# 5. CASE STUDIES

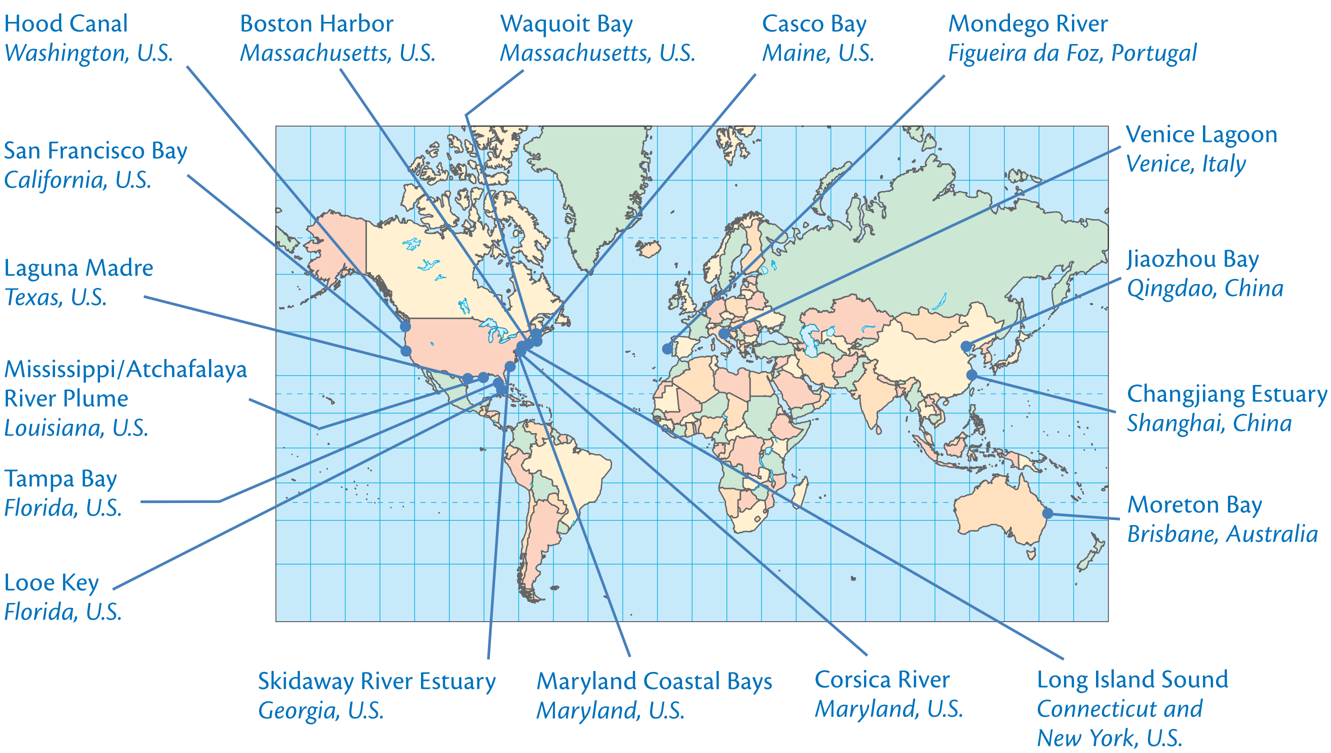
## EXAMINING EUTROPHICATION IN OTHER SYSTEMS: CASE STUDIES

### 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.

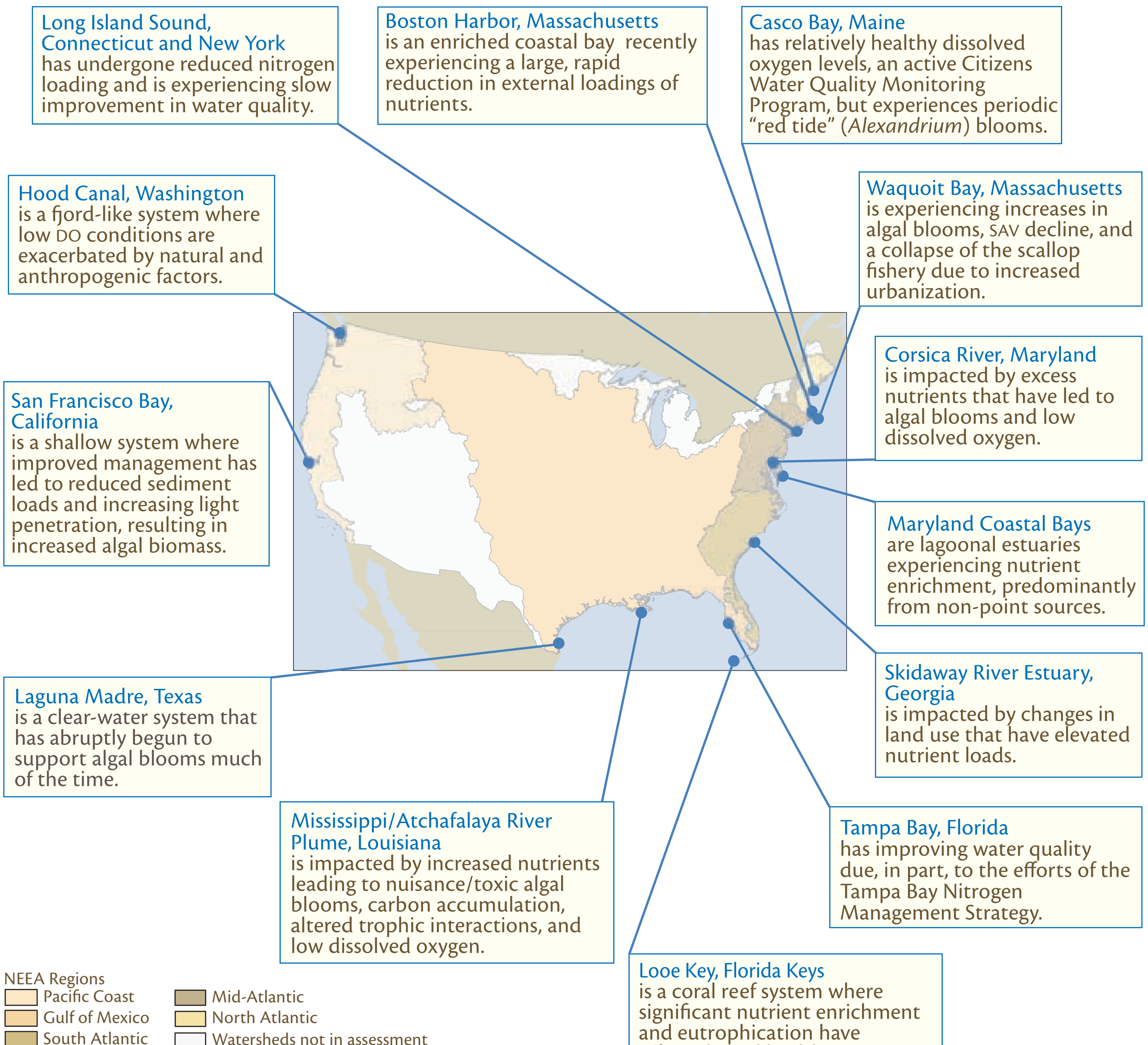
Research and monitoring conducted during the past decade have revealed that eutrophication impacts are not restricted to any particular part of the U.S. coastline, nor solely to the U.S.; these impacts have been noted in estuaries and coastal water bodies around the globe. In most cases, progression 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

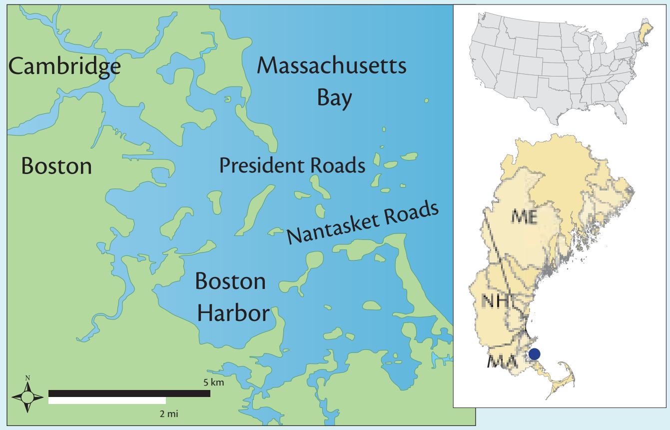



(Source: National Estuarine Eutrophication Assessment)

