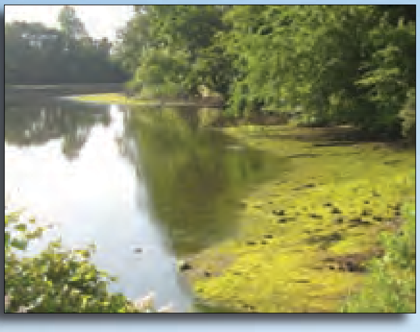
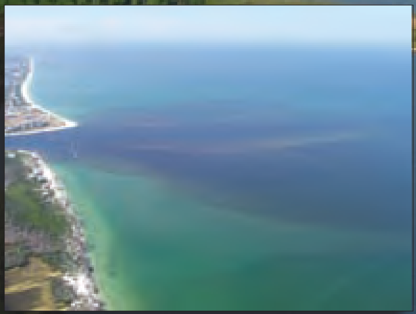
EFFECTS OF NUTRIENT ENRICHMENT IN THE NATION'S ESTUARIES:

A Decade of Change





National Estuarine Eutrophication Assessment Update

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National Estuarine Eutrophication Assessment
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Effects of Nutrient Enrichment In The Nation's Estuaries:
A Decade of Change

Assessing change in eutrophic condition
from the early 1990s to 2004

National Estuarine Eutrophication Assessment Update

EFFECTS OF NUTRIENT ENRICHMENT IN THE NATION'S ESTUARIES: *A DECADE OF CHANGE*

National Estuarine Eutrophication Assessment

National Estuarine Eutrophication Update

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CHESAPEAKE EcoCheck
Assessing and forecasting ecosystem status

FOREWORD

In 1999, the National Estuarine Eutrophication Assessment described the scale, scope, and characteristics of nutrient enrichment and eutrophic conditions in the Nation's estuaries. At the time, it was the most comprehensive examination ever reported of nutrient-related water quality impacts, their causes, and expected changes in condition in U.S. coastal water bodies. The results showed that most estuarine systems exhibited some level of eutrophication impact in the early 1990s. One of the main aims of the report was to develop a national strategy to limit the nutrient enrichment problems affecting U.S. estuarine and coastal water bodies.

This updated 2007 report continues to examine eutrophic conditions into the 2000s. It attempts to look at changes that occurred in the past decade, and analyze the Nation's progress in addressing what we now see as a ubiquitous problem. Coastal eutrophication is a global problem not limited to U.S. coastal waters. This report highlights the nutrient contamination in selected coastal systems throughout the U.S., Europe, Australia, and China in an effort to share what we know about the development of eutrophication, and to provide successful solutions to better manage the problem.

In addition to gaining a broader view of the issue, this report has enhanced and improved upon earlier work in other ways. The innovative assessment approach using the experience and knowledge base of experts from around the Nation has been transformed into a web-enabled tool. This web-based tool allows investigators to share data and information effectively and communicate in a standardized manner. This represents one of few instances where web-based communication has been accomplished for ecological monitoring on such a large scale (accessible at *http://ian.umces.edu/neea* or *http://www.eutro.us*). Effective communication is vital because the assessment will be updated on a periodic basis. The development of a complementary human use/socioeconomic indicator is also a significant enhancement designed to bridge the gap between scientific and public interest.

Additionally, this report provides a valuable context for a number of ongoing and planned activities designed to address estuarine eutrophication such as the multi-agency National Coastal Condition Report and the Gulf of Mexico Alliance Governors' Action Plan.

We encourage you to use this work to stimulate further scientific and management efforts to protect our precious coastal resources.

John H. Dunnigan
Assistant Administrator
for Ocean Services and
Coastal Zone Management

Dr. Donald F. Boesch
President
University of Maryland,
Center for Environmental Science

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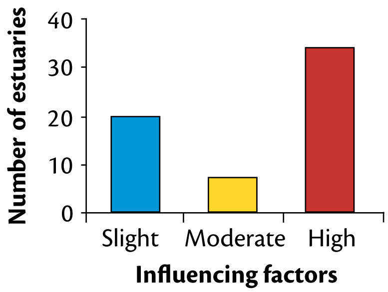
KEY FINDINGS

1. The majority of estuaries assessed were highly influenced by human-related activities.

Highly influenced estuaries had high nitrogen loads compared to the estuary's dilution or flushing capacity (Figure 1). High nitrogen loads were largely attributed to the influence of expanding and dense coastal human populations.

Figure 1. Factors influencing eutrophication (nitrogen load and susceptibility) were high for the majority of assessed systems.



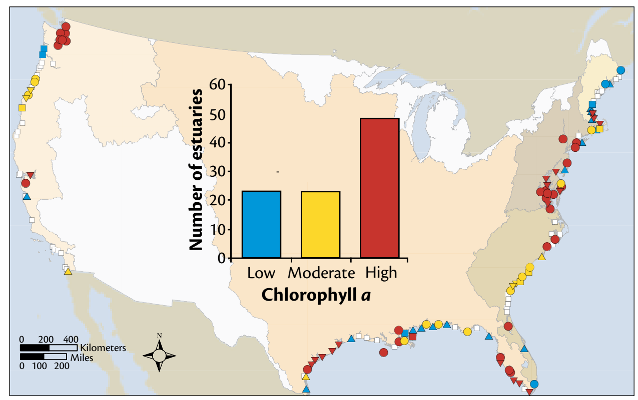
2. The majority of estuaries assessed had overall eutrophic conditions rated as moderate to high.

Eutrophication has a predictable suite of symptoms including increased chlorophyll *a*, macroalgae and nuisance/toxic blooms, decreased dissolved oxygen, and submerged aquatic vegetation loss (Figure 2).

3. The most commonly occurring eutrophic symptom was high spatial coverage and high frequency of elevated chlorophyll *a* levels.

Most estuaries also exhibited at least one other moderate to high symptom expression in addition to chlorophyll *a* (Figure 3).

Figure 3. A high chlorophyll *a* rating was observed in a large number of the Nation's estuaries.



4. Overall eutrophic condition and symptom expressions were geographically variable.

There were differences in eutrophic status among estuaries in close proximity (Figure 4). The net effect of this variability was that there was no national

Figure 2. A conceptualization of the relationship between overall eutrophic conditions, associated eutrophic symptoms, and influencing factors (nitrogen loads and susceptibility).

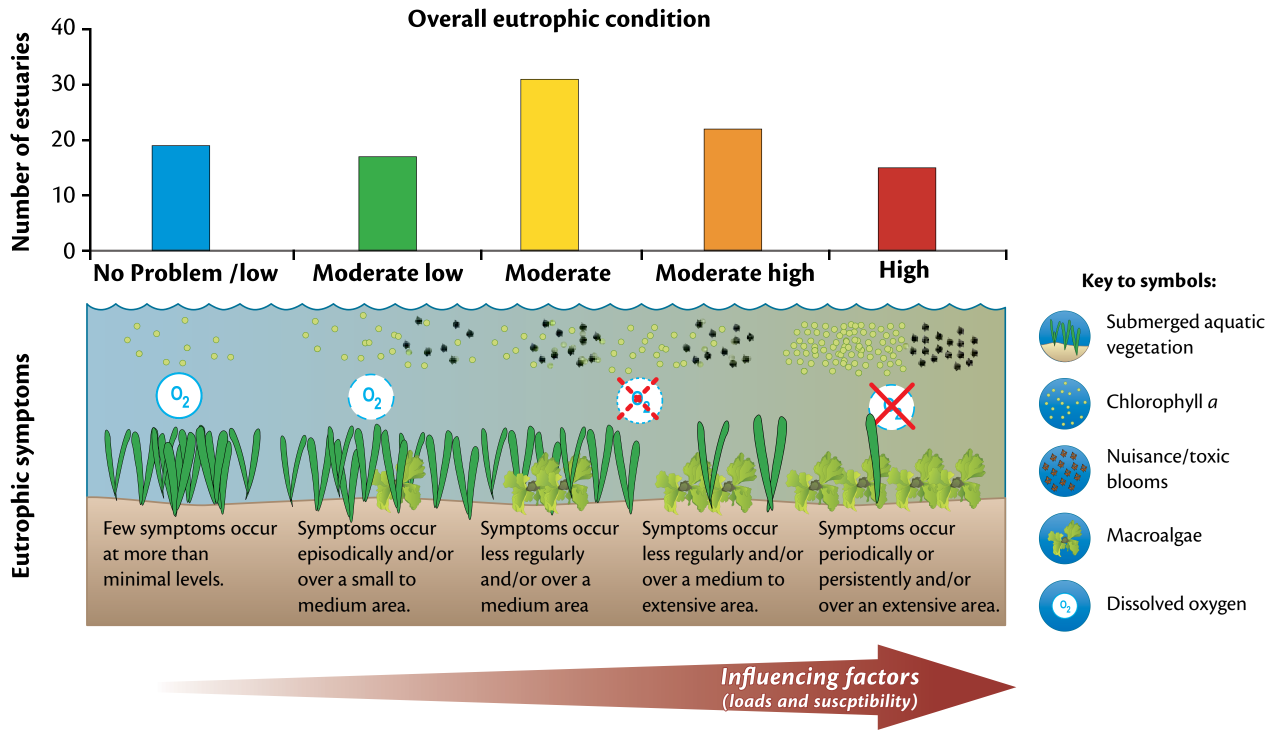
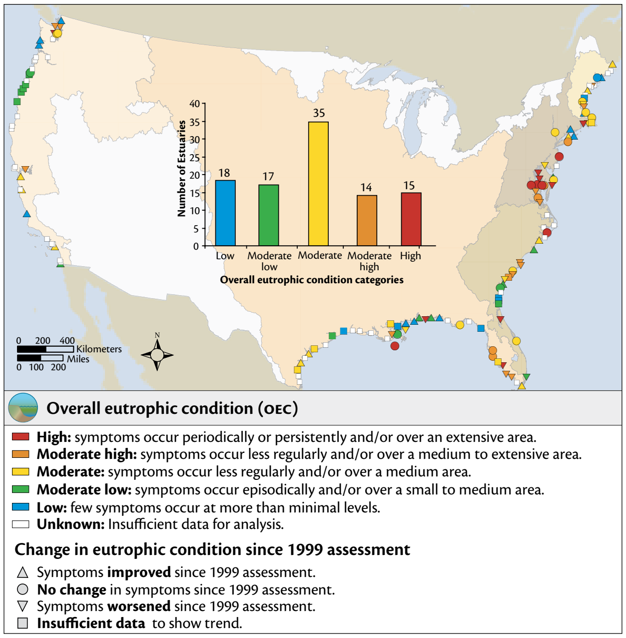


Figure 4. National overall eutrophic condition was geographically variable.

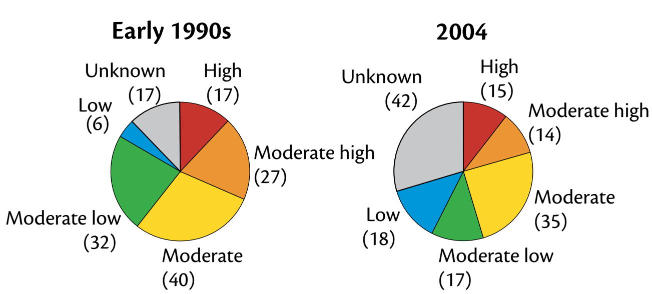


pattern of overall eutrophic conditions or symptom expressions except that the largest concentration of highly eutrophic systems was in the mid-Atlantic.

5. Comparison of eutrophic conditions assessed from the early 1990s to 2004 indicates similar levels of eutrophication.

Direct comparison of eutrophic status between assessments was impeded by reduced data availability in 2004 (70% of systems in 2004 vs. 88% in 1990s) due in part to changes in the data collection method (*see chapter 3: National assessment*). If only assessed systems are considered, conditions have improved in 13 estuaries, worsened in 13, and remained the same in 32 systems. In 1999, 69% of assessed systems (72% of assessed area) had moderate to high eutrophic conditions compared to 65% of assessed systems (78% of assessed area) in 2004 (Figure 5).

Figure 5. Number of estuaries in each eutrophication category in the early 1990s (1999 assessment) and 2004 (this assessment).



6. Considerations for management action, monitoring, research, and communication (Figure 6)

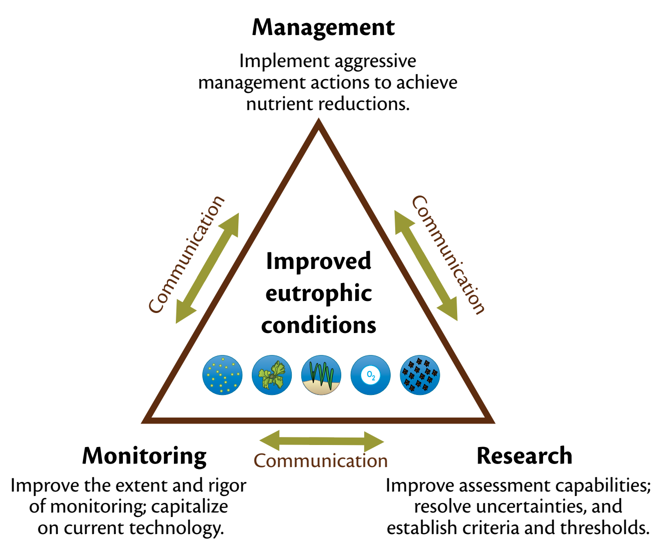
Management: Implement more aggressive action to achieve nutrient reductions for widespread reductions in eutrophic conditions. Notable improvements have been achieved (e.g., Tampa Bay and Boston Harbor) with aggressive management intervention, but these are isolated cases.

Monitoring: Capitalize on technology (e.g., observing systems, remote sensing) to improve comprehensive assessment of eutrophication in a coordinated and timely fashion. Future national assessments would benefit from rigorous, easily accessible data (both *in situ* and remotely sensed) provided on the web by local and regional assessment programs.

Research: Focus on improving monitoring and assessment of eutrophication, resolving uncertainties, and establishing criteria and thresholds. In particular, macroalgae and submerged aquatic vegetation indicators should be improved. Elucidate potential and evaluate current management options.

Communication: Engage resource managers, researchers, policy makers, and the community with frequent assessment updates at local, regional, and national levels. Environmental report cards, illustrative graphics, and maps, will foster interest and inform, and empower the public to support critical management action.

Figure 6. Improvements in eutrophic condition can only be achieved by management, research, and monitoring programs working together.



EXECUTIVE SUMMARY

Chapter 1: Introduction and Background

- The National Estuarine Eutrophication Assessment (NEEA) is a tool for evaluating both current eutrophic condition and the effectiveness of management actions aimed at reducing eutrophic condition.
- Eutrophication is caused by excess nutrients and is expressed by symptoms such as increased chlorophyll *a* and macroalgae, and decreased dissolved oxygen.
- Widespread coastal eutrophication has been reported in a previous national assessment (Bricker et al. 1999). As coastal populations continue to increase, experts are concerned that eutrophication and associated symptoms are also increasing. In response to this concern, it was decided that the 1999 assessment should be updated.
- This update of the 1999 assessment identifies current eutrophic status and changes since the early 1990s, tracks management progress, and identifies potential solutions for eutrophication.
- To facilitate this and future assessments, an online survey tool was developed. This tool allows investigators to share data and information effectively, providing a common language by which they can communicate with one another in a standardized manner.

Chapter 2: Approach

- The NEEA evaluates eutrophication by examining (1) influencing factors; (2) eutrophic symptoms; (3) overall eutrophic condition; (4) future outlook; and, (5) combining the results into one overall rating (ASSETS).
- In this report, factors influencing eutrophication are nitrogen load and the estuary's susceptibility to nitrogen (dilution and flushing rates).
- Overall eutrophic condition is based on assessment of 5 symptoms: chlorophyll *a*, macroalgae, dissolved oxygen, submerged aquatic vegetation and nuisance/toxic blooms. Eutrophic condition is determined by evaluating the occurrence, spatial coverage and frequency of these symptoms.
- Eutrophic condition is predicted for year 2020 (future outlook) based on expected changes in nutrient loads and the estuary's susceptibility to these loads.
- The influencing factors, overall eutrophic condition, and future outlook results are combined into an overall system rating (ASSETS).
- Completeness and reliability of the assessment is based on the temporal and spatial availability of data.

Chapter 3: National Assessment

- The majority of estuaries assessed were highly influenced by human-related activities. Influencing factor ratings were high from New York to Texas, low in the North Atlantic, and mostly unknown in the Pacific region.
- Eutrophication is a widespread problem, with the majority of assessed estuaries showing signs of eutrophication—65% of the assessed systems, representing 78% of assessed estuarine area, had moderate to high overall eutrophic conditions.
- The most common symptoms of eutrophication were high spatial coverage and frequency of elevated chlorophyll *a* (phytoplankton)—50% of the assessed estuaries, representing 72% of assessed area, had a high chlorophyll *a* rating.
- There were no regional or national patterns of highly eutrophic conditions found in systems along all coastlines. However, the mid-Atlantic region was the most impacted overall.
- Survey participants predicted worsening conditions by 2020 in 65% of estuaries and improvements in 20% of estuaries.
- Change analysis showed that conditions in most assessed systems remained the same since the early 1990s (32 systems, 77% assessed area). Changes were observed in smaller systems; 13 systems (9% assessed area) improved and 13 systems (14% assessed area) worsened.
- Assessment of eutrophic condition was impeded by reduced reporting in 2004 as there were inadequate data for 30% of surveyed estuaries, compared to only 12% of estuaries in the early 1990s. This was largely a result of the data collection method, the online survey for the 2004 data versus use of site visits and workshops in addition to a survey for the 1999 assessment.

Chapter 4: Regional Assessments

- This assessment divides the nation's estuaries into five regions: North Atlantic, mid-Atlantic, South Atlantic, Gulf of Mexico, and Pacific Coast. Estuaries are divided into these regions to facilitate discussion and application to management.

North Atlantic (Maine to Cape Cod)

- North Atlantic estuaries are small, deep, and well-flushed by tides, with generally small watersheds. Factors influencing eutrophication were low for all reported systems.
- North Atlantic estuaries were the least impacted nationally: no estuaries had a high overall eutrophic condition rating. However, the outlook for this region raises concern, with conditions predicted to worsen in most estuaries.

Mid-Atlantic (Cape Cod to Chesapeake Bay)

- Mid-Atlantic estuaries and coastal lagoons are relatively large, moderately deep, have a moderate watershed size, and are poorly flushed. Factors influencing eutrophication were high for the majority of estuaries.
- Mid-Atlantic estuaries were the most impacted nationally: the majority of estuaries recorded a moderate high or high overall eutrophic condition rating, with

more than one third of the estuaries having worsened since the early 1990s.

South Atlantic (North Carolina to Florida)

- South Atlantic estuaries are mostly of medium size, shallow, and well flushed. They have moderately sized watersheds with relatively high population. Factors influencing eutrophication were spatially variable, with high influencing factor ratings in over one third of the assessed estuaries.
- Problematic levels of chlorophyll *a* and dissolved oxygen were the main symptoms of eutrophication in this region, although the majority of estuaries had moderate or low eutrophic condition.

Gulf of Mexico (Florida to Texas)

- Gulf of Mexico estuaries are mostly large, shallow, and poorly flushed. They tend to have very large watersheds with low to moderate populations. Factors influencing eutrophication were high for most assessed estuaries.
- A small proportion of estuaries had high or moderately high overall eutrophic condition. Gulf of Mexico estuaries were characterized by high, and often worsening, chlorophyll *a* symptoms.

Pacific region (California to Washington)

- The Pacific region has numerous small, deep, and moderately well flushed estuaries with moderately sized watersheds. Very few estuaries in this region have nutrient load data available.
- Most estuaries with high to moderate eutrophic condition were located in Washington and central California with chlorophyll *a* and dissolved oxygen being the symptoms of concern.

Chapter 5: Case studies

- A diversity of national and international case studies are presented to illustrate the various impacts of eutrophication. In some cases, the associated management and monitoring responses are presented. Themes of the case studies include:
  - *Diversion of sewage effluent to offshore discharge reduced eutrophic symptoms (Boston Harbor).*
  - *Monitoring suggests anthropogenic and riverine sources of nutrients (Casco Bay).*
  - *Reduction in point source nutrients ameliorated hypoxia in the 1990s (Long Island Sound).*
  - *Trend reversal in water quality improvements likely caused by recent increase in diffuse nutrient load (Maryland Coastal Bays).*
  - *Predictable large scale hypoxia from nation's largest drainage basin due to nutrient loads (Mississippi-Atchafalaya Plume).*
  - *Deteriorating dissolved oxygen conditions occurring in a well mixed coastal waterway (Skidaway River Estuary).*
  - *Seagrass recovery after historic losses due to nitrogen load reductions (Tampa Bay).*
  - *Continuous water quality monitoring data helps to explain extreme events such as fish kills (Corsica River).*
  - *The complex factors causing low dissolved oxygen events require ongoing research, monitoring and modeling (Hood Canal).*
  - *Ecosystem transition occurred with initiation of brown tides (Laguna Madre).*
  - *Nutrients and climate change pose threat to coral reefs (Looe Key).*
  - *Holistic ecosystem evaluation needed to discern causes of chlorophyll* a *increases (San Francisco Bay).*
  - *Eutrophication symptoms, due to increased nitrogen load, include increased phytoplankton and macroalgae, and decline in seagrass (Waquoit Bay).*
  - *Rapid large scale increase in eutrophic symptoms (nuisance/toxic blooms, chlorophyll* a*, and dissolved oxygen) have occurred (Changjiang Estuary, China).*
  - *Threats from eutrophication to large scale aquaculture stimulate nutrient management (Jiaozhou Bay, China).*
  - *Seasonal macroalgae blooms lead to seagrass loss (Mondego River, Portugal).*
  - *Sewage plume mapping tracks nutrient reductions (Moreton Bay, Australia).*
  - *Flood protection measure can accentuate eutrophic symptoms (e.g., dissolved oxygen, macroalgae, and loss of submerged aquatic vegetation) (Venice Lagoon, Italy).*

Chapter 6: Improvements to the methods

- The NEEA aims to improve the methods used to assess eutrophic condition of the nation's estuaries. Some of these improvements are based on recommendations of survey and workshop participants.
- Some improvements currently being addressed (and summarized in the report) are: (1) exploring linkages with EPA's National Coastal Assessment; (2) developing indicators of socioeconomic/human-use impacts; (3) developing a type classification scheme for the nation's estuaries; and (4) improving methods of evaluating eutrophic condition, especially for submerged aquatic vegetation and macroalgae abundance.

Chapter 7: Conclusions and Considerations for Management

- Reducing eutrophic conditions in estuaries requires coordinated and integrated action that balances management action, efficient monitoring to assess the effectiveness of the management, targeted research, and a communication campaign aimed at engaging the broader community. Major recommendations are:
  - *Implement more aggressive management actions to reduce nutrients for improvements in eutrophic condition.*
  - *Capitalize on monitoring technological innovations (e.g., observing systems, remote sensing, web resources) to improve comprehensive assessment of eutrophication status in a coordinated and timely fashion.*
  - *Focus research on improving assessment capability, resolving uncertainty, and establishing criteria/thresholds.*
  - *Engage resource managers, researchers, policy makers, and the community with frequent assessment updates at local, regional, and national levels.*
  - *Develop tools to quantitatively relate the effectiveness of mitigation strategies in response to policy actions.*

1. INTRODUCTION AND BACKGROUND

UNDERSTANDING EUTROPHICATION

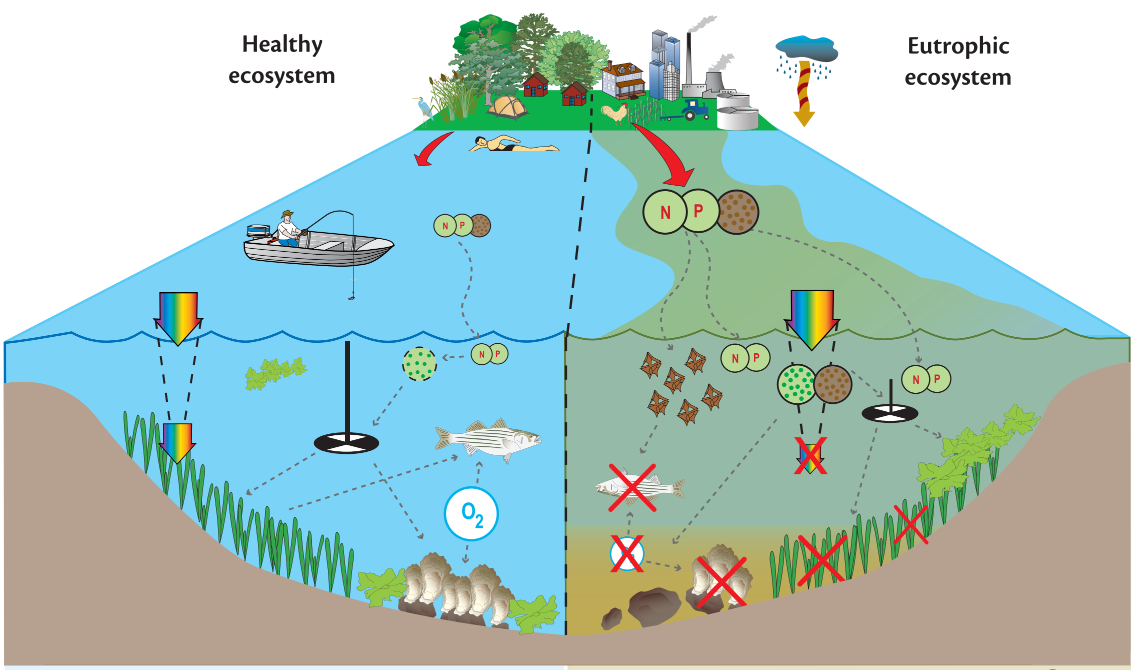
What is eutrophication?

- Eutrophication is a process in which the addition of nutrients (largely nitrogen and phosphorus) to water bodies stimulates algal growth. Excessive nutrient inputs may lead to other more serious problems such as low dissolved oxygen and loss of submerged aquatic vegetation (SAV).
- In recent decades, human activities and population growth have greatly increased nutrient inputs to systems, leading to degraded water quality and impairments of estuarine resources for human use.

Source: Bricker et al., 1999

Nutrient additions to aquatic systems occur naturally due to geological weathering and inputs from ocean upwelling. However, in recent decades, population growth and its related nutrient sources, such as agriculture, wastewater treatment plants, urban runoff, and consumption of fossil fuels (atmospheric deposition), have increased nutrient inputs to many times their natural levels, accelerating eutrophication (Figure 1.1). Nutrient increases can threaten biota, as well as lead to impairment to aesthetics, health, fishing opportunities and success, tourism, and real estate value. For this reason, management efforts should address nutrient inputs to restore and protect coastal resources.

Figure 1.1. Conceptual diagram comparing a healthy system with no or low eutrophic condition to an unhealthy system exhibiting eutrophic symptoms.



In healthy ecosystems, nutrient inputs, specifically nitrogen and phosphorus, occur at a rate that stimulates a level of macroalgal and phytoplankton (chlorophyll *a*) growth in balance with grazer biota. A low level of chlorophyll *a* in the water column helps keep water clarity high, allowing light to penetrate deep enough to reach submerged aquatic vegetation. Low levels of phytoplankton and macroalgae result in dissolved oxygen levels most suitable for healthy fish and shellfish so that humans can enjoy the benefits that a coastal environment provides.

In a eutrophic ecosystem, increased sediment and nutrient loads from farming, urban development, water treatment plants, and industry, in combination with atmospheric nitrogen, help trigger both macroalgae and phytoplankton (chlorophyll *a*) blooms, exceeding the capacity of grazer control. These blooms can result in decreased water clarity, decreased light penetration, decreased dissolved oxygen, loss of submerged aquatic vegetation, nuisance/toxic algal blooms and the contamination or die off of fish and shellfish.

Impacts of eutrophic symptoms

Increased nutrient inputs promote a progression of symptoms beginning with excessive growth of phytoplankton and macroalgae to the point where grazers cannot control growth. These blooms may be problematic, potentially lasting for months at a time and blocking sunlight to light-dependent submerged aquatic vegetation (SAV). In addition to increased growth, changes in naturally occurring ratios of nutrients may also affect which species dominate, potentially leading to nuisance/toxic algal blooms. These blooms may also lead to other more serious symptoms that affect biota, such as low dissolved oxygen and loss of SAV.

Once water column nutrients have been depleted by phytoplankton and macroalgae and these blooms die, the bacteria decomposing the algae then consume oxygen, making it less available to surrounding aerobic aquatic life. Consequently, fish and invertebrate kills may occur due to hypoxia and anoxia, conditions of low to no dissolved oxygen.

In some estuaries, the assimilative capacity, or inherent ability to absorb nutrients, is initially reduced by poor flushing or other factors. These particularly sensitive estuaries may be adversely affected by even slightly increased inputs, impacting such activities as commercial and recreational fishing, boating, swimming, and tourism.

Ben Longstaff, EcoCheck (NOAA/University of Maryland Center for Environmental Science)

A nuisance algal bloom grows rapidly, consuming resources and potentially blocking light to SAV in Chesapeake Bay.

Key terms and phrases

Assimilative capacity—the ability of water bodies to receive wastewater or toxic materials without harmful effects and without damage to aquatic life or humans who consume the water.

Eutrophic symptoms—the signs of poor ecosystem health in water bodies brought on by increased nutrient inputs (see Figure 1.1).

Flushing time—the time it takes for freshwater entering an estuary to pass through to the ocean.

Low dissolved oxygen—low (hypoxic) to no (anoxic) levels of oxygen (vital for aquatic life) in the water.

Nuisance algal blooms—algal growth so rapid or extensive that it influences water clarity, decreases oxygen levels (upon decomposition), clogs filter-feeder siphons, and crowds out other organisms.

Toxic algal blooms—large growths of toxin-producing algae that directly impact the health of organisms and may also contain toxins dangerous to humans.

Source: Estuarine Research Federation (http://erf.org/).

Eutrophic symptoms may also cause risks to human health, resulting from consumption of shellfish contaminated with algal toxins or direct exposure to waterborne toxins.

Other causes of eutrophic symptoms

It should be noted that although nutrients cause eutrophic symptoms, other human and natural influences may affect symptom expression. These influences include engineered water flow, development, dredging, overfishing, and disease. For example, engineered water flow can contribute to eutrophic symptoms by decreasing flushing rates in estuaries. Disease lowers assimilative capacity by decimating wetlands, submerged aquatic vegetation, and filter feeders. In addition to nitrogen and phosphorus, there are other nutrients (e.g., carbon) and trace elements (e.g., silica) that may affect the onset of symptoms, but their role is less understood.

Climate change may also be a significant influence on the development of future eutrophic symptoms. Because warmer water holds less oxygen, global warming may lower dissolved oxygen. Or, flushing times and exchange rates may increase with rising sea levels and increased rainfall. With changing hydrology, there is also a possibility of the exacerbation or novel occurrence of stratification (see page 38, *Eutrophication and Climate Change*).

CONDUCTING A NATIONAL ASSESSMENT

Why conduct a national assessment?

- Nearly all estuaries in the United States show signs of eutrophication.
- Experts are concerned that eutrophication and associated symptoms are increasing.
- A national assessment allows for a more informed method of creating, evaluating, and updating management plans that address eutrophication.

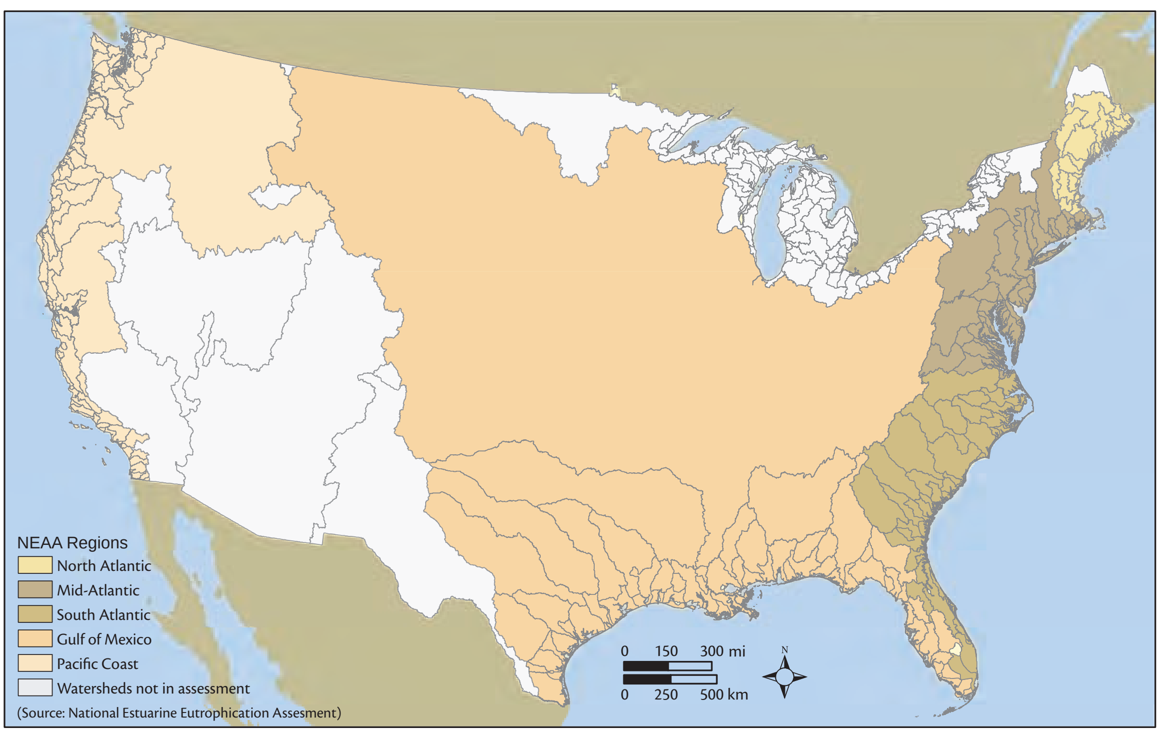
National Oceanic and Atmospheric Administration

Long Island Sound, one of the many estuaries in the United States exhibiting eutrophic symptoms.

Coastal eutrophication is a widespread national problem, though scale, intensity, and impact vary widely (Bricker et al. 1999). Whether nutrient additions result in degraded water quality depends on the extent of inputs and an estuary's susceptibility. As changes in conditions are evaluated and tracked to try to prevent further degradation, monitoring and assessment become increasingly important. A national assessment is needed to synthesize local and regional information on the eutrophic status of systems (Figure 1.2).

For several decades, scientists and natural resource managers have worked to understand, document, and improve the complex, adverse ecosystem changes associated with eutrophication. Of late, the consequences of these symptoms have become more apparent, including extensive SAV loss, the associated loss of fish habitat, worsening episodes of low dissolved oxygen in coastal systems, and longer-lasting or first-time nuisance/toxic algal blooms. These issues have led to legislative action such as the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (reauthorized in 2004; P.L. 105-383), that calls in part for the research and assessment of hypoxia and harmful algal blooms as well as the development of mitigation strategies.

Figure 1.2. The five regions in the National Estuarine Eutrophication Assessment.



The National Estuarine Eutrophication Assessment groups the Nation's estuaries into five geographic regions. The unique features of the water bodies in these regions influence the expression of eutrophic symptoms.

UPDATING THE ASSESSMENT

Why create an update?

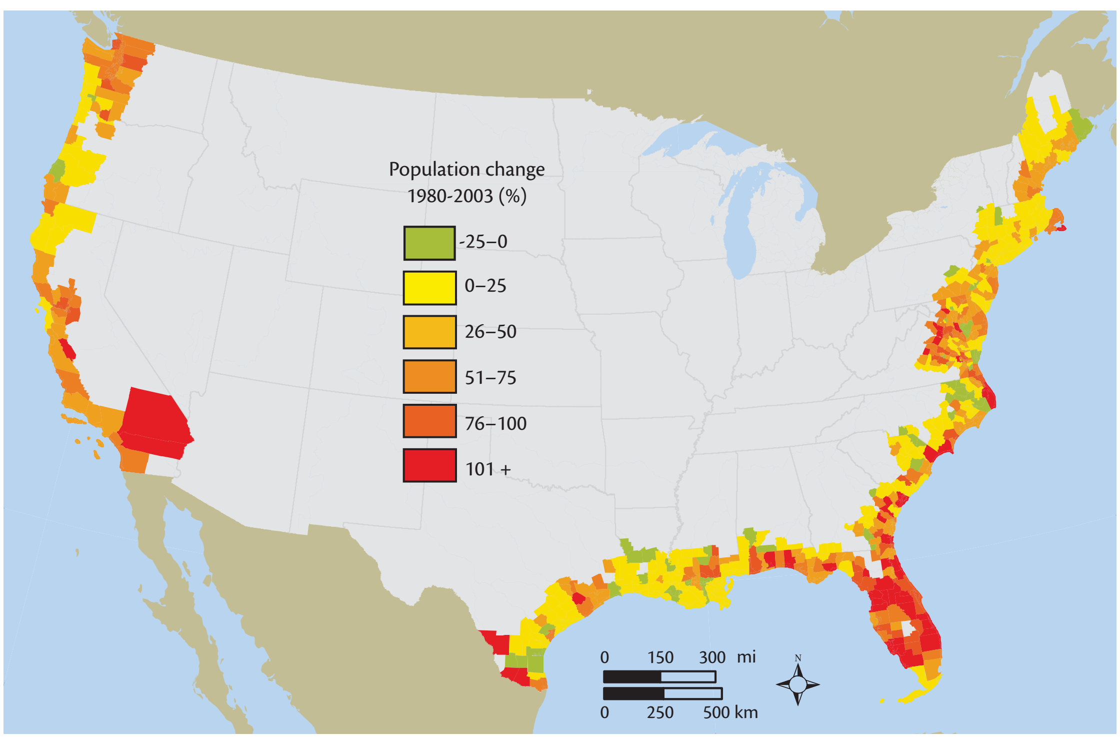
An update to the 1999 assessment will:

- Identify locations of changes that have occurred;
- Determine what influenced these changes; and
- Increase scientific, management, and community involvement.

Given the rising concern of the scientific community and the public about the health of U.S. estuaries, the National Oceanic and Atmospheric Administration (NOAA) began to evaluate the need for a more deliberate National response to the problem of estuarine eutrophication in the early 1990s. The *National Estuarine Eutrophication Assessment*, a survey of the extent, severity, types, and probable causes of eutrophic symptoms, was conducted in the early 1990s and released by Bricker et al. in 1999. The results showed that for 84 of 138 systems included in the study, overall eutrophic conditions were at a moderate to high level, occurring along all coastlines. Sixty-nine of these systems also showed impairment of everyday uses, including swimming and consumption of fish due to lower abundance or quality. Alarmingly, experts contributing to the report suggested that conditions in 86 of the 138 estuaries were expected to become worse by the year 2020 due to high-density populations and significant population increases currently occurring or expected in coastal areas. This is of particular concern for nutrient-sensitive estuaries with assimilative capacities that may not accommodate new loading scenarios. Only eight estuaries where management measures had been or were about to be implemented were projected to improve with time. The poor prognosis for the health of the Nation's estuaries suggested that regular updates were needed to assess the health of these systems and to evaluate the success of management strategies (Bricker et al. 2004).

This update is an attempt to look at the changes in estuaries that have occurred since the 1999 assessment. It should be noted that two new systems, Wells and Waquoit Bays, have been added to this assessment. Considering the significant increase in U.S. coastal and upstream population density, this assessment is vital (Figure 1.3). The updated assessment focuses on evaluating where and why eutrophic changes have occurred and what can be done to prevent future worsening conditions. In addition, it is hoped that public involvement will be stimulated by presenting the best available information about these problems to concerned citizens, resource managers, and policy makers.

Figure 1.3. Percent population change in coastal counties from 1980–2003.



NOAA's Spatial Trends in Coastal Socioeconomics website, a product of the Coastal and Ocean Resource Economics Program (http://marineeconomics.noaa.gov/socioeconomics/)

Population growth is occurring rapidly in coastal regions, and consequently increasing nutrient inputs and stress on coastal ecosystems.

DEVELOPING AN ONLINE TOOL FOR ASSESSMENT UPDATES

What can the new online survey do?

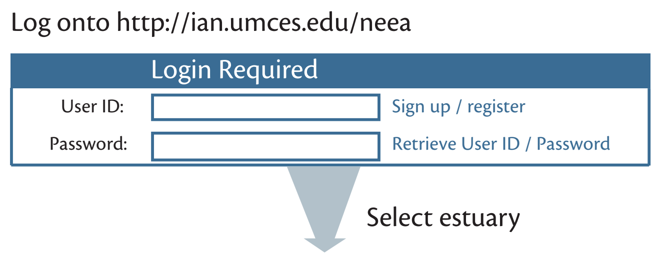
- Provide researchers, legislators, and concerned citizens access to a resource library.
- The online survey also allows researchers to enter their own data that automatically generates analytical outputs including:
  - A conceptual diagram of eutrophication in the system;
  - A spreadsheet of data;
  - Printable, site-specific graphics; and
  - A summary of data and graphics in PDF form.

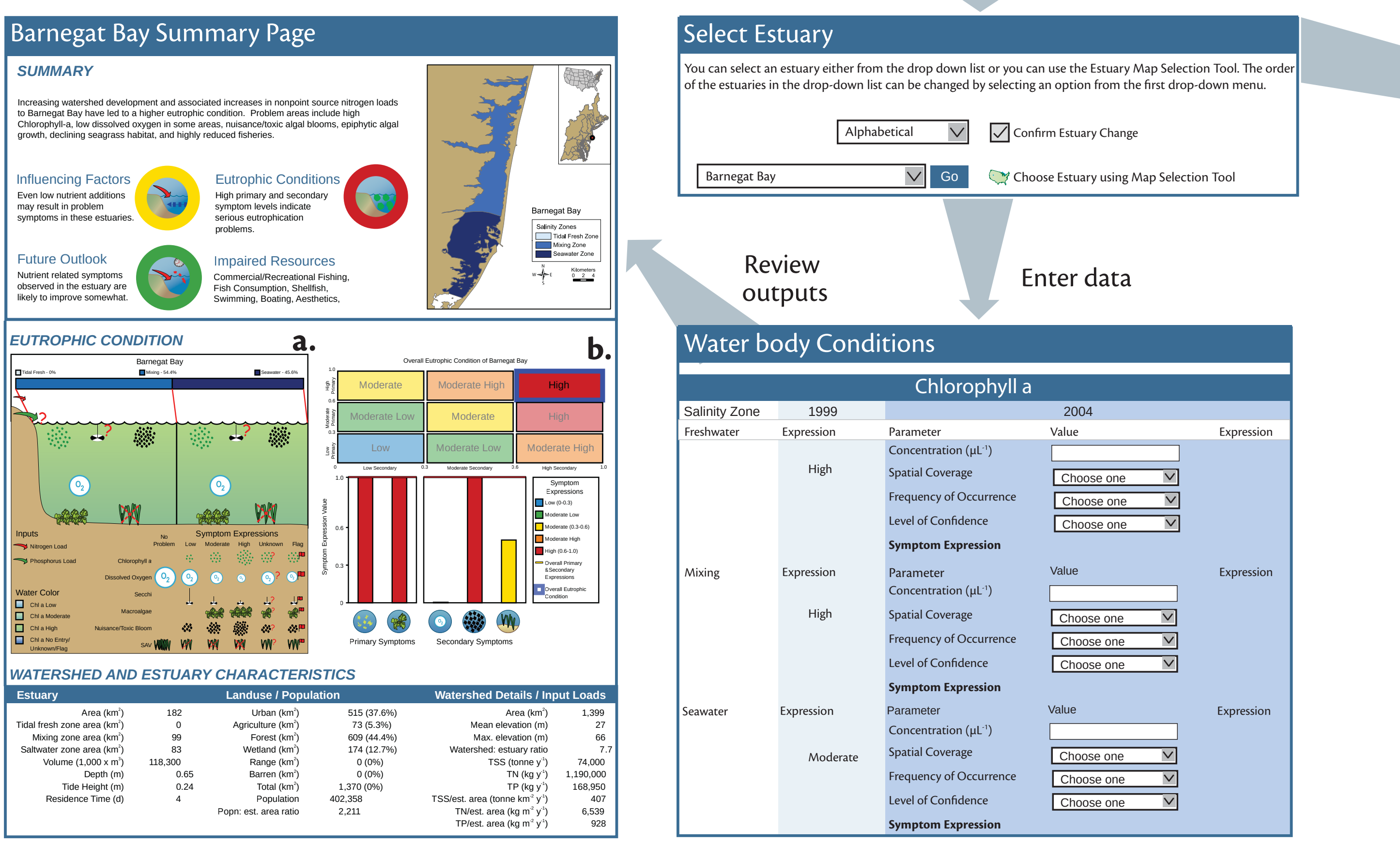
Online survey

The online survey allows participants to enter specific data to be automatically calculated into symptom expressions. In contrast, the original 1999 report involved gathering data in the form of a survey of categorical responses (e.g., low, medium, high). It was necessary to use categorical responses because resources were unavailable for collection, storage, and processing of data for 138 systems. However, the new survey provides a quick, cost-effective method for gathering synthesized information, allowing access to the original data sources. The eutrophic symptoms selected for inclusion represent the most easily

Figure 1.4. One of the improvements to the survey was an accessible online survey with automatically generated data products.

After logging on and entering data, participants can review automatically generated analytical tools including a conceptual diagram illustrating the conditions in the participant's system, printable graphics, and a summary of their data. Participants can also access resources such as the estuary database, conceptual diagrams, publications, and an image library.





National Oceanic and Atmospheric Administration

Experts from the Pacific Coast region add and evaluate data at the National Estuarine Eutrophication Assessment Update Workshop. More than 50 experts attended the workshop to share data and review the Update's procedures and products.

measured and diagnostic indicators available for describing eutrophic changes in different systems.

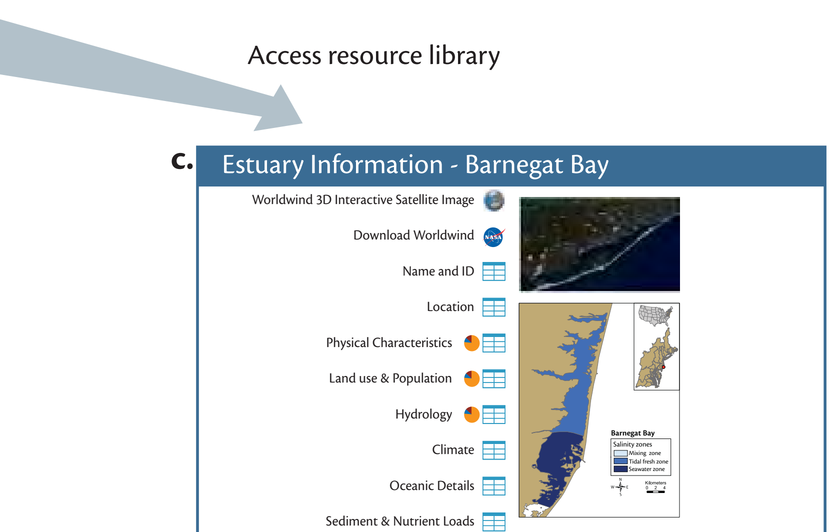
If participants wish to analyze their own data, they can enter data by using the instructions provided on the website. Once the data have been entered, the survey automatically calculates the expression values for each indicator and the overall eutrophic condition (see *Chapter 2: Approach*). The website then generates graphics of the results, which can be downloaded from the site. Thus, participants can retrieve site-specific information based on the data entered (Figure 1.4a,b).

The survey automatically generates several additional graphics for participants. These include a summary page with printable graphics and a conceptual diagram illustrating the conditions in the participant's system (Figure 1.4a, b). In addition to improving the survey with the online tool, the survey has also been enhanced by increased accessibility. This update and future assessments will be available online at *ian.umces.edu/neea* or *www.eutro.us*. Online access enables a greater number of experts to participate, and also facilitates periodic updates of the assessment in the future (every two to five years).

Resource library

In addition to collecting data, the online tool provides participants with a library of resources they can download and use for their analyses. For example, participants can download estuary information such as physical and hydrologic data, salinity zone and remote sensing maps, land use statistics, and other descriptive data for context (Figure 1.4c). Participants also can refer to previous eutrophication and water quality reports such as the *National Estuarine Eutrophication Assessment 1999* (Bricker et al. 1999) and the *State of Maryland's Coastal Bays* (Wazniak et al., 2004). Thus, the online tool provides a means for data collection, analysis, and distribution.

c.



Physical Characteristics

Parameter	Value	Metadata
Estuary Area (km^2)	182	Estuary area, calculated from NOAA shapefiles
Tidal Fresh Zone (km^2)	0	Tidal Fresh area, calculated from NOAA shapefiles
Mixing Zone Area (km^2)	99	Mixing Zone area, calculated from NOAA shapefiles
Saltwater Zone Area (km^2)	83	Saltwater area, calculated from NOAA shapefiles
Tidal Fresh Blackwater	No	Refers to whether the Tidal Fresh Zone in this estuary is considered to be Blackwater
Mixing Zone Blackwater	No	Refers to whether the Mixing Zone in this estuary is considered to be Blackwater
Seawater Blackwater	No	Refers to whether the Seawater Zone in this estuary is considered to be Blackwater
Estuary Volume (m^2)	118300000	Best estimate of volume from digital bathymetric chart if available; otherwise NOAA planimetry
Estuary Depth (m)	0.65	From digital athymetric chart if available; otherwise NOAA

APPLICATION OF THE UPDATE

How is information generated by the update applied?

Information about eutrophic status:
- Provides a basis for management action;
- Tracks the success of management strategies; and
- Identifies the possible causes of eutrophication, and potential solutions.

National Oceanic and Atmospheric Administration

NEEA updates can help develop sound management strategies such as the wetlands restoration project shown here. After the new stalks of *Spartina* are planted in a vulnerable estuary in coastal Louisiana, they will help to improve water quality and increase shoreline stability.

This in-depth look at the present trophic status of the Nation's coastal systems and changes since the 1999 assessment provides a basis for the sound management of precious coastal resources. Future updates will track the successes of management strategies by monitoring changes and trends in the trophic status of systems.

The 1999 assessment concluded that estuarine eutrophication is indeed a problem of national significance. The original study indicated that human-related nutrient sources, both nearby and far removed, are substantial contributors to eutrophic conditions within estuaries. Furthermore, many estuarine watersheds cross state boundaries, requiring regional, subregional, and interagency cooperation. Similarly, there are many important needs with regard to research, monitoring, and assessment that call for a cogent national strategy. In many instances, eutrophication research has been conducted on a parochial and piecemeal basis, which can impede rapid advances in scientific understanding of the linkages between eutrophication and marine resources. A strategy is needed to address these problems, especially one that effectively integrates watershed-specific approaches to assessment and management into a comprehensive approach.

The results of this update should be used to help better focus national attention on existing and emerging priority areas for action. The framework incorporates the overall eutrophic condition of an estuary, its natural susceptibility to retain nutrients and develop related problems, and the level of nutrient inputs. This information will help to set priorities for successful management.

The report is organized to describe the approach and methods used for the assessment (Chapter 2) and the results on a national (Chapter 3) and regional (Chapter 4) basis. Chapter 5 is a collection of case studies highlighting the different manifestations of coastal eutrophication in systems in the United States, Europe, China, and Australia. Chapter 6 describes the ongoing improvements to the assessment methods. Finally, Chapter 7 describes the recommended research, monitoring, and management actions to be taken, given the results of the assessment.

2. APPROACH

EVALUATING EUTROPHICATION

How do we evaluate eutrophication?

The eutrophic condition of a system is evaluated by examining the following three components:

- **Influencing factors:** physical, hydrologic, and anthropogenic.
- **Overall eutrophic condition:** derived from data for five eutrophic symptoms (Figure 2.2).
- **Future outlook:** expected changes in the system.

These components are then combined to provide a single rating for the estuary, called ASSETS.

Influencing factors

In order to provide a sound basis for coastal resource management, this assessment evaluates the factors that influence water quality (Figure 2.1). This evaluation requires the inclusion of national data sets such as physical and hydrologic characteristics and nutrient loading. Influencing factors help establish a link between a system's natural sensitivity to eutrophication and the nutrient loading and eutrophic symptoms actually observed. This understanding also helps illustrate the relationship between eutrophic conditions and use impairments.

Overall eutrophic condition

The assessment of a system's eutrophic condition is based on a compilation of information for five water quality variables related to nutrient enrichment (Figure 2.2). The data set includes concentration or occurrence of problem conditions, and also characteristics such as duration, spatial coverage, frequency of occurrence of observed conditions, and data confidence. An increase in two of the primary symptoms—chlorophyll *a* (phytoplankton biomass) and macroalgal abundance—represents the first possible stage of water quality degradation associated with eutrophication. In the 1999 assessment, epiphytes were also used as a primary symptom indicator (Bricker et al. 1999). However, they have been omitted from the current assessment due to the lack of a standard measure and data availability (Bricker et al. 2006, Scavia and Bricker 2006). The three secondary symptoms represent more serious impacts: low dissolved oxygen levels, loss of submerged aquatic vegetation, and occurrences of nuisance/toxic algal blooms. Nutrient concentrations are not used because they reflect the net biological, physical, and chemical processes such that even a severely degraded water body may exhibit low

Figure 2.1. The NEEA update evaluates influencing factors, eutrophic symptoms, and future outlook for the system.

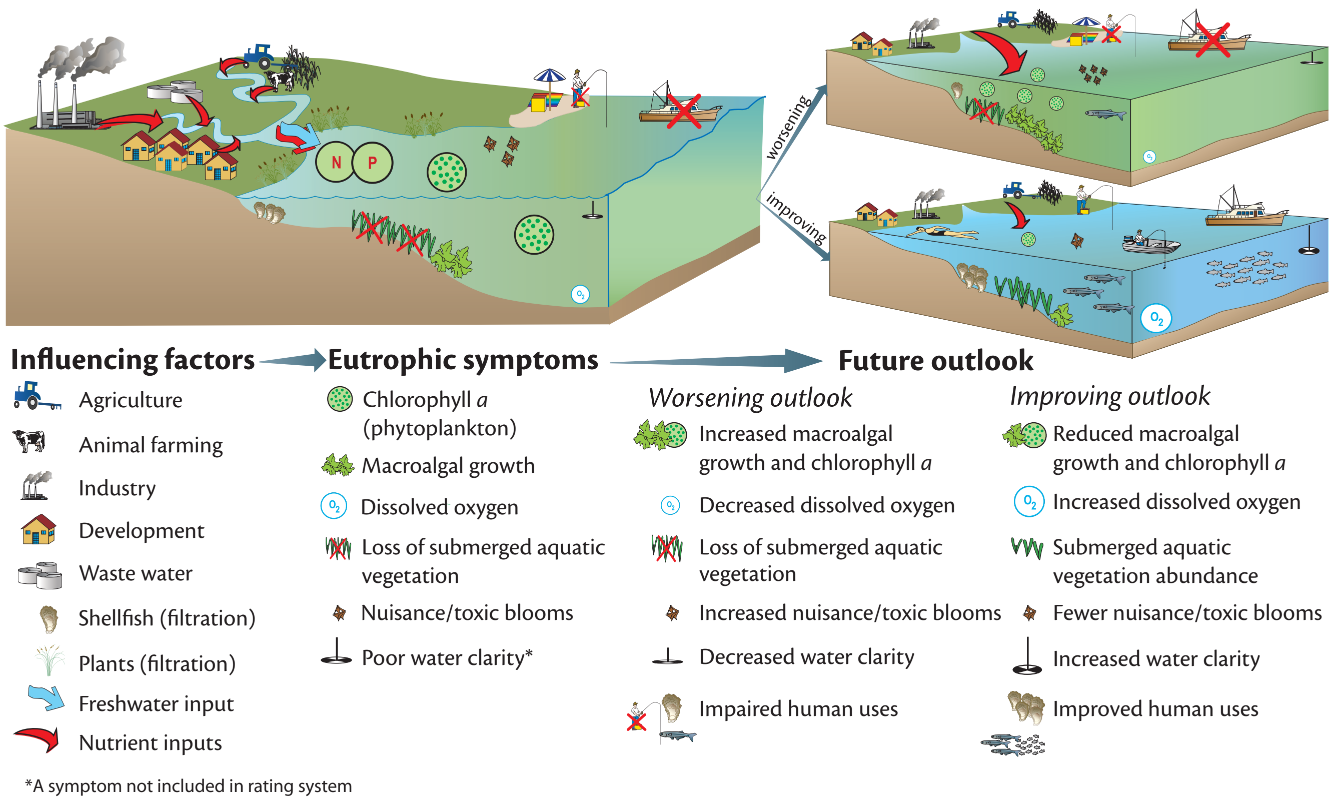
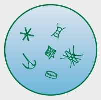
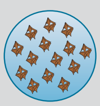


Figure 2.2. A description of the eutrophic symptoms included in this assessment.

Primary symptoms		Description
	Chlorophyll *a* (Phytoplankton)	A measure used to indicate the amount of microscopic algae (phytoplankton) growing in a water body. High concentrations can lead to low dissolved oxygen levels as a result of decomposition.
	Macroalgal blooms	Large algae commonly referred to as "seaweed." Blooms can cause losses of submerged aquatic vegetation by blocking sunlight. Additionally, blooms may 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.
Secondary symptoms		**Description**
	Dissolved oxygen	Low dissolved oxygen is a eutrophic symptom because it occurs as a result of decomposing organic matter (from dense algal blooms), which sinks to the bottom and uses oxygen during decay. Low dissolved oxygen can cause fish kills, habitat loss, and degraded aesthetic values, resulting in the loss of tourism and recreational water use.
	Submerged aquatic vegetation	Loss of submerged aquatic vegetation (SAV) occurs when dense algal blooms caused by excess nutrient additions (and absence of grazers) decrease water clarity and light penetration. Turbidity caused by other factors (e.g., wave energy, color) similarly affects SAV. The loss of SAV can have negative effects on an estuary's functionality and may impact some fisheries due to loss of a critical nursery habitat.
	Nuisance/toxic blooms	Thought to be caused by a change in the natural mixture of nutrients that occurs when nutrient inputs increase over a long period of time. These blooms may release toxins that kill fish and shellfish. Human health problems may also occur due to the consumption of contaminated shellfish or from inhalation of airborne toxins. Many nuisance/toxic blooms occur naturally, some are advected into estuaries from the ocean; the role of nutrient enrichment is unclear.

concentrations due to uptake by phytoplankton and macroalgae. Conversely, a relatively healthy system might have high nutrient concentrations due to low algal uptake as a result of light-limiting turbid waters, or may simply flush nutrients so quickly that phytoplankton do not have the opportunity to bloom extensively. For these reasons, nutrient concentrations may not serve as accurate indicators.

In many estuaries, primary symptoms lead to more serious secondary symptoms, including low dissolved oxygen, loss of submerged aquatic vegetation (SAV), and nuisance/toxic blooms. In some cases, secondary symptoms can exist in the estuary without originating from primary symptoms. This occurs in many North Atlantic estuaries, where toxic algal blooms are transported into the system from the coastal ocean. Such systems were consequently given a lower rating for nuisance/toxic blooms. Low ratings were also used because it is unclear whether offshore nuisance/toxic algal blooms grow and are maintained as a result of land-based nutrient sources (an increasing problem, regardless of bloom origin).

Future outlook

The assessment also evaluates the future outlook for a system to try to forecast national trends over long periods of time. In this update, future outlook combines the susceptibility of a system and the predicted future nutrient loads to determine whether conditions will worsen or improve. In addition, recommendations for potential management responses to eutrophication were developed from conclusions based upon the evaluation of influencing factors and future outlook.

Primary and secondary symptoms

Primary symptoms (phytoplankton and macroalgal abundance) represent the first possible stage of water quality degradation due to eutrophication. Because short-term nutrient measurements are highly variable, nitrogen and phosphorus concentrations cannot be used as a measure of eutrophication.

Secondary symptoms often represent a more advanced stage of eutrophication. In some cases, secondary symptoms can exist without the presence of primary symptoms.

DETERMINING INFLUENCING FACTORS

How are influencing factors evaluated?

The influencing factors for a system take into account both the natural characteristics of, and human impacts to systems. They are determined by calculating susceptibility and nitrogen load:

- Susceptibility is a measure of a system's nutrient retention based upon flushing and dilution.
- Nitrogen loads are the amount of nitrogen input to a system. For influencing factors, nitrogen loads are estimated as a ratio between ocean and land inputs (see pages 12-13).

Jane Thomas, University of Maryland Center for Env. Science

Flushing, one of the components of susceptibility, refers to an estuary's ability to move freshwater out to the ocean. Above, waters of different salinities mix in Ocean City Inlet, Maryland.

Susceptibility

Susceptibility is an estimate of the natural tendency of an estuary to retain or flush nutrients. In general, susceptibility is influenced by the flow of water. The flushing capability of a system is determined by tidal action and the amount of freshwater flowing in from its tributaries. In most cases, if the water (and therefore nutrients) are flushed quickly, there is insufficient time for eutrophic symptoms to develop (i.e., low susceptibility). However, if the estuary has a long residence time, there is time for nutrients to be taken up by algae and for blooms to develop. This assessment uses physical and hydrologic data to separately define dilution and flushing ratings. When combined, these produce a susceptibility rating.

In addition to evaluating influencing factors, susceptibility can be used to forecast not only the extent to which eutrophic symptoms may occur, but also what symptoms may potentially occur. For example, in some shallow lagoonal systems, additional nutrients will result in increased macroalgal abundance rather than high concentrations of phytoplankton/chlorophyll *a* (Nobre et al. 2005). A typology of these systems is being developed in order to increase projection accuracy by accounting for differences in how systems respond to nutrient inputs (see *Chapter 6*).

Calculating influencing factors

Overall, the impact of influencing factors for an estuarine system is determined by a matrix (figure at right). Several calculations were made to create the matrix. First, both susceptibility and load were determined for each estuary and placed in one of three categories: low, moderate, or high. The load refers to a ratio of land-based to oceanic nitrogen inputs, with a high rating indicating primarily land-based inputs (Bricker et al. 2003; Ferriera et al. 2007). The estuary's susceptibility and nutrient loads were compared in a matrix and given an influencing factors rating. For example, an estuary with low nutrient loads and moderate susceptibility is moderately/slightly influenced. Each of the systems in the survey can fall into one of five categories: slightly influenced, moderately/slightly influenced, moderately influenced, highly/moderately influenced, and highly influenced (see Bricker et al. 1999 for details).

Determination of influencing factors

Susceptibility *(flushing and dilution)*	low nitrogen input	moderate nitrogen input	high nitrogen input
high susceptibility	Moderately influenced	Highly/moderately influenced*	Highly influenced
moderate susceptibility	Moderately/slightly influenced*	Moderately influenced	Highly/moderately influenced*
low susceptibility	Slightly influenced	Slightly influenced	Moderately/slightly influenced*

Load *(nitrogen ratio)*

Due to the uncertainty in loading estimates, moderately/slightly and slightly influenced have been combined to both be slightly influenced, and highly/moderately and highly influenced are combined to be highly influenced throughout the report (colors indicate grouping).

Nitrogen load

Nitrogen loads are the critical component for determining an influencing factors score. Although there are data for both nitrogen and phosphorus loads, only nitrogen is analyzed because it is typically the limiting nutrient in estuaries and coastal waters. However, it is known that in some systems or seasons phosphorus may be the limiting nutrient. While natural processes contribute some nitrogen inputs, for many systems, inputs are now mostly human-related, from concentrated point sources such as wastewater treatment, or non-point sources such as urban runoff, agriculture, and atmospheric deposition.

In this update, two sources are used for load estimates: the online survey entries and the Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen model (WATERSN, see box at right). The online survey allowed experts to enter information regarding the magnitude and projected changes for nutrient loads. Results from the WATERSN model were used as a source of load data for systems where this information was not entered online.

The USGS SPARROW model (SPAtially Referenced Regressions On Watershed Attributes) load estimates (Smith et al. 1997) were used in the 1999 assessment but were unavailable for this study. A comparison of WATERSN and SPARROW results was made to determine the suitability of the WATERSN results for use here. When the SPARROW results (only base year 1987 available) were compared statistically with WATERSN model results (base year 1997), they were found to be significantly different. In general, the WATERSN estimates were higher than the SPARROW load estimates. The WATERSN results were compared statistically with the loads entered into the online survey by participants for 11 systems (only systems where both were available) and found to be not significantly different. Furthermore, the WATERSN estimates use a time frame similar to the data entered in the online survey and had a much more recent base year than the SPARROW estimates. Therefore, WATERSN estimates were used in areas where participants did not provide loads. Due to the change in load estimate methods between the two assessments, a trend analysis was not performed.

For this assessment, the loading component is estimated as the ratio of nitrogen coming from the land (i.e., human-related) to that coming from the ocean and is given a rating of low, moderate, or high (Bricker et al. 2003; Ferreira et al. 2007). For example, a high rating means that greater than 80% of the nutrient load comes from land, whereas a low rating signifies a land-percentage of less than 20%. This rating also provides insight into loading management, since loads to systems with primarily ocean-derived nitrogen are not easily controlled. Understanding the sizes of current and expected future loads provides further insight into the application and success of management measures.

Suzanne Bricker, NOAA

NEEA participants, experts from each region or system, contribute data to the NEEA website.

Determining load using the online survey and WATERSN estimates

Load estimates, when available, were contributed by participants who either attended the national workshop, or remotely accessed the NEEA online database. The most current loading estimates were used, though the methods for calculating loads may vary. The online survey offered the option of including estimates for dissolved inorganic nutrients or total nitrogen and phosphorus, to strengthen the resulting database with all available nutrient information for each estuary.

For those systems which had no available loading information, a model was used. The model, called WATERSN (Castro et al. 2001), provided loading data for 32 systems along the Atlantic and Gulf coasts. These loading estimates were based on watershed attributes, using 1997 as a base year for data.

After being compiled, the loading estimates were used to help determine the influencing factors of each individual system and to expand the depth of the NEEA database.

DETERMINING EUTROPHIC CONDITION

How is the eutrophic condition evaluated?

Eutrophic condition ratings are determined by evaluating the occurrence, spatial coverage, and frequency (of problem levels) of each symptom in each salinity zone of an estuary. These individual symptom ratings are then synthesized in a matrix that assigns an overall rating for the system.

Symptom expressions and values

In order to evaluate symptom expressions and values, a rating system was developed to integrate information for the primary and secondary symptoms. The four steps of the process are described in Figure 2.3: (1) determining symptom expression values, (2) calculating system values, (3) assigning categories for primary and secondary symptoms, and (4) determining the overall eutrophic condition.

Determining symptom expression

The first step in determining the eutrophic condition is to calculate an expression value for each eutrophic symptom. The symptom expression value is a combination of the concentration, frequency of occurrence, and spatial coverage of problem levels of each indicator (see box at right and figure 2.4). Symptom expressions are high, moderate, low, or no problem. However, throughout the report, low and no problem are combined into a single rating of low for discussion and tabulation.

Calculating estuary system value

After the symptom expression is determined for all five symptoms and for each salinity zone, the estuary-wide values for each symptom are calculated by taking the symptom (e.g., chlorophyll *a*) values in each salinity zone and creating a combined estuary-wide value for that symptom.

Assigning categories for primary and secondary symptoms

The rating system used in the NEEA averages the primary symptoms (chlorophyll *a* and macroalgae), giving them equal weight. The resulting values are highest for estuaries with multiple primary symptoms that occur with great frequency, over large spatial areas of the estuary, and for extended periods of time. In contrast, low scores indicate estuaries that exhibit few, if any, of the primary symptoms.

Symptom expression index values

Each symptom expression index value combines the following three measurements:

The extreme concentration or problem occurrence of the symptom. For example, for chlorophyll *a*, the 90th percentile of annual chlorophyll *a* data would be used in the calculation. If, however, the symptom present is low dissolved oxygen, the 10th percentile of annual data would be used.

The frequency with which the problem occurs. For example, if the symptom occurs episodically, annually, or persistently.

The area of the system over which the symptom was observed. The calculation uses the percent of area of the estuary over which the problem levels of a symptom are observed.

Using a precautionary approach to evaluate secondary symptoms, the highest of the secondary symptom expression values is selected as representative of more serious impacts within the estuary. An average of the symptom expression values is not used because normal measurements for dissolved oxygen might, for instance, obscure high losses of SAV. In addition, the higher weight given to the secondary symptoms recognizes that these symptoms are indicative of more advanced nutrient-related impacts.

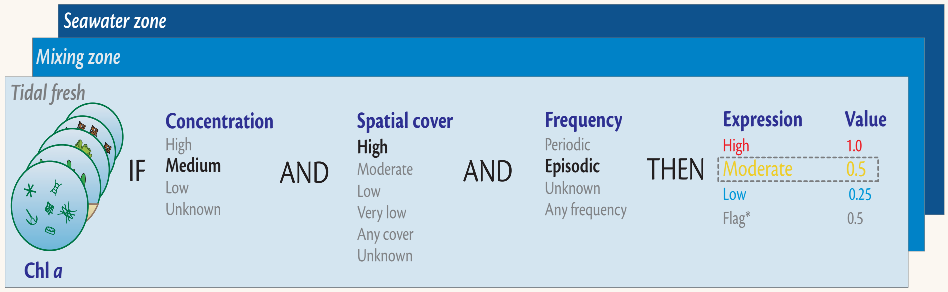
National Oceanic and Atmospheric Administration

Determining the overall eutrophic condition of an estuary allows researchers to track the water quality changes in a system such as Otter Island, South Carolina, shown here.

Figure 2.3. Determination of overall eutrophic condition.

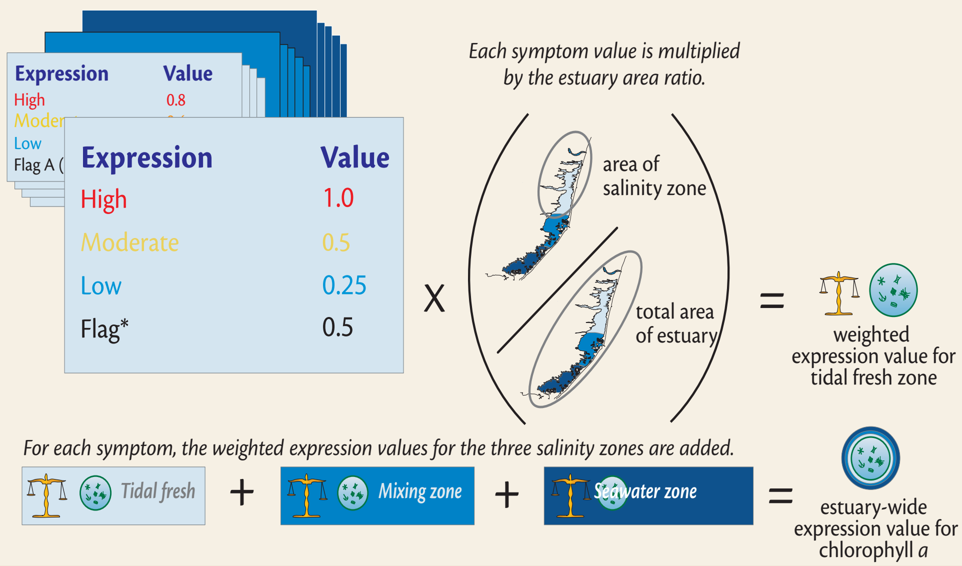
Step 1: Determine expression value for each eutrophic symptom in each salinity zone.

Eutrophic symptom expression values are determined for *each* symptom in *each* salinity zone (seawater, mixing, and tidal fresh), resulting in a total of 15 calculations. The expression is based on a set of IF, AND, THEN, decision rules that incorporate the symptom level (e.g., concentration), spatial coverage, and frequency.



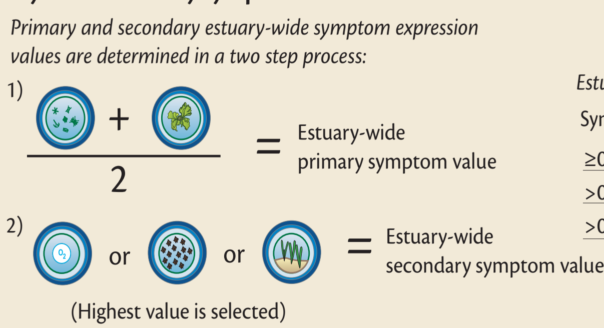
Step 2: Calculate estuary-wide symptom expressions (using chlorophyll *a* as an example).

The expression values are then used to calculate estuary-wide symptom expressions for each symptom. First, each expression value is multiplied by the area of the salinity zone and divided by the entire area of the system to establish the weighted value. Then, the weighted expression values in the tidal fresh, mixing, and seawater zone for each symptom are totaled to calculate the estuary-wide symptom expression value. This process is repeated for all five eutrophic symptoms. Note that "no problem" is the rating assigned if the value is 0, but that "no problem" and low are combined for discussion and tabulation throughout the report.



Step 3: Assign categories for primary and secondary symptoms.

The average of the primary symptoms is calculated to represent the estuary-wide primary symptom value. The highest of the secondary symptom values is chosen to represent the estuary-wide secondary symptom expression value and rating. The highest value is chosen because an average might obscure the severity of a symptom if the other two have very low values (a precautionary approach).



Estuary-wide symptom rating is determined:

Symptom expression value	Symptom rating
≥0 to ≤ 0.3	Low
>0.3 to ≤ 0.6	Medium
>0.6 to ≤ 1	High

Step 4: Determine overall eutrophic condition.

A matrix is used to combine the estuary-wide primary and secondary symptom values into an overall eutrophic condition rating according to the categories at right. Thresholds between rating categories were agreed on by the scientific advisory committee and participants from the 1999 assessment (Bricker et al. 1999).

	Low Secondary (0–0.3)	Moderate Secondary (0.3–0.6)	High Secondary (0.6–1.0)
High Primary (0.6–1.0)	Moderate	Moderate high	High
Moderate Primary (0.3–0.6)	Moderate low	Moderate	High
Low Primary (0–0.3)	Low	Moderate low	Moderate high

*Flags are used to identify components for which data were inadequate or unknown. In these cases, assumptions were made based on conservative estimates that unknown spatial coverage is at least 10% of a zone, frequency at least episodic, and duration at least days.

Determining overall eutrophic condition

To help facilitate the determination of overall eutrophic condition, the range of scores assigned to eutrophic symptoms are divided into categories of high, moderate, and low (Figure 2.3). Primary and secondary ratings are then compared in a matrix so that an overall eutrophic condition rating can be assigned to the estuaries.

Estuaries having high scores for both primary and secondary conditions are considered to have an overall high level of eutrophication (Figure 2.3). Likewise, estuaries with low primary and secondary values are assigned an overall low level of eutrophication. Estuaries with other combinations are interpreted and assigned a rating using the matrix as a guide (Figure 2.4). Those with few primary symptoms (and low numeric ratings) are considered to be relatively unaffected by nutrient-related conditions. Most estuaries show varying degrees of both primary and secondary symptoms, so that the meaning of the rating may be more difficult to determine:

Epiphytes, such as the ones shown here growing on submerged aquatic vegetation in Biscayne Bay, Florida, can also serve as further evidence of eutrophication.

Moderate to high primary symptoms and low secondary symptoms

Estuaries with well-developed problems associated with elevated chlorophyll *a* and/or macroalgal blooms are in the early stages of eutrophication and may be on the edge of developing more serious conditions.

Low primary symptoms and moderate to high secondary symptoms

There are a few possible interpretations for estuaries with advanced secondary symptoms but less developed primary symptoms (*see box below*).

Advanced secondary eutrophic symptoms in the absence of primary symptoms

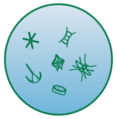
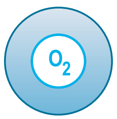
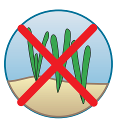
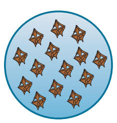
Researchers have determined several reasons for the occurrence of secondary eutrophic symptoms in the absence of primary symptoms. For some estuaries, secondary symptoms (e.g., nuisance/toxic blooms) can be transported from offshore coastal areas rather than originating within the estuary (many North Atlantic estuaries function in this way). In addition, some blooms have no relation to nutrient conditions. As a result, this assessment provides a lower rating for blooms when it is clear that they originate offshore and are therefore not related to nutrient loads.

Alternatively, it is possible that nutrient-related water quality conditions have recently improved, but that the response time to reduce secondary symptoms is longer than for the primary symptoms. The secondary symptoms that remain may be residual conditions that also may improve as nutrient concentrations continue to decrease.

Finally, it is possible that the secondary conditions may occur without being necessarily related to nutrient enrichment. Some submerged aquatic vegetation losses in Chincoteague Bay, Maryland, for example, are related to dredging operations rather than to nutrient conditions. Also, in warmer climates, dissolved oxygen concentrations may be lower on average than cooler systems due to decreased oxygen solubility as water temperature rises.

Nuisance/toxic blooms, such as the cyanobacterial bloom above, is a secondary symptom of eutrophication.

Figure 2.4. Descriptions of the ratings used in the NEEA update.

