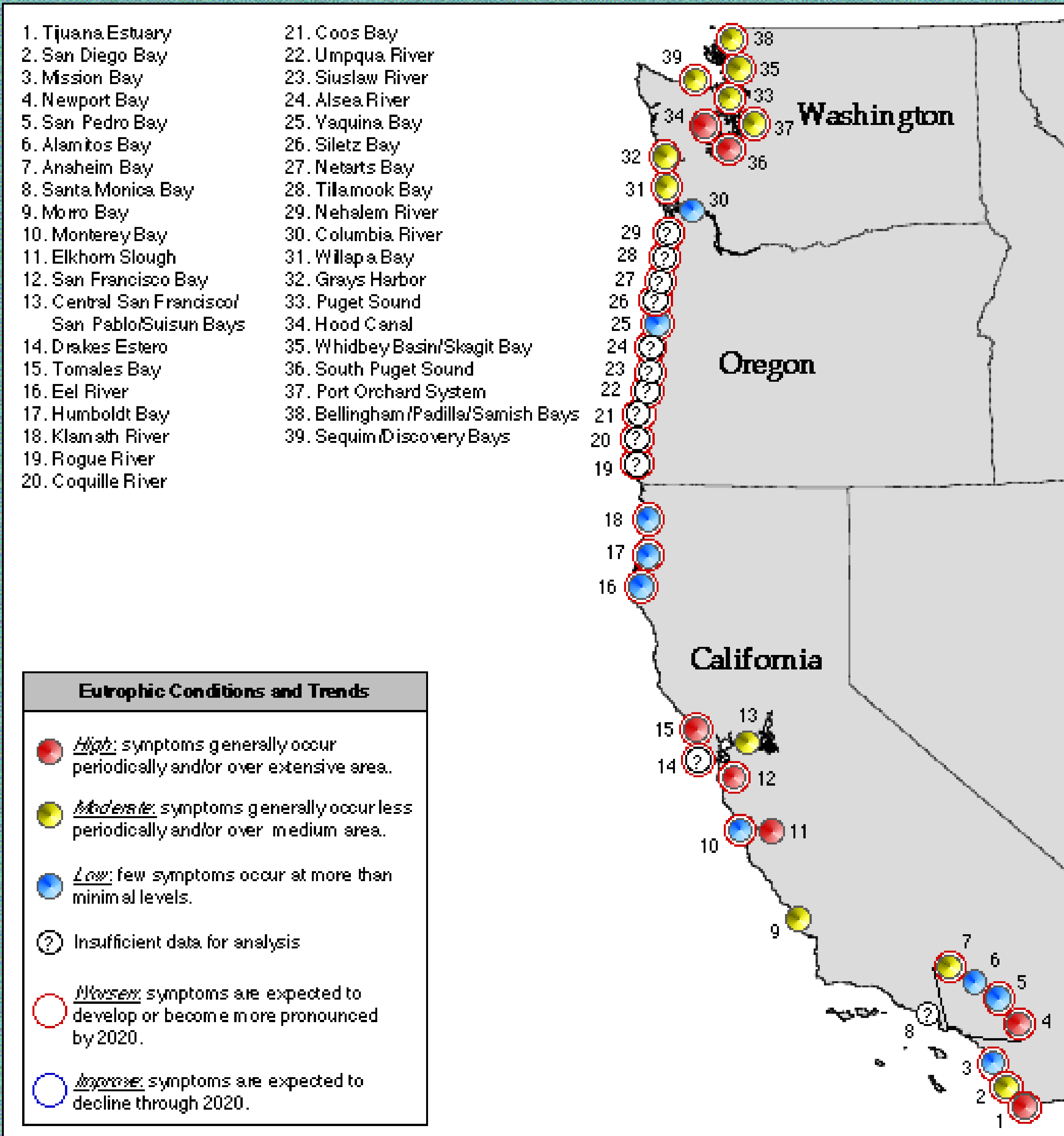

Figure 13. Summary of eutrophication and future outlook for estuaries of the Pacific region.

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Appendix A1. Expression of Eutrophic Condition and Symptoms in the Nation's Estuaries: North Atlantic Region

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High | Moderate | Low | No Expression | Improving Symptom | Insufficient Data

North Atlantic

Estuary	Eutrophic Condition	Symptom Expression: Primary: Chlorophyll a	Primary: Epiphytes	Primary: Macroalgae	Secondary: Low Dissolved Oxygen	Secondary: SAV Loss	Secondary: Nuisance/Toxic Blooms
St. Croix River/Cobscook Bay	High	Low	Low	High	Low	Improving Symptom	High
Englishman Bay	High	Moderate	No Expression	High	No Expression	Insufficient Data	Moderate
Narraguagus Bay	High	Moderate	No Expression	No Expression	No Expression	Insufficient Data	High
Blue Hill Bay	Low	Moderate	No Expression	No Expression	No Expression	No Expression	Low
Penobscot Bay	Low	Low	No Expression	No Expression	No Expression	Insufficient Data	No Expression
Muscongus Bay	Low	Moderate	No Expression	No Expression	Low	Insufficient Data	Low
Damariscotta River	Moderate	Moderate	No Expression	No Expression	No Expression	No Expression	Moderate
Sheepscot Bay	High	Moderate	No Expression	Moderate	Low	Insufficient Data	High
Kennebec/Androscoggin Rivers	Low	Moderate	No Expression	No Expression	Low	No Expression	No Expression
Casco Bay	High	Moderate	Low	Moderate	Improving Symptom	Moderate	High
Saco Bay	Moderate	Low	Insufficient Data	No Expression	Low	Insufficient Data	High
Great Bay	Moderate	Moderate	Low	Moderate	Low	Improving Symptom	Low
Hampton Harbor Estuary	Low	Moderate	No Expression	No Expression	Low	No Expression	No Expression
Merrimack River	Insufficient Data	Insufficient Data	Insufficient Data	Insufficient Data	Insufficient Data	Moderate	Insufficient Data
Plum Island Sound	Low	Moderate	No Expression	No Expression	Low	No Expression	No Expression
Massachusetts Bay	Moderate	Moderate	No Expression	High	No Expression	Low	Moderate
Boston Harbor	High	Moderate	High	Moderate	Moderate	Low	No Expression
Cape Cod Bay	Moderate	Moderate	No Expression	Low	Low	Low	Low