## 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.



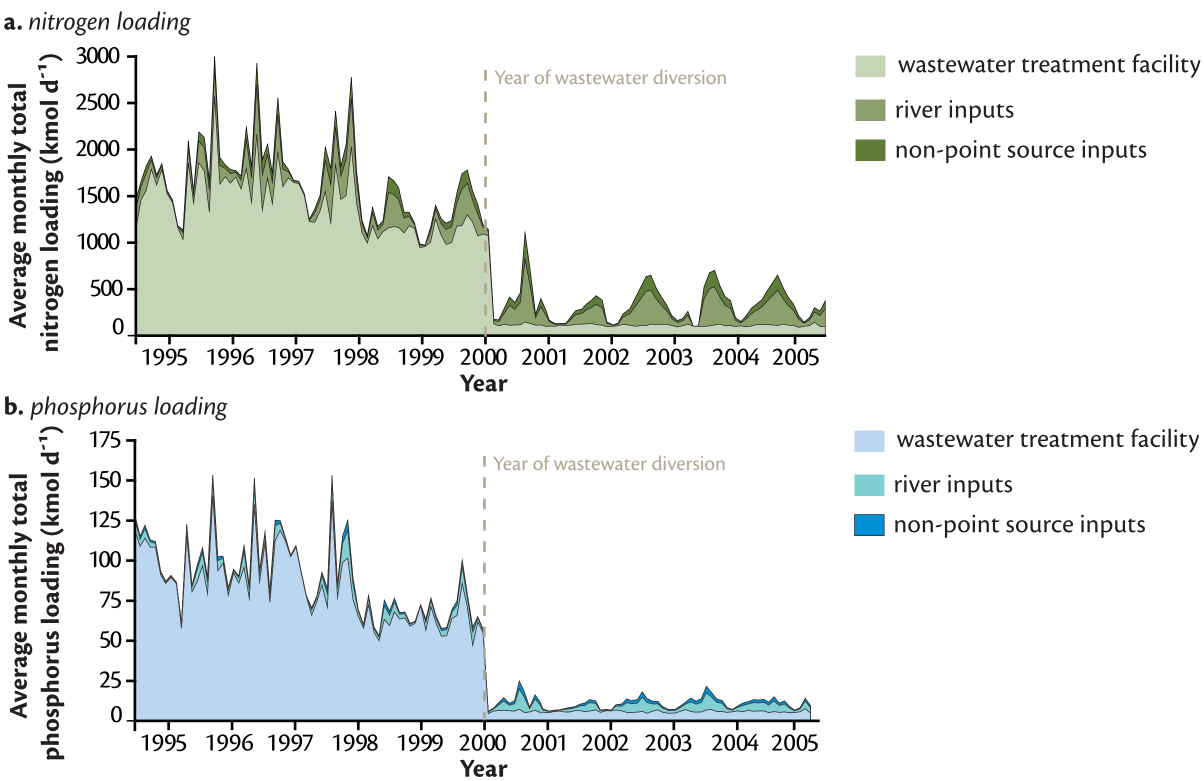

### Decreased nutrient loads

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

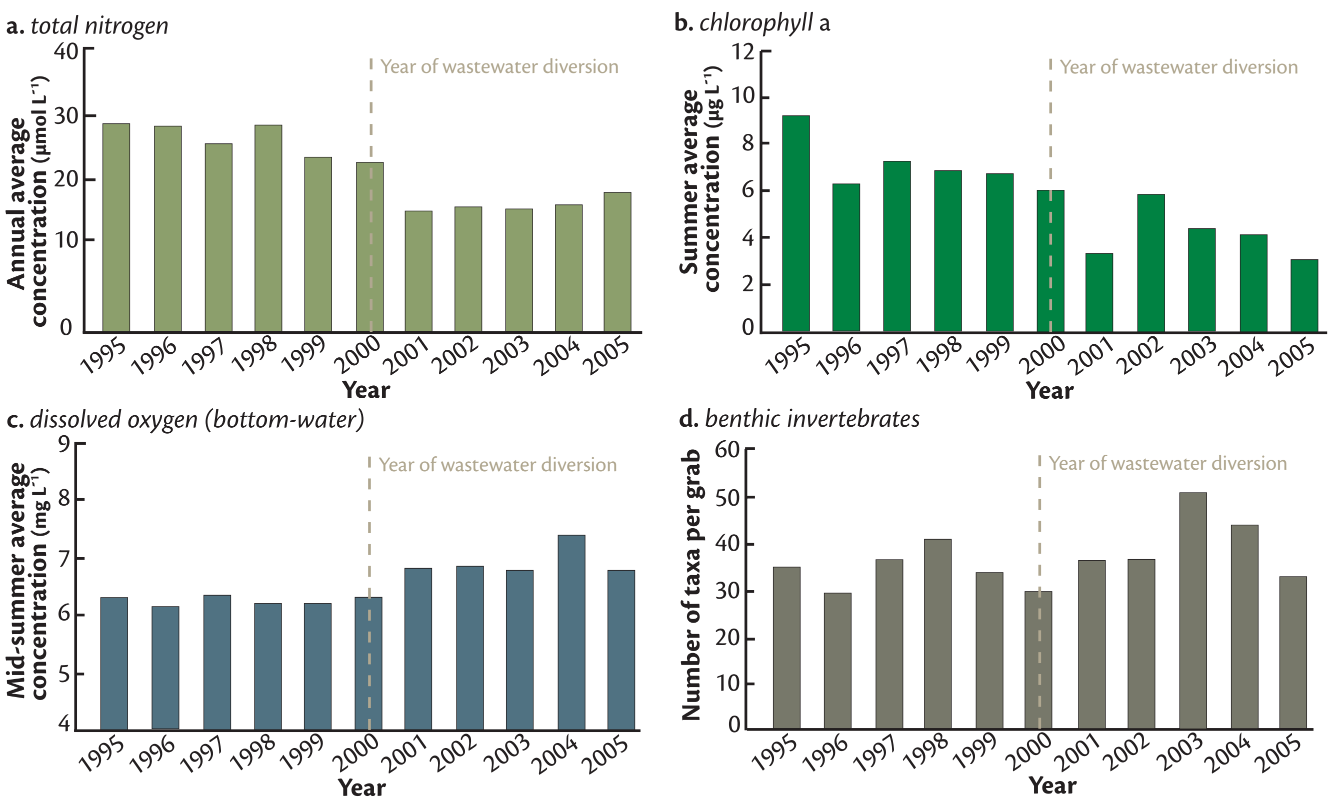
Far less is known about the effects of decreased nutrient loadings than increased loadings on coastal bays and estuaries. Boston Harbor's unique situation may be relevant to other bays and estuaries subjected to large, rapid reductions in nutrient inputs.

## References

Taylor, D.I. (2005). Relationships between changes in eutrophication-related water quality, and loadings to Boston Harbor. Environmental Quality Department technical report series 2005-21. Boston, MA: Massachusetts Water Resources Authority, Boston, MA.

Taylor, D.I. (2006). Five years after wastewater diversion: an update of water quality improvements in Boston Harbor. Environmental Quality Department technical report series 2006-16. Boston, MA: Massachusetts Water Resources Authority, Boston, MA.

**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

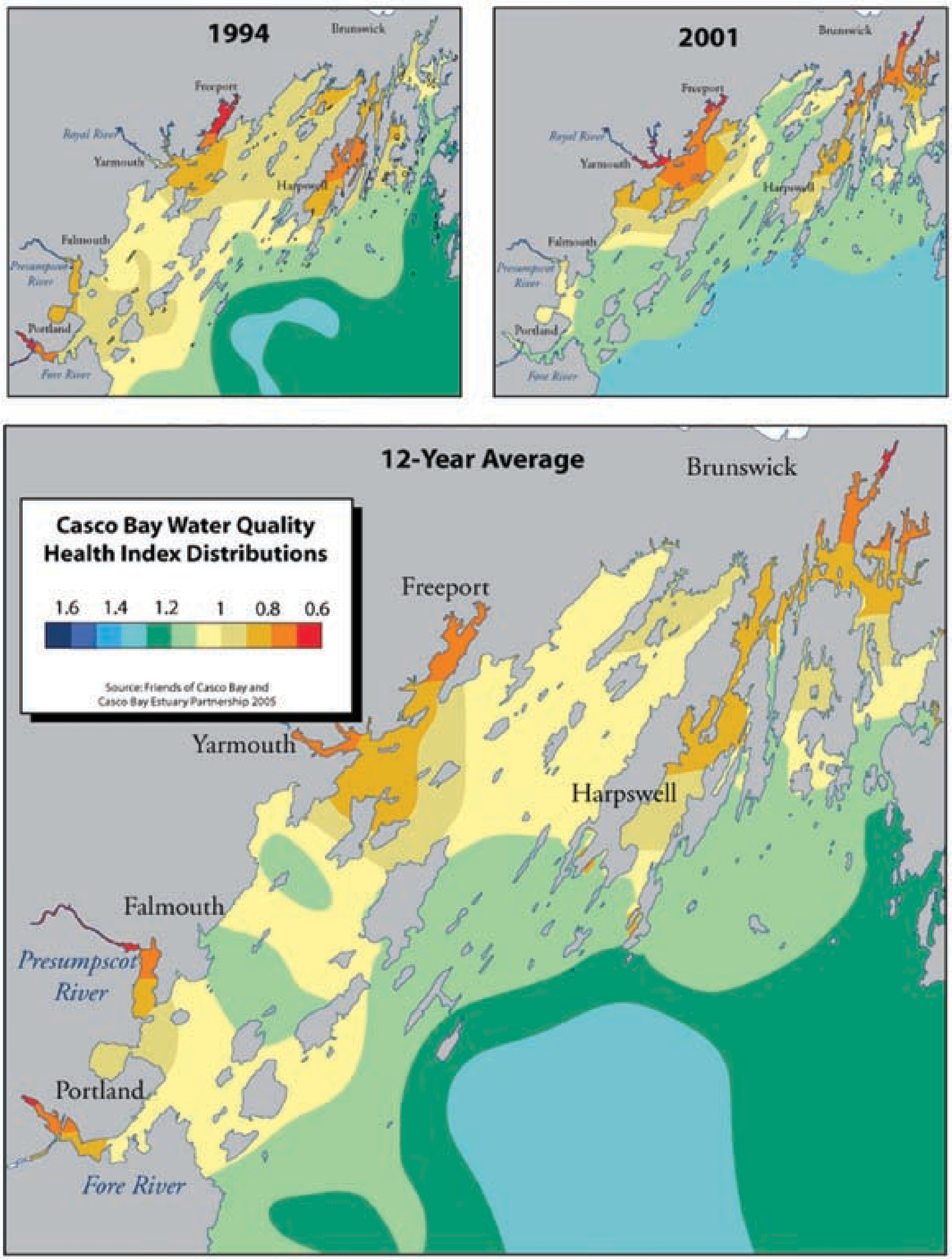
The 12 years of monitoring data have been used to develop the Casco Bay Water Quality Health Index (Figure 5.3). The index combines several water quality parameters to provide a reliable, uncomplicated indicator of the Bay's overall surface water quality. The index is based on DO percent saturation and 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

Friends of Casco Bay

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.