Symptom	Parameters	Expression: Low	Expression: Moderate	Expression: High
Chlorophyll *a* (phytoplankton)  Typical high concentration (µg L^{-1}) in an annual cycle determined as the 90th percentile value.	*Spatial coverage:* High >50%; Moderate 25–50%; Low 10–25%; Very low 0–10% *Frequency:* Episodic; Periodic; Persistent *Concentration:* High >20 µg L^{-1}; Medium 5–20 µg L^{-1}; Low 0–5 µg L^{-1}	*Low symptom expression:* *Conc. / Coverage / Frequency* low / any / any medium / mod. - v. low / episodic high / low - v. low / episodic	*Moderate symptom expression:* *Conc. / Coverage / Frequency* medium / high / episodic medium / moderate / periodic high / low - v. low / periodic high / moderate / episodic	*High symptom expression:* *Conc. / Coverage / Frequency* medium / high / periodic high / mod. - high / periodic high / high / episodic
Macroalgae  Causes a detrimental impact on any natural resource.	*Frequency of problem:* Episodic (occasional/random) Periodic (seasonal, annual, predictable) Persistent (always/continuous)	No macroalgal bloom problems have been observed.	Episodic macroalgal bloom problems have been observed.	Periodic or persistent macroalgal bloom problems have been observed.
Dissolved oxygen  Typical low concentration (determined as the 10th percentile value) in an annual cycle.	*Spatial coverage:* High >50%; Moderate 25–50%; Low 10–25%; Very low 0–10% *Frequency:* Episodic; Periodic; Persistent *State:* Anoxia 0 mg L^{-1}; Hypoxia 0–2 mg L^{-1}; Biol. stress 2–5 mg L^{-1}	*Low symptom expression:* *State / Coverage / Frequency* anoxia / mod. - low / episodic anoxia / very low / periodic hypoxia / low - v. low / periodic hypoxia / moderate / episodic stress / any / episodic stress / mod. - v. low / periodic	*Moderate symptom expression:* *State / Coverage / Frequency* anoxia / high / episodic anoxia / low / periodic hypoxia / moderate / periodic hypoxia / high / episodic stress / high / periodic	*High symptom expression:* *State / Coverage / Frequency* anoxia / moderate - high / periodic hypoxia / high / periodic
Submerged aquatic vegetation  A change in SAV spatial area observed since 1990.	*Magnitude of change:* High >50% Moderate 25–50% Low 10–25% Very low 0–10%	The magnitude of SAV loss is low to very low.	The magnitude of SAV loss is moderate.	The magnitude of SAV loss is high.
Nuisance/toxic blooms  Causes detrimental impact on any natural resources.	*Duration:* Persistent, seasonal, months, variable, weeks, days, weeks to seasonal, weeks to months, or days to weeks *Frequency:* Episodic, periodic, or persistent	Blooms are either a) short in duration (days) and periodic in frequency; or b) moderate in duration (days to weeks) and episodic in frequency.	Blooms are either a) moderate in duration (days to weeks) and periodic in frequency; or b) long in duration (weeks to months) and episodic in frequency.	Blooms are long in duration (weeks, months, seasonal) and periodic in frequency.

*For further technical documentation of the methods, refer to Bricker et al. 1999 and Bricker et al. 2003.

Through the use of a simple model, the current framework was established to help understand the sequence, processes, and symptoms associated with nutrient enrichment. Despite its limitations, it represents an attempt to synthesize enormous volumes of data and derive a single value for eutrophication in each estuary, essentially representing a complex process in a simple way. Furthermore, modifications are in progress to improve the method (*Chapter 6: Improvements to the assessment*). With this foundation, the next step is to better understand the negative impacts on the human uses of estuaries and to provide insight for the development of a holistic approach to management with future outlook in mind.

State 305b reporting requirements

Under section 305b, the Clean Water Act requires each state to prepare a biennial report on the health of their streams, rivers, lakes, and estuaries. These reports are reviewed by Congress to determine how far each state has progressed toward making the Nation's water bodies fishable and swimmable.

State 305b reports are submitted to the Environmental Protection Agency (EPA), which also provides reporting guidelines to the states during each reporting period. Then, the EPA compiles and summarizes the information that will be presented to Congress. These reports are an important tool because they are the main vehicle for evaluating current water quality conditions and the progress that has been made toward improving water quality nationwide.

Source: www.epa.gov/Region8/water/monitoring/

Use impairments

In the original 1999 report, use impairments were evaluated to try to capture the cost that eutrophic symptoms impose on the human dimension of estuaries. These impacts may include, but are not limited to, recreational activities such as swimming, fishing and boating, commercial operations, and tourism. A list of possible impairments was developed from state 305b reporting requirements (see text box, top right). Expert judgment from the participants was used to evaluate local use impairments.

In addition to investigating use impairments, this update also includes information about living resource impairments. This additional information was collected in an attempt to link more directly the causes and manifestations of use impairments and to provide a stronger basis for the development of management plans.

Jane Hawkey, University of Maryland Center for Env. Science

Eutrophic symptoms can lead to use impairments such as restricted commercial and recreational fishing and closed waterways.

DETERMINING FUTURE OUTLOOK

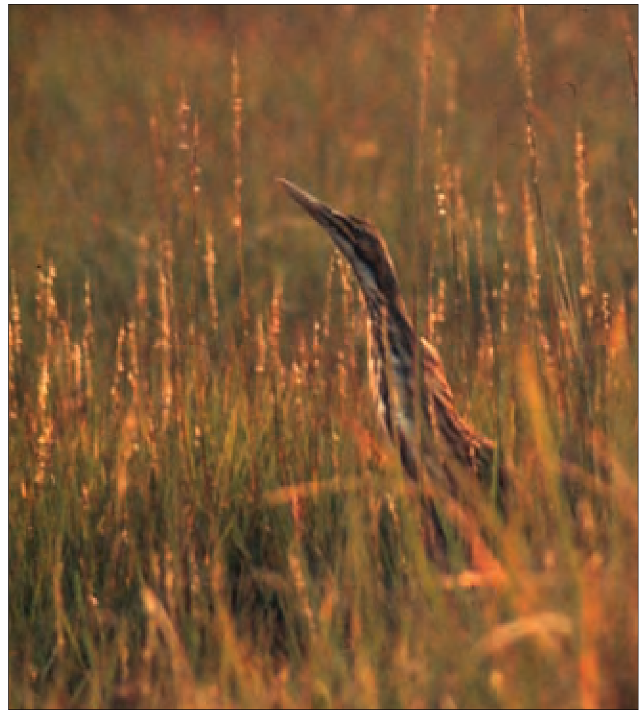
How is the future outlook for an estuary evaluated?

Like influencing factors and overall eutrophic condition, the future outlook for an estuary is ultimately determined by a matrix. This matrix combines two factors:

- System susceptibility
- Predicted future loads to the system

The future outlook is designed to estimate future changes in eutrophic condition based on expected changes in nutrient inputs to a system.

Similar to influencing factors and eutrophic conditions, future outlook is determined by a matrix that combines the susceptibility of a system with expected changes in nutrient loads. Predictions of nutrient loading (categorized as increase, decrease, or no change) are based on predicted population increase, planned and/or recently implemented management actions, and expected changes in watershed use. Results from the 2004 update will show whether conditions predicted by the 1999 report have yet been realized (predictions are for year 2020).



National Oceanic and Atmospheric Administration

An American bittern in Narragansett Bay, Rhode Island. These birds are very sensitive to changes in estuarine health. Future outlook in this study attempts to project which estuaries will remain healthy enough to support such sensitive organisms.

Calculating future outlook

The analysis for future outlook is an attempt to determine whether conditions in an estuary will worsen, improve, or remain unchanged over the next 20 years.

In this analysis, expected nutrient input changes were used to predict whether eutrophic conditions will improve or worsen. The system's susceptibility to nutrients is then used to determine the magnitude of this change. Population projections are used as a primary indicator of the level of future nutrient input changes. However, population projections are unpredictable. Therefore, experts at the NEEA update workshop were asked to predict changes in nutrient load, based on their knowledge of likely changes in land use, management measures, and other activities that affect nutrient loading.

Determination of the future outlook

Susceptibility *(flushing and dilution)*	decreasing nitrogen load	no change	increasing nitrogen load
low susceptibility	Improve high Symptoms likely to improve substantially	No change Symptoms will most likely remain unchanged	Worsen low Symptoms likely to worsen only minimally
moderate susceptibility	Improve low Symptoms likely to improve	No change Symptoms will most likely remain unchanged	Worsen high Symptoms are likely to substantially worsen
high susceptibility	Improve low Symptoms likely to improve somewhat	No change Symptoms will most likely remain unchanged	Worsen high Symptoms are likely to substantially worsen

Expected future load *(nitrogen input)*

ASSESSMENT OF ESTUARINE TROPHIC STATUS (ASSETS)

How is an ASSETS rating evaluated?*

The ASSETS rating is a combination of the following three components:

- Influencing factors
- Overall eutrophic condition
- Future outlook

**More information about ASSETS may be found at* http://eutro.org/

In an effort to simplify the comparison of the status of systems, the last step is to combine the influencing factor, overall eutrophic condition, and future outlook components into a single overall score for each system. The ratings for influencing factors, overall eutrophic condition, and future outlook are combined in a matrix to provide an overall grade or score which may fall into one of five categories: High, good, moderate, poor, or bad. These categories are color coded following international convention and provide a scale for setting reference conditions for different types of systems (Bricker et al. 2003).

The high grade will not be assigned if the expected future outlook is for worsening conditions, but a system may be rated as good based on high or good eutrophic condition and influencing factors, even if the expectation is that it will worsen in the future. Poor and bad grades reflect a range of undesirable pressure and state conditions, even if there are management plans for recovery.

Data completeness and reliability

In order to evaluate the reliability of the assessment, a measurement of data completeness and reliability (DCR) of the dataset was calculated. This is important because the assessment uses a combination of symptom indicator data, which are derived from a variety of sources and levels of certainty. Additionally, data for all indicators were not available for all systems. The robustness of the assessment is affected by missing data (e.g., spatially or temporally limited), and data that are judged to be based upon speculative inference.

The DCR is defined as the percent of the total estuarine area for which data are considered highly certain for all or most indicators. A DCR rating is made for each of the five symptom variables, incorporating scores for both completeness (whether data is entered for symptoms [e.g., concentration] and symptom characteristics [e.g., spatial coverage, frequency]), and the level of confidence of data used for the assessment. The symptom DCR values are averaged for an overall eutrophic condition DCR rating. A score of 76–100%, or high DCR, means that there are complete data of high certainty for the majority of the estuary. A system with moderate DCR has complete, high certainty data in 51–75% of its area and a low DCR means that there are complete, high certainty data in 50% of the system or less.

National Oceanic and Atmospheric Administration

Participants at the National Estuarine Eutrophication Assessment Update workshop held in Maryland in May 2006.

3.NATIONAL ASSESSMENT

SUMMARIZING THE NATION'S EUTROPHIC CONDITION

- Majority of estuaries showed signs of eutrophication.
- Most common symptom of eutrophication was high chlorophyll *a*.
- High overall eutrophic conditions were observed in many systems.

The majority of U.S. estuaries assessed displayed at least one symptom of eutrophication, suggesting a large-scale, national problem. Of the systems assessed, 29 had moderate high to high eutrophic condition (Figure 3.1). Estuaries in this category are characterized by symptoms that are extensive (covering 50% or more of the system) and/or are persistent. Estuaries with high eutrophic conditions occurred in all regions of the nation except for the North Atlantic region (Figure 3.3). The mid-Atlantic region recorded the greatest proportion of highly eutrophic systems. Estuaries with high overall eutrophic conditions were generally those that received the greatest nitrogen loads.

A large proportion of the estuaries surveyed had moderate eutrophic condition ratings (Figure 3.1). Estuaries in this category are characterized by symptoms that are periodic and occur over a moderate proportion of the estuary. Systems with low eutrophic condition occurred in all regions, with the highest proportions recorded in the Gulf of Mexico and North Atlantic (Figure 3.3). During the decade between the two NEEA studies (the 1999 report reflected conditions in the early 1990s), conditions in 13 systems (9% of area assessed) had improved and in 13 systems (14% of assessed area) had worsened, but most remained the same (77% of assessed area). However, the number of systems with inadequate data for assessment has increased from 17 in the 1999 assessment to 42 systems in the current study. This is likely due to a change in data collection methods: an eight-year process for the 1999 assessment involving site visits, and regional and national workshops, compared to a two-year process for 2004 involving an online survey and a national workshop.

The overall eutrophic condition rating is based on the combined level of expression of five symptoms: chlorophyll *a*, macroalgae, dissolved oxygen, nuisance/toxic blooms, and submerged aquatic vegetation (SAV). The large number of estuaries with high chlorophyll *a* symptom expression is a clear signal that eutrophication is a widespread problem (Figure 3.2). The high symptom expression indicates that increased nutrient loads are stimulating phytoplankton growth. Although macroalgae data were relatively sparse, symptom expression was moderate or high for 33 systems.

Elevated phytoplankton and macroalgae biomass can lead to drops in dissolved oxygen levels resulting from microbial breakdown. The data for dissolved oxygen indicate that while a few areas are affected, the vast majority of systems do not experience dissolved oxygen problems (Figure 3.2).

Another eutrophic symptom, nuisance/toxic blooms, can have human health, ecological, and aesthetic effects on an estuary. This assessment shows that most of the nation's estuaries are not affected by these blooms, and those that do are located primarily in the mid-Atlantic region.

Submerged aquatic vegetation is often a critical habitat within an estuary, providing protection from predators and a food source for juvenile organisms. This assessment showed that most SAV beds remained stable between the early 1990s and 2000s.

Figure 3.1. Number of estuaries in each of the overall eutrophic condition categories.

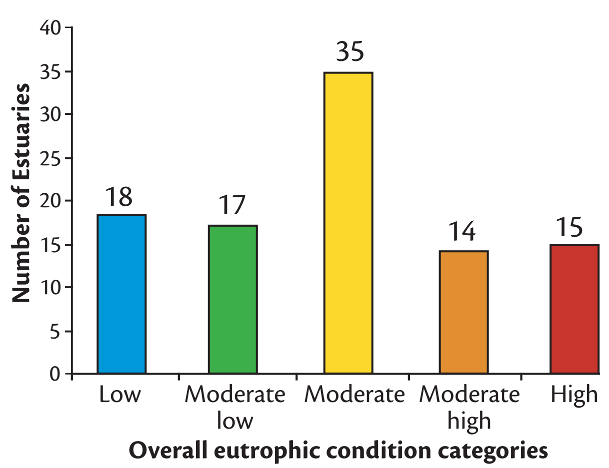


Figure 3.2. Distribution of symptoms and symptom expressions.

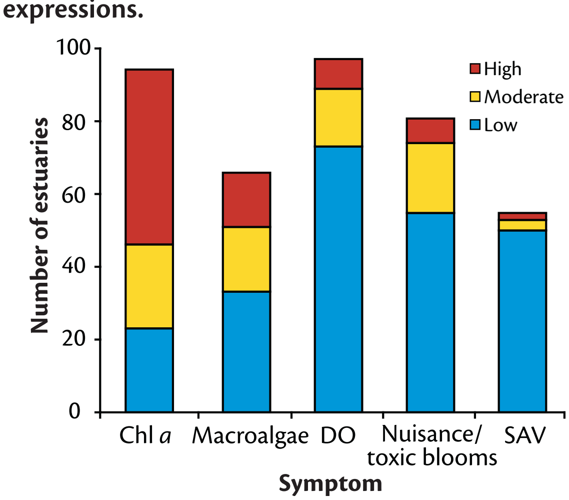


Figure 3.3. Summary of overall eutrophic conditions (OEC) in the five regions. Bar graphs show the % of estuaries in each category; ratios above graphs are the number of estuaries able to be assessed for OEC/number in each region.

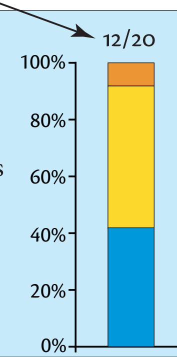
This report divides the Nation's estuaries into five regions: North Atlantic, mid-Atlantic, South Atlantic, Gulf of Mexico and Pacific Coast. Estuaries are divided into these regions to facilitate discussion at regional scales. Chapter 4 provides a detailed assessment and discussion of the eutrophic condition of each region. At right is a brief summary of the eutrophic conditions within each region.

Overall eutrophic condition

- **High:** symptoms occur periodically or persistently and/or over an extensive area.
- **Moderate high:** symptoms occur less regularly and/or over a medium to extensive area.
- **Moderate:** symptoms occur less regularly and/or over a medium area.
- **Moderate low:** symptoms occur episodically and/or over a small to medium area.
- **Low:** few symptoms occur at more than minimal levels.

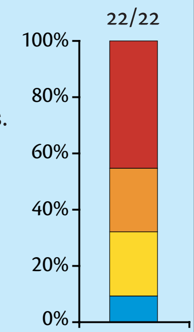
North Atlantic region

- Factors influencing eutrophication were low for all assessed systems.
- The least impacted region: no systems recorded a high OEC rating.
- Some systems had worsening chlorophyll *a* and macroalgae symptom expressions.



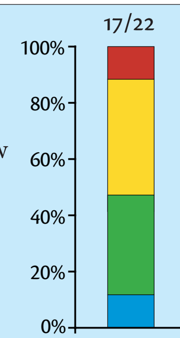
Mid-Atlantic region

- Factors influencing eutrophication were high for the majority of systems.
- The most impacted region: a majority of systems recorded a moderate high or high OEC.
- High chlorophyll *a* expression was observed in the majority of systems.



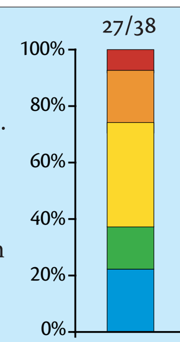
South Atlantic region

- Factors influencing eutrophication were spatially variable.
- A similar number of estuaries had low and high OEC ratings.
- Almost half of those systems had moderate problems with dissolved oxygen.



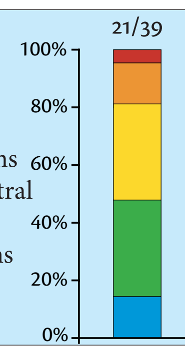
Gulf of Mexico region

- Factors influencing eutrophication were high for most assessed estuaries.
- A small proportion of estuaries had high or moderate high overall eutrophic condition. These systems were characterized by high, and often worsening, chlorophyll *a* symptoms.



Pacific Coast region

- Very few estuaries have nutrient load data available.
- Most estuaries with reported problems were located in Washington and central California, with chlorophyll *a* and dissolved oxygen being the symptoms of concern.



EXPLORING PHYSICAL CHARACTERISTICS ON A NATIONAL SCALE

The great diversity of the 141 estuarine and coastal systems included in this assessment lies in their geographic location, physical and hydrologic characteristics (e.g., landscape elevation and climate), watershed population, and land use. These characteristics have strong influences on the potential for eutrophication.

Although this assessment does not include all U.S. estuaries, it represents greater than 90% of the total freshwater flow into coastal systems and covers an equal water body surface area. Headwaters of Atlantic coast estuaries mostly originate from the Appalachian Mountains, a relatively low-lying range that follows the eastern U.S. shoreline (Figure 3.4a). In the north, the Appalachian Mountains are relatively close to the coast, leading to short and steep watersheds of higher elevation (Table 3.1). Toward the south, the range is farther inland, leading to longer and flatter watersheds of lower elevation (typically half that of northern watersheds). Estuary type also changes from river mouth estuaries in the north to lagoon systems in the south. The headwaters of Pacific Coast estuaries also originate in the mountains, but from a diversity of ranges including the Rocky Mountains, Coastal Range, and Sierra Nevada. The north Pacific coastal systems have the highest watershed elevations of any region (Table 3.1) due to the coastal mountain ranges. While most systems in the Gulf of Mexico are located in low-lying watersheds, some watersheds in the west extend into the Sierra Nevada, giving them higher mean elevations than the rest of the region.

Estuary size varies nationally and regionally (Table 3.1). The mid-Atlantic region, for example, includes the large Chesapeake Bay and much smaller coastal lagoonal systems. The fjords in the northern Pacific Coast and North Atlantic regions are the deepest systems. Watershed size is also variable within regions. For instance, the Gulf of Mexico region includes the massive Mississippi River basin as well as the small coastal watersheds of Florida. The ratio of watershed area to estuarine area may exert a significant influence on the development of eutrophication, especially in areas of dense watershed population. This ratio can be used as an indicator of the influence of watershed-based inputs on the estuary. The systems in the Gulf of Mexico and Pacific Coast regions have the highest ratios, showing input from a large watershed into a smaller water body. The potential influence on these systems is greater than for systems in the North and mid-Atlantic regions where the ratio is much smaller.

Rainfall also influences the delivery of nutrients to a system. The driest watersheds are located in the southern Pacific Coast and western Gulf of Mexico regions (Table 3.1). Land cover in these areas tends to be dominated by grassland, shrub land, and savanna (Figure 3.4b). Rainfall along the north and mid-Atlantic coast is higher, with land cover in these regions dominated by deciduous and evergreen forests. The northern Pacific Coast region is also dominated by deciduous and evergreen vegetation. The South Atlantic and eastern Gulf of Mexico regions have a subtropical climate, with higher annual rainfall and land cover dominated by

Table 3.1. Summary of physical characteristics for each region and within regions.*

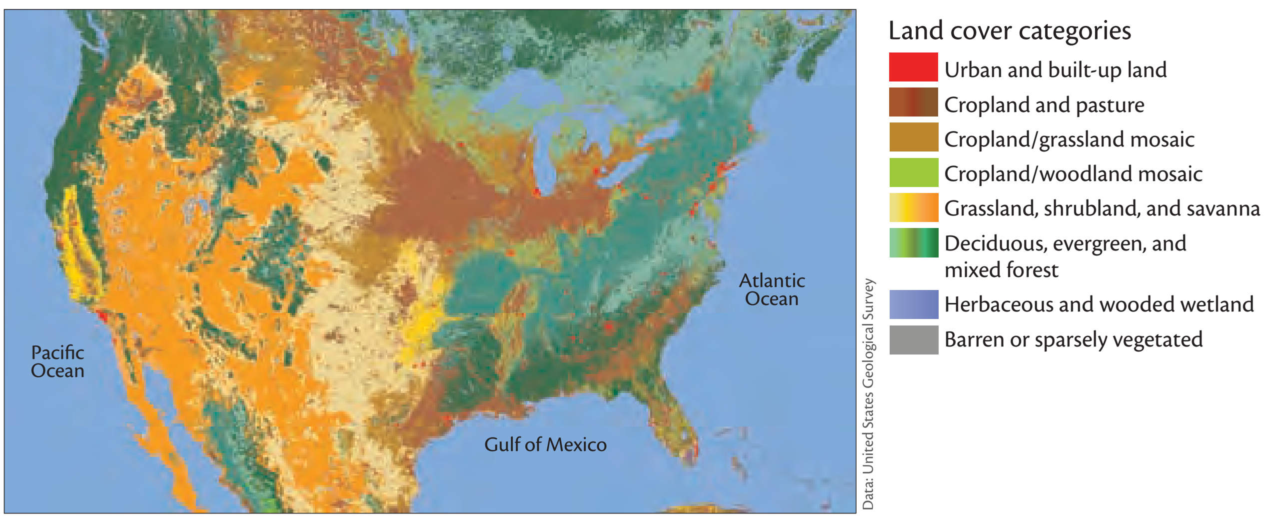
Region	Mean estuarine area (km^2)	Mean depth (m)	Tidal range (m)	Mean watershed area (km^2)	Mean watershed elevation (m)	Mean annual precipitation (m)	Average annual temperature (° C)	Average frost days (days)
North Atlantic	**264**	**12.9**	**2.8**	**4284**	**100**	**1.16**	**8**	**156**
mid-Atlantic	**923**	**4.7**	**0.80**	**13,521**	**116**	**1.12**	**13**	**106**
estuaries	1140	5.7	0.86	17,137	147	--	--	--
lagoons	189	1.4	0.59	1232	12.6	--	--	--
South Atlantic	**534**	**2.9**	**1.21**	**15,043**	**58**	**1.32**	**19**	**36**
NC to GA	522	3.2	1.32	15,678	66	1.31	19	41
Florida	761	1.4	0.48	11,018	9	1.33	23	5
Gulf of Mexico**	**822**	**1.7**	**0.41**	**109,545**	**107**	**1.33**	**22**	**12**
FL MS LA AL	882	1.8	0.47	133,068	73	1.46	22	13
TX	667	1.6	0.26	46,031	198	0.98	22	9
Pacific	**182**	**14**	**1.5**	**25,209**	**401**	**1.14**	**12**	**57**
fjord	438	66	2.4	5,822	477	1.07	10	73
river mouth	133	6.9	1.4	42,039	459	1.71	12	66
lagoons	75	3.5	1.1	1,297	271	0.29	16	23

*Data source: S.V. Smith (2003).
**Does not include Mississippi River to avoid biasing the results due to its extreme watershed size.

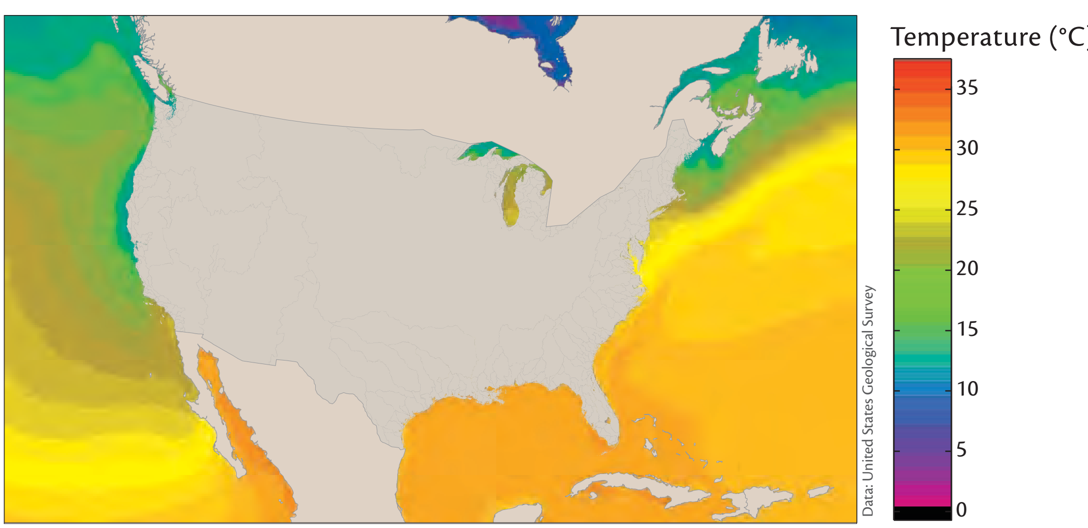
Figure 3.4. Elevation and major rivers, land cover, and sea surface temperature on a national scale.

a. *elevation and major rivers in the United States.*

b. *1993 land cover in the United States.*



c. *average (1985-2001) summer (July-September) sea surface temperature.*



crop land and woodland. Climate along the coast is modulated by ocean temperatures, which are much warmer on average along the Gulf of Mexico and South Atlantic regions than along the Pacific Coast and North Atlantic regions (Figure 3.4c). The annual mean temperatures also reflect this modulating influence. The number of frost days mirrors regional temperature differences; the North Atlantic region has 156 frost days per year, the northern Pacific Coast region 79 and the Gulf of Mexico region just 12 frost days per year (Table 3.1).

Nutrients

Although both phosphorus and nitrogen can cause nutrient enrichment problems in estuaries, only nitrogen inputs are included in this assessment because nitrogen is typically the limiting nutrient in estuaries and coastal water bodies. For this reason, nitrogen values were used for primary estimates of nutrient inputs. These estimates were based on participant entries to the online survey as well as load estimates from the Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen (WATERSN, Castro et al. 2001) model. WATERSN is a numerical model of inputs to coastal systems, taking into account nitrogen inputs from sewage, urban and agricultural runoff (crops and animals), atmospheric deposition, and forest runoff (see *Chapter 2: Approach*).

While nitrogen input data and load estimates were available for only 64 systems, some patterns were notable. With a few exceptions (i.e., San Francisco Bay North, Mississippi River), nitrogen loads were highest in the mid-Atlantic region, correlating with high populations (Figures 3.5 and 3.6). In the Gulf of Mexico region, high loads corresponded with high agricultural activity and the Mississippi River outflow (Figure 3.6). An analysis of these loads was performed in order to identify whether the loading source is primarily the watershed and is related to human activities, or if it comes from ocean inputs. With the exception of systems in the North Atlantic region, more than 75% of the systems evaluated have nutrient loads derived mainly from the watershed.

Caroline Wicks, EcoCheck (NOAA/University of Maryland Center for Environmental Science)

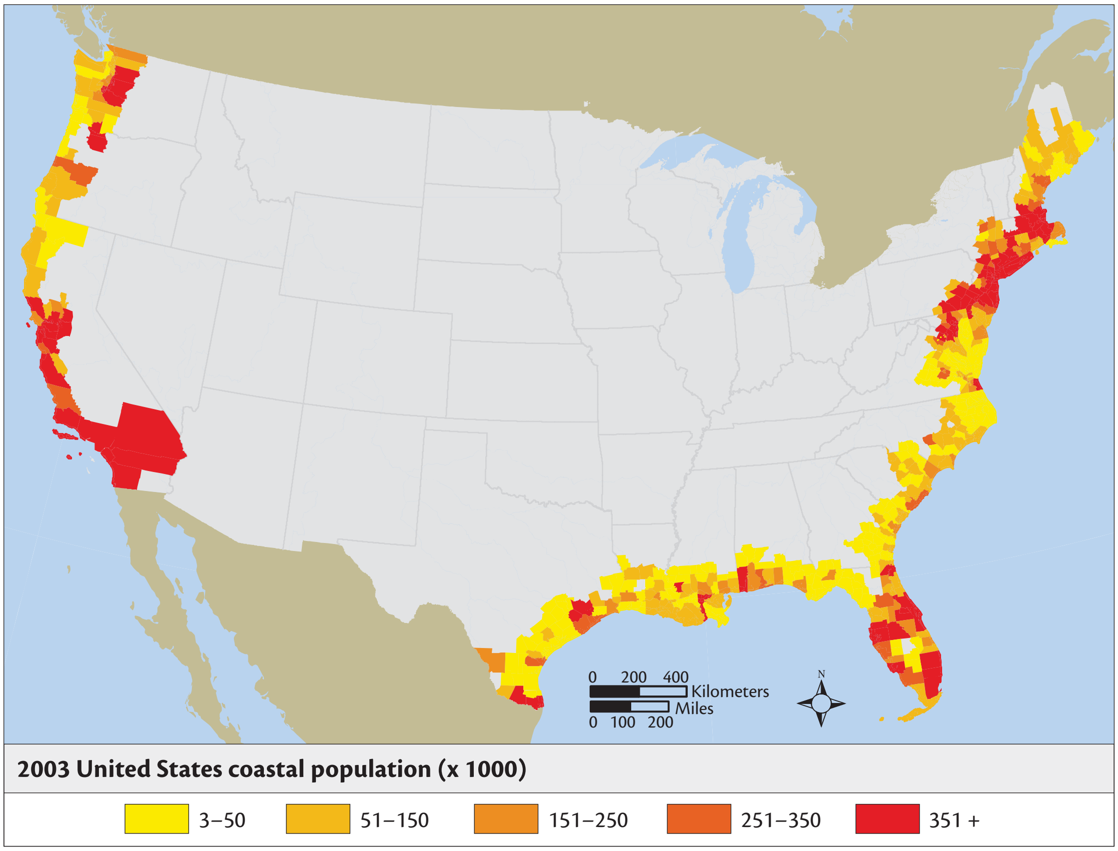
Nutrient loads to the subtropical systems of southern Florida are highly variable.

Jane Thomas, University of Maryland Center for Environmental Science

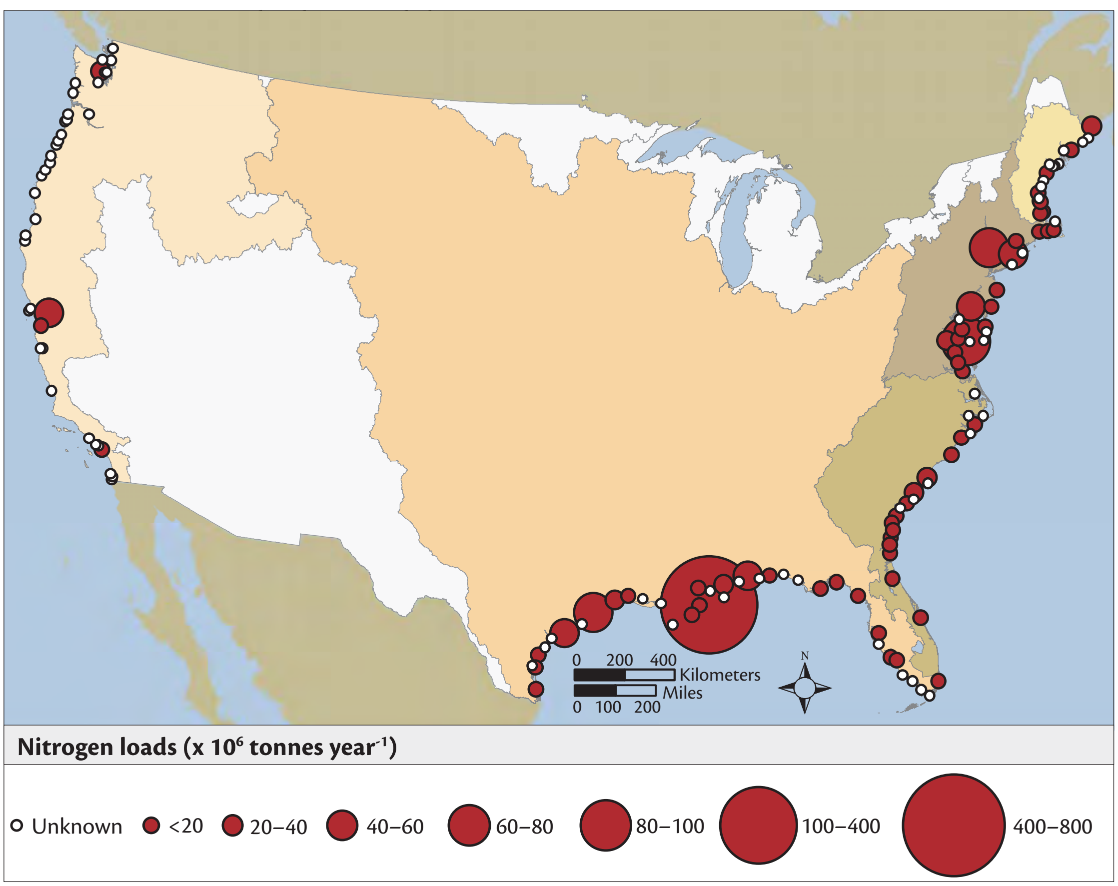
Wastewater treatment plants (point sources) such as the one pictured above can be a large source of nutrients to estuaries.

Trends

In the 1999 report, nitrogen load estimates from the USGS SPARROW model were used to determine an influencing factors score (Smith et al. 1997). Unfortunately, the updated SPARROW model estimates were not available in time to use in this analysis. Therefore, workshop participant estimates and results of the WATERSN model were used for systems with available data. When the WATERSN model results were statistically compared to load data contributed by individual participants, the results were not significantly different. Due to the difference in time frames and methods used by the SPARROW model, the WATERSN model, and participant estimated loads, a trend analysis was not possible.



Data source: NOAA's Spatial Trends in Coastal Socioeconomics website, a product of the Coastal and Ocean Resource Economics Program (http://marineeconomics.noaa.gov/socioeconomics/)



Data sources: Castro et al. 2001 and NEEA online survey (www.eutro.us)

ASSESSING EUTROPHICATION ON A NATIONAL SCALE

Influencing factors

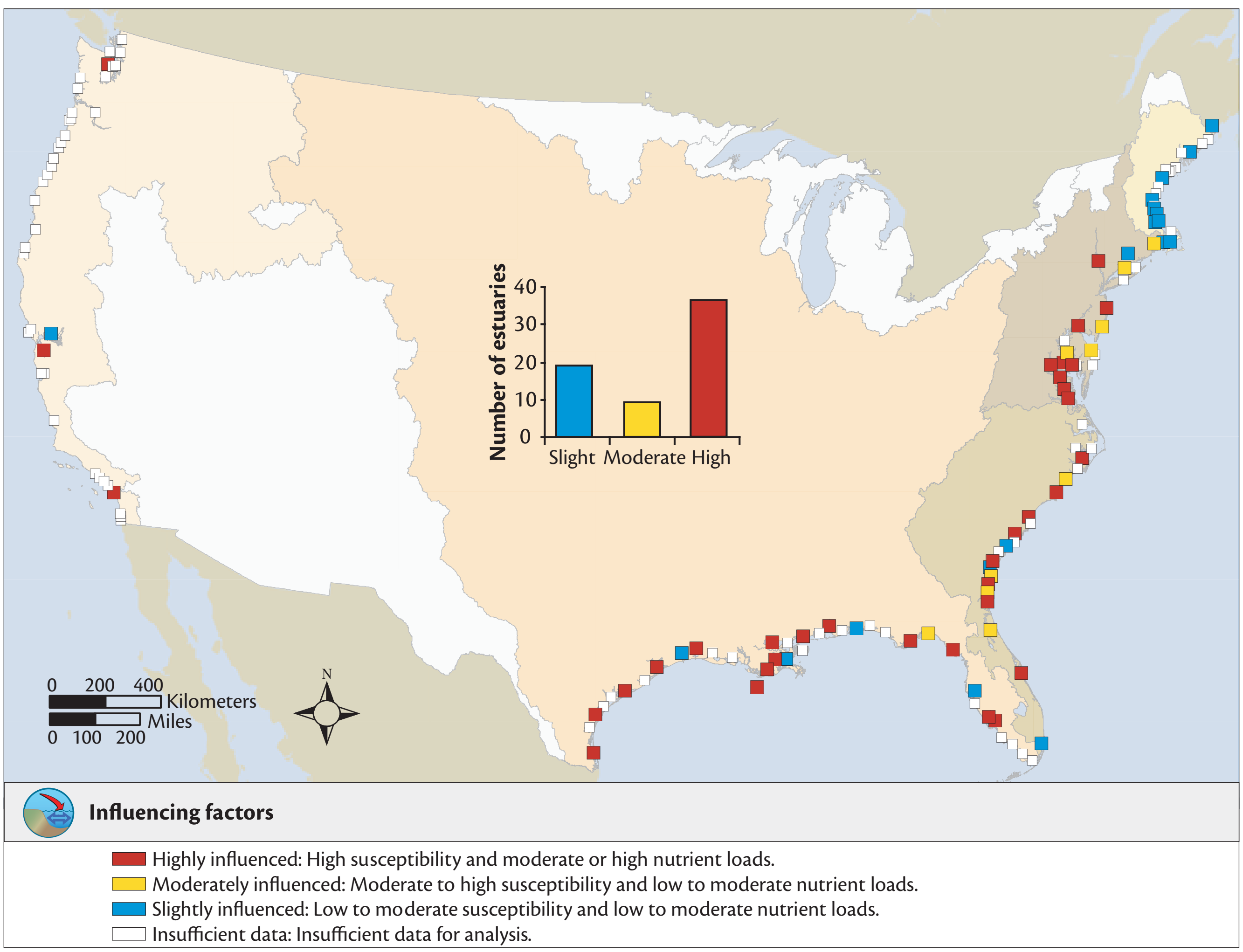
- The majority of systems assessed were highly influenced by human-related activities.
- The North Atlantic region was the least influenced.

The majority of systems assessed (36 of 64) had high influencing factors ratings, indicating that these estuaries received a large amount of nitrogen compared to their capacity to dilute or flush nutrients. However, no estuaries in the North Atlantic region had a high rating. Low influencing factors in this region are likely due to relatively low nitrogen loads and strong tidal flushing. In contrast, high ratings in the mid-Atlantic region resulted from high nitrogen loads relative to susceptibility (Figure 3.7).

Estuaries with low influencing factors ratings were located in regions other than the North Atlantic region and interestingly, were often in close proximity to estuaries with high influencing factors ratings. The high geographic variability of nitrogen loading and susceptibility indicates the need for locally tailored management action.

While the relationship between influencing factors and eutrophic condition is discussed later in this chapter, there are notable patterns existing between the two. For example, of the 15 estuaries with high overall eutrophic condition scores (OEC), 13 had high susceptibility scores. In contrast, of the 35 systems with moderate low or low OEC scores, 31 had low or moderate susceptibility. Eleven of these 31 systems had a low or moderate low OEC rating despite high nutrient loads. These systems seem able to naturally suppress eutrophication. The relationship between influencing factors and eutrophic condition is not entirely predictable at a national level, reiterating a need for local management.

Figure 3.7. Factors influencing eutrophication on a national scale.



Symptom expressions

- Chlorophyll *a* was the most frequently expressed eutrophic symptom nationally.
- Macroalgae was an occasional problem, and where present, has become worse.
- Except for a few locations, dissolved oxygen was not a major national problem.
- Nuisance/toxic blooms were a problem in the mid- and South Atlantic regions.
- Submerged aquatic vegetation loss was not a major national problem.

The primary symptoms of increased nutrient concentrations in the water column are high levels of chlorophyll *a* and/or macroalgae (see *Chapter 3*, Table 2.2). Once primary symptoms are observed at high levels, an estuary is in the first stages of displaying problematic eutrophic conditions. While high levels of primary symptoms are strong indicators of the onset of eutrophication, secondary symptoms (dissolved oxygen, nuisance/toxic blooms, and submerged aquatic vegetation) indicate more serious problems, even at moderate levels.

Half of the estuaries for which there were data for evaluation exhibited high chlorophyll *a* symptom expression, indicating that many of the Nation's estuaries are exhibiting initial signs of eutrophication. While estuaries with high chlorophyll *a* expression were found along all coastlines, the North Atlantic region had relatively few systems with high chlorophyll *a* expression (Figure 3.8a).

Information on macroalgae was limited. However, the data available showed a low or no problem symptom expression for half of the assessed systems. High macroalgae expression was observed in 15 estuaries (Figure 3.8b). In some cases, high levels of macroalgae may be a natural occurrence and not an indication of eutrophication.

Dissolved oxygen has the most complete national dataset (DO) compared with other symptoms. This assessment shows that only a few (8) estuaries have high DO symptom expression, with the vast majority (73 of the 97 systems with DO data) rated at a low or no problem expression (Figure 3.8c). However, low dissolved oxygen levels are a significant problem in localized areas.

Adrian Jones, University of Maryland Center for Environmental Science

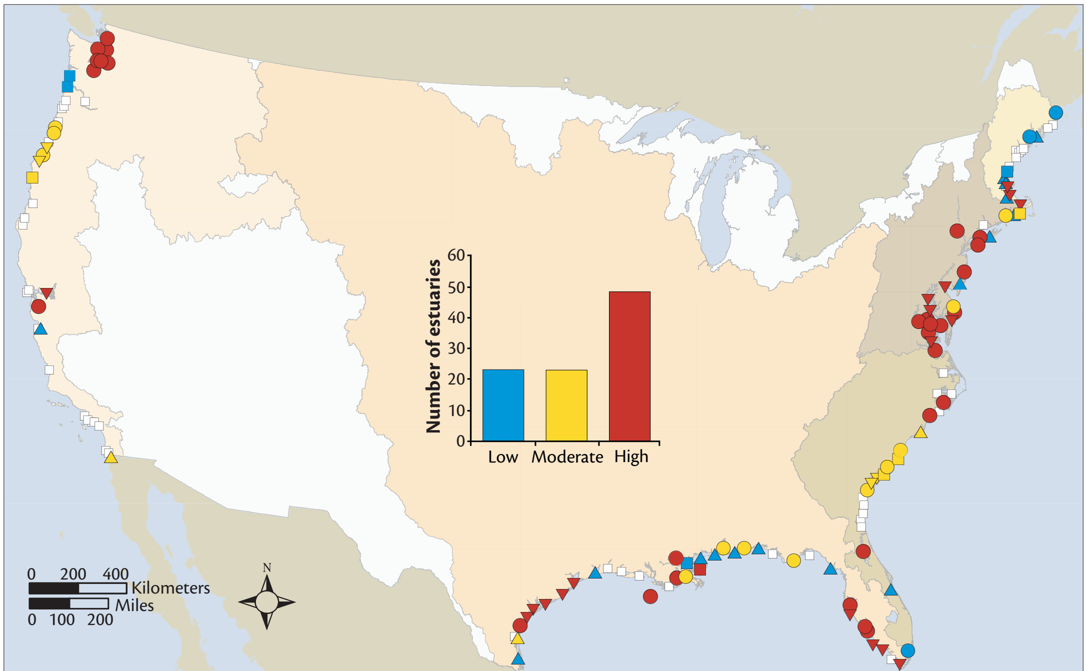
Loss of submerged aquatic vegetation is an indicator of eutrophication.

Of the 81 systems for which nuisance/toxic bloom data were reported, 26 exhibited a moderate or high symptom expression. While systems with moderate or high bloom expression occurred along all coasts, the majority were located in the mid-Atlantic region (Figure 3.8d).

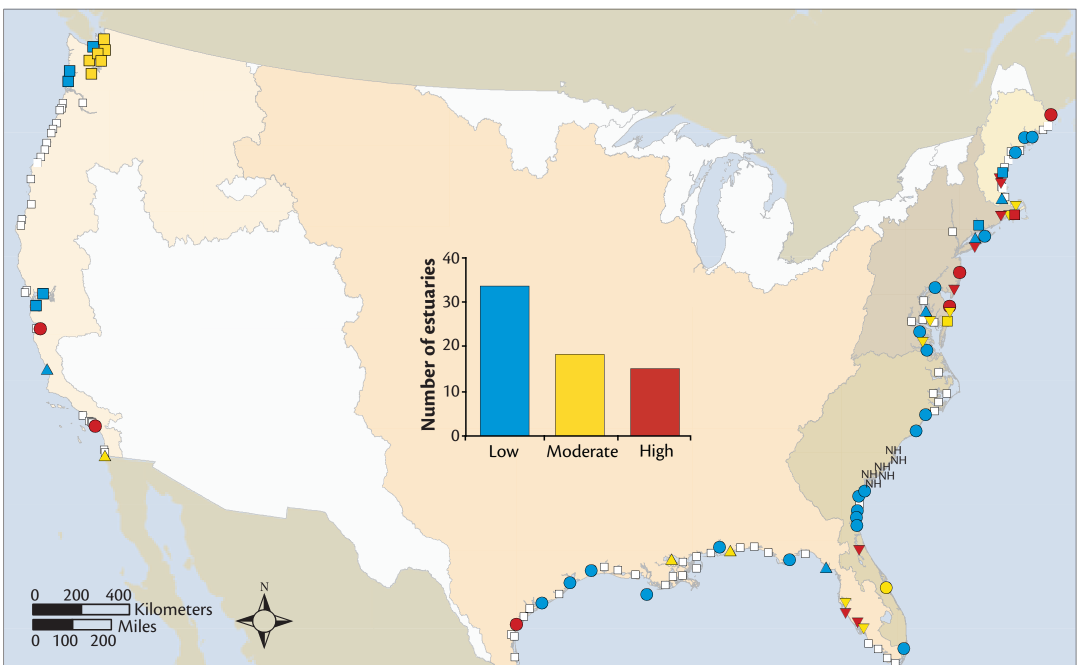
Data for submerged aquatic vegetation (SAV) were scarce, with only 55 systems reporting on conditions. Of the systems for which SAV data were available, the vast majority (50) reported low or no problem symptom expression, indicating no or little loss of SAV in the early 1990's to 2004 period (Figure 3.8e). Those systems recording a moderate or high SAV symptom expression were located in the mid-Atlantic region. It is notable that 13 systems (one in the mid- and 12 in the South Atlantic region) have not historically had SAV and thus this indicator cannot be used.

Overall, moderate or high levels of at least one secondary symptom was observed in 44 estuaries, representing 41% of the Nation's total and 56% of the assessed estuarine surface area—an indication that eutrophication is well developed and potentially causing problems in over half of U.S. estuaries.

Figure 3.8 Individual symptom expressions on a national scale.

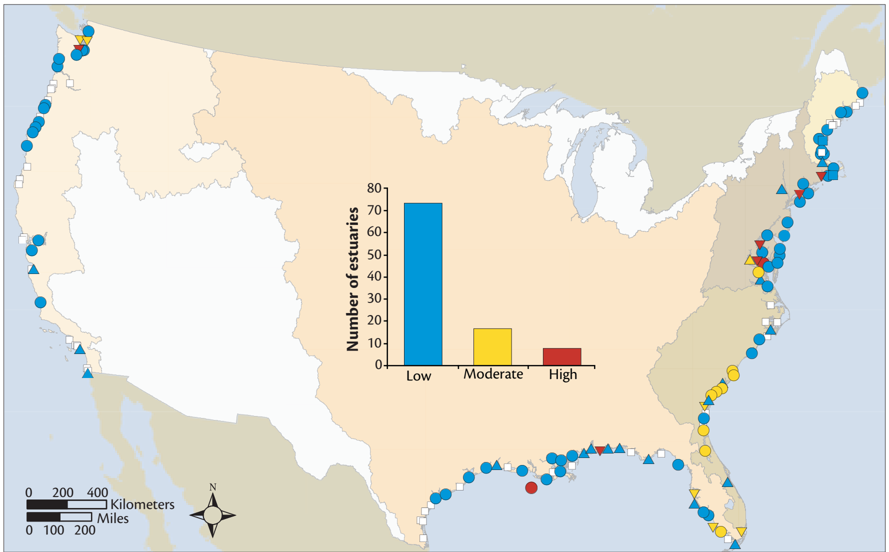


a) Chlorophyll *a*

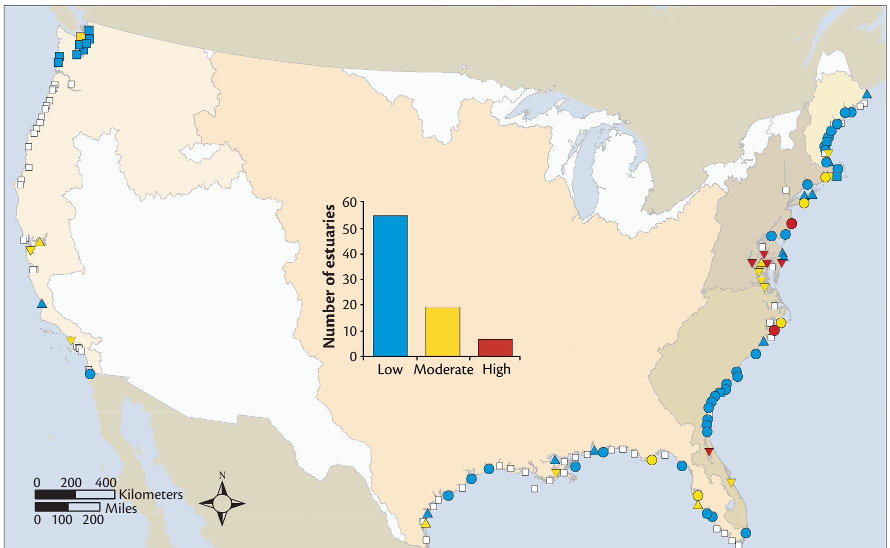


b) Macroalgae

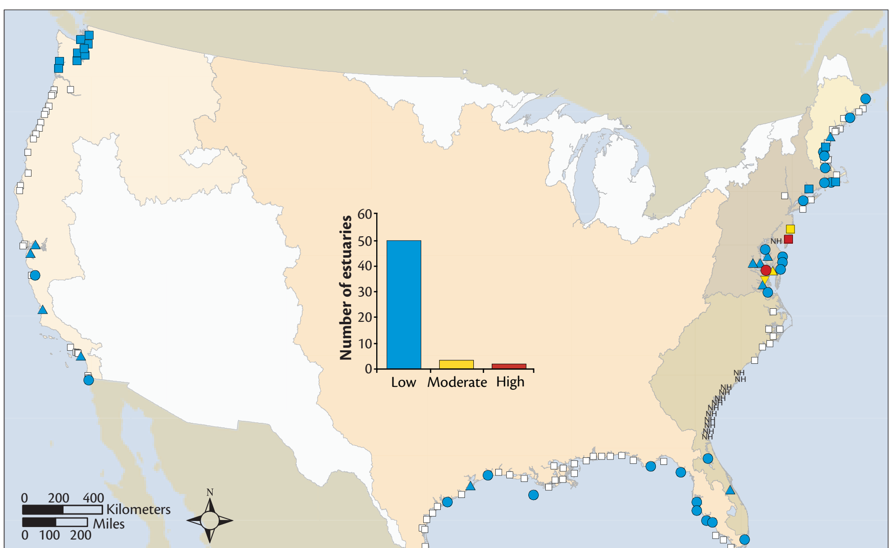
Symptom Expression	Change since 1999 assessment
High: symptoms generally occur periodically or persistently and/or over an extensive area.	Symptoms **improved** since 1999 assessment.
Moderate: symptoms generally occur less regularly and/or over a medium area.	**No change** in symptoms since 1999 assessment.
Low: few symptoms occur at more than minimal levels.	Symptoms **worsened** since 1999 assessment.
Unknown: Insufficient data for analysis.	**Insufficient data** to show trend.
NH Not historically observed.	



c) Dissolved oxygen



d) Nuisance/toxic blooms



e) Submerged aquatic vegetation

Eutrophic conditions

- Eutrophication was a widespread problem throughout most of the Nation.
- Majority of systems for which data were available were moderately to highly eutrophic.
- There were no regional or national spatial patterns of symptoms.
- The mid-Atlantic region was the most impacted.

The assessment of overall eutrophic condition (OEC) is based on five symptoms: chlorophyll *a*, macroalgae, dissolved oxygen, nuisance/toxic blooms, and submerged aquatic vegetation. The expression level of each is determined by the concentration or problem occurrence, spatial coverage, frequency of occurrence, and for nuisance/toxic algal blooms, the duration of the bloom (see *Chapter 2,* Figure 2.3).

Eutrophication is a widespread problem throughout most of the regions (Figure 3.9). Overall, 29 estuaries had a moderate high or high OEC rating, representing 39% of the total assessed estuarine surface area. An additional 35 estuaries exhibited moderate eutrophic conditions. When considered together, estuaries with moderate to high conditions represent 78% of the assessed estuarine surface area. Estuaries with high OEC ratings were mainly located in the mid-Atlantic region. The largest concentration of highly eutrophic estuaries occurred around Chesapeake Bay, an area that also had high influencing factor ratings.

There were 35 systems (21% of assessed surface area) which exhibited low to moderate low overall eutrophic conditions. More than half of these estuaries were located in the Gulf of Mexico and Pacific Coast regions. Low to moderate low overall eutrophic conditions in the Pacific Coast region are a result of moderate chlorophyll *a* and low dissolved oxygen symptom expressions. While nitrogen load data were only available for four systems in this region, these systems have a moderate or low susceptibility to nutrients. Although the North Atlantic region had a predominance of estuaries with low influencing factors ratings, the OEC ratings in the region varied from low to moderate high, with most systems having a low or moderate OEC condition.

Data confidence and reliability (DCR) varied among systems. The general trend showed moderate DCR ratings in systems with high overall eutrophic conditions but low DCR ratings in systems with moderate or low OEC ratings. Most of the systems with high confidence are located in the North and mid-Atlantic regions, while those with low confidence are located in the Gulf of Mexico and Pacific Coast regions.

Changes in eutrophic condition since the 1990s

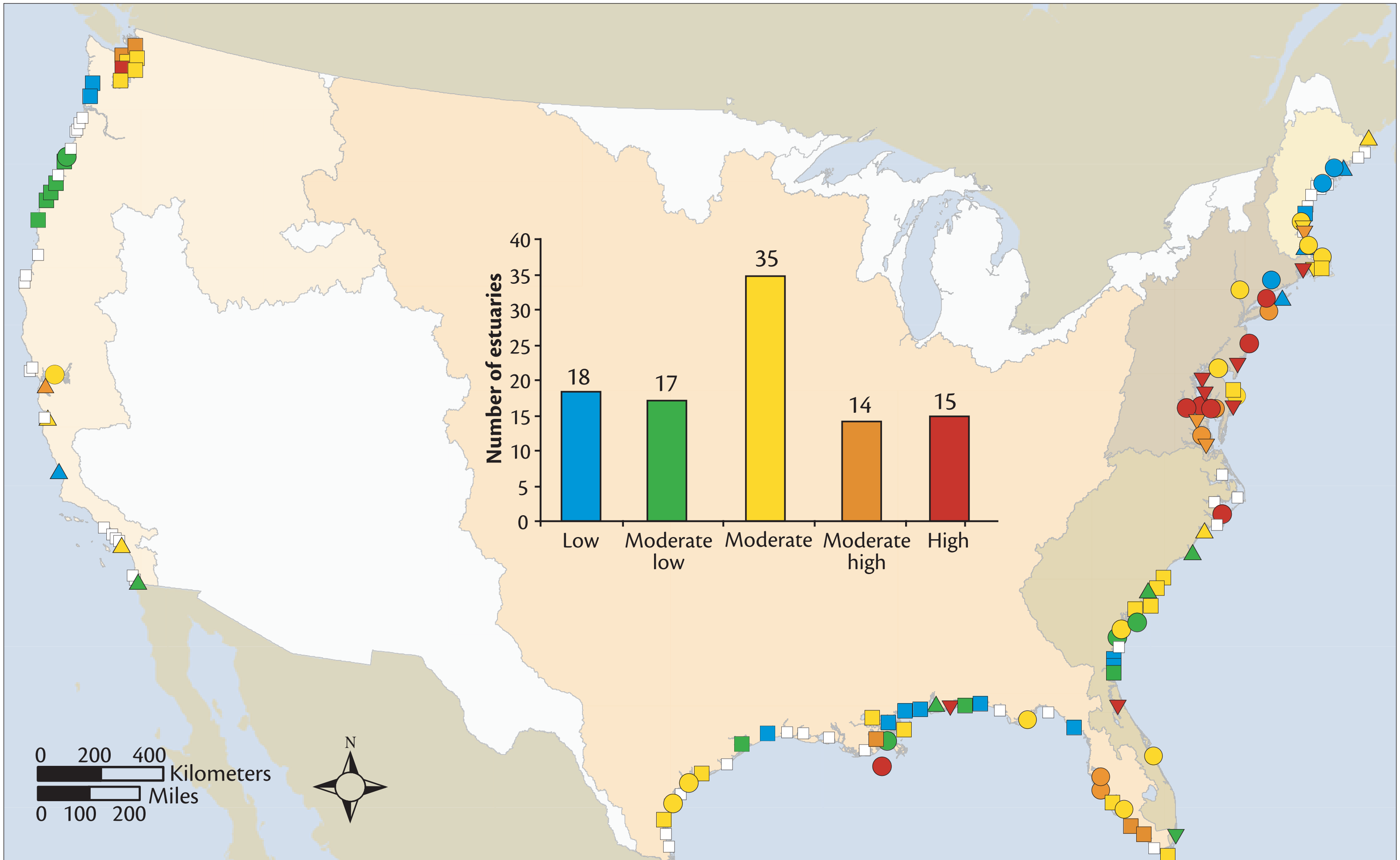
Changes in overall eutrophic condition since the 1999 assessment revealed that equal numbers of systems had worsened and improved. Among the systems where data were available for comparison (58), 13 had improved (9% of assessed surface area), 13 had worsened (14% assessed surface area), and 32 had remained the same (77% assessed surface area). There were fewer systems with high overall eutrophic conditions in 2004 (15) than a decade ago (17). The assessed estuarine surface area with moderate to high overall eutrophic conditions has remained about the same from 72% in the early 1990s to 78% in this assessment. It is evident from these results that changes have occurred predominantly in the smaller systems. However, these results must be viewed with caution, because the total number of systems for which conditions are unknown has increased from 17 in the 1999 assessment to 42 in this assessment. Similar to the 1999 survey, the Pacific Coast region had the least robust data and the lowest assessment confidence.

The data gaps and low confidence in some of the results highlight the need for systematic monitoring. The same is true for trend analysis of the individual symptom results. While it is possible to say that there were 48 systems exhibiting high chlorophyll *a* levels compared to only 39 systems a decade ago, there were many more systems in 2004 for which data were unknown. Likewise, there were 42 systems with high and moderate levels of dissolved oxygen problems a decade ago; in 2004 only 24 systems exhibited high or moderate problems. It is tempting to evaluate and make conclusions about management success during the past decade based upon these numbers. However, more systems need to be characterized before any conclusions can be made.

Allison Dungan, Univ. of MD Center for Env. Science

Wetlands help filter nutrients out of water bodies.

Figure 3.9. Overall eutrophic condition on a national scale.



Overall eutrophic condition (OEC)

- **High:** symptoms occur periodically or persistently and/or over an extensive area.
- **Moderate high:** symptoms occur less regularly and/or over a medium to extensive area.
- **Moderate:** symptoms occur less regularly and/or over a medium area.
- **Moderate low:** symptoms occur episodically and/or over a small to medium area.
- **Low:** few symptoms occur at more than minimal levels.
- **Unknown:** Insufficient data for analysis.

Change in eutrophic condition since 1999 assessment

- △ Symptoms **improved** since 1999 assessment.
- ○ **No change** in symptoms since 1999 assessment.
- ▽ Symptoms **worsened** since 1999 assessment.
- □ **Insufficient data** to show trend.

Future outlook

• Survey participants predicted worsening conditions in 65% and improvements in 19% of the systems assessed.

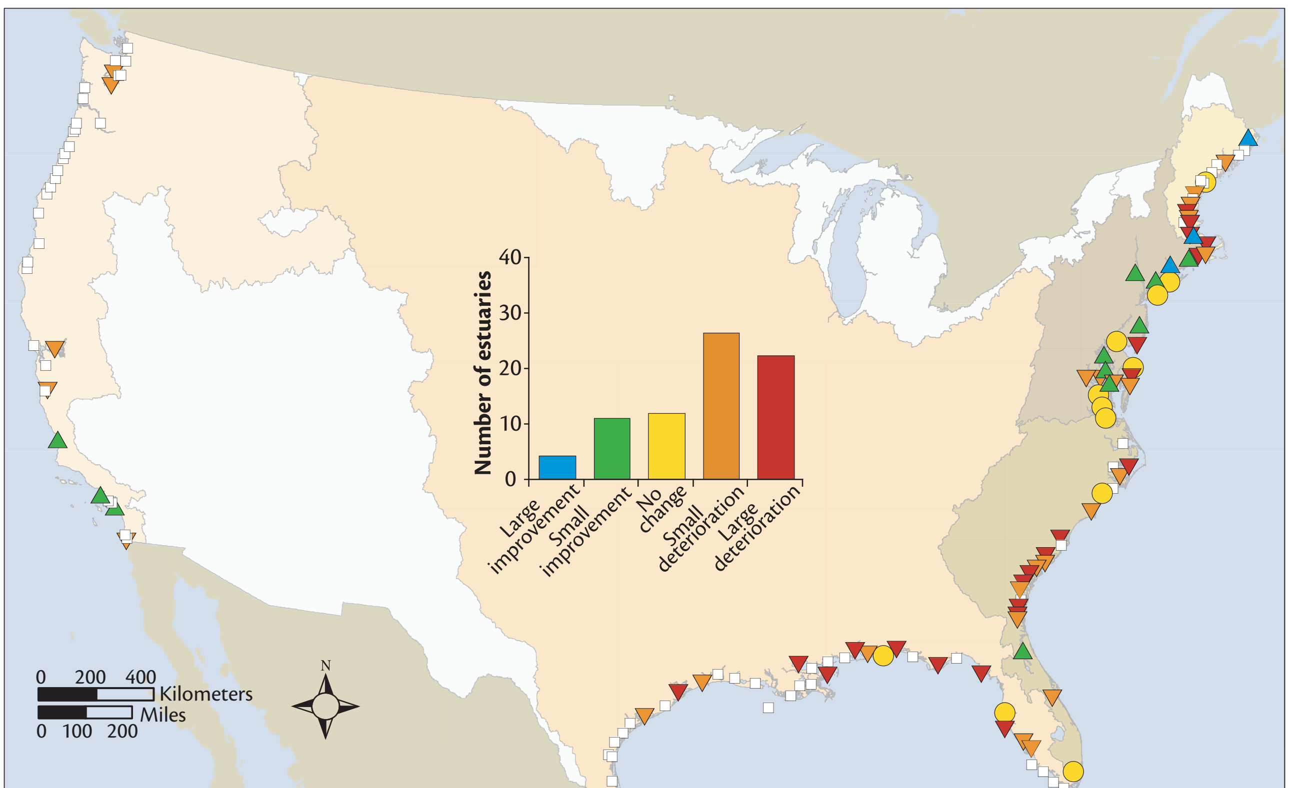
Future outlook is based upon predicted population growth and specific management and development planned within the systems. This assessment projects a bleak outlook for the Nation's estuaries, as overall eutrophic condition was predicted to worsen in 48 systems, stay the same in 11, and improve in only 14 systems by 2020 (Figure 3.10). Future outlook was not determined for 67 systems, perhaps illustrating uncertainty in future eutrophic condition.

There are presently 12 systems with a moderate low to low overall eutrophic condition but moderate to high susceptibility and a worsening future outlook. Although most (65% of assessed) systems are predicted to worsen, particularly if nutrient inputs increase, the systems with low eutrophic conditions and moderate to high susceptibility should be a priority for protective management because they are the most at risk. The potential for changes in nutrient loads and hydrology due to climate change should also be explored when considering the future of estuaries (See page 38).

Changes in the past decade

Analysis of actual changes in relation to the 1999 assessment predictions showed that some have already been realized. A complete analysis of the accuracy of these predictions cannot be made until 2020, the year for which the projections were made. However, interim changes can be examined; of the 86 systems expected to worsen, 12 have worsened. Of the eight systems expected to improve, one system has improved.

Figure 3.10. Future outlook on eutrophic condition on a national scale.



Future outlook

- **Large deterioration:** Moderate to high susceptibility and expected increases in nutrient loads.
- **Small deterioration:** Low susceptibility and expected future increases in nutrient loads.
- **No change:** Any susceptibility but no expected change in nutrient loads.
- **Small improvement:** High to moderate susceptibility and expected future decrease in nutrient loads.
- **Large improvement:** Low susceptibility and expected future decreases in nutrient loads.
- **Unknown:** Insufficient data for analysis.

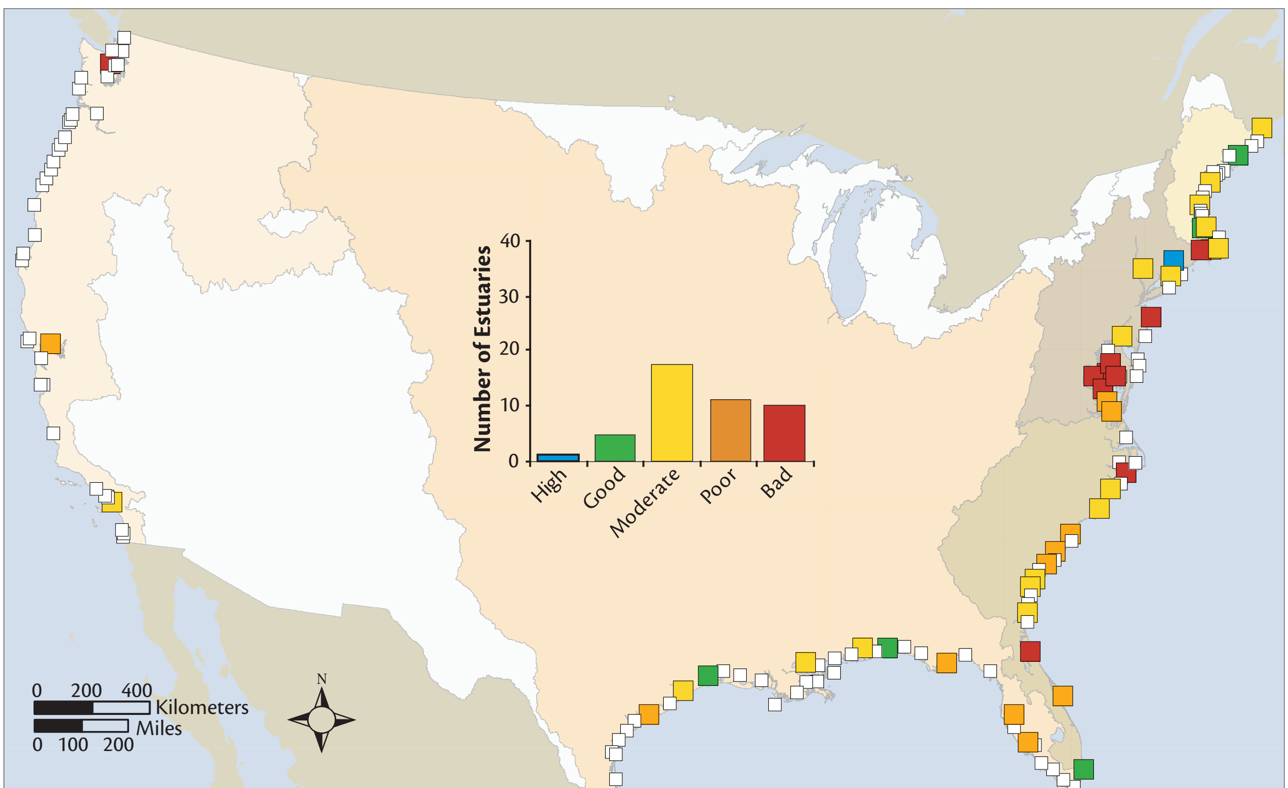
Assessment of estuarine trophic status

- The majority of estuaries were rated moderate to bad.
- This rating could only be conducted when data for all three factors (influencing factors, OEC, and future outlook) were available. Therefore, only 48 systems out of 141 were rated.

The ASSETS (assessment of estuarine trophic status) rating, a combination of the three components (influencing factors, overall eutrophic condition, future outlook), is created in order to provide one overall score for a system. These scores fall into one of five categories: high, good, moderate, poor, or bad. A system may be rated as good based upon high or good conditions of influencing factors and overall eutrophic condition, even if the system is expected to worsen in the future. Poor and bad grades reflect a range of undesirable influencing factors and overall eutrophic conditions, even if there are management plans for recovery.

As the assignment of an ASSETS rating requires data for all three components, there were only adequate data for determination of an ASSETS rating for 48 systems (Figure 3.11). Only one system was rated as high (Connecticut River), while five were rated as good (Biscayne Bay, Pensacola Bay, Blue Hill Bay, Sabine Lake, Boston Harbor). Eighteen were rated as moderate and 24 systems were rated as poor or bad. The single rating of ASSETS allows simple comparisons between and among systems. It has been applied at a national (this study) and international level (http://www.eutro.org). The intent is to share lessons learned and encourage more pro-active approaches to the maintenance of estuarine health.

Figure 3.11. ASSETS ratings on a national scale.



Assessment of estuarine trophic status (ASSETS)

- Bad: Moderate to high pressure, moderate high to high eutrophic condition, and any expected future change in eutrophic condition.
- Poor: Moderate low to high pressure, moderate to moderate high eutrophic condition and any expected future change in condition.
- Moderate: Any pressure, moderate low to moderate high eutrophic condition, and any expected future change in eutrophic condition.
- Good: Low to moderate pressure, low to moderate low eutrophic condition, and any expected future change in condition.
- High: Low pressure, low eutrophic condition, and any expected improvement or no future change in eutrophic condition.
- Unknown: Insufficient data for analysis.


Shih-Nan Chen, University of Maryland Center for Environmental Science

Tourism in the Pacific Coast region has remained unaffected by eutrophication.

Impaired uses

- Systems with moderate to high impacts also exhibited moderate to high overall eutrophic conditions.
- The top use impairments reported for all regions were to commercial and recreational fishing, shellfish harvesting, fish consumption, swimming, and aesthetics.
- The top four causes of impairments were agriculture (crops and animal operations), wastewater treatment plants, urban runoff, and atmospheric deposition.

The finding that about two thirds of the estuaries assessed have moderate to high expression of eutrophication is of considerable importance. Eutrophic symptoms may negatively impact estuarine resources in a variety of ways. For instance, fish kills associated with low dissolved oxygen and nuisance/toxic blooms impact commercial fishery landings. Declines in tourism occur when noxious smells (caused by hypoxia or anoxia) and floating algal mats create unfavorable aesthetic conditions. Additionally, risks to human health increase when the toxins from algal blooms accumulate in edible fish and shellfish. Furthermore, when toxins become airborne, they may cause respiratory problems after inhalation. While this report does not directly address economic losses, an additional socioeconomic indicator is currently under development (see *Chapter 6*). This indicator may also address the detriment to seasonal economies when eutrophic symptoms occur during the height of the tourist and/or fishing seasons.

Although the magnitude of impacts to living resources and human uses of these water bodies cannot currently be quantified, the survey asked participants to identify impacts they suspected to be caused by eutrophic symptoms. Out of the 48 systems with adequate data, 14 noted considerable impacts to living resources while 17 noted moderate impacts. Seventeen reported slight to no impact. Those with reported impacts were mostly located in the mid-Atlantic, South Atlantic, and Gulf of Mexico regions. The majority of systems with moderate to considerable impacts generally exhibited moderate to high overall eutrophic conditions. Top use impairments reported for all regions were commercial and recreational fishing, shellfish harvesting, fish consumption, swimming, and aesthetics. Some South Atlantic and Gulf of Mexico systems also noted tourism as being impaired.

The overall top four causes of these use impairments were listed as agriculture (crops and animal operations), wastewater treatment plants, urban runoff, and atmospheric deposition. Animal operations and crop agriculture were noted mostly for systems in the mid- and South Atlantic regions while exurban development (outside boundaries of urban areas) was reported in the South Atlantic region. Combined sewer overflow and onsite septic tanks were problematic mainly for the Gulf of Mexico region, and to a lesser degree in the North and mid-Atlantic regions.

Considerations for management actions

It is important to manage from a watershed perspective, focusing on sources of nutrients which are controllable for the system in question. It is also importatnt that the level of susceptibility, eutrophic condition, and future outlook be used to set management priorities. On a national basis, the most frequently noted management targets are wastewater treatment, urban runoff, onsite septic tanks, and atmospheric deposition. In all regions except for the North Atlantic, non-point sources remain a primary focus.

Notable among point sources were combined sewer overflows in the North Atlantic region and wastewater treatment plants in all regions. Animal operations and crop agriculture were named as management targets for systems in the mid-Atlantic, South Atlantic, and Gulf of Mexico regions. Forestry activities were named for the Pacific Coast region. Of the non-point sources, atmospheric deposition and urban runoff were among the most frequently named management targets for all regions.

Data gaps and research needs

Monitoring

Currently, the greatest monitoring need is for data which better characterize the levels of eutrophic symptoms in estuaries (see box below). Helping to fulfill this need are the following recommendations:

- Long-term comprehensive monitoring programs incorporating typology and minimum sampling frequencies for each indicator (see *Chapter 6*).
- *In situ* sampling should be coordinated with user-driven, integrated programs designed for routinely providing satellite and remote sensing information such as the U.S. Integrated Ocean Observing System (IOOS) and the National Water Quality Monitoring Network (NWQMN).
- Internally, the web-based data entry format should also be refined so that data summaries can be automatically calculated and disseminated.
- Better monitoring of living resources.

Research

Nutrient loads are critical to the development of the nutrient input-estuarine response relationships, without which management measures cannot be planned or implemented. A large effort should go toward improving the ability to estimate loads in a timely manner (only 64 systems in this assessment had load data available). Other recommendations are:

- Identify and quantify nutrient sources.
- Gain a greater understanding of nuisance macroalgae as an indicator (i.e., key taxa for specific systems) and problem level thresholds.
- Define a more robust metric for monitoring SAV biomass and spatial coverage.
- Evaluate nuisance/toxic blooms with respect to shifts in phytoplankton community composition.
- Investigate estuarine boundaries, susceptibility, and typology to improve assessment accuracy by modifying indicator thresholds by system type.
- Investigate the link between eutrophication and impacts to living resources and/or human uses of estuaries and incorporate this into the assessment in order to promote public awareness and support for management (see *Chapter 6*).
- Investigate the potential influences of climate change on eutrophication.

Management

A challenge to the management community is to address the eutrophic status of systems and approach the issue on a local to regional scale. The following are options or tools to improve the management of eutrophic systems:

- Develop templates for regular "report cards" that are accessible, easy to understand, and disseminated on a regular basis.
- Establish a link between air and water regulatory programs, as atmospheric deposition is one of the top noted targets for nutrient management.
- Foster partnerships between NOAA and EPA to improve current national assessments, particularly the assessment methods.
- Total Maximum Daily Load (TMDL) and non-point Source (NPS) programs should continue efforts to reduce nutrient loads from both point and non-point sources.
- Develop public support through outreach and education on best management practices (BMPS) and other locally implementable actions.