High | Moderate | Low | No Expression | Improving Symptom | Insufficient Data

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Appendix A2. Expression of Eutrophic Condition and Symptoms in the Nation's Estuaries: Middle Atlantic Region

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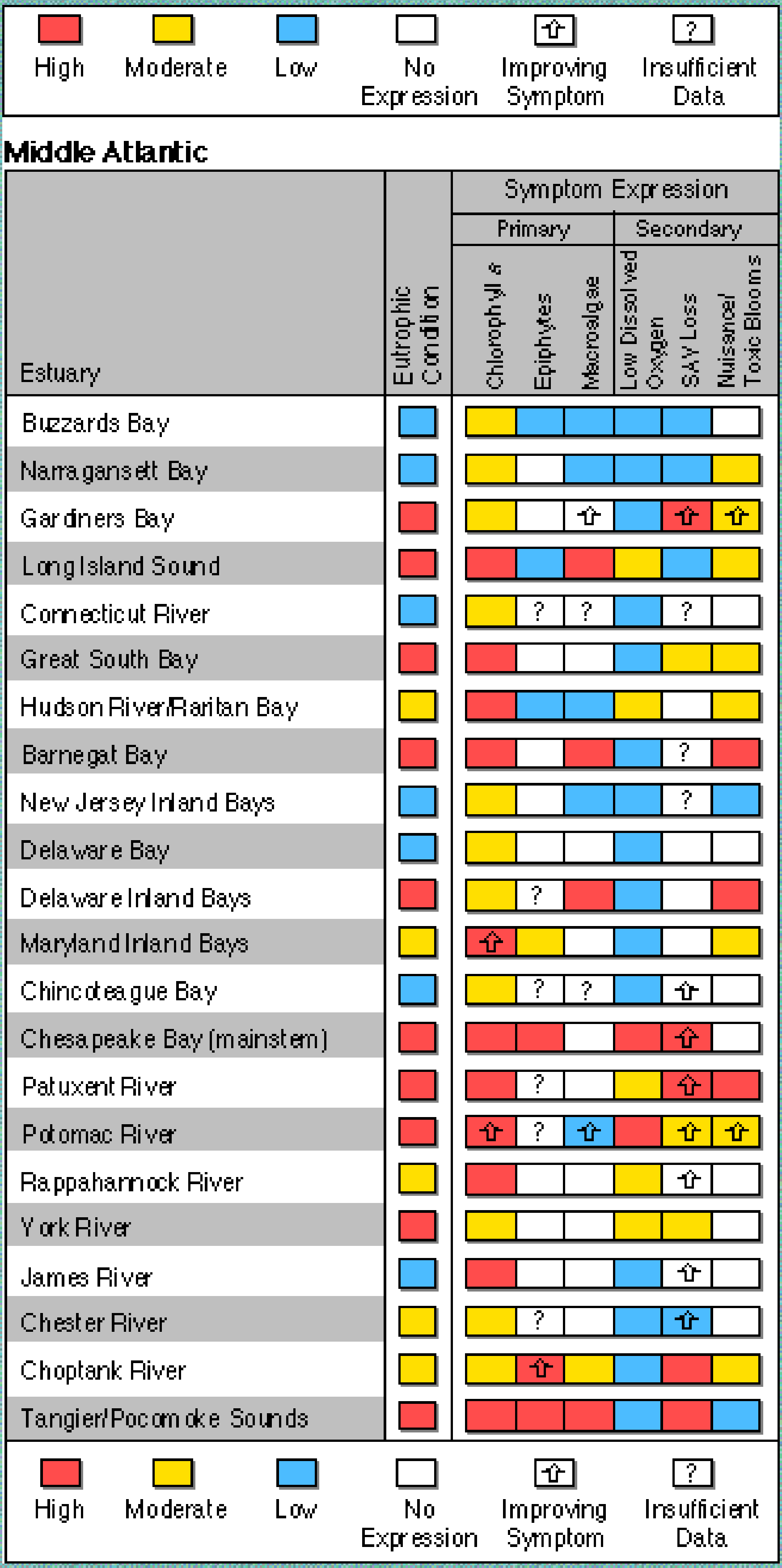

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Appendix A3. Expression of Eutrophic Condition and Symptoms in the Nation's Estuaries: South Atlantic Region