## References

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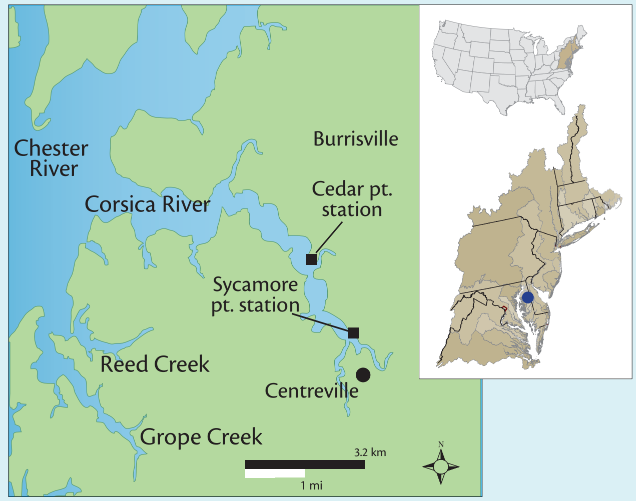
Townsend, D.W., N.R. Pettigrew, and A.C. Thomas. (2005). On the nature of *Alexandrium fundyense* blooms in the Gulf of Maine. *Deep Sea Research*. Part II (52) 19–21. pp. 2603–2630.

## 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.



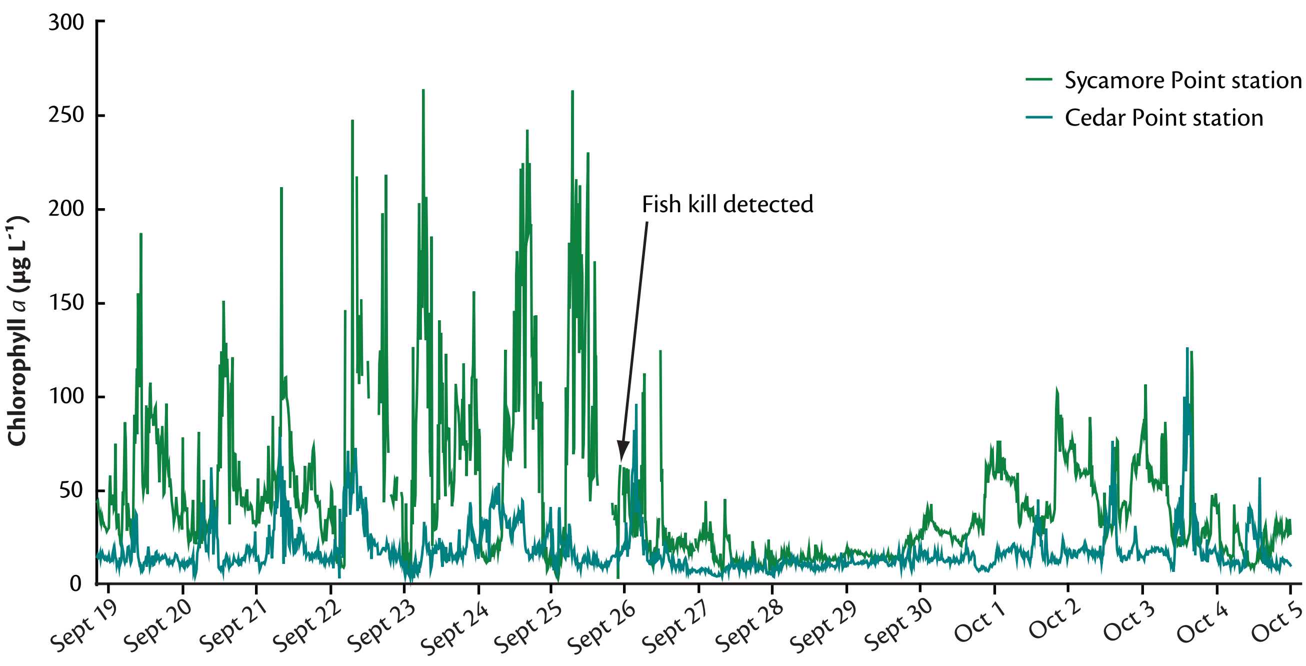

### Impaired use

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

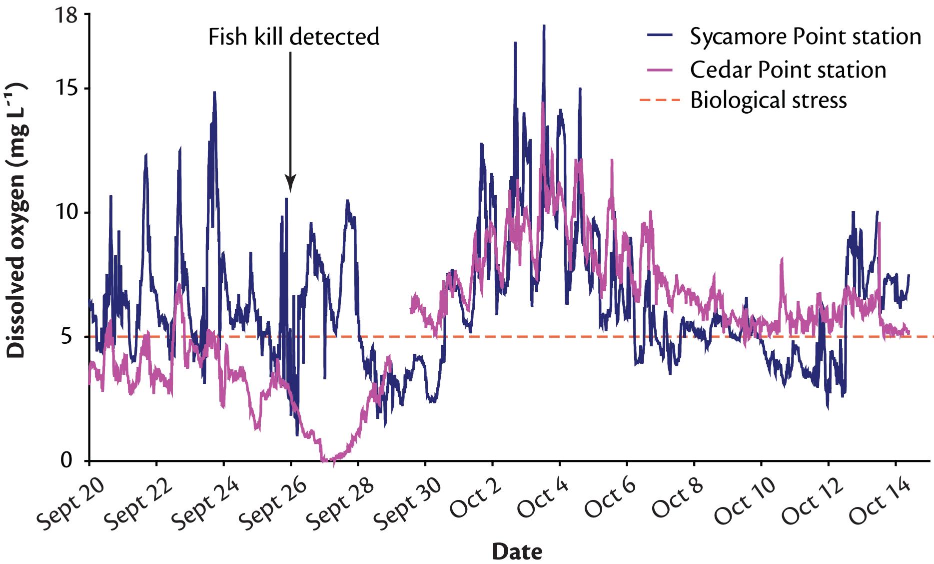
Although nitrogen and phosphorus are necessary to support aquatic life, excess nutrients can lead to algal

**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.**





Fish kill caused by low dissolved oxygen in Corsica River.

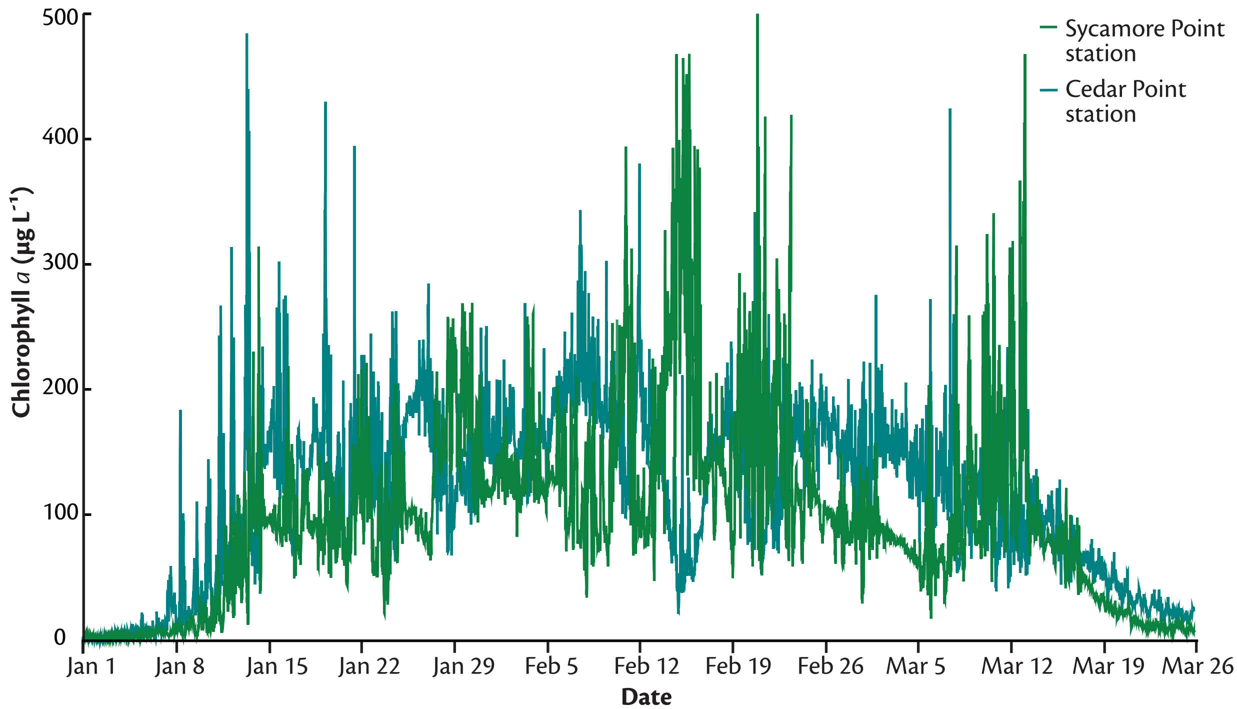
blooms, which contribute to low dissolved oxygen when the blooms die-off. One such algal bloom resulted in a fish kill detected on 26 September 2005 during routine water quality monitoring conducted by the Maryland Department of Natural Resources (DNR). The fish kill intensified as it continued throughout 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 veneficum*) 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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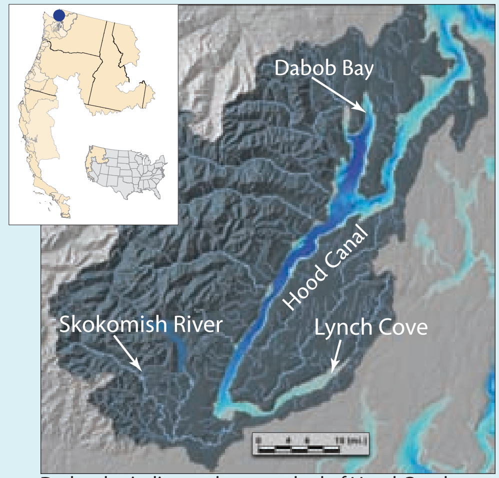
## HOOD CANAL, WA: *The complex factors causing low dissolved oxygen events require ongoing research, monitoring, and modeling*