For the following 42 estuaries, there was insufficient data to assess overall eutrophic conditions:

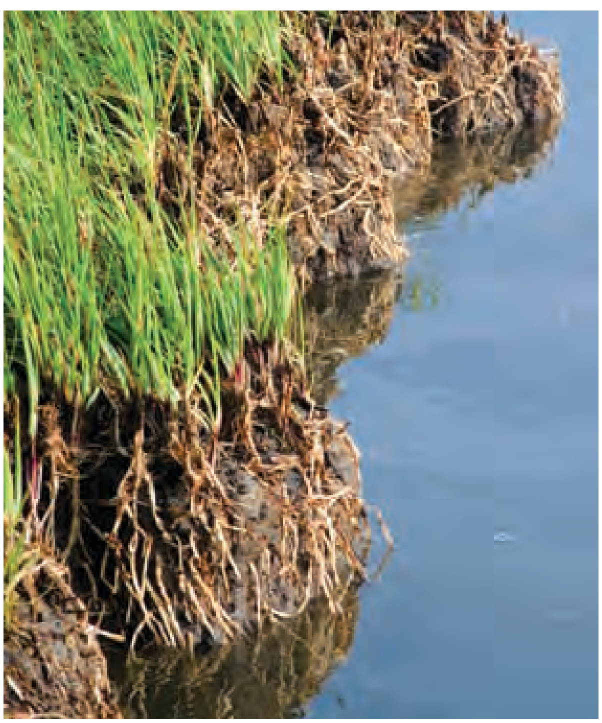
Alamitos Bay	Englishman Bay	Pamlico/Pungo Rivers
Albemarle Sound	Humboldt Bay	Saco Bay
Anaheim Bay	Kennebec/Androscoggin River	San Diego Bay
Apalachee Bay	Klamath River	San Pedro Bay
Aransas Bay	Lower Laguna Madre	Santa Monica Bay
Atchafalaya/Vermilion Bays	Mermentau Estuary	Sheepscot Bay
Baffin Bay	Merrimack River	Siletz Bay
Bogue Sound	Mission Bay	Siuslaw River
Brazos River	Monterey Bay	South Ten Thousand Islands
Calcasieu Lake	Muscongus Bay	St. Andrew Bay
Casco Bay	Narraguagus Bay	St. Catherines/Sapelo Sounds
Columbia River	Nehalem River	Terrebonne/Timbalier Bays
Drakes Estero	Netarts Bay	Tillamook Bay
Eel River	Pamlico Sound	Tomales Bay

EUTROPHICATION AND CLIMATE CHANGE

As this chapter illustrates, the Nation's estuaries are under stress from nutrient loads which have led to a range of eutrophic symptoms. Survey respondents predicted that in many regions these pressures will increase in the future, leading to worsening conditions. However, these predictions did not account for the effects of climate change. The factors associated with climate change that are expected to have the greatest impacts on coastal eutrophication are: increased temperatures, sea level rise, and changes in precipitation and freshwater runoff.

Temperature

Increased temperatures will have several effects on coastal eutrophication. Most coastal species are adapted to a specific range of temperatures. Increases in water temperatures may lead to expanded ranges of undesirable species. Higher temperatures may also lead to increased algal growth and longer growing seasons, potentially increasing problems associated with excessive algal growth and nuisance/toxic blooms. Additionally, warmer waters hold less dissolved oxygen, therefore potentially exacerbating hypoxia. Temperature-related stratification of the water column may also worsen, having a further negative effect on dissolved oxygen levels.



Adrian Jones, University of Maryland Center for Environmental Science

Marsh erosion and inundation are just some of the potential impacts expected to exacerbate eutrophication. Marshes act as a major nutrient sink, without which loads will be even greater.

Sea level rise

Climate change models predict increased melting of polar icecaps and changes in precipitation patterns, leading to sea level rise and changes in water balance and circulation patterns in coastal systems. Sea level rise will gradually inundate coastal lands, causing increased erosion and sediment delivery to water bodies, and potentially flooding wetlands. The increased sediment load and subsequent turbidity increase may cause submerged aquatic vegetation loss. The positive feedback between increased erosion and algal growth (as erosion increases, sediment associated nutrients also increase, stimulating growth) may also increase turbidity. The loss of wetlands, which act as nutrient sinks, will further increase nutrient delivery to estuaries.

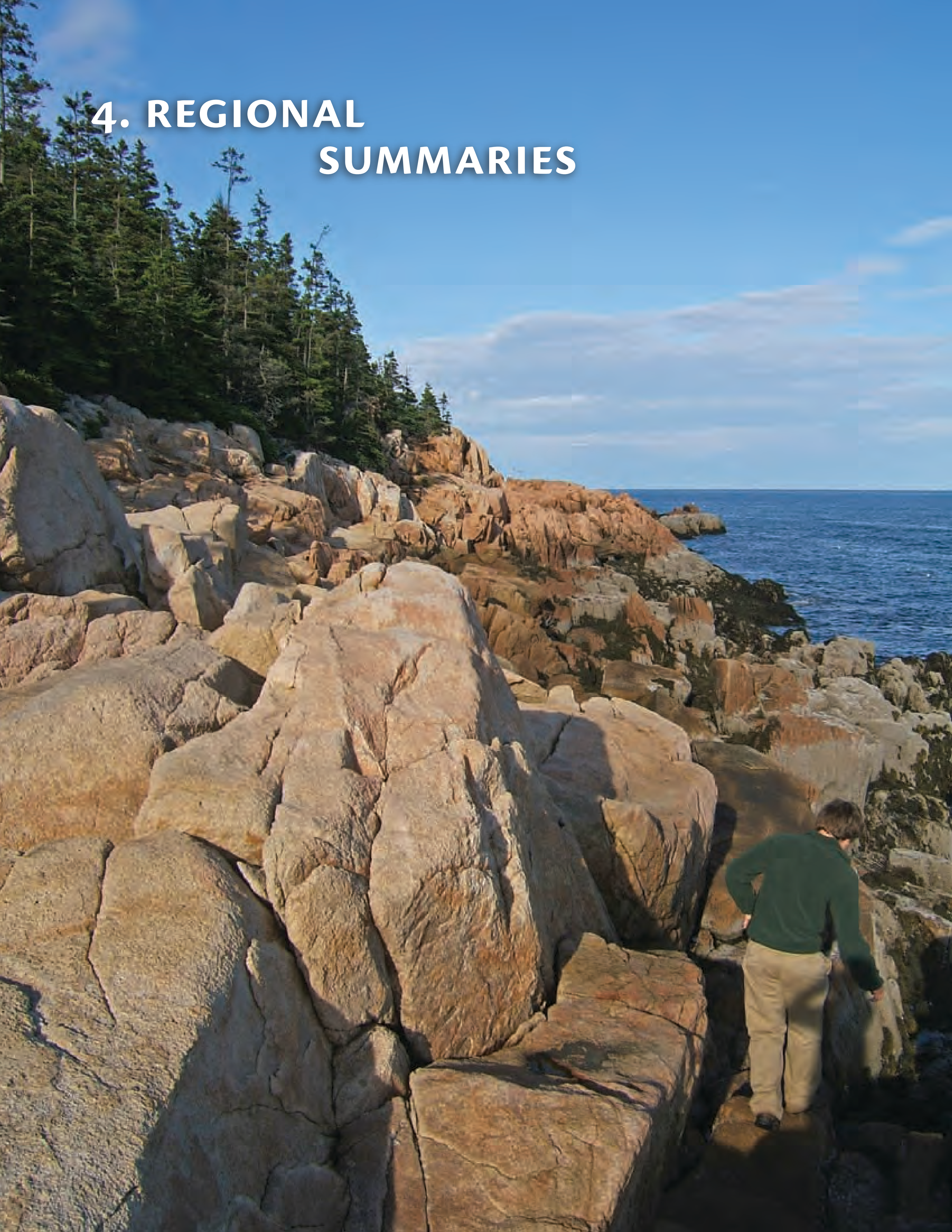
Precipitation and freshwater runoff

Changes in precipitation may affect: runoff from land, stratification, oxygen concentrations in bottom waters, and water circulation patterns. Decreased precipitation and freshwater runoff may alter food webs by decreasing nutrient loads, thereby reducing algal growth. Although reduced river flow causes decreased inputs, it also increases residence time. Therefore, eutrophic problems may increase near the sources of nutrients that are not a function of river flow, such as from point sources (i.e., sewage treatment plants). Potential excessive algal blooms near point source outfalls may also lead to local incidents of hypoxia in bottom waters. In contrast, increased rainfall and runoff may increase nutrient loads, leading to stimulation of algal growth and density-driven stratification. However, the increase in freshwater inflow would also reduce residence time, reducing the probability of blooms in some systems. In regions of engineered water flow (e.g., South Atlantic and Gulf of Mexico), the impacts of changes in the amount of runoff will depend on how water management strategies control regional hydrology.

Level of certainty

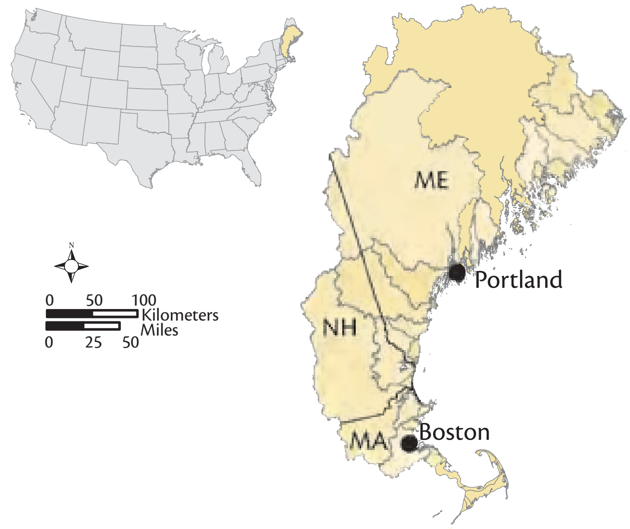
Predictions concerning the effects of climate change have varying degrees of certainty. There is a moderate degree of certainty in predictions of how increases in temperature will affect plant physiology, aquatic oxygen concentrations, and effects of sea level rise on flooding of wetlands and erosion. There is less certainty regarding temperature's influence on water circulation patterns and the effects of climate change on precipitation (IPCC 2001, Kennedy et al. 2002).

4. REGIONAL SUMMARIES



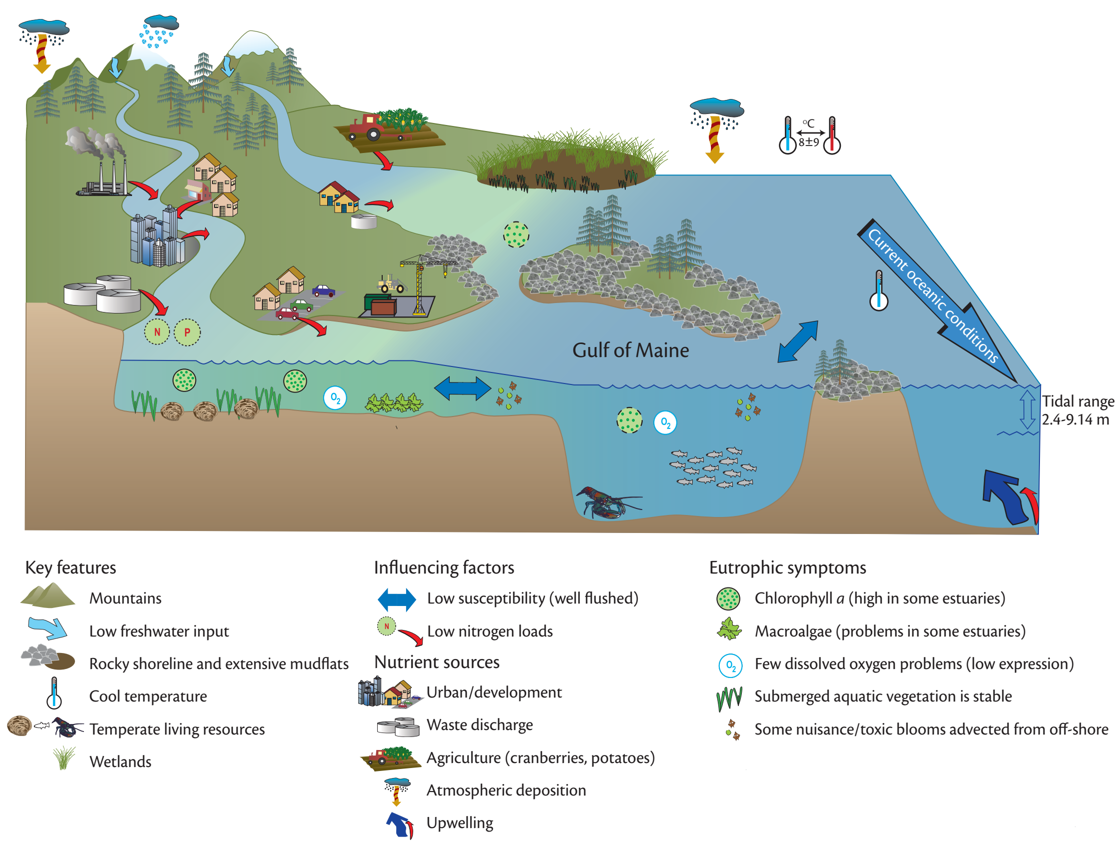
NORTH ATLANTIC REGION

- Factors influencing eutrophication were low for all assessed systems (9 out of 20 in the region).
- The least impacted region—no systems had a high overall eutrophic condition rating.
- Some systems had worsening chlorophyll *a* and macroalgae.



The North Atlantic region includes 20 estuarine systems, encompassing roughly 5,300 km^2 of water surface area. In the north, the coastal shoreline consists mainly of drowned river valleys characterized by numerous small embayments, rocky shorelines, wave-cut cliffs, and large, rocky islands (Figure 4.1). The southern part consists of drowned river valleys characterized by cobble, gravel, and sand beaches, and extensive tidal marshes. Average depth ranges from less than one meter to more than 45 meters. The large tidal ranges, about two to five meters, result in a high degree of tidal flushing, often combined with low freshwater input. The high tidal range and circulation patterns in the Gulf of Maine result in offshore waters contributing nutrients and toxic algal blooms to some of the northern systems. The North Atlantic climate is cooler than the other regions, with an average annual air temperature of 8°C, 156 frost days, and 1.2 m precipitation per year. The average regional watershed population density is 65 people km^{-2} and major population centers are Portland and Boston.

Figure 4.1. Conceptual diagram of North Atlantic key features, major nutrient sources, and resulting symptoms.



Influencing factors

- All systems for which data were available exhibited low influencing factors.

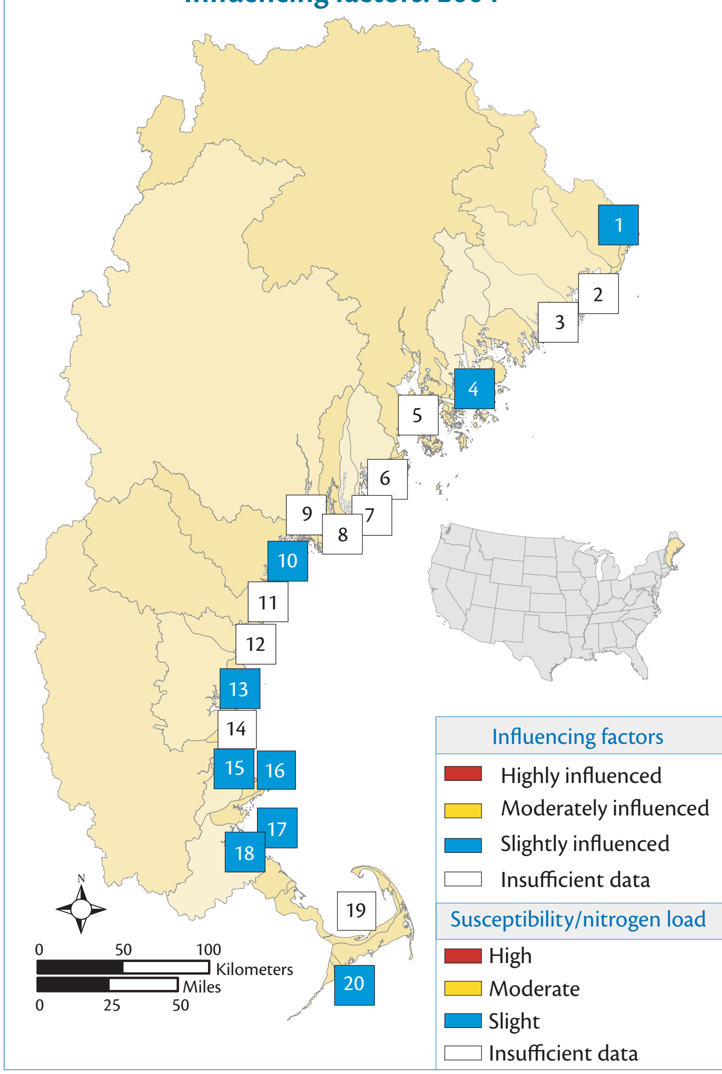
Nitrogen loads, represented as the ratio of watershed to oceanic inputs, are rated as high in only one North Atlantic system and low in eight others (Figure 4.2). Overall, this region has low human influence due to low freshwater inflow and generally sparse population. Dominant sources of nutrients in this region are wastewater treatment, urban runoff, septic tanks, and atmospheric deposition. For northern systems, offshore coastal waters may be a more significant source of nutrients than land based sources. Susceptibility is predominantly low, resulting from high tidal flushing and moderate to good dilution capabilities of systems. A particularly notable reduction in influencing factors since the 1999 assessment occurred in Boston Harbor, due to the diversion of wastewater treatment plant discharge.

Caroline Wicks, EcoCheck (NOAA/University of Maryland Center for Env. Science)

Rocky shorelines are common along the North Atlantic coast.

Figure 4.2. Map of influencing factors ratings, ratings of components of influencing factors, and 1999 ratings in the North Atlantic region.

Influencing factors: 2004



Influencing factors: comparisons

Estuary	Influencing factors (2004)	Susceptibility (2004)	Nitrogen load (2004)	Influencing factors (1999)
1. St. Croix R./Cobscook Bay	Slight	Slight	Slight	Slight
2. Englishman Bay	Insufficient data	Slight	Insufficient data	Slight
3. Narraguagus Bay	Insufficient data	Slight	Insufficient data	Slight
4. Blue Hill Bay	Slight	Slight	Slight	Slight
5. Penobscot Bay	Insufficient data	Slight	Insufficient data	Slight
6. Muscongus Bay	Insufficient data	Slight	Insufficient data	Slight
7. Damariscotta River	Insufficient data	Moderate	Insufficient data	Moderate
8. Sheepscot Bay	Insufficient data	Moderate	Insufficient data	Slight
9. Kennebec/Androscoggin R.	Insufficient data	Slight	Insufficient data	Slight
10. Casco Bay	Slight	Slight	Slight	Slight
11. Saco Bay	Insufficient data	Slight	Insufficient data	Slight
12. Wells Bay	Insufficient data	Slight	Insufficient data	Insufficient data
13. Great Bay	Slight	Moderate	Slight	Slight
14. Hampton Harbor Estuary	Insufficient data	Slight	Insufficient data	Slight
15. Merrimack River	Slight	Slight	High	Slight
16. Plum Island Sound	Slight	Moderate	Slight	High
17. Massachusetts Bay	Slight	Slight	Slight	Moderate
18. Boston Harbor	Slight	Moderate	Slight	High
19. Cape Cod Bay	Insufficient data	Moderate	Insufficient data	Slight
20. Waquoit Bay	Slight	Slight	Slight	Insufficient data

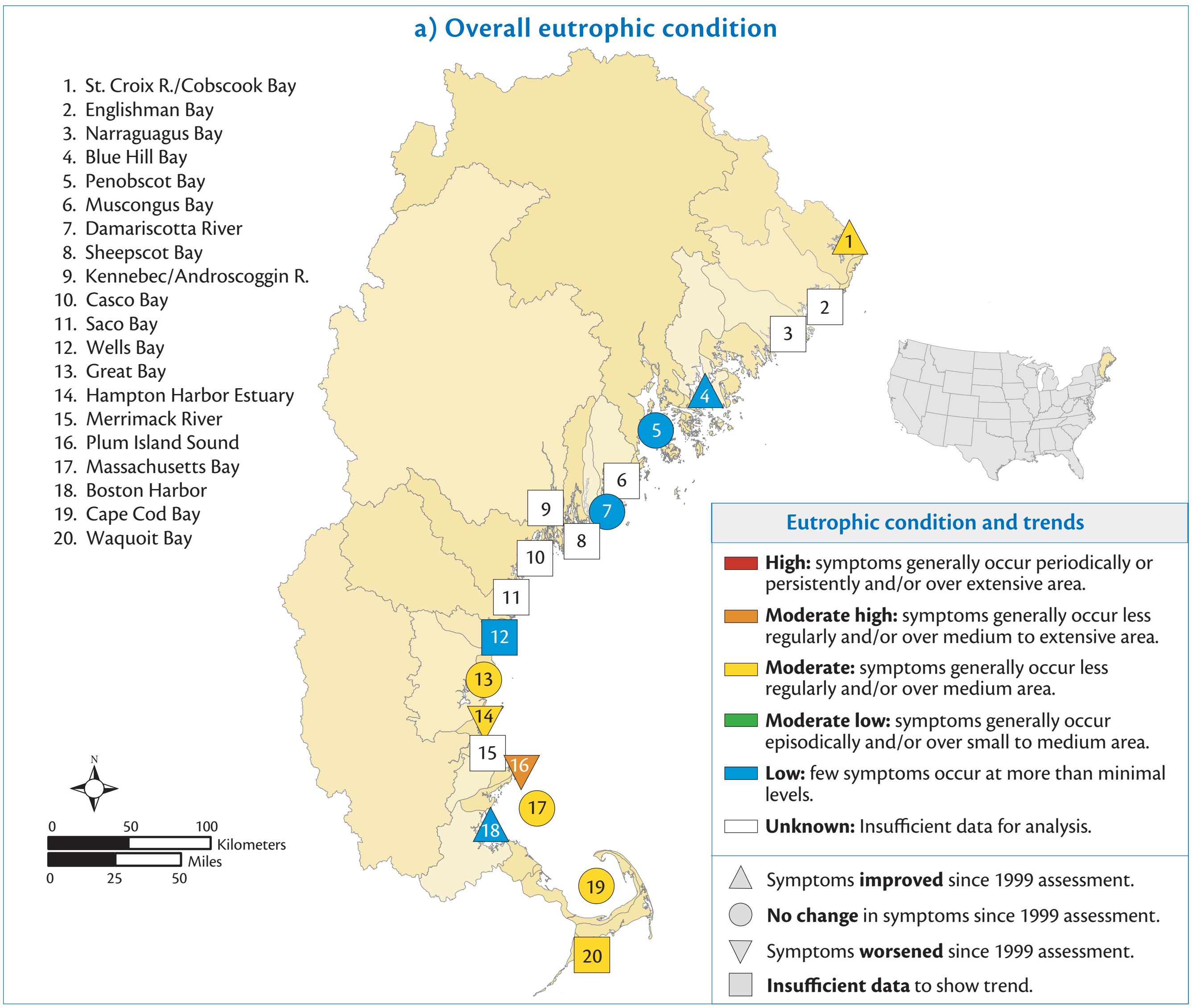
Overall eutrophic condition

- This is the least impacted region; no North Atlantic systems had high overall eutrophic condition (OEC).
- The majority of systems had a moderate or low OEC.
- There was some cause for concern for chlorophyll *a* and macroalgae.
- Toxic offshore blooms which leave cysts (potential future blooms) were an emerging issue.

The North Atlantic region is the least eutrophic region in the nation, with the majority of systems having moderate or low overall eutrophic condition (Figure 4.3a-b). Furthermore, no estuaries in this region recorded high overall eutrophic condition—a unique feature, as all other regions have at least one estuary with a high rating. One system was classified as having moderate high eutrophic conditions, with chlorophyll *a* and nuisance/toxic blooms as the major contributing symptoms.

One notable characteristic in systems of this region is the annual occurrence of nuisance/toxic blooms, which cause shellfish bed closures. However, for systems such as Massachusetts, Cape Cod, Saco, and Casco Bays, these blooms originate offshore and are advected into the systems. For this reason, the nuisance/toxic bloom rating for these systems has been adjusted to low since the blooms do not originate within the system. An emerging issue is the possibility that these blooms, mostly of *Alexandrium* spp., may eventually originate within estuaries, due to cysts that have settled in the estuarine sediments.

Figure 4.3. (a) Map of overall eutrophic condition (OEC) and (b) the combination of individual eutrophic symptoms which constitute OEC ratings in the North Atlantic region.



The overall confidence in the assessments for this region is low due to almost a third of the systems (eight) having inadequate data for assessment. Where data were available, confidence is moderate to high.

Eutrophic symptom expressions

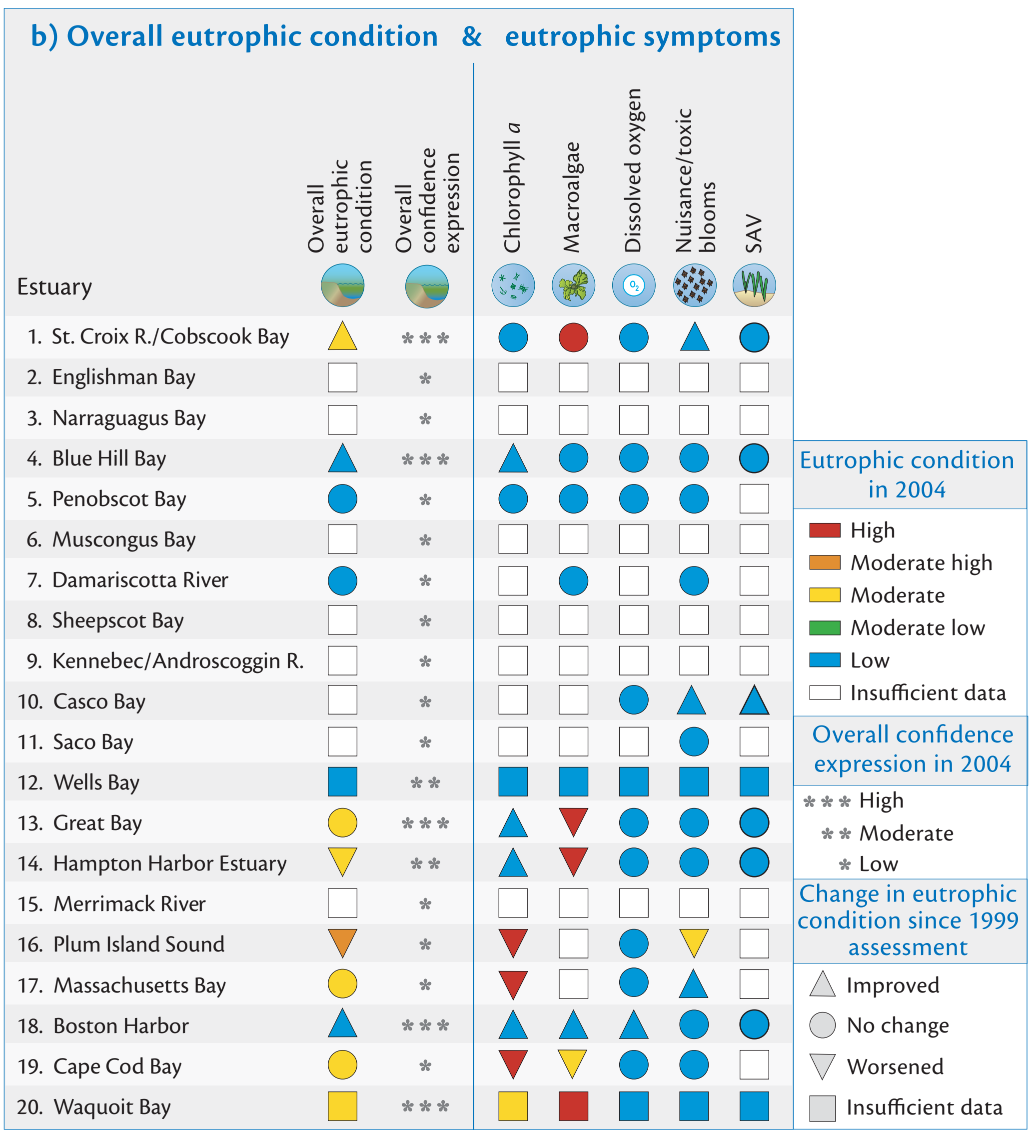
Systems with moderate or moderate high overall eutrophic condition were characterized by having one high symptom expression, which in this region was most often chlorophyll *a* and macroalgae.

While most estuaries had one high symptom expression, the majority of symptom expressions were low. For the primary symptoms, chlorophyll *a* was expressed as low in seven of the eleven estuaries for which the symptom was reported. Similarly, macroalgae symptom expressions were low in five of the ten reported estuaries. For the secondary symptoms, dissolved oxygen problems were low in all twelve systems, and losses of submerged aquatic vegetation (SAV) were low in all eight systems for which there were data.

Changes in eutrophic condition since the 1990s

Overall eutrophic conditions worsened in two systems, improved in three systems, and did not change in five when compared to the 1999 report (Figure 4.3a-b). Chlorophyll *a* changed in more systems than any of the other symptoms, showing improvements in four systems and worsening conditions in three systems. Of the data available, dissolved oxygen displayed the least amount of change.

Of particular interest is the improvement of eutrophic condition in Boston Harbor, which had moderate high eutrophic status in the 1990s, but currently has a rating of low. All symptom improvements were attributed to sewage treatment upgrades and the move of the wastewater outfall from the harbor into Massachusetts Bay.



Future outlook

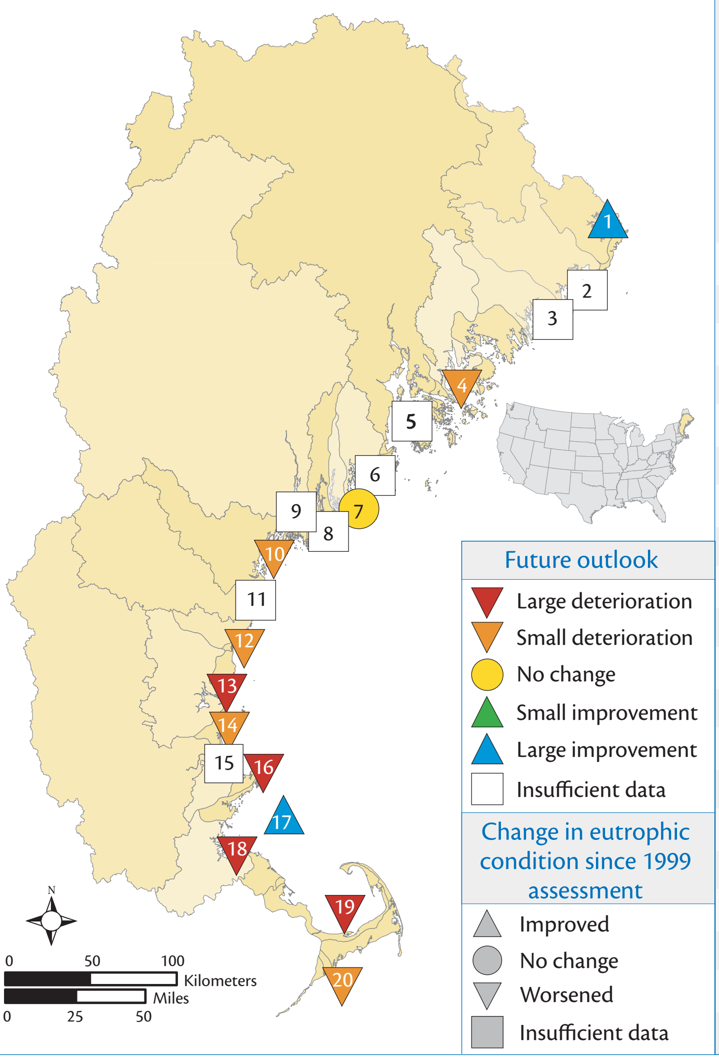
- There was a bleak outlook for future conditions; most systems for which an evaluation was made were expected to worsen in the future.
- The future outlook has not changed from the early 1990s.

The overall future outlook for the North Atlantic region predicts worsening conditions. Eutrophication symptoms were predicted to worsen in nine of the assessed systems and to improve in only two (Figure 4.4). For the nine systems expected to worsen, nutrient loads are anticipated to increase due to wastewater treatment, urban runoff, onsite septic tanks, combined sewer overflow (Cape Cod Bay only), atmospheric deposition, increasing impervious surfaces, and fertilizer use. For all systems, an increase in coastal population (affecting land use distribution and subsequent nutrient loads) is likely to augment nutrient loads from all of these sources.

Though it is premature to make conclusions about the accuracy of the 1999 assessment's future outlook, in six out of nine systems (for which comparison could be made), actual changes trended in the same direction as predicted. Worsening conditions due to increased nutrient loads are expected in Boston Harbor, Great Bay, Plum Island Sound, and Cape Cod Bay (Figure 4.4). Conversely, loads to St. Croix River/Cobscook Bay and Massachusetts Bay are expected to decrease due to improvements in onsite septic tanks, storm water management, restoration of eroding stream beds, and a reduction in salmon aquaculture. These changes are expected to occur by 2020.

Figure 4.4. Future outlook in 2004 and comparison with 1999 future outlook.

Future outlook in 2004



Future outlook comparisons

Estuary	Future outlook in 2004	Actual change in eutrophic condition (1999–2004)	Future outlook in 1999
1. St. Croix R./Cobscook Bay	Large improvement	Worsened	Large deterioration
2. Englishman Bay	Insufficient data	Insufficient data	No change
3. Narraguagus Bay	Insufficient data	Insufficient data	No change
4. Blue Hill Bay	Small deterioration	Improved	Small deterioration
5. Penobscot Bay	Insufficient data	No change	No change
6. Muscongus Bay	Insufficient data	Insufficient data	No change
7. Damariscotta River	No change	No change	Small deterioration
8. Sheepscot Bay	Insufficient data	Insufficient data	No change
9. Kennebec/Androscoggin R.	Insufficient data	Insufficient data	No change
10. Casco Bay	Small deterioration	Insufficient data	Small improvement
11. Saco Bay	Insufficient data	Insufficient data	No change
12. Wells Bay	Small deterioration	Insufficient data	Insufficient data
13. Great Bay	Large deterioration	No change	Large deterioration
14. Hampton Harbor Estuary	Small deterioration	Worsened	Small deterioration
15. Merrimack River	Insufficient data	Insufficient data	No change
16. Plum Island Sound	Large deterioration	Worsened	Large deterioration
17. Massachusetts Bay	Large improvement	Insufficient data	Small deterioration
18. Boston Harbor	Large deterioration	Improved	Small improvement
19. Cape Cod Bay	Large deterioration	No change	No change
20. Waquoit Bay	Small deterioration	Insufficient data	Insufficient data

National Oceanic and Atmospheric Administration

Fishing boats tied up at the Portland Marine Trade Center in Portland, Maine. Monitoring use impairments is important to understanding how eutrophication influences commercial and recreational fishing.

Assessment of Estuarine Trophic Status (ASSETS)

There were seven systems for which an ASSETS rating (combination of influencing factors, overall eutrophic condition, and future outlook) could be made. Two systems were rated as good (Boston Harbor, Blue Hill Bay), four were rated as moderate (St. Croix River/Cobscook Bay, Great Bay, Massachusetts Bay, and Waquoit Bay), and one as poor (Plum Island Sound).

Impaired uses

- Three systems had impaired living resources.
- Causes of impairments were reported as river input, wastewater treatment, combined sewer outflow, urban runoff, fertilizer, and onsite septics.
- Six systems had human use impairments (primarily shellfish harvesting, and recreational and commercial fishing).
- There were no clear correlations between overall eutrophic condition and impacts to living resources.

Living resources were identified as being considerably impaired in only one estuary (Waquoit Bay), a result of onsite septic tanks and fertilizer. Two additional systems reported moderate to slight impacts (Boston Harbor and Great Bay) due to river inputs, wastewater treatment, combined sewer overflow (combination of WWTP and sewer overflow), and urban runoff. However, this information was available for only five of the twenty systems.

Use impairments were reported for six systems (Damariscotta River, Great Bay, Hampton Harbor, Boston Harbor, Cape Cod Bay, Waquoit Bay) with the most frequently noted impairment being shellfish harvesting. Other impacts include recreational and commercial fishing and fish consumption, aesthetics, and swimming.

There does not seem to be a clear correlation between the level of overall eutrophic condition and impacts to living resources. For instance, Waquoit Bay (moderate OEC) had considerably impacted living resources while St. Croix River/Cobscook Bay, also with moderate overall eutrophic condition, had no impacts. This is likely due to the quantitative nature of the OEC rating and the qualitative nature of use impairment reporting (i.e., these impairments occurred during the time period, but degree of impairment was not noted). The difference could also reflect the subtlety that nuisance/toxic blooms, which may be advected from offshore, are in many North Atlantic systems not considered a result of eutrophication. Therefore a comparison between the two is difficult. All systems with some level of eutrophic condition reported impairments.

Potential management concerns

The nutrient sources noted as the causes of impairments to living resources were combined sewer overflow, wastewater treatment, onsite septic tanks, urban runoff, fertilizer use, and river inputs. Atmospheric inputs were also noted as a cause for changes in load during the past decade. All of these warrant management attention given that they are also reported as potential causes of future nutrient increases and worsening conditions.

Data gaps and research needs

Monitoring

Approximately one third of the systems included in this region had insufficient data for assessment. It is recommended that there be an emphasis on better regional monitoring of all indicators, submerged aquatic vegetation and macroalgae in particular. This includes improved assessments of nutrient inputs from rivers, groundwater, and aquaculture so that the causes of observed problems can be identified and addressed. A monitoring program should provide a unified approach for sampling and analyzing indicators (i.e., macroalgae) in all systems, including annual sampling with more intensive sampling during seasons that are problematic (i.e., summer).

Research

A better understanding of circulation dynamics is needed in these systems. Also, improved estimates of population growth and land use impacts and distribution are needed in order to make accurate projections about future conditions. For systems with seasonal population changes, more research is needed in order to assess the effects of winter-summer population changes on eutrophic conditions in estuaries. Finally, improved macroalgal monitoring and assessment techniques are recommended.

Kate Boicourt, EcoCheck (NOAA/University of Maryland Center for Env. Science)

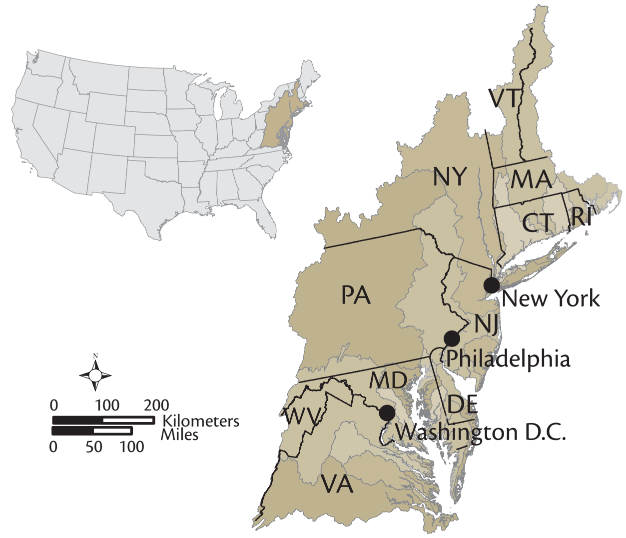
A volunteer taking water samples to monitor for toxic bloom species of algae in Penobscot Bay, Maine.

Management

The survey should be adjusted to accurately reflect relative conditions in different systems. Participants at the NEEA workshop noted that the assessment method should be improved so that the relative conditions among systems in this region would be more accurately reflected. For instance, they argued that despite the improvements to Boston Harbor, the eutrophic conditions of Great Bay are still better than those of Boston Harbor, contrary to the results of the survey. It is important that the relative ratings accurately reflect conditions since this will impact the prioritization of systems needing management and thus the application of scarce resources to improve conditions. For the most part the systems in this region are not presently highly impacted.

MID–ATLANTIC REGION

- Factors influencing eutrophication were high for the majority of systems.
- The most impacted of all the regions—majority of systems had a moderate high or high overall eutrophic condition rating.
- High chlorophyll *a* symptom expression was observed in the majority of systems.



The mid-Atlantic region includes 22 estuaries, encompassing more than 20,300 km^2 of water surface area. This is a temperate region with an average annual air temperature of 12°C, 101 frost days, and 1.1 m precipitation per year. These systems are generally of two types: drowned river valleys and coastal lagoons. The drowned river valleys are characterized by deep channels, relatively high exchange with the ocean, and moderate to high freshwater inflow (Figure 4.5a). Average depths for all systems in the region range from 0.65–19.5 m with drowned river valley systems having an average of 4.7 m. Tidal range is on average 0.86 m and tidal flushing is dominant in the northern systems. These watersheds encompass major population centers including Providence, RI, Hartford, CT, New York City, NY, Philadelphia, PA, Baltimore, MD, Washington, DC, and Richmond, VA. The regional average population density is 156 people per km^2 of catchment, with significant acreage also dedicated to agricultural activity.

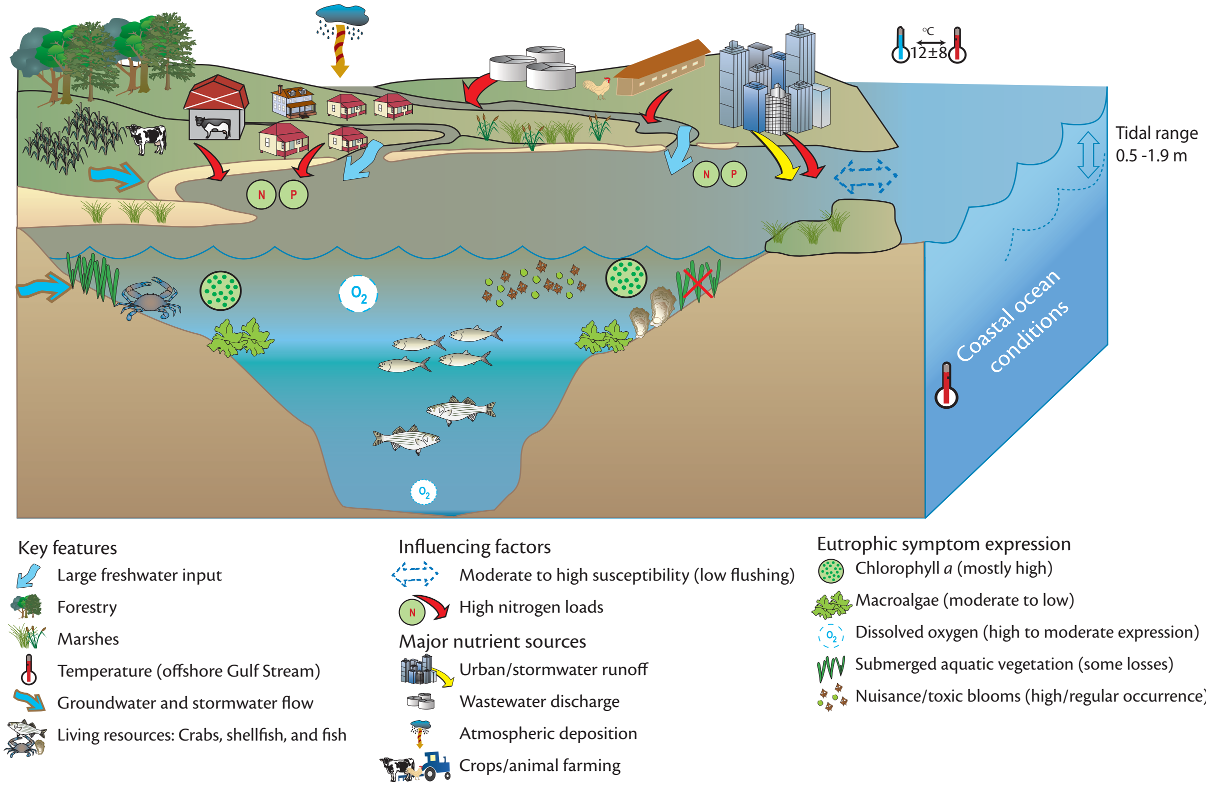
Coastal lagoons are shallow (2 m or less), and are enclosed by barrier lagoons which limit oceanic exchange (Figure 4.5b). Typically, freshwater inflow is very low, and the average lagoonal tidal range is small (0.49 m) compared to the regional range (0.24-1.85 m). These characteristics result in longer flushing times than those of the drowned river valley estuaries. Coastal lagoon watersheds also are subject to significant agricultural activity and dynamic population, due to summertime tourism of beaches and towns along the Atlantic coastline.

Narragansett Bay is an estuary in Rhode Island typical of the drowned river valleys in the mid-Atlantic region.

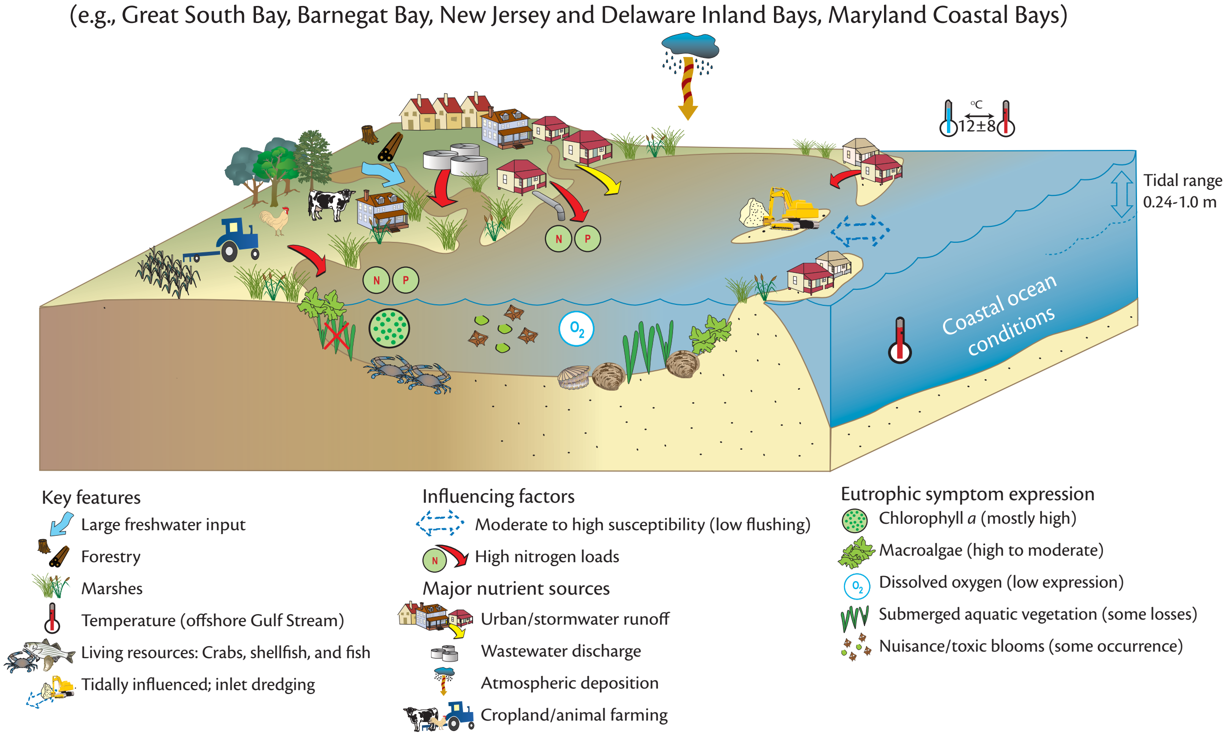
The mid-Atlantic region contains many coastal lagoons such as the one seen here. Assateague Island is a barrier island that protects Sinepuxent Bay, Maryland.

Figure 4.5. Conceptual diagram of mid-Atlantic key features, major nutrient sources, and resulting symptoms.

a. drowned river valleys
(e.g., Chesapeake Bay, Delaware Bay, Long Island Sound, Buzzards Bay, Narragansett Bay)



b. coastal lagoons
(e.g., Great South Bay, Barnegat Bay, New Jersey and Delaware Inland Bays, Maryland Coastal Bays)



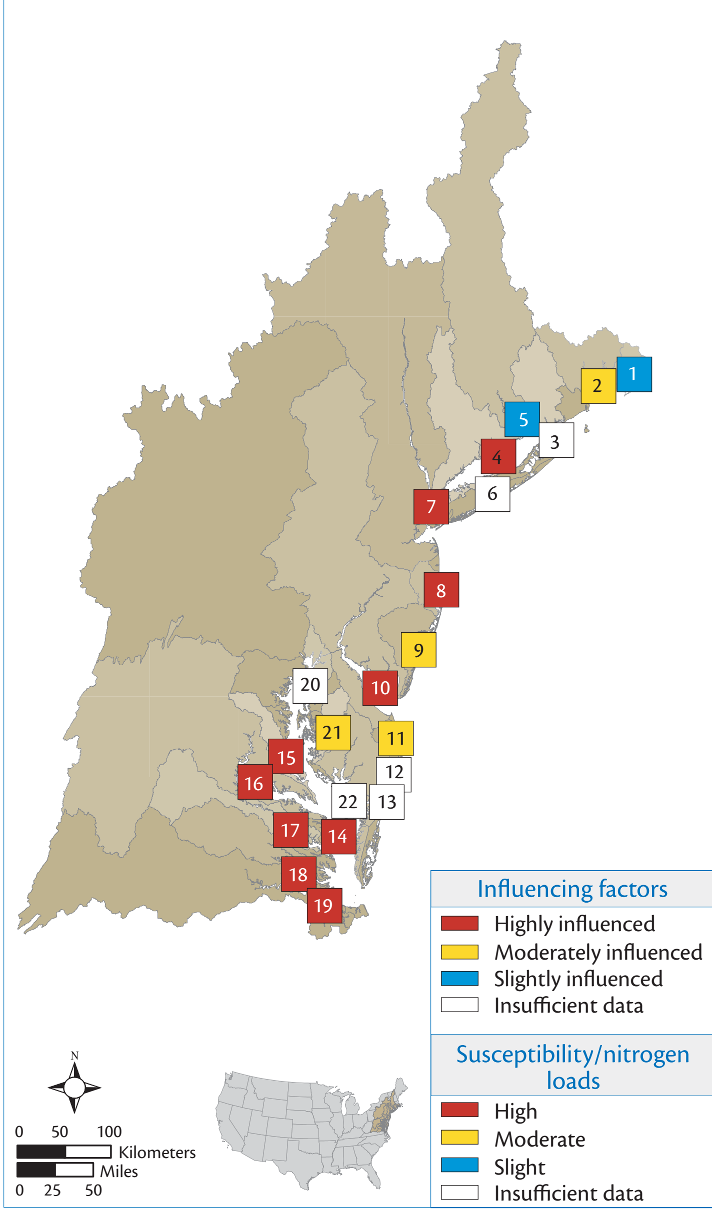
Influencing factors

- The majority of evaluated systems had moderate or high influencing factors.

Nitrogen loads (measured as the ratio of watershed to oceanic nitrogen inputs, see *Chapter 2: Approach*) in this region are mostly considered high, although for six systems, load estimates were unknown (Figure 4.6). All of the mid-Atlantic systems are characterized as moderately to highly susceptible to development of nutrient-related problems. The 14 that are highly susceptible include the coastal lagoons with low dilution and low flushing capabilities, as well as some estuaries that have lower freshwater inputs and smaller tidal ranges. Of the primary nutrient inputs identified for these systems, agricultural activities, wastewater treatment, and urban runoff were the most frequently noted sources. Other sources include onsite septic tanks, combined sewer overflow, and atmospheric deposition. There were no significant differences in the sources of nutrients between the drowned river valleys and coastal lagoons. The combination of higher susceptibility to nutrients and moderate to high nitrogen loads results in these systems having mostly moderate to high influencing factor scores (Figure 4.6)

Figure 4.6. Map of influencing factors ratings, ratings of components of influencing factors, and 1999 ratings in the mid-Atlantic region.

Influencing factors: 2004



Influencing factors: comparisons

Estuary	Influencing factors (2004)	Susceptibility (2004)	Nitrogen loads (2004)	Influencing factors (1999)
1. Buzzards Bay	Slight	Moderate	Slight	Slight
2. Narragansett Bay	Moderate	Moderate	Moderate	High
3. Gardiners Bay	Insufficient data	Moderate	Insufficient data	Slight
4. Long Island Sound	High	Moderate	High	Moderate
5. Connecticut River	Slight	Slight	High	Slight
6. Great South Bay	Insufficient data	High	Insufficient data	Moderate
7. Hudson River/Raritan Bay	High	Moderate	High	High
8. Barnegat Bay	High	High	High	High
9. New Jersey Inland Bays	Moderate	High	Moderate	High
10. Delaware Bay	High	Moderate	High	High
11. Delaware Inland Bays	Moderate	High	Slight	High
12. N. Maryland Coastal Bays (Isle of Wight/Assawoman)	Insufficient data	High	Insufficient data	Moderate
13. S. Maryland Coastal Bays (Chincoteague/Sinepuxent)	Insufficient data	High	Insufficient data	Moderate
14. Chesapeake Bay Mainstem	High	High	High	High
15. Patuxent River	High	High	High	High
16. Potomac River	High	High	High	High
17. Rappahannock River	High	High	High	High
18. York River	High	High	Moderate	High
19. James River	High	Moderate	High	High
20. Chester River	Insufficient data	High	Insufficient data	High
21. Choptank River	Moderate	High	Slight	High
22. Tangier/Pocomoke Sounds	Insufficient data	High	Insufficient data	High

Overall eutrophic condition

- This was the most impacted region; the majority of systems had a moderate high to high overall eutrophic condition rating.
- High chlorophyll *a* symptom expression was reported for the majority of systems.
- The majority of systems showing changes have worsened since the early 1990s.

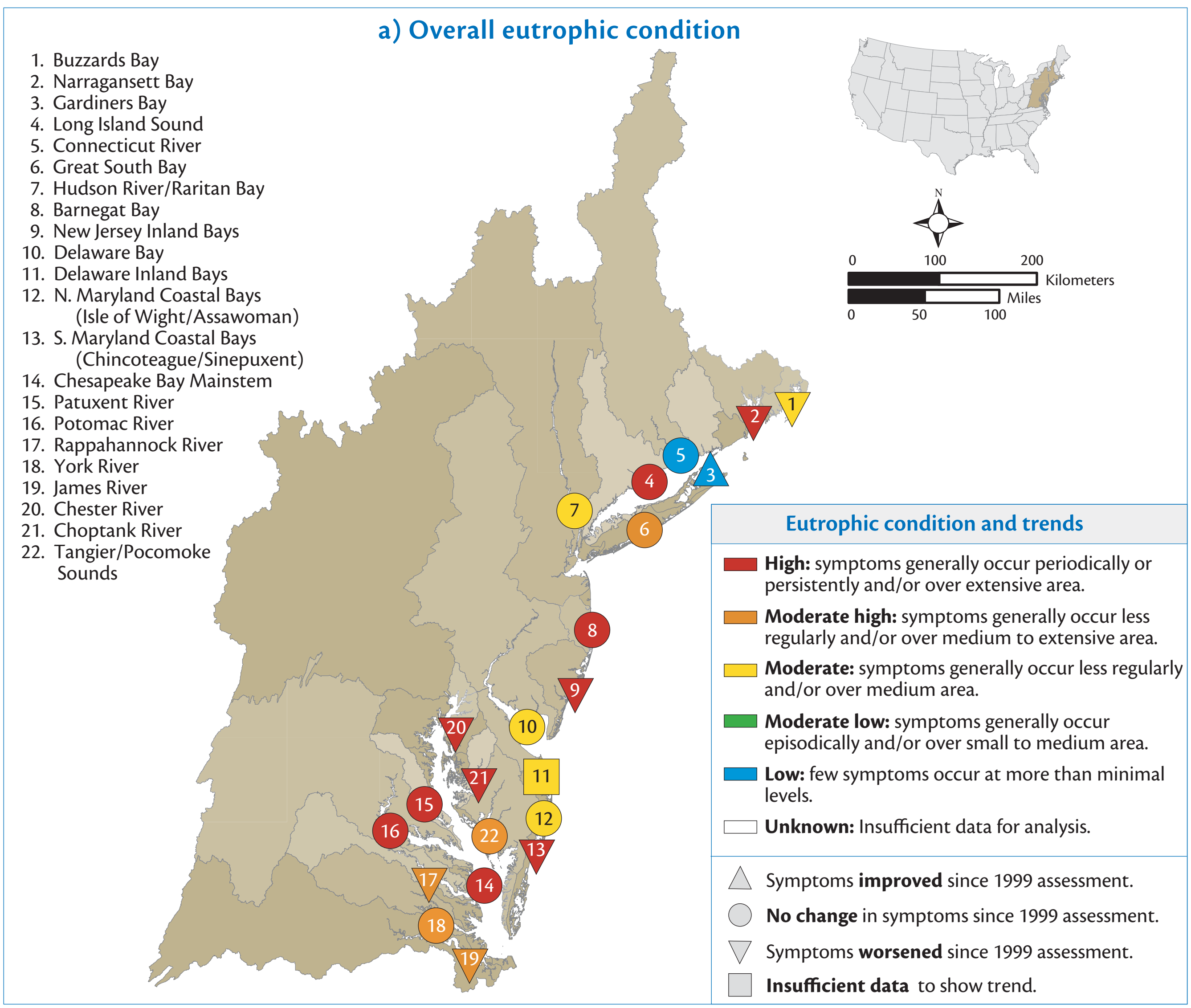
The mid-Atlantic region is the most impacted of all the NEEA regions, with the majority of assessed systems having moderate high to high overall eutrophic condition (Figure 4.7a-b). Only two of the assessed systems had a low overall eutrophic condition (Gardiners Bay and Connecticut River).

The mid-Atlantic has the most complete dataset of all the regions, with overall eutrophic conditions assessed for all systems. The fifteen systems with moderate high to high overall eutrophic conditions are distributed throughout the region and show various combinations of symptoms. All except Narragansett Bay had high levels of chlorophyll *a* and dissolved oxygen problems. Many also have problems with nuisance/toxic blooms. The coastal lagoons received more highly impacted scores as a group than the drowned river estuaries. The overall confidence in eutrophic condition assessment for the region was moderate, the highest of any of the regions.

Eutrophic symptom expressions

More than half of the systems in this region exhibited high levels of at least one of the five symptoms.

Figure 4.7. (a) Map of overall eutrophic condition (OEC) and (b) the combination of individual eutrophic symptoms which constitute OEC ratings in the mid-Atlantic region.



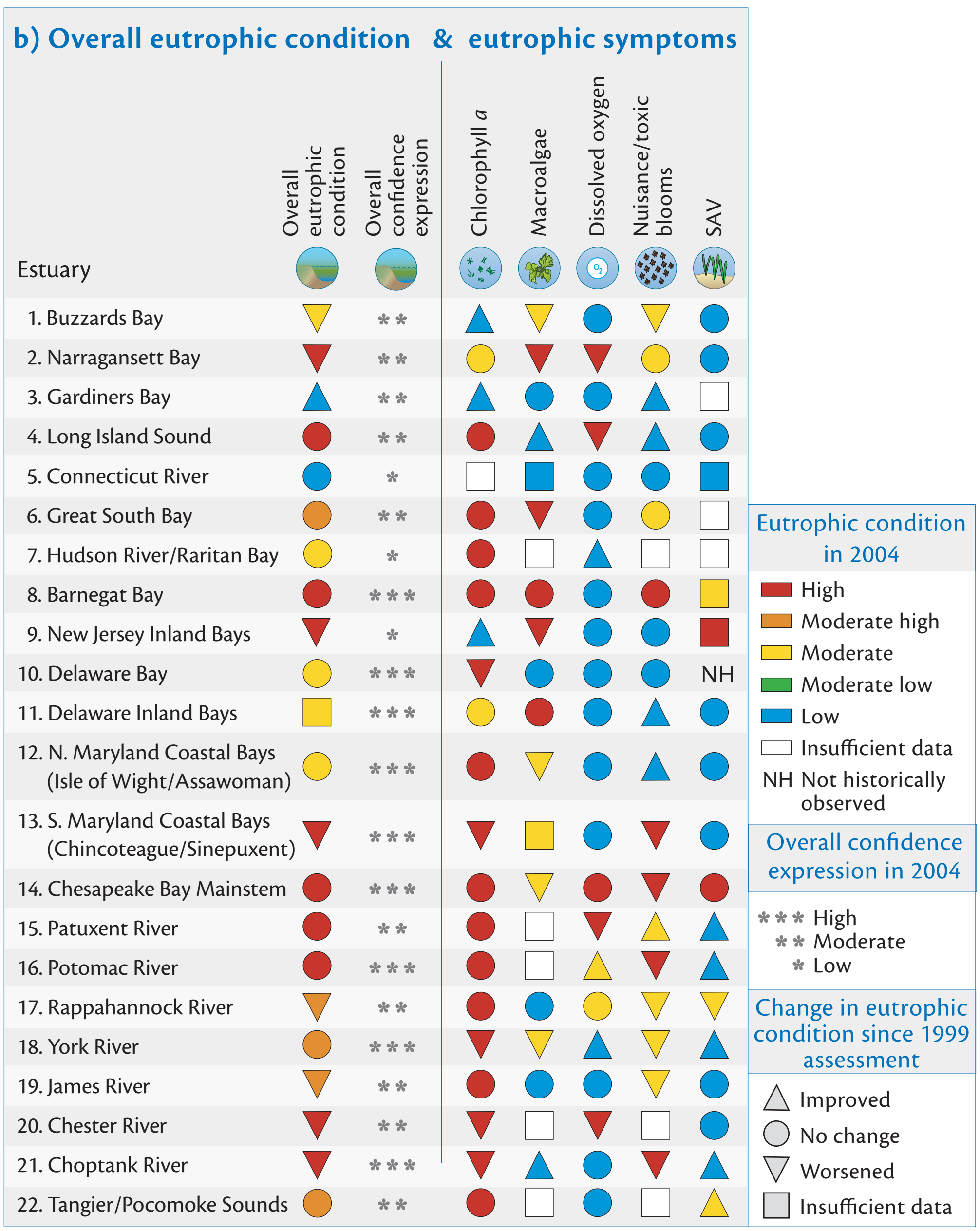
However, many systems had two symptoms with a high score. Of the primary symptoms, chlorophyll *a* levels were the most pronounced, with sixteen systems exhibiting high and only three systems exhibiting low expression (Figure 4.7b). Macroalgae conditions were moderate in five and high in five systems.

Nuisance/toxic blooms were the most significant of the secondary symptoms, with twelve systems exhibiting moderate to high levels of nuisance/toxic blooms. Dissolved oxygen problems occurred at moderate to high levels in seven systems. Five systems experienced moderate to high level losses of submerged aquatic vegetation since the early 1990s.

Changes in eutrophic condition since the 1990s

Overall eutrophic conditions have worsened in eight systems and improved in one since the early 1990s (Figure 4.7a-b). A greater number of systems exhibited worsening (with the exception of SAV) rather than improving eutrophic symptoms. Submerged aquatic vegetation improved in more systems than worsened.

Gardiners Bay demonstrated notable improvements since the 1990s in chlorophyll a and nuisance/toxic blooms. In Gardiners Bay, decreased nitrogen loads and chlorophyll *a* levels contributed to an improved overall eutrophic condition score. However, the absence of SAV data in 2004 for the system versus a high impact in 1999 could have biased the results in this case.



Future outlook

- The assessment revealed a north-south gradient; conditions were mostly expected to improve in the northern and worsen in the southern systems.
- Future outlook was more optimistic than in the early 1990s, though the majority of 1990s predictions have not yet been realized.

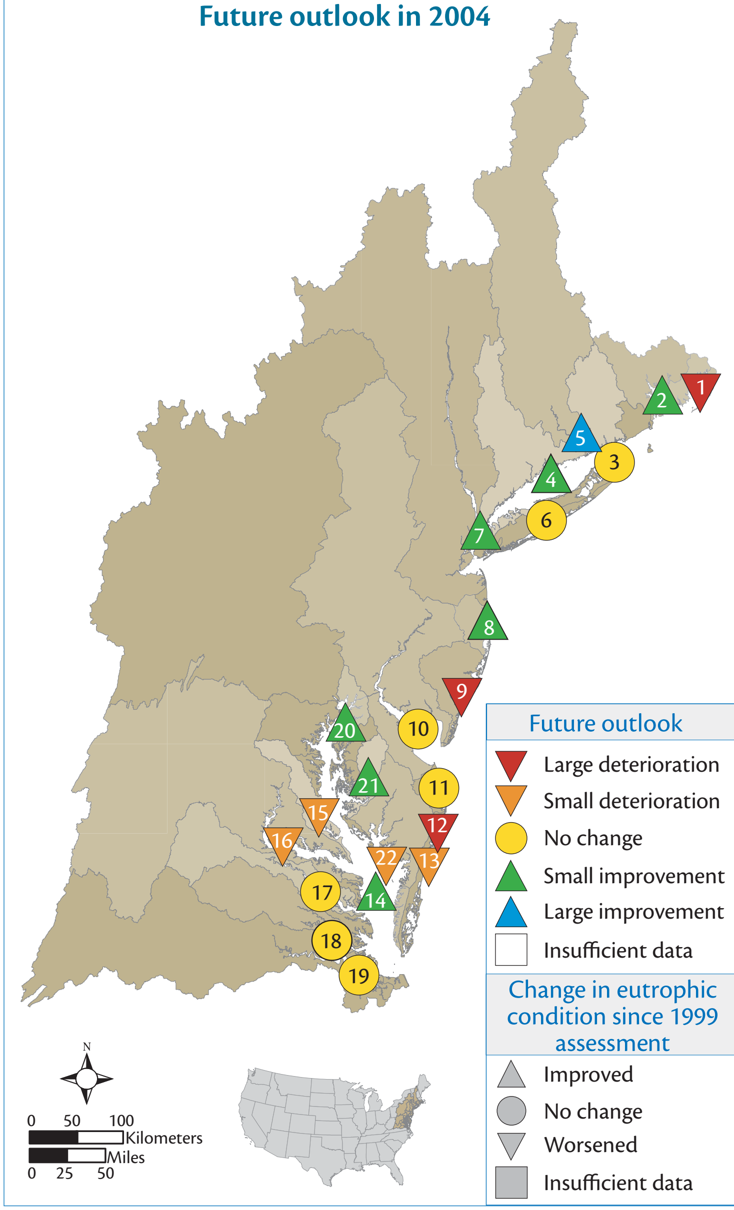
Eutrophic conditions are expected to worsen significantly in three systems and to a lesser degree in four others (Figure 4.8). These predictions are based on expected nutrient load increases from wastewater treatment, septic tanks, agriculture, and urban runoff. The coastal population in this region is expected to increase, resulting in nutrient load increases.

Of the eight systems expected to improve, only the Connecticut River is expected to do so significantly due to reductions in upstream nutrient sources. Combined sewer overflow improvements are expected to result in improvements to Barnegat Bay.

The 2004 future outlook is more optimistic than it was in the early 1990s, predicting that more systems will improve than worsen. For the systems where an evaluation was possible, the future outlook from the 1990s has been realized in ten systems but not for 12 others (Figure 4.8). It must be kept in mind that these expected changes were for the year 2020. While some areas demonstrate condition changes sooner than

Figure 4.8. Future outlook in 2004 and comparison with 1999 future outlook.

Future outlook in 2004



Future outlook comparisons

Estuary	Future outlook in 2004	Actual change in eutrophic condition (1999–2004)	Future outlook in 1999
1. Buzzards Bay	Large deterioration	Worsened	No change
2. Narragansett Bay	Small improvement	Worsened	No change
3. Gardiners Bay	No change	Improved	No change
4. Long Island Sound	Small improvement	No change	No change
5. Connecticut River	Large improvement	No change	No change
6. Great South Bay	No change	No change	No change
7. Hudson River/Raritan Bay	Small improvement	No change	No change
8. Barnegat Bay	Small improvement	No change	Small deterioration
9. New Jersey Inland Bays	Large deterioration	Worsened	Large deterioration
10. Delaware Bay	No change	No change	No change
11. Delaware Inland Bays	No change	Insufficient data	No change
12. N. Maryland Coastal Bays (Isle of Wight/Assawoman)	Large deterioration	No change	Small deterioration
13. S. Maryland Coastal Bays (Chincoteague/Sinepuxent)	Small deterioration	Worsened	Small deterioration
14. Chesapeake Bay Mainstem	Small improvement	No change	Small deterioration
15. Patuxent River	Small deterioration	No change	Small deterioration
16. Potomac River	Small deterioration	No change	Small deterioration
17. Rappahannock River	No change	Worsened	Small deterioration
18. York River	No change	No change	Large deterioration
19. James River	No change	Worsened	Small deterioration
20. Chester River	Small improvement	Worsened	Small deterioration
21. Choptank River	Small improvement	Worsened	Small deterioration
22. Tangier/Pocomoke Sounds	Small deterioration	No change	Large deterioration

Jeff Folino, Richard Stockton College of New Jersey

Improvements to sewage systems are expected to improve water quality in Barnegat Bay, New Jersey.

others, the accuracy of these particular predictions should be addressed in 2020, or predictions should be made for a shorter time scale.

Assessment of Estuarine Trophic Status (ASSETS)

An ASSETS rating, (combination of influencing factors, OEC, and future outlook), was made for 16 systems, with nine systems rated as bad (Narragansett Bay, Barnegat Bay, Patuxent River, Potomac River, Rappahannock River, Choptank River and Chesapeake Bay mainstem, Long Island Sound, New Jersey Inland Bays), two as poor (York and James Rivers), four as moderate (Buzzards Bay, Hudson River/Raritan Bay, Delaware Bay, Delaware Inland Bays) and one as high (Connecticut River).

Impaired uses

- More than half the systems in this region had impacts to living resources.
- Causes of impairments included agriculture (crops and animal operations), wastewater treatment, urban runoff, atmospheric deposition, onsite septic tanks, and combined sewer overflow.
- Thirteen systems were affected by human use impairments (primarily shellfishing, and recreational and commercial fishing).

More than half of the systems in this region (14) had impacts to living resources from eutrophication. Eight systems had considerable impacts (Narragansett Bay, Barnegat Bay, Patuxent River, Potomac River, Choptank River, Chesapeake Bay Mainstem, Hudson River/Raritan Bay, Tangier/Pocomoke Sounds) while six others had moderate impacts (Buzzards Bay, Long Island Sound, Great South Bay, Rappahannock River, York River, James River) and one had slight impacts (Connecticut River). There is a good correspondence in this region between moderate to high level eutrophic conditions and moderate to considerable impacts to living resources. Notable causes were wastewater treatment, agriculture (crops and animal operations), urban runoff, atmospheric deposition, onsite septic tanks, and combined sewer overflow. Forestry activities were a problem only in the York River watershed. Estuarine and lagoonal systems demonstrated similar impacts to living resources.

For the thirteen systems reporting use impairments, the most often reported impairments were to fishing (shellfish, recreational, and commercial). Impairments were also reported for aesthetics, fish consumption, and swimming. There is no difference in the use impairments between the estuarine and lagoonal systems.

Potential management concerns

The nutrient sources contributing to living resource and use impairments were wastewater treatment, agriculture, urban runoff, atmospheric deposition, onsite septic tanks, and combined sewer overflow. Future increases in nutrient load from these sources are expected as a result of an overall increase in coastal populations. It is important that these sources be given management attention, since these systems for the most part are already moderately to highly impacted and many are expected to worsen.

National Oceanic and Atmospheric Administration

Children exploring tide pools along the shores of Buzzards Bay, Massachusetts. Monitoring and managing eutrophic conditions will ensure continued enjoyment of the estuary.

Data gaps and research needs

Monitoring

Although the data in this region is the most robust nationally, it is still inadequate to document trends (particularly restoration) in many estuaries. Additional monitoring is needed so that trends can be better evaluated in the future. In particular, monitoring data for both chlorophyll *a* and macroalgae are needed, as well as a standardized assessment method for the latter. Improved estimates of nutrient sources and loads are also needed.

Research

Wet atmospheric deposition is currently characterized by the National Atmospheric Deposition Program (NADP) network. In general, better estimates of all atmospheric sources are needed, though dry deposition is in particular need of greater characterization. Additionally, a focus should be placed on determining the importance of the localized effects of animal feeding operations. Determining the nutrient inputs to and exports from coastal watersheds is also a research challenge. Nutrients are either stored within the watersheds (N or P in biomass, soils, or groundwater) or denitrified (N), and the importance of these pathways should be explored. And finally, the ability of living resources to tolerate eutrophic conditions should be examined.

Management

Measures should be implemented to guide development so that it does not grow as sprawl (vertical vs horizontal growth). In this way, waste streams can be concentrated for more efficient treatment and possible recycling to agricultural areas. Vertical growth must be accompanied by advanced treatment or recycling in order to prevent increased nutrient loading. Such management measures should be implemented and vigorously enforced at both the regional and national level, as many airsheds and watersheds exceed political boundaries. Examples of where this has been effective are the Clean Air Act, leading to reduced sulfate emissions, the ban of phosphorus in detergents, and the permitting of point sources.

USDA Natural Resources Conservation Service

Studying the impacts of animal feeding operations on nutrient loads and eutrophic conditions could help communities in the mid-Atlantic region design and implement management plans, and potentially reduce these loads.

SOUTH ATLANTIC REGION

- Diverse range of eutrophic conditions occurred in this region; the number of estuaries with high eutrophic condition was similar to the number of estuaries with low eutrophic condition.
- A large number of systems had moderate dissolved oxygen symptom expression.

The South Atlantic region includes 22 systems, encompassing more than 12,182 km² of water surface area. The region is comprised of extensive barrier and sea islands which parallel the shoreline (Figure 4.9). This coastal environment consists of shallow lagoonal estuaries, extensive tidal marshes, and drowned river valleys. Dendritic systems with extensive salt marshes are mostly found in the northern part of this region. Regionally, tidal ranges vary from 0.15 to 2.2 m. In the northern part of this region, tidal range is higher on average (1.3 m) than in the Florida systems (0.48 m), and influences mixing in the water column, primarily near the inlets. In the northern systems, depths are also greater, averaging 3.2 m compared to the Florida systems' 1.4 m. The overall regional depth range is 0.65–19.5 m. Climate is temperate to subtropical, with annual mean temperatures of 19°C, 36 frost days per year, and an average precipitation of 1.3 m per year. 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 (Figure 4.9a). Circulation along the Florida coast is dominated by wind forcing and human engineering (Figure 4.9b). Dominant land uses are agriculture and industry, and to a lesser extent, forestry. The average regional population density is six people per km² of catchment, with the density in the northern catchments much less on average (3 people km^{-2}) than in Florida catchments (43 people km^{-2}). Major population centers include Miami and Jacksonville, Florida and Savannah, Georgia.

National Oceanic and Atmospheric Administration

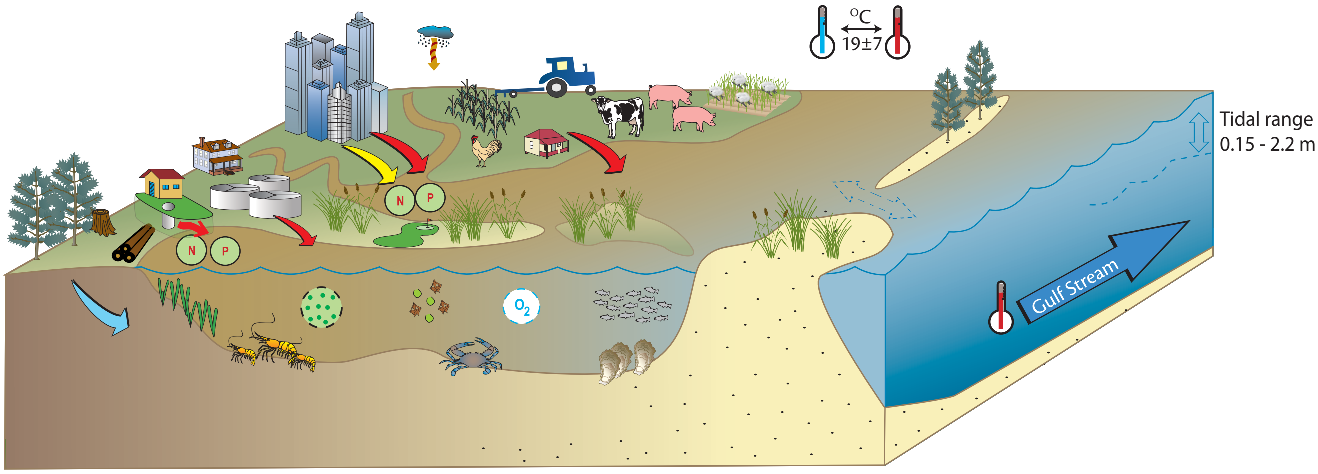
The extensive barrier islands in the South Atlantic region support wetlands such as the one pictured above near Charleston, South Carolina.

National Oceanic and Atmospheric Administration

The South Atlantic region has many mangrove forests such as this one in southern Florida.