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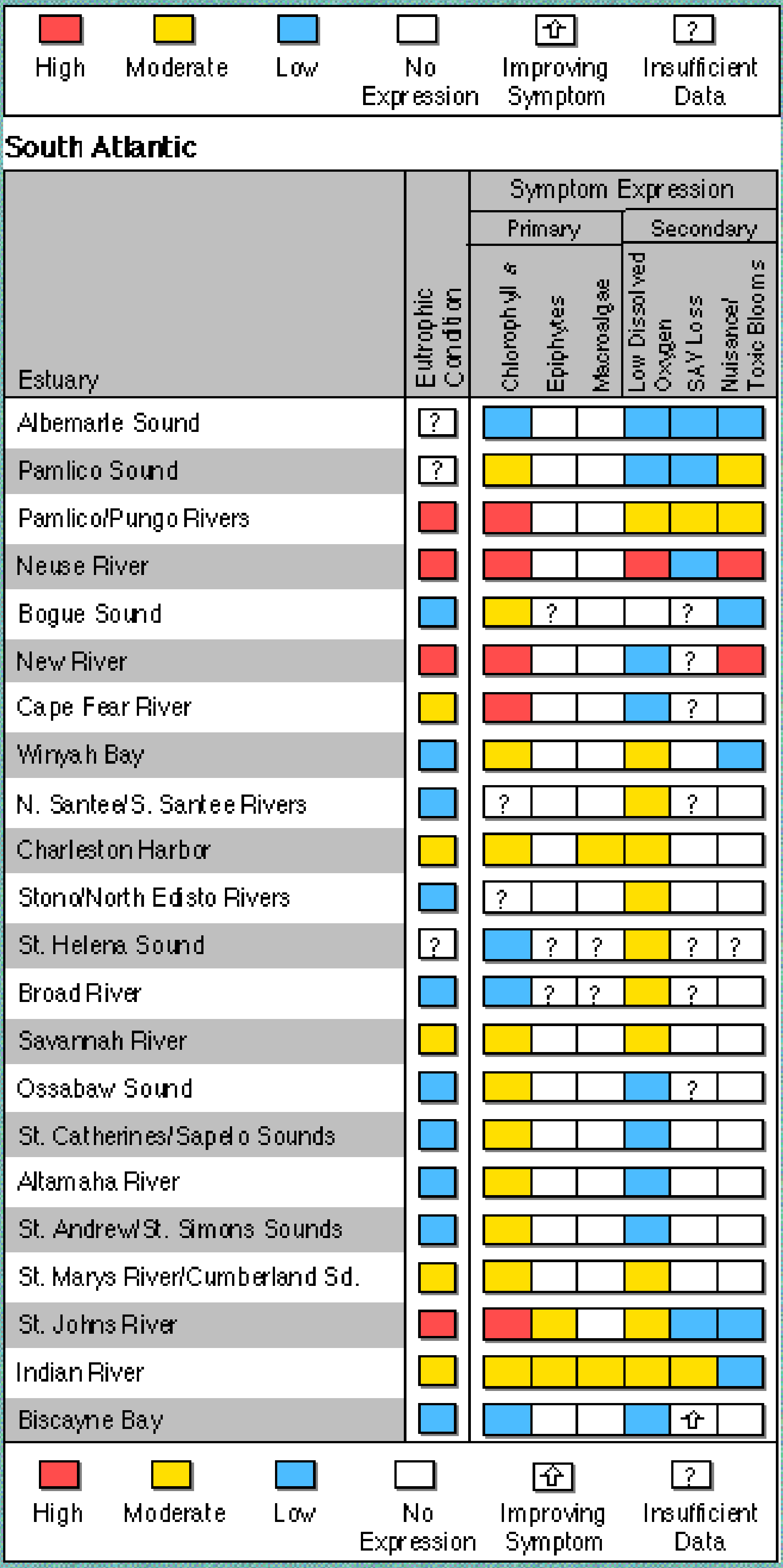

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Appendix A4. Expression of Eutrophic Condition and Symptoms in the Nation's Estuaries: Gulf of Mexico Region

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High | Moderate | Low | No Expression | Improving Symptom | Insufficient Data