*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

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

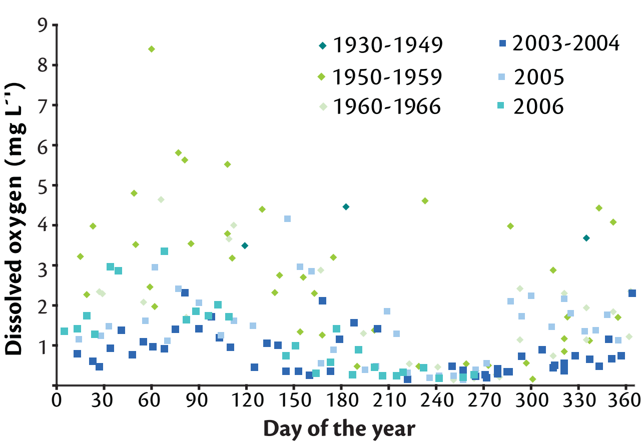
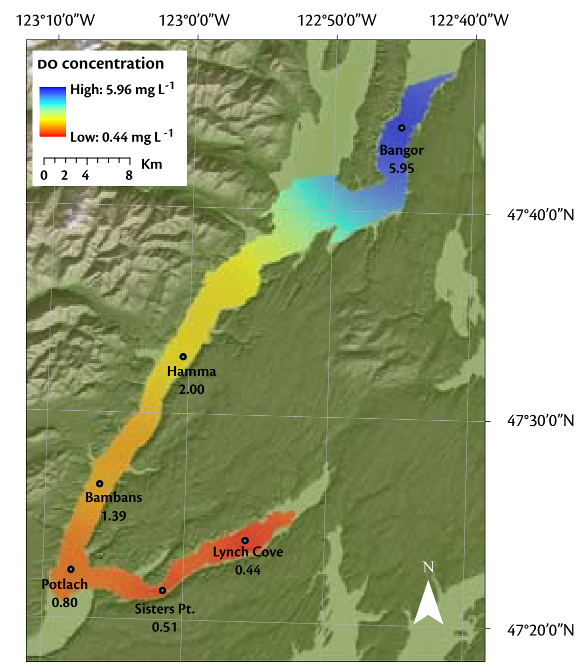



**Figure 5.8. August 2006 interpolation reflecting typical pattern of low DO concentrations.**




occurred recently with high frequency, during 2002-2004, and an extensive event in September 2006.

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.

## 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 5.9. Factors influencing low DO in Hood Canal.**

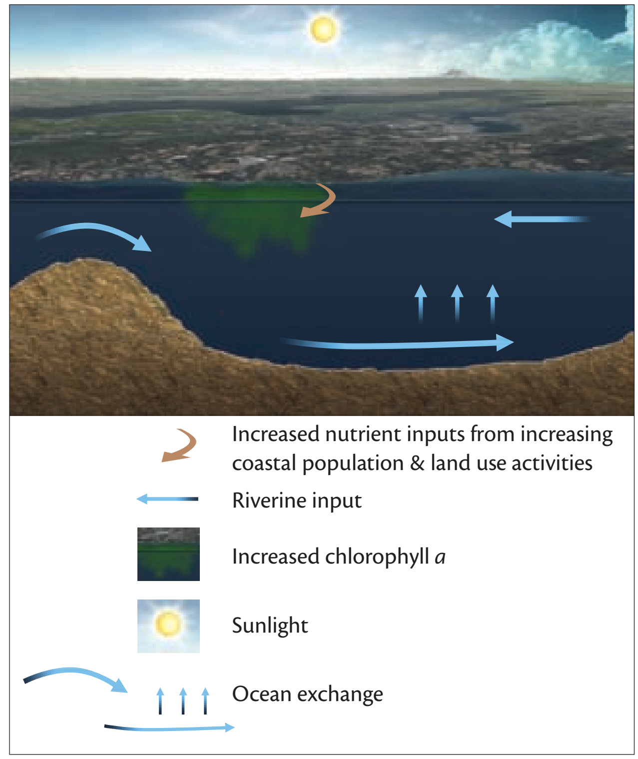



**Figure 5.10. Density of seawater coming into Puget Sound/Hood Canal from ocean & within Puget Sound.**

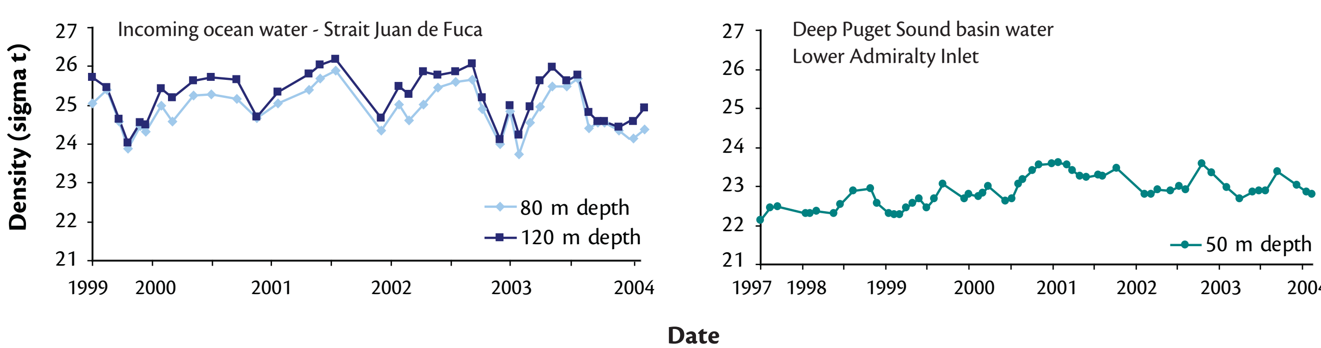
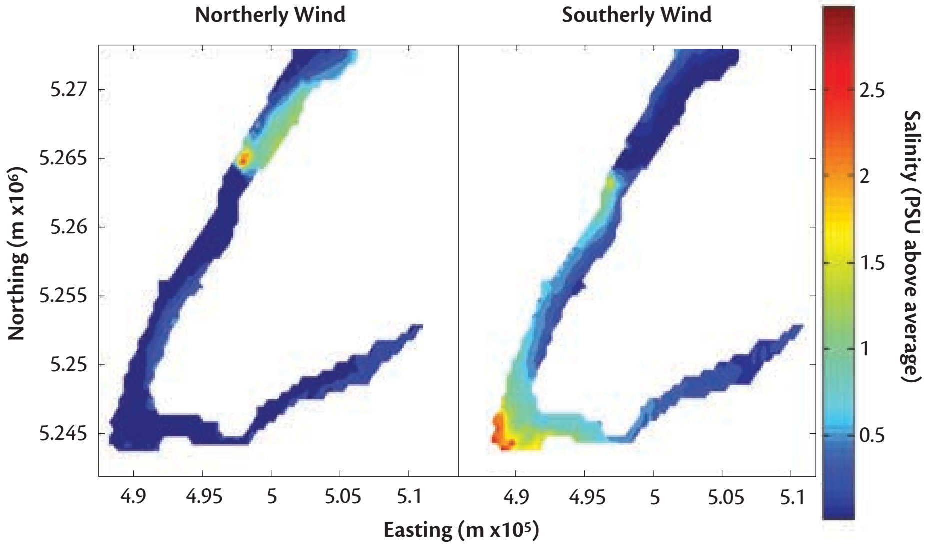