Figure 4.9. Conceptual diagram of South Atlantic key features, major nutrient sources, and resulting symptoms.

a. Georgia to North Carolina



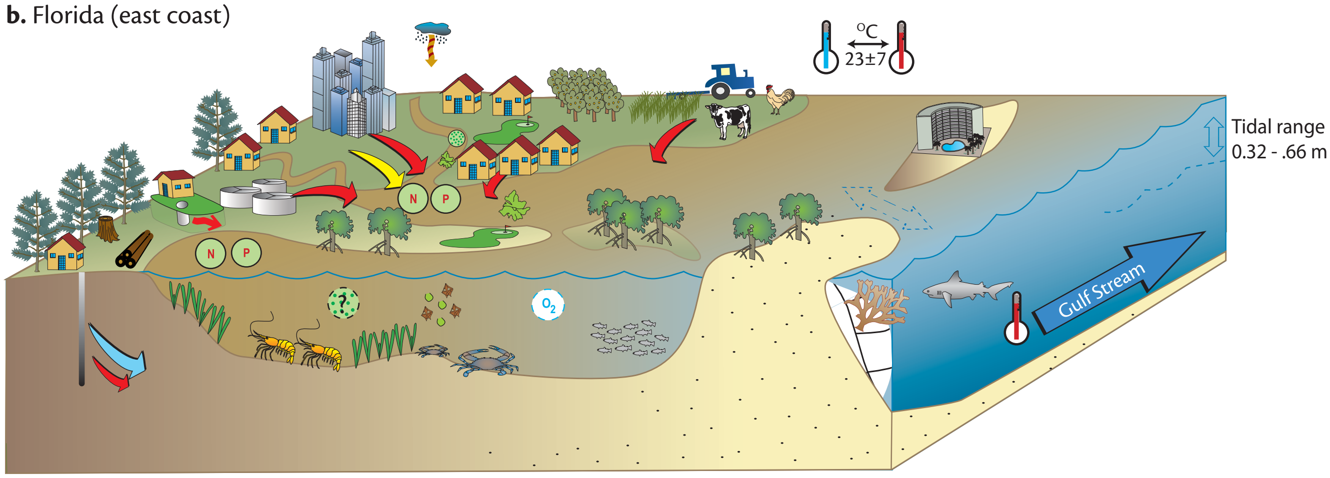
Key features
- Shallow lagoons, riverine networks
- Warm temperatures (Gulf Stream)
- Sandy/muddy bottoms
- Extensive marshes; seagrass
- Groundwater
- Stormwater
- Living resources: shellfish, fish
- Forestry operations/silviculture

Influencing factors
- Moderate to high susceptibility (low flushing)
- High nitrogen loads

Major nutrient sources
- Hog/cattle/poultry farms
- Agriculture (corn, tobacco, cotton, peanuts, etc.)
- Urban & suburban, Golf courses
- Septic/wastewater
- Atmospheric deposition

Eutrophic symptom expression
- Chlorophyll *a* (mostly moderate)
- Macroalgae (low)
- Dissolved oxygen (moderate to low)
- Submerged aquatic vegetation (insufficient data)
- Nuisance/toxic blooms (mostly low)

b. Florida (east coast)



Key features
- Shallow lagoons, riverine networks
- Warm temperatures (Gulf Stream)
- Sandy/muddy bottoms
- Mangroves
- Coral reefs
- Groundwater
- Stormwater
- Living resources: shellfish, fish
- Silviculture (loblolly pine)

Influencing factors
- Moderate to high susceptibility (low flushing)
- High nitrogen loads

Major nutrient sources
- Cattle/poultry farms
- Agriculture (citrus, sugar cane, cotton, etc.)
- Urban & suburban, Golf courses
- Septic/wastewater discharges/injection wells
- Atmospheric deposition

Eutrophic symptom expression
- Chlorophyll *a* (mostly unknown)
- Macroalgae (mostly low)
- Dissolved oxygen (moderate to low expression)
- Submerged aquatic vegetation (low-no change)
- Nuisance/toxic blooms (mostly low)

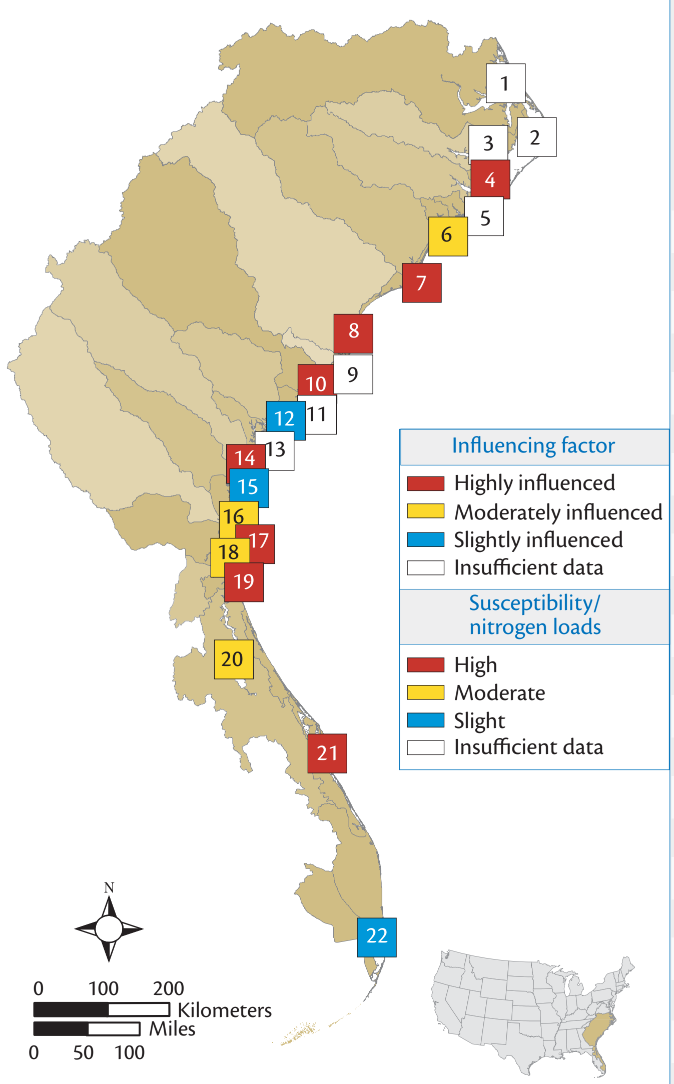
Influencing factors

> • Factors influencing eutrophication were spatially variable in the South Atlantic region.

Nitrogen loads in this region, represented as the ratio of land based to oceanic sources, were highly variable. Thirteen have high or moderate loading, only two systems have low nitrogen loads (Figure 4.10). The dominant sources of nutrients to the systems in this region are agricultural activities (animal operations and crops), wastewater treatment, atmospheric deposition, urban runoff, and exurban (i.e., beyond urban areas) development. The most notable nutrient source is animal operations, which is a local problem in North and South Carolina. Susceptibility of these systems is mostly moderate or high due to the restricted exchange through inlets and moderate to low dilution capability. Influencing factors are a reflection of the generally high loads and moderate to high susceptibility to develop problems.

Figure 4.10. Map of influencing factors ratings, ratings of components of influencing factors, and 1999 ratings in the South Atlantic region.

Influencing factors: 2004



Influencing factors: comparisons

Estuary	2004 Influencing factors	2004 Susceptibility	2004 Nitrogen loads	1999 Influencing factors
1. Albemarle Sound	Insufficient data	Moderate	Insufficient data	Moderately influenced
2. Pamlico Sound	Insufficient data	Moderate	Insufficient data	Moderately influenced
3. Pamlico/Pungo Rivers	Insufficient data	High	Insufficient data	Highly influenced
4. Neuse River	Highly influenced	High	High	Highly influenced
5. Bogue Sound	Insufficient data	High	Insufficient data	Slightly influenced
6. New River	Moderately influenced	High	Slight	Highly influenced
7. Cape Fear River	Highly influenced	Moderate	High	Moderately influenced
8. Winyah Bay	Highly influenced	Moderate	High	Moderately influenced
9. N. Santee/S. Santee Rivers	Insufficient data	Moderate	Insufficient data	Slightly influenced
10. Charleston Harbor	Highly influenced	Moderate	High	Moderately influenced
11. Stono/North Edisto Rivers	Insufficient data	High	Insufficient data	Moderately influenced
12. St. Helena Sound	Slightly influenced	Slight	High	Slightly influenced
13. Broad River	Insufficient data	Moderate	Insufficient data	Slightly influenced
14. Savannah River	Highly influenced	Moderate	High	Moderately influenced
15. Ossabaw Sound	Slightly influenced	Slight	High	Slightly influenced
16. St. Catherines/Sapelo Sounds	Moderately influenced	Moderate	Moderate	Slightly influenced
17. Altamaha River	Highly influenced	Moderate	High	Moderately influenced
18. St. Andrew/St. Simons Sounds	Moderately influenced	Moderate	Moderate	Slightly influenced
19. St. Marys River/Cumberland Sound	Highly influenced	High	High	Moderately influenced
20. St. Johns River	Moderately influenced	High	Slight	Moderately influenced
21. Indian River	Highly influenced	High	High	Moderately influenced
22. Biscayne Bay	Slightly influenced	Slight	High	Insufficient data

Overall eutrophic condition

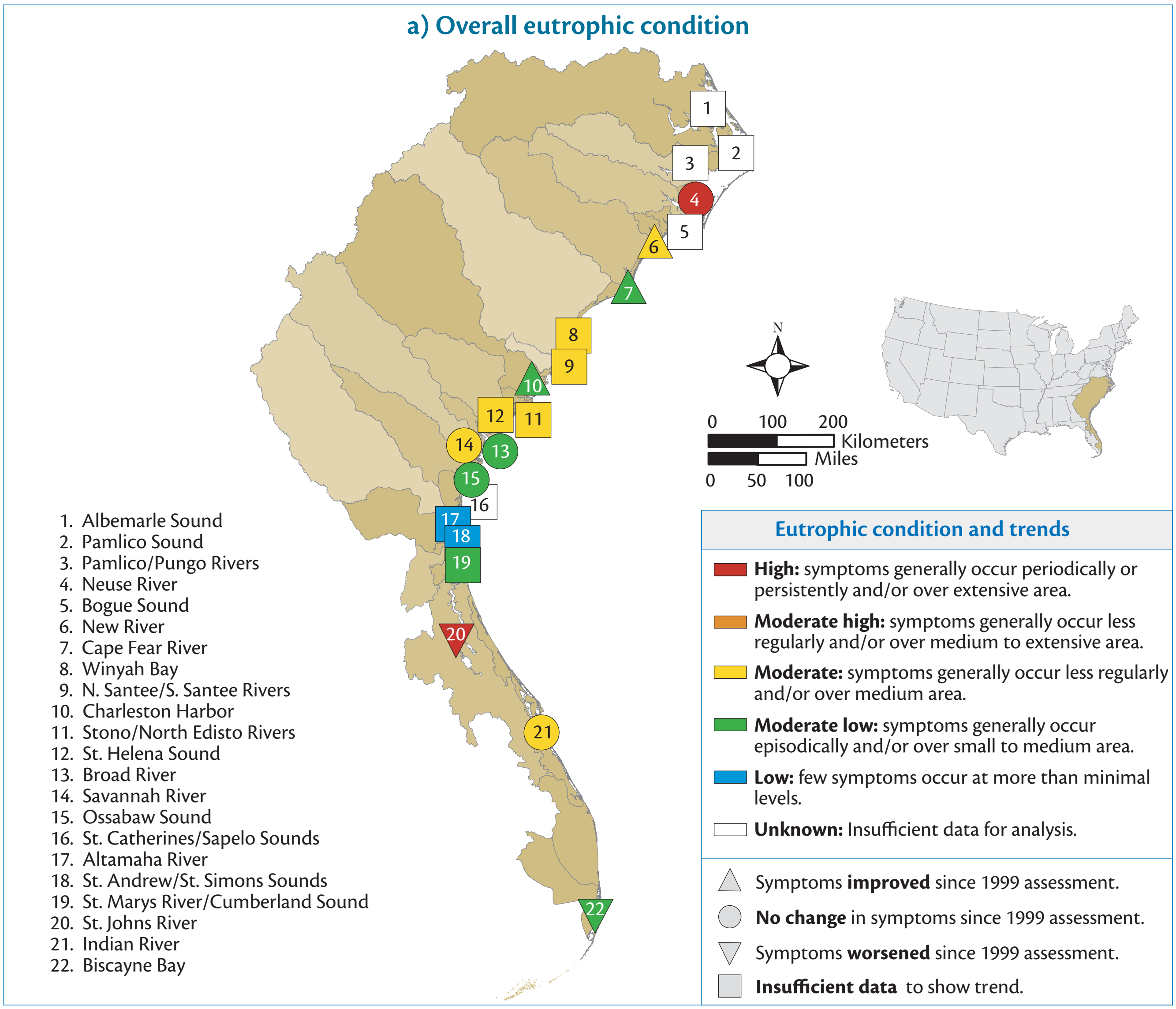
- Most systems in this region had moderate or low eutrophic condition
- The systems with a rating of high had problematic levels of chlorophyll *a* and nuisance/toxic blooms.

The overall eutrophic condition in this region is mostly moderate and low (15 systems, Figure 4.11), though two systems exhibit a high rating. Symptoms leading to the higher eutrophic conditions were predominantly chlorophyll *a* and nuisance/toxic blooms. The confidence in the overall condition assessment was mostly moderate and high for the systems assessed. However, since there were additional estuaries (5) within the region for which data were unavailable, a more extensive characterization is needed in order to properly observe regional trends.

Eutrophic symptom expressions

Like most other regions, high chlorophyll *a* was the most common sign of eutrophication exhibited within the estuaries. Of the 17 assessed estuaries, three had high chlorophyll *a* symptom expressions. While

Figure 4.11. (a) Map of overall eutrophic condition (OEC) and (b) the combination of individual eutrophic symptoms which constitute OEC ratings in the South Atlantic region.

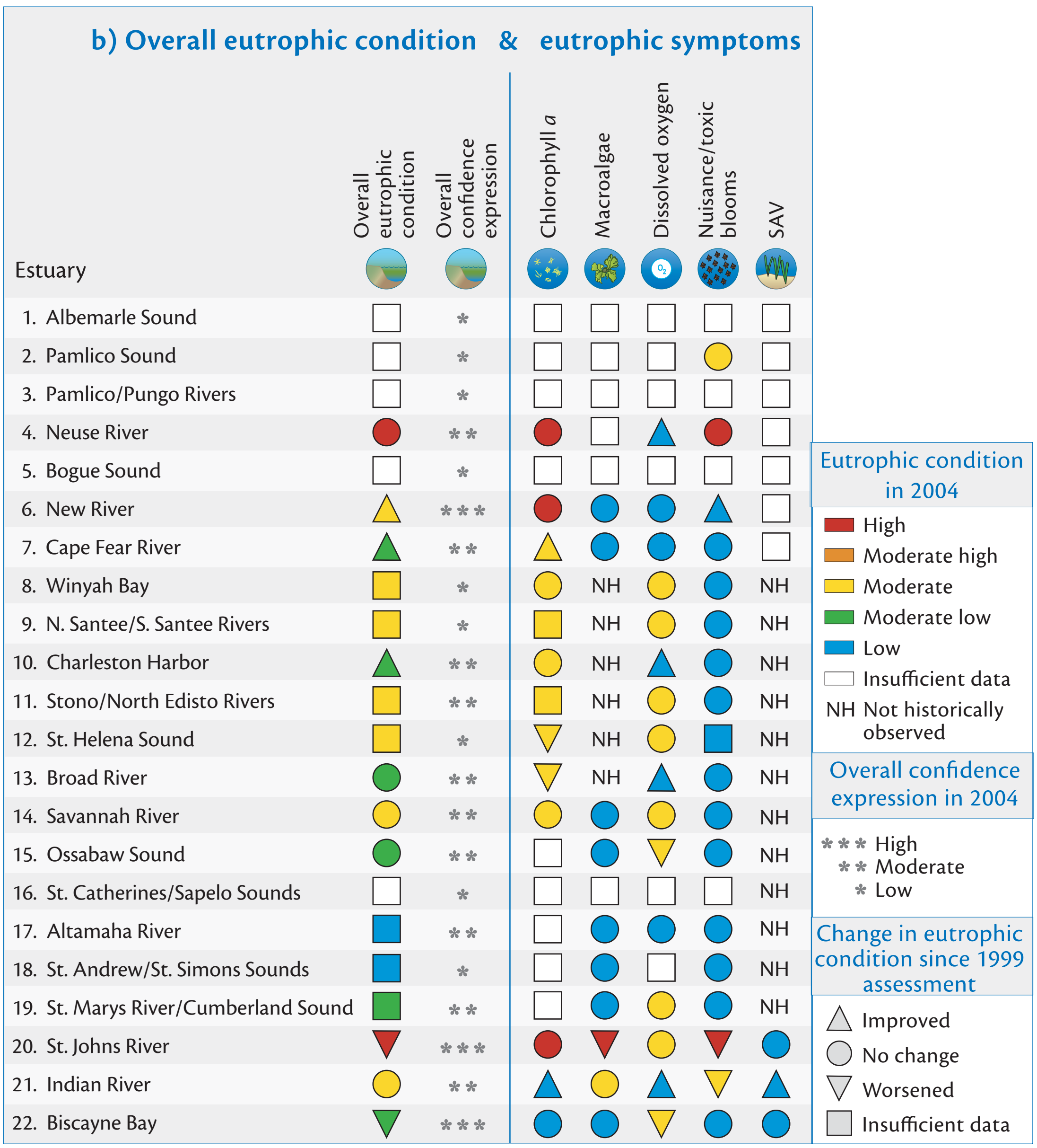


most other symptoms were generally low, dissolved oxygen was moderate in many estuaries.

Two systems in the region (the Neuse and St. Johns Rivers) had two or more high symptom expressions, indicating that they are more eutrophic than the other systems assessed. Symptoms with high ratings in these estuaries were macroalgae in the St. Johns River, chlorophyll *a*, and nuisance/toxic blooms for both the Neuse River and St. Johns River. Data for macroalgae and SAV loss were sparse. For many systems, these indicators have not historically been observed (Figure 4.11b). A different indicator should be developed and used in these systems.

Changes in eutrophic condition since the 1990s

Since the first assessment, conditions in three South Atlantic systems have improved, while conditions in two have worsened. A trend analysis was not possible for most systems because the indicators used in each time frame were incomparable (Figure 4.11). Although it is not explicitly reflected by this assessment, dissolved oxygen problems are known to have increased in some other South Atlantic systems. These estuaries are well-mixed, and therefore, the declining dissolved oxygen levels are of great concern (Verity et al. 2006).



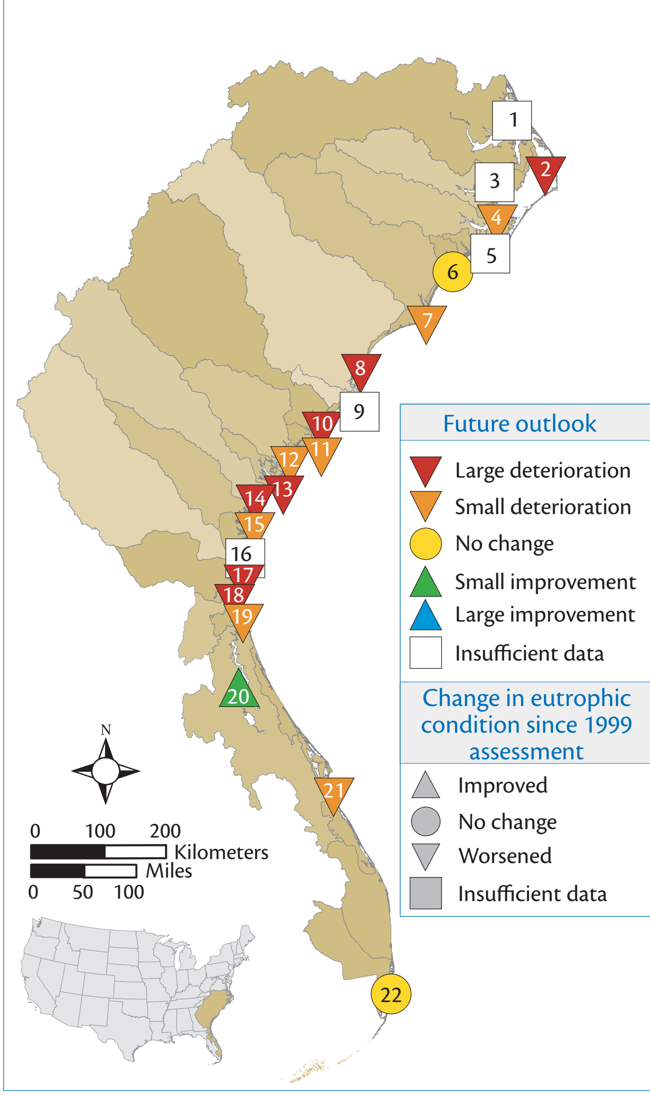
Future outlook

- Predictions were bleak; most evaluated systems were expected to worsen. Only St. Johns River was expected to improve.
- The future outlook has not changed since the early 1990s.
- Predictions have been fulfilled for four out of ten systems for which an evaluation could be made.

Based on the survey respondents, 14 estuaries throughout the region are predicted to develop worsening eutrophication conditions and seven are expected to worsen significantly (Figure 4.12) by 2020. Most of these systems presently exhibit low or moderate conditions. Worsening conditions are based on expectations of increased nutrient loads, mostly to a low or moderate degree. The Indian River is the exception, with a large increase (50-100% of present loads) in atmospheric and urban nitrogen load predicted as a result of expected population increases. Most nutrient load increases are expected to come from increases in wastewater treatment, atmospheric deposition, animal operations, exurban development (i.e., beyond the boundaries of urban regions), and onsite septic tanks (St. Helena Sound only). Increasing development and coastal population contributes greatly to the sources named above.

Only one system (St. Johns River) is expected to improve in the future as a result of a planned Total

Figure 4.12. Future outlook in 2004 and comparison with 1999 future outlook.



Future outlook comparisons

Estuary	Future outlook in 2004	Actual change in eutrophic condition (1999 - 2004)	Future outlook in 1999
1. Albemarle Sound	Insufficient data	Insufficient data	Small deterioration
2. Pamlico Sound	Large deterioration	Insufficient data	No change
3. Pamlico/Pungo Rivers	Insufficient data	Insufficient data	No change
4. Neuse River	Small deterioration	No change	No change
5. Bogue Sound	Insufficient data	Insufficient data	Small improvement
6. New River	No change	Improved	Small improvement
7. Cape Fear River	Small deterioration	Improved	No change
8. Winyah Bay	Large deterioration	Insufficient data	No change
9. N. Santee/S. Santee Rivers	Insufficient data	Insufficient data	No change
10. Charleston Harbor	Large deterioration	Improved	Large deterioration
11. Stono/North Edisto Rivers	Small deterioration	Insufficient data	No change
12. St. Helena Sound	Small deterioration	Insufficient data	Small improvement
13. Broad River	Large deterioration	No change	Large deterioration
14. Savannah River	Large deterioration	No change	Small deterioration
15. Ossabaw Sound	Small deterioration	No change	Small deterioration
16. St. Catherines/Sapelo Sounds	Insufficient data	Insufficient data	Large deterioration
17. Altamaha River	Large deterioration	Insufficient data	Small deterioration
18. St. Andrew/St. Simons Sounds	Large deterioration	Insufficient data	Large deterioration
19. St. Marys River/Cumberland Sound	Small deterioration	Insufficient data	Large deterioration
20. St. Johns River	Small improvement	Worsened	Large deterioration
21. Indian River	Small deterioration	No change	Large deterioration
22. Biscayne Bay	No change	Worsened	Large deterioration

National Oceanic and Atmospheric Administration

Wildlife such as this great blue heron in a North Carolina estuary are also affected by eutrophic impacts to fisheries.

Maximum Daily Load (TMDL). If implemented, the TMDL will reduce nutrient loads from National Pollution Discharge Elimination System facilities. However, increasing development and other exacerbating factors, such as water withdrawals and dredging, are increasing residence time in St. Johns, which may increase susceptibility and counterbalance improvements.

The future outlook at present is the same as in the early 1990s–worsening conditions expected in the majority of systems. For the ten systems where evaluation was possible, the future outlook from the 1990s has been realized for four systems but as yet does not agree with 2004 results for six systems (Figure 4.12). This result may stem from the fact that these expected changes are for the year 2020. While some areas demonstrate condition changes sooner than others, the accuracy of these particular predictions should be addressed in 2020, or predictions should be made for a shorter time scale.

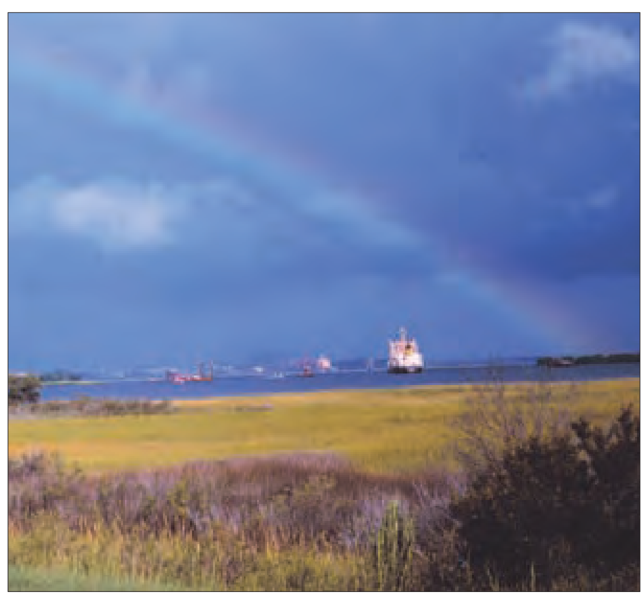
Assessment of Estuarine Trophic Status (ASSETS)

ASSETS ratings were made for 12 systems, with the Neuse River and St. Johns River rated as bad, Winyah Bay, Savannah River and Indian River rated as poor, six systems as moderate (St. Andrew/St. Simons Sound, Cape Fear River, St. Helena Sound, Charleston Harbor, New River, and Ossabaw Sound), and Biscayne Bay rated as good. There were two systems (Altamaha River and St. Marys River/Cumberland Sound) for which the ASSETS rating was not made even though all three components, influencing factors, overall eutrophic condition, and future outlook were available. The reason is that these systems have high influencing factors but the eutrophic conditions are low. This is a combination that is flagged for further investigation since it is unlikely that a system can have high inputs but low expression of conditions. This can occur when the susceptibility is low, but for these systems susceptibility is moderate. It is likely that this result is an artifact of incorrectly drawn boundaries of these systems. This would potentially cause incorrect assessment of conditions and susceptibility, since the system boundaries would potentially include different spatial area, flow, and circulation conditions. The boundaries of these systems will be re-evaluated prior to the next assessment. It is also possibly the result of the highly colored water of these systems, which limits algal growth despite high nitrogen input.

Impaired uses

- Two systems hadd considerable, and four moderate or slight impacts to living resources.
- Contributing to impairment were agriculture (crops and animal operations), atmospheric deposition, urban runoff, and wastewater treatment.
- Thirteen systems had human use impairments (primarily shellfish harvesting, and recreational and commercial fishing).
- Living resources were most impaired in systems expressing moderate to high OEC.

Impacts to living resources were reported for eight systems in this region, with two having considerable impairment (Neuse River and St. Johns River), four moderate or slight (New River, Cape Fear River,



National Oceanic and Atmospheric Administration

Commercial and recreational ships on Winyah Bay, SC.

Indian River, Biscayne Bay) and two (Ossabaw Sound, St. Marys River/Cumberland Sound) having no impacts. The level of impact was not reported for the remaining 14 systems. There is a correspondence between eutrophic condition and living resource impacts in both the Neuse and St. Johns Rivers, rated with a high OEC, as well as considerable impacts to living resources. Estuaries with moderate conditions also report impacts to living resources. The most often named causes of impacts to living resources are agriculture (animal operations and crops), urban runoff, wastewater treatment, and atmospheric deposition. Other reported causes are rangeland/pasture and dredging.

Eight systems had human use impairments, mostly to shellfish, fish consumption, swimming, and commercial and recreational fishing. Aesthetics were reported to be impaired for the Neuse River, while boating, tourism, and aesthetics were reported as impaired in St. Johns River.


Caroline Wicks, EcoCheck (NOAA/University of Maryland Center for Env. Science)

Juvenile barracuda in the shallow waters of Fort Zachary Taylor Historic State Park, Key West, Florida.

Potential management concerns

Important management concerns for systems with high and moderate eutrophic conditions are those nutrient sources listed as impacts to living resources (above section). Management measures should be implemented as quickly as possible. Though many of these systems currently exhibit low eutrophication-related impacts, their moderate to high susceptibility, coupled with expected increases in nutrient loading, may lead to worsening conditions more easily than in low susceptibility systems. Additionally, highly susceptible systems with high eutrophic impact will be more difficult to remediate. Thus managers should act now to prevent worsening conditions.

Data gaps and research needs

Monitoring

The need for data in this region is critical. Given the projected increases in population and the high susceptibility of many of the systems, time series data


National Oceanic and Atmospheric Administration

Shrimp boats on the Altamaha River, Georgia.

Caroline Wicks, EcoCheck (NOAA/University of Maryland Center for Environmental Science)

Sunset Key, Florida; Future management plans will have to balance the needs of the ecosystem with recreational activities.

are particularly needed for tracking trends. Presently there are few recent data, and the North Carolina Division of Environment and Natural Resources has cut back on spatial coverage of water quality stations, particularly along barrier islands and large lagoonal systems. Regular monitoring should be a priority in this region, especially in Albemarle, Currituck, and Bogue Sounds, and the Pamlico and Savannah Rivers, which have no regular monitoring.

Research

Load estimates for almost one third of these systems are unknown. A focus for research should be to provide total loads and organic/inorganic nutrient loads as well as identifying the primary sources so that management measures can be applied successfully. Research is needed to determine the importance of local effects from animal feeding operations (e.g., ammonia (NH_3) emissions from pig farms on the North Carolina coast) and runoff from land application of waste. With regard to the indicators used in the assessment, some systems in this region do not have native SAV and macroalgae due partially to the presence of colored water (i.e., blackwater). Therefore, their presence/absence may not be an issue of eutrophication. Indicators will be reevaluated for particular types of systems prior to the next assessment in order to improve accuracy (see *Chapter 6: Improvements*). Additionally, low dissolved oxygen in some systems may be the result of microbial processes rather than decomposition of algae, as shown by Verity et al. (2006). This should be investigated further.

Management

Important management concerns for systems in this region are all related to increased population in the coastal zone and concomitant development. The most notable management concerns are urban runoff, wastewater treatment, and atmospheric deposition for the region. For North and South Carolina, the priority for management should be animal operations.

GULF OF MEXICO REGION

- Due to high nutrient loads and high susceptibility, most estuaries assessed had a high influencing factors rating.
- Only a small proportion of estuaries recorded high or moderate high overall eutrophic condition.
- Systems with moderate or moderate high eutrophic condition were characterized by high, and often worsening, chlorophyll *a* symptoms.

The Gulf of Mexico region includes 37 estuaries and the Mississippi River Plume, encompassing more than 30,577 km^2 of water surface area. The region is comprised of a gently sloping, lowland part of the Gulf Coastal Plain (Figure 4.13). Estuarine and coastal environments are highly diverse, consisting of unrestricted open bays, semi-enclosed lagoons, tidal marshes, and delta complexes. The freshwater naturally flowing into the estuaries may fluctuate greatly in the Gulf region, and depends upon seasonal rainfall patterns. Average annual precipitation is 0.98 m in the western Gulf region and 1.46 m in the eastern Gulf region, with a regional average of 1.33 m per year. Estuarine circulation patterns are generally wind driven and coastal waters are usually warmer than in other regions due to the subtropical climate, with an average annual temperature of 22°C and 12 frost days per year. Estuaries have fairly low tidal energy (0.03–0.81 m tide range, 0.40 m avg.), and water depths are typically shallow when compared to estuaries in other regions (0.05–7.01 m depth range, 1.85 m average). Land use activity in these watersheds is typically dominated by agriculture. Major population centers include Houston, New Orleans, and Tampa. Average regional population density is 26 people per km^2.

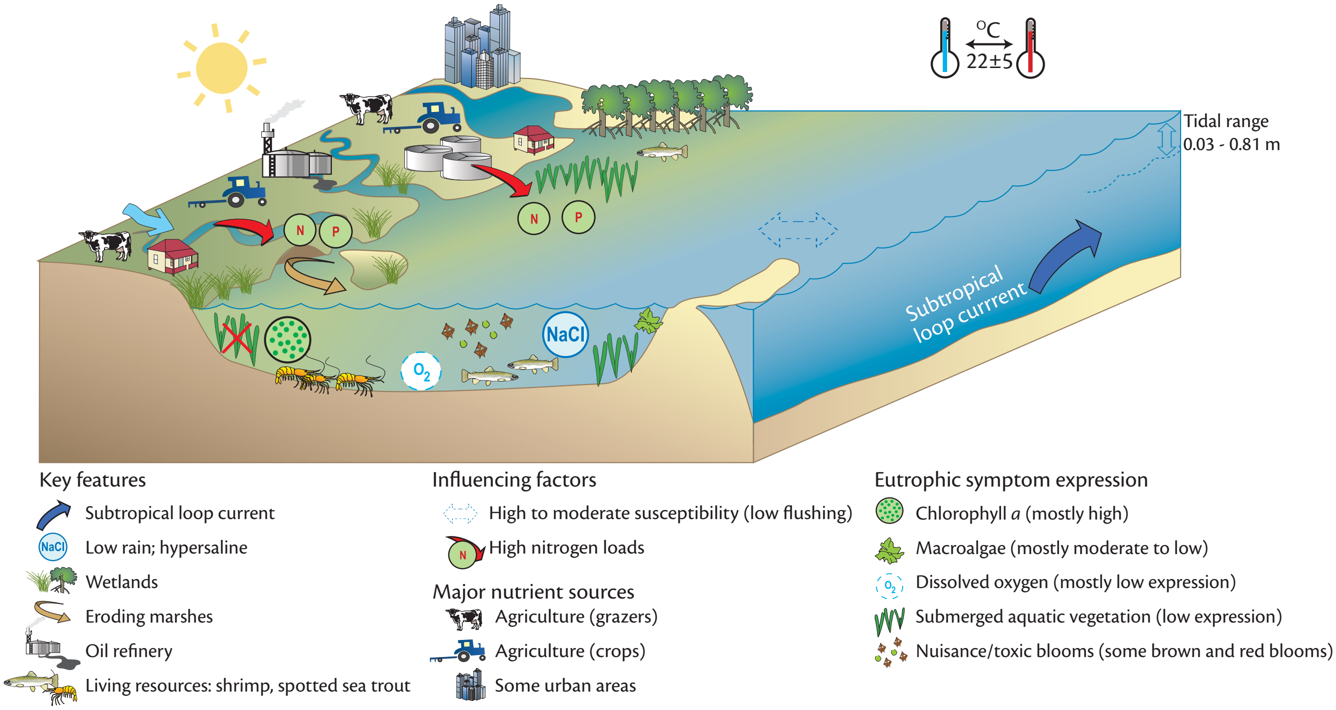
USDA National Resource Conservation Service

The Gulf of Mexico region contains several cypress wetlands such as these along the Mississippi River.

Tom Wazniak, University of Maryland Center for Environmental Science

Wetlands such as these in coastal Lousiana are common in the Gulf region.

Figure 4.13. Conceptual diagram of Gulf of Mexico key features, major nutrient sources, and resulting symptoms.



Tim Carruthers, University of Maryland Center for Environmental Science

Oil extraction rig among eroding wetlands looking towards the Gulf of Mexico, southeast of Houma in coastal Louisiana.

Influencing factors

- Most systems for which an evaluation could be made had high influencing factors.

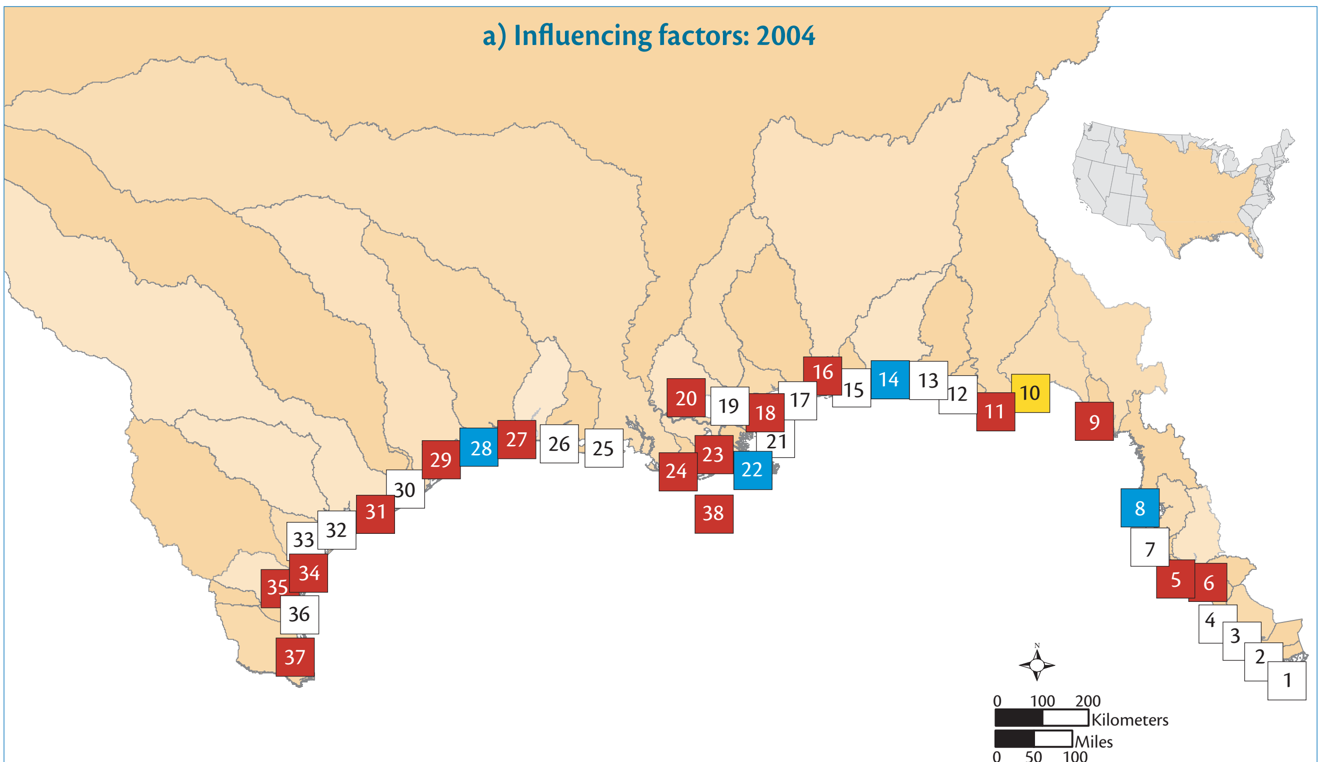
Watershed nitrogen inputs were high in over 80% of the systems assessed. However, nitrogen loading data are fairly limited in the Gulf regions with no information available for approximately half of the systems (Figure 4.14). Nitrogen loading data were considered low for only two of the 38 systems, Tampa and Pensacola Bays. Understandably, the Mississippi River has the largest nutrient load of all U.S. rivers. Nutrient load estimates for the Mississippi were used to calculate influencing factor ratings for both the Mississippi River and Mississippi/Atchafalaya Plume.

In general, the Gulf region has a high human influence because of the high level of agricultural activities. Dominant sources of nutrients to systems in this region are wastewater treatment, urban runoff, and agriculture (crops).

Most estuaries in this region have shallow depths and small tidal ranges, leading to low dilution and flushing rates. As a consequence, most estuaries have either a moderate or high susceptibility to nutrient loading (Figure 4.14).

The combined effects of high nitrogen loads and a moderate or high susceptibility to nutrients results in most systems having a high influencing factors rating (except for Tampa and Pensacola Bays).

Figure 4.14. (a) Map of influencing factors ratings and (b) ratings of components of influencing factors and 1999 ratings in the Gulf of Mexico region.



1. Florida Bay
2. S. Ten Thousand Islands
3. N. Ten Thousand Islands
4. Rookery Bay
5. Charlotte Harbor
6. Caloosahatchee River
7. Sarasota Bay
8. Tampa Bay
9. Suwannee River
10. Apalachee Bay
11. Apalachicola Bay
12. St. Andrew Bay
13. Choctawhatchee Bay
14. Pensacola Bay
15. Perdido Bay
16. Mobile Bay
17. East Mississippi Sound
18. West Mississippi Sound
19. Lake Borgne
20. Lake Pontchartrain
21. Breton/Chandeleur Sounds
22. Mississippi River
23. Barataria Bay
24. Terrebonne/Timbalier Bays
25. Atchafalaya/Vermilion Bays
26. Mermentau Estuary
27. Calcasieu Lake
28. Sabine Lake
29. Galveston Bay
30. Brazos River
31. Matagorda Bay
32. San Antonio Bay
33. Aransas Bay
34. Corpus Christi Bay
35. Upper Laguna Madre
36. Baffin Bay
37. Lower Laguna Madre
38. Mississippi/Atchafalaya Plume

Influencing factors

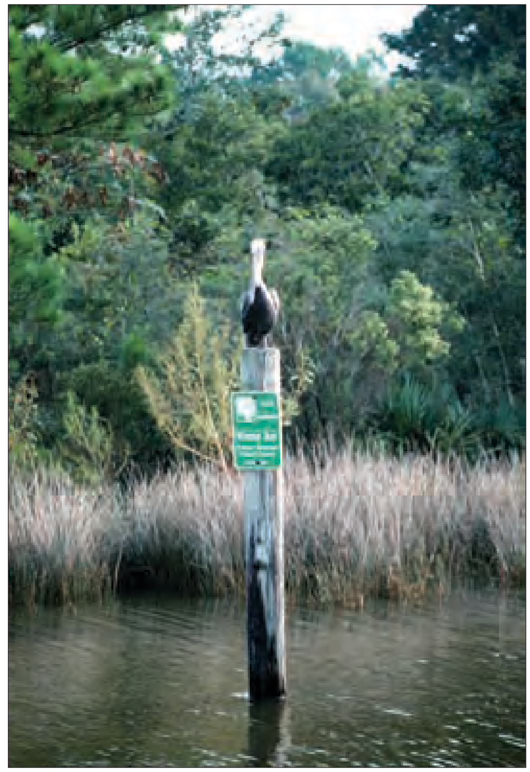
- Highly influenced
- Moderately influenced
- Slightly influenced
- Insufficient data

b) Influencing factors: comparisons

Estuary	2004 Influencing factors	2004 Susceptibility	2004 Nitrogen loads	1999 Influencing factors
1. Florida Bay	Insufficient data	Moderate	Insufficient data	High
2. S. Ten Thousand Islands	Insufficient data	High	Insufficient data	High
3. N. Ten Thousand Islands	Insufficient data	High	Insufficient data	Moderate
4. Rookery Bay	Insufficient data	High	Insufficient data	Slight
5. Charlotte Harbor	High	High	High	High
6. Caloosahatchee River	High	Moderate	High	High
7. Sarasota Bay	Insufficient data	Moderate	Insufficient data	High
8. Tampa Bay	Slight	Moderate	Slight	High
9. Suwannee River	High	Moderate	High	Slight
10. Apalachee Bay	Moderate	Moderate	Moderate	Slight
11. Apalachicola Bay	High	Moderate	High	High
12. St. Andrew Bay	Insufficient data	Moderate	Insufficient data	Moderate
13. Choctawhatchee Bay	Insufficient data	Moderate	Insufficient data	High
14. Pensacola Bay	Slight	Moderate	Slight	High
15. Perdido Bay	Insufficient data	High	Insufficient data	High
16. Mobile Bay	High	Moderate	High	Moderate
17. East Mississippi Sound	Insufficient data	Moderate	Insufficient data	Moderate
18. West Mississippi Sound	High	Moderate	High	Moderate
19. Lake Borgne	Insufficient data	Moderate	Insufficient data	Moderate
20. Lake Pontchartrain	High	Moderate	High	High
21. Breton/Chandeleur Sounds	Insufficient data	Moderate	Insufficient data	Slight
22. Mississippi River	Slight	Slight	High	Moderate
23. Barataria Bay	High	Moderate	High	Moderate
24. Terrebonne/Timbalier Bays	High	High	Moderate	Moderate
25. Atchafalaya/Vermilion Bays	Insufficient data	Slight	Insufficient data	Moderate
26. Mermentau Estuary	Insufficient data	Moderate	Insufficient data	Slight
27. Calcasieu Lake	High	Moderate	High	High
28. Sabine Lake	Slight	Slight	High	Slight
29. Galveston Bay	High	Moderate	High	High
30. Brazos River	Insufficient data	Moderate	Insufficient data	Moderate
31. Matagorda Bay	High	High	High	High
32. San Antonio Bay	Insufficient data	Moderate	Insufficient data	High
33. Aransas Bay	Insufficient data	High	Insufficient data	Moderate
34. Corpus Christi Bay	High	High	High	High
35. Upper Laguna Madre	High	High	High	High
36. Baffin Bay	Insufficient data	High	Insufficient data	High
37. Lower Laguna Madre	High	High	High	High
38. Mississippi/Atchafalaya Plume	High	Moderate	High	High

Influencing factors
- Highly influenced
- Moderately influenced
- Slightly influenced
- Insufficient data

Susceptibility/nitrogen loads
- High
- Moderate
- Slight
- Insufficient data



National Oceanic and Atmospheric Administration

A Brown Pelican in Weeks Bay National Estuarine Research Reserve, Alabama.

Overall eutrophic condition

- This region had relatively few estuaries with a high overall eutrophic condition (OEC).
- There was a greater proportion of systems with a low to moderate overall eutrophic condition in this region compared to other regions.

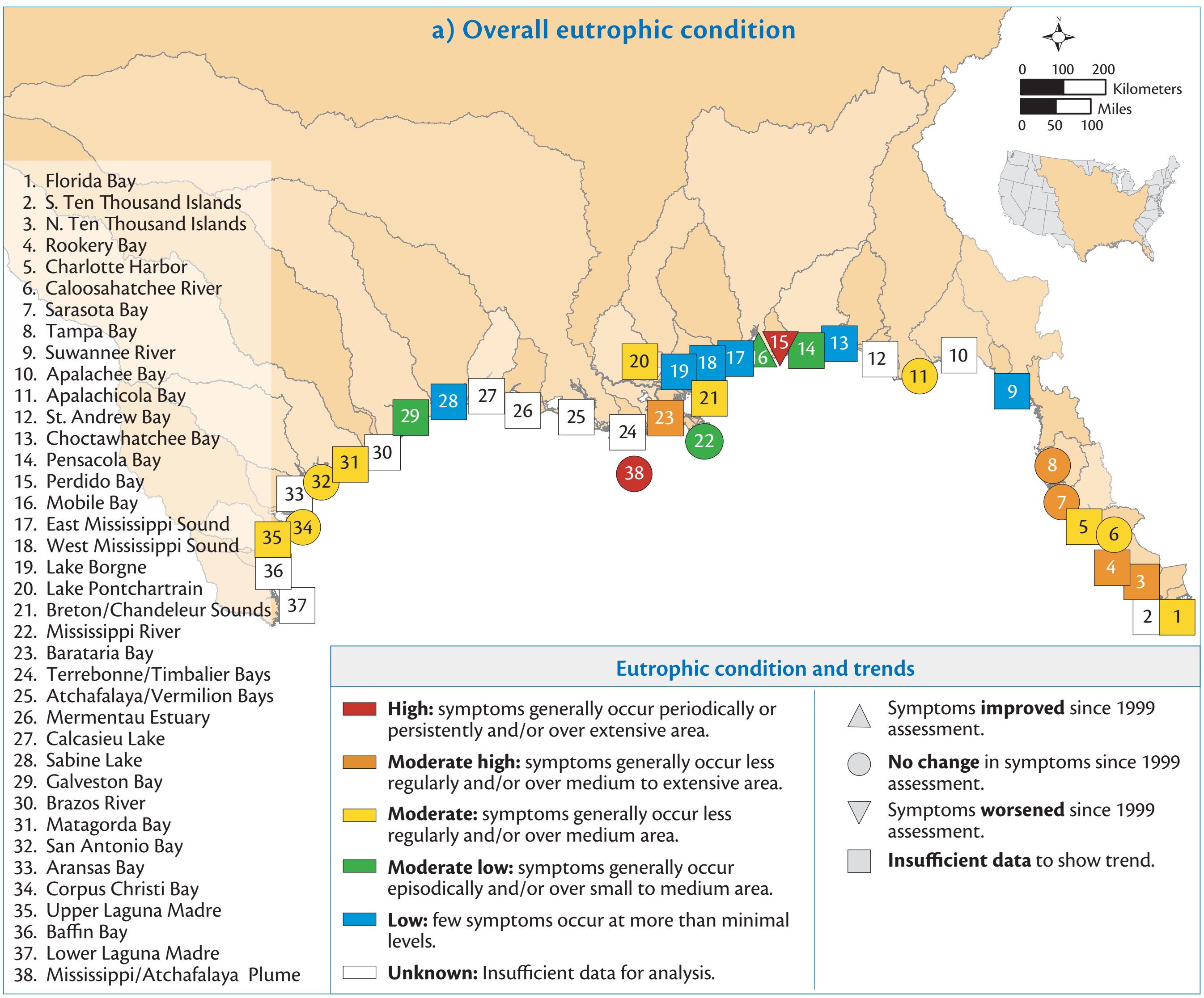
Most estuaries (20) in this region were characterized by moderate to low OEC, with relatively few estuaries receiving a high rating (Figure 4.15). Estuaries on the Florida peninsula tended to have moderate high OEC whereas estuaries assessed in Texas tended to have moderate conditions. In Mississippi and Alabama, a large proportion of estuaries had moderate low or low OEC (Figure 4.15).

Confidence in eutrophic condition ratings were mostly moderate and low. This is because many systems have data for only two symptoms and when data were available, there was a high degree of uncertainty. Furthermore, the overall confidence for the region was low due to the large number of systems that were not evaluated. The need for more data prevented definitive or complete characterization of this region.

Eutrophic symptom expressions

For systems where data were available, most symptoms show low and moderate level expressions, with the exception of chlorophyll *a*, for which 17 systems had high level conditions and five had moderate level conditions. The other primary symptom, macroalgae, was observed at high levels in

Figure 4.15. a) Map of overall eutrophic condition (OEC) and (b) the combination of individual eutrophic symptoms which constitute OEC ratings in the Gulf of Mexico region.



b) Overall eutrophic condition & eutrophic symptoms

Estuary	Overall eutrophic condition	Overall confidence expression	Chlorophyll *a*	Macroalgae	Dissolved oxygen	Nuisance/ toxic blooms	SAV
1. Florida Bay	Moderate ■	*	High ▼	□	Low ▲	□	□
2. S. Ten Thousand Islands	□	*	□	□	□	□	□
3. N. Ten Thousand Islands	Moderate high ■	*	High ▼	□	Moderate ●	□	□
4. Rookery Bay	Moderate high ■	*	High ▼	□	Moderate ▼	□	□
5. Charlotte Harbor	Moderate ■	* *	High ●	High ▼	Low ●	Low ●	Low ●
6. Caloosahatchee River	Moderate ●	* *	High ●	Moderate ▼	Low ●	Low ●	Low ●
7. Sarasota Bay	Moderate high ●	* *	High ▼	High ▼	Low ▲	Moderate ▲	Low ●
8. Tampa Bay	Moderate high ●	* *	High ●	Moderate ▼	Moderate ▼	Moderate ●	Low ●
9. Suwannee River	Low ■ [a]	* *	Low ▲	Low ▲	Low ●	Low ●	Low ●
10. Apalachee Bay	□	*	□	□	□	□	□
11. Apalachicola Bay	Moderate ●	* *	Moderate ●	Low ●	Low ▲	Moderate ●	Low ●
12. St. Andrew Bay	□	*	□	□	□	□	□
13. Choctawhatchee Bay	Low ■	*	Low ▲	□	Low ▲	□	□
14. Pensacola Bay	Moderate low ■	*	Moderate ●	□	Low ▲	□	□
15. Perdido Bay	High ▼	* *	Low ▲	Moderate ▲	High ▼	Low ●	Low ●
16. Mobile Bay	Moderate low ▲	*	Moderate ●	Low ●	Low ▲	Low ▲	□
17. East Mississippi Sound	Low ■	*	Low ▲	□	Low ▲	□	□
18. West Mississippi Sound	Low ■	*	Low ▲	□	Low ●	□	□
19. Lake Borgne	Low ■	*	Low ■	□	Low ●	□	□
20. Lake Pontchartrain	Moderate ■	*	High ●	Moderate ▲	Low ●	Low ▲	□
21. Breton/Chandeleur Sounds	Moderate ■	*	High ■	□	□	Low ●	□
22. Mississippi River	Moderate low ●	*	Moderate ●	□	Low ●	□	□
23. Barataria Bay	Moderate high ■	*	High ●	□	□	Moderate ▼	□
24. Terrebonne/Timbalier Bays	□	*	□	□	Low ●	□	□
25. Atchafalaya/Vermilion Bays	□	*	□	□	Low ●	□	□
26. Mermentau Estuary	□	*	□	□	□	□	□
27. Calcasieu Lake	□	*	□	□	Low ▲	□	□
28. Sabine Lake	Low ■	* *	Low ▲	Low ●	Low ●	Low ●	Low ●
29. Galveston Bay	Moderate low ■	* *	High ▼	Low ●	Low ●	Low ●	Low ▲
30. Brazos River	□	*	High ▼	□	□	□	□
31. Matagorda Bay	Moderate ■	*	High ▼	Low ●	Low ●	Low ●	Low ●
32. San Antonio Bay	Moderate ●	*	High ▼	□	Low ●	□	□
33. Aransas Bay	□	*	High ▼	□	□	□	□
34. Corpus Christi Bay	Moderate ●	*	High ●	High ●	□	Low ▲	□
35. Upper Laguna Madre	Moderate ■	*	Moderate ▲	□	□	Moderate ▲	□
36. Baffin Bay	□	*	□	□	□	□	□
37. Lower Laguna Madre	□	*	Low ▲	□	□	□	□
38. Mississippi/Atchafalaya Plume	High ●	*	High ●	Low ●	High ●	□	Low ●

[a] For Suwannee River, variability in rainfall precludes determination of change.

Eutrophic condition in 2004
- High
- Moderate high
- Moderate
- Moderate low
- Low
- Insufficient data

Overall confidence expression in 2004
- * * * High
- * * Moderate
- * Low

Change in eutrophic condition since 1999 assessment
- ▲ Improved
- ● No change
- ▼ Worsened
- ■ Insufficient data

only three systems and moderate in four. However, there was a paucity of data for this indicator, with 24 systems having unknown levels. The systems with high chlorophyll *a* expression were mostly located in Florida and Texas. Of the secondary symptoms, significant dissolved oxygen problems were reported in only two systems (Perdido Bay and the Mississippi Plume). All 11 assessed systems had a low level loss of submerged aquatic vegetation. Five estuaries had moderate nuisance/toxic bloom expressions and 11 were rated as low (Figure 4.15).

Changes in eutrophic condition since the 1990s

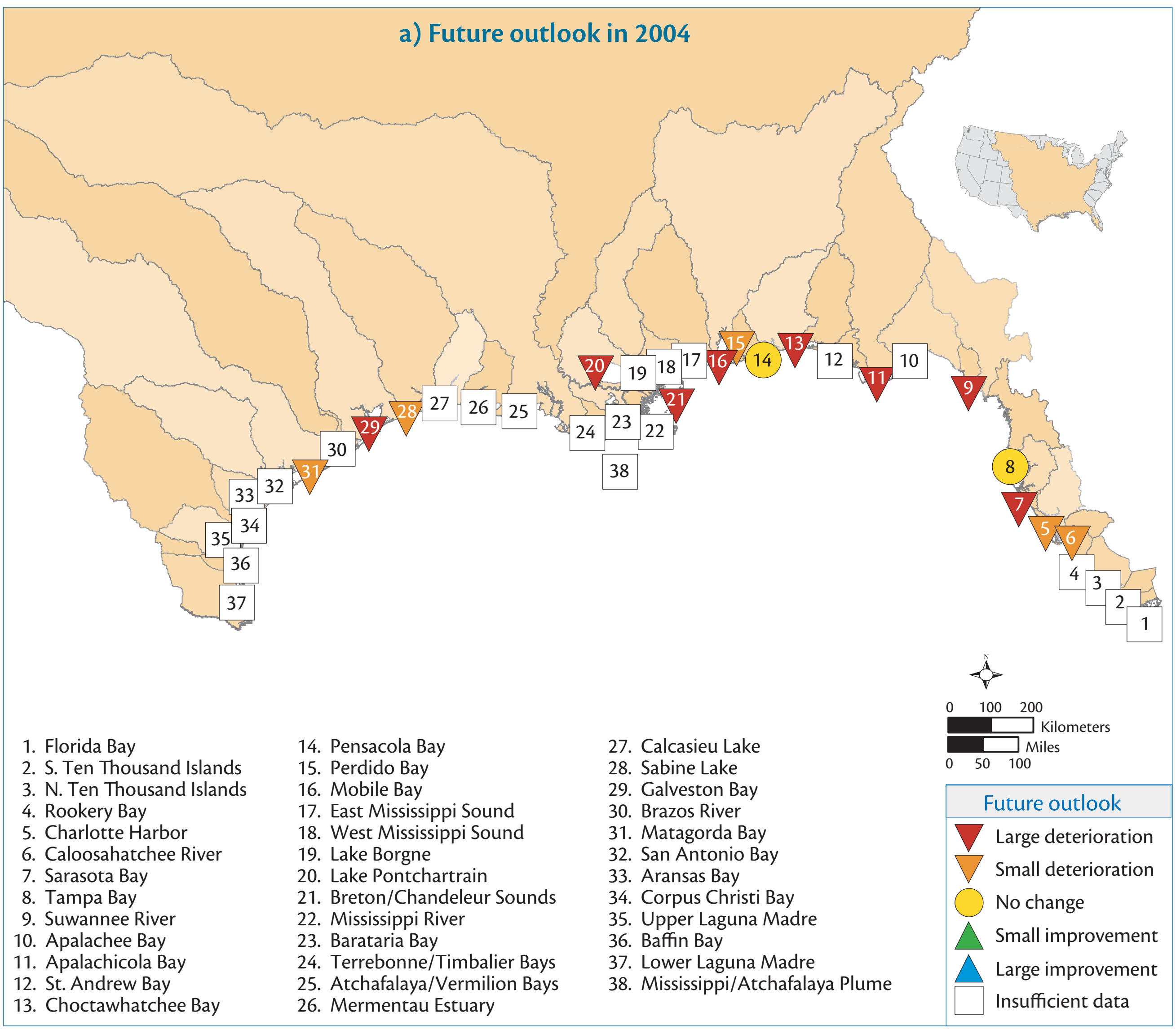
Since the 1999 assessment, conditions have become worse in one system and have improved in another. Worsening conditions in Perdido Bay are accounted for by a decrease in dissolved oxygen. In Mobile Bay, improvements in dissolved oxygen and nuisance/toxic blooms were noted. For 16 systems, assessments were made in both 1999 and 2004. However, a trend analysis was not possible because the indicators used were not comparable between assessments (Figure 4.15).

Future outlook

- Future outlook was bleak, with conditions expected to worsen in all but two of the assessed systems.
- Future outlook has not changed since the last assessment (early 1990s).

Of the 38 Gulf region estuaries studied, 13 were predicted to develop worsening conditions, eight to a high degree and five to a lesser degree (Figure 4.16). For Tampa Bay, which has seen noted regrowth

Figure 4.16. (a) Map of Gulf of Mexico future outlook in 2004 and (b) in comparison with the 1999 future outlook.



b) Future outlook comparisons

Estuary	Future outlook in 2004	Actual change in eutrophic condition (1999 - 2004)	Future outlook in 1999
1. Florida Bay	Insufficient data	Insufficient data	Small improvement
2. S. Ten Thousand Islands	Insufficient data	Insufficient data	Small deterioration
3. N. Ten Thousand Islands	Insufficient data	Insufficient data	Small deterioration
4. Rookery Bay	Insufficient data	Insufficient data	No change
5. Charlotte Harbor	Small deterioration	Insufficient data	Small deterioration
6. Caloosahatchee River	Small deterioration	No change	Small deterioration
7. Sarasota Bay	Large deterioration	No change	Small deterioration
8. Tampa Bay	No change	No change	No change
9. Suwannee River	Large deterioration	Insufficient data	Small deterioration
10. Apalachee Bay	Insufficient data	Insufficient data	Small deterioration
11. Apalachicola Bay	Large deterioration	No change	Small deterioration
12. St. Andrew Bay	Insufficient data	Insufficient data	Small deterioration
13. Choctawhatchee Bay	Large deterioration	Insufficient data	Small deterioration
14. Pensacola Bay	No change	Insufficient data	Small deterioration
15. Perdido Bay	Small deterioration	Worsened	Small deterioration
16. Mobile Bay	Large deterioration	Improved	No change
17. East Mississippi Sound	Insufficient data	Insufficient data	No change
18. West Mississippi Sound	Insufficient data	Insufficient data	No change
19. Lake Borgne	Insufficient data	Insufficient data	No change
20. Lake Pontchartrain	Large deterioration	Insufficient data	Large deterioration
21. Breton/Chandeleur Sounds	Large deterioration	Insufficient data	Small improvement
22. Mississippi River	Insufficient data	No change	No change
23. Barataria Bay	Insufficient data	Insufficient data	No change
24. Terrebonne/Timbalier Bays	Insufficient data	Insufficient data	Small deterioration
25. Atchafalaya/Vermilion Bays	Insufficient data	Insufficient data	No change
26. Mermentau Estuary	Insufficient data	Insufficient data	Small improvement
27. Calcasieu Lake	Insufficient data	Insufficient data	Small deterioration
28. Sabine Lake	Small deterioration	Insufficient data	No change
29. Galveston Bay	Large deterioration	Insufficient data	Small deterioration
30. Brazos River	Insufficient data	Insufficient data	No change
31. Matagorda Bay	Small deterioration	Insufficient data	Small deterioration
32. San Antonio Bay	Insufficient data	No change	Small deterioration
33. Aransas Bay	Insufficient data	Insufficient data	No change
34. Corpus Christi Bay	Insufficient data	No change	Large deterioration
35. Upper Laguna Madre	Insufficient data	Insufficient data	Large deterioration
36. Baffin Bay	Insufficient data	Insufficient data	Large deterioration
37. Lower Laguna Madre	Insufficient data	Insufficient data	Large deterioration
38. Mississippi/Atchafalaya Plume	Insufficient data	No change	Large deterioration

Future outlook
- Large deterioration
- Small deterioration
- No change
- Small improvement
- Large improvement
- Insufficient data

Change in eutrophic condition since 1999 assessment
- Improved
- No change
- Worsened
- Insufficient data

and gains in spatial coverage of submerged aquatic vegetation in the past, the conditions are expected to remain the same due to management strategies to compensate for expected increases in nutrient loads from population growth. For Charlotte Harbor, the prediction of worsening conditions is due to land use conversions from low to highly intensive usage (e.g., rangeland to row crops or urban). Other expected factors potentially influencing future changes in this region are urban runoff, wastewater treatment, industry, atmospheric deposition, animal operations (Sabine Lake), and agriculture (crops and rangeland or pasture).

There were no systems for which conditions were expected to improve. Future conditions for 23 systems are unknown, making it difficult to draw conclusions about future conditions in the region. What can be noted is that for many of the systems expected to worsen, present conditions are moderate or low and susceptibility is moderate. These systems are at risk of future degradation and should be a priority for management.

The future outlook is the same as it was in the early 1990s, with worsening conditions predicted in all systems for which data were available. For the ten systems where an evaluation was possible, predictions have been realized in only three systems as of this interim date (predictions are for year 2020). This result may stem from the fact that these expected changes are for the year 2020. While some areas demonstrate condition changes sooner than others, the accuracy of these particular predictions should be addressed in 2020, or predictions should be made for a shorter time scale.

Assessment of Estuarine Trophic Status (ASSETS)

An ASSETS rating which combines influencing factors, overall eutrophic condition, and future outlook could be made for ten of the 38 systems. Two systems were rated as good (Pensacola Bay, Sabine Lake), two systems were rated as moderate (Mobile Bay and Galveston Bay), and six as poor (Charlotte Harbor, Apalachicola Bay, Caloosahatchee River, Matagorda Bay, Tampa Bay, and Lake Ponchartrain).

Impaired uses

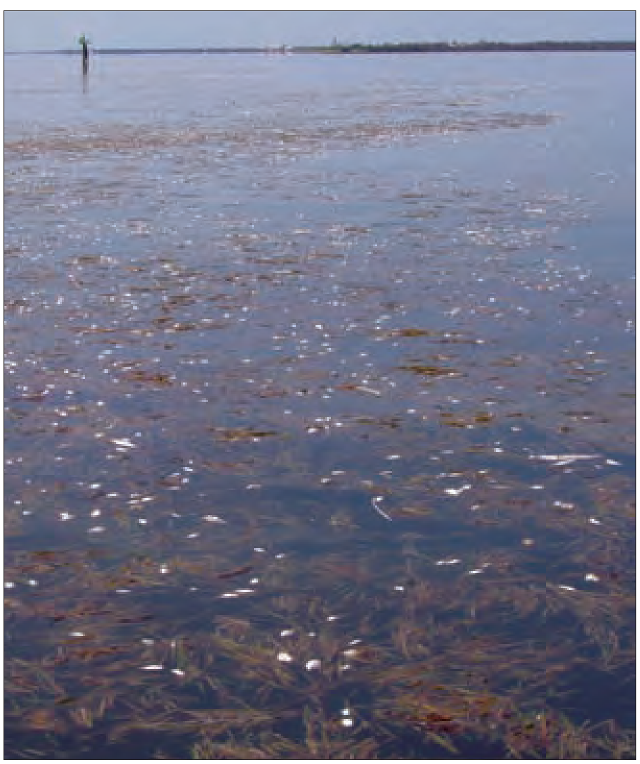
- Twelve systems had impacts to living resources, seven either moderate or high.
- The most noted causes of impacts to living resources were wastewater treatment, urban runoff, onsite septic tanks, and agriculture.
- Only six systems had human use impairments (primarily shellfish, commercial and recreational fishing, swimming, and aesthetics).
- Living resources were most impaired in systems with higher level overall eutrophic conditions.

Living resources were reported as being impaired in twelve systems, with considerable impacts noted in two systems (Sarasota Bay, Perdido Bay), moderate in five systems (Charlotte Harbor, Choctawhatchee Bay, Lake Ponchartrain, Barataria Bay, Mississippi/ Atchafalaya River Plume), and slight or no impacts in an additional six systems (Apalachicola Bay, Pensacola Bay, Breton/Chandeleur Sound, Sabine Lake, Matagorda Bay, Suwannee River). The causes of these impairments were primarily wastewater treatment, urban runoff, and onsite septic tanks. Industry, atmospheric deposition, combined sewer overflows, and agriculture were also noted. For Charlotte Harbor, moderate impacts to living resources are caused by land use conversions from low to more intensive usage (e.g., rangeland to row crops or urban) and for Breton/Chandeleur Sounds, recent river diversion has resulted in observations of chlorophyll $a > 50\ \mu g\ l^{-1}$. In this region, the level of impact to living resources corresponds to the level of eutrophic conditions.

Use impairments were reported in 6 systems (Caloosahatchee River, Sarasota Bay, Apalachicola Bay, Choctawhatchee Bay, Pensacola Bay, Perdido Bay), while impairments to the remaining 32 estuaries are unknown. Shellfish, commercial and recreational fishing, swimming, and aesthetics were the most often noted impairments. However, tourism, boating, fish consumption, and impacts to the municipal water supply (Caloosahatchee River), were also noted. Impairments were most often observed in systems with moderate to high eutrophic conditions but were also reported in systems with low ratings.

Peter Doering, South Florida Water Management District

A cyanobacteria bloom in Caloosahatchee River, Florida.



Peter Doering, South Florida Water Management District

Dead fish from a red tide in the Pine Island Sound region of Charlotte Harbor, Florida.

Potential management concerns

The most often noted sources of nutrients were urban runoff, wastewater treatment, atmospheric deposition, and onsite septic tanks (Florida systems). The nutrient loads from agricultural practices in this region also continue to be a major management concern. Both point and non-point nutrient sources are expected to cause worsening conditions in the future and so should be targeted for management (see "Monitoring," below). The systems that are moderately or highly susceptible and at present show moderate eutrophic conditions, use impairments, and impacts to living resources, should be a priority for management.

U.S. Department of Transportation, Maritime Administration

Tanker ships in the Houston Ship Canal. Monitoring in the canal suggests improvements in water quality.

Data gaps and research needs

Monitoring

There are many data gaps for many systems in this region. Routine monitoring should be a priority so that water quality can be evaluated and trends tracked through time. Load estimates for this region are also scarce. There are examples of both improving (e.g., Mobile Bay) as well as degrading (e.g., Perdido Bay) conditions. There are also systems without overall eutrophic change, which have decreasing point sources but increasing non-point sources, which should be targeted for monitoring.

Research

Over half of the systems in this region did not have load estimates, which are critical for determining the causes of observed living resource and use impairments. They are also needed for prescribing best management practices in order to improve conditions. It is recommended that research focus on the development of loading estimates for the region. Furthermore, the relative roles of nitrogen and phosphorus in the development of eutrophic conditions should be explored. Given that increased circulation to these systems may alleviate eutrophication to some degree, research should also include inlet circulation and approaches to inlet management.

Management

Major management foci should include improvements to wastewater treatment, onsite septic tanks, and re-designs of combined sewer overflow. Reductions of urban and industry runoff and atmospheric deposition were also named as targets for management. Though management action should focus on identifying and managing nutrient sources, there is also a strong need to close the data gaps which may affect these decisions. Efforts should be allocated toward the improvement and organization of routine monitoring systems.

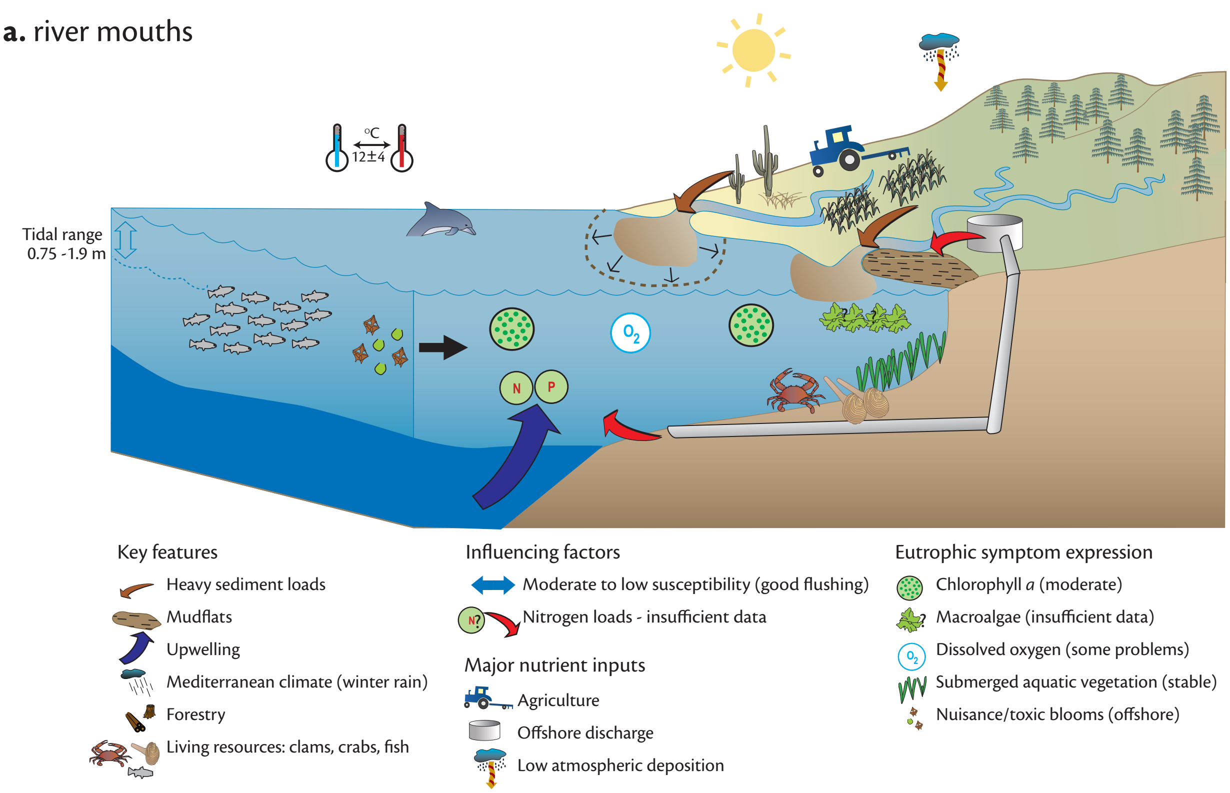
PACIFIC COAST REGION

- Very few estuaries have nutrient load data available.
- Most estuaries with reported problems were located in Washington State and central California, with chlorophyll *a* and dissolved oxygen being the major eutrophic symptoms.
- Only one system was rated with a high overall eutrophic condition.

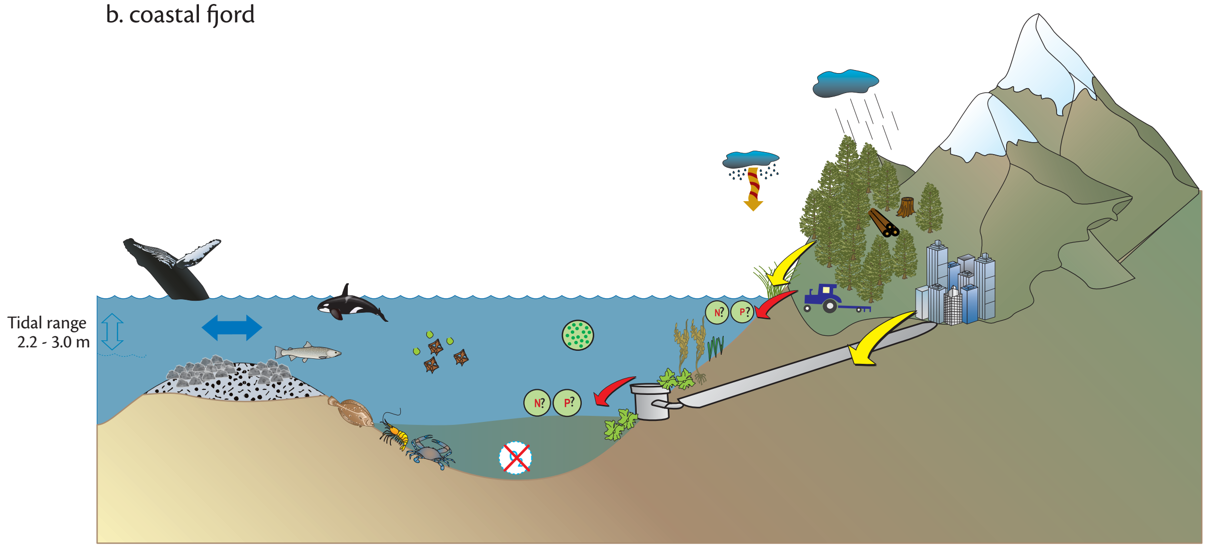
The Pacific Coast region includes 39 estuaries, encompassing more than 7,113 km^2 of water surface area. The region consists of a relatively straight and uninterrupted shoreline with rocky shores, sandy beaches, and occasional river outlets (Figure 4.17a-c). Limited areas of flat, lowland environments support estuaries, bays, and lagoons. The river mouth estuaries are found in Oregon (Figure 4.17a), the fjord systems in northern Washington State (Figure 4.17b), and the lagoons are mostly found in California (Figure 4.17c). The water bodies along the Pacific coast 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. Tidal range is variable (0.75–3.0 m), with higher averages found in the fjord systems (2.4 m). Likewise, the depth range is large (0.2–96m), with higher average depths found in the Washington State fjord systems (66 m). Precipitation in the northern part of the region (1.7 m yr^{-1}) is more than

Figure 4.17. Conceptual diagram of Pacific Coast key features, major nutrient sources, and resulting symptoms.

a. river mouths



b. coastal fjord



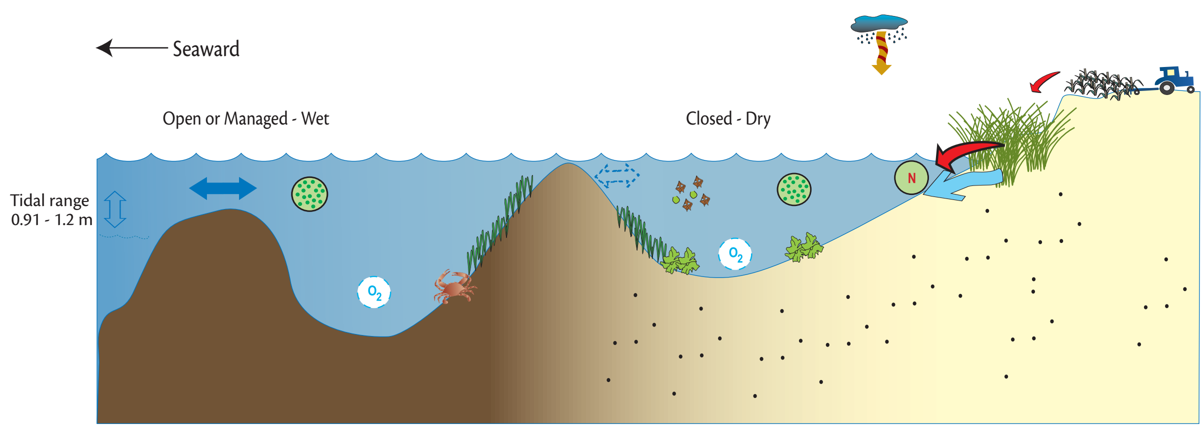
Key features
- Rocky
- Mediterranean climate
- Fringing marsh and seagrass
- Kelp beds
- Forestry
- Living resources: crabs, fish

Influencing factors
- Moderate to low susceptibility (good flushing)
- Nitrogen loads - insufficient data

Major nutrient sources
- Agriculture
- Urban; offshore discharges
- Stormwater
- Low atmospheric deposition

Eutrophic symptom expression
- Chlorophyll *a* (high)
- Macroalgae (moderate)
- Dissolved oxygen (moderate to low expression)
- Submerged aquatic vegetation (stable or nonexistent)
- Nuisance/toxic blooms (low)

c. lagoons



Key features
- Freshwater inflow
- Muddy and sandy bottoms
- Small marsh
- Seagrass beds
- Living resources: crabs

Influencing factors
- Moderate to low susceptibility (poor flushing)
- Hign nitrogen loads

Major nutrient inputs
- Agriculture
- Low atmospheric deposition

Eutrophic symptom expression
- Chlorophyll *a* (high)
- Macroalgae (mostly low)
- Dissolved oxygen (some problems)
- Submerged aquatic vegetation (stable)
- Nuisance/toxic blooms (moderate)

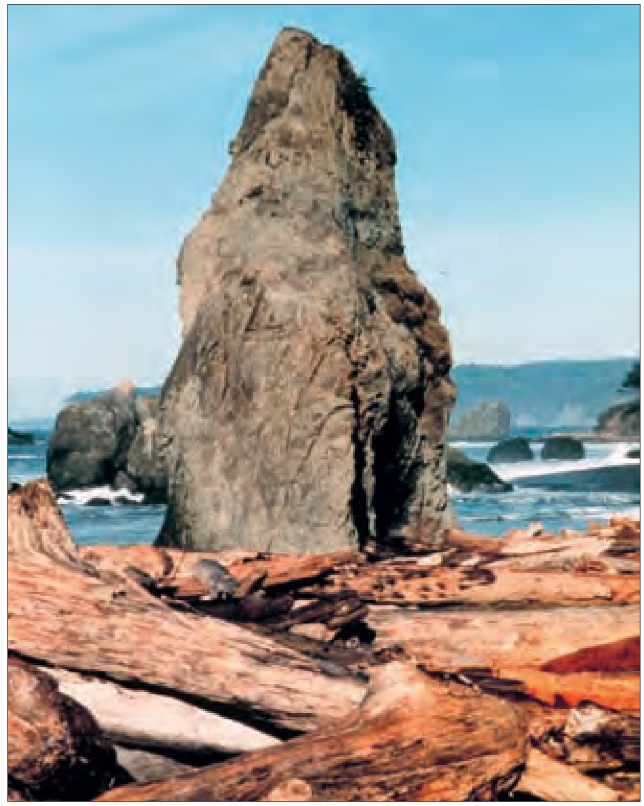
twice that recorded in California (0.57 m yr^{-1}). Air temperature and frost days show a similar pattern in Washington and Oregon, with average annual temperatures of 10°C and 79 frost days per year, while California averages annual temperatures of 15°C and 35 frost days per year. Some of the major population centers include Los Angeles, San Diego, San Francisco, and Seattle. Average population densities are also distinctly different in the northern and southern part of this region, with an average of 106 people per km^2 in California compared to 10 people per square kilometer in Washington and Oregon. The regional average population density is 33 people per km^2. Forestry, agriculture, and industry are the dominant land uses in the region (Figure 4.17a-c).