Gulf of Mexico

Estuary	Eutrophic Condition	Symptom Expression: Primary: Chlorophyll a	Epiphytes	Macroalgae	Secondary: Low Dissolved Oxygen	SAV Loss	Nuisance/Toxic Blooms
Florida Bay	High	Moderate	High	High	High	Moderate	Moderate
South Ten Thousand Islands	High	Moderate	No Expression	No Expression	High	Low	No Expression
North Ten Thousand Islands	Moderate	Moderate	No Expression	No Expression	Moderate	?	No Expression
Rookery Bay	Low	Low	No Expression	No Expression	Low	No Expression	No Expression
Charlotte Harbor	High	High	Moderate	No Expression	High	Low	Moderate
Caloosahatchee River	High	High	No Expression	No Expression	Low	Low	No Expression
Sarasota Bay	High	Moderate, Improving	High	Low, Improving	Moderate	No Expression, Improving	High
Tampa Bay	High	High, Improving	No Expression	No Expression, Improving	Low, Improving	No Expression, Improving	Moderate, Improving
Suwannee River	Moderate	Moderate	No Expression	Moderate	Low	No Expression	Low
Apalachee Bay	Low	Moderate	No Expression	No Expression	Low	No Expression	Moderate
Apalachicola Bay	Moderate	Moderate	No Expression	No Expression	Moderate	No Expression	Moderate
St. Andrew Bay	Moderate	Moderate	Low	Low	Moderate	?	Low
Choctawhatchee Bay	High	Moderate	High	Low	Moderate	Moderate	High
Pensacola Bay	Moderate	Moderate	?	?	Moderate	Moderate	No Expression
Perdido Bay	High	Moderate	No Expression	High	Moderate	No Expression	Low
Mobile Bay	Moderate	Moderate	No Expression	No Expression	Moderate	Low	Moderate
East Mississippi Sound	Moderate	Moderate	No Expression	No Expression	Moderate	Moderate	Low
West Mississippi Sound	Low	Moderate, Improving	Low	No Expression	Low	Moderate, Improving	Low
Lake Borgne	?	?	?	?	No Expression	?	Moderate
Lake Pontchartrain	High	Moderate	High	High	Low	High	Moderate
Breton/Chandeleur Sounds	Low	?	?	No Expression	Low	Low	No Expression
Mississippi River	Low	Moderate	No Expression	No Expression	Low	No Expression	No Expression
Barataria Bay	Moderate	High	No Expression	No Expression	Moderate	No Expression	Low
Terrebonne/Timbalier Bays	Moderate	High	No Expression	No Expression	Low	No Expression, Improving	Low
Atchafalaya/Vermilion Bays	Moderate	High	No Expression	No Expression	Low	Low	No Expression
Mississippi River Plume	High	High	No Expression	No Expression	High	No Expression	High
Mermentau Estuary	Low	?	No Expression	No Expression	No Expression	No Expression	No Expression
Calcasieu Lake	High	High	No Expression	No Expression	Moderate, Improving	Moderate	High
Sabine Lake	Moderate	Moderate	No Expression	No Expression	Low, Improving	No Expression	Low
Galveston Bay	High	Moderate, Improving	No Expression	No Expression	Low, Improving	High	Low, Improving
Brazos River	Moderate	Moderate, Improving	No Expression	No Expression	Moderate	No Expression	Low
Matagorda Bay	Moderate	Moderate	No Expression	No Expression	Low	No Expression	Low
San Antonio Bay	High	Moderate	High	High	Low	Low	Low
Aransas Bay	Moderate	Moderate	Moderate	High	Low, Improving	Low	Low
Corpus Christi Bay	High	High	High	High	Low	No Expression	High
Upper Laguna Madre	High	High	No Expression	No Expression	Moderate	Moderate	High
Baffin Bay	High	High	No Expression	No Expression	Low	No Expression	High
Lower Laguna Madre	High	High	No Expression	No Expression	Low	Moderate	High

High | Moderate | Low | No Expression | Improving Symptom | Insufficient Data

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Appendix A5. Expression of Eutrophic Condition and Symptoms in the Nation's Estuaries: Pacific Region

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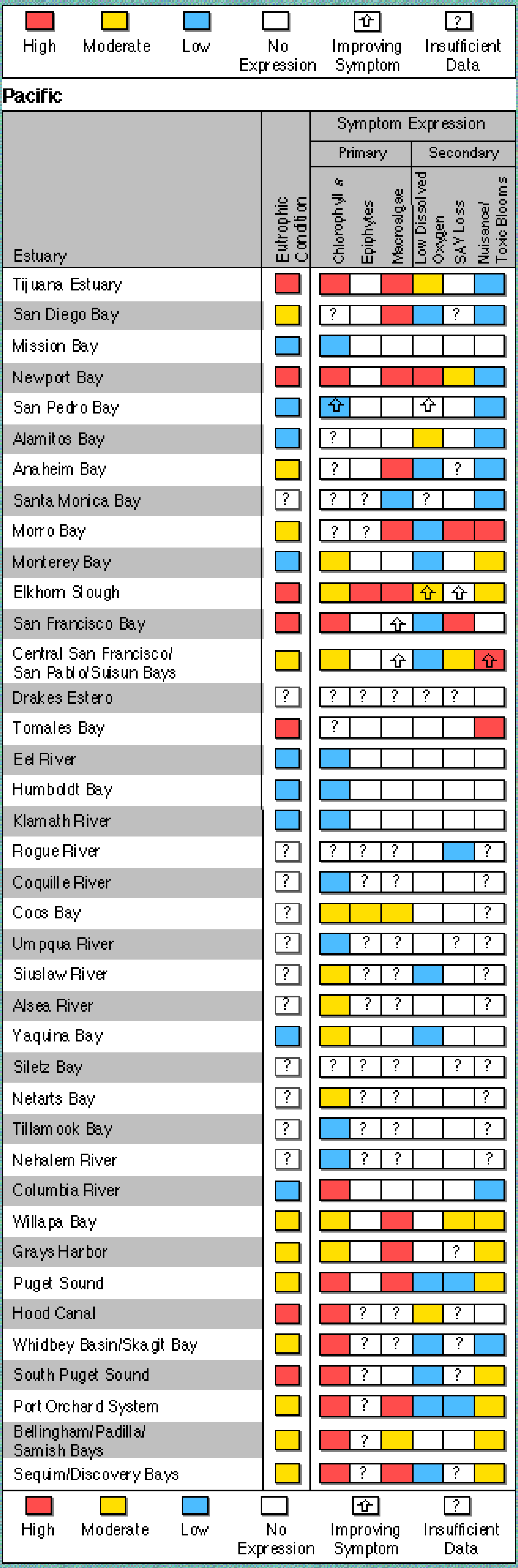