**Figure 5.11. UW-PRISM model results for Hood Canal showing the effect of wind on sea surface salinity. Higher than usual salinity (warm colors) would be associated with deep, low DO water reaching the surface.***




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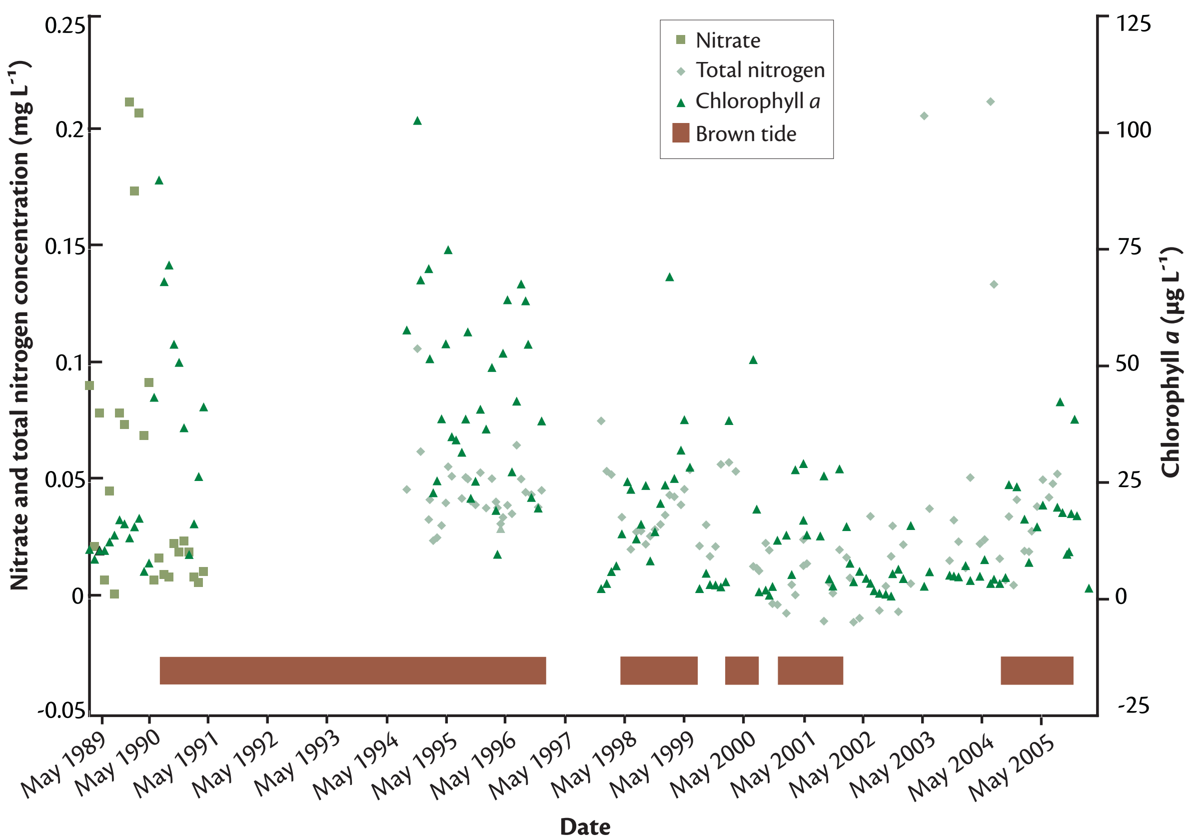
**Figure 5.12. Inorganic nitrogen and chlorophyll *a* in Laguna Madre from 1989–2006.***

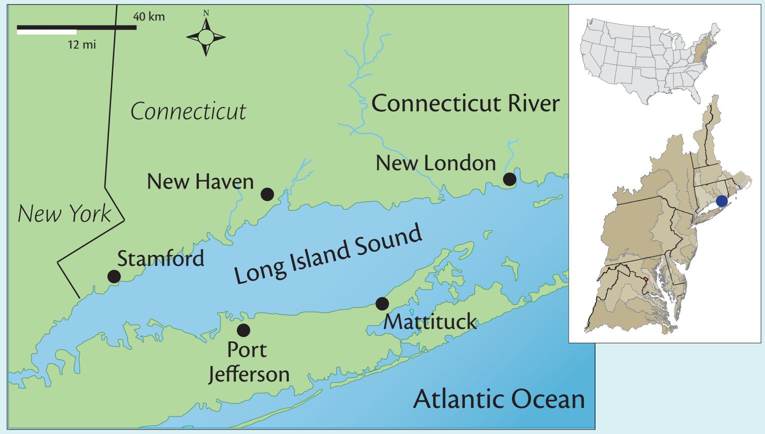



***Data for 1989–2006 are from an average of many stations, adapted from Figure 2 in Stockwell, D.A. et al. (1993) In T.J. Smayda and Y. Shimizu (eds.). Toxic Phytoplankton Blooms in the Sea. Elsevier Scientific Publishers. New York. p. 693–698. For 1994–2006, all data were from one station near the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

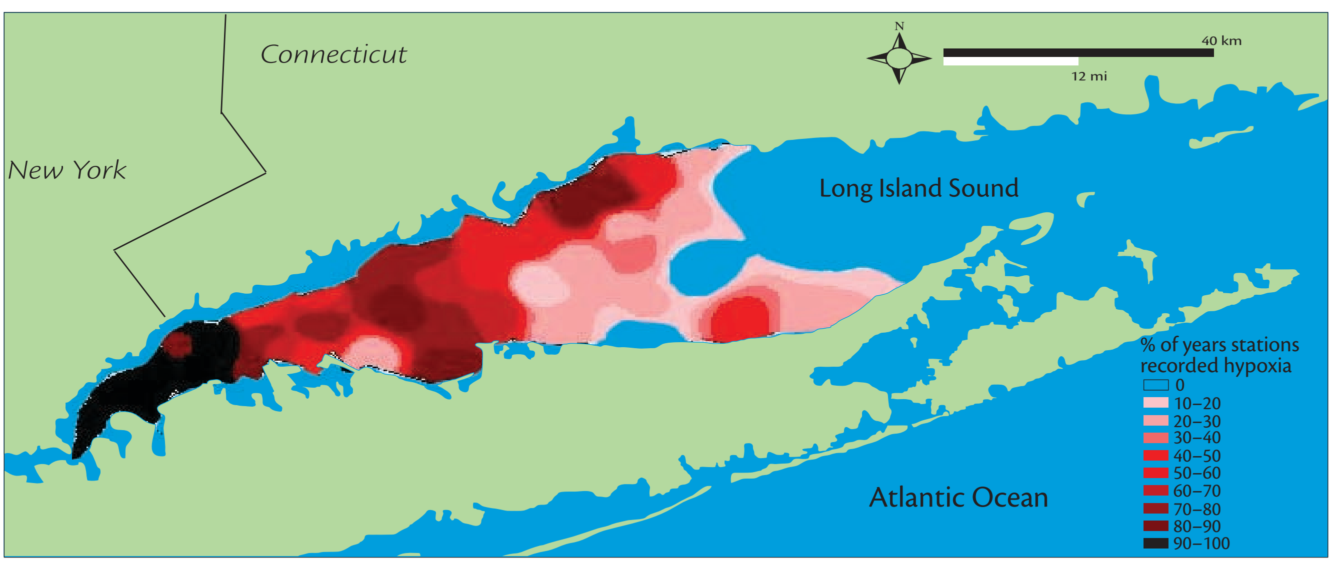
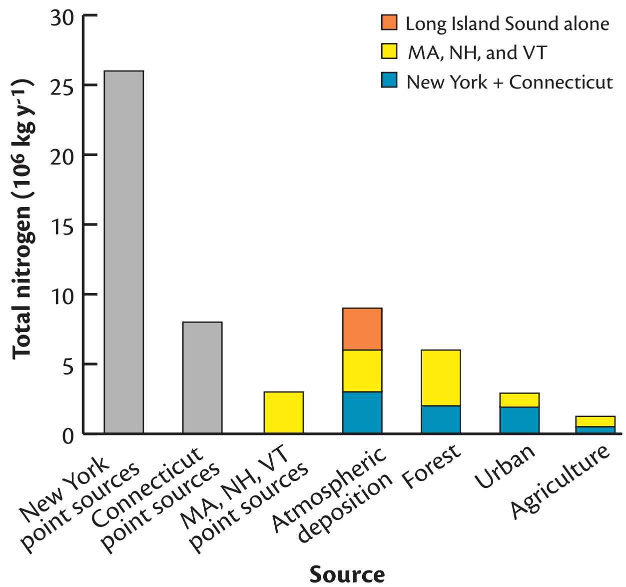


**Figure 5.14. Nitrogen loads to Long Island Sound, ca. 1990.**




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.