Influencing factors

- There were insufficient data to make conclusions about influencing factors in this region.

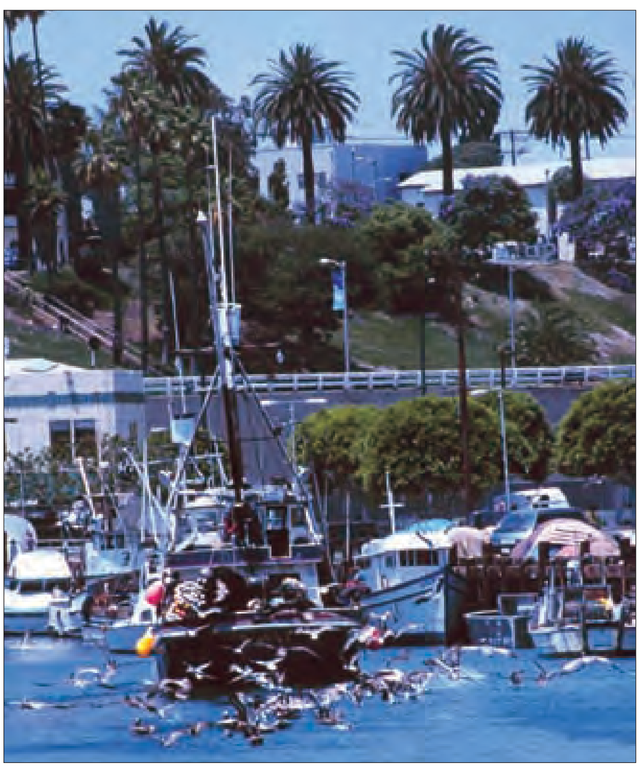
There were very little nutrient loading data for the Pacific Coast region; only four systems had load estimates (Figure 4.18). The load to Newport Bay, San Francisco Bay South, and Hood Canal are all classified as high. The susceptibility of systems in this region is varied, with the lagoonal systems in California characterized mostly by high susceptibility, due to low dilution and flushing capability. Alternatively, the river mouth estuaries in Oregon and Washington state are moderately susceptible on account of high flushing but low dilution capability. The fjord type systems in Washington State are in general less susceptible than other systems, due to high dilution and moderate flushing capability. These combinations lead to high values for influencing factors in Newport Bay and Hood Canal and moderate low in San Francisco Bay North.

It is not possible to conclude anything about influencing factors in this region, due to a lack of data. However, it is expected that the human influence on the expression of eutrophic symptoms is very high. Southern California systems in particular have high human influence because they are among the top ten U.S. estuaries with respect to watershed population density. Tijuana Estuary is also notable because three-quarters of the watershed is located in Mexico, making management an international challenge.



National Oceanic and Atmospheric Administration

Pinnacle rocks and weather-beaten logs are characteristic of water bodies in Oregon and Washington.

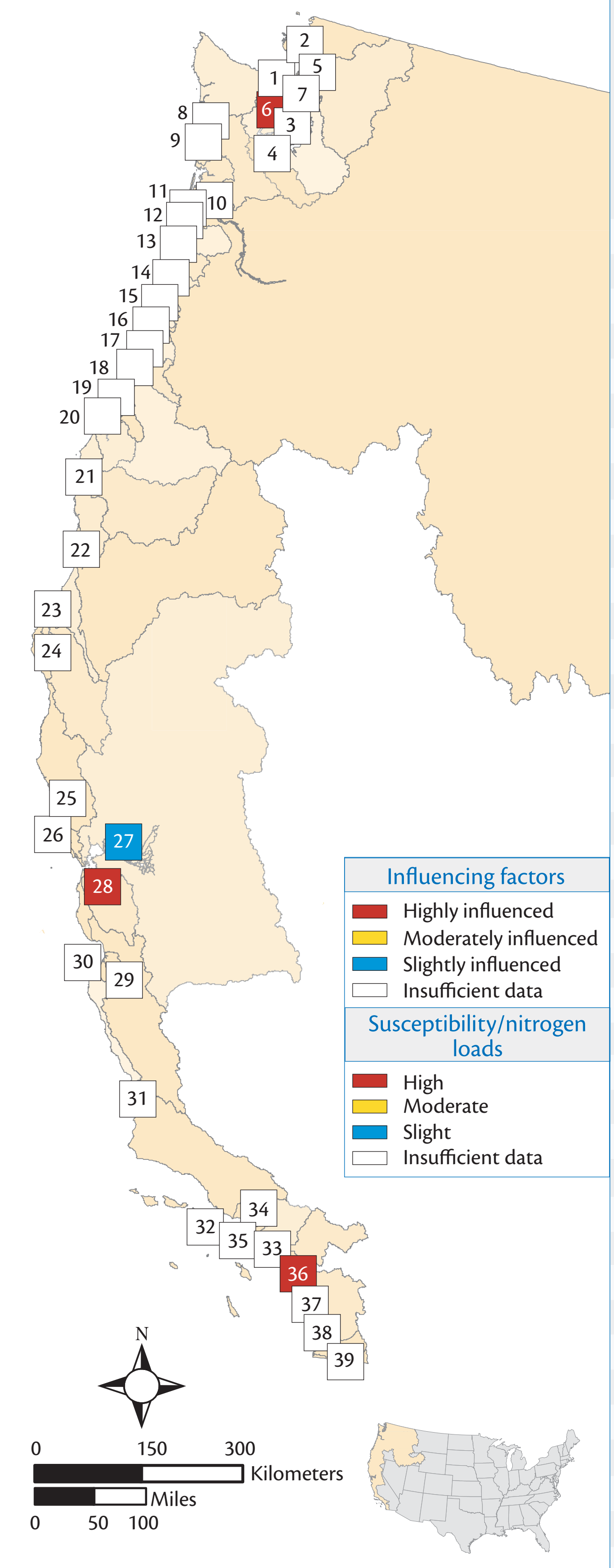


National Oceanic and Atmospheric Administration

Pelicans following a fishing boat in San Pedro Bay, California. California estuaries are typically lagoons.

Figure 4.18. Map of influencing factors ratings, ratings of components of influencing factors, and 1999 ratings in the Pacific region.

Influencing factors: 2004



Influencing factors: comparisons

Estuary	Influencing factors (2004)	Susceptibility (2004)	Nitrogen loads (2004)	Influencing factors (1999)
1. Sequim/Discovery Bays	Insufficient data	Moderate	Insufficient data	Moderately influenced
2. Bellingham/Padilla/Samish Bays	Insufficient data	Moderate	Insufficient data	Moderately influenced
3. Port Orchard System	Insufficient data	Moderate	Insufficient data	Moderately influenced
4. South Puget Sound	Insufficient data	High	Insufficient data	Moderately influenced
5. Skagit Bay/Whidbey Basin	Insufficient data	Moderate	Insufficient data	Moderately influenced
6. Hood Canal	Highly influenced	High	High	Highly influenced
7. Puget Sound	Insufficient data	Slight	Insufficient data	Slightly influenced
8. Grays Harbor	Insufficient data	Slight	Insufficient data	Slightly influenced
9. Willapa Bay	Insufficient data	Slight	Insufficient data	Slightly influenced
10. Columbia River	Insufficient data	Slight	Insufficient data	Slightly influenced
11. Nehalem River	Insufficient data	Moderate	Insufficient data	Moderately influenced
12. Tillamook Bay	Insufficient data	Moderate	Insufficient data	Moderately influenced
13. Netarts Bay	Insufficient data	High	Insufficient data	Moderately influenced
14. Siletz Bay	Insufficient data	Moderate	Insufficient data	Slightly influenced
15. Yaquina Bay	Insufficient data	Moderate	Insufficient data	Slightly influenced
16. Alsea River	Insufficient data	Moderate	Insufficient data	Moderately influenced
17. Siuslaw River	Insufficient data	Moderate	Insufficient data	Moderately influenced
18. Umpqua River	Insufficient data	Moderate	Insufficient data	Slightly influenced
19. Coos Bay	Insufficient data	Moderate	Insufficient data	Moderately influenced
20. Coquille River	Insufficient data	Moderate	Insufficient data	Slightly influenced
21. Rogue River	Insufficient data	Moderate	Insufficient data	Moderately influenced
22. Klamath River	Insufficient data	Moderate	Insufficient data	Slightly influenced
23. Humboldt Bay	Insufficient data	High	Insufficient data	Highly influenced
24. Eel River	Insufficient data	Moderate	Insufficient data	Moderately influenced
25. Tomales Bay	Insufficient data	High	Insufficient data	Highly influenced
26. Drakes Estero	Insufficient data	Slight	Insufficient data	Highly influenced
27. San Francisco Bay North	Slightly influenced	Slight	High	Slightly influenced
28. San Francisco Bay South	Highly influenced	Moderate	High	Highly influenced
29. Elkhorn Slough	Insufficient data	High	Insufficient data	Highly influenced
30. Monterey Bay	Insufficient data	Slight	Insufficient data	Slightly influenced
31. Morro Bay	Insufficient data	High	Insufficient data	Highly influenced
32. Santa Monica Bay	Insufficient data	Moderate	Insufficient data	Highly influenced
33. Anaheim Bay	Insufficient data	High	Insufficient data	Highly influenced
34. Alamitos Bays	Insufficient data	High	Insufficient data	Insufficient data
35. San Pedro Bay	Insufficient data	High	Insufficient data	Highly influenced
36. Newport Bay	Highly influenced	High	High	Highly influenced
37. Mission Bay	Insufficient data	High	Insufficient data	Highly influenced
38. San Diego Bay	Insufficient data	High	Insufficient data	Highly influenced
39. Tijuana Estuary	Insufficient data	High	Insufficient data	Highly influenced

Overall eutrophic condition

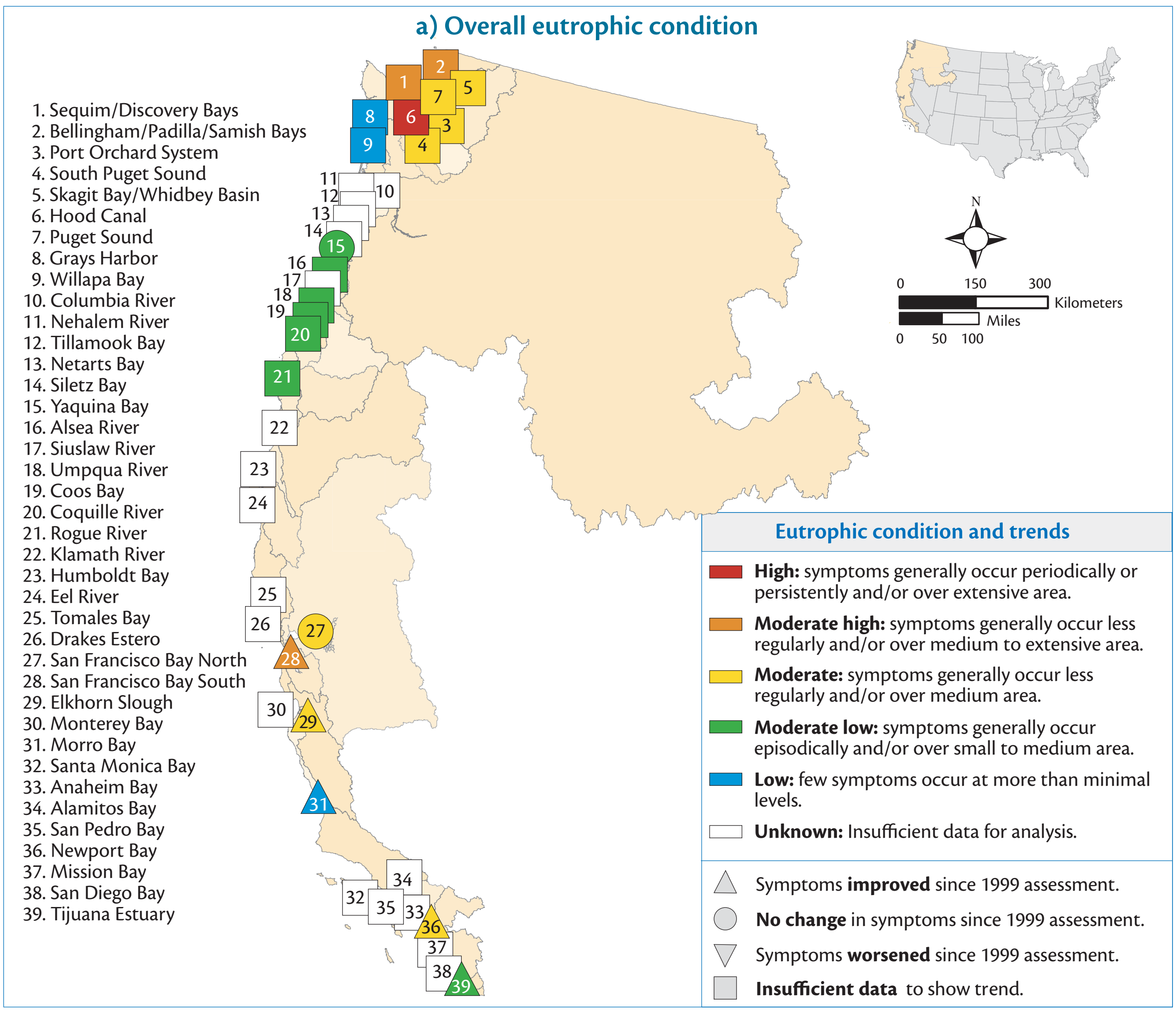
- Only one system had an overall eutrophic condition (OEC) rating of high.
- Most of the eutrophic estuaries in this region are located in Washington State and central California, with chlorophyll *a* and dissolved oxygen as the major symptom expressions.

Due to a lack of data, only half of the systems in this region were assigned an overall eutrophic condition rating (OEC). Of the assessed systems, those with moderate high to high OEC were located in the Puget Sound and San Francisco areas (Figure 4.19). In contrast, estuaries in the Oregon region all had moderate low overall eutrophic condition ratings.

Tim Carruthers, University of Maryland Center for Environmental Science

Estuarine mud flat at Morro Bay, California, showing extensive macroalgae growth.

Figure 4.19. (a) Map of overall eutrophic condition (OEC) and (b) the combination of individual eutrophic symptoms which constitute OEC ratings in the Pacific Coast.



b) Overall eutrophic condition & eutrophic symptoms

Estuary	Overall eutrophic condition	Overall confidence expression	Chlorophyll *a*	Macroalgae	Dissolved oxygen	Nuisance/toxic blooms	SAV
1. Sequim/Discovery Bays	Orange ■	* *	Red ●	Blue ■	Yellow ▼	Yellow ■	Blue ■
2. Bellingham/Padilla/Samish Bays	Orange ■	* *	Red ●	Yellow ■	Yellow ▼	Blue ■	Blue ■
3. Port Orchard System	Yellow ■	* *	Red ●	Yellow ■	Blue ●	Blue ■	Blue ■
4. South Puget Sound	Yellow ■	*	Red ●	Yellow ■	Blue ●	Blue ■	Blue ■
5. Skagit Bay/Whidbey Basin	Yellow ■	* *	Red ●	Yellow ■	Yellow ▼	Blue ■	Blue ■
6. Hood Canal	Red ■	* *	Red ●	Yellow ■	Red ▼	Blue ■	Blue ■
7. Puget Sound	Yellow ■	* *	Red ●	Yellow ■	Blue ●	Blue ■	Blue ●
8. Grays Harbor	Blue ■	* *	Blue ■	Blue ■	Blue ●	Blue ■	Blue ■
9. Willapa Bay	Blue ■	*	Blue ■	Blue ■	Blue ●	Blue ■	Blue ■
10. Columbia River	□	*	□	□	□	□	□
11-13 (Nehalem River, Tillamook Bay, and Netarts Bay are unknown for all indicators)							
14. Siletz Bay	□	*	□	□	□	□	□
15. Yaquina Bay	Green ●	*	Yellow ●	□	Blue ●	□	□
16. Alsea River	Green ■	*	Yellow ●	□	Blue ●	□	□
17. Siuslaw River	□	*	□	□	□	□	□
18. Umpqua River	Green ■	*	Yellow ▼	□	Blue ●	□	□
19. Coos Bay	Green ■	*	Yellow ●	□	Blue ●	□	□
20. Coquille River	Green ■	*	Yellow ▼	□	Blue ●	□	□
21. Rogue River	Green ■	*	Yellow ■	□	Blue ●	□	□
22. Klamath River	□	*	□	□	□	□	□
23-25 (Humboldt Bay, Eel River, and Tomales Bay are unknown for all indicators)							
26. Drakes Estero	□	*	□	□	□	□	□
27. San Francisco Bay North	Yellow ●	* *	Red ▼	Blue ■	Blue ●	Yellow ▲	Blue ▲
28. San Francisco Bay South	Orange ▲	*	Red ●	Blue ■	Blue ●	Yellow ▼	Blue ▲
29. Elkhorn Slough	Yellow ▲	* *	Blue ▲	Red ●	Blue ▲	□	Blue ●
30. Monterey Bay	□	*	□	□	□	□	□
31. Morro Bay	Blue ▲	* *	□	Blue ▲	Blue ●	Blue ▲	Blue ▲
32. Santa Monica Bay	□	*	□	□	□	Yellow ▼	□
33. Anaheim Bay	□	*	□	□	□	□	□
34. Alamitos Bay	□	*	□	□	□	□	□
35. San Pedro Bay	□	*	□	□	□	□	□
36. Newport Bay	Yellow ▲	*	□	Red ●	Blue ▲	□	Blue ▲
37. Mission Bay	□	*	□	□	□	□	□
38. San Diego Bay	□	*	□	□	□	□	□
39. Tijuana Estuary	Green ▲	* *	Yellow ▲	Yellow ▲	Blue ▲	Blue ●	Blue ●

Eutrophic condition in 2004

- Red: High
- Orange: Moderate high
- Yellow: Moderate
- Green: Moderate low
- Blue: Low
- White: Insufficient data

Overall confidence expression in 2004

- * * * High
- * * Moderate
- * Low

Change in eutrophic condition since 1999 assessment

- ▲ Improved
- ● No change
- ▼ Worsened
- ■ Insufficient data

Shih-Nan Chen, University of Maryland Center for Environmental Science

An algal bloom in the Columbia River near Astoria, Oregon.

In general, the symptoms contributing most to the higher level eutrophic conditions were elevated levels of chlorophyll *a* and dissolved oxygen problems. The confidence in the assessment of individual systems and overall confidence in the region was mostly low due to low availability of data (Figure 4.19).

Eutrophic symptom expressions

Of the primary symptoms, chlorophyll *a* was expressed at high levels in nine systems, and at moderate levels in seven systems. Macroalgae data were reported for 15 systems, with a symptom expression of high in two, moderate in seven, and low in six estuaries. Of the secondary symptoms, dissolved oxygen was high in one system, moderate in three, and low or no problem in 17 systems. However, in a few systems (Bellingham/Padilla/Samish and Sequim/Discovery Bays), these ratings may not be effective at representing dissolved oxygen conditions. These particular systems are influenced by inflows of upwelled oceanic water which is low in dissolved oxygen, and therefore contributes to dissolved oxygen problems which might otherwise be attributed to human influence. Nuisance/toxic blooms were reported for only five systems, with moderate level problems observed in only two systems. Loss of submerged aquatic vegetation was reported as low or no problem for nine systems, while the remaining 30 systems were unknown. Part of the reason for the paucity of data for the Oregon systems is that other issues, such as contaminants, are considered more of a pressing concern than eutrophication.

Changes in eutrophic condition since the 1990s

Comparison of data with the 1999 assessment shows that five systems have improved, mostly due to improved chlorophyll *a* and dissolved oxygen conditions. Two systems have remained the same since the 1999 assessment but for most systems a change could not be determined (Figure 4.19). It is difficult to draw any conclusions about patterns in this region due to a lack of data for recent conditions and thus trends analysis.

Future outlook

- There were insufficient data to make any conclusions about future outlook.
- Of the eight systems for which future outlook was reported, most are expected to worsen.

Five estuaries in the Pacific Coast region were predicted to develop worsening conditions in the future, while three were predicted to improve. There was no information for 31 systems.

The reported reasons for worsening conditions were onsite septic tanks, urban runoff, and forestry (the latter in Hood Canal only). The potential reasons for future improvement were noted as changes to industry, urban runoff (Newport Bay), and agriculture. Expected improvements in Santa Monica Bay are attributed to the Total Maximum Daily Load (TMDL) for Malibu Creek, which is expected to decrease the nutrient loads. However, these may be offset by increased atmospheric inputs. Consequently, the decrease is expected to be small.

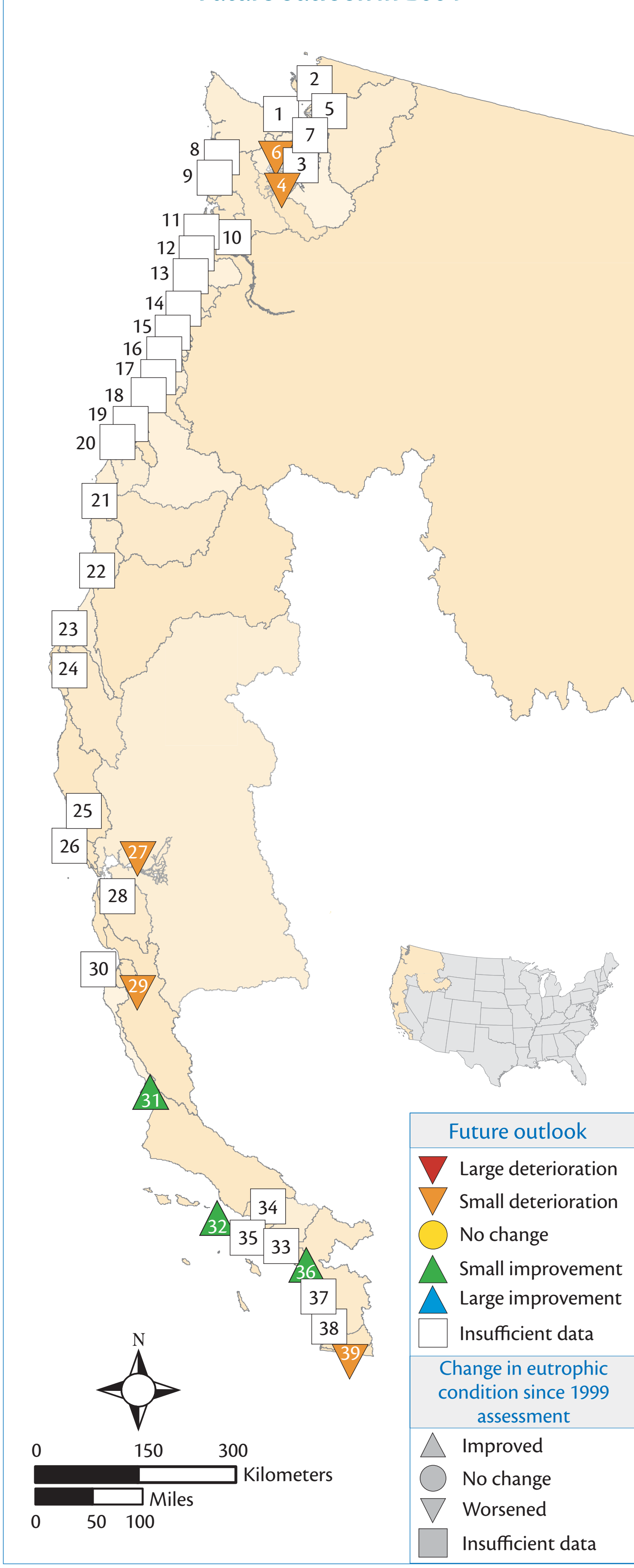
There is insufficient data to make overall conclusions about future outlook. Of the seven systems for which a comparison could be made, only one was consistent with future outlook predictions from 1999 (San Francisco Bay North). This result may stem from the fact that these expected changes are for the year 2020. While some areas demonstrate condition changes sooner than others, the accuracy of these particular predictions should be addressed in 2020, or predictions should be made for a shorter time scale.

Assessment of Estuarine Trophic Status (ASSETS)

Only three systems received an ASSETS rating, which combines influencing factors, overall eutrophic condition, and future outlook. Hood Canal was characterized as bad, and both Newport and San Francisco Bay as moderate.

Figure 4.20. Future outlook in 2004 and comparison with 1999 future outlook.

Future outlook in 2004



Future outlook comparisons

Estuary	Future outlook in 2004	Actual change in eutrophic condition (1999 - 2004)	Future outlook in 1999
1. Sequim/Discovery Bays	Insufficient data	Insufficient data	Small deterioration
2. Bellingham/Padilla/Samish Bays	Insufficient data	Insufficient data	Small deterioration
3. Port Orchard System	Insufficient data	Insufficient data	Small deterioration
4. South Puget Sound	Small deterioration	Insufficient data	Large deterioration
5. Skagit Bay/Whidbey Basin	Insufficient data	Insufficient data	Small deterioration
6. Hood Canal	Small deterioration	Insufficient data	Large deterioration
7. Puget Sound	Insufficient data	Insufficient data	Small deterioration
8. Grays Harbor	Insufficient data	Insufficient data	Small deterioration
9. Willapa Bay	Insufficient data	Insufficient data	Small deterioration
10. Columbia River	Insufficient data	Insufficient data	No change
11. Nehalem River, Tillamook Bay, and Netarts Bay are unknown for future outlook and overall eutrophic condition.			
14. Siletz Bay	Insufficient data	Insufficient data	Small deterioration
15. Yaquina Bay	Insufficient data	No change	Small deterioration
16. Alsea River	Insufficient data	Insufficient data	Small deterioration
17. Siuslaw River	Insufficient data	Insufficient data	Small deterioration
18. Umpqua River	Insufficient data	Insufficient data	Small deterioration
19. Coos Bay	Insufficient data	Insufficient data	Small deterioration
20. Coquille River	Insufficient data	Insufficient data	Small deterioration
21. Rogue River	Insufficient data	Insufficient data	Small deterioration
22. Klamath River	Insufficient data	Insufficient data	No change
23. Humboldt Bay	Insufficient data	Insufficient data	No change
24. Eel River	Insufficient data	Insufficient data	Small deterioration
25. Tomales Bay	Insufficient data	Insufficient data	Large deterioration
26. Drakes Estero	Insufficient data	Insufficient data	Large deterioration
27. San Francisco Bay North	Small deterioration	No change	No change
28. San Francisco Bay South	Insufficient data	Improved	Small deterioration
29. Elkhorn Slough	Small deterioration	Improved	No change
30. Monterey Bay	Insufficient data	Insufficient data	Small deterioration
31. Morro Bay	Small improvement	Improved	No change
32. Santa Monica Bay	Small improvement	Insufficient data	No change
33. Anaheim Bay	Insufficient data	Insufficient data	Small deterioration
34. Alamitos Bay	Insufficient data	Insufficient data	Insufficient data
35. San Pedro Bay	Insufficient data	Insufficient data	Small deterioration
36. Newport Bay	Small improvement	Improved	Large deterioration
37. Mission Bay	Insufficient data	Insufficient data	Small deterioration
38. San Diego Bay	Insufficient data	Insufficient data	Large deterioration
39. Tijuana Estuary	Small deterioration	Improved	Large deterioration

Impaired uses

- Six systems had impacts to living resources.
- Human uses were reported to be impaired in only one system, for commercial and recreational fishing; other systems are unknown.

Considerable impacts to living resources were reported for Newport Bay, moderate impacts for Elkhorn Slough and Hood Canal, and slight for Klamath River, Tijuana Estuary, and Morro Bay. The reasons for impacts to living resources, noted only for Klamath River, were agriculture, upstream land use, and upriver hydroelectric and diversion projects that reduce flow downstream.

Potential management concerns

Potential sources to target for improvements to overall eutrophic condition in Washington estuaries are wastewater treatment, urban runoff, on-site animal operations, agriculture, and forestry. In southern California, wastewater treatment, urbanization, stormwater, industry, agriculture, and forestry were cited.

Data gaps and research needs

Monitoring

The estuaries of the Pacific Coast are predominantly understudied. Therefore, there is a need for baseline monitoring of basic water quality parameters on an annual time frame in these areas. Additionally, better loading estimates should be a top priority. Forecasting models for prioritization of systems for management, integration of sampling technologies, assessment of variation among current indicators, and use of restoration effectiveness measures should be encouraged. *In situ* sampling should be coordinated with programs designed for satellite and remotely sensed observations, such as the U.S. Integrated Ocean Observing System (IOOS) to maximize data resources. Data and results should also be shared with programs like the National Water Quality Monitoring Network (NWQMN) for coordinated wide distribution.


USDA National Resources Conservation Service

Downtown Seattle, Washington. As urbanization and impervious surfaces increase, more research and monitoring, and better nutrient management will be needed.


USDA Forest Service, National Wild and Scenic Rivers System

Living resources in the Klamath River, California, are impacted by river diversions and reduced flow.

Research

Priorities for research in this region include improving the understanding of: (1) improve understanding of the mechanisms involved with nutrient loads, including the role of groundwater pulses, hydrologic alteration, impervious surfaces, and significant weather events; (2) the interactions of complicating and synergistic factors such as food web and predator alterations, climate change, and shoreline hardening; (3) the development of operational forecasting models, and (4) development of better techniques for load and flushing estimates, and (5) refinement of the susceptibility index.

Management

It is important to evaluate impacts of various nutrient sources, including population, onsite septics (exurban areas), agriculture, wastewater treatment, atmospheric loading and deposition, impervious surfaces, and urban runoff in order to implement appropriate management measures. Integration of EPA (regulatory) and NOAA and USGS (assessment) approaches should also be explored. A much better understanding is needed of the linkages between nutrient inputs, productivity, and eutrophication.

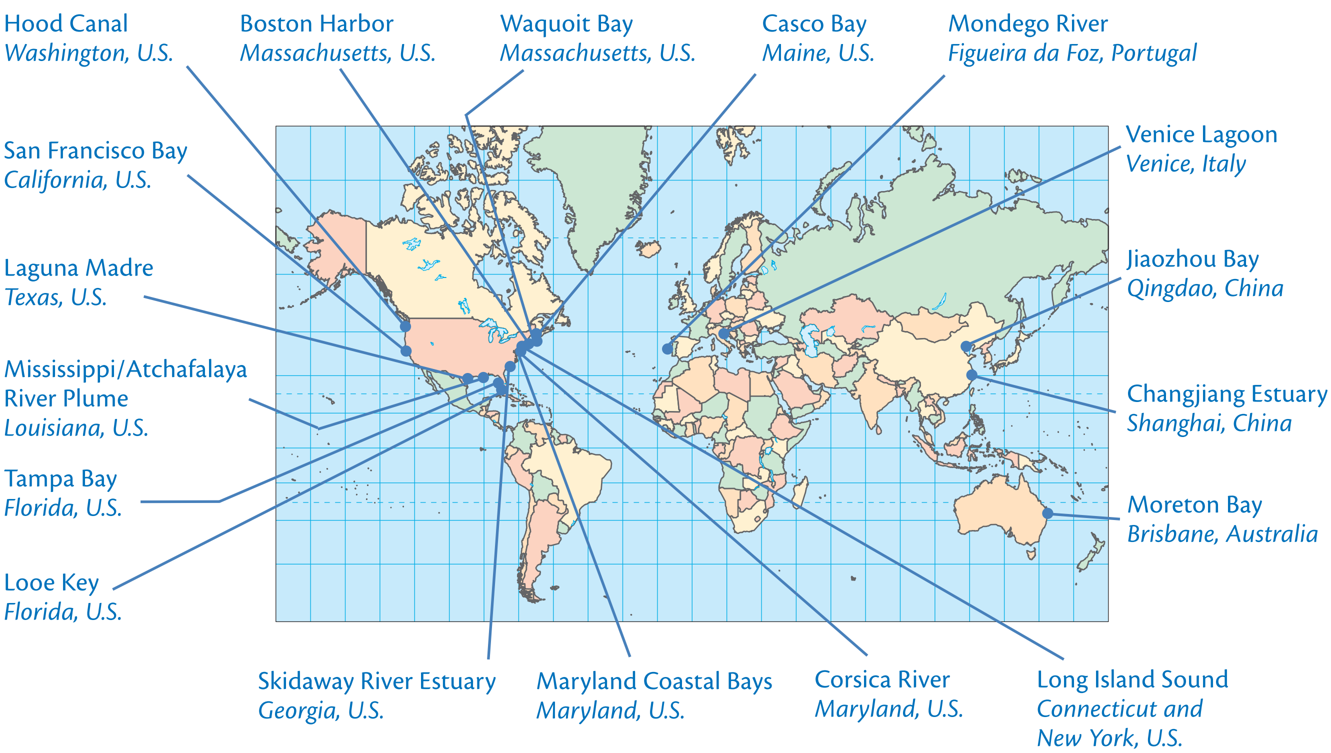
5. CASE STUDIES

EXAMINING EUTROPHICATION IN OTHER SYSTEMS: CASE STUDIES

What can other systems tell us about eutrophication?
By investigating the causes and implications of eutrophication across the globe, we can learn new, successful ways to manage and monitor estuaries.

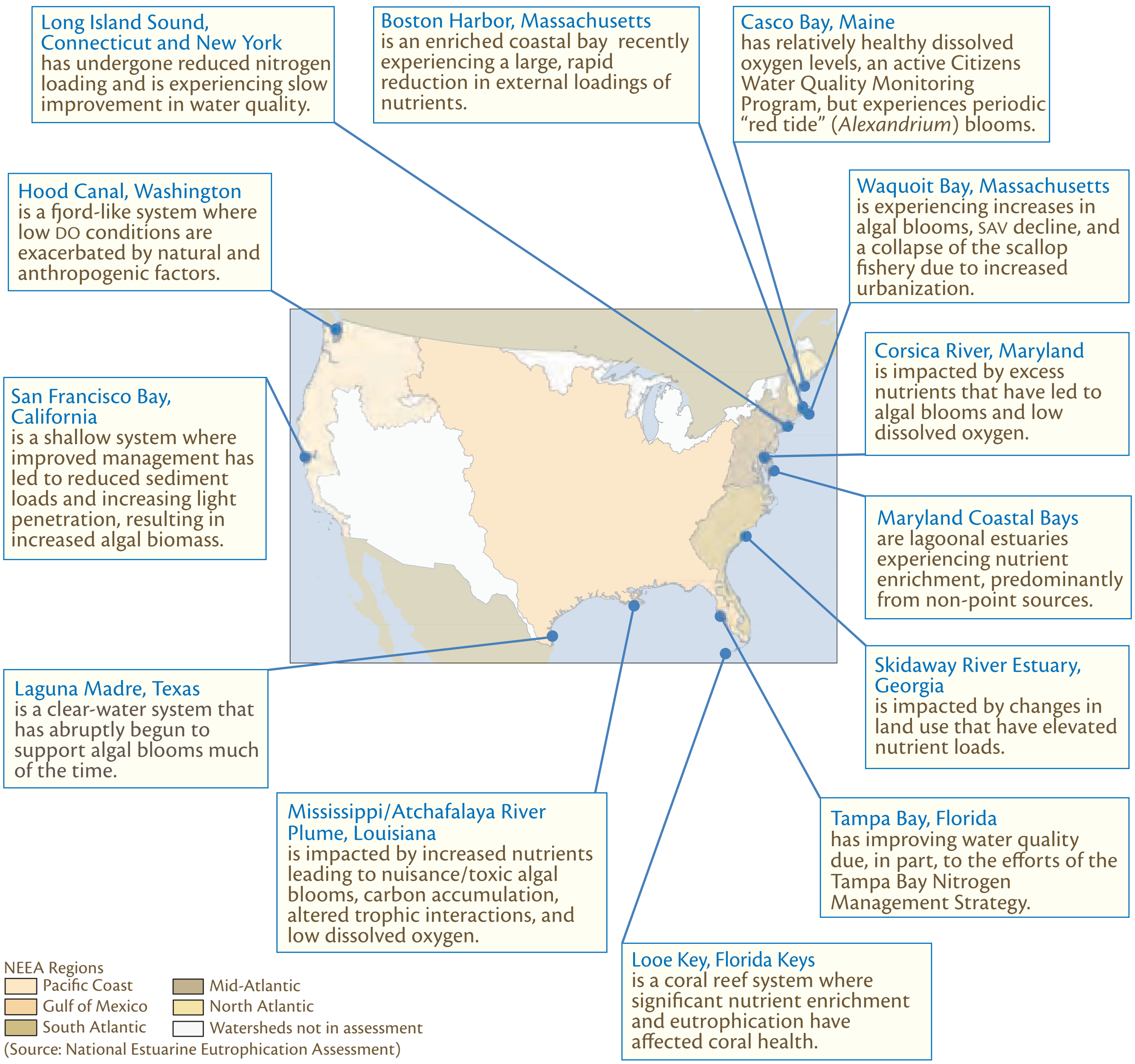
Research and monitoring conducted during the past decade have revealed that eutrophication impacts are not restricted to any particular part of the U.S. coastline, nor solely to the U.S.; these impacts have been noted in estuaries and coastal water bodies around the globe. In most cases, progression begins in the same way and with similar symptoms. Most often these include high chlorophyll *a* or macroalgae, low dissolved oxygen, losses of submerged aquatic vegetation, and occurrences of nuisance/toxic blooms. While these symptoms do not all appear in each impacted system, and different combinations of symptoms occur, there are commonalities. Some results suggest that the symptom expression is consistent among systems from the same geomorphological and hydrological type. For instance, macroalgal problems seem to be observed in coastal lagoons more than in fjords or drowned river valleys, while dissolved oxygen is typically not a problem in coastal lagoons because the shallow depth allows for water column mixing.

Case study map



The case studies presented here include estuaries in the U.S., Australia, China, Portugal, and Italy. These studies serve as examples of monitoring and research programs that have been or are being used to develop management plans. In some places the outcomes of implemented management measures are also presented and should serve as encouragement that nutrient-related problems can be improved upon with proper management attention. These case studies are meant to illustrate the various impacts of eutrophication that occur in different systems, how these systems might provide insight to emerging problems in the same type of estuaries, and—most importantly—how the application of carefully planned management measures has relieved eutrophication in some estuaries. Furthermore, these case studies provide the basis for successful management approaches that may be used in other systems, both in the U.S. and abroad. (For more information bout international assessment results, go to: http://www.eutro.org)

U.S. case study map

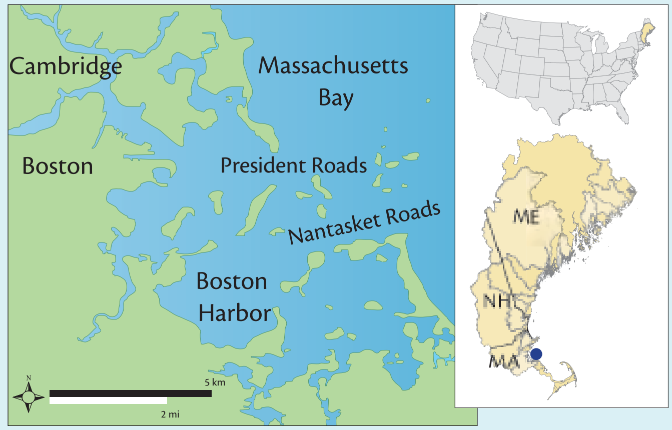


(Source: National Estuarine Eutrophication Assessment)

BOSTON HARBOR, MA: *Diversion of effluent to offshore reduced eutrophic symptoms*

David Taylor, Massachusetts Water Resources Authority

Boston Harbor, Massachusetts, is an urbanized bay in the northeast, surrounded by the city of Boston and its outlying communities. The Harbor has an area of 108 km², and an average depth of 6.5 m. It has an average tidal range of 3.5 m, and an average hydraulic residence time of 4–7 days. Two large channels, President Roads and Nantasket Roads, connect the Harbor to Massachusetts Bay. Boston Harbor is also home to the Boston Harbor Islands National Park, which consists of 34 islands located around the greater Boston shoreline.



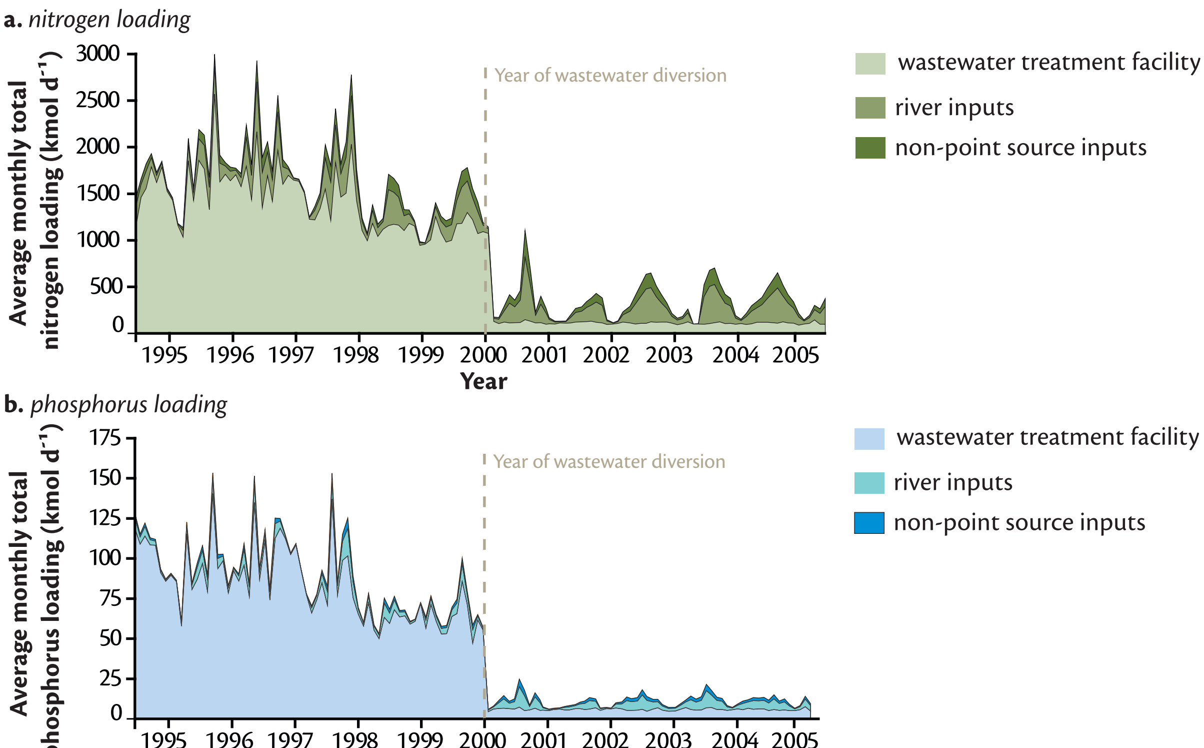
Decreased nutrient loads

Boston Harbor provides a unique example of an enriched coastal bay that has recently experienced a large, rapid reduction in external loadings of nutrients. Prior to 2000, the harbor received elevated nutrient loads, largely from wastewater discharges from metropolitan Boston. In 2000, these discharges were diverted 15 km offshore for diffusion into the bottom-waters of Massachusetts Bay. The diversion ended more than a century of direct wastewater treatment plant discharges and decreased external total nitrogen (TN) and total phosphorus (TP) loads by approximately 80% (Figure 5.1).

History of nutrients in this region

Symptoms of eutrophication documented in the Harbor before diversion included elevated concentrations of nitrogen, phosphorus, elevated concentrations of chlorophyll *a* (phytoplankton biomass), and low bottom-water concentrations of dissolved oxygen (DO). Other symptoms included the presence of benthic invertebrate communities

Figure 5.1. Total nitrogen and total phosphorus loading to Boston Harbor partitioned by source.



typical of degraded environments and loss of historic submerged aquatic vegetation.

Over the five years since discharges to the Harbor were ended, Harbor-wide average concentrations of total nitrogen (Figure 5.2a) and total phosphorus have decreased by 35% and 30%, respectively. Average summer chlorophyll *a* concentrations have decreased by 40% (Figure 5.2b). During mid-summer, average bottom-water DO concentrations have increased by 5% (Figure 5.2c).

Other changes in the Harbor have included decreased water column primary productivity, lowered benthic metabolism, and increased diversity of its benthic invertebrate communities (Figure 5.2d). Numerical modeling of the changes in the Harbor water column produced a good fit with real time data.

Future outlook

The responses of the Harbor water column to the end of direct wastewater treatment plant discharges were rapid, and have been sustained through the five years since the diversion. For the benthos, the changes have been slower, and are still underway. It will be interesting to see how the Harbor functions under its new, lower nutrient regime. Pilot studies are underway to determine the feasibility of restoring submerged aquatic vegetation in the Harbor.

Massachusetts Water Resources Authority

Boston Harbor contains numerous uninhabited islands.

Implications for other systems

Far less is known about the effects of decreased nutrient loadings than increased loadings on coastal bays and estuaries. Boston Harbor's unique situation may be relevant to other bays and estuaries subjected to large, rapid reductions in nutrient inputs.

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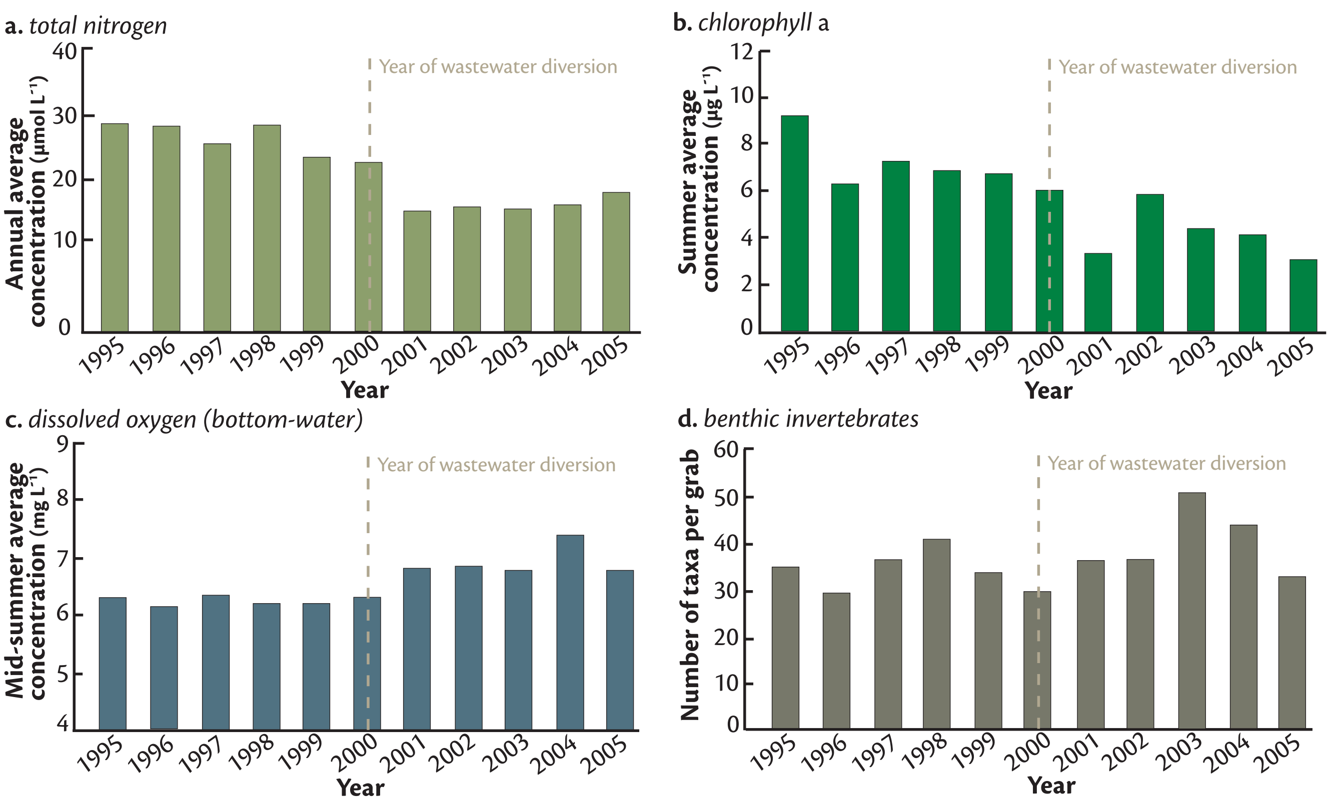
Figure 5.2. Changes in Boston Harbor nutrient concentrations and associated effects since wastewater diversion. Differences between periods before and after diversion tested using Mann-Whitney test.



CASCO BAY, ME: *Monitoring suggests anthropogenic and riverine sources of nutrients*

Diane M. Gould, U.S. Environmental Protection Agency

Casco Bay, in the Gulf of Maine, covers 593 km² of water surface. The Bay has 930 km of shoreline with rocky headlands, over 700 islands, and numerous coves and bays, including finger-like drowned river valleys in the northeast part of the bay. The 2,551 km² watershed is located in the most densely populated part of Maine, with its 41 cities and towns holding a quarter of the state's population. Since 1970, most of the Casco Bay watershed communities have surged in growth, many of them more than doubling in size. Impervious surface now covers 5.9% of the watershed, with the highest levels along the coast and transportation corridors. Casco Bay shows signs of anthropogenic stress, including elevated concentrations of toxic chemicals in the sediments and bacterially-polluted closed shellfish beds. Since 1990, Casco Bay has been part of the National Estuary Program, with local, state, and federal partners focused on protecting and preserving the resources of the bay.

Influences of anthropogenic nutrients

Casco Bay is located in the Acadian biogeographic province where the water is relatively cold and well-flushed, compared with the waters of the Virginian province (Cape Cod and southward). The colder waters of the Bay should make it less susceptible to oxygen stress than the warmer waters further south. But, the questions remain: 1) what effect are anthropogenic nutrients having on the bay? 2) are there areas of low dissolved oxygen? 3) if so, what is causing the low DO and how is it changing over time? 4) are there other indicators of eutrophication? For example, are the periodic outbreaks of red tide in Casco Bay evidence of excess coastal nutrient inputs?

History of anthropogenic nutrients in this region

The water quality of Casco Bay is an important indicator of the overall health of the bay's ecosystem. The levels of dissolved oxygen and nutrients, for example, have a major impact on the health of the biological community. Friends of Casco Bay (FOCB), with support from Casco Bay Estuary Partnership (CBEP), have successfully conducted the ongoing Citizens Water Quality Monitoring Program in the Bay since 1993. The program is carried out with the aid of more than 100 citizen volunteers who sample surface waters at 80 shore-based stations. They also assist FOCB professional staff with sampling at 11 profile stations located throughout Casco Bay. Measurements include temperature, salinity, pH,

Table 5.1. Summary statistics for all estuarine surface data in Casco Bay (1993–2004).

	Water depth (m)	Temp (°C)	Salinity (psu)	DO (mg L^{-1})	DO (% saturation)	pH	Secchi Depth* (m)
Mean	7.25	12.95	29.03	9.20	103.5	7.94	2.98
Standard deviation	7.68	5.36	4.48	1.48	12.1	0.19	1.42
Minimum	0.1	-3.0	0.0	2.6	33.9	6.0	0.2
Maximum	55	30.0	34.0	14.9	177.5	8.6	15.3
Count	7022	8408	8329	8214	8126	7966	3808

***Secchi depth is a measure of water clarity. For Secchi depth, the summary statistics were calculated from 40 selected sites (FOCB and CBEP 2006).**

Table 5.2. Summary statistics for all nutrient data in Casco Bay (2001–2004).

	$NO_3 + NO_2$ (μM)	NH_4 (μM)	SIO_4 (μM)	PO_4 (μM)
Mean	2.57	2.60	6.97	0.95
Standard deviation	3.15	3.29	4.89	0.56
Minimum	0.0	0.0	0.0	0.0
Maximum	16.65	23.98	30.32	3.23
Count	1307	1302	1337	1338

water clarity, and dissolved oxygen (Table 5.1). Fluorescence of chlorophyll and dissolved inorganic nutrient measurements were added to the FOCB monitoring program in 2001.

An analysis of 12 years of water quality data (1993–2004) indicates that overall water quality in Casco Bay is generally good. Dissolved oxygen (DO) is usually well above state standards and not close to levels that would impair biological processes. DO concentrations in coastal waters are a dynamic property, varying spatially and temporally depending on physical, seasonal, biotic, and anthropogenic influences. A few areas of concern were found in locations with potentially heavy nutrient loading either directly from point sources (Portland Harbor) or indirectly from riverine and other non–point sources (Royal River, Presumpscot River, and Harraseeket River) and also in waters where restricted circulation may exacerbate low DO conditions (New Meadows River and Quahog Bay). Nevertheless, low DO events tend to be exceptions rather than the rule in Casco Bay waters (FOCB and CBEP 2006). The minimum and maximum values for each of the parameters in Table 5.1 provide a good representation of the variability among sites, across the bay, and over time.

The mean nutrient concentrations for nitrate plus nitrite (NO_3+NO_2), ammonia (NH_4), silicate (SIO_4), and phosphate (PO_4) are typical of northeastern coastal waters, but the highest values measured suggest anthropogenic and riverine inputs (Table 5.2).

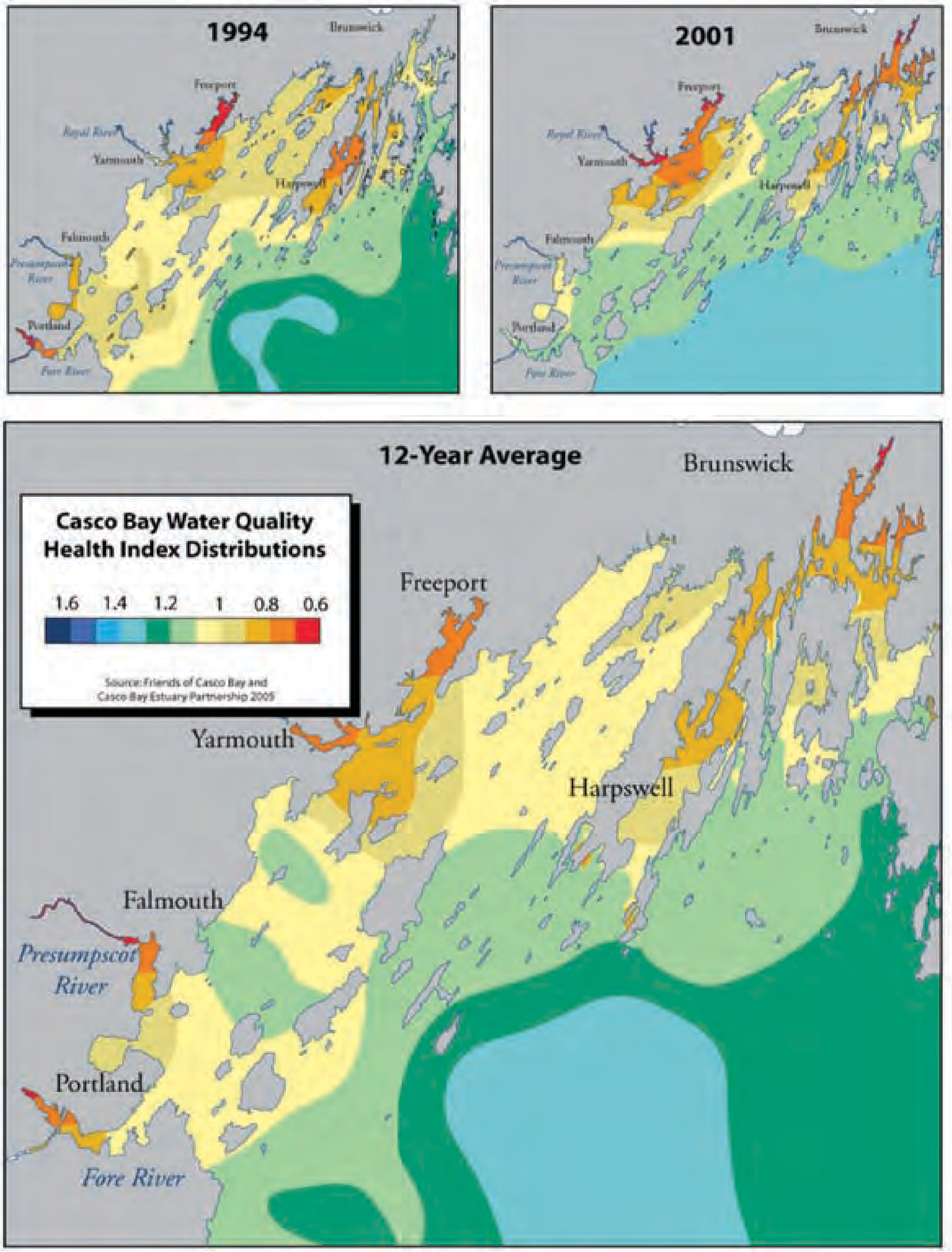
Management concerns

The 12 years of monitoring data have been used to develop the Casco Bay Water Quality Health Index (Figure 5.3). The index combines several water quality parameters to provide a reliable, uncomplicated indicator of the Bay's overall surface water quality. The index is based on DO percent saturation and water clarity. Both of these parameters are useful as measures of water quality and the impacts of eutrophication. For each monitoring site, the summer means of these two parameters are scored on their relative position between conservatively set low and high thresholds (65–95% and 0.5–3.5 m). The mean of these two values is the final index score. By summarizing these environmental parameters into one score, sites can be ranked, areas of concern identified, and trends in water quality may become more apparent over time.With a few exceptions, water quality is generally quite good throughout Casco Bay. Trends in the 12-year data set indicate that overall DO concentrations are increasing, which suggests that management actions focused on protecting the Bay's waters are having a positive impact.

Outbreaks of the red tide organism *Alexandrium fundyense* have sometimes been suggested as an indicator of eutrophication. During the spring and summer, red tide blooms are a common occurrence in Casco Bay. In 2005, an extensive bloom lasting from May to July covered the coast of southern New England from central Maine to Nantucket Island and Martha's Vineyard, closing shellfish beds and causing economic disaster for commercial harvesters. From a management perspective, it is important to

A citizen volunteer monitor from the Friends of the Casco Bay takes water quality measurements.

Figure 5.3. Casco Bay Water Quality Health Index distributions.*



* The poorest surface water quality is indicated by a score of 0.6 (red), the best by a score of 1.6 (dark blue). On average, the lowest scores are found in Portland Harbor, in the vicinity of the Presumpscot and Royal Rivers, and in the restricted embayments in Northeastern Casco Bay. There is a clear inshore–to–offshore increase in the index with the highest score consistently calculated for the site near Halfway Rock. This is due to both higher DO levels and greater water clarity further away from anthropogenic and riverine inputs. Year-to-year variability is evident in the distribution of the index as indicated by the plots for 1994 and 2001. In 1994, low DO concentrations were observed at numerous sites along the northeastern coastline and are depicted here as lower scores further offshore. In 2001, water quality was better throughout much of Casco Bay, though low scores were still seen at a few of the areas of concern. Note that most of the sites score ≥1, indicating that even when using relatively conservative low and high thresholds, surface water quality appears to be good throughout most of Casco Bay (FOCB and CBEP 2006).

understand how red tide blooms are initiated and maintained in Casco Bay and other coastal areas. Recent studies conducted in the Gulf of Maine indicate that *Alexandrium* blooms are initiated from cyst beds located offshore and are moved onshore to shellfish areas by wind-driven transport. The blooms are fed by nutrients originating in the Gulf source waters. Source waters with high nitrogen and nitrogen-to-silicon ratios favor the development of *Alexandrium* blooms in offshore waters. The intense bloom of 2005 likely resulted from high freshwater inputs into the Gulf and unusual wind patterns, with numerous northeast storms in spring and early summer (Anderson et al. 2005, Townsend et al. 2005, Keafer et al. 2005). This research suggests that red tide outbreaks are not a useful indicator of anthropogenic eutrophication in Casco Bay, since the blooms are initiated offshore and fed by offshore sources of nutrients in the Gulf of Maine.

Future outlook

FOCB is continuing its long-term monitoring of the water quality of the Bay, looking for trouble spots and assessing temporal and spatial trends in dissolved oxygen, nutrients, and other parameters. For the past several years, CBEP and FOCB have been studying the cause of low DO in the bottom waters of Quahog Bay, located in the northeastern part of the bay. Results of a 2005 deployment of Acoustic Doppler Current Profilers suggest that the bottom waters of Quahog Bay have little exchange with waters from outside the Bay, leading to accumulation of organic matter and high bacterial respiration which drives the low DO levels. Further studies in summer 2006 assessed the role of circulation in the bottom waters during the warmest and most oxygen-depleted time of year.

Implications for other systems

The results of the 12-year water quality analysis in Casco Bay suggest that generally the cold, well-flushed waters of the Gulf of Maine are less impacted by eutrophication than waters farther south. Areas with potentially heavy nutrient loading, for example, where there are major point sources and at the mouths of rivers, or where circulation is restricted, are vulnerable to low dissolved oxygen.

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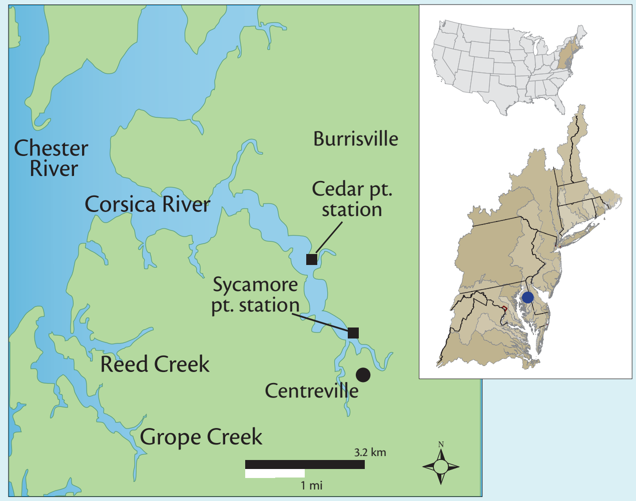
CORSICA RIVER, MD: *Water quality monitoring helps explain extreme events*

William D. Romano, Mark Trice, and Peter Tango, MD Department of Natural Resources

The Corsica River is located in the Chester River basin on Maryland's Eastern Shore. Designated uses are assigned to habitats in this and other state waterways under the Code of Maryland Regulation. Each use is associated with supporting water quality criteria. Portions of the River's watershed do not meet their designated use and are tracked as impaired waters under Section 303(d) of the Federal Clean Water Act. These impairments in the watershed are due to excessive nutrients (nitrogen & phosphorus), fecal coliform bacteria, sediment, poor biotic communities, and a fish consumption advisory based on toxic compounds such as polychlorinated biphenyls (PCBs) and dieldrin. The tidal portion of the Corsica River was listed as an impaired water in 1996 for nutrients, and is the focus of this case study.



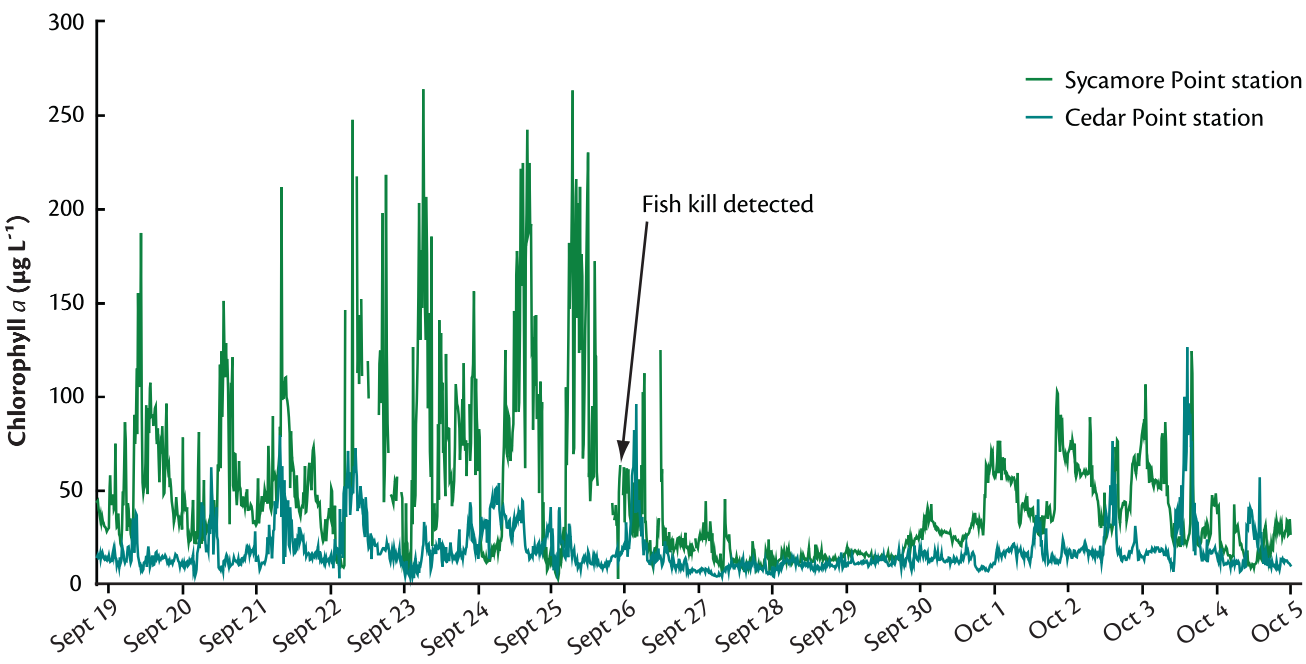
Impaired use

The April 2000 report *Total Maximum Daily Loads of Nitrogen and Phosphorus for Corsica River* stated that impairment by nitrogen and phosphorus contributes to excessive algal blooms and dissolved oxygen concentrations that do not meet the State of Maryland open-water, 30-day standard of 5.0 mg L^{-1} (Maryland Department of the Environment 2000). The algae, dissolved oxygen, and light limitation problems resulting from excess nitrogen and phosphorus have caused impairments and led to the Corsica River not meeting its designated uses. Water quality conditions for 2005 and 2006 are available at *www.eyesonthebay.net* (MDDNR).

History of impaired use in this region

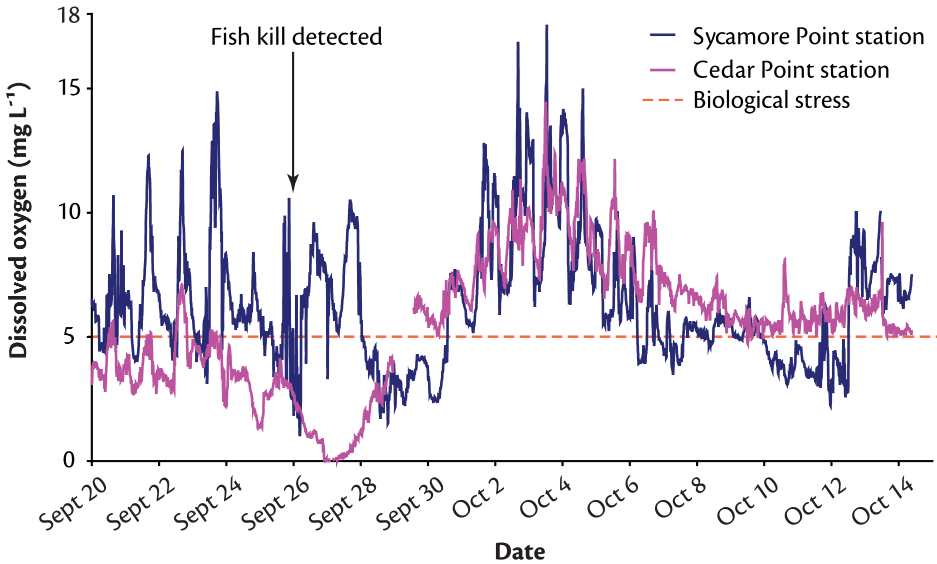
Although nitrogen and phosphorus are necessary to support aquatic life, excess nutrients can lead to algal

Figure 5.4. Continuously monitored chlorophyll *a on the Corsica River. Concentrations at Sycamore Pt. reached nearly 300 µg L^{-1} during the third week of Sept., 2005 (fall fish kill), decreasing dramatically during the last week.**



*Chlorophyll *a* is in this case measured by fluorescence.

Figure 5.5 Dissolved oxygen concentrations at Sycamore Point and Cedar Point in 2005.



Mark Trice, Maryland Department of Natural Resources

Fish kill caused by low dissolved oxygen in Corsica River.

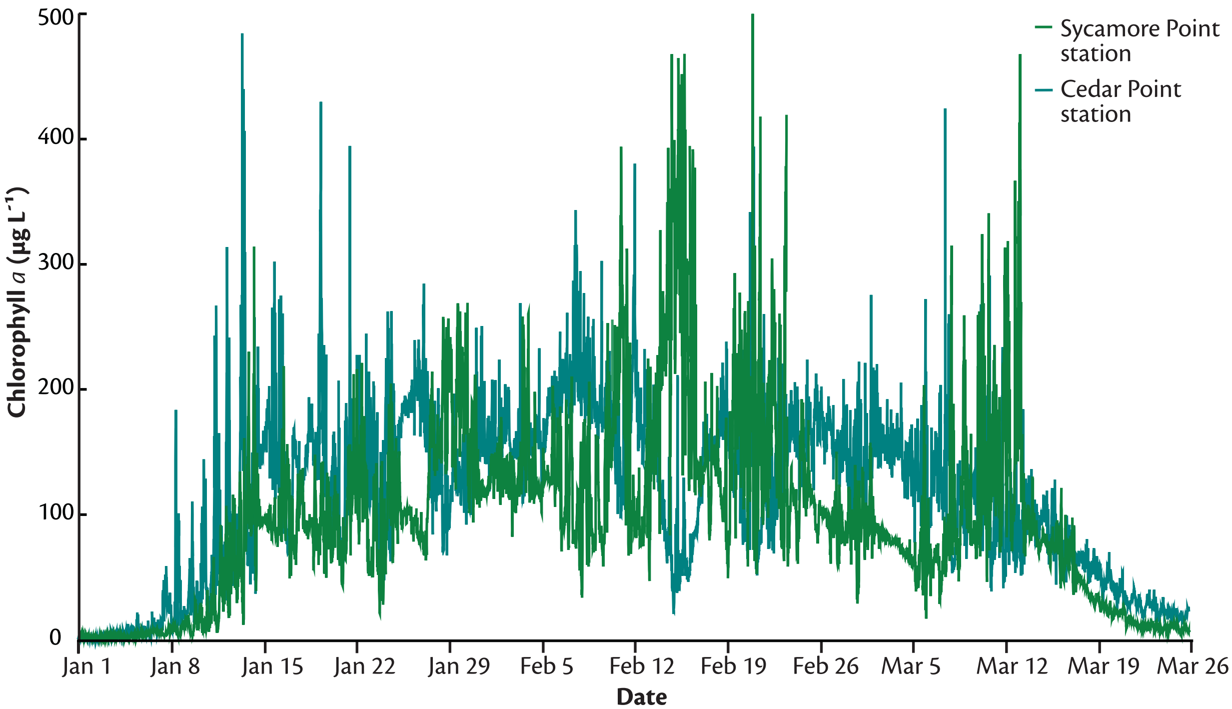
blooms, which contribute to low dissolved oxygen when the blooms die-off. One such algal bloom resulted in a fish kill detected on 26 September 2005 during routine water quality monitoring conducted by the Maryland Department of Natural Resources (DNR). The fish kill intensified as it continued throughout the week, and an estimated 50,000 fish had died by 29 September. The fish kill is considered the result of the combined stresses from low dissolved oxygen, and the presence of sufficient 'karlotoxins' (potent chemicals associated with the algal species *Karlodinium venificum*) in the water to impair fish health. Water samples collected over 8 km of river during the kill on 26 September and 27 (n=6; 3 each day) contained concentrations of karlotoxin KmTx[1] with a maximum of approximately 60 µg L^{-1} and mean KmTx[1] of 26.6 µg L^{-1}. Stressful to lethal levels of dissolved oxygen were located in parts of the Corsica River throughout the week and salinity levels showed increases. Karlotoxins were also shown to be present in areas with dying fish containing dissolved oxygen concentrations averaging less than 5 mg L^{-1} each day with detection of hypoxic (2 mg L^{-1}) episodes. Necropsy only found gill tissue deterioration (M. Matsche, NOAA Oxford Laboratory, pers. comm.), consistent with laboratory findings of karlotoxin effects (Deeds 2003, Deeds et al. 2006). The combined effects of low or no dissolved oxygen availability in some regions and algal toxins at critical effects levels are largely considered to have combined to produce the kill.

Data collected by DNR at the Sycamore Point and Cedar Point continuous monitoring stations indicated a persistent algal bloom during much of September, with total chlorophyll *a* concentrations at Sycamore Point reaching nearly 300 µg L^{-1} (Figure 5.4). Chlorophyll *a* concentrations abruptly declined at the end of the month and started to rise again by 1 October. At the Cedar Point station dissolved oxygen started a downward trend below 5 mg L^{-1}, levels considered stressful to most fish, beginning 23 September (Figure 5.5). Dissolved oxygen levels reached zero (anoxic conditions) on 27 September at Cedar Point. Upstream at Sycamore Point, dissolved oxygen concentrations declined beginning 24 September, going below 5 mg L^{-1} on 25 September and below 2 mg L^{-1} (hypoxic conditions) on 27 September. Similar events occurred in 2006.

Future outlook

The five-year, $19 million Corsica River Pilot Project was developed in an effort to improve water quality throughout the 25,298-acre watershed and remove the river from the Impaired Waters List (303(d) list). To achieve the goals of improving water quality and delisting the river, a number of federal, state, and local government agencies, and non-profit groups are

Figure 5.6. Continuously monitored chlorophyll *a* on the Corsica River during the winter of 2006.



planning to implement a series of best management practices (BMPs), including cover crops, wetlands restoration, storm water retrofits, septic system upgrades, wastewater treatment plant upgrades, and oyster and submerged aquatic vegetation restoration. The BMPs will focus on reducing nutrients from agricultural sources, which account for 86% of the nitrogen load and 84% of the phosphorus load, based on model results (Maryland Department of the Environment 2000).

Water quality and biological monitoring will be used to judge the success of the Pilot Project. Water quality monitoring will include the assessment of dissolved oxygen, chlorophyll *a*, nutrients, and water clarity. This monitoring will take place at a new long-term ambient monitoring station in the tidal area, two continuous monitors that take water quality readings around-the-clock at 15-minute intervals, and water quality mapping, which will enable field crews to monitor water quality over wide areas of the river. Continuous monitors will be deployed and water quality cruises will be scheduled for April–October, which coincides with the submerged aquatic vegetation growing season. Biological monitoring will include assessing oyster populations (mortality, growth, disease infection, spat set, and number of oysters by size class) and aerial and ground surveys for submerged aquatic vegetation.

The best management practices planned for the Corsica River Pilot Project cannot be implemented too soon. After the fall bloom of *Karlodinium venificum* abated, a winter bloom of *Heterocapsa rotundata* was detected. Chlorophyll *a* concentrations at Sycamore Point ranged from 1–470 µg L^{-1} and averaged 97 µg L^{-1} for January–March 2006 (Figure 5.6). Concentrations at Cedar Point ranged from 2 µg L^{-1} to 245 µg L^{-1} and averaged 58 µg L^{-1} during the winter bloom. Interestingly, chlorophyll *a* levels decreased following periods of no rainfall, suggesting the inherent ability of the system to respond to reduced nutrient inputs from non-point sources.

Implications for other systems

If the nutrient reduction strategies implemented in the Corsica River Pilot Project result in improvements to water quality and living resources, the Project can serve as an example to managers who wish to implement BMPs in other watersheds.