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Appendix B1. Overall Human Influence on Expression of Eutrophic Conditions: North Atlantic Region

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North Atlantic

High | Moderate | Low | ? Insufficient Data

Estuary	Eutrophic Condition	Influencing Factors: Overall Human Influence	Influencing Factors: Susceptibility	Influencing Factors: Nitrogen Input
Boston Harbor	High	High	Moderate	High
Sheepscot Bay	High	Low	Moderate	Moderate
St. Croix River/Cobscook Bay	High	Low	Low	Moderate
Englishman Bay	High	Low	Low	Low
Narraguagus Bay	High	Low	Low	Low
Casco Bay	High	Low	Low	Low
Damariscotta River	Moderate	Moderate	Moderate	Moderate
Massachusetts Bay	Moderate	Moderate	Low	High
Great Bay	Moderate	Low	Moderate	Low
Saco Bay	Moderate	Low	Low	Low
Cape Cod Bay	Moderate	Low	Moderate	Low
Plum Island Sound	Low	High	Moderate	High
Hampton Harbor Estuary	Low	Low	Low	Low
Muscongus Bay	Low	Low	Low	Moderate
Penobscot Bay	Low	Low	Low	Moderate
Kennebec/Androscoggin Rivers	Low	Low	Low	Moderate
Blue Hill Bay	Low	Low	Low	Low
Merrimack River	?	Low	Low	Low

High | Moderate | Low | ? Insufficient Data

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Appendix B2. Overall Human Influence on Expression of Eutrophic Conditions: Middle Atlantic Region

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Middle Atlantic

High | Moderate | Low | ? Insufficient Data

Estuary	Eutrophic Condition	Influencing Factors: Overall Human Influence	Influencing Factors: Susceptibility	Influencing Factors: Nitrogen Input
Chesapeake Bay	High	High	High	Moderate
Barnegat Bay	High	High	High	Moderate
Delaware Inland Bays	High	High	High	Low
Patuxent River	High	High	High	Moderate
Potomac River	High	High	High	Moderate
Tangier/Pocomoke Sounds	High	High	High	High
Long Island Sound	High	High	High	Moderate
York River	High	High	High	Low
Great South Bay	High	Moderate	High	Low
Gardiners Bay	High	Low	Moderate	Low
Rappahannock River	Moderate	High	High	Moderate
Hudson River/Raritan Bay	Moderate	High	Moderate	High
Chester River	Moderate	High	High	Moderate
Choptank River	Moderate	High	High	Moderate
Maryland Inland Bays	Moderate	Moderate	High	Low
Narragansett Bay	Low	High	Moderate	High
New Jersey Inland Bays	Low	High	High	Moderate
Delaware Bay	Low	High	Moderate	High
James River	Low	High	Moderate	Moderate
Connecticut River	Low	Moderate	Moderate	Moderate
Chincoteague Bay	Low	Moderate	High	Low
Buzzards Bay	Low	Low	Moderate	Low

High | Moderate | Low | ? Insufficient Data

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Appendix B3. Overall Human Influence on Expression of Eutrophic Conditions: South Atlantic Region

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South Atlantic

High | Moderate | Low | ? Insufficient Data

Estuary	Eutrophic Condition	Influencing Factors: Overall Human Influence	Influencing Factors: Susceptibility	Influencing Factors: Nitrogen Input
Neuse River	High	High	High	High
Pamlico/Pungo Rivers	High	High	High	Moderate
New River	High	High	Low	Moderate
St. Johns River	High	Moderate	High	Low
Cape Fear River	Moderate	Moderate	High	Moderate
Charleston Harbor	Moderate	Moderate	Moderate	Moderate
Indian River	Moderate	Moderate	High	Low
St. Marys River/Cumberland Sound	Moderate	Low	Moderate	Low
Savannah River	Moderate	Low	Low	Moderate
Winyah Bay	Low	Moderate	Moderate	Moderate
Stono/North Edisto Rivers	Low	Moderate	High	Low
N. Santee/S. Santee Rivers	Low	Low	Moderate	Low
Broad River	Low	Low	Moderate	Low
St. Catherines/Sapelo Sounds	Low	Low	Moderate	Low
St. Andrew/St. Simons Sounds	Low	Low	Moderate	Low
Bogue Sound	Low	Low	High	Low
Ossabaw Sound	Low	Low	Low	Moderate
Altamaha River	Low	Low	Moderate	Moderate
Biscayne Bay	Low	?	High	?
Albemarle Sound	?	Moderate	Moderate	Moderate
Pamlico Sound	?	Moderate	?	Moderate
St. Helena Sound	?	Low	Low	Low

High | Moderate | Low | ? Insufficient Data

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Appendix B4. Overall Human Influence on Expression of Eutrophic Conditions: Gulf of Mexico Region