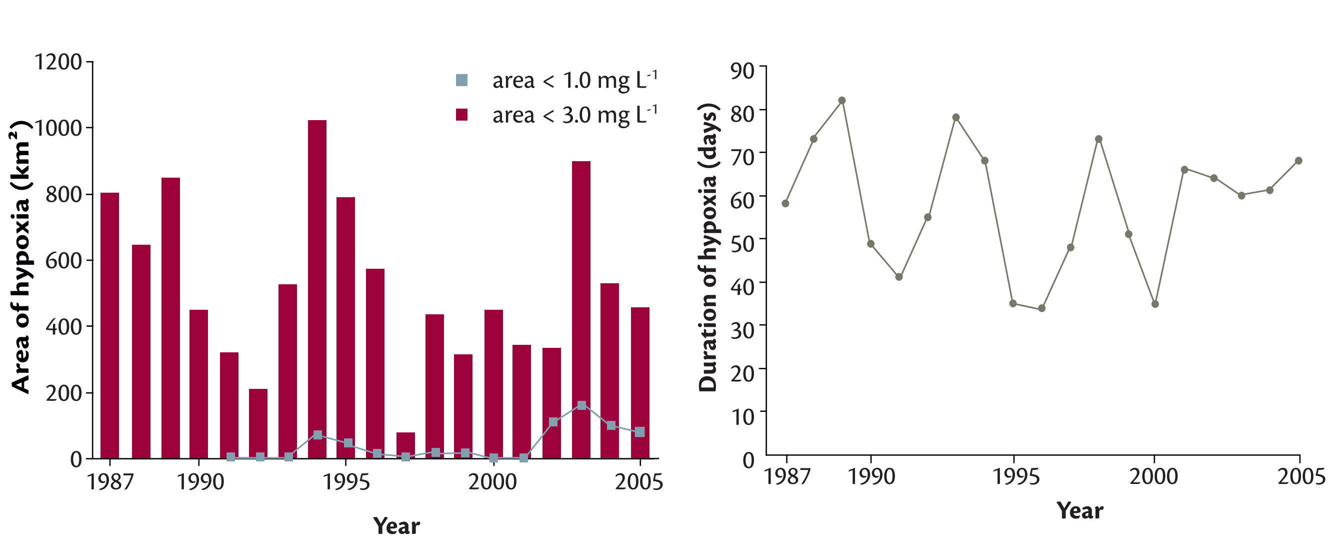
## Management concerns

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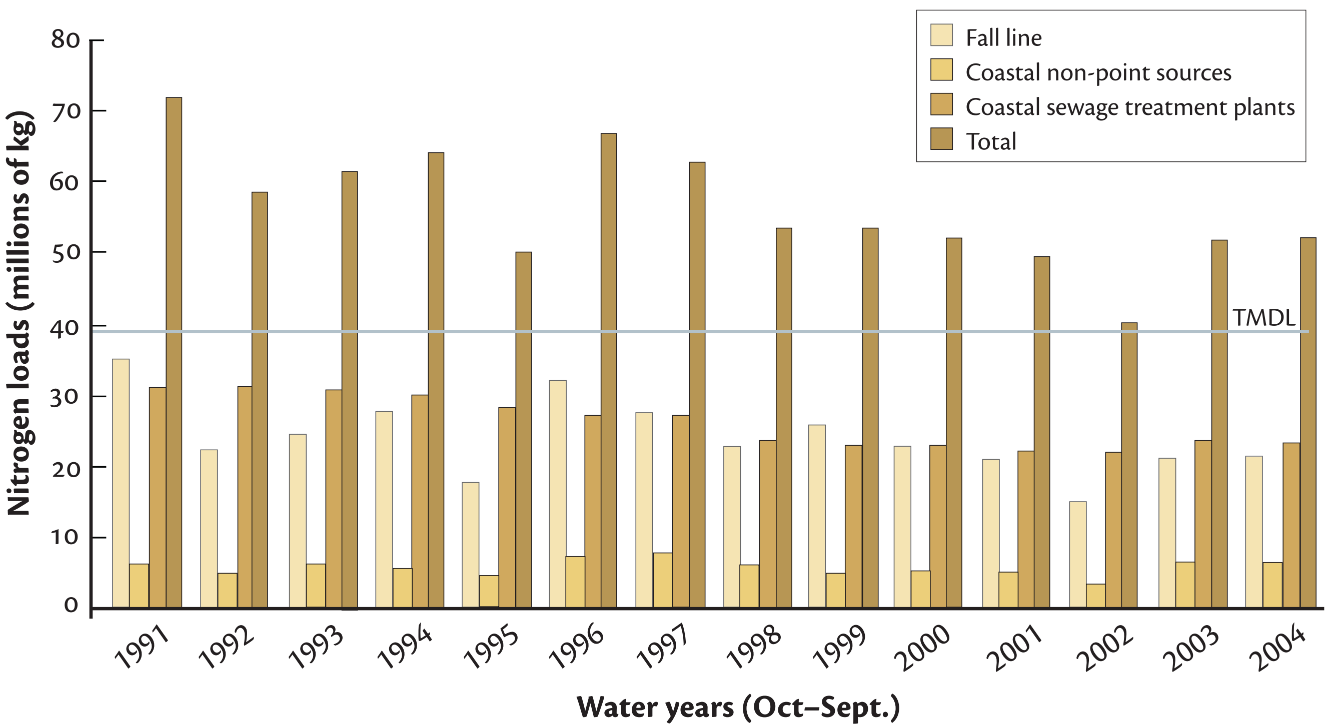
**Figure 5.16. Estimated nitrogen loads to Long Island Sound, 1991–2004.**



## *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 km² 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.

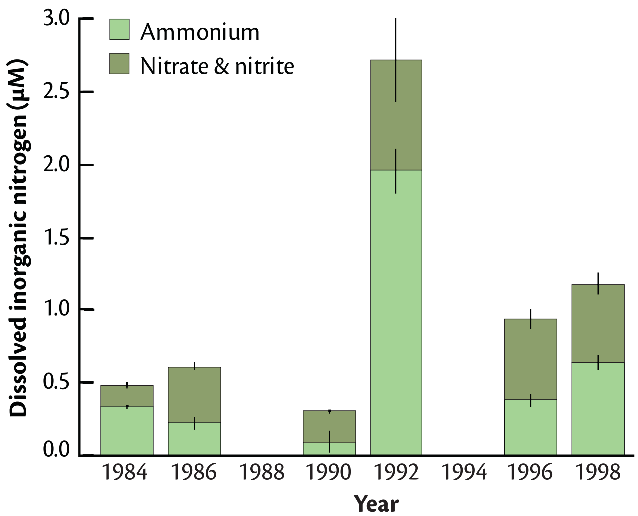
Reef building corals require optically clear water ($K < 0.18\ m^{-1}$) and high levels of downwelling irradiance (Yentsch et al. 2002), but optical clarity of water in the Florida Keys has diminished in recent decades, as evidenced by higher average water column light attenuation coefficients ($K\ m^{-1}$) 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

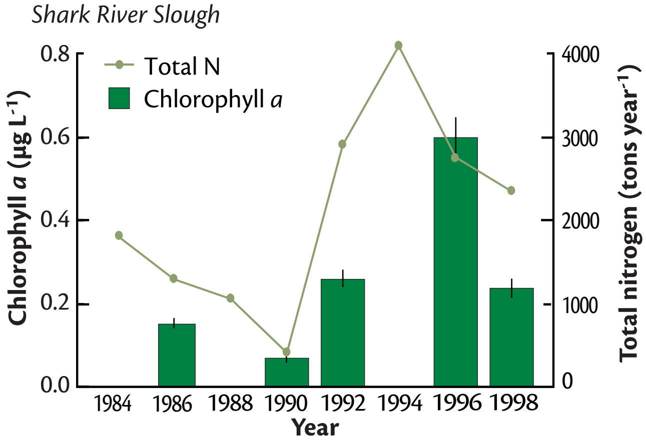
Because of the influences of expected increases in residential population growth and climate change in the Florida Keys and South Florida, the issues associated with eutrophication and coral reef degradation will become more pressing. Because coral reefs are subject to the effects of climate change, 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.