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HOOD CANAL, WA: *The complex factors causing low dissolved oxygen events require ongoing research, monitoring, and modeling*

Jan Newton, University of Washington

Hood Canal, a fjord-like sub-basin of Puget Sound, Washington State, is a long (110 km), deep (100–200 m), narrow (1–2 km), productive (4000 mg C mg^{-2} d^{-1}) estuary with strong seawater density stratification (Δ sigma-t >2 all year) and slow circulation (months to year). Tidal range is 3.2 m and a sill near the mouth restricts exchange with Puget Sound. These conditions are conducive to seasonally low dissolved oxygen (DO) concentrations, which have been observed in records dating back to the 1930s. However, since the mid-1990s, the frequency, duration, and spatial extent of the hypoxia have increased. Because of extended fish kill events caused by low DO during the early 2000s, the Washington State Department of Fish and Wildlife indefinitely closed many fisheries in Hood Canal in 2003.

Dark color indicates the watershed of Hood Canal.

Decreases in dissolved oxygen over time

Dissolved oxygen concentrations in the deep waters of southern Hood Canal measured during the 1990s and 2000s are lower than those from the 1950s and 1960s, taken in the same manner (Figure 5.7). Additionally, the hypoxia is sustained through a longer portion of the year or, in some locations, all year long.

The location of the lowest DO concentration is in the southern reaches of Hood Canal, toward Lynch Cove (Figure 5.8). However, seasonally low DO develops at mid-depth along the mainstem as well. Episodic southerly wind events have been implicated in stimulating fish kills due to sudden upwelling of the subsurface DO minimum. Although biota kills in Hood Canal have been reported as far back as the 1920s (Fagergren et al. 2004), these events have occurred recently with high frequency, during 2002-2004, and an extensive event in September 2006.

Figure 5.7. Current and historical dissolved oxygen levels in southern Hood Canal near Lynch Cove.

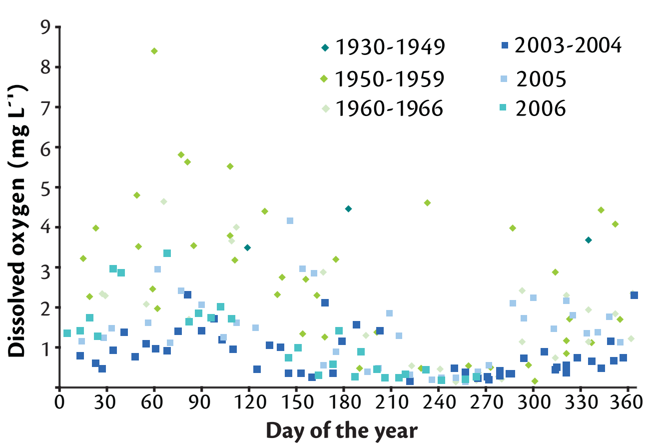
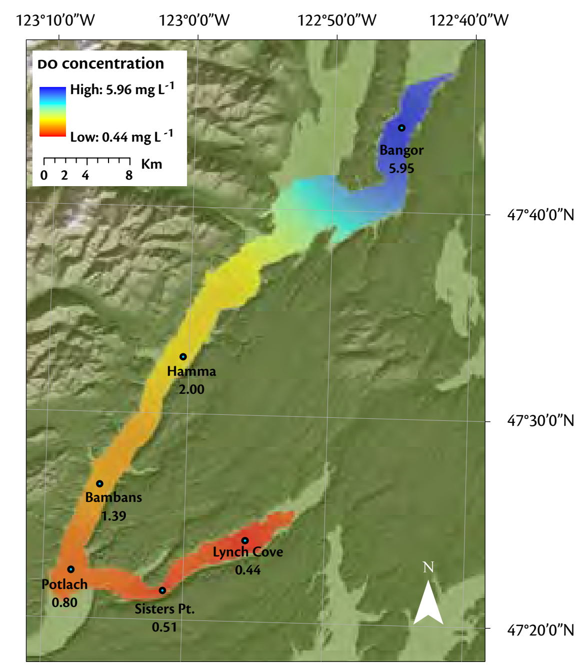


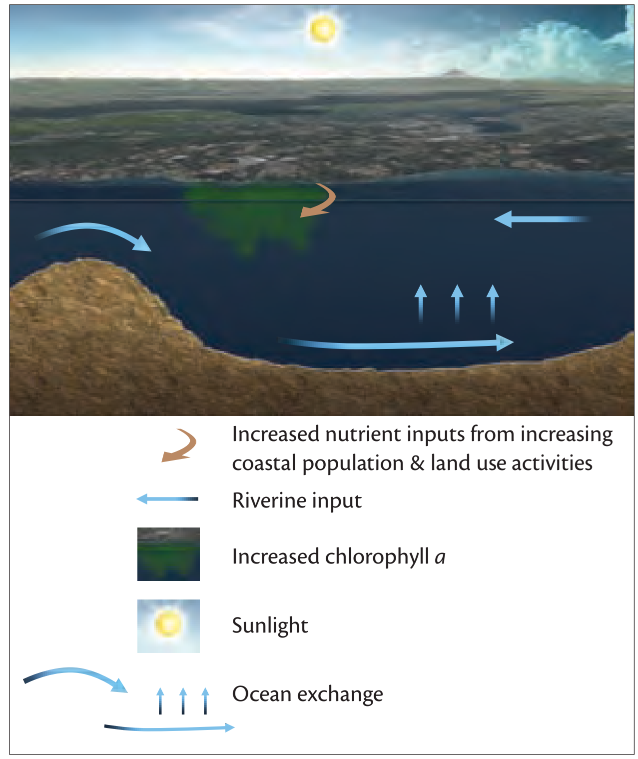
Figure 5.8. August 2006 interpolation reflecting typical pattern of low DO concentrations.



The University of Washington recorded low DO concentrations in Hood Canal as early as the 1930s and during the 1950s-1960s (Collias et al. 1974). At that time the hypoxia was largely confined to Lynch Cove and southern Hood Canal and lasted for three to six months. In 1991, NOAA scientists documented low DO concentrations in Hood Canal and Lynch Cove (Paulson et al. 1993) that appeared to be getting worse and speculated that anthropogenic sources of nitrogen could be a factor (Curl and Paulson 1991).

The slow overturning circulation of Hood Canal is known to be a natural factor conducive to seasonal hypoxia (Warner et al. 2001). Reports on results from the Puget Sound Ambient Monitoring Program during the 1990s showed more months with DO below 5 mg L^{-1} than were observed during the 1950s (Newton et al. 1995, Newton et al. 1998, Newton et al. 2002). These data, plus those collected presently through the Hood Canal Dissolved Oxygen Program (*www.hoodcanal.washington.edu*), show increased persistence and severity of the average DO concentration in southern Hood Canal.

Figure 5.9. Factors influencing low DO in Hood Canal.



Factors affecting dissolved oxygen levels

Causes for the severe and seemingly deteriorating low DO conditions are complex and may include changes in oceanic water properties that affect flushing; human-mediated loading of nitrogen or organics that could affect oxygen demand; changes in river flow delivery that could affect stratification and/or flushing; and changes in local weather forcing that could have wide-ranging effects (Figure 5.9).

Phytoplankton production in Hood Canal is limited by nitrogen; surface production can be enhanced as much as 300% by addition of nitrogen (Newton et al. 1995). Of all the Puget Sound regional systems, Hood Canal is most sensitive to nitrogen (Newton et al. 2002), but the change of nitrogen loading from the watershed to Hood Canal over time is not well known. Key sources of nitrogen loading are being better assessed (Fagergren et al. 2004, Paulson et al. 2006), but the temporal and spatial effects of these loads on oxygen is not adequately known. Septic fields and agricultural runoff are suspected, but other factors may be important. Changes in forests from conifers to alders that fix nitrogen may play a large role. Re-occupation of General Land Office surveys show riparian alders are much more common in 2003 than in 1870; over this period, 57.9% of cedar-spruce forest type sites transitioned to hardwood/mixed forest, dominated by red alder (Labbe et al. 2006).

Ocean dynamics may also be a major influence. Flushing of Hood Canal is driven by a push from incoming high-density Pacific Ocean water. Density of incoming water was relatively light during 2003-4 compared to earlier parts of the record (Figure 5.10). Additionally, the water within Puget Sound and Hood Canal was relatively denser than earlier in the record, primarily driven by a strong 'densification' during the

Figure 5.10. Density of seawater coming into Puget Sound/Hood Canal from ocean & within Puget Sound.

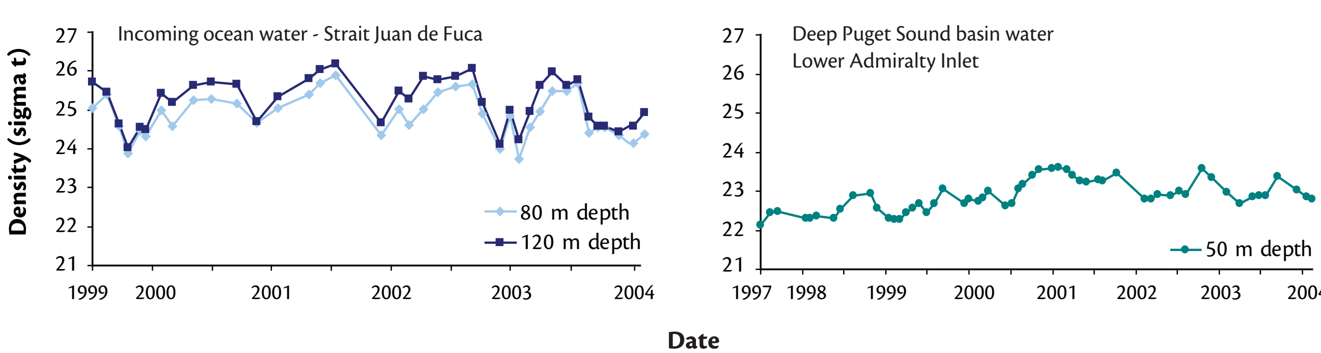
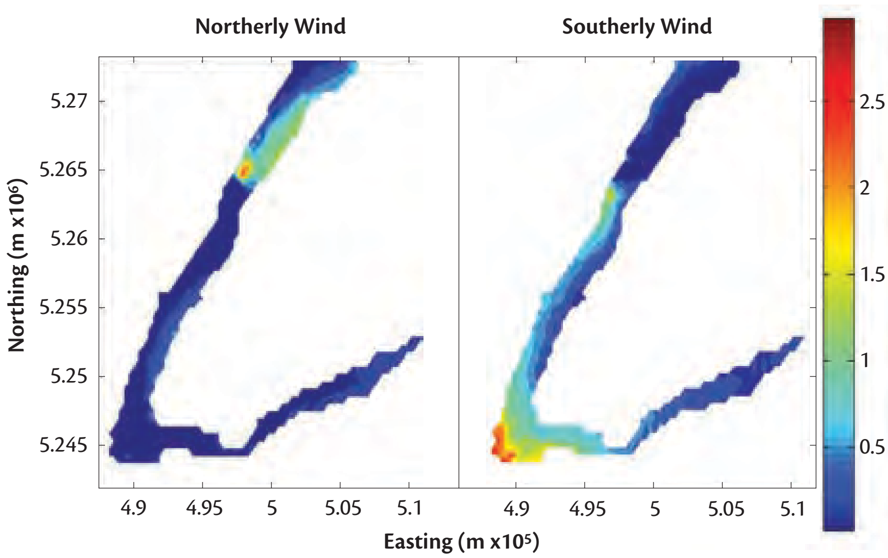


Figure 5.11. UW-PRISM model results for Hood Canal showing the effect of wind on sea surface salinity. Higher than usual salinity (warm colors) would be associated with deep, low DO water reaching the surface.*



*** The pattern shown for southerly winds is consistent with where fish kills are observed most intensely (e.g., September 2006 fish kill event).**

2000-2001 drought (Newton et al. 2003).

A weaker density gradient in 2003-4 would be consistent with a longer residence time in the estuary, allowing more respiration to occur before flushing, and contributing to the particularly low DO concentrations observed those years. Further evidence for an ocean-climate role in determining Hood Canal DO is seen from a correlation of low DO concentrations with weak coastal ocean upwelling, meaning that incoming ocean water is less dense and less likely to stimulate flushing of the estuary, despite having more oxygen. River flow changes affecting stratification may also be a factor.

The main tributary of Hood Canal, the Skokomish River, is impounded for hydroelectric power generation. While the dam dates back to 1926, the release of freshwater has changed substantially over the decades, as both population and power selling have increased. Alteration of the timing of flow, such as added freshwater flow in summertime, leads to enhanced stratification that minimizes vertical mixing, potentially enhancing the occurrence of hypoxia.

Climate variation may influence DO via several mechanisms, including sunnier summers (2003 and 2004, 2006), changes in precipitation (drought in 2000–2001, very wet in 2005), increasing temperature (a seawater temperature increase has been noted, though this alone cannot account for the DO variation), and wind.

Winds are important for driving both the outer Washington coast wind-mediated upwelling and for local processes. The outer coast upwelling intensity affects the water properties of the incoming ocean water to Hood Canal. The local winds can induce localized upwelling in Hood Canal and can be important for determining if fish kills occur. Models show that during and after a period of southerly winds, surface salinity becomes high, indicating that deep waters (with low DO) have upwelled and could potentially eliminate any refugia that biota could be using at the surface (Figure 5.11). The Great Bend area of Hood Canal and along the western shore of the main-stem are where fish kills are most severe.

Wind-mediated local upwelling was an important stimulant of the 2006 fish kill event where oxygen, quite low all summer, was at a minimum sub-surface (approximately 20 m) and was pushed up by an

HCDOP Emergency Response Team

Low dissolved oxygen conditions during a sustained portion of the year are associated with observations of dead benthos such as this lingcod.

oceanic intrusion of high density water (HCDOP 2007b). A shift from northerlies to southerlies caused sudden outcropping of the hypoxic water to the surface, and caught 1000's of fish in that layer. While this event contributed to a better understanding of the dynamics that increase risk for a fish kill event, the cause for the increasing severity and persistence of the hypoxia in Hood Canal is still not fully understood.

Future outlook

A focused observational-modeling study, the Hood Canal Dissolved Oxygen Program Integrated Assessment and Modeling Study, is being conducted to address the quantitative balance of these factors in driving observed hypoxia using a suite of observational data and models, both watershed and coupled physical/biological marine models (*http://www.hoodcanal.washington.edu*). The goal is to determine sources of low DO in Hood Canal and the effect on marine life, then work with local, state, federal, and tribal policymakers to evaluate potential corrective actions that could restore and maintain a level of DO that could reduce stress on marine life.

Implications for other systems

Hood Canal is regionally unique in its fjord-like nature, but other Puget Sound inlets have similar attributes. Of common interest is the effect of coastal Pacific Ocean upwelling and water properties on driving hypoxia intensity in Puget Sound and other west coast estuaries.

University of Washington http://orca.ocean.washington.edu/index.html

Oceanic Remote Chemical Analyzer (ORCA) moorings provide near real-time data of water and atmospheric conditions.

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LAGUNA MADRE, TX: Ecosystem transition occurred with initiation of brown tides

Chris Onuf, U.S. Geological Survey and Ken Dunton, University of Texas at Austin

Laguna Madre, the southern-most bay system along the Texas coast, is a long (190 km), narrow (10 km at its widest), shallow (<3 m, except in dredged channels) estuary with limited circulation (turnover time >1 year). Seasonally and meteorologically driven changes in water level are more important than lunar tides in driving water exchange. Annually, evaporation is approximately twice precipitation, and no permanent stream discharges into the lagoon. As a result, the waters of the lagoon are hypersaline most of the time. In addition, submerged aquatic vegetation meadows cover approximately two thirds of the bottom. In the satellite photo at right, colors indicate land use: green (tilled fields), yellow-brown/red (grazing land), purple (urbanized; intensive agriculture—south of Corpus Christi and in the lower Rio Grande Valley), and mottled green (grassland with migrating sand dunes, south of Baffin Bay).

Persistent algal bloom—the Texas brown tide

Laguna Madre was known for its clear water until a phytoplankton bloom developed in spring 1990 and persisted long enough to earn its own name—the Texas brown tide. The first episode lasted until 1997, and others of shorter duration have occurred since, including one in progress as recently as December 2005. Although not acutely toxic to most of the biota, the bloom reduced light reaching the bottom long enough to eliminate 12 km^2 of submerged aquatic vegetation from deeper areas of the lagoon, and little recovery has occurred since. The concern is that a historically clear-water system has abruptly converted to one that supports algal blooms much of the time without obvious cause.

History of brown tides in this region

A retrospective analysis of the algal bloom conducted primarily by scientists at the University of Texas Marine Science Institute has demonstrated that the bloom initiated in Baffin Bay—a tributary of Upper Laguna Madre—in early 1990. The initiation of the brown tide is probably linked to a variety of unusual circumstances. A long drought period culminating in high salinities, and a hard freeze coinciding with extremely low water, preceded the initiation of the brown tide. The high salinity eliminated most species of phytoplankton and grazers. The hard freeze caused a major fish kill and even greater loss of invertebrates on the exposed mudflats. The bloom organism, *Aureoumbra lagunensis*, tolerates high salinities but is relatively slow growing and cannot assimilate nitrate. Despite its slow growth rate, *A. lagunensis* achieved bloom densities exceeding a million cells per ml, which was attributed to a lack of grazing pressure and availability of ammonium released from decaying fish and invertebrates. Other factors that contributed to the long persistence of the bloom include unpalatability or a feeding-depressant effect on most grazers tested, the low flushing rate of the system, and a nutrient subsidy from the gradual die-back of submerged aquatic vegetation. Although this *ad hoc* reconstruction accounts for the dynamics and controls of the first brown tide episode reasonably well, it is less satisfactory in accounting for the resurgence of the brown tide in subsequent episodes. Evidently, the blooms can be sustained at low levels of available nitrogen (Figure 5.12) and perhaps can be kick-started from resting stages in the sediments.

Future outlook of algal blooms

Laguna Madre is bordered primarily by a national park, a wildlife refuge, and very large ranches. The extreme north and south ends are becoming increasingly urbanized. Irrigation return waters from the Lower Rio Grande Valley agricultural district and wastewater inputs from most of the region's rapidly growing municipalities ultimately discharge into the middle reaches of lower Laguna Madre. Despite historic and current low nutrient loading, the lagoon has been subject to remarkably long-lasting dense blooms in the past 15 years. The very low flushing rate of the system must be a key determinant of its susceptibility to blooms, along with the exceptionally good adaptation of *A. lagunensis* to the unusual aquatic environment afforded by the lagoon. Any increase in nutrient inputs is likely to exacerbate the susceptibility of the lagoon to blooms. A watershed management plan associated with a Total Maximum Daily Load process for the main agricultural drainage area may counteract some of the effects of continuing development in the watershed.

Implications for other systems

Laguna Madre is an end member of the spectrum of U.S. estuaries in terms of salinity regime and flushing. If warming and drying trends continue, and if freshwater diversion increases as population increases, some other estuaries will become similar to Laguna Madre, especially the lagoonal portions of other Texas bays. Comparisons with other brown tide-supporting bays also would be of mutual value.

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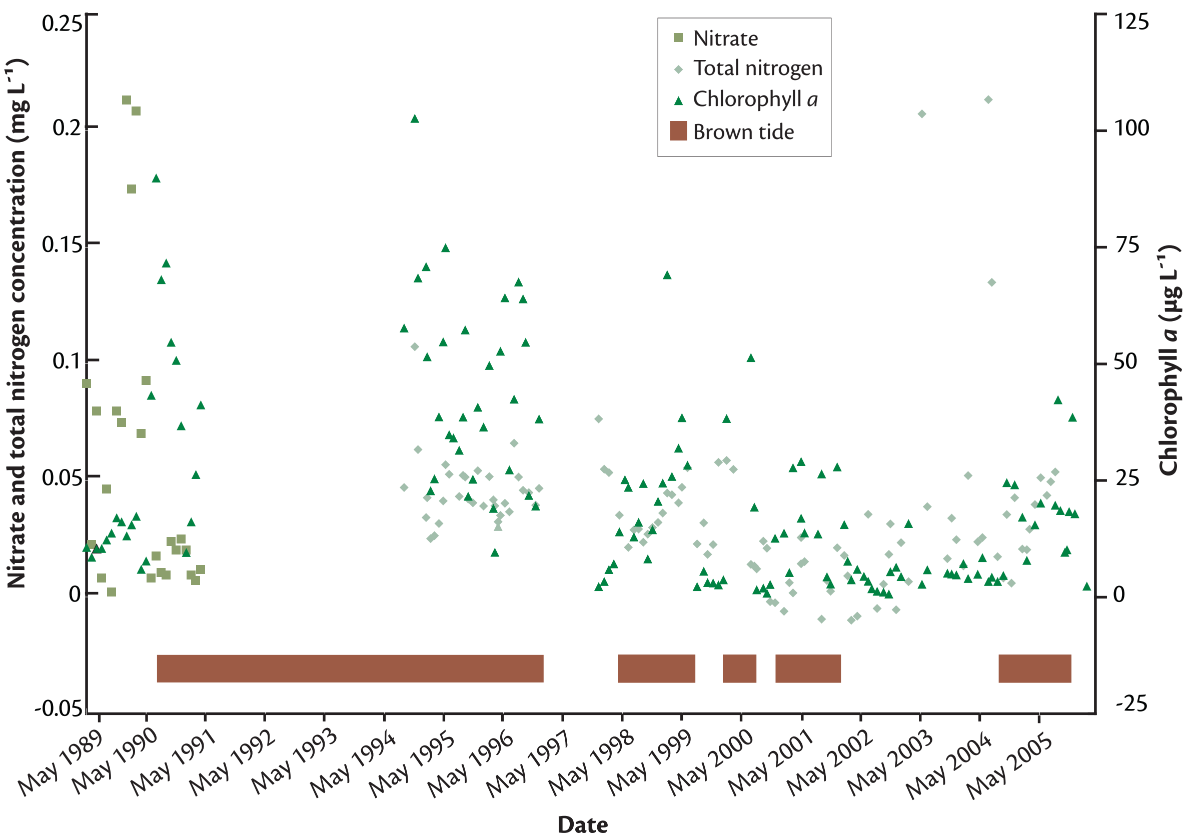
Figure 5.12. Inorganic nitrogen and chlorophyll *a* in Laguna Madre from 1989–2006.*

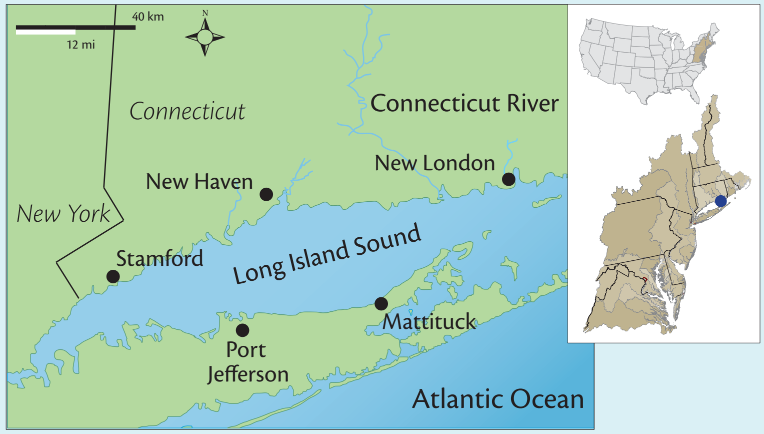


*Data for 1989–2006 are from an average of many stations, adapted from Figure 2 in Stockwell, D.A. et al. (1993) In T.J. Smayda and Y. Shimizu (eds.). Toxic Phytoplankton Blooms in the Sea. Elsevier Scientific Publishers. New York. p. 693–698. For 1994–2006, all data were from one station near the middle of upper Laguna Madre (K. Dunton, unpublished data).

LONG ISLAND SOUND, CT & NY: *Point source reductions lessened hypoxia in 1990s*

Paul E. Stacey, Connecticut Department of Environmental Protection

Long Island Sound is a large (3,056 km²) estuary, shared by Connecticut and New York. Its unique configuration connects it with the Atlantic Ocean via The Race River in the east and via the East River in the west. The Connecticut River, very near the sound's eastern terminus, contributes about two thirds of its freshwater input. Tidal amplitude ranges from about 2 m in the west to less than 1 m in the east. The Sound is moderately flushed, with mean residence times of 2–3 months. A highly developed watershed contributes to eutrophication.



Seasonal low dissolved oxygen

Long Island Sound has a large and highly developed watershed. Nitrogen contributions from the watershed, combined with strong summer thermal stratification in its western half, renders Long Island Sound susceptible to seasonal low dissolved oxygen levels (hypoxia). Since 1985, the causes and effects of hypoxia have been the subject of intensive monitoring, modeling, and research through the Long Island Sound Study (LISS). Hypoxia most seriously affects the western half of the Sound where dissolved oxygen (DO) concentrations fall well below Connecticut and New York standards each summer (Figure 5.13). Dissolved oxygen levels below 3 mg L^{-1} are usually observed, levels below 2 mg L^{-1} are not uncommon, and during some years portions of the Sound's bottom waters become anoxic (<1 mg L^{-1}).

History of dissolved oxygen in this region

Long Island Sound is surrounded by a highly urbanized landscape, including New York City in the west and sprawling metropolises in Long Island and Connecticut. Primary sources of nitrogen include sewage treatment plants (STP), non–point source runoff, and atmospheric deposition, all driven by human habitation of the watershed and airshed (Figure 5.14). Monitoring of Long Island Sound conducted by the Connecticut Department of Environmental Protection on behalf of the LISS has shown an annual recurrence and persistence of hypoxia over the last 15 years (Figure 5.15). Despite significant gains in reducing nitrogen loads by both Connecticut and New York under a Total Maximum Daily Load (TMDL) approved in 2001, oxygen improvements have been slow and masked by weather-driven variability.

Figure 5.13. Frequency of hypoxia in Long Island Sound, 1994–2002.

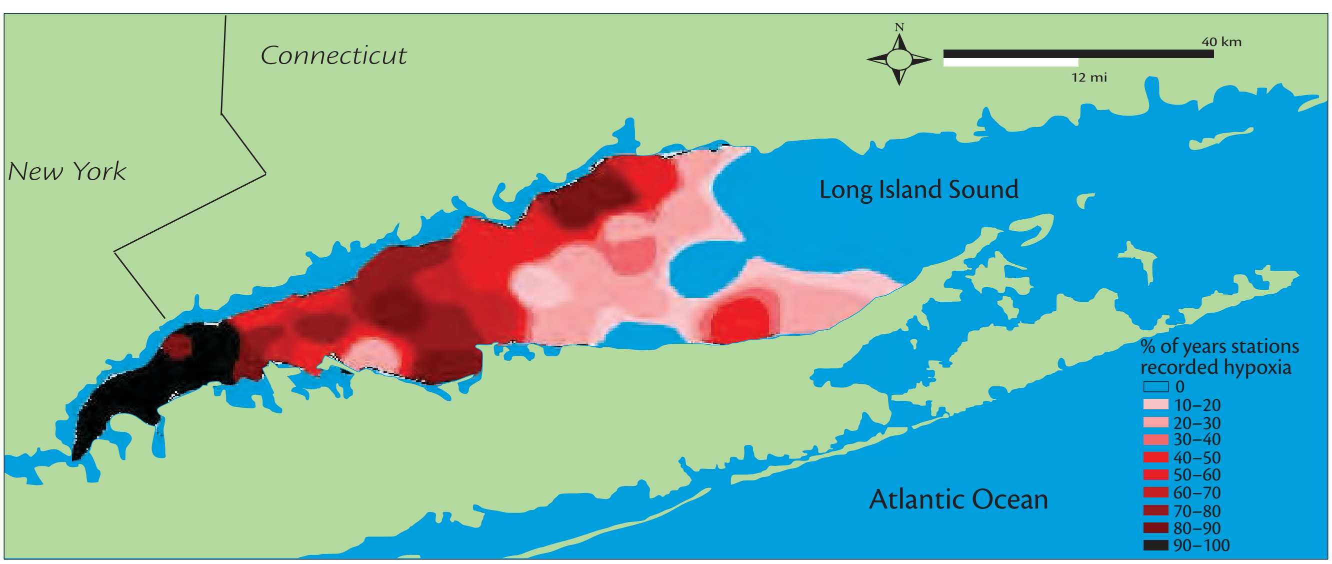
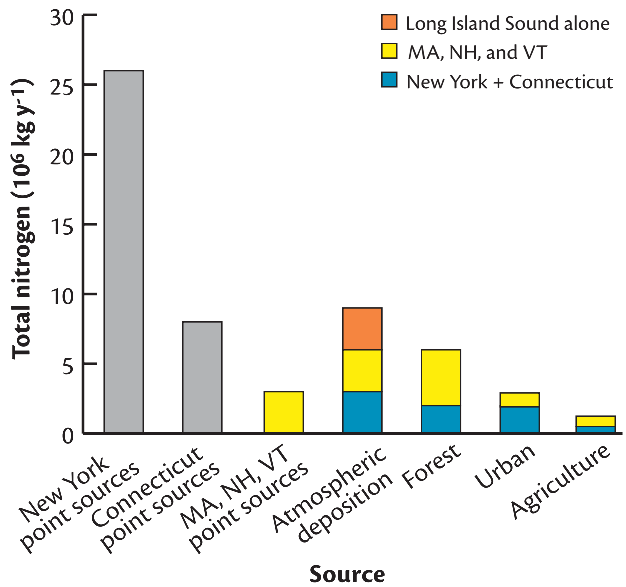


Figure 5.14. Nitrogen loads to Long Island Sound, ca. 1990.



Population continues to grow within the already densely-populated Long Island Sound basin, and contributes to the nitrogen load from STPs, as well as from non–point sources. This impact is large; since 1985, Connecticut's land conversion rate to developed uses was 11.3% for a population that had grown about 8.6%. Per capita consumption of land is outstripping population growth in Connecticut and throughout the basin.

Nitrogen enrichment, coupled with the sound's sensitivity to hypoxia due to relatively long residence time and seasonally strong stratification, leads to unhealthy conditions that are environmentally and economically costly for the sound and its users. Furthermore, submerged aquatic vegetation decline has been observed in many eastern Long Island Sound embayments and is believed to be linked to nitrogen enrichment. Nitrogen reductions to protect SAV will be much more stringent and difficult to attain than for low dissolved oxygen.

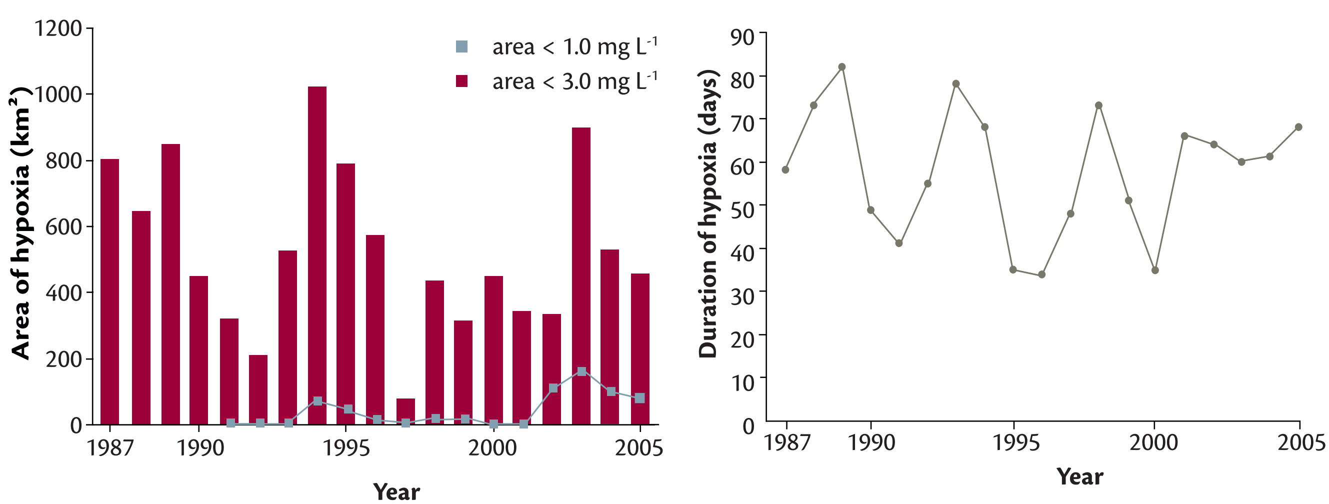
Management concerns

Considering that nature contributes at most about 10,000 metric tons of nitrogen every year to the Sound from its watershed, the nearly 38,000 metric tons per year added by more than 100 sewage treatment plants located along the coast and throughout the drainage basin have greatly enriched the ecosystem. Another 12,500 metric tons of nitrogen are contributed each year from non–point sources coming from excessive fertilizer added to lawns or agricultural crops, emissions (from automobiles, power plants, and industry), and animal wastes (including home septic systems).

Future outlook

Through the Long Island Sound partnership, a dissolved oxygen total maximum daily load (TMDL) was completed by Connecticut and New York and approved by the Environmental Protection Agency in 2001. Both states have aggressively pursued sewage treatment plant nitrogen control using biological processes and nitrogen loads are trending downward (Figure 5.16). New York has relied upon traditional permitting programs to limit individual STPs while Connecticut has instituted a state–wide nitrogen trading program for 79 municipal STPs. Collectively, the two states have accomplished a 30% reduction

Figure 5.15. The areal extent and duration of Long Island Sound hypoxia, 1987–2005.



in STP nitrogen loads towards the TMDL target of 60–65%. Connecticut and New York are also relying on stormwater permitting and non-point source programs to meet a 10% reduction target for urban and agricultural lands.

The non-point sources are more difficult and costly to control, especially atmospheric deposition, much of which originates from jurisdictions other than Connecticut and New York. If attained, promised reductions from Federal Clean Air Act initiatives will help Long Island Sound tremendously. The LISS is also working with Massachusetts, New Hampshire, and Vermont, states that share the Long Island Sound watershed, to ascertain what level of reduction might be cost-effectively achieved from those states.

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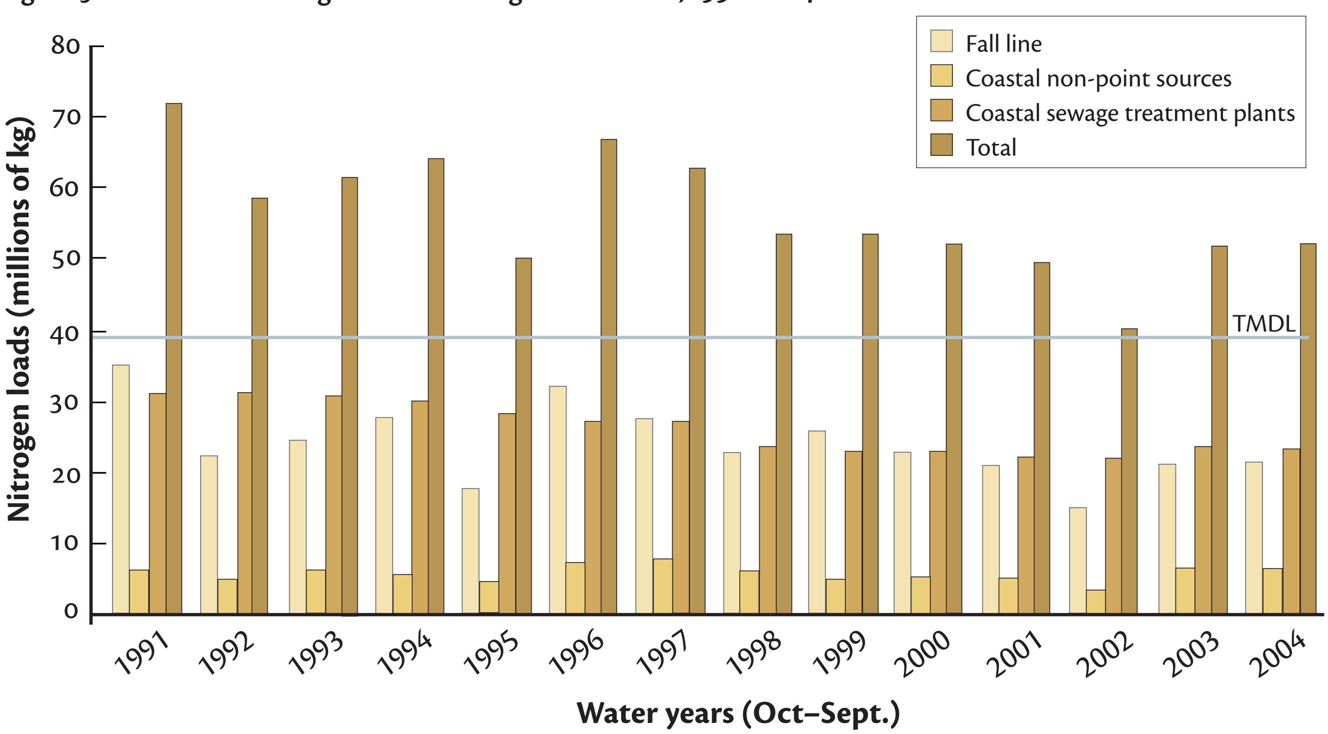
Figure 5.16. Estimated nitrogen loads to Long Island Sound, 1991–2004.



LOOE KEY, FL: Nutrients and climate change pose threat to coral reefs

Brian Lapointe, Brad Bedford, and Rex Baumberger, Harbor Branch Oceanographic Institution

Looe Key is a coral reef approximately 0.3 km^2 in area, located 7 km south of Big Pine Key in the lower Florida Keys. Increasing sewage discharges from development in the Florida Keys and stormwater runoff from agricultural areas of South Florida have increased nutrient concentrations at Looe Key over the past two decades, affecting optical clarity essential for coral health and increasing prevalence of macroalgae.

Brian Lapointe, Harbor Branch Oceanographic Institution

Nutrient enrichment and coral reefs

Coral reefs worldwide are threatened by a variety of human activities, including land-based nutrient pollution, the eutrophic effects of which may be exacerbated by climate change (e.g., precipitation, hurricanes). Looe Key, a National Marine Sanctuary since 1983, has experienced significant eutrophication as a result of human activities in its watershed (Lapointe et al. 2002). A significant increase in water column dissolved inorganic nitrogen (DIN) in the early and mid-1990s correlated with increased water deliveries and nitrogen loads from Shark River Slough which drains a significant portion of the Everglades Agricultural Area south of Lake Okeechobee (Figure 5.17a,b). The resulting eutrophication in the 1990s included blooms of phytoplankton (Figure 5.17b) and macroalgae, as well as a 250% increase in the incidence of coral diseases, including 'white pox' which afflicts elkhorn coral (*Acropora palmata*) and is caused by the fecal coliform bacterium, S*erratia marcescens* (Patterson et al. 2002).

History of coral reef impacts in this region

Coral reefs are biologically diverse ecosystems well known to be sensitive to low-level nutrient concentration increases. In South Florida, drainage of wetlands, increasing urbanization, and agricultural activity have increased nutrient loads to coastal waters in recent decades. During the early 1980s and again in the 1990s, South Florida water managers dramatically increased flows of nutrient-rich fresh water from agricultural areas of the northern Everglades to the Florida Bay/Florida Keys region (Figure 5.17b). Following these increased nitrogen loads, macroalgae and phytoplankton blooms increased in duration, frequency, and magnitude. Outflows of turbid, nutrient-enriched water from Florida Bay have negatively impacted coral reef communities of the Florida Keys National Marine Sanctuary (FKNMS), including Looe Key. Between 1996 and 1999, living coral cover in the FKNMS declined by 38%, to an average of 6.4% coverage, and elkhorn coral populations that once dominated the shallow fore reef at Looe Key have decreased by more than 95% (Porter et al. 2002). This loss of coral cover has resulted primarily from eutrophication, expressed as algal blooms (phytoplankton, macroalgae, turf algae, cyanobacteria), coral diseases (including black-band, yellow-band, and white-pox disease), and decreased water clarity, though these impacts may have been exacerbated by climate change.

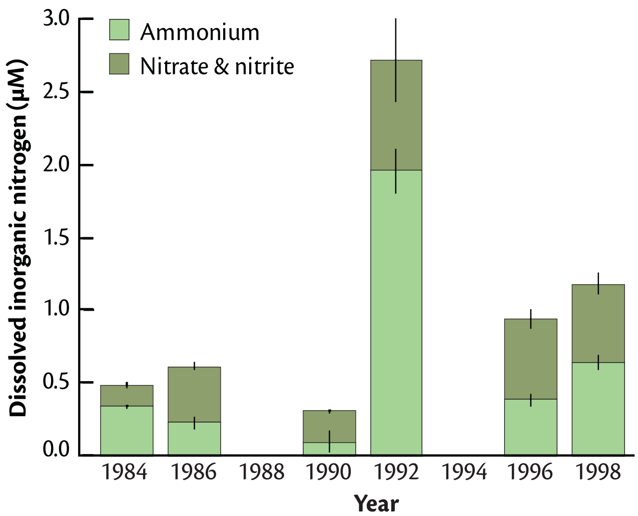
Reef building corals require optically clear water ($K < 0.18\ m^{-1}$) and high levels of downwelling irradiance (Yentsch et al. 2002), but optical clarity of water in the Florida Keys has diminished in recent decades, as evidenced by higher average water column light attenuation coefficients ($K\ m^{-1}$) than were observed in the past. This reduced light availability, stemming from degradation of water quality, has presented an additional threat to coral survival. The increase in nutrient concentrations in recent decades has supported increased macroalgal growth and reproduction at Looe Key. For example, blooms of the green alga *Codium isthmocladum*, a well-known nutrient indicator species not found at Looe Key before the early 1980s, have appeared in recent years and continue to develop in response to increasing nutrients. Stable nitrogen isotope data have also been used to demonstrate that land-based nitrogen enrichment from sewage in the Florida Keys and from agricultural sources in South Florida have supported macroalgal blooms at Looe Key in recent years (Lapointe et al. 2004). Nitrogen-enhanced macroalgal growth has also overwhelmed the ability of herbivores to control macroalgal biomass at Looe Key, despite high rates of grazing by large populations of parrotfish and surgeonfish.

Future outlook

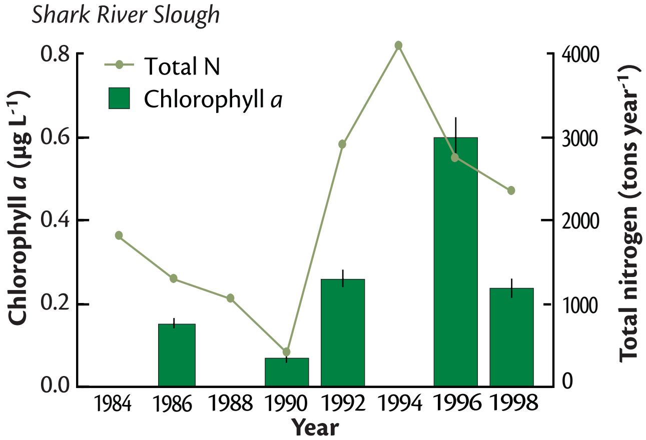
Because of the influences of expected increases in residential population growth and climate change in the Florida Keys and South Florida, the issues associated with eutrophication and coral reef degradation will become more pressing. Because coral reefs are subject to the effects of climate change, which has increased the frequency of mass coral bleaching events globally (Buddemeier et al. 2004), coral bleaching is likely to become a chronic source of stress for Caribbean reefs in the near future (McWilliams et al. 2005). These combined stresses may work in a synergistic manner to hasten the loss of coral reefs at Looe Key. The Everglades Restoration Plan in particular includes policies that could increase water flow and nitrogen loads to western Florida Bay and the Florida Keys. A better understanding of the combined pressures contributing to this problem will be required if it is to be managed effectively, and new approaches must include methods for the removal of nitrogen from Shark River Slough before discharge into coastal waters.

Figure 5.17. Nutrient enrichment in Looe Key reef.*

a. *Annual mean dissolved inorganic nitrogen at Looe Key*



b. *Annual chlorophyll* a *and total nitrogen flux from Shark River Slough*



***While unusual in many systems, ammonium was higher than nitrate & nitrite periodically, especially during a big spike in '92 following a release of large amounts of ammonia-based fertilizers used on sugarcane fields.**

Implications for other systems

As part of the FKNMS, Looe Key has been a 'No-take Zone' protected from overfishing since 1983. As such, it is a prime location for the study of eutrophication impacts on reef fish assemblages in the absence of local fishing pressure. Comparisons among fish censuses conducted in the early 1980s (Bohnsack et al. 1987) and in 2002 indicated that snapper, grouper, and grunt populations had decreased by more than 75% during that time, whereas herbivorous fish populations such as parrotfish and surgeonfish had doubled. These data illustrate the importance of water quality to the survival of coral reef habitat and to the sustainability of associated reef fish populations.

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MD COASTAL BAYS: Trend reversal likely caused by recent increase in diffuse nutrients

Catherine Wazniak and Matthew Hall, MD Dept. of Natural Resources; Brian Sturgis, National Park Service

The Maryland Coastal Bays are lagoonal estuaries located behind the barrier islands of Fenwick and Assateague. The bays are characterized by shallow depths (average 2 m), high salinities (average 25 psu), sandy sediments, and limited freshwater flow. Circulation in the bays is controlled by wind and tides. Tidal exchange with the ocean is limited to two inlets, one dividing Fenwick and Assateague Islands and the second in Virginia, south of Chincoteague Island. The Coastal Bays are classified as microtidal (0.12–1.04 m) and flushing is slow (10–21 days in the northern and 63 in the southern bays). The flat landscape and sandy soils allow rainwater to seep into the ground quickly, so that groundwater serves as a major source of freshwater. These natural characteristics drive ecosystem processes, but these processes are affected by anthropogenic influences.

Trends in eutrophication

Due to the long residence time of water within the estuary, nutrient enrichment is the primary threat to biological impairment in the Maryland Coastal Bays. Nutrient loads to the bays are dominated by non-point sources (e.g., surface runoff, groundwater, atmospheric deposition, and shoreline erosion) (Boynton et al. 1996, Wells et al. 2004). Negative impacts of eutrophication contribute to the deteriorating conditions of bay resources on which the economy depends.

Managers need to know whether or not eutrophication is increasing. Trend analyses (either improving or degrading water quality) were used to determine whether management actions were helping to improve conditions in the bays. Data collected from 1987 to present by the National Park Service at Assateague Island National Seashore in the southern bays were used to analyze potential linear and non-linear trends.

History of eutrophication in this region

Until 2005, linear trends were the historic method for analyzing change in the bays. Linear trends showed a majority of stations with no significant trend. Among those with a trend, most were significantly decreasing in nutrients. Only two stations had significantly increasing linear trends in nutrients (Figure 5.18a). These two stations had no proximate point source discharges. Therefore, increases in nutrients and subsequent chlorophyll *a* concentrations were believed to be from local non-point sources. Recent nitrogen isotope ratio studies revealed sources of highly processed nitrogen in the areas of these two stations, which may indicate sewage/septic inputs (Jones et al. 2004).

Non-linear trend (quadratic) analysis was undertaken because observations of raw data indicated the potential for trend reversals not detected using linear trend analyses (i.e., trends that shifted direction over the period of record) (see Figure 5.18b). Of the 18 stations tested for polynomial trends, 89% had significant quadratic trends (concave or U-shaped) in total nitrogen (TN), 78% for total phosphorus (TP), and 50% for chlorophyll *a* (Figure 5.18b). All of these significant quadratic trends were from a decreasing condition to either an increasing or not significant (asymptotic) condition. Additionally, 83% of the sites were significantly degrading post-inflection in terms of TN, 61% for TP, and 33% for chlorophyll *a* (Figure 5.18b). Critical inflection points for these trends ranged between the years 1995 and 2000. These dates were used to frame a time of vital change for the estuary (Figure 5.19).

Management concerns

Managers and scientists are concerned that leveling of submerged aquatic vegetation (SAV) abundance coincides with the inflection period of nutrient/chlorophyll *a* trend reversals (current SAV coverage is believed to occupy 67% of potential habitat).

The variability of SAV among segments (6% habitat occupied in St. Martin River vs. 77% in Sinepuxent Bay) has been directly correlated to the regional water quality index that combines TN, TP, chlorophyll *a*, and DO (r^2=0.66; p <0.05) (Wazniak et al. in press).

The widespread distribution of currently degrading trends throughout the southern bays indicates a large-scale non-point source impacting water quality. Land cover in these watersheds is predominantly forest, agriculture, and wetlands. Groundwater inputs from agriculture or increased septic inputs, as well as increases in atmospheric deposition, may explain the currently increasing nutrients. Since delivery of groundwater to the bays is much slower than surface runoff (several years to decades compared to hours or days), nutrients currently entering the bays may have been applied to the land many years ago (Dillow et al. 2002). Dissolved organic nitrogen is believed to be driving the currently increasing TN trends in the southern bays (Glibert et al. in press). Current trend reversals are a warning sign that efforts to protect this fragile ecosystem must increase.

Future outlook

To accurately evaluate eutrophication, both types of trends are important to assess the effectiveness of management actions and habitat value for living resources. Though water quality appears to be worsening, critical SAV habitat criteria have not yet been exceeded (Wazniak et al. 2004). However, if degrading trends continue, the bays will lose an important habitat as well as the living resources that depend on it.

Implications for other systems

The water quality trends observed in the Maryland Coastal Bays may also be observed in other coastal systems that have reduced point sources but are struggling to keep non-point sources under control.

Figure 5.18. Water quality trend analyses.

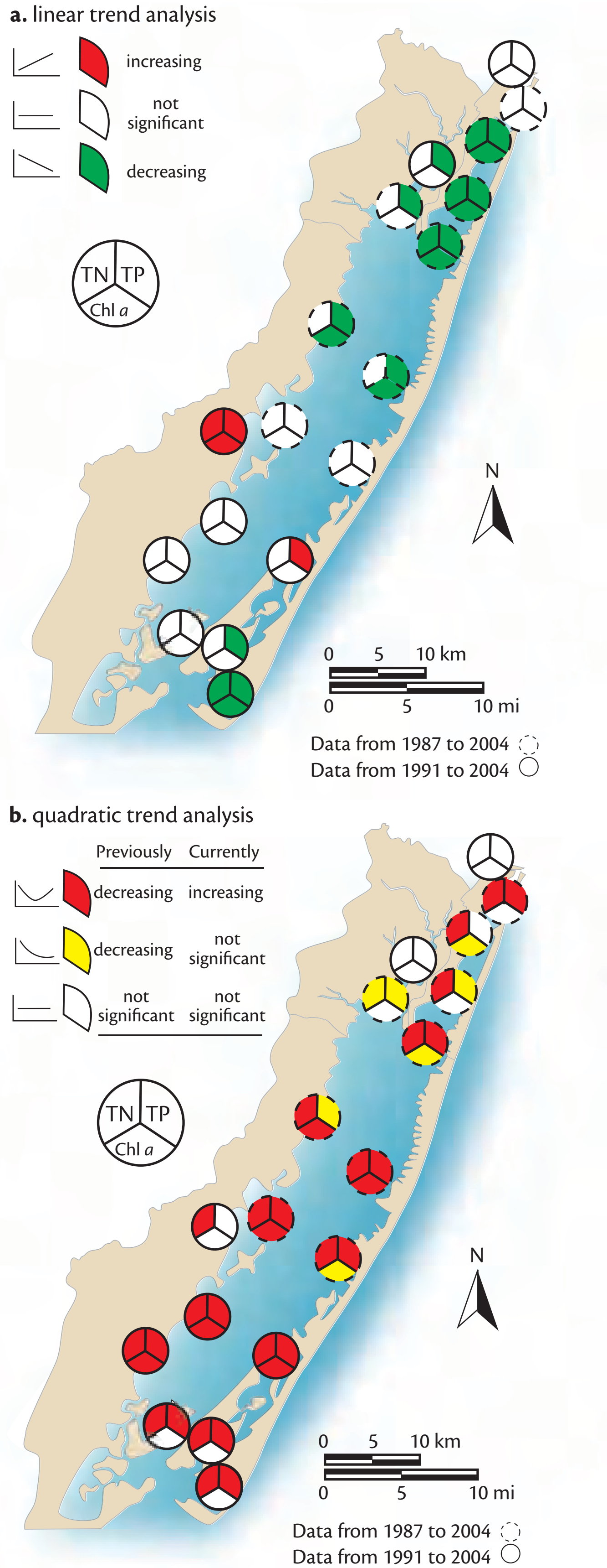
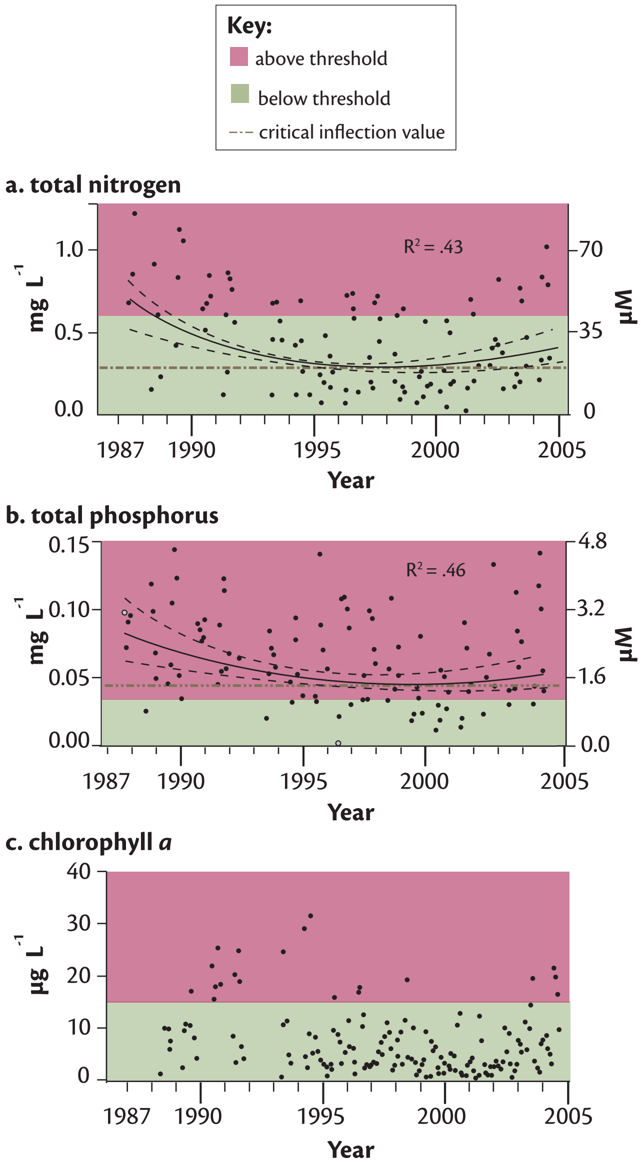


Figure 5.19. Non-linear trends at a single station.*



*__a.__ The solid black line identifies the quadratic curve fit of TN over time with surrounding dashed black lines representing upper and lower 95% confidence intervals.Toward the end of the date range, the critical inflection value is not encompassed by the confidence limits; TN is significantly increasing. **b.** Is similar to **a.**, except that the post-critical value upward trend in TP is not significant. **c.** No trends were found in the chlorophyll *a* data.

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MISSISSIPPI-ATCHAFALAYA RIVER PLUME, LA: *Predictable large scale hypoxia from the Nation's largest drainage basin due to nutrient loads*

Nancy N. Rabalais, Louisiana Universities Marine Consortium

The Mississippi River watershed encompasses 41% of the lower 48 states in the U.S. The drainage enters the Gulf of Mexico through two deltas, the Mississippi River birdfoot delta southeast of New Orleans, Louisiana, and one-third of the flow via the Atchafalaya River delta 200 km to the west on the central Louisiana coast. River and landscape alterations over two centuries have significantly lessened the buffering capacity of the watershed and anthropogenic additions of nutrients have resulted in eutrophication and hypoxia in the last half-century.

The Gulf of Mexico's Dead Zone

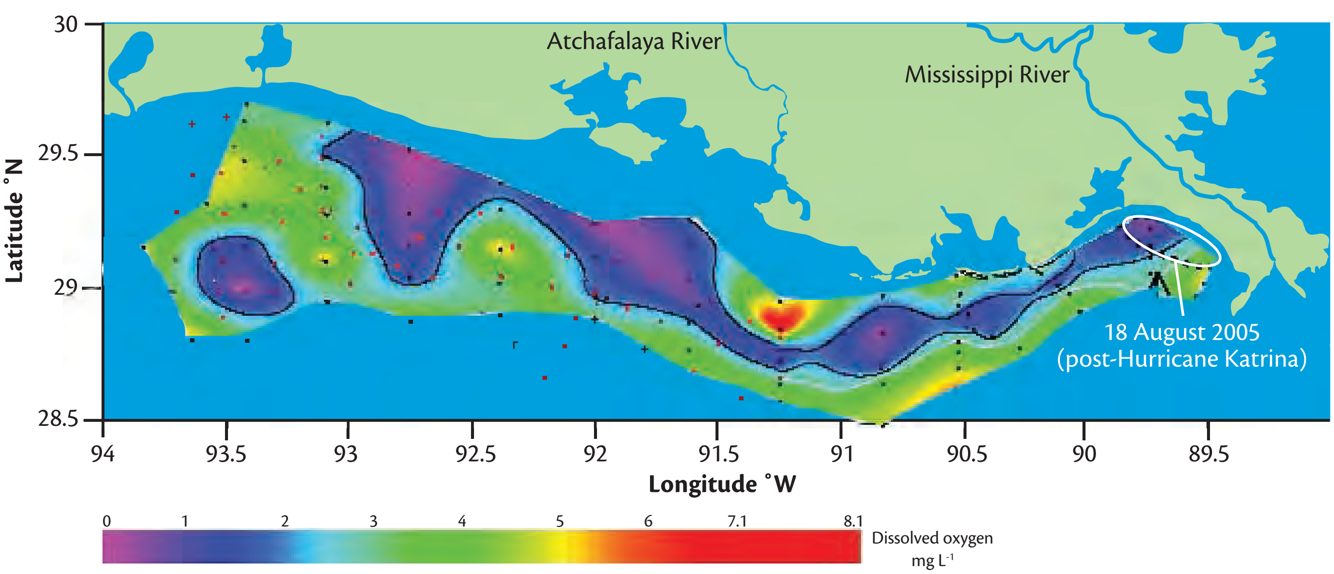
Increases in nutrients and changes in their relative proportions to each other have led to noxious algal blooms, increased algal biomass and carbon accumulation, shifts in phytoplankton community structure, altered trophic interactions, and low dissolved oxygen. Few marine animals can survive in these persistently and severely low summer oxygen concentrations—they must escape or succumb to the low oxygen. The area of hypoxia in the Gulf of Mexico is therefore commonly known as the Dead Zone.

History of hypoxia in the region

The northern Gulf of Mexico hypoxic zone, adjacent to and influenced by the Mississippi and Atchafalaya Rivers, is the largest such zone of oxygen-depleted coastal waters in the U.S. and the western Atlantic Ocean. The mid-summer extent of bottom-water low DO (<2 mg L^{-1}) averages 12,700 km^2 since systematic mapping began in 1985, and reached its maximal size to date of 22,000 km^2 in 2002 (summer 2005 depicted in Figure 5.20).

Hypoxic waters are most prevalent from late spring through late summer, and typically present between

Figure 5.20. Distribution of bottom-water dissolved oxygen on 24–29 July 2005. Post-Hurricane Katrina, water was heavily mixed so that the low DO area was reduced to the area indicated in white (18 August 2005).



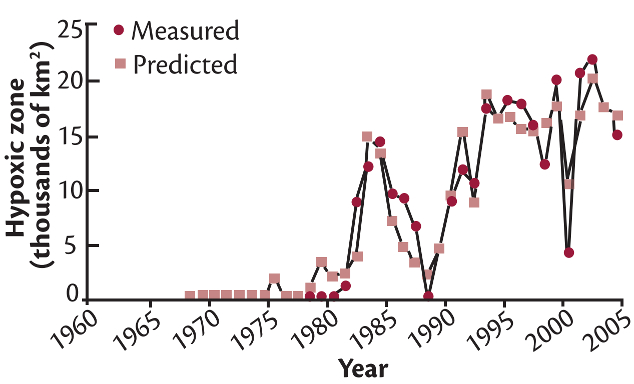
5 and 40 m. While low DO is commonly thought of as a bottom-water condition, oxygen depleted waters often extend up into the lower half to two-thirds of the water column of the hypoxic area.

The Mississippi River system is the dominant source of freshwater, sediments, and nutrients to the northern Gulf of Mexico. These constituents are carried predominantly westward along the Louisiana/Texas inner to mid-continental shelf, especially during peak spring discharge. Although the area of river influence is an open continental shelf, the magnitude of flow, annual current regime, and average 75-day residence time for fresh water result in an unbounded estuary, stratified for much of the year. This stratification is due primarily to salinity differences, but intensifies in summer with thermal warming of surface waters.

Seasonal hypoxia—spring through fall—is the result of the persistent stratification coupled with high organic production in overlying surface waters fueled by river-derived nutrients. The nutrients delivered from the Mississippi River basin support primary productivity within the immediate vicinity of the river discharges as well as across the broader continental shelf. Flux of fixed carbon to the lower water column and seabed in the form of senescent phytoplankton, zooplankton fecal pellets, or aggregates provides a large carbon source for decomposition by aerobic bacteria, which in turn leads to hypoxia. Tropical storms, hurricanes, and cold front passages disrupt the hypoxia until stratification re-establishes and oxygen depletion processes continue.

In the last half of the 20th century, the average annual nitrate concentration of the Mississippi River doubled, and the mean silicate concentration was reduced by 50%. The flux of nitrate-N to the Gulf of Mexico has averaged nearly one million metric tons per year since 1980, about three times larger than it was 30 years before. There is considerable research that supports the causal relationship of nutrient-enhanced primary production in the northern Gulf of Mexico and oxygen depletion in the lower water column (Figure 5.21). The accumulated evidence of observational data, paleoindicators in sediments, and empirical models shows a trend of increased primary production in the 20th century that sharply increased in the 1950s and was accompanied by more severe or persistent hypoxia beginning in the 1960s–1970s and became most pronounced in the 1990s.

Figure 5.21. Model-predicted size of hypoxia.*



***The results of a model predicting the size of the hypoxic zone from 1968–2004.The equation is : y(km²) = -1337953.4 + 672.1589 (Year + 0.0998)(May flux as nitrate + nitrite), (Turner et al. 2006).**

Future outlook

An *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) was endorsed by federal agencies, states, and tribal governments. The plan's environmental goal of a hypoxic zone smaller than 5,000 km^2 (five-year running average) by the year 2015 will require an overall nitrogen load reduction of 30–45%. Implementation will be based on a series of voluntary and incentive-based activities, including proper timing and amount of fertilizer applications, best management practices on agricultural lands, wetland restoration and creation, river hydrology remediation, riparian buffer strips, and nutrient removal from storm- and wastewater.

Implications for other systems

The continued and accelerated export of nitrogen and phosphorus to the world's coastal ocean is the trajectory to be expected unless societal intervention in the form of controls or changes in culture are pursued. Increases in dissolved inorganic nitrogen by 2050 are predicted for most world regions due to predicted large increases in population and increased fertilizer use to grow food to meet the dietary demands of that population and increased industrialization.

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SAN FRANCISCO BAY, CA: *Comprehensive ecosystem evaluation needed to discern causes of chlorophyll* a *increases*

Michael Connor, San Francisco Estuary Institute

San Francisco Bay is the largest estuary on the West Coast of the U.S., encompassing about 1,325 km^2 of open water, with a catchment of 119,181 km^2. About 40% of the land area of California drains into the bay through the Sacramento-San Joaquin River Delta (a large area of diked and drained swampland in the northern estuary). The southern embayments receive less than a tenth of the freshwater flow in comparison to the northern portion of the Bay. The Bay is shallow, with approximately one-sixth of its area exposed during high tides (mean tidal height 1.5 m) and another one-third of the total area less than 1.8 m deep and an overall mean depth of 5.6 m.

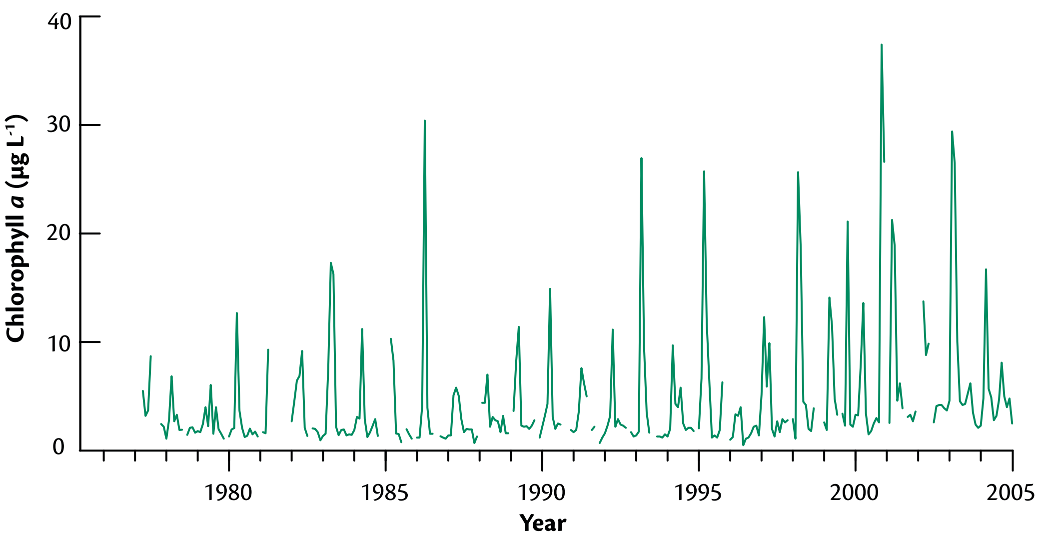
Phytoplankton biomass

Phytoplankton biomass in much of San Francisco Bay has increased by more than 5% per year from 1993–2004 (Figure 5.22) according to a new analysis by Jassby and Cloern (*www.sfei.org/rmp/pulse/2006/index.html*). They find that both the size of the bloom (particularly the fall bloom) and baseline chlorophyll *a* concentrations have significantly increased. During this time, modeled primary production has also doubled. Cloern et al. (2006) have listed eight possible mechanisms to account for the increased biomass (Figure 5.23). Only two of these—nutrient concentrations and stratification—can be eliminated as potential causes. Changes in these mechanisms are consistent with observed changes in biomass. However, due to insufficient data, it is not possible to determine what, if any, impact introduced invertebrate herbivores have on phytoplankton biomass (Cloern et al. 2006). All the other possible mechanisms have changes that are consistent with the change in biomass.

History of phytoplankton biomass in this region

The U.S. Geological Survey (USGS) has conducted the San Francisco Bay Water Quality Program since 1969, one of the Nation's longest-running time series of phytoplankton measurements (*sfbay.wr.usgs.gov/access/wqdata/*). Earlier publications from Cloern et al. show that the bay had low phytoplankton biomass relative to its high nutrient concentrations. Cloern hypothesized that the Bay was not nutrient limited, but light limited because of low water clarity caused by riverine sediment inputs and tidal and wind

Figure 5.22. Phytoplankton biomass (indicated by chlorophyll *a*) has increased in San Francisco Bay.

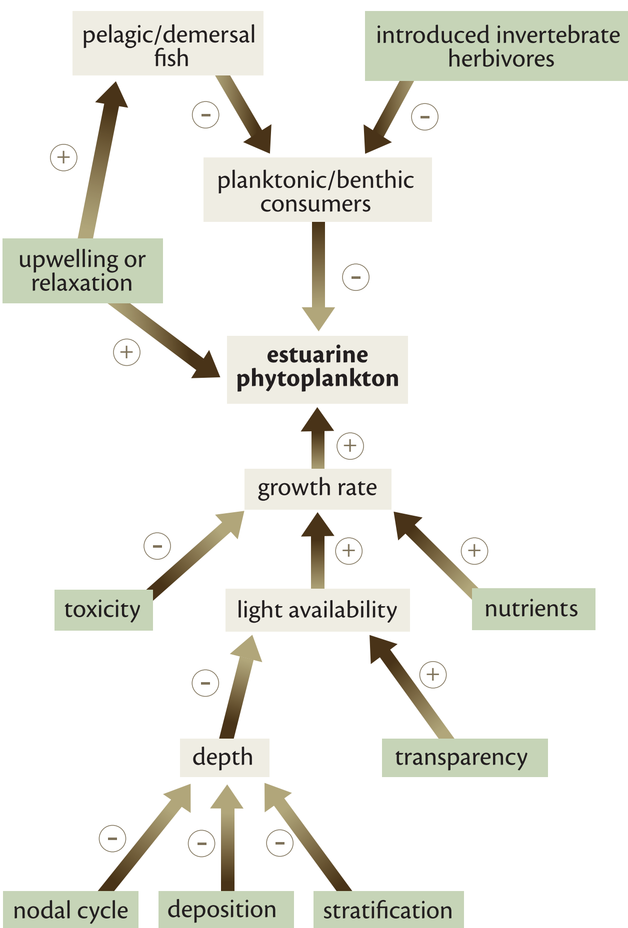


resuspension in shallow habitats. In the mid-1980s, phytoplankton concentrations in brackish habitats were dramatically reduced by the introduction of the Asiatic clam (*Corbula amurensis*). Observations over the past decade reveal increased phytoplankton biomass in marine domains of the Bay.

Management concerns

The first question about the trend in phytoplankton biomass is whether or not it is desirable. There is no evidence of concomitant dissolved oxygen problems, but there is some evidence of increased harmful algal blooms (HABs). On the other hand, the bay fishery is quite small and increased algal production at the right times of the year could be beneficial. The second question is how management actions are affecting the trend. Management actions in the past 20 years may be responsible for the trends. The loads of toxic contaminants, particularly metals and ammonium that could inhibit phytoplankton production, have declined significantly. Improved watershed management and damming of rivers are probably responsible for the reduction in sediment loads to the bay and increased light penetration.

Figure 5.23. The eight possible mechanisms affecting estuarine phytoplankton biomass (green boxes) and the positive (+) or negative (–) effects these mechanisms have on estuarine processes.




Linda Wanzyck

Water quality monitoring in San Francisco Bay.

Future outlook

The massive restoration of Bay Area wetlands (goal of ~100,000 acres) will potentially change the bay's light limitation and therefore its phytoplankton biomass. USGS's South Bay suspended sediment model predicts that increases in wetland area (as proposed under the South Bay Salt Pond Project) could result in increased sediment deposition onto wetlands and a subsequent decrease in suspended sediments in the water column. Increased light penetration could result in higher phytoplankton productivity.

Implications for other systems

The switch of the Bay from a light-limited to a nutrient-limited system as a result of restoration projects along its edges has implications to other systems with large-scale restoration projects.

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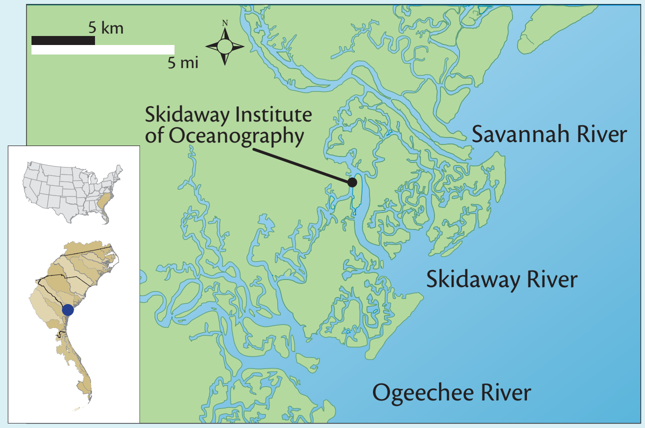
SKIDAWAY RIVER ESTUARY, GA: *Deteriorating dissolved oxygen conditions occurring in a well mixed coastal waterway*

Peter Verity, Skidaway Institute of Oceanography

Estuaries along the coast of the southeastern U.S. occur as a series of riverine estuaries with large watersheds, interspersed with numerous smaller lagoons and tidal creeks primarily influenced by local runoff. Most estuaries in this region have been considered to be relatively pristine, but those for which data are available show elevated concentrations of both organic and inorganic nutrients. For example, there is clear evidence over the past 20 years of increases in inorganic and organic nutrients, plankton, and particulate matter in the Skidaway River estuary (Verity et al. 1993, 2006; Verity 2002a,b). The Skidaway is representative of a lagoonal estuary dominated by tidal exchange (tides ranging from 2–3 m), waters typically 5–10 m deep, and connections to major rivers in the north and south via tidal creeks.

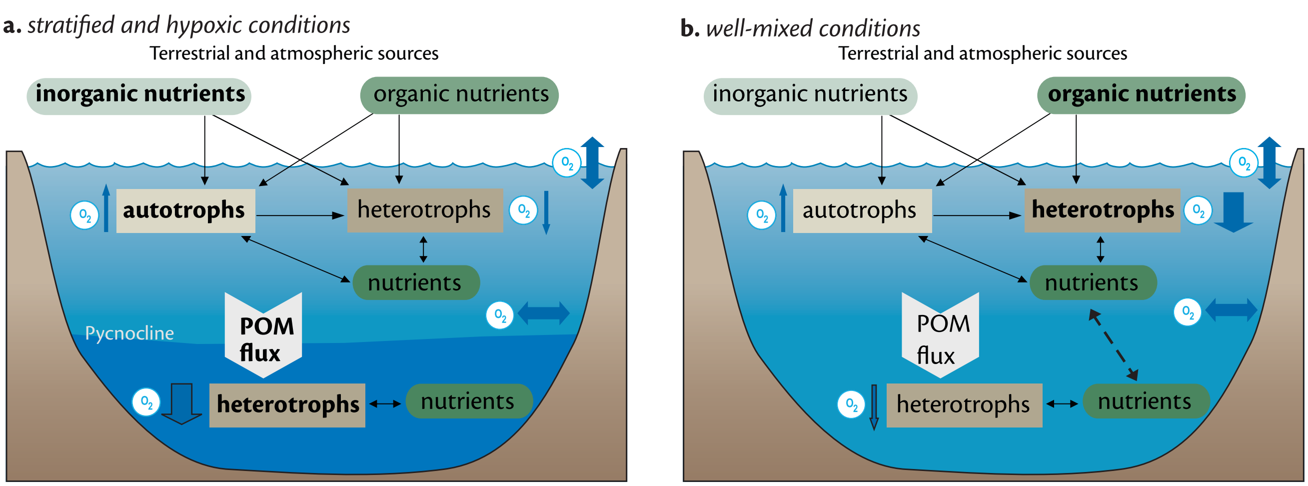


Issue of concern: urban impacts

The increasing ambient concentrations of nutrients likely find their source in elevated supply rates from surrounding environments that support increasing human densities, changes in land use patterns from natural to managed ecosystems, and/or conversion to agriculture, silviculture, and animal farms. For example, almost 17,000 new housing units were built within the estuarine and fluvial drainage area of the Savannah River, Georgia, during 1999–2000. From 1980–2000, the number of housing units increased from <300,000 to over 400,000 in this region, while the population grew from ca. 850,000 to 1,100,000 inhabitants. Non-point source (NPS) runoff in Georgia, including the influence of septic tanks (34%), urban NPS runoff (20%), agricultural NPS runoff (29%), and wildlife (61%), impacted water quality in 38 out of 59 sub-watersheds (Fletcher et al. 1998). Upstream pollution sources further affected 15 out of 59 watersheds in Georgia.

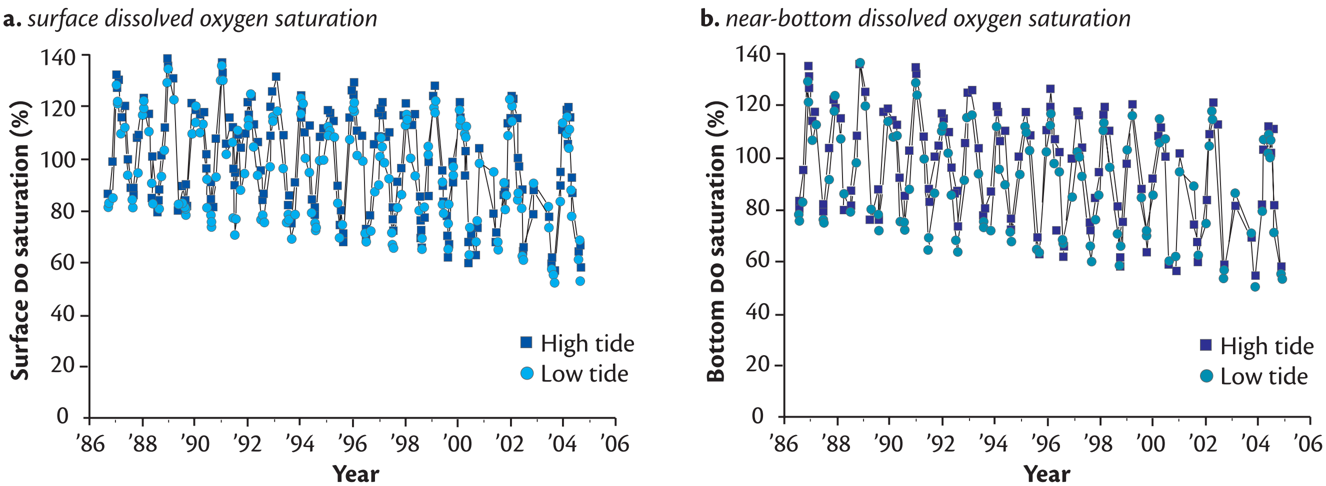
The traditional explanation of the relationship between eutrophication and hypoxia is as follows: high nutrient loading tends to stimulate phytoplankton production in surface waters, resulting in a bloom. This organic material sinks to the bottom where it is decomposed, and if the water column is stratified, then dissolved oxygen in the bottom water can become depleted (Figure 5.24a).