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Gulf of Mexico

High | Moderate | Low | ? Insufficient Data

Estuary	Eutrophic Condition	Influencing Factors: Overall Human Influence	Influencing Factors: Susceptibility	Influencing Factors: Nitrogen Input
Perdido Bay	High	High	High	Moderate
Baffin Bay	High	High	High	Moderate
Upper Laguna Madre	High	High	High	Moderate
Charlotte Harbor	High	High	High	Low
Lower Laguna Madre	High	High	High	Low
Corpus Christi Bay	High	High	High	Low
South Ten Thousand Islands	High	High	High	?
Sarasota Bay	High	High	Moderate	High
Caloosahatchee River	High	High	Moderate	Moderate
Tampa Bay	High	High	Moderate	Moderate
Choctawhatchee Bay	High	High	Moderate	Moderate
Lake Pontchartrain	High	High	Moderate	Moderate
Calcasieu Lake	High	High	Moderate	Moderate
Galveston Bay	High	High	Moderate	Moderate
San Antonio Bay	High	High	Moderate	Low
Florida Bay	High	High	Moderate	?
Mississippi River Plume	High	High	?	?
Matagorda Bay	Moderate	High	High	Low
Apalachicola Bay	Moderate	High	Moderate	Moderate
Pensacola Bay	Moderate	High	Moderate	Moderate
Sabine Lake	Moderate	High	Moderate	Moderate
Terrebonne/Timbalier Bays	Moderate	Moderate	High	Low
Aransas Bay	Moderate	Moderate	High	Moderate
North Ten Thousand Islands	Moderate	Moderate	High	?
Mobile Bay	Moderate	Moderate	Moderate	Moderate
East Mississippi Sound	Moderate	Moderate	Moderate	Moderate
Barataria Bay	Moderate	Moderate	Moderate	Moderate
St. Andrew Bay	Moderate	Moderate	Moderate	Low
Brazos River	Moderate	Moderate	Moderate	Low
Atchafalaya/Vermilion Bays	Moderate	Moderate	Low	Low
Suwannee River	Moderate	Low	Moderate	Low
West Mississippi Sound	Low	Moderate	Moderate	Moderate
Mississippi River	Low	Moderate	Low	Moderate
Mermentau Estuary	Low	Low	Moderate	Moderate
Apalachee Bay	Low	Low	Moderate	Low
Breton/Chandeleur Sounds	Low	Low	Moderate	Low
Rookery Bay	Low	Low	Low	?
Lake Borgne	?	Moderate	Moderate	Moderate

High | Moderate | Low | ? Insufficient Data

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Appendix B5. Overall Human Influence on Expression of Eutrophic Conditions: Pacific Region

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Pacific

High | Moderate | Low | ? Insufficient Data

Estuary	Eutrophic Condition	Influencing Factors: Overall Human Influence	Influencing Factors: Susceptibility	Influencing Factors: Nitrogen Input
Tijuana Estuary	High	High	High	High
Newport Bay	High	High	High	High
San Francisco Bay	High	High	Moderate	Moderate
Elkhorn Slough	High	High	High	Moderate
Tomales Bay	High	High	High	Moderate
Hood Canal	High	High	High	Low
South Puget Sound	High	High	High	Moderate
Anaheim Bay	Moderate	High	High	High
San Diego Bay	Moderate	High	High	Moderate
Morro Bay	Moderate	High	High	Moderate
Whidbey Basin/Skagit Bay	Moderate	Moderate	Moderate	Moderate
Port Orchard System	Moderate	Moderate	Moderate	Moderate
Bellingham/Padilla/Samish Bays	Moderate	Moderate	Moderate	?
Sequim/Discovery Bays	Moderate	Moderate	Moderate	?
Willapa Bay	Moderate	Low	Low	Moderate
Grays Harbor	Moderate	Low	Low	Moderate
Puget Sound	Moderate	Low	Low	Moderate
Central San Francisco/San Pablo/Suisun Bays	Moderate	Low	Low	Moderate
San Pedro Bay	Low	High	High	High
Mission Bay	Low	High	High	Moderate
Humboldt Bay	Low	High	High	Moderate
Eel River	Low	Moderate	Moderate	Moderate
Monterey Bay	Low	Low	Low	Low
Yaquina Bay	Low	Low	Moderate	Low
Klamath River	Low	Low	Moderate	Low
Columbia River	Low	Low	Low	Low
Alamitos Bay	Low	?	High	?
Santa Monica Bay	?	High	Moderate	High
Drakes Estero	?	High	Low	Moderate
Coos Bay	?	Moderate	Moderate	Moderate
Siuslaw River	?	Moderate	Moderate	Moderate
Tillamook Bay	?	Moderate	Moderate	Moderate
Rogue River	?	Moderate	Moderate	Moderate
Alsea River	?	Moderate	Moderate	Moderate
Netarts Bay	?	Moderate	High	Moderate
Nehalem River	?	Moderate	Moderate	Moderate
Coquille River	?	Low	Moderate	Low
Umpqua River	?	Low	Moderate	Low
Siletz Bay	?	Low	Moderate	Low