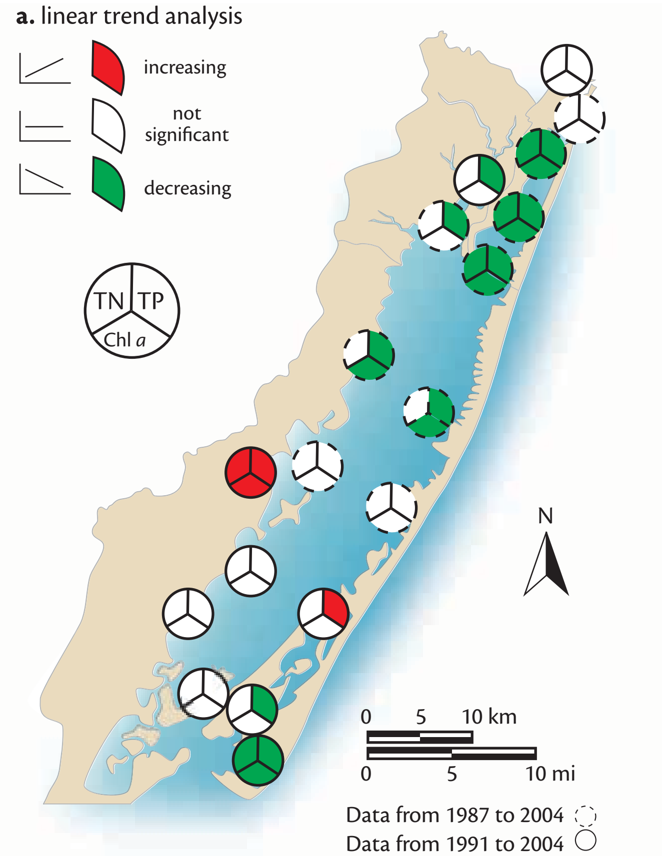
## Future outlook

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.**



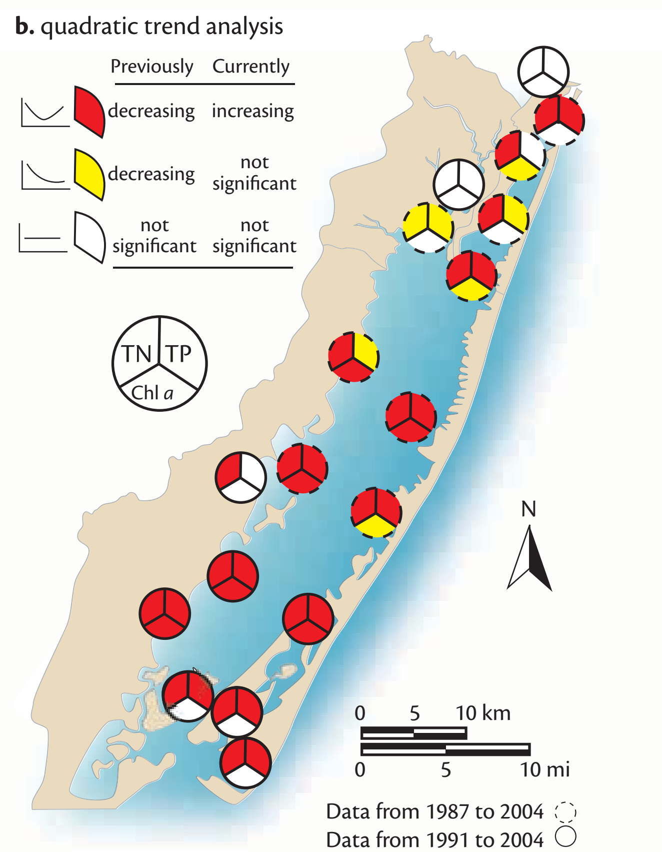
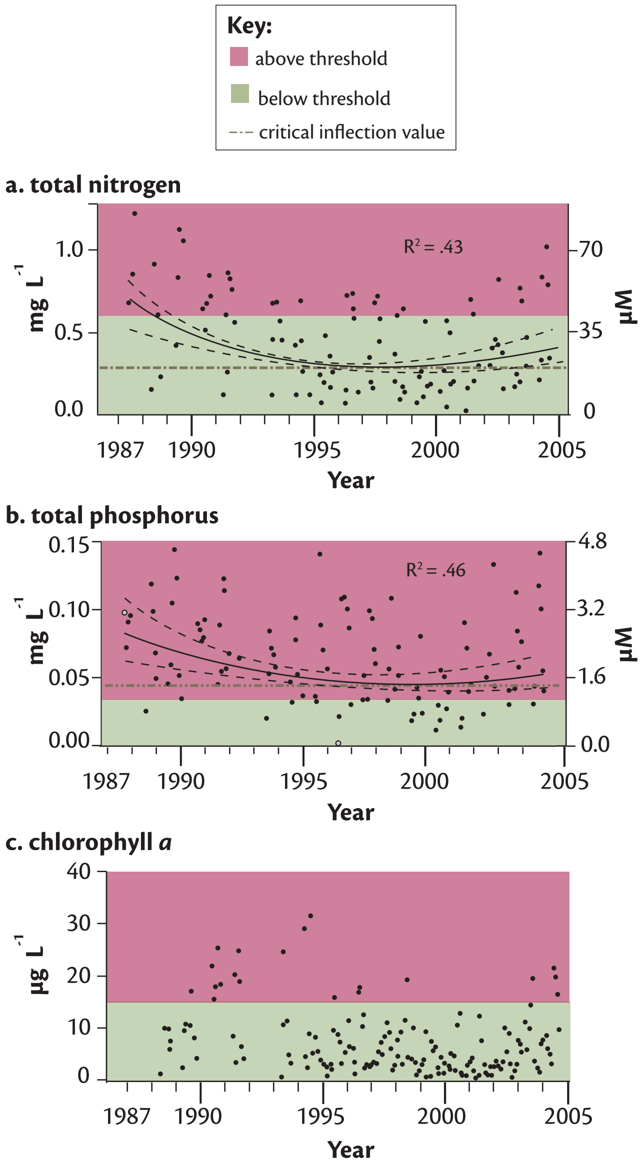



**Figure 5.19. Non-linear trends at a single station.***




***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

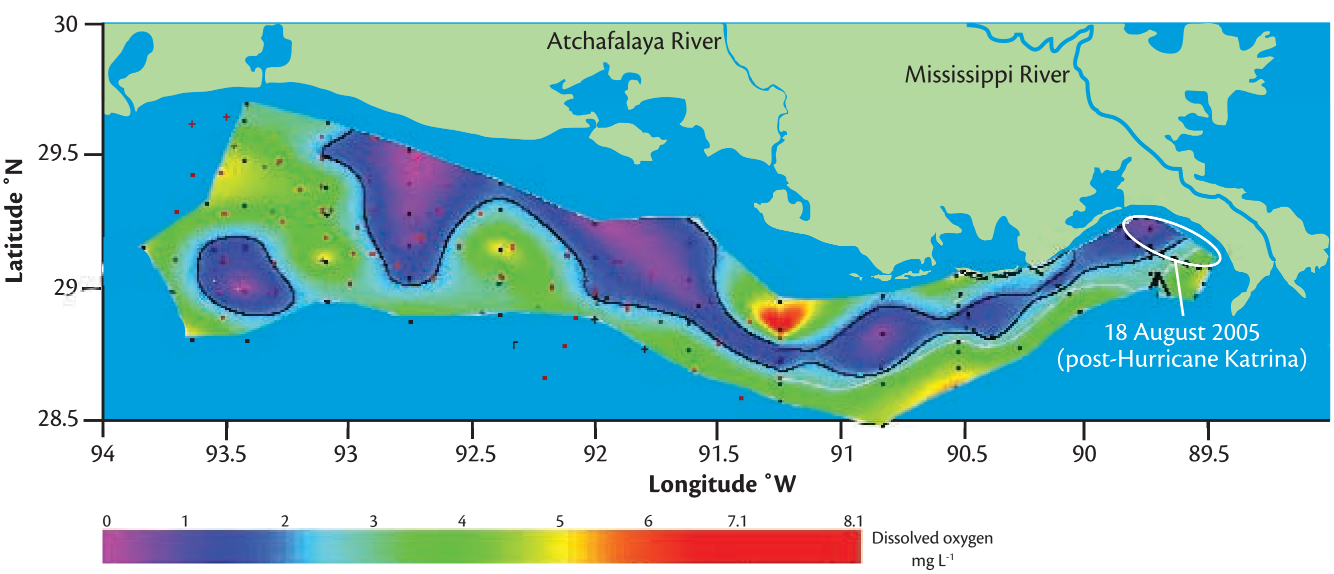
Increases in nutrients and changes in their relative proportions to each other have led to noxious algal blooms, increased algal biomass and carbon accumulation, shifts in phytoplankton community structure, altered trophic interactions, and low dissolved oxygen. Few marine animals can survive in these 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).**



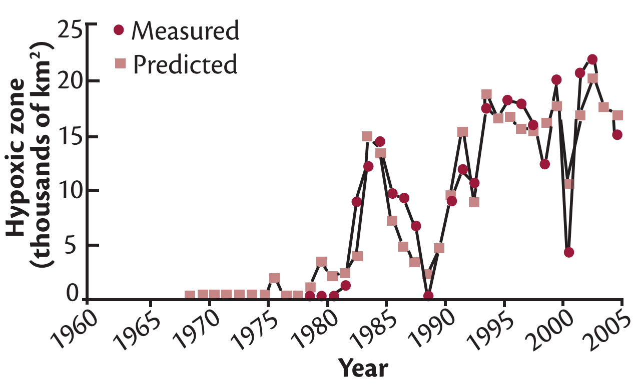
5 and 40 m. While low DO is commonly thought of as a bottom-water condition, oxygen depleted waters often extend up into the lower half to two-thirds of the water column of the hypoxic area.

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 : $y(km^2) = -1337953.4 + 672.1589$ (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.