Figure 5.24. Conceptual model of circumstances leading to hypoxia in (a) stratified and (b) well-mixed conditions.



In stratified systems (**a**), when organic material sinks below the pycnocline, it is decomposed at depth where it cannot be reventilated with either adjacent water or the atmosphere. In well-mixed systems (**b**), oxygen consumption in surface waters occurs faster than autotrophic production and reventilation.

Figure 5.25. Low dissolved oxygen in Skidaway River estuary, 1986–2006.



This conceptual model has been successfully applied to explain low DO concentrations in many systems. According to this model, most of the estuaries in the South Atlantic Bight should be relatively safe from hypoxia because they tend to be well-mixed by the high tidal amplitudes experienced in the region. In contrast to conventional wisdom, percent oxygen saturation is steadily declining in the lower reaches of rivers and estuaries of Georgia (Figure 5.25), concurrent with increases in ambient concentrations of nutrients, chlorophyll *a*, and other indicators of eutrophication such as bacterial abundance. These observations suggest that hypoxia can occur directly from stimulation of microbial respiration, despite strong vertical and horizontal mixing (Figure 5.24b). Concentrations of NO_3^-, NH_4^+, PO_4^{3-}, $Si(OH)_4$, and dissolved organic nitrogen were significantly negatively correlated with both DO concentration and percent saturation (Verity et al. 2006). Similar declines in DO have been observed over the past 15–20 years in the major rivers feeding estuaries in Georgia, including the Savannah, Ogeechee, Altamaha, and Satilla Rivers (*www.epa.gov/STORET/*). Low DO concentrations are also observed in data from the Coastal Resources Division of the Georgia Department of Natural Resources, which began monthly sampling in March 2000.

Future outlook and implications for other systems

The mechanism causing DO depletion differs in southeastern U.S. systems from the traditional paradigm, these results suggest that each year during which loading is increased, the bacteria metabolism 'wheel' spins incrementally faster, causing long-term decreases in DO and gradual increases in net system heterotrophy. Given that so much of the U.S. coast is comprised of well-mixed riverine and tidal lagoon estuaries, the question of whether insights developed for stratified systems are applicable in well-mixed estuaries is highly relevant to understanding ecosystem ecology and wise land use planning, managing ecosystems, and formulating public policy regarding land-water connections in the presence of human population growth and coastal development. These results also emphasize the inherent value of long-term data sets, which increase in value as they lengthen in age. Such monitoring and assessment activities allow identification of trends in these systems and assessment of the efficacy of management measures put in place to prevent or minimize their ecological degradation.

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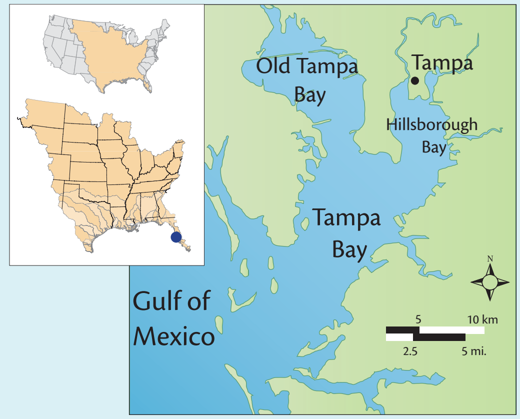
TAMPA BAY, FL: *Large seagrass recovery due to nitrogen load reductions*

Holly Greening, Tampa Bay Estuary Program

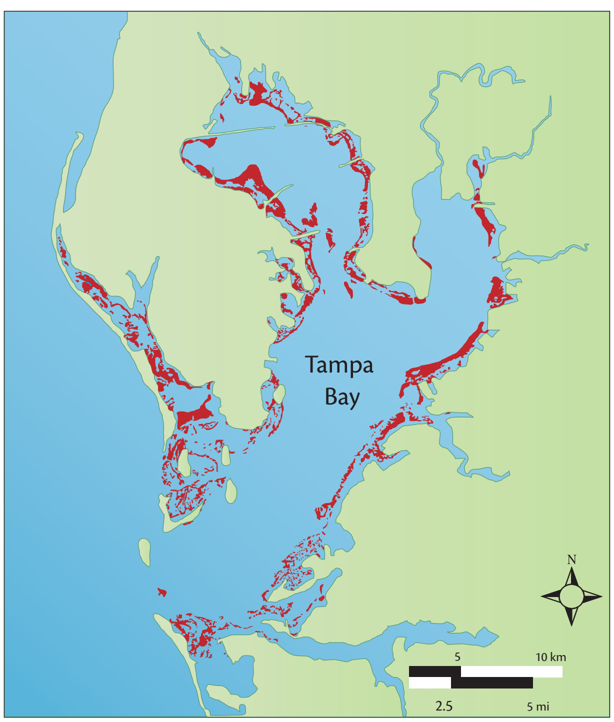
The Tampa Bay estuary is located on the eastern shore of the Gulf of Mexico in Florida, U.S. At more than 1000 km², it is Florida's largest open water estuary. More than 2.5 million people live in the 5,700 km² watershed, with a 20% increase in population projected by 2010. Land use in the watershed is mixed, with about 40% of the watershed undeveloped, 35% agricultural, 16% residential, and the remaining commercial and mining.



Submerged aquatic vegetation loss

Major habitats in the Tampa Bay estuary include mangroves, salt marshes, and submerged aquatic vegetation (SAV). Each of these habitats has experienced significant reductions in extent since the 1950s, due to physical disturbance (dredge and fill operations) and water quality degradation. The primary cause of loss, excess nitrogen loading, resulted in increased algae concentrations, leading to reduced light availability for shallow-water (<3 m depth) SAV.

Figure 5.26. Submerged aquatic vegetation cover loss in Tampa Bay from 1950–1990.



History of SAV loss in this region

As early as the 1970s, many eutrophication symptoms were observed in Tampa Bay. Phytoplankton and macroalgal blooms were common occurrences leading to odor and aesthetic impairment. In addition, hypoxia and anoxia development in some areas of the Bay led to adverse responses in the benthic community of Tampa Bay. In the 1970s, near entire loss of the benthos was common in late summer along the western shoreline of Hillsborough Bay, the most urbanized segment of Tampa Bay. The most visible symptom of eutrophication in Tampa Bay was the increased degree of light attenuation accompanying elevated algal biomass. The concomitant submerged aquatic vegetation loss during this period was also dramatic. In 1950, more than 39,500 acres of SAV were present. By the early 1980s, over half of this area was lost (Figure 5.26).

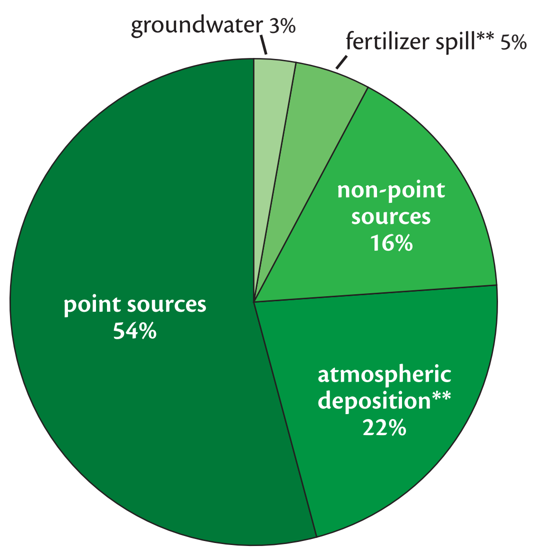
Since the mid-1970s, a number of actions were taken to address the problem of excessive nitrogen loading to Tampa Bay. First, in 1980, all municipal wastewater treatment plants were required to provide Advanced Wastewater Treatment (AWT) for discharges directly to the bay and its tributaries. AWT required total nitrogen concentrations in wastewater discharged to the bay to not exceed 3 mg L^{-1}, reducing nitrogen loads from this source by 90%. In addition to significant reductions in nitrogen loadings from municipal wastewater treatment plants, stormwater regulations enacted in the 1980s also contributed to reduced nitrogen loads to the bay. Lastly, the phosphate industry initiated a number of best management practices (BMPs) to reduce nitrogen and phosphorus loads resulting from fertilizer spills from port facilities from which fertilizer products are shipped. These BMPs involved building containment structures around the transfer station which eliminated the stormwater runoff of nutrients from the docks.

The above management actions resulted in a significant reduction (60%) in estimated nitrogen loading from 1985–2003 compared to the estimated loadings from the mid–1970s. Also, the relative contributions from various nitrogen sources have changed appreciably since the 1970s (Figure 5.27).

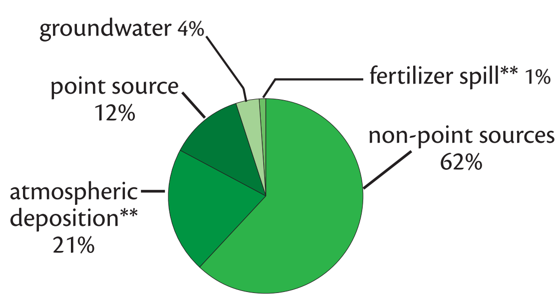
The Tampa Bay Estuary Program (TBEP), a partnership that includes three regulatory agencies and six local governments, has built on the resource-based approach initiated by earlier management efforts. The program has developed water quality models to quantify linkages between nitrogen loads and bay water quality, and models that link water quality to submerged aquatic vegetation goals.

Figure 5.27. Nitrogen loading in Tampa Bay.*

a. *Nitrogen sources in Tampa Bay during the 1970s (10,000 tons y^{-1})*



b. *Nitrogen sources in Tampa Bay from 1998-2003 (4,100 tons y^{-1}); relative size reflects the reduction from 1970s loads (41%)*



***While fertilizer spills and groundwater are separated from other nutrient sources, they are considered point and non-point sources, respectively.**
****Directly onto the Bay's surface**

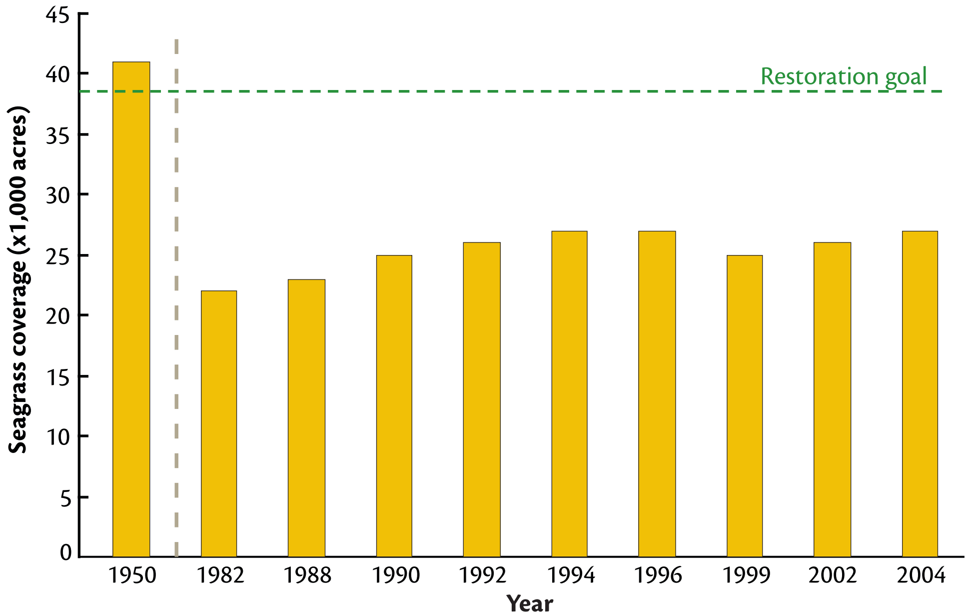
A nitrogen management strategy is being implemented by public and private entities to reduce and maintain nutrient loads to support water quality conditions necessary for submerged aquatic vegetation recovery to 1950s levels. The Tampa Bay Nitrogen Management Consortium, consisting of local electric utilities, industries, and agricultural interests, as well as local governments and regulatory agencies, is implementing nutrient reduction projects throughout the watershed to support the load reduction goal of 17 tons total nitrogen per year. The types of nutrient reduction projects included in the Consortium's Nitrogen Management Action Plan range from traditional nutrient reduction projects such as stormwater upgrades, industrial retrofits, and agricultural best management practices to actions not primarily associated with nutrient reduction, such as land acquisition and habitat restoration projects. More than 300 projects submitted by local governments, agencies, and industries from 1995–2000 have resulted in an estimated 134 tons y^{-1} reduction in nitrogen loading to Tampa Bay from the completed projects through 2000. Reductions from these projects exceed the cumulative 1995–1999 reduction goal of 84 tons per year by 60%.

Trends in water column chlorophyll *a* concentrations for the four major bay segments show similar patterns: levels far exceeded adopted targets until the mid–1980s when concentrations decreased significantly, followed by fluctuations around the target in recent years. Submerged aquatic vegetation extent shows a similar apparent response to decreased TN loading and increased water clarity in the 1980s, with a general increase in coverage starting around 1988 (Figure 5.28). Fluctuations in chlorophyll *a* and submerged aquatic vegetation coverage since about 1990 appear to be associated with rainfall amounts.

Future outlook

The Tampa Bay management community has agreed that protecting and restoring Tampa Bay living resources is of primary importance and has developed nitrogen loading targets for Tampa Bay based on the water quality requirements of native submerged aquatic vegetation species. A long-term goal has been adopted to achieve 38,054 acres of submerged aquatic vegetation in Tampa Bay, or 95% of that observed in 1950. To reach the long-term submerged aquatic vegetation restoration goal, a 7% increase in nitrogen loading associated with a projected 20% increase in the watershed's human population by 2010 must be offset. Government and agency partners in the Tampa Bay Estuary Program and private

Figure 5.28. Tampa Bay submerged aquatic vegetation (SAV) coverage.*



Goal*: recover an additional 10,976 acres of SAV over 2004 levels, while preserving the bay's existing 27,024 acres. ***Status*: between 1988–1996, SAV acreage increased 200–300 acres per year. El Niño rains resulted in losses of about 2,000 acres between 1996–1999. In January 2002, SAV acreage increased by 1,237 acres. By January 2004, submerged aquatic vegetation acreage had increased an additional 946 acres, resulting in the highest observed acreage estimated since 1950.

industries participating in the Nitrogen Management Consortium have identified and committed to specific nitrogen load reduction projects to ensure that the water quality conditions necessary to meet the long-term living resource restoration goals for Tampa Bay are achieved. Water quality conditions and submerged aquatic vegetation coverage have shown steady improvements since the mid 1980s, apparently in response to the initial reductions in nitrogen loading from wastewater treatment facilities and in more recent years through the watershed-wide efforts of the Tampa Bay Nitrogen Management Strategy partners.

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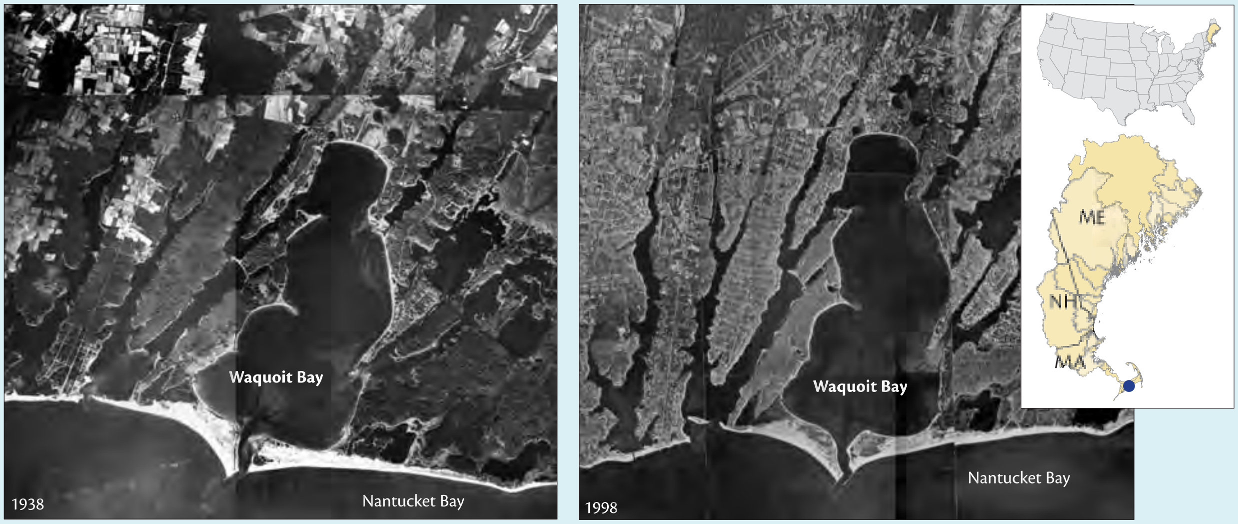
WAQUOIT BAY, MA: *Increased nitrogen load leads to increased eutrophic symptoms*

Ivan Valiela and Mirta Teichberg, Boston University Marine Program



Waquoit Bay is an estuarine system in Cape Cod, Massachusetts, with a watershed that has experienced much urban sprawl during recent decades. This urbanization has resulted in increased nitrogen loads to the bay.

Increasing algal biomass

Increased nitrogen reaching Waquoit Bay during the last half of the 20th century has led to increases in macroalgal and phytoplankton blooms, decreased water clarity, decline in submerged aquatic vegetation (Figure 5.29), and a collapse of scallop catch.

The large crop of nitrogen-fed macroalgae has become a dominant feature of Waquoit Bay. Macroalgal canopies reach a depth of 75 cm in places, and sometimes drift on shore, prompting news headlines ("Algae clogs [sic] Cape beaches", Cape Cod Times, June 28, 2003; "Massive algae [sic] bloom mars Waquoit Bay; nitrogen blamed", *Falmouth Enterprise*, July 1, 2003).

The history of land use on Cape Cod since the 17^{th} century is, much like that of coastal areas anywhere in the world, a shift away from forests toward intensely used land covers. Today, land use is dominated by urban sprawl, which has led to pervasive environmental, economic, social, and aesthetic consequences for the people, land, and adjoining estuaries. Urbanization has been accompanied by increases in land-derived nitrogen inputs to the Bay toward the end of the 20^{th} century (Figure 5.29). Wastewater inputs furnished much of the nitrogen that led to these increases.

Different estuaries within the Waquoit estuarine system are subject to different loads; comparisons among these estuaries provided compelling inferential evidence that increased nitrogen loads were the agents of change that restructured

Sophia Fox

Macroalgal bloom in Waquoit Bay during the summer of 2004.

function and composition of species of Waquoit food webs, moving from a SAV-dominated to a macroalgal-dominated system. Stable isotopic data unambiguously demonstrated that it was the nitrogen from land—primarily from wastewater—that forced the notable environmental shifts seen in Waquoit Bay. The shift from a submerged aquatic vegetation to macroalgal-dominated community has some beneficial effects, including sequestering nutrients, and furnishing more and better food particles for suspension-feeders such as bivalves. The macroalgal canopy, however, also has detrimental effects. In addition to the decline in scallop catch from Waquoit Bay due to SAV loss, there are also episodes of hypoxia and anoxia due to greater oxygen

Figure 5.29. Time course of total wastewater, fertilizer, and atmospheric N loads (Bowen and Valiela 2001).

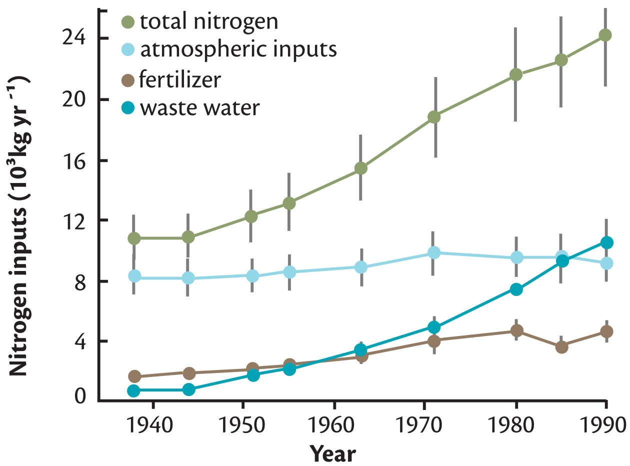
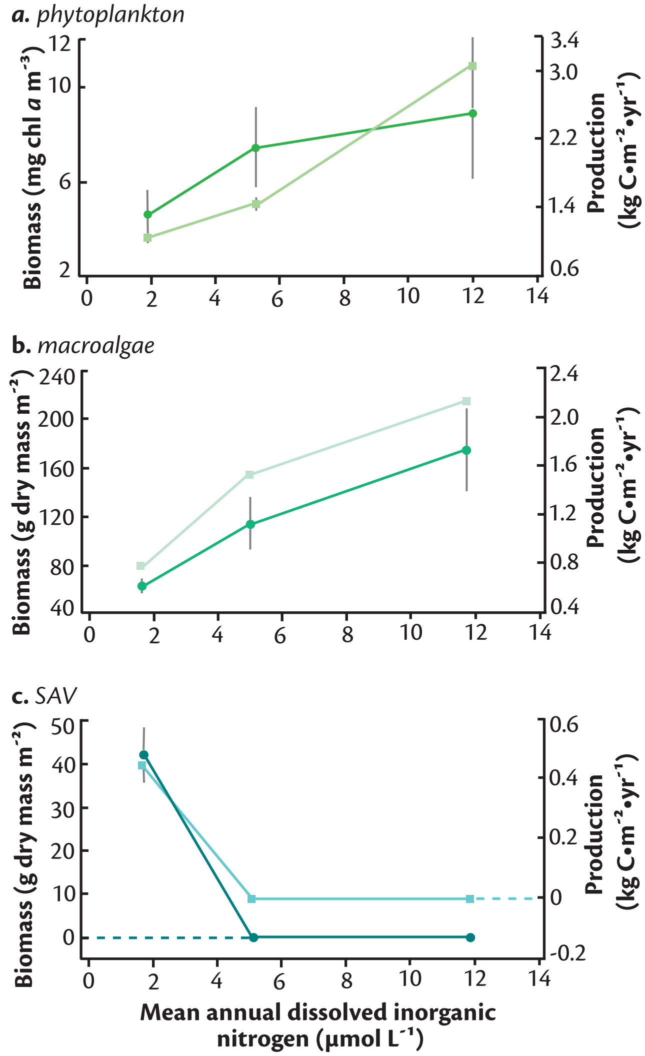


Figure 5.30. Biomass and dissolved inorganic N.



Biomass (circles) and production (squares) of phytoplankton, macroalgae, and SAV in relation to the dissolved inorganic nitrogen content of the water in three estuaries of Waquoit Bay that received different land derived nitrogen loads (from Valiela et al. 2000).

consumption by macroalgae. This has led to kills of fish, shellfish, and other organisms. These episodes have become more frequent in conjunction with increases in land-derived nitrogen loads.

The increased rate of macroalgal growth, and lower abundance of bottom-dwelling animals in estuaries (including grazers of macroalgae), has reshuffled key ecological control processes. In estuaries of the Waquoit Bay system where land-derived nutrient loads are low, grazing rates roughly matched growth rates of macroalgae. In these conditions, macroalgal canopies cannot proliferate. Where nitrogen loads have become larger, however, the balance has shifted: rates of macroalgal growth have increased, and there are fewer grazers, so that grazing rates are reduced (Figure 5.30).

Future outlook

Since coastal population growth (particularly in urbanized settings) will increase markedly, the issues associated with eutrophication will surely become more pressing in this century. New knowledge will be needed to solve the problem of macroalgal blooms. Improved understanding of controls of related processes will help, as will new approaches to intercept nutrient sources on land before they enter estuaries.

Implications for other systems

Waquoit Bay is a microcosm that illustrates the basic and applied nutrient-related issues arising elsewhere. The work done there solidifies the role of nitrogen as a control of estuarine production, establishes the crucial coupling between land and coastal sea, and pinpoints the influence of human-related land use on the way coastal water ecosystems function.

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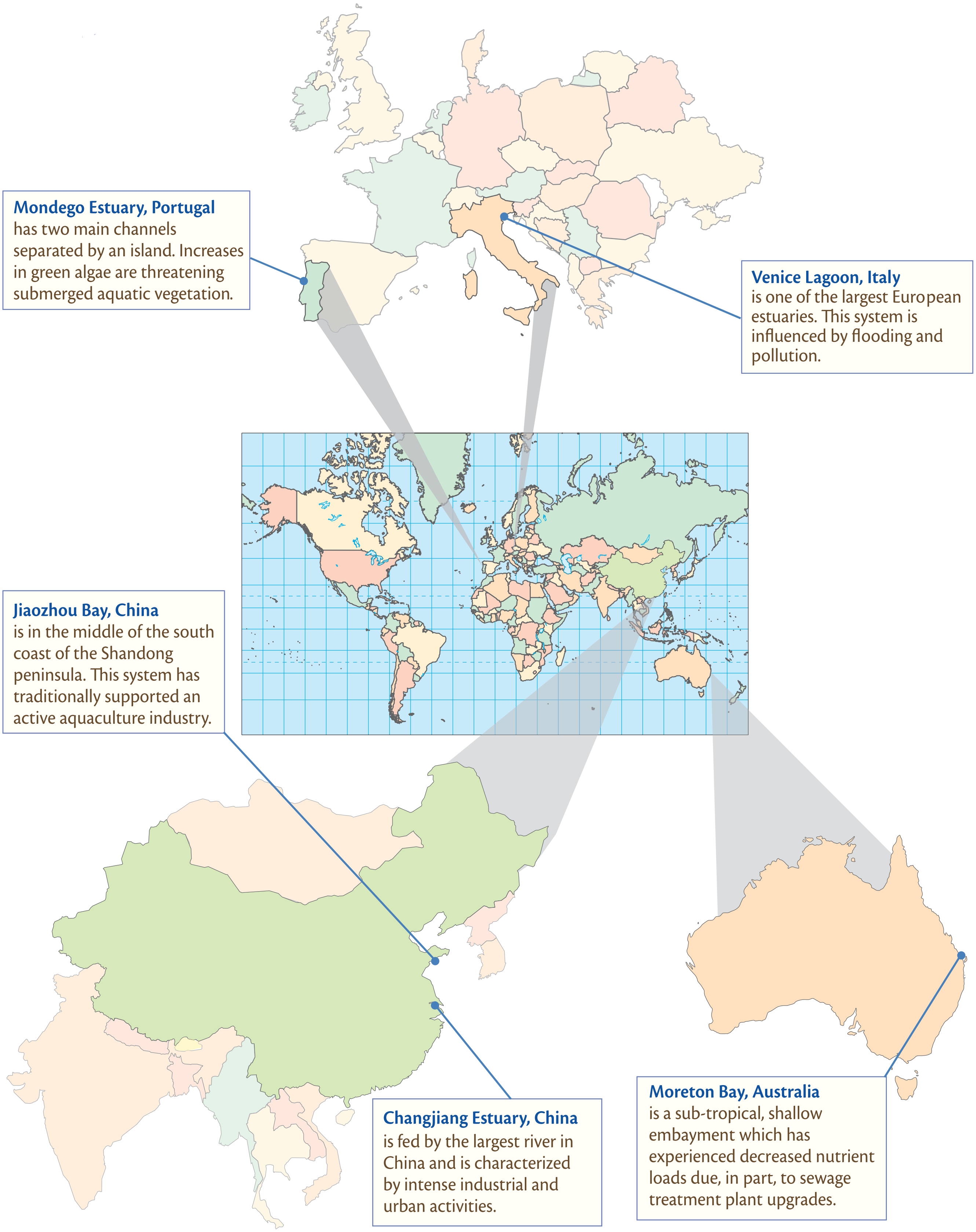
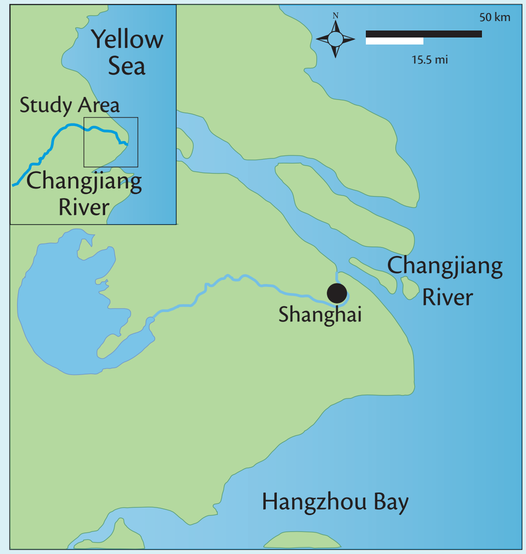
International case study maps



CHANGJIANG (YANGTZE) ESTUARY, CHINA: *Rapid, large-scale increases in eutrophic symptoms*

Baodong Wang and Mingyuan Zhu, First Institute of Oceanography; Yongjin Xiao, University of Algarve

Changjiang River (Yangtze River), is the largest in China, and empties into the East China Sea. Extending about 6,300 km from the Qinghai-Tibet Plateau eastward to East China, the Changjiang River Basin is characterized by intense industrial and urban activity—especially in the lower reaches and estuary. The river has an average flow of 29,000 $m^3 s^{-1}$, carrying about 480 million tons of sediment to the estuarine and coastal area. The huge Changjiang drainage basin is located in a heavily populated temperate area with a total area of 1.94 ×10^6 km^2 and settlements of 400 million people. As a major pathway of nutrients, Changjiang River channels anthropogenic impacts from the catchments to the estuary and adjacent coastal waters (Chen and Chen 2003).



Issue of concern: nuisance/toxic blooms

Nuisance/toxic blooms are frequently observed in Changjiang Estuary and its extended coastal waters. The East China Sea is an area where the most severe HABS occur among the four Chinese seas, accounting for 45% of the total recorded number. Since the 1990s, the frequency of nuisance/toxic blooms in this area has increased, and the durations and sizes of affected areas increase continually. In 2002, there were 51 bloom occurrences observed in Changjiang estuary and adjacent coastal areas (Guan & Zhan 2003).

Toxic species of algae are often observed in Changjiang Estuary, such as *Alexandrium* sp. and *Gymnodrium* sp. They lead to kills of zoobenthos and fish, which also damage nearby fishing grounds such as the Zhoushan fishing ground.

Another concern of this area is that hypoxia in near-bottom waters in the Changjiang River mouth has become more and more serious since the first recorded incident in the 1950s (Li & Daler 2004).

Influencing factors

As a result of increased fertilizer application and effluent from cities in the Changjiang River basin, nutrient concentrations (dissolved inorganic nitrogen and phosphate) have increased exponentially and by a factor of five, respectively, from the 1960s to the 1990s (Duan and Zhang 2001). On the other hand, silicate concentrations decreased by two thirds from the 1960s–1990s (Wang 2006). Since 1985, the nitrogen-to-phosphorus ratio has increased to 125 and stayed nearly constant, while the silicon-to-nitrogen ratio decreased to 1.0 in the 1990s.

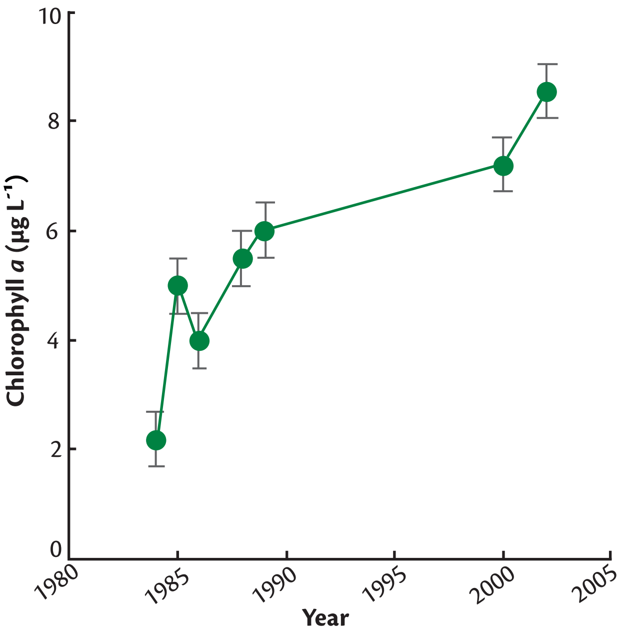
Due to the differences in sampling time, place, methods of analysis, and annual and seasonal variations, there are some uncertainties in the nutrient fluxes of the Changjiang. According to a survey by Liu et al. (2002), the concentration of dissolved inorganic nitrogen increased from 15 µmol L^{-1} in 1968 to 118 µmol L^{-1} in 1997.

Dilution volume in Changjiang Estuary was estimated as approximately 6.375 x 10^{11} m^3 at the upper stratified layer (mean thickness of 12.5 m). With the mean salinities in the upper stratified layer and offshore as 25 psu and 30 psu, the dilution potential is classified as moderate. With a tidal range of 2.7 m and discharge from Changjiang River as large as 925 x 10^{11} $m^3 y^{-1}$ (Che et al. 2003), Changjiang Estuary falls into the moderate category in flushing potential.

Characteristic eutrophic symptoms

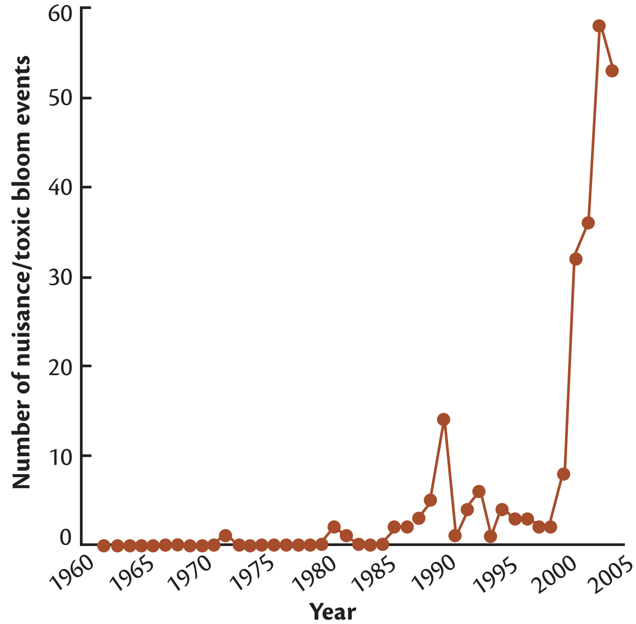
During the last two decades, chlorophyll *a* concentrations increased by four times (Figure 5.31). The 90th percentile value for chlorophyll *a* is 15 µg L^{-1}, which in Assessment of Estuarine Trophic Status (ASSETS), is considered medium (5–20 µg L^{-1}). The elevated phytoplankton biomass, as indicated by chlorophyll *a* concentrations, has caused an increase in bloom events in the river plume. Incidents of nuisance/toxic blooms in the Changjiang estuary and adjacent coastal areas were rare before 1985 but have increased rapidly since then (Figure 5.32).

Figure 5.31. Summer variation of chlorophyll *a* in Changjiang Estuary, 1980–2005.



August chlorophyll *a* concentrations in the surface water of Changjiang Estuary have varied during the last two decades.

Figure 5.32. Number of nuisance/toxic bloom events over the last 40 years.



Nuisance/toxic blooms in Changjiang estuary have occured more frequently since 1985.

According to a survey conducted by Li et al. (2002), a hypoxic zone (<2 mg L^{-1}) of 13,700 km^2 was found with an average thickness of 20 m at the bottom of Changjiang estuary, with a minimum oxygen value of 1 mg L^{-1} (Figure 5.33). The extent of the dissolved oxygen deficiency extended to the 100 m isobath in a southeastward direction along the bottom of the continental shelf of the East China Sea. During the last two decades, the minimum dissolved oxygen values in the low oxygen region of Changjiang Estuary have decreased from 2.85 mg L^{-1} to 1 mg L^{-1}. In the hypoxic zone, the apparent oxygen utilization was 5.8 mg L^{-1} and the total oxygen depletion approximately 1.59 x 10^6 tons.

Figure 5.33. The estimated hypoxic areas in Changjiang Estuary in 1999 (Li et al., 2002).

Future outlook

Based on China's strategic planning for development, the Changjiang drainage basin is expected to provide approximately 10^7–10^8 tons y^{-1} more food in order to feed the increased population within the next 50 years, which will probably cause a further increase in fertilizer application in a region of dense population and intensive agriculture (Zhang et al. 1999). If the dissolved inorganic nitrogen concentrations keep increasing at the same rate that they have been in the last two decades, the load will be about 4.06×10^6 tons y^{-1}, twice as much as that in 1998. In addition, construction of the Three Gorges Dam has begun and is expected to reduce silicate drastically by trapping silicate-laden sediments behind the dam. Therefore, the silicon-to-nitrogen ratio is predicted to decrease further. Thus, the eutrophic conditions in Changjiang estuary are projected to worsen.

Assessment of estuarine trophic status

The ASSETS screening model (Bricker et al. 2003) was chosen as an integrated approach for eutrophication assessment in Changjiang Estuary. The 90th percentile value for chlorophyll *a* is in the moderate category, while nuisance/toxic blooms are observed frequently, indicating a high level of expression for secondary symptoms.

The overall ASSETS rating is bad, based on the conditions obtained for influencing factors and overall eutrophic condition, and the expected increase of nutrient pressure given by the future outlook assessment (Table 5.3).

The main issues identified for Changjiang estuary are: (1) pressure from the huge population living in the Changjiang River basin; (2) nuisance/toxic blooms, which have increased tenfold during the last two decades; and (3) the construction of Three Gorges Dam, expected to reduce flow and to modify hydrological scenarios.

Table 5.3. ASSETS rating for Changjiang estuary.

Overall ASSETS rating: bad

	Symptom expression	ASSETS SCORE
Influencing factors		
susceptibility	moderate	high
nutrient loads	high	
Eutrophic conditions		
chlorophyll *a*	moderate	high
macroalgae	unknown	
dissolved oxygen	low	
loss of SAV	unknown	
nuisance/toxic blooms	high	
Future outlook		
future nutrient loads	increasing	large deterioration

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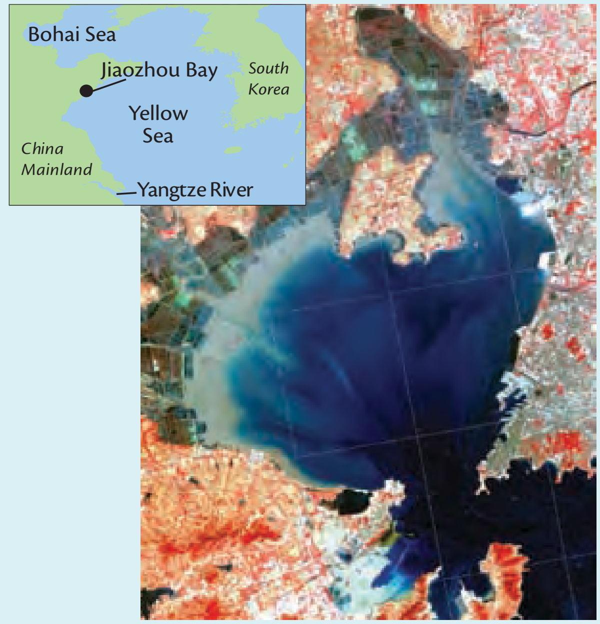
JIAOZHOU BAY, CHINA: Threats from eutrophication to large scale aquaculture stimulate nutrient management

Mingyuan Zhu and Xuelei Zhang, First Institute of Oceanography

Jiaozhou Bay is the largest bay along the south coast of Shandong Peninsula, draining into the Yellow Sea basin. The bay is located next to the city of Qingdao (pop. 7.3 million), with an area of 382 km^2, a volume of 3.1×10^9 m^3, and a perimeter of 194 km (Li et al. 2006, Wang et al. 2006). The southeast and southwest shores of the bay are rocky, and are the location of two large ports. Almost one sixth of the bay area is intertidal, and is used for clam aquaculture. The average tidal range is 2.8 m with an average water exchange ratio of about 0.1 per day (Liu 1992). More than ten rivers flow into Jiaozhou Bay. The total flow of the four largest (Dagu River, Yang River, Baisha River and Moshui River) amounts to over 8×10^8 m^3 y^{-1}. However, since the damming of the rivers in the 1970s, the rivers have become seasonal, bringing municipal sewage and agricultural run off, and flowing into the bay mainly in the summer. The flow of Dagu River is estimated to have decreased by two thirds (Li et al. 2006) because of dams.

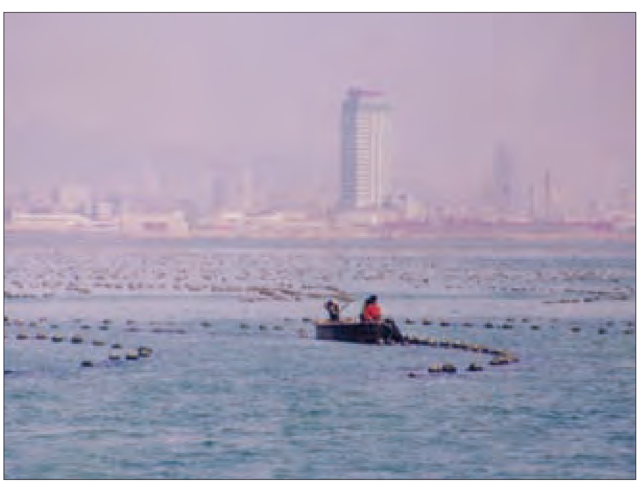


Issue of concern: nuisance/toxic blooms

The main issue in Jiaozhou Bay is the increase of nuisance/toxic blooms. Since the first record in 1990 (Li and Li 1996), blooms have increased both in frequency and scale (Han et al. 2004), although most events are non-toxic. During this period, there was one bloom event in 1990, 2003, and each year from 1997-2001. For example, there was a bloom of the diatom *Skeletonema costatum* of 10 km^2 in 1998 (Huo et al. 2001) and a bloom of another diatom, *Coscinodiscus asteromphalus,* of 200 km^2 in 2003 (IOCAS 2003). Other main causative species include *Eucampia zoodiacus*, *Noctiluca scintillans,* and *Mesodinium rubrum* (Wang et al. 2006).

Influencing factors

From the 1960s to the 1990s, both nitrate and ammonia concentration increased, leading to a net increase of dissolved inorganic nitrogen (Figure 5.34). Phosphate concentration increased from the 1960s to the '80s, then decreased (Figure 5.35, Liu 1992, Shen



Xuelei Zhang, First Institute of Oceanography, China

Longline suspension culture of oysters and scallops in the Bay.

Xuelei Zhang, First Institute of Oceanography, China

Manila clam culture occurs in the intertidal zone of the Bay.

Figure 5.34. Dissolved inorganic nitrogen concentrations in Jiaozhou Bay.

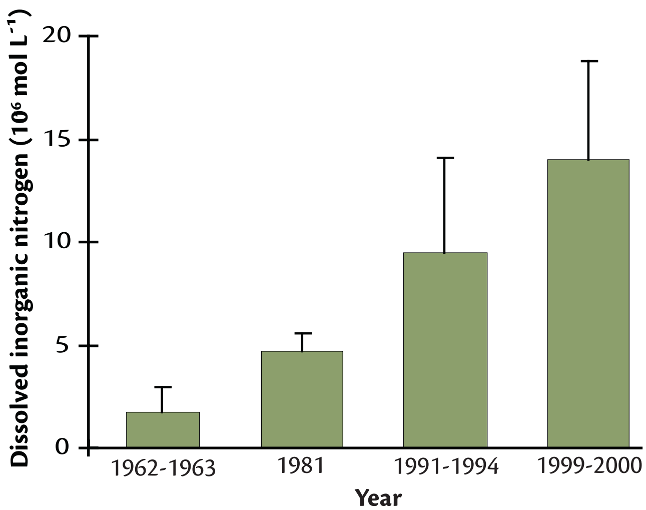


Figure 5.35. Phosphate concentrations in Jiaozhou Bay.

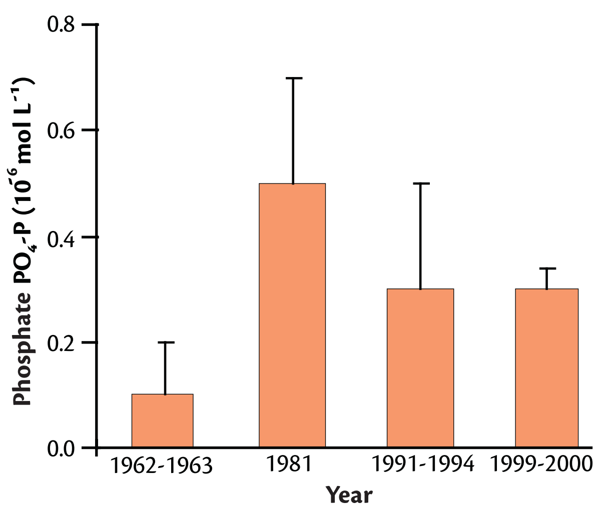


Figure 5.36. Nitrogen to phosphate ratios in the Bay.

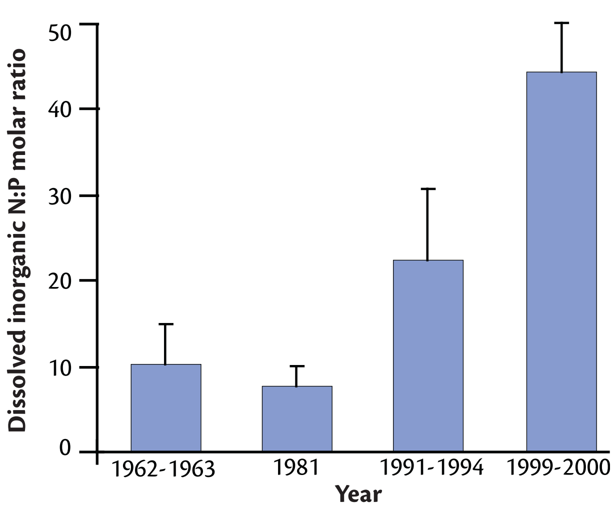


Figure 5.37. The shellfish aquaculture areas in Jiaozhou Bay in the late 1990s.

In the 1990s shellfish aquaculture in Jiaozhou Bay became an important industry. Some of the most common species grown in the bay include clams and scallops.

Table 5.4. Area of shellfish aquaculture in Jiaozhou Bay in the late 1990s.

Species	Area (km^2)	Production (tons y^{-1})
Manila clam	81.8	197,900
Mussel	3.13	74,500
Chinese scallop	2.33	2,100
Bay scallop	11.8	42,200

et al. 1995). As a result, the nitrogen-phosphorus ratio increased from about 10 in the 1960s to 30 in the late 1990s, indicating a shift from nitrogen to phosphate limitation (Figure 5.36). The silicate concentration decreased with the reduction of freshwater discharge (In the dry season, there is silicate limitation).

Role of aquaculture in Jiaozhou Bay

In the 1960s, there was some kelp culture along the east coast of Jiaozhou Bay. Since the 1980s, shrimp and shellfish culture have been developing in the bay. In the 1990s, shellfish culture became more important. The main species include the Manila clam (*Ruditapes philipinnarum*), blue mussel (*Mytilus edulis*), Chinese scallop (*Chlamys farreri*), and bay scallop (*Argopecten irradians)* (Figure 5.37 and Table 5.4).

Future outlook

As the city and adjacent areas develop economically, and as Qingdao prepares to host the sailing event of the Beijing Olympics in 2008, more attention has focused on the environmental issues relating to economic development. The number of wastewater treatment plants will increase, more restrictive pollutant emission regulations will come into effect, and land sources of nutrients will stabilize (Wang et al. 2006). As a consequence, the eutrophication issue in Jiaozhou Bay is expected to improve in the future, although the reduction in the production of filter-feeding shellfish may impact top-down control of phytoplankton.

Assessment of estuarine trophic status (ASSETS)

Table 5.5 shows a synthesis of the application of ASSETS to Jiaozhou Bay. The system receives a substantial nutrient load from the city of Qingdao and rivers which discharge into the bay. However, the system is classified as moderate in terms of pressure, due to its tidally-driven exchange with the Yellow Sea, which reduces susceptibility. In addition to the strong tidal exchange, top-down pressure from shellfish aquaculture further contributes to the system's low eutrophic conditions. The future outlook is mixed: on the one hand, management measures will reduce nutrient loading, but on the other the reduction of shellfish aquaculture may result in a more significant expression of eutrophication symptoms. Overall, future outlook predicts a slight improvement in eutrophic condition. The final ASSETS rating for Jiaozhou Bay is moderate, based on the classifications for influencing factors, eutrophic conditions, and future outlook.

Table 5.5. ASSETS rating for Jiaozhou Bay.
Overall ASSETS rating: moderate

	Symptom expression	ASSETS SCORE
Influencing factors		
susceptibility	moderate	moderate
nutrient loads	low	
Eutrophic conditions		
chlorophyll *a*	low	low
macroalgae	no problem	
dissolved oxygen	low	
loss of SAV	low	
nuisance/toxic algal blooms	low	
Future outlook		
future nutrient loads	decreasing	small improvement

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Acknowledgements

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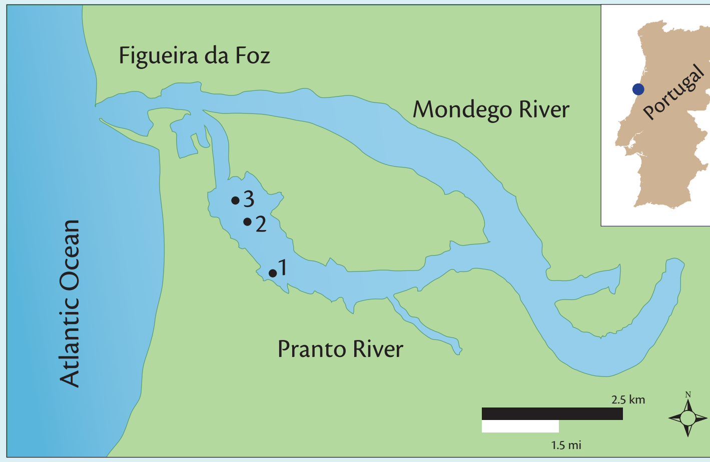
MONDEGO RIVER, PORTUGAL: *Seasonal macroalgae blooms lead to seagrass loss*

Joao G. Ferreira and Teresa C. Simas, IMAR (Institute of Marine Research), New University of Lisbon

The Mondego River drains a 6,670 km^2 watershed, and ends in a tidal estuary on the west coast of Portugal at Figueira de Foz. The estuary has a surface area of 11 km^2. It branches into two channels (north and south) separated by an island (Murraceira). The northern channel is deeper (5–10 m during high tide, tidal range 2–3 m), while the southern one has a maximum depth of 2–4 m during high tide and is largely silted in the upstream areas. The main freshwater discharge from the river therefore flows through the northern channel, and water circulation in the south channel is mainly tidally driven, with irregular (small) freshwater inputs from the Pranto River, which is regulated by a sluice located 3 km upstream.



Mondego Estuary morphology and location of 3 stations in problem area (data for 36 sampling stations cover the whole domain).

Issue of concern: loss of SAV

In the south channel of Mondego Estuary there is a high biomass of the opportunistic green algae *Enteromorpha* and *Ulva*, which now replace areas formerly covered by the submerged aquatic vegetation *Zostera noltii* and the saltmarsh species *Spartina maritima*. Although these macroalgae are also observed in the north channel, regular *Enteromorpha* blooms are especially prevalent in the inner parts of the south channel. These blooms have severe repercussions on the ecology of the ecosystem because they smother benthic animals, and cause huge fluctuations in dissolved oxygen, leading to mortalities on higher trophic levels. The changes in state observed in the south channel are caused by a combination of excessive nutrient loading and high susceptibility.

Influencing factors

Nutrients

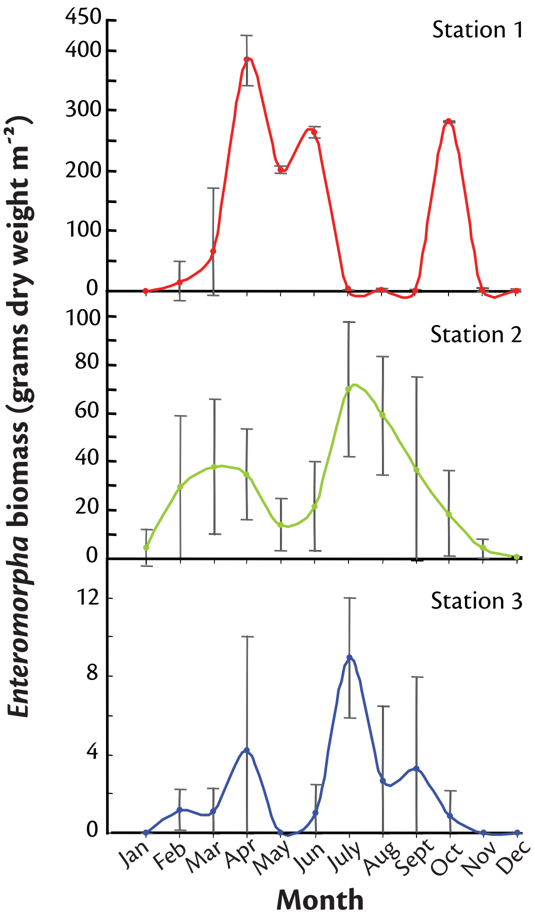
Nutrients from domestic sources come primarily from the population of Figueira da Foz and the Mondego River discharge. The sewage of about 90% of the population is discharged to the system without treatment. No data on nutrient inputs from industry and agriculture on the shores of the estuary were available. Inputs from the Mondego River were calculated using discharge data and concentrations of nitrogen and phosphorus measured in the river. Annual loads into the north channel are about 92 tons of nitrogen and four tons of phosphorus.

Since the eutrophication problems are mainly identified in the south channel, it is important to consider all the potential nutrient contributions to this area. The Pranto River is considered the main anthropogenic source of nutrients (agricultural and sewage-related) to the south channel. Agriculture occurring in the catchment is primarily rice (45%) and corn (51%). In the Pranto River basin, 50–80% of the population has a sewage system linked to wastewater treatment plants, corresponding to an annual domestic load into the south channel of 51 tons of nitrogen and 23 tons of phosphorus.

Susceptibility

The tidal excursion is greater in the northern channel, which receives the main freshwater inflow, causing high daily salinity fluctuations. The south channel of the estuary is less affected by human activity. But due to its low depth, restricted circulation, and discharge of inorganic nutrients from the Pranto River, the south channel is considered to be more vulnerable to environmental pressures. Due to the reduced water circulation in the system, which is mainly driven by tides, the dilution potential in the south channel can be considered low. The only freshwater input to the south channel comes from the Pranto River, during periods when the sluice is opened. This occurs from October to March, so the flushing potential is considered high for only half of the year, and low during summer and spring, since it depends solely on the tide.

Figure 5.38. Monthly means of *Enteromorpha* biomass in the south channel of the Mondego estuary in 1993–1994.



Characteristic eutrophic symptoms

Macroalgae

The growth dynamics of the most abundant green algae (*Enteromorpha intestinalis* and *Enteromorpha compressa*) were studied in a biomass gradient transect in the south channel of the estuary. Biomasses at the three sampling stations (Figure 5.38) decrease downstream. Although algae are present throughout the year at all sampling stations, the most abundant blooms occur in spring and early autumn at Station 1. At the other two stations, the macroalgal growing season starts in late winter and maximum biomass usually occurs in spring, with a second peak in mid-summer (Figure 5.38).

The macroalgal blooms in the south channel of the estuary are mainly controlled by excessive nutrient loading, hydrodynamics, and changes in salinity. The optimum salinity range for these macroalgae is 17–22 psu. *Enteromorpha* blooms are directly related to increased salinity in the south channel, which occurs in months of low rainfall, when the Pranto sluice is closed to maintain the water level in the paddy fields. In this situation, the water circulation depends on tides. When the sluice is opened, freshwater is discharged into the south channel, and free-floating materials are exported to the ocean. Advective transport is a significant mechanism controlling macroalgal biomass, particularly for free-floating species such as *Ulva*. Although *Enteromorpha* is attached to the bottom, the bed shear stress due to the current (1.4 m s^{-1}) is sufficient to cause export to the ocean.

The agricultural practices in the Pranto watershed, coupled to the freshwater discharge regime, appear to be the main factors for the dissolved nitrogen and organic matter enrichment of the south channel of the estuary. Organic matter accumulates in the sediment and decomposes, releasing ammonia, which is a primary driver of macroalgal blooms.

Submerged aquatic vegetation

Zostera noltii meadows, which in the past occupied most of the subtidal estuarine area, are presently restricted to the downstream section of the south channel. Thus, there has been a decrease in the area occupied by submerged aquatic vegetation (SAV) since the early 1980s, although no data on the percentage loss are available.

The overgrowth of green algae is the main cause of SAV losses due to reduced light availability and smothering. In the downstream part of the south channel, the annual peaks of *Zostera noltii* biomass can be observed during the growing season in spring and summer. The lowest biomass values are in late winter (Figure 5.39).

Figure 5.39. *Zostera* spatial coverage in the south channel of the Mondego estuary.

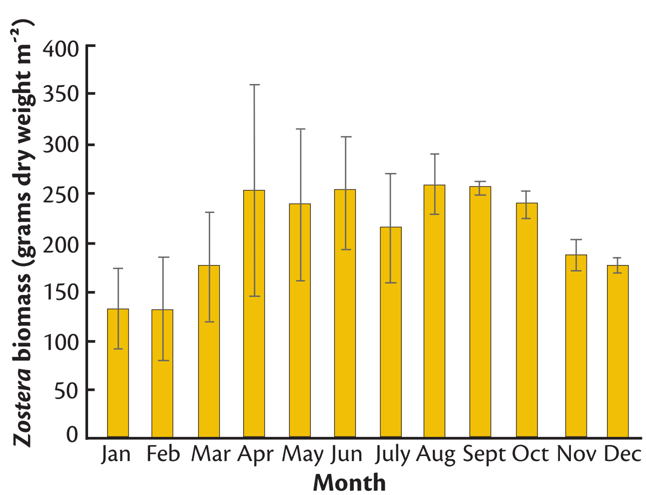
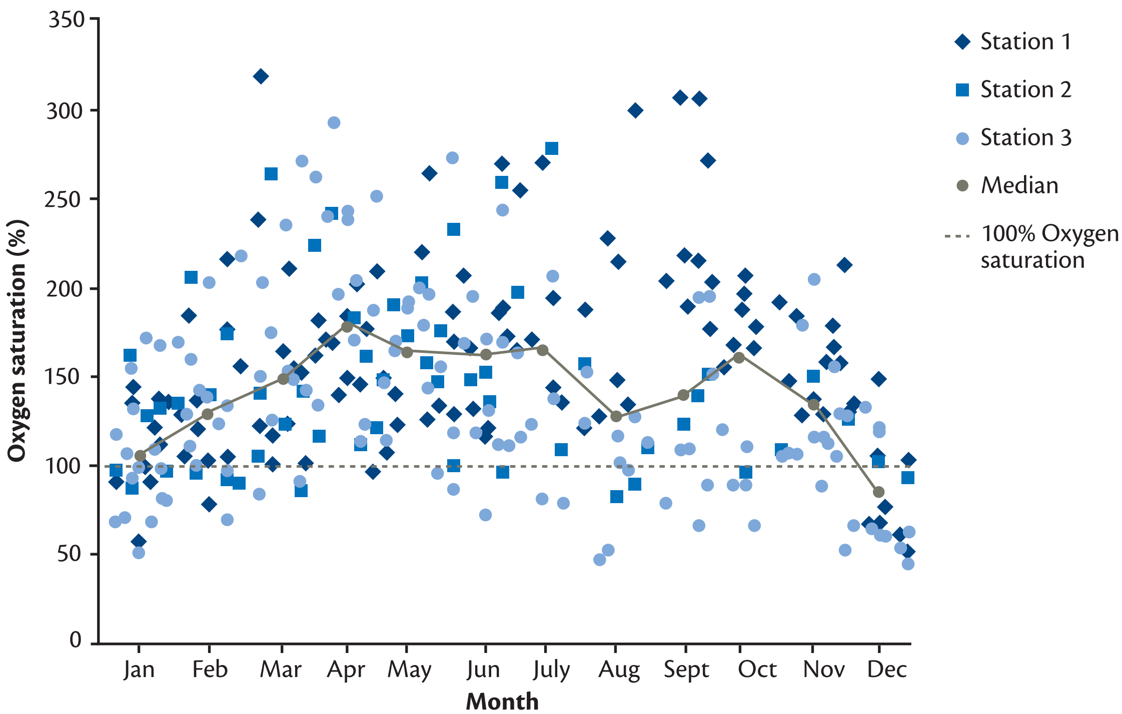


Figure 5.40. Oxygen saturation in the south channel of the Mondego estuary 1993–1997.



Dissolved oxygen

Figure 5.40 illustrates the fluctuations in dissolved oxygen in the south channel, which appear to be related to macroalgal biomass. A typical pattern of high supersaturation (reaching 300%) can be observed in daytime, followed by hypoxic conditions during the night. The typical consequences of this variability are the disappearance of species which tolerate a specific range of oxygen in the water, increased mortality of the macrobenthos, and subsequent organic decomposition.

Future outlook

The Portuguese national legislation on wastewater discharge stipulates that treatment plants should be implemented by 2006 in urban centers with populations of 2,000–15,000. Thus, it is expected that the sewage-derived loading to the estuary will decrease. However, the same cannot be concluded for nutrient inputs from agriculture, which are dependent on the future agricultural practices in the catchment. Since the main pressures on eutrophication are due to the nutrient inputs from agriculture, no clear improvement can be presently identified.

Assessment of estuarine trophic status (ASSETS)

The ASSETS (Assessment of Estuarine Trophic Status) model was chosen as an integrated approach for eutrophication assessment in the Mondego estuary (Table 5.6). According to ASSETS, the 90th percentile value for chlorophyll *a* is in the low (<5 micrograms chl *a* L^{-1}) and medium (5–20 micrograms chl *a* L^{-1}) categories, and the dissolved oxygen is generally above the 5 mg L^{-1} threshold, indicating no oxygen problems, except in tidal freshwater (P_{10} = 4.9 mg L^{-1}).

The macroalgal classification shows that parts of the system are impaired, particularly in the south channel, due to excessive blooms of *Enteromorpha* and *Ulva*, which locally cause oxygen problems and increase mortality of benthic bivalves, with consequences for the cockle (*Cerastoderma edule*) fishery. The overall eutrophic condition classification was moderate low.

The overall ASSETS grade obtained was moderate, based on the moderate high rating for influencing factors, moderate low score for eutrophic condition, and the expectation of 'no change' in nutrient loads given by future outlook. In summary, the main issues identified for the Mondego estuary are: (1) existence of eutrophic areas in the south channel, with increased macroalgae, loss of SAV, and DO problems as the main symptoms; (2) causes of these macroalgal blooms are apparently linked to the management of the Pranto sluice (when the sluice is opened, high loads of nutrients are discharged to the South channel, leading to organic enrichment in the sediment. When closed, the salinity increase and associated nutrient availability triggers algal blooms); and (3) management measures should consider improved agriculture practices in the Pranto basin and propose eco-technological solutions.

Table 5.6. ASSETS rating for Mondego estuary.

Overall ASSETS rating: moderate

	Symptom expression	ASSETS SCORE
Influencing factors		highly/ moderately influenced
susceptibility	low	
nutrient loads	moderate	
Eutrophic conditions		
chlorophyll *a*	moderate	
macroalgae	moderate	moderate
dissolved oxygen	low	low
loss of SAV	low	
nuisance/toxic algal blooms	low	
Future outlook		
future nutrient loads	no change	no change

Implications for other systems

These types of eutrophic symptoms of nutrient enrichment have been observed in many shallow coastal systems, including the Venice Lagoon, Lac de Tunis, and the Ria Formosa. The relevance of type-specific thresholds and/or approaches for eutrophication assessment in shallow systems with macroalgal problems is exemplified in the present case study. The current NEEA and ASSETS oxygen thresholds do not reflect the absolute deviation in dissolved oxygen from 100% saturation, which may be an important indicator of eutrophication. One possibility for adapting the oxygen indicator would be to set thresholds based on the proportion of data which deviate from 100% saturation. Figure 5.41 shows an example, where there is a 95% deviation from saturation values in 90% of the samples (the P_{90}), i.e., a very 'noisy' dissolved oxygen distribution. This indicates abnormal macroalgae productivity and respiration over the diel cycle. By contrast, the P_{90} value for the north channel, where macroalgal problems are not evident, is 21%, indicating that the data are much closer to 100% saturation.

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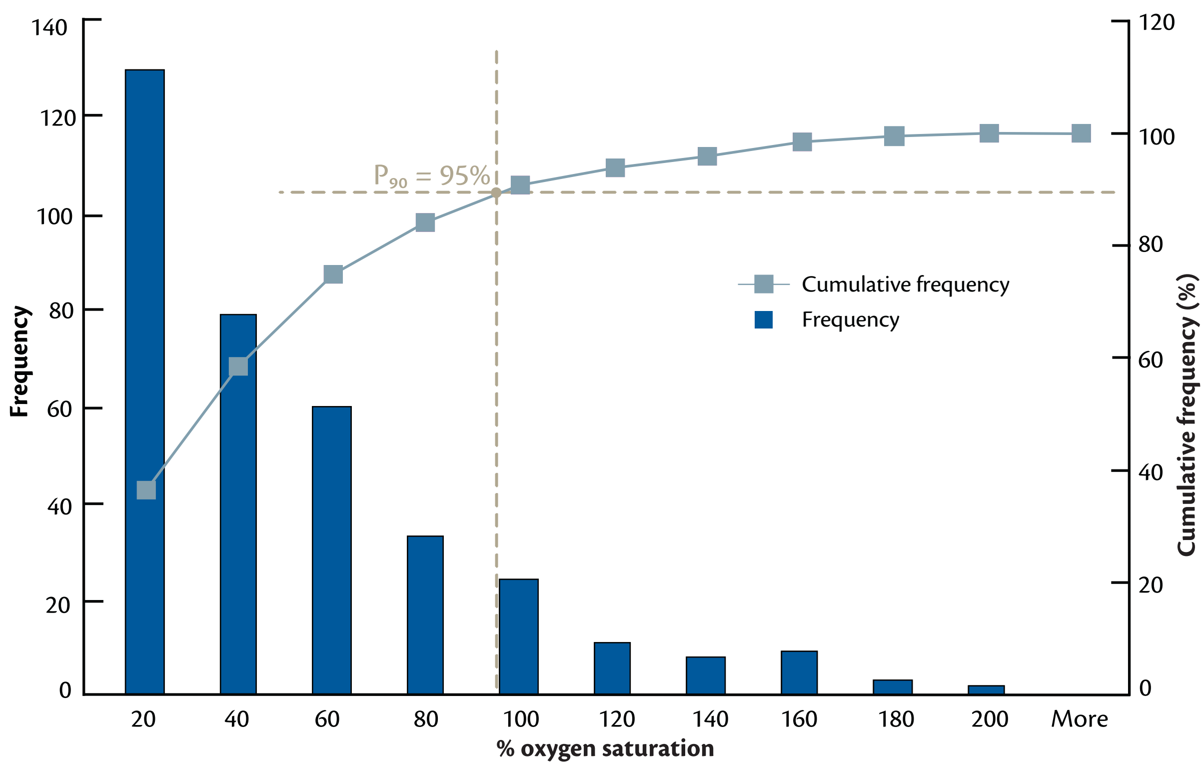
Figure 5.41. Absolute deviation from full oxygen saturation in the south channel of Mondego estuary, 1993–1997.



MORETON BAY, AUSTRALIA: *Sewage plume mapping tracks nutrient reductions*

Ben Longstaff and Bill Dennison, University of Maryland Center for Environmental Science

Moreton Bay is a sub-tropical, shallow embayment (1.5×10^3 km^2) located halfway along the east coast of Australia. Its drainage watershed (2.1×10^4 km^2) contains an urban center with a population of approximately 1.5 million people. Development is concentrated on the western side of the bay and high nutrient concentrations in surrounding waters reflect this urban influence. Many of the region's wastewater treatment plants are being upgraded to reduce the amount of nitrogen discharged into the bay. A novel monitoring approach, based on nitrogen isotope ratio in macroalgae, was established to help track the extent of sewage nitrogen.

Issue of concern: nitrogen loading

In the mid 1990s, a regional partnership and strategy was formed to spearhead the restoration and protection of Moreton Bay. A comprehensive study of Moreton Bay (Dennison and Abal 1999) determined that the Bay was nitrogen limited, and that restoration efforts should focus on reducing nitrogen loads. Upgrading wastewater treatment plants (WWTP) was identified as the first course of action. During the Moreton Bay study, a unique method for mapping sewage nitrogen plumes was developed (Costanzo et al. 2001), providing an important tool for assessing the effectiveness of the upgrades. Sewage plume mapping was conducted in 1998, before any upgrades, and this assessment was critical in illustrating areas of the Bay most impacted by sewage, and hence where WWTP upgrades should occur.

Sewage treatment plants upgraded

Upgraded sewage treatment plants started to become operational in 2000, with the most significant load reduction occurring at the Brisbane River mouth. Sewage treatment plant upgrades during this period resulted in a 60% reduction in nitrogen loads from those treatment plants (Figure 5.42). Upgrades

Figure 5.42. Change in sewage nitrogen loading into Moreton Bay and tidal estuaries, 1998–2003.

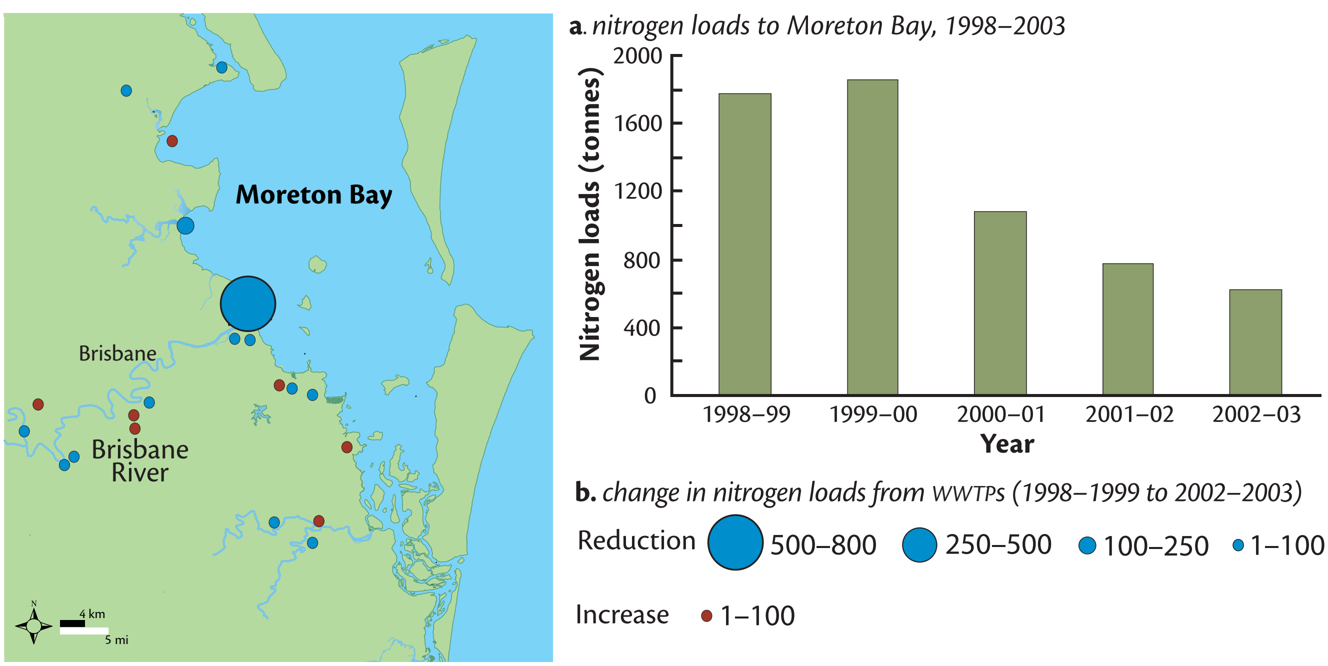
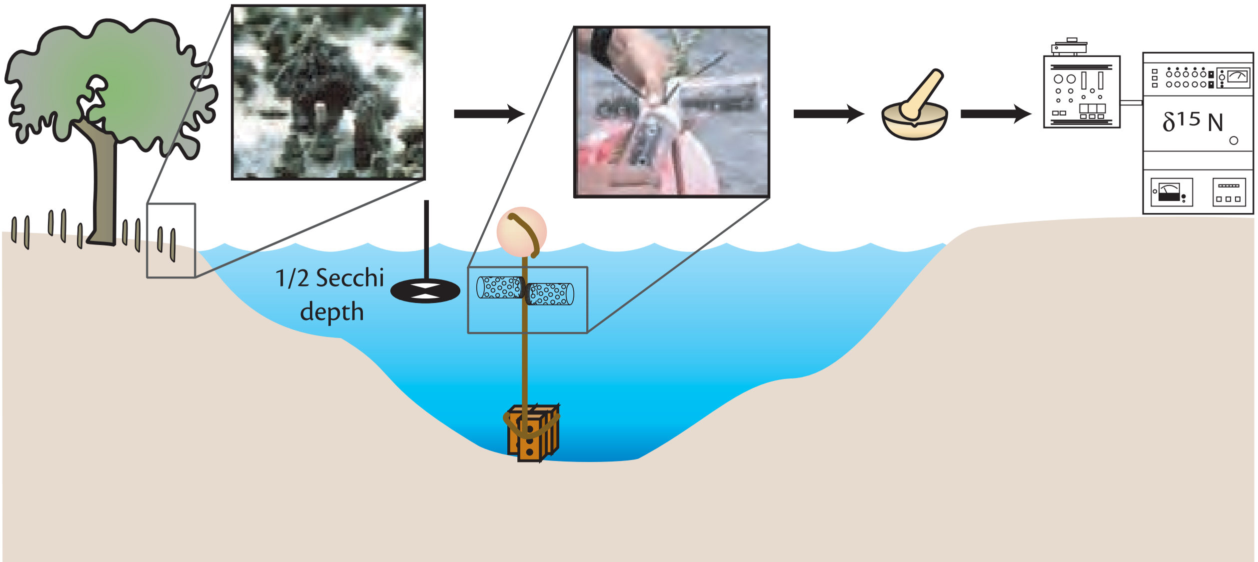


Figure 5.43. Sewage plume mapping process for Moreton Bay.



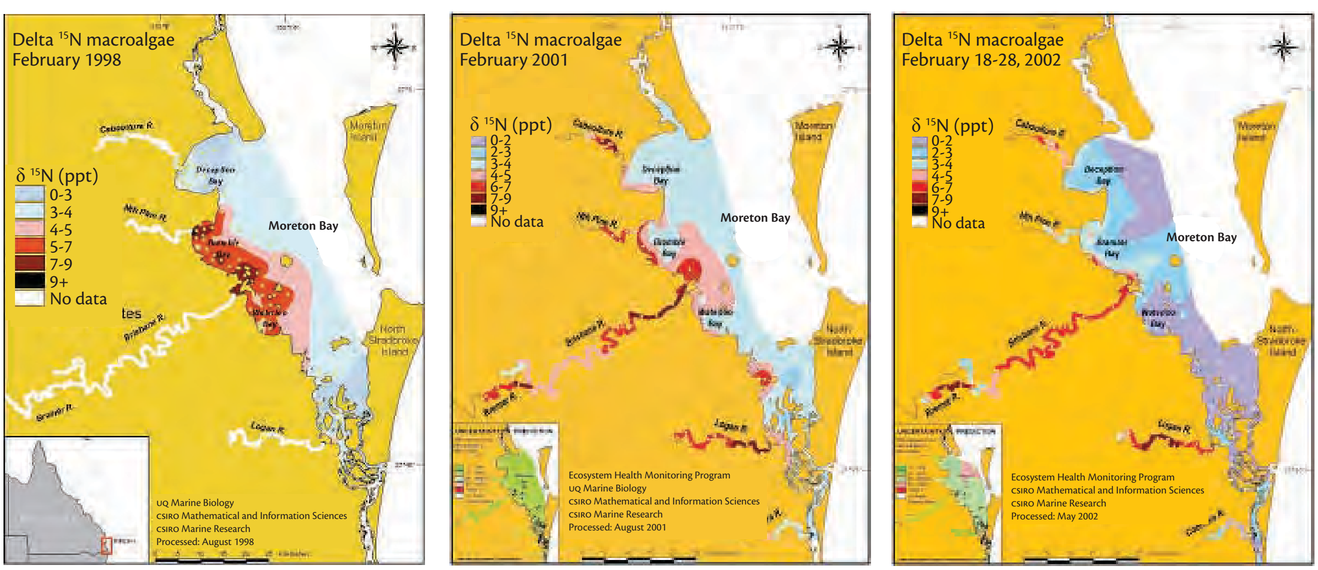
Collect macroalgae (or other indicator organisms such as oysters or submerged aquatic vegetation) from a site distant from nutrient sources, incubate *in situ*, then dry, grind, and analyze on a stable isotope mass spectrometer for determination of $\delta^{15}N$.

of smaller WWTP continued through 2000–2003, resulting in a smaller overall reduction. Sewage nitrogen was mapped using nitrogen stable isotope ratio ($\delta^{15}N$) each summer from 1998–2003. Samples of the red macroalga, *Catenella nipae*, were collected from a low nutrient environment on the eastern side of Moreton Bay. The macroalgae were deployed at over 100 sites. At each site, the macroalgae were housed in transparent, perforated chambers and suspended in the water column for 4 days at half Secchi disk depth (Figure 5.43). Following collection, the nitrogen stable isotope ratio in the plant material was determined using a mass spectrometer. Stable isotope ratios were spatially interpolated using universal Kriging (Cressie 1993).