High | Moderate | Low | ? Insufficient Data

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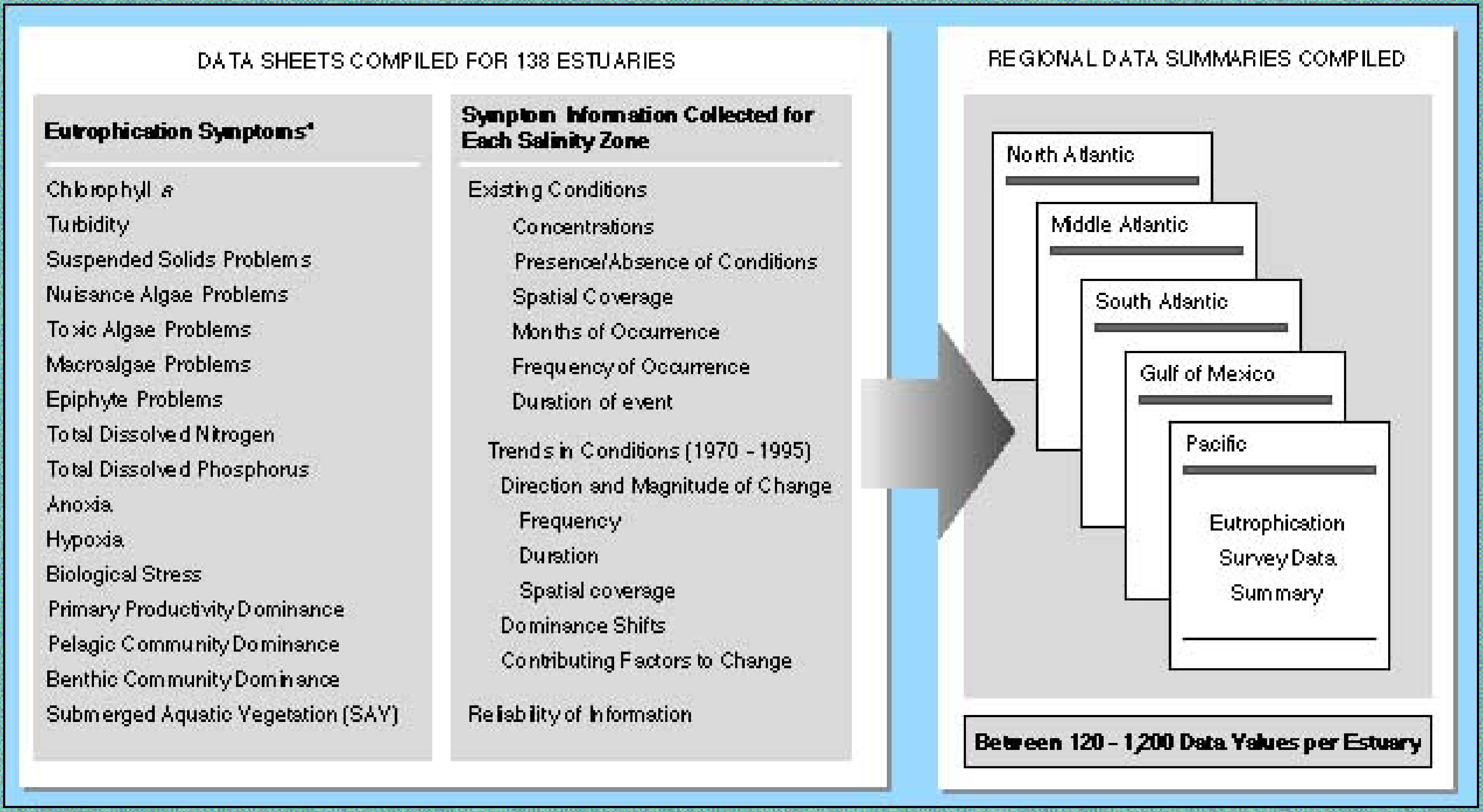

Figure 1. Data parameters for survey of eutrophication-related symptoms in 138 estuaries of the coterminous United States collected between 1992 and 1998.

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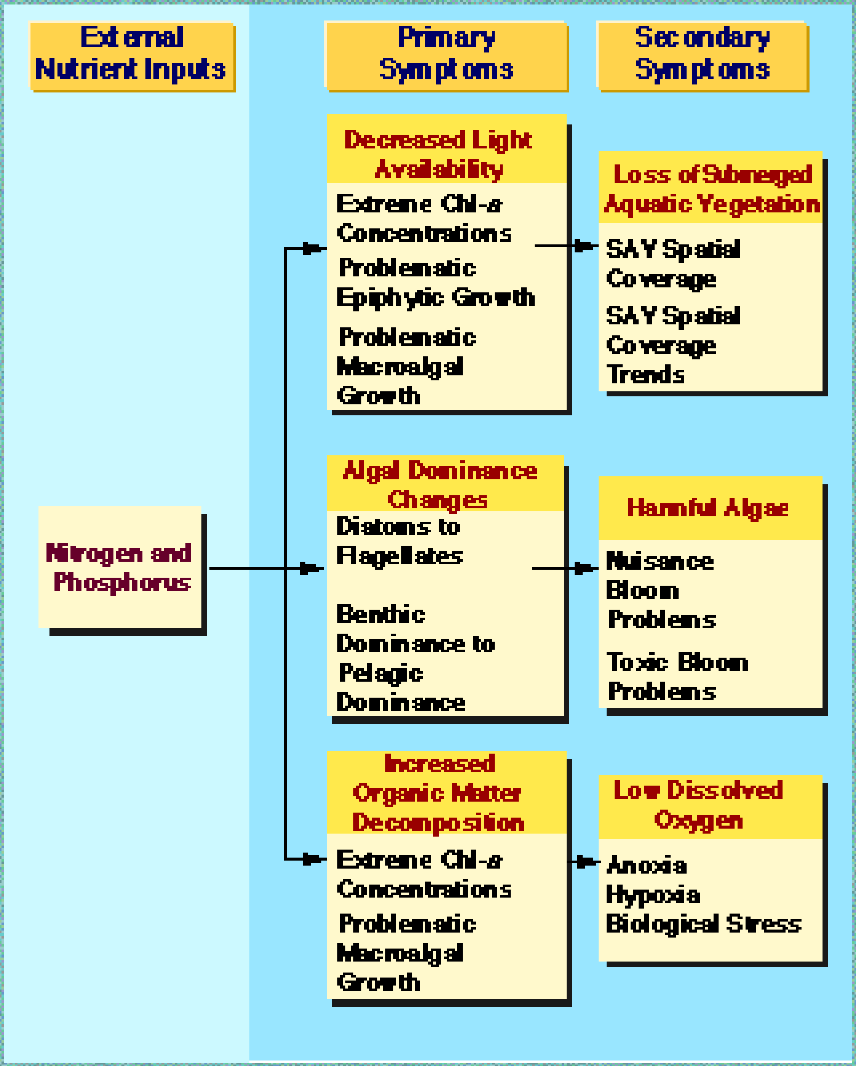