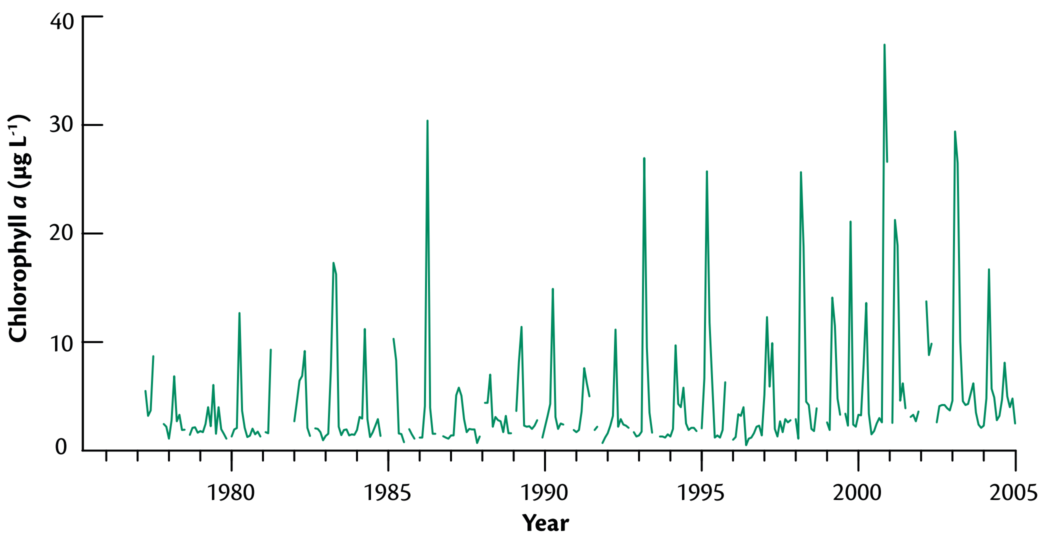

### Phytoplankton biomass

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.**

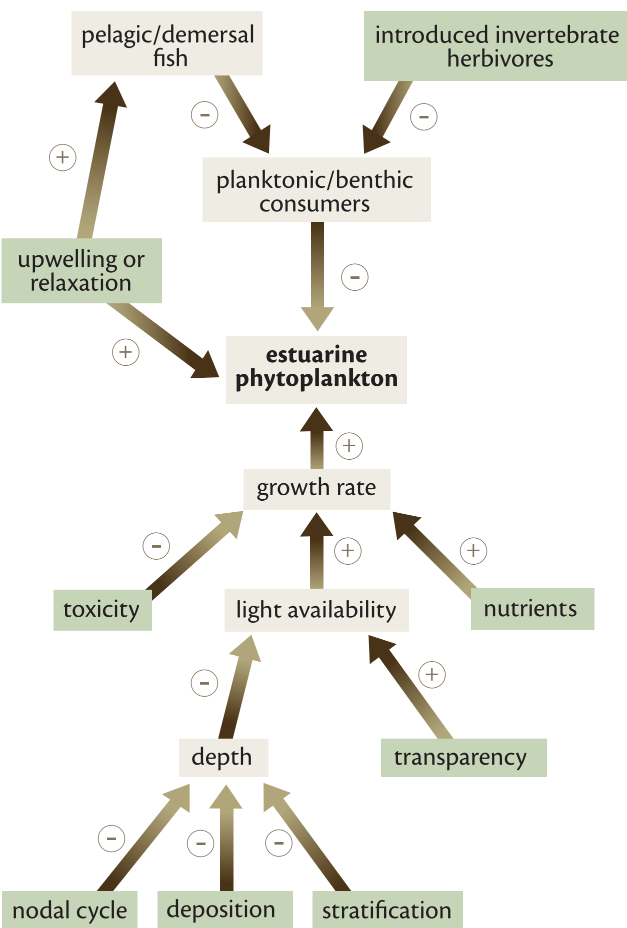


resuspension in shallow habitats. In the mid-1980s, phytoplankton concentrations in brackish habitats were dramatically reduced by the introduction of the Asiatic clam (*Corbula amurensis*). Observations over the past decade reveal increased phytoplankton biomass in marine domains of the Bay.

## 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.**





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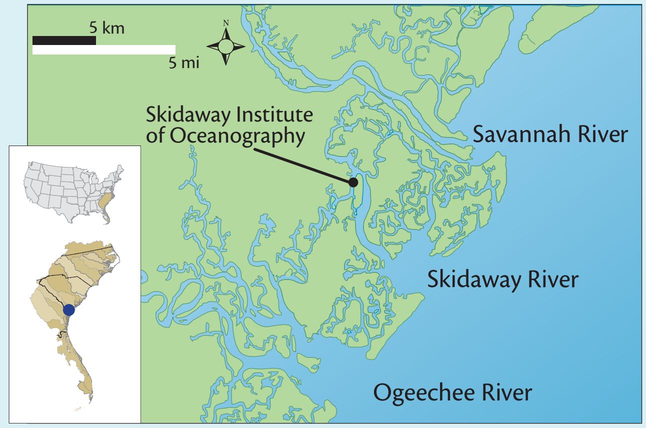
# SKIDAWAY RIVER ESTUARY, GA: *Deterioriating dissolved oxygen conditions occurring in a well mixed coastal waterway*

*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.

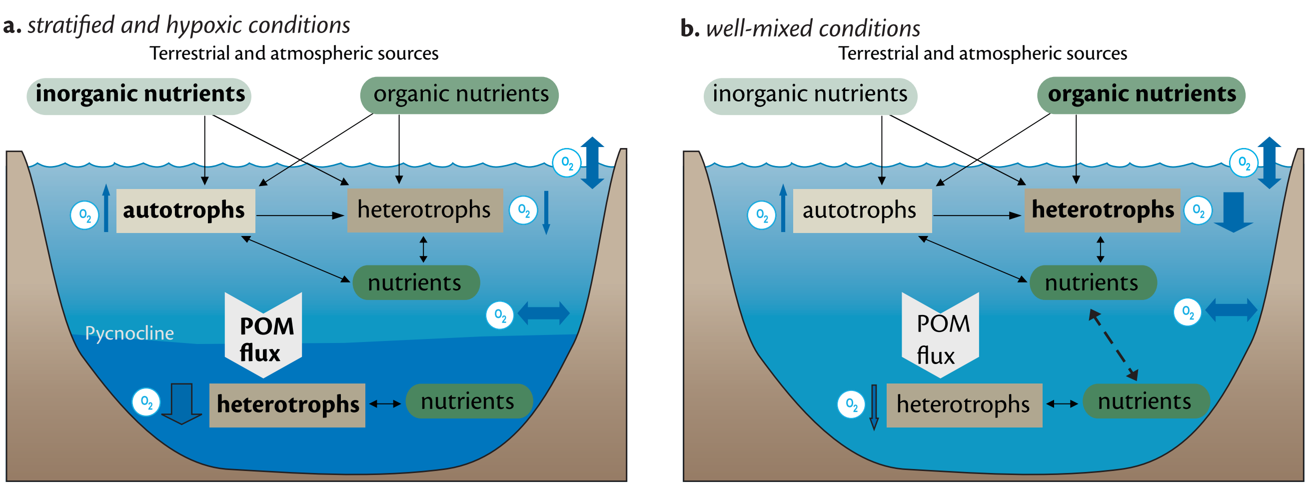



## Issue of concern: urban impacts

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).

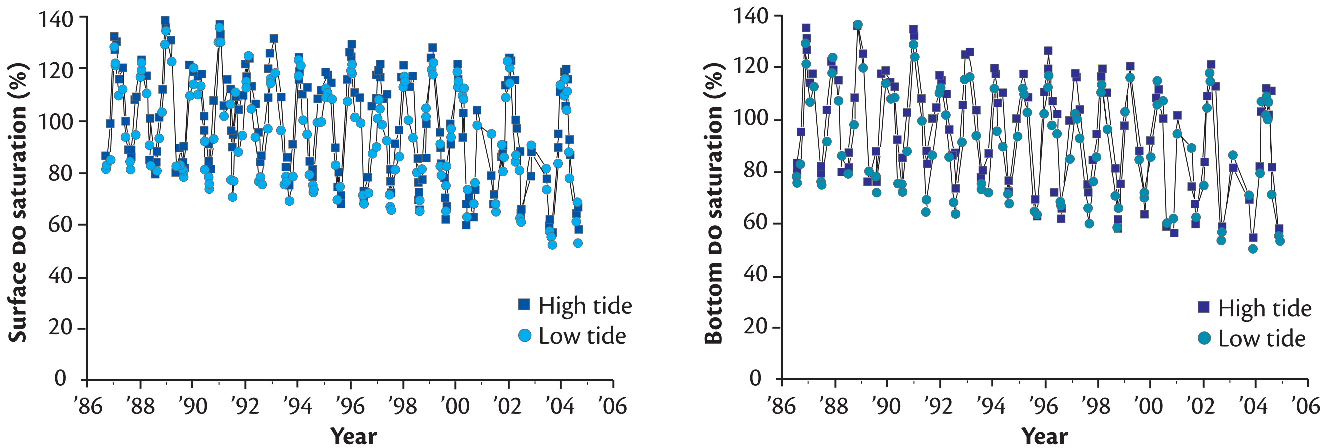
**Figure 5.24. Conceptual model of circumstances leading to hypoxia in (a) stratified and (b) well-mixed conditions.**




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.**

**a.** *surface dissolved oxygen saturation* **b.** *near-bottom dissolved oxygen saturation*




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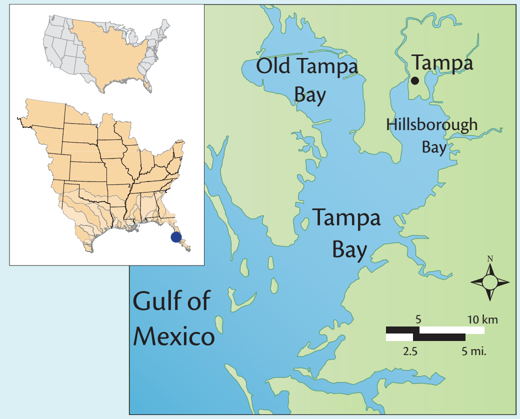
## *TAMPA