Nitrogen plume diminishes

Sewage nitrogen mapping in 1998 (before WWTP upgrades) revealed a large sewage nitrogen plume in the western region of Moreton Bay (Figure 5.44). It is evident that measurable changes in sewage nitrogen plumes have been recorded since the upgrades, with

Figure 5.44. Extent of sewage nitrogen plume extending into Moreton Bay, 1998–2002.



the most significant plume reduction corresponding to the period of greatest nitrogen load reduction. This technique has demonstrated its usefulness to managers in providing timely and informative feedback on the effects of reducing sewage nitrogen loads to coastal environments.

Assessment of estuarine trophic status (ASSETS)

Moreton Bay (not including tributaries such as the Brisbane River) is characterized by low primary symptom expression. Chlorophyll *a* levels in the central and eastern regions of the Bay tend to be low (~0.5 to 1 µg L^{-1}) and relatively stable, where as levels in the western embayments are higher, with blooms (5-10 µg L^{-1}) tending to occur in warmer summer months. Blooms of *Ulva* (macroalgae) use to be a regular summer occurrence in some of the western embayments, but these blooms have declined since wastewater treatment plant nitrogen loads were reduced in the early 2000s. The only secondary symptom of major concern in Moreton Bay is the occurrence of *Lyngbya majuscula*, a toxic filamentous cyanobacterium that generally occurs in shallow seagrass beds during warm and calm periods. *Lyngbya* smothers seagrass, clogs fishing gear, and washes up onto local beaches, leading to closures and in some cases necessitating removal by earth moving equipment. *Lyngbya* contains a diverse range of toxins that can cause symptoms such as skin irritations and nausea in humans. Occurrence of *Lyngbya* is one symptom leading to an overall ASSETS rating of poor for Moreton Bay.

Table 5.7. ASSETS rating for Moreton Bay.
Overall ASSETS rating: poor

	Symptom expression	ASSETS SCORE
Influencing factors		
susceptibility	moderate	moderate
nutrient loads	moderate	
Eutrophic conditions		
chlorophyll *a*	low	moderate high
macroalgae	low	
dissolved oxygen	low	
loss of SAV	low	
nuisance/toxic algal blooms	high	
Future outlook		
future nutrient loads	decreasing	small improvement

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VENICE LAGOON, ITALY: *Flood protection measure can accentuate eutrophication*

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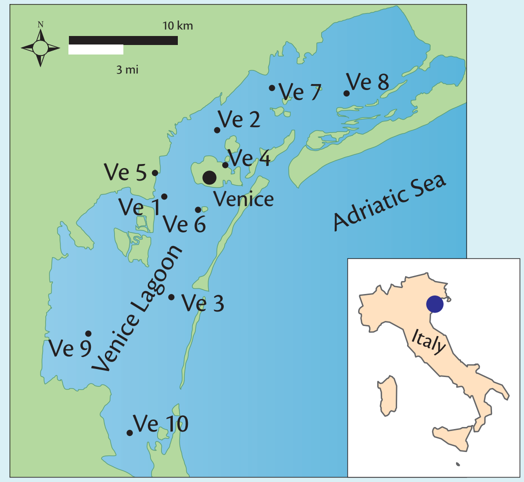
Venice Lagoon is one of the largest European estuaries, with a total surface area of 550 km^2, of which 360 are open to tidal exchange. The lagoon is located along the northeast coast of the Adriatic Sea in Italy, Southern Europe. It is a shallow water basin, with a mean depth of approximately 1.5 m, and is connected to the sea by three inlets. The average tributary discharge, about 35 $m^3 s^{-1}$, is small in comparison with the volume exchanged at each tidal cycle. The lagoon watershed is 1850 km^2 and the main freshwater discharge from the rivers flows into the northern part of the lagoon, which receives about 45% of the total tributary discharge. (Study sites Ve 1–Ve 10 shown on map.)



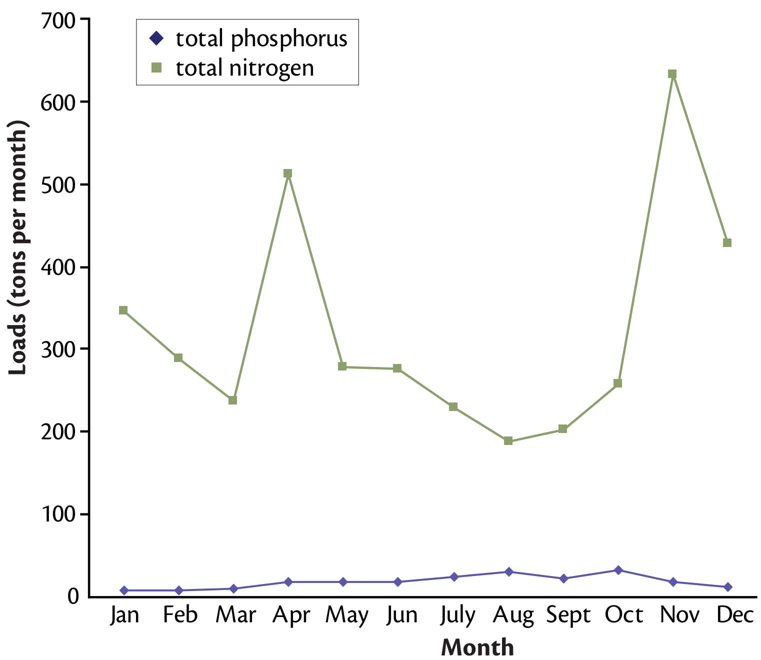
Issue of concern: flood & pollution management

Due to management actions that have diminished effluent discharge into the lagoon, eutrophication does not seem to be the main threat to Venice Lagoon at present (Figure 5.45). The current environmental problems are the maintenance of the morphological features of the lagoon and the protection of the city of Venice from flooding, and the contamination of large areas used as uncontrolled dump sites for industrial waste and the pollutants released by these contaminated sediments.

History of pollutants in this region

The uncontrolled discharge of nutrients during the 1960s and the 1970s contributed to hypertrophic conditions, which appeared during the 1980s, when the density of macroalgae (*Ulva rigida*) reached values as high as 20 kg fresh weight m^{-2} in large areas of the central part of the lagoon (Sfriso et al. 1989). In order to reduce the loads of nitrogen and phosphorus, wastewater treatment plants (WWTPs) were built and phosphorus was banned from detergents in the 1980s. These actions have led to a marked decrease in

Figure 5.45. Total nitrogen and total phosphorus loading to Venice Lagoon, 1999.



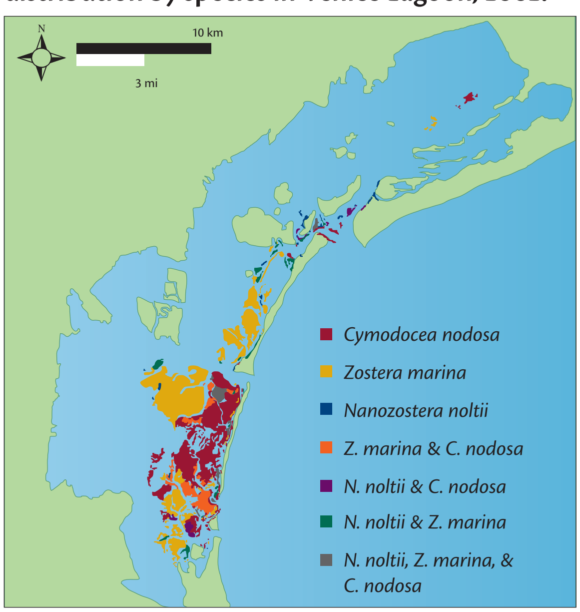
Stefano Ciavatta, University of Venice

Maintaining the original features of Venice Lagoon, while trying to prevent flooding has proved to be challenging.

the concentration of ammonia and soluble reactive phosphorus (SRP) (Pastres et al. 2004). As a result, during the last fifteen years, macroalgae biomass has markedly decreased, while submerged aquatic vegetation meadows, mainly *Zostera marina* and *Cymodocea nodosa*, are progressively re-colonizing large areas in the central and southern part of the lagoon (Figure 5.46).

Currently, the main sources of nitrogen and phosphorus are the tributaries, the effluents from WWTPs and factories located in the industrial zone, and the urban wastewater from the city of Venice. Current nutrient inputs from the tributaries were estimated using discharge data and concentrations of nitrogen and phosphorus measured in the year 1999

Figure 5.46. Submerged aquatic vegetation distribution by species in Venice Lagoon, 2002.



(Collavini et al. 2005). The annual tributary loads amount to 4000 tons y^{-1} of nitrogen and 230 tons y^{-1} of phosphorus. The effluents from the industrial zone still contribute approximately 1000 tons y^{-1} of nitrogen and 72 tons y^{-1} of phosphorus, a significant amount for Venice Lagoon.

Characteristic eutrophic symptoms

Macroalgae

Macroalgae coverage and density have dramatically decreased in the last two decades. The results of an extensive survey carried out in 2002 indicate that macroalgae are now mainly present in the south, in association with submerged aquatic vegetation meadows (SELC 2005). Small patches of macroalgae can be found in the central and northern parts of the lagoon, with densities not exceeding 0.5 kg fw m^{-2}.

Submerged aquatic vegetation

The spatial distribution of the three submerged aquatic vegetation species which can be found in Venice Lagoon (*Zostera marina*, *Nanozostera noltii*, and *Cymodocea nodosa*) is shown in Figure 5.46. Although the total area covered by submerged aquatic vegetation, about 54 km^2, has not changed much since the first systematic survey was carried out in 1992, the species abundance has varied significantly. In particular, the area covered by pure *Nanozostera noltii* meadows dropped from 14.36 km^2 in 1992 to 0.7 km^2 in 2002, while the area covered by *Zostera marina* increased from 2.66 to 22 km^2. The marked decrease in *Nanozostera noltii* could be caused by a general decreased water clarity and reduction in available habitat due to the introduction of clam aquaculture. Habitat has been particularly compromised in edges of small canals in the north. *Zostera marina* are also

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Small patches of macroalgae can be found in the central and northern parts of Venice Lagoon.

much taller, and less likely to be affected by reduced light than *Nanozostera noltii*.

Dissolved oxygen

In the 1970s and 1980s, due to massive amounts of decaying macroalgae, large areas in the central part of the lagoon suffered from severe anoxia. Since 2002, accurate information about the fluctuations of dissolved oxygen in Venice Lagoon are provided by SAMANET, the network for real time water quality monitoring, which is managed by the Venice Water Authority. Temperature, salinity, dissolved oxygen, pH, water clarity, and chlorophyll *a* are measured every 30 minutes using automatic probes at the ten stations shown in the area map (Ferrari et al. 2004). The mean, minimum, and maximum daily values, averaged over the five stations Ve1–Ve5 for the years 2004 and 2005, are shown in Figure 5.47. These stations have been operating since 2004. The minimum daily values do not fall below 40% saturation, indicating that dissolved oxygen levels are adequate for aquatic life. Data collected during the monthly cruises conducted at the 23 monitoring stations over 2001–2005 are in agreement with the above findings.

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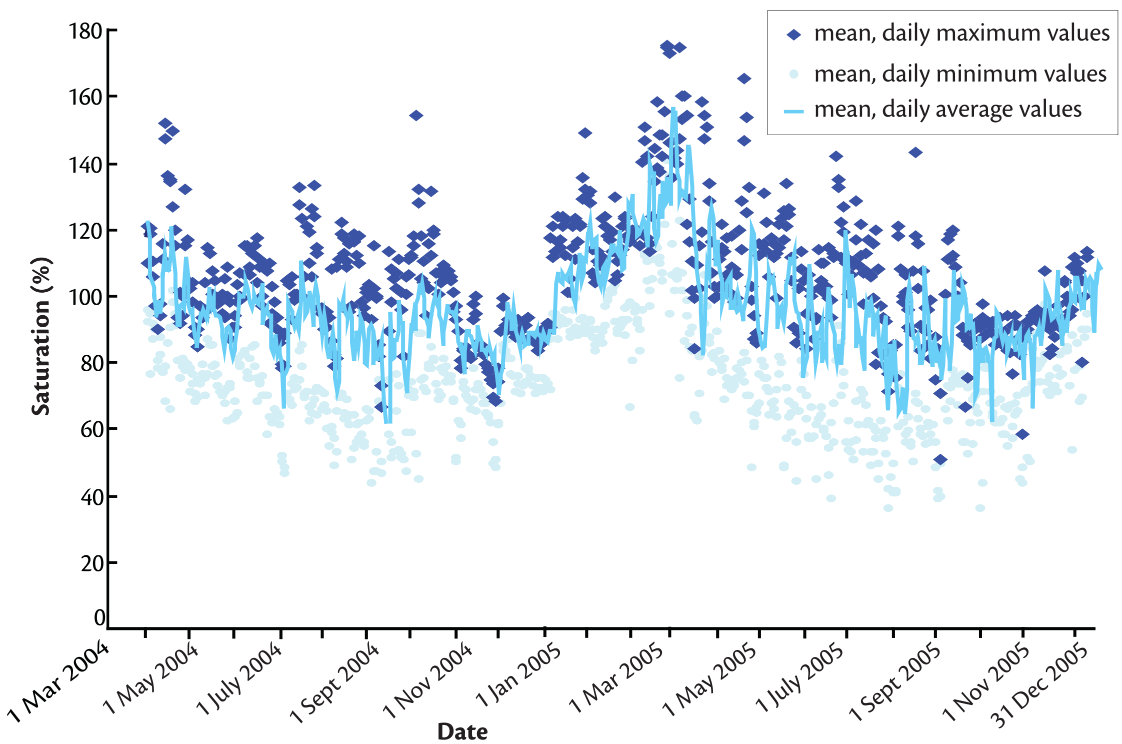
Piazza San Marco, Venice, during the agua alta–the annual winter flooding.

Figure 5.47. Dissolved oxygen at stations Ve1–Ve5, 2004–2005.



Future outlook

Several statutory bodies are entrusted with different aspects of managing Venice Lagoon. The control of nutrient loads is entrusted to the Regional Council, which has planned the construction of new wastewater treatment plants and phytodepuration plants, in order to counterbalance the likely increase in the population in the watershed. Effluents from the industrial zone are closely monitored by the Venice Water Authority in order to observe the effect of the application of the best available technology to reduce loads, as required by special legislation for Venice.

Implications for other systems

The trends of the trophic state observed in Venice Lagoon in the last 30 years indicate that the management actions taken for counteracting the severe eutrophication symptoms experienced in the 1980s were successful. To this regard, it can be noted that the average concentration of soluble reactive phosphorus in the year 2005 was 7.9 µg L^{-1} (Cossarini et al. 2006). Furthermore, in many areas the benthic community has recovered quite rapidly, as the quality of water and sediment has improved in the last fifteen years. At present, eutrophication seems to be under control, even though monitoring is still required to detect early signs of a reverse in this positive trend.

Assessment of estuarine trophic status (ASSETS)

The ASSETS screening model was applied in order to assess the present eutrophication status of Venice Lagoon. For assessment, the most recent available data was used, including nutrient input measurements collected in 1999 by DRAIN (monitoring of major tributaries during 1998-2000, Collavini et al. 2005), water quality data collected monthly at 30 lagoon sites during 2001–2003 by MELa1 (Pastres and Solidoro 2004), and submerged aquatic vegetation distribution data from 2002 (SELC 2005).

On the basis of these data, the lagoon was classified as a seawater zone in the ASSETS scheme because the average salinity is higher than 25 psu at all sampling sites. The 90th percentile value for chlorophyll *a* (24.4 g chl *a* L^{-1}) was determined to be high, while the dissolved oxygen 10th percentile was 6 mg L^{-1}, indicating no oxygen problems. The biomass level of macroalgae is not a problem for the lagoon at this time, and the increasing direction of change and moderate magnitude of the submerged aquatic vegetation biomass suggest good condition of SAV. As a consequence, the overall eutrophic condition was low. The influencing factors rating for the lagoon was classified as moderate, while the future outlook was estimated to improve to a small degree. By combining these indices, the overall ASSETS rating obtained for Venice Lagoon was classified as good.

Table 5.7. ASSETS rating for Venice Lagoon.

Overall ASSETS rating: good

	Symptom expression	ASSETS SCORE
Influencing factors		
susceptibility	moderate	moderate
nutrient loads	moderate	
Eutrophic conditions		
chlorophyll *a*	low	low
macroalgae	low	
dissolved oxygen	low	
loss of SAV	low	
nuisance/toxic algal blooms	low	
Future outlook		
future nutrient loads	decreasing	small improvement

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6. IMPROVEMENTS TO THE ASSESSMENT

IMPROVING THE METHOD

- The accuracy of the methods used in the NEEA continues to improve for the future.
- Linkages between EPA's National Coastal Assessment and the NEEA program were examined.
- An indicator for socioeconomic/human use impacts to Barnegat Bay is described.
- An estuarine classification scheme, or typology, is under development.
- The method of evaluating eutrophic condition is being improved, especially for SAV and macroalgal abundance.

Developing methods which accurately assess the eutrophic conditions of the nation's estuaries is a significant challenge, especially considering the huge diversity of estuaries present, their varying sensitivities to nutrients, and their diverse functional characteristics. With assistance from U.S. and international eutrophication experts, a set of methods has been developed over the past 16 years (see Bricker et al. 1999, 2003, 2004, 2006; Scavia and Bricker 2006; see *www.eutro.org* for more details), leading to those included in this assessment. While the established methods have provided a relatively reliable assessment of the Nation's estuaries, the NEEA continually seeks improvement.

Since the first NEEA assessment in 1999, two workshops have been held, with over 40 experts from across the nation participating in each (Bricker et al. 2004, this study). These workshops have provided an excellent opportunity to seek recommendations on how the methods can be improved. This chapter highlights some of the main recommendations made at the workshops and by survey participants.

Recommendation #1: The overall recommendation from both workshops was to develop a long term, coordinated eutrophication monitoring and assessment program to help managers address problems in coastal water bodies on a national basis.

Response #1: At present there is no comprehensive, national monitoring program which samples the same eutrophication indicators in all U.S. waterbodies. This fact makes a national assessment such as this one difficult to achieve. The NEEA team has worked with state, federal, academic, and non-governmental organization experts for the past sixteen years to identify the appropriate indicators to be used for this assessment. Mechanisms for coordinated acquisition of pertinent data from existing programs as well as national overarching data collection programs (e.g.,

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Developing a socioeconomic indicator will help researchers and managers understand how eutrophication impacts human uses such as commercial fishing.

Integrated Ocean Observing System, National Water Quality Monitoring Network, EPA National Coastal Assessment) are being discussed and developed. The team will work further to influence the development of standardized methods of indicator measurement.

Recommendation #2: Develop a strategy of reporting and meeting time frames, with the specific recommendation of providing periodic updates of the assessment.

Response #2: The NEEA team is reviewing the options for providing more frequent updates. Challenges currently being addressed include determining: (i) the most appropriate frequency for which the assessment should be repeated, (ii) how to make the assessment program sustainable when repeated at shorter time frames (the online survey form developed for this update is one example already undertaken), and (iii) the appropriate mechanisms for reporting assessment results when conducted at greater frequencies.

Recommendation #3: Develop a framework for increasing the accuracy and reliability of data entered into the survey.

Response #3: An inherent challenge of surveying the Nation's estuaries using data from multiple sources is accounting for the diversity of data quality entered. Quality and completeness of data entered is not only dependent upon the monitoring data available, but also upon the diligence of the survey respondents. The NEEA team will continue to improve data quality by developing the recommended framework. This framework will include factors such as: (i) providing detailed guidelines and protocols, (ii) an opportunity to obtain training and support, (iii) improving the methods used to assess eutrophic symptom expression (see below), (iv) developing tools for managers, and (v) making all of this available online.

Recommendation #4: Improve the accuracy of the macroalgae indicator by: (i) requiring a spatial coverage assessment, (ii) defining the thresholds at which macroalgal abundance is considered a eutrophic symptom responding to excess nutrients, and (iii) developing standardized monitoring protocols to enable better comparison of results.

Response #4: The current set of characteristics used to assess macroalgae symptom expression is insufficient to differentiate between naturally occurring levels of macroalgal abundance and those signifying eutrophication. The NEEA team, with regional and national experts, will work to improve the survey methods and elucidate eutrophic responses. This process includes the development of a list of macroalgae nuisance species that when present are indicative of eutrophic conditions.

Recommendation #5: Improve the submerged aquatic vegetation (SAV) indicator by including both spatial coverage and biomass, basing values on the absolute value of change in area rather than on percent change in area. The indicator should be able to account for losses before the survey period. For those systems which have not historically had SAV, a different indicator should be developed.

Response #5: With regional and national SAV experts, the NEEA team will refine the SAV indicator to address the shortcomings identified by survey respondents. Some methods under development look promising and will be considered as a starting point (e.g., using linear measures of shoreline with SAV in place of traditional area measures, Latimer et al. 2006).

Recommendation #6: Develop a classification of estuaries using physical and hydrologic characteristics to describe and group systems by their susceptibility and the type of eutrophic conditions expressed.

Abundant green algae in a shallow bay. One suggestion for improving the method is adding a spatial coverage component to the macroalgae indicator.

Response #6: NOAA has commissioned the development of a type classification as the first step in improvements to the method. A useful and functional typology appears achievable (see below for details about the development of this classification).

Recommendation #7: Establish the link between eutrophication symptoms and the loss of beneficial uses/aquatic life use through development of an economic/human use indicator.

Response #7: Few studies have linked human dimensions or socioeconomic cost to nutrient impaired coastal water quality. In response to this recommendation, NOAA commissioned the development of a socioeconomic indicator. Its application in Barnegat Bay is described in this chapter. Complementing the existing eutrophication indicators, the socioeconomic aspect will illustrate the impacts and potential economic losses to human uses of coastal systems as a result of nutrient related water quality degradation.

Recommendation #8: Establish a link between the NEEA eutrophic symptom indicators and EPA's National Coastal Assessment Water Quality Index indicators. Work with EPA on the establishment of nutrient criteria (particularly biocriteria) for estuaries.

Response #8: The NEEA team, with EPA, is exploring linkages between the two national assessment programs with the aim of identifying potential collaborations. An intensive comparison between the programs is planned for 2007–2008, whereby a full set of recommendations will be provided. Currently, the two assessments have been compared and contrasted (See next page).

COMPARING THE EPA NATIONAL COASTAL ASSESSMENT WITH THE NEEA

- Two programs (NEEA and NCA) assess estuarine condition at a national scale.
- Both programs indicate a similar present condition of moderate or fair, but NCA shows improvements since the early 1990s while NEEA shows no change in condition over the same time period.


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The NEEA uses information from a variety of sources, ranging from large-scale, fixed-monitoring stations to manually deployed instruments.

Given the widespread problems and possible long-term impacts of eutrophication in U.S. and global coastal water bodies, it is not surprising that two national assessments have evolved, one conducted by the Environmental Protection Agency (EPA) and the other (the NEEA) by NOAA. The goal of the EPA National Coastal Assessment (NCA) is to document ecological conditions and trends throughout the Nation's estuaries through assessment of water and sediment quality, benthic community and coastal habitat health, and fish tissue contaminant concentrations. This is a broader goal than that of the NEEA, which evaluates the status and trends of nutrients only in coastal systems, the causes of observed impairments, and predicts future conditions based on demographic changes and management implementation. The intent of the NEEA is to provide a basis for the development of management measures to protect water bodies from further nutrient-related degradation. The EPA's NCA includes a nutrient related index, the Water Quality Index (WQI), which is comparable to the NEEA overall eutrophic condition component. Since both assessment frameworks are national in scope, it was recommended at the 2006 NEEA workshop that a link be established between NEEA and NCA WQI, while still recognizing the different goals of each program. This chapter highlights the first step in establishing this link by comparing results of the NCA WQI and results of the NEEA assessment of overall eutrophic condition.

Table 6.1 compares the results of the NCA water quality index and the NEEA overall eutrophication condition rating. The time frame represented by the NCA comparison is approximately 5 years (1990–1996 vs 1996–2000 USEPA 2001, 2005) while that of the NEEA is 10 years (early 1990s vs early 2000s; Bricker et al. 1999; this study). The NCA results are based on a comparison of both regional and national area-weighted WQI scores using five component indicators: dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), water clarity, chlorophyll *a*, and dissolved oxygen (Table 6.2). The indicators are all given equal weight in an index formulation. The NCA WQI data were collected at stations that were randomly selected, using the EPA Environmental Monitoring and Assessment Program's (EMAP) probabilistic sampling framework. Data were sampled

Table 6.1. Comparison of trends in nutrient related conditions for NCA WQI and NEEA overall eutrophic condition. Scale is 1 - 5 (1 = poor and 5 = good). Changes are reflected as (△) for improvements and (◯) for no change.

	NCA Water Quality Index*			NEEA Overall Eutrophic Condition**		
	1990–1996	1996–2000	Change	Early 1990's	Early 2000's	Change
National	2	3	△	3	3	◯
Northeast***	1	2	△	3	3	◯
Southeast	4	4	◯	3	3	◯
Gulf	1	3	△	3	3	◯
Pacific	1	3	△	3	3	◯

* NCA WQI methods changed between the 1990-1996 and 1996-2000 groups; the 1990-1996 scores were recalculated using the current methods.
**Note that NEEA uses only 90 of 141 systems for analysis; the 51 systems with unknown conditions in either or both years were not included in this comparison.
***NEEA results from the North and mid-Atlantic regions combined to calculate the Northest region.

once per year during a summer index period (June to October) which typically represents the time period of greatest observed nutrient-related impacts (USEPA, 2001a). The NCA sampling regime provides 90% confidence in the results for its condition indicator for the U.S. and subregions (i.e., states). The NCA water quality index for U.S. estuaries (national scores) typically includes the Great Lakes and Puerto Rico, but for this assessment only contiguous U.S. water bodies are included for direct comparison to those in the NEEA.

The NEEA results are based on regional and nationally weighted averages of the number of systems assigned a particular overall eutrophic condition level. This level is based on annual data for five indicators:chlorophyll *a*, macroalgal abundance, dissolved oxygen, nuisance/toxic blooms, and loss of submerged aquatic vegetation (Table 6.2). The dissolved oxygen, nuisance/toxic blooms, and loss of submerged aquatic vegetation results are given a higher weight as a precautionary measure, recognizing that they are indicative of more well developed nutrient-related degradation. While the North and mid-Atlantic are considered separate regions in the NEEA, they have been combined here and called the Northeast region for comparison to the region boundaries used by the NCA.

The national NCA survey results indicate an overall improvement in estuarine condition for the 5-year change analysis while the NEEA shows no changes for the 10-year change analysis. However, the most recent results for both surveys are the same, indicating moderate level conditions nationally. A detailed and statistically rigorous assessment of the WQI change is included in the National Coastal Condition Report III (in review). Regionally, the NCA results suggest improvement in all but the Southeast region, which remains unchanged. In contrast, the NEEA results suggest that conditions in all regions have remained the same since the early 1990s. Both NCA and NEEA identify the Northeast region (i.e., Chesapeake Bay and tributaries as the southern boundary and Maine systems as the northern boundary) as the most highly impacted region. The most recent NCA results report that 61% of the Northeast coastal area is rated as fair to poor (19% as poor, 42% as fair). Comparable NEEA results report that 79% of Northeast systems are rated moderate to poor (47% poor, 32% moderate).

Table 6.2. Indicator variables used for assessing the NCA Water Quality Index and NEEA overall eutrophic condition.

Indicator variable	NCA[1]	NEEA[2]
DIN	X	
DIP	X	
Water clarity	X	
Dissolved oxygen	X	X
Chlorophyll *a*	X	X
Macroalgae		X
Nuisance/toxic blooms		X
SAV loss		X

[1]The NCA does not weight the variables in the formulation of the WQI.

[2]The NEEA weights dissolved oxygen, nuisance/toxic blooms, and loss of SAV more heavily than chlorophyll *a* and macroalgae (*see text for explanation*).

While the comparability of the recent national results is encouraging, the variation in regional results and trends suggests that the differences between methods should be investigated further. In addition to the different indicators used by these methods, there are differences in sampling time frames. Furthermore, the NCA random stratified sampling program is designed to evaluate conditions for 100% of the estuarine water area, reporting results on a regional basis, while the NEEA is designed to evaluate conditions within individual water bodies, representing greater than 90% of continental U.S. estuarine area and greater than 90% of freshwater discharge to the U.S. coastal zone. These results can be summarized into regional and national perspectives.

This brief comparison of the national results is encouraging. A more detailed comparative study planned for 2008 should elucidate reasons for differences between the programs, and an approach for using the best of both for future assessments.

DETERMINING TYPOLOGY

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> Typology is a type classification of systems, determined by and grouped according to their sensitivity to nutrients and functional characteristics.

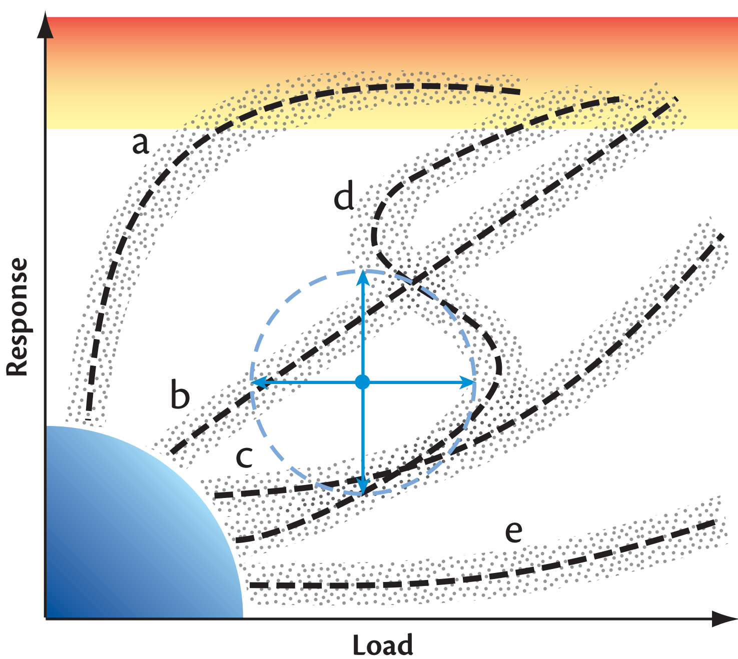
Type classification of U.S. estuaries is motivated by the need for two types of information — the sensitivity (or vulnerability) of specific estuaries or classes of estuaries to nutrient addition and the similarities between estuaries. Sensitivity reflects the degree of eutrophication (or the severity of eutrophication symptoms) to be expected for a given nutrient load. Similarity analysis identifies groups of estuaries that are similar not only in their sensitivities, but also in the functional characteristics contributing to this sensitivity. Such groups will have members subject to a variety of conditions and stressors, providing a broader perspective on the range and nature of responses. Also, similar systems can presumably be addressed with similar management approaches, permitting the transfer of knowledge and experience, and economies of scale — the primary goal for type classification in the NEEA.

The eutrophication assessment results presented in this report are a classification — a typology of eutrophication symptom intensity, categorized in the form of the classified variable, overall eutrophic condition (OEC). These scores, or classes, represent the system's observed nutrient-related water quality conditions. The OEC itself is a composite index, based on scores assigned to five eutrophic symptom variables. This index is very informative with regard to communicating the status of U.S. estuaries, and particularly in making useful comparisons among systems that may express a similar level of degradation, but with a different composition of symptoms.

Figure 6.1. shows a conceptual model illustrating the need for a functional typology. It illustrates various pathways that an estuary might follow in moving from an undisturbed natural state to a highly eutrophic condition as nutrient load increases. The blue arrows are intended to represent a semi-quantitative assessment of uncertainty at any given point on the graph. Sensitive estuaries are represented by the nearly vertical lines at the left side of the plot, while resilient estuaries with a high and robust assimilative capacity follow semi-horizontal pathways near the bottom of the plot. The highly curved paths illustrate possible situations for estuaries with critical thresholds — a phenomenon described in text box 1.

For management purposes, it is desirable to identify types including all of the estuaries likely to follow a particular envelope of eutrophication trajectories, regardless of where they are in terms of load or response when assessed. Ideally, this

Figure 6.1. Conceptual model of a few possible eutrophication trajectories as a function of nutrient load.



Typology	
a.	a highly sensitive system
b.	a linear response is often assumed but seldom encountered
c.	an initially robust system that becomes more sensitive with time
d.	hysteresis, in which responses change dramatically once a threshold is reached, and in which the position on the response axis may depend on whether the load is being increased or decreased
e.	a very insensitive system
(blue swatch)	pristine conditions
(red-yellow swatch)	extreme eutrophication
(dashed circle with cross)	represents a semi-quantitative assessment of uncertainty at any given point

would help to identify critical thresholds before major transitions occur, managing systems to avoid more complicated, less easily reversed problems. An example in Figure 6.1. is system d, which reaches a threshold after which even reduced nutrient loads continue to drive increasing eutrophication. Similarly, a system following path c or e into the extreme eutrophic zone might return along path a or b as the load is reduced, requiring nearly pristine conditions and a substantial amount of time to recover.

A complication in the analysis is that our estimates of load necessarily contain a substantial uncertainty, and the measures of status (“response” axis position) do not necessarily identify consistent or calibrated differences. This is illustrated in Figure 6.1. by a data point with x- and y-error bars (blue arrows), showing a possible range of uncertainty in the plotted position of an observed estuary. Not only do an unlimited number of trajectories fit through the circle of uncertainties, but successive observations do not reliably define a path unless they are widely separated on the graph — usually not a desirable occurrence! Even with uncertainties narrowed, successive points can only support a linear extrapolation, which would probably miss upcoming thresholds. Details such as the duration and temporal variation in load are important to a comprehensive analysis, but it is not practical for a manager to get involved at this level.

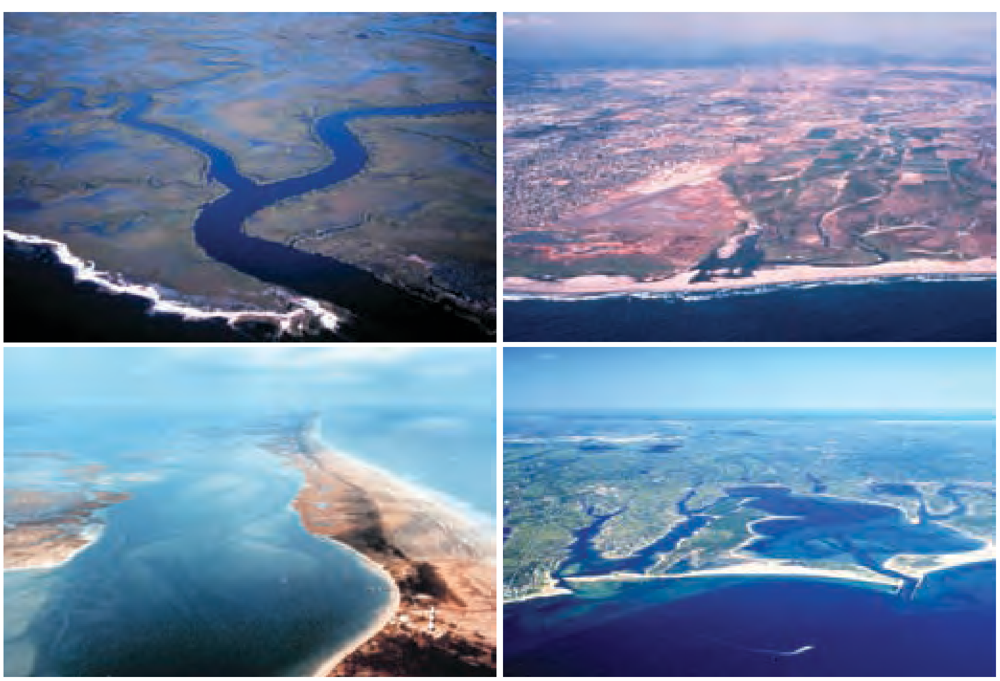
These complications and uncertainties illustrate the need for a predictive classification system for

Text Box 1: Critical thresholds and other factors effecting the response of coastal waters to nutrient loads[1]

Nonlinear responses and critical thresholds — Typically, nutrient budgets give a linearized picture of system response to changes in flows and loads, which can potentially predict how systems respond to relatively small changes. However, some systems respond in a highly nonlinear fashion, such as the loss of keystone species, with modest changes in load. Once a state change occurs, restoration can be extremely difficult.

Load per unit area of receiving waters — The capacity of a coastal system to process nutrient loads is related to the surface area of receiving waters. For systems with long residence times, load per unit area of receiving waters tends to determine ecological impact. Thus, small, poorly flushed coastal systems with small catchments and low runoff but large point source inputs are particularly vulnerable. Coastal lagoons often have these characteristics, as runoff is typically low and exchange with the ocean is restricted or intermittent. Urban sprawl with high loading is likely to increase the number of such systems. Small systems with large catchments may be vulnerable if flow is highly seasonal or diverted. Conversely, very large systems (coastal seas and large embayments) may show little broad-scale impact if loads per unit area are small and oceanic exchange is significant.

[1]Adapted and expanded from Le Tissier et al. (2006)



National Oceanic and Atmospheric Administration

The wide variety of estuary sensitivities and influences (physical, chemical, and hydrologic) calls for a determination of typology in order to better assess systems in a comprehensive, large-scale manner.

a diverse assemblage of systems, where detailed mechanistic understanding and the supporting databases are generally lacking. Systematic efforts to achieve this within the NEEA are summarized below.

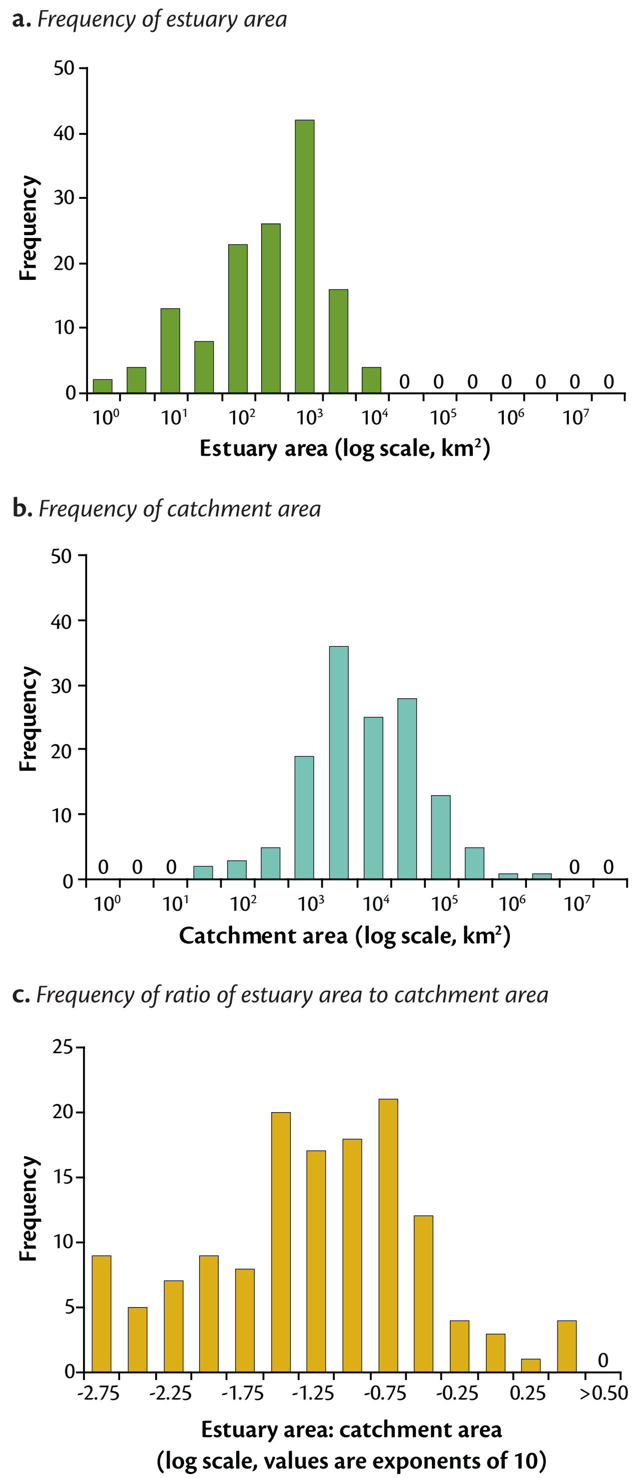
Estuarine typology development

In order to meet the rigorous demands of developing a classification system to serve as a proxy for critical differences between systems, a process of geospatial clustering based on a broad spectrum of environmental variables has been adopted. The basic typology approach used is that employed by the Land-Ocean Interactions in the Coastal Zone (LOICZ) project — a joint effort of the International Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Program (IHDP). The clustering tool groups systems based on their similarity with regard to selected biogeochemical characteristics. LOICZ aims to understand the role of the global coastal zone in natural biogeochemical cycles of the planet, and the degree and significance of its alteration by humans.

Due to the need to compare and integrate information across diverse coastal systems ranging from well-studied to essentially unknown, LOICZ-related tools and a linked global typology database (http://hercules.kgs.ku.edu/hexacoral/envirodata/hex_modfilt_firststep3dev1.cfm) have been developed. The tools, WebLOICZview (palantir.swarthmore.edu/loicz) and DISCO (narya.engin.swarthmore.edu/disco), are web-based geospatial clustering applications. DISCO, a second-generation application, offers a variety of user-controlled options including: (i) supervised and unsupervised k-means clustering, (ii) fuzzy k-means clustering, (iii) dataset manipulation, (iv) cluster comparison and stability evaluation, and (v) plotting of color-coded cluster points by geographic coordinates or on any two-variable plot from the dataset. Developments, applications, and findings of the first phase of the LOICZ project are described in Crossland et al. (2005).

The original LOICZ approach was designed for global application, with the recognition that it would be applied to many data-poor regions. The NEEA effort had both requirements for more refined and specific assessment products, and the advantage of working in a relatively data-rich region. This made possible a U.S. database more detailed than the LOICZ global database, and a prototype database of the U.S. estuaries and their watersheds was developed. The database consists of estuary and catchment variables assembled from available data sources, plus systems specific indices and composite variables created

Figure 6.2. Size distribution of estuarine and watershed areas included in the NEEA.



a. Histogram of $\log_{10}$ of estuary areas (km²); **b.** Histogram of $\log_{10}$ of catchment size (km²); **c.** Histogram of $\log_{10}$ of the Estuary/Catchment area ratio.

specifically to support the functional typology effort. Text box 2 (*see next page*) presents examples and discussions of some of the key factors known to influence estuary response to loading. In addition to calculated estimates of some of these factors (load/area and exchange time), the database offers a selection of geomorphic, hydrologic, and other variables which influence characteristics such as load and exchange time.

Workshops were held to evaluate and upgrade both the database and the DISCO tool, and to enlist the expertise of the estuarine scientific community in developing and testing a methodology for the group of systems included in the NEEA (Figure 6.2. shows some physical characteristics of these systems). A number of promising formulations of an estuary classification system were developed; one example is shown in Figure 6.3. In this case, variables used were estuary depth, percent of the system's mouth that is open to exchange, freshwater input, tidal range, and average temperature. These factors are directly relevant to residence time and are significant components of the factors listed in text box 2 (*see next page*). A large majority of the estuaries were contained in only six clusters, with groupings appearing reasonable to expert judgment. However, there was no reliable way to tell whether or not this classification actually reflected functional, mechanistic similarities suitable as a basis for management.

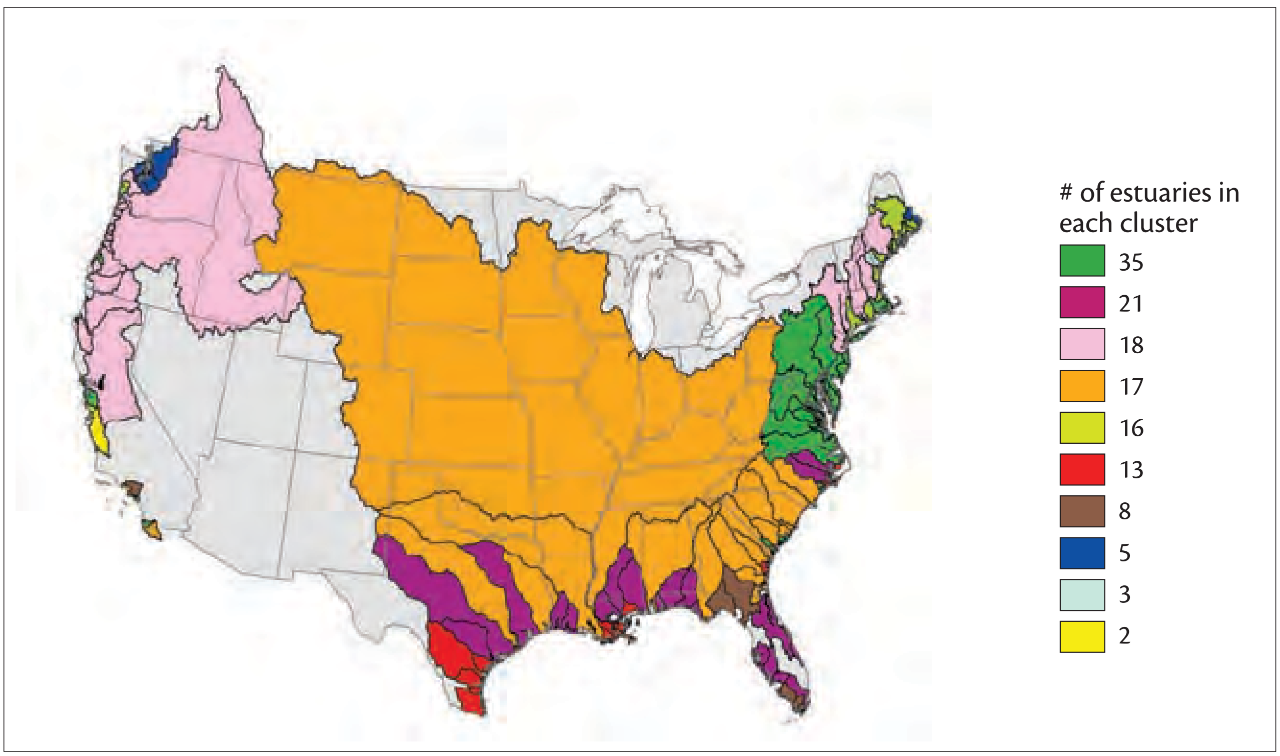
Needs and challenges

The efforts named above have revealed (or reinforced) several critical issues. To evaluate clusters in terms of function, a larger amount of quality data is needed for several classes of features. Some of these, such as the variability or seasonality of freshwater inflow, are partially addressed by the existing database and can be improved with only modest effort. The four categories that appear most important for improvement are:

- Ecosystem and biogeochemical function indicators;
- Measures of stratification;
- Characterization of system response to load; and,
- Interaction between changes in hydrology and load history.

These variables would permit consistent and more precise placement of datapoints on a practical version of Figure 6.1, and would provide more focus on the critical time dimension.

Figure 6.3. Example of estuarine classification. Estuaries were classified based on depth, percent of mouth open to exchange, freshwater input, tidal range, and average temperature.*



*Note geographic groupings, and that 85% of the systems are described by six clusters.

Text Box 2: Key factors affecting the response of coastal waters to changing nutrient loads[1]

Residence time — vulnerability to nutrient loads increases with longer residence times, determining the capacity of internal biogeochemical processes to transform and retain nutrients. Residence time is determined by the relative interaction of riverine flows and flushing by marine exchange. Systems with short residence times (days) tend to reflect the biogeochemical state of the dominant boundary (river or marine). If river flows dominate, most of the load is exported to the adjacent sea. With long exchange times (weeks to months), inorganic nutrients can be transformed into organic matter (autotrophic), or conversely, can transform organic matter to inorganic nutrients and carbon (heterotrophic). With little exchange, internal nutrient sinks and carbon may dominate (through denitrification or burial). Such systems are likely to be sensitive to changes in loads. Exchange times may change from days or less during floods, to months during the dry season.

Vertical Stratification — Vertically stratified systems are more likely to show adverse eutrophic symptoms from positive feedback. Stratification inhibits vertical mixing, restricting oxygen supply to bottom waters and sediments, and increasing nutrient availability (positive feedback). As nutrient supply and organic matter increase, sediment respiration also increases, further depleting dissolved oxygen. As bottom waters become hypoxic or anoxic, changes in sediment chemistry and microbial processes lead to reduced denitrification efficiency and desorption of phosphate bound to sediments, resulting in further increases in nutrient supply, or a reduction in nutrient sinks.

Relationship between nutrients and freshwater flow — The degree of correlation between load and freshwater flow is also crucial to estuarine response. If load is disconnected from riverine flow (e.g., sewage, large atmospheric deposition, or oceanic inputs), estuarine response is expected to be different from cases where loads vary closely with flow (e.g., river dominated systems). Estuarine responses are frequently coupled to residence time through several mechanisms, both biotic and abiotic (Nixon et al. 1996; Howarth et al. 2000; Smith et al. 2005a; Swaney et al. in press). When river discharge controls residence time, it affects the estuarine response indirectly through these mechanisms as well as by the nutrient load. Low flows can result in longer processing times of lower loads; high flows in shorter processing times of higher loads. When nutrient loads are independent of discharge, processing time is independent of load, and therefore intermediate responses could be expected (greater processing at high loads, less processing at low loads).

[1]Adapted and expanded from Le Tissier et al. (2006)

Ecosystem and biogeochemical function

Biogeochemical function (e.g., nitrogen fixation, denitrification) can be estimated using the LOICZ biogeochemical budget methodology (Smith et al. 2005a); some estuaries have already been characterized in this fashion. Completion of the estuarine budget dataset would require additional effort, and in some cases, probably additional data. For example, in some arid systems, the cap on salinity at oceanic values, with no allowance for hypersaline (net evaporative) systems, needs to be replaced with actual values. Information on communities whose responses may be particularly telling (e.g., macrophytes) is probably available for many of the Nation's estuaries, but has not been collected in a consistent format or location.

Stratification

The EPA has supplied a database of georeferenced surface and bottom salinity measurements, which permits direct determination of stratification; these data are being evaluated and processed for inclusion in the database. In addition to the stratification itself, it appears that dataset may also support classifying the estuaries by salinity zone, which will help provide more precise system characterizations.

System response to load

While the NEEA provides a large national dataset concerning the overall status of eutrophication in U.S. systems, this typology is not a particularly useful basis for further statistically-based mechanistic typologies. Although the component symptoms all reflect estuary conditions resulting from nutrient loading, these symptoms are not necessarily equivalent or interchangeable in their relationships to estuary function. The relative intensity of the symptoms reflects functional and structural differences between how systems condition their responses to changing nutrient loads. The five-class composite index (OEC) is derived by a quantitative (although subjective) method of combining the symptom scores (*see Chapter 2: Approach*). The OEC probably cannot be treated as a well-defined continuous variable, however, as it is made up of non-equivalent component scores in varying proportions. This means that it can have multiple non-unique relationships to environmental characteristics, depending upon how the score is achieved. Its usefulness is very limited because combining the symptom scores tends to blur functional distinctions between systems.

Ideally, the typologies for the symptom expressions would be developed on the basis of system responses and estuary characteristics. This would leave open the options of combining individual typologies into a master classification system, or classification based upon the nature and intensity of dominant symptoms. However, basing typology upon these characteristics has not been practical for three reasons:

- The lack of quantitative, continuous measures of response which are comparable among systems;
- The small number of credible categories (three) into which the symptom scores are classified translates to little discriminatory power; and
- The number of total systems is too small for statistically robust analysis, and even smaller for systems which exhibit a useful signal for any individual symptom.

The last point (sample size) could partially be addressed by treating defined salinity zones as individual systems. This would not only permit more precise assignment of some of the characteristics, but it would also at least double the total number of (sub)systems considered, although zones may be small or lacking data in some estuaries. Because a few systems (e.g., Chesapeake Bay) are estuary complexes, they may have multiple salinity zones of some or all three types. In these cases, individual zones of the same type will almost certainly differ among themselves in terms of response.

As a basis for developing an analytical typology of eutrophication, desirable characteristics of a response variable include:

- A direct and mechanistically understood relationship to nutrient loading;
- Quantitative measurements;
- Comparability and availability of data for all estuarine systems;
- Extended time series, so that responses can be evaluated with respect to averages, trends, and variability of environmental factors; and
- A wide range of observable values (i.e., sensitivity and discrimination power).

When combined with ground-truth measurements, remote sensing observations of chlorophyll *a* have the potential to address the last four of the desired characteristics. Enhanced primary productivity is one of the major and generally well-understood outcomes of excessive nutrient loading.

Monthly composites of estimated chlorophyll *a* concentrations and turbidity values based on SeaWiFS images have been obtained from the NOAA Center for Coastal Monitoring and Assessment. The dataset covers the period September 1997 through November 2004, and provides a reasonably complete data series for 107 of the 141 estuaries. The satellite data are based on 1100 x 1100 meter pixels, so that small estuaries or estuarine sub-systems with one dimension less than several kilometers are typically lost when the images are masked to avoid land contributions. In addition, systems routinely obscured by clouds may not be reliably characterized.

Although the number of estuaries with satellite chlorophyll *a* coverage is a smaller subset of an already small sample, concentration estimates can be evaluated and assigned at the level of the salinity zones within the estuaries. If the zones (tidal fresh, mixing, and seawater) can be treated as separate systems, then the total number of systems is significantly expanded.

The satellite-derived estimates are in general agreement with the classifications derived in the original NEEA assessment. The chlorophyll *a*, overall eutrophication condition, overall primary symptom, and overall secondary symptom expression scores all vary in the same sense as the concentration groupings, and differences between scores tend not to be statistically significant. The reverse is also true; when systems are sorted by the chlorophyll *a* or eutrophication variables, the average satellite chlorophyll *a* values of the groups vary in the same sense, but with large, overlapping standard deviations.

Some of the reasons for the weak positive relationships among ostensibly comparable variables (e.g., chlorophyll *a* measured *in situ* and estimated from SeaWiFS remote sensing color data) can be

SeaWiFS, NASA

SeaWiFS imaging is a world-wide data resource, useful for scientists interested in observing global primary production and phytoplankton patterns.

identified from Figure 6.4, which also illustrates the recently acquired datasets and some challenges faced when using them in conjunction with the NEEA results.

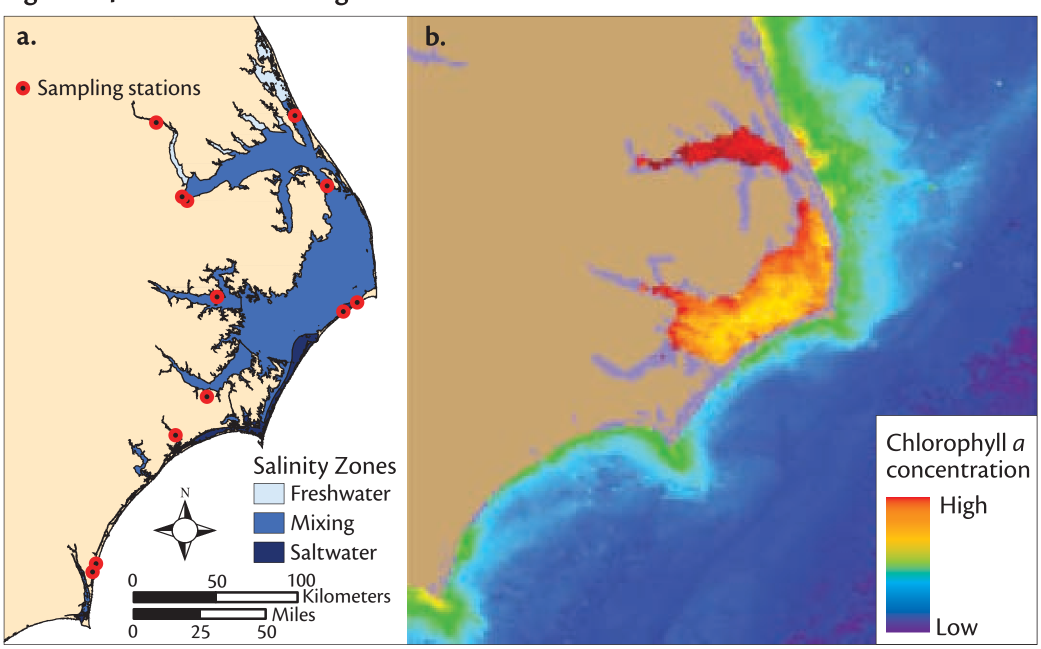
Figure 6.4.b demonstrates a tendency of chlorophyll *a* concentrations to increase as the shoreline is approached, and also that a substantial extent of the nearshore water is masked out of the chlorophyll *a* analysis. This implies (1) there is not a reliable overlap between the parts of the water bodies reported on by the two methods, and (2) that the assessment efforts do not include consistently georeferenced field locations of chlorophyll *a* determinations (these would permit straightforward geographic comparison with the satellite data). The salinity measurement points tend to be close to land and/or a zone boundary, so that stratification estimates are probably more relevant to the NEEA observations than to the satellite data. Bringing these three datasets together for combination or comparison could be addressed with higher resolution, large-area satellite data (if available), but the nearshore chlorophyll *a* estimates are more likely to be influenced by signals from the shallow bottom. Available bathymetric data combined with turbidity estimates would make it possible to exclude areas of probable interference, but this would require a substantial effort in data acquisition and processing. Greater attention to *in situ* chlorophyll *a* analyses from the areas of satellite coverage would provide important comparisons between the two approaches and help to identify the sources of present discrepancies.

The NEEA classifications are based on extreme conditions (e.g., lowest value dissolved oxygen, highest chlorophyll *a*), the spatial area of a salinity zone over which those values are observed, and the frequency of occurrence (Bricker et al. 1999). Location is not considered, and there is no quantitative standardization of the areas and durations of occurrence within or between estuaries. These factors complicate their comparison with the standardized remote sensing determinations.

Figure 6.5 graphically compares satellite and assessment score values for three groups of estuaries (identified by clustering mean maximum monthly satellite concentrations), with both exponential and linear data models. For this comparison, data were grouped into three best-fitting categories according to the magnitude of their concentrations. As the chlorophyll *a* concentration levels of SeaWiFS data only go up to about 21 µg L^{-1}, the difference in magnitude between these data and that of the NEEA is large. This makes finding a significant relationship difficult. While it is evident that a common signal is being communicated, the lack of significant difference is clear in the results of figure 6.5, as standard deviation ranges overlap.

Figure 6.5a compares the NEEA overall eutrophic condition (OEC) with the satellite-determined

Figure 6.4. Pamlico Sound region of the North Carolina coast.



a. Map of Pamlico Sound sampling stations **b**. A processed SeaWiFS image of the same region, September 1997. Note the masking (brown) that extends into the water bodies, and the smaller, unanalyzed estuaries. The salinity zones shown in **a.** are generally outside the region that SeaWiFS can measure.

chlorophyll a results, and figure 6.5b compares the OEC with the NEEA Chlorophyll a index. The plots show both exponential and linear data models. Because the OEC reflects responses other than chlorophyll *a* concentration (i.e., spatial coverage and occurrence frequency of macroalgae, dissolved oxygen, nuisance/toxic blooms, and SAV), there is no real justification for forcing the curve through the origin; a positive intercept on the OEC axis would be reasonable. Figure 6.5.c shows the NEEA chlorophyll *a* index compared to the SeaWiFS mean maximum monthly value; this relationship is forced through the origin on the assumption that zero chlorophyll *a* would be a common point. This assumption should be treated with caution, since the SeaWiFS chlorophyll estimates are not corrected for turbidity contributions, so the curve might have a positive x-axis intercept. The ranges of values correspond to about half of the index range and two thirds of the satellite value range, with the low concentrations not represented in either case.Although the correlation is apparently strong and positive, statistical significance and the sensitivity of the relationship between symptom expressions and satellite data, and between OEC and either SeaWiFS or NEEA chlorophyll *a* estimates are all low.

The positions of the data ranges on the plots tend to support the viewpoint that most systems are significantly impacted—there are clearly relatively few points falling in the low-concentration, low-impact ranges. This enables the separation of systems with probable recovery or prevention potential from those most likely to be irretrievably altered. Separation with the goal of prioritization is an important management tool, and one that may be addressed by a mechanistically-oriented typology.

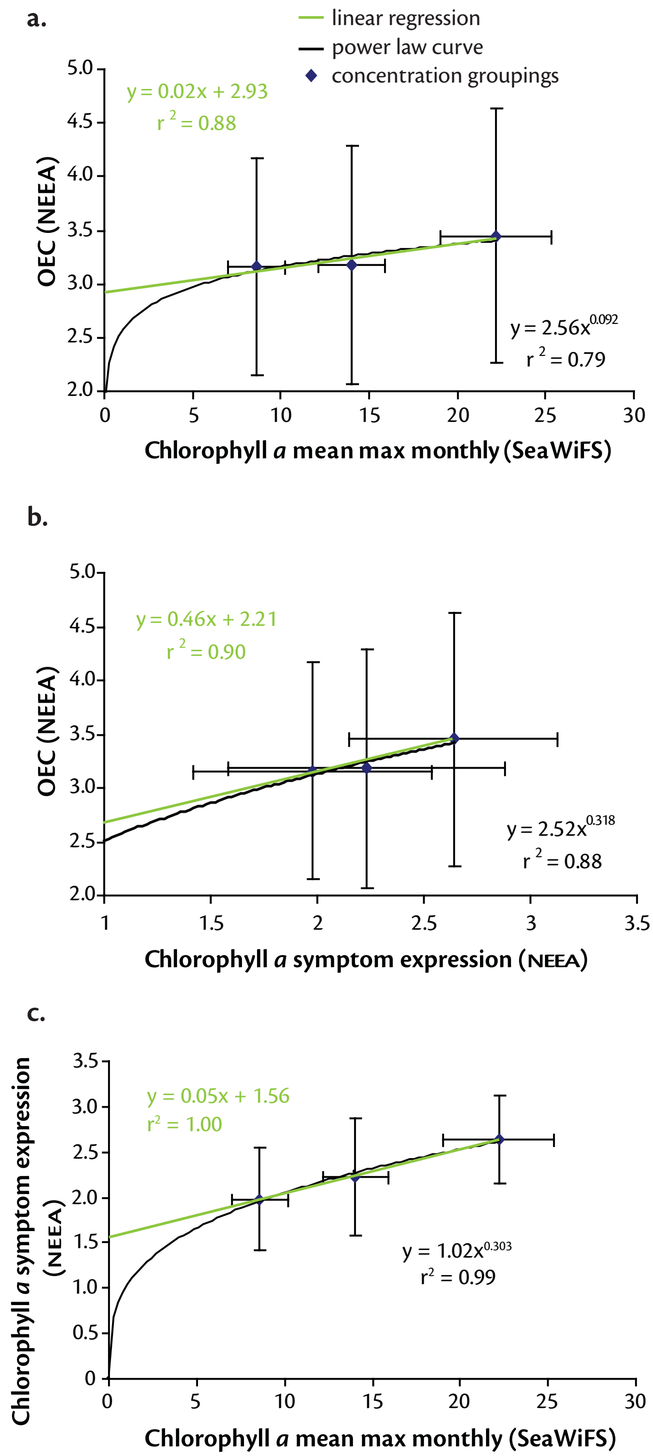
Discussion

Considerable progress has been made in classifying the estuarine systems, and the goal of a useful typology appears achievable. It will, however, require continued effort in terms of scientific analysis, data acquisition, and agency cooperation.

Biogeochemical budgeting or similar process assessments can be developed to provide additional data for vulnerability assessment, and to provide intermediate functional analyses, such as those at the global scale by Smith et al. (2003, 2005a). Those studies addressed the issue of loads rather than of sensitivity, and developed bivariate equations (Log Runoff and Log Population) that described nutrient loads with relatively high r^2 values.

Remotely sensed extreme chlorophyll *a* values appear to make a significant contribution to the assessment of eutrophication level and sensitivity, but more work is required to relate these data to existing

Figure 6.5. Comparison of chlorophyll *a* data, and estimates obtained from NEEA and SeaWiFS. Overall eutrophic condition ratings and symptom expressions are compared to clustered data values.



a. Comparison of OEC and SeaWiFS chlorophyll *a* concentration estimates. **b.** comparison of the NEEA OEC index (max. value = 5) with the chlorophyll *a* symptom expression. **c.** comparison of the NEEA chlorophyll *a* index (max. value = 3) with the SeaWiFS-estimated concentration. Error bars represent standard deviation from the mean.

assessment indices, or to modify their formulation in order to improve sensitivity and comparability.

It is noted that smaller estuaries are systematically excluded from the satellite chlorophyll *a* database because their dimensions are small relative to the pixel size. This needs to be compensated for in any management-oriented typology, since the small systems are more variable and vulnerable (Smith et al. 2005b), and thus more likely to be poorly characterized. Their high between-system variability is a significant management (and perhaps classification) issue, as it implies increased difficulty when extrapolating from one small system to another without a robust (and physically understandable) basis for the classification. As to the edge effects in the larger estuaries, this can be addressed either with higher resolution chlorophyll *a* determinations, or by better calibration of analytical results against the satellite estimates (so that small systems can consistently be assessed on a basis comparable to that used for the larger ones). Figure 6.2 illustrates catchment and estuary size distributions for the U.S. systems; a large fraction of the systems are below the 10^4-10^5 km^2 threshold identified by Smith et al. (2005b) for small catchments. These issues are the subject of continuing efforts to develop a typology which may be used to discriminate estuary and coastal water body types for use in the transfer and application of successful management approaches.

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DEVELOPING A HUMAN USE INDICATOR FOR BARNEGAT BAY

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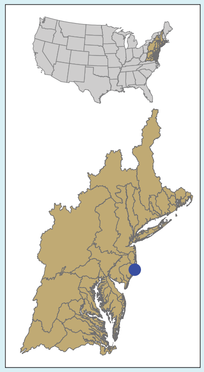
- As a further way to enhance the understanding of how eutrophication affects ecosystem health, a human-use indicator is tested in Barnegat Bay.
- This indicator allows for analysis of how eutrophication affects human populations, whereas most impact assessments consider only the human impact to an environmental system.



The traditional approach to assessing coastal eutrophication and related water quality issues has focused on causes stemming from human activities. Recently, there has been great interest in looking at the issue from a different perspective: documenting how eutrophication and water quality affect human uses of coastal waters and estuaries (USEPA 2005). This chapter highlights progress in the development of an indicator for one of the many possible impacts to human uses of an estuary. This indicator complements the NEEA method and provides a more complete picture of the system.

Given the complex nature of eutrophication, there are a variety of potential human-use impacts, including impacts to commercial and recreational fishing, fish consumption, swimming, boating, aesthetics, and tourism (Bricker et al. 1999, EPA 2005). Recreational fishing is an important activity in most estuaries and one that is often directly impacted by eutrophication. Lipton and Hicks (1999, 2003) demonstrated that recreational fishing for striped bass in Chesapeake Bay and the Patuxent River sub-estuary was negatively impacted by low bottom dissolved oxygen levels. Another recent study linked changes in recreational fish catch rate for three species (bluefish, striped bass, winter flounder) to changes in bottom water dissolved oxygen in 12 Gulf of Maine and mid-Atlantic systems, with striped bass being the most affected of the three (Bricker et al. 2006).

Through the Marine Recreational Fisheries Statistics Survey (MRFSS), the National Marine Fisheries Service regularly conducts surveys of recreational fishing activity and success in most U.S. estuarine systems. This fishing data can be combined with water quality monitoring data and analyzed to determine whether recreational fishing catch rates are related to eutrophic conditions within particular estuarine systems. When a significant relationship is found, recreational fishing catch rates, with appropriate adjustments for other influencing factors, can be used as an indicator of human use impairment due to eutrophication. With additional data and analysis, a dollar value estimate of lost economic welfare can be estimated directly using techniques such as travel cost and random utility models (Herriges and Kling 1999). Alternatively, with a large number of recreational fishing value studies available in the literature, an approximation of lost economic value can also be determined using benefits transfer (Walsh et al. 1992).

Barnegat Bay is an excellent candidate for the application of recreational fish catches as a human use indicator. Surrounded by a large population center, Barnegat Bay sees a lot of recreational fishing activity. Barnegat Bay is also frequented by a variety of recreational species targeted by fishermen. According to MRFSS data, the three species most targeted on Barnegat Bay fishing trips are summer flounder (42%), striped bass (19%), and bluefish (7.5%). The following analysis focuses on these three species.

Edward Pastula, National Marine Fisheries Service

Recreational fishing is just one activity to be incorporated into a human use indicator for estuaries.

Methodology

Individual recreational fishermen can be thought of as biased samplers of the estuarine fish population. They are biased in that they are not randomly sampling the population, but using their knowledge of past fish catches, seasonality, weather conditions, and other factors to increase the probability they will catch fish. They are also not standardized samplers; some are more experienced and better at using this information than others. The catch of these individual fishermen is modeled as a function of their fishing avidity, captured by their response to the MRFSS question asking how many times they have gone fishing in the past year (FDAY). The catch rate during the individual fishing trip is also a function of the migratory and seasonal nature of the targeted species. To measure the fluctuating stocks available to fishermen, the catch rate is averaged (catch per hour fished) over all fishing trips and over years for each species in a month (MCR). The other factors potentially affecting catch rate are related to environmental conditions at the time of fishing, such as salinity (SALIN), water temperature (TEMP), chlorophyll *a* concentrations (CHLORA), and dissolved oxygen (DO), which is the variable most linked to eutrophication. The model used to estimate catch is then:

$$(1)\quad TC_{i,j,m} = \alpha + \beta1\,MCR_{j,m} + \beta2HRSF_i + \beta3FDAY_i + \beta4SALIN_m + \beta5CHLORA_m + \beta6TEMP_m + \beta7DO_m + \beta8(DO_m)^2 + \beta9(DO_m{*}TEMP_m)$$

where $TC_{i,j,m}$ is the expected catch of recreational angler i, fishing for species j (striped bass, bluefish, or summer flounder) in month m, and $HRSF_i$ is the number of hours fished on the fishing trip by angler i. Parameters to be estimated in the statistical model are represented by α and β1–β9.

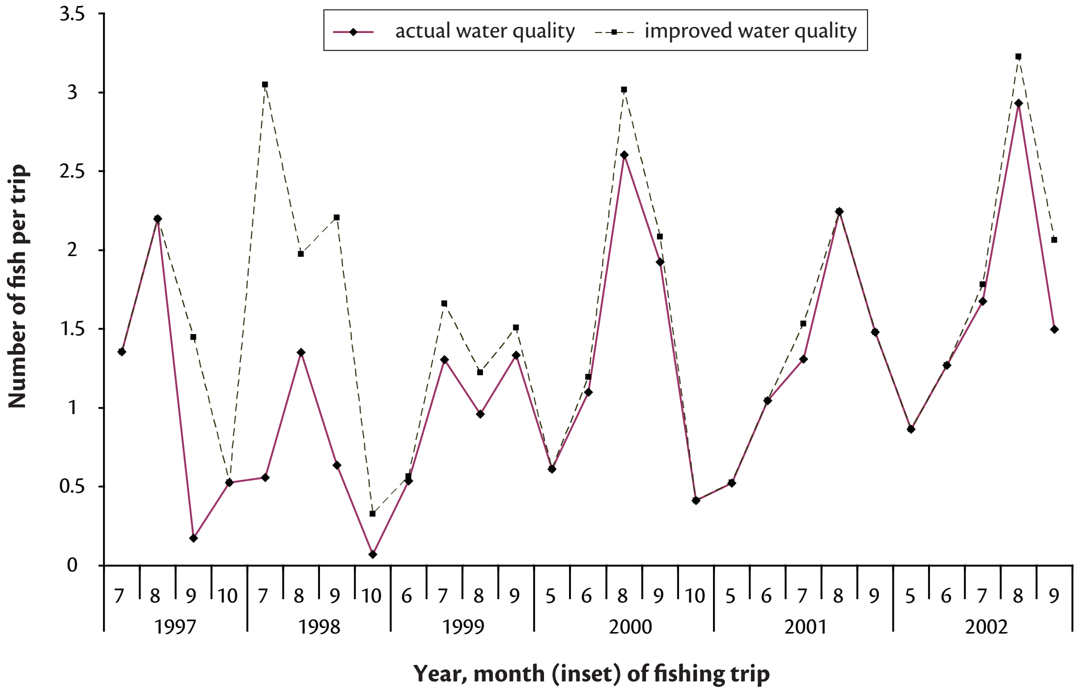
Recreational fishing data collected in the MRFSS in New Jersey was obtained for 1993–2002. Only fishermen intercept survey data, not the telephone interviews, were used for this analysis. Intercept data records catch rates for individual fishermen on a specific fishing trip. For this analysis, only fishermen that indicated striped bass, winter flounder, or bluefish were their primary or secondary target species were selected. Many fishermen indicate that they are not targeting a specific species, and these are excluded from our study. To determine whether a New Jersey fisherman was fishing in Barnegat Bay, a geographic information system analysis was used to select only the intercept sites that fell within the Barnegat Bay boundary.

Salinity, temperature, and dissolved oxygen data for Barnegat Bay sampling stations were averaged by month and year and then matched to the month and year of the fishing trip from the MRFSS data. Because Barnegat Bay is considered a relatively shallow and well-mixed estuary, data measurements at different depths were averaged.

Table 6.2. Parameter estimates from Poisson regression of striped bass, bluefish, and summer flounder recreational fishing trips in Barnegat Bay, NJ. An "*" indicates significance at 90% Confidence Interval.

Variable	Bluefish	Striped Bass	Summer Flounder
Intercept	0.0583	-10.2257	-32.3057*
Hours fished	0.1452*	0.2516*	0.2056*
Days fished in 12-month pd.	-0.0023*	0.007*	0.0046*
Mean catch rate	3.5274*	10.8873*	1.9921*
Mean DO	0.7391	1.6092	7.481*
Mean DO^2	-0.0956	-0.0966	-0.4423*
Mean salinity	-0.0105	-0.0129	-0.0746*
Mean temp.	-0.0818	0.0385	0.5802
Mean DO x mean temp.	-0.0015	-0.0093	-0.0622
Mean Chl *a*	0.0208*	0.0774*	-0.1356*
Number of observations	446	939	458

Figure 6.6. Barnegat Bay monthly average summer flounder actual catch per recreational fishing trip (solid line), and predicted catch rates under improved water quality (WQ) conditions (dashed line).



Results

Equation 1 was estimated for each of the target species using a Poisson regression due to the fact that there are a large number of fishing trips for which catch was zero. Estimation results are given in Table 6.2. The two water quality measurements related to eutrophication that are included in the model are dissolved oxygen and chlorophyll *a*. Chlorophyll *a* levels had a significant and positive impact on bluefish and striped bass recreational catches and a significant, but negative impact on summer flounder catches.

Dissolved oxygen is incorporated into the model in a quadratic form allowing for diminishing marginal improvements in catches as dissolved oxygen levels increase. An interactive term between dissolved oxygen and water temperature is also included in the model. None of the terms containing dissolved oxygen had a significant impact on either striped bass or bluefish recreational catches. For summer flounder, both the DO and DO^2 parameter estimates were significant at the 90% confidence level, but the dissolved oxygen-temperature cross-product term was not significant.

Based on the results in Table 6.2, it appears that neither striped bass nor bluefish are good indicators of human use impairment due to eutrophication in Barnegat Bay. This does not mean that impairment is not occurring, just that the impact is difficult to detect with current data. For example, more spatially explicit analysis might reveal an impact not apparent from the aggregated catch and water quality data. Lipton and Hicks (1999) found this to be the case for striped bass in the Chesapeake Bay where catches linked to specific water quality stations were shown to be negatively impacted by low dissolved oxygen.

For Barnegat Bay, summer flounder, the most sought after species, is a good indicator of the human use impacts of eutrophication. The solid line in Figure 6.6 shows the average actual catch of summer flounder in a month for the period from 1997-2002. The statistical model was then used to predict summer flounder catches under different water quality conditions. Specifically, an upper limit on chlorophyll *a* concentrations was set so that they could not exceed the sample averages of 7.12 $\mu g\ L^{-1}$, and a lower limit on dissolved oxygen of 6.51 $mg\ L^{-1}$. The dashed line in Figure 6.6 represents the predicted summer flounder catches under these improved water quality conditions, and the distance between the two lines is the impairment due to eutrophication. In some months, the limits are rarely exceeded and there is no difference in expected catches. Overall, the average catch of summer flounder is reduced from the predicted average of 1.25 fish per trip to 0.92 fish per trip, a 26% reduction.

To illustrate the economic magnitude of the reduction in recreational fish catch due to eutrophication, some of the estimates made for mid-Atlantic fisheries by McConnell and Strand (1994) were examined. Using a Poisson regression and random utility model, they estimated that increasing catch rates of mid-Atlantic fishermen by 0.5 fish per trip increased the net value of the trip to the fishermen by $7.51-$8.13, depending on the month. The average catch rate for Barnegat Bay is increased by one-third or 67% of the McConnell and Strand rate. However, to adjust for diminishing marginal utility, 75% of the mid-point of the McConnell and Strand value is taken and adjusted to current (2005) dollars to yield an estimate of increased value per trip of $10.26. Given that 42% of New Jersey fishing trips target summer flounder and there were 5.9 million inland fishing trips in New Jersey (MRFSS data), we roughly estimate that eutrophication costs these fishermen an average of $25.4 million per year in net benefits.

This example demonstrates a method to determine the impact of eutrophication on an economic basis. Additionally, this indicator is generally transferable and the intent is to develop it for use as a nationally applicable indicator. However, before a full application can be made, similar analyses must be performed to determine the appropriate fish species to use in different systems around the country.

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