Figure 2. Simple model used to interpret eutrophication survey of 138 estuaries and the Mississippi River Plume.

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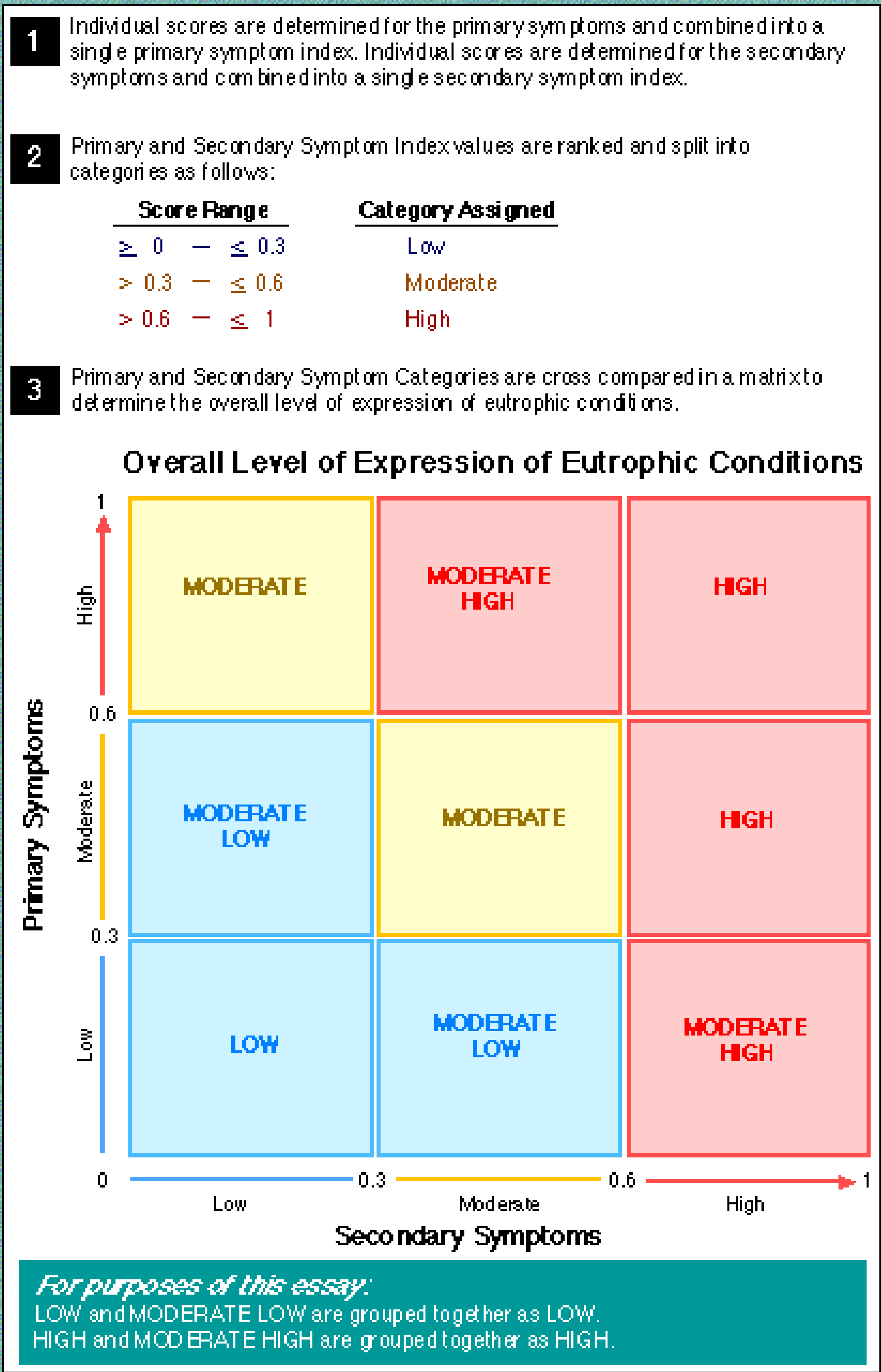

Figure 3. Matrix used to assign overall level of expression of eutrophic conditions in an estuary.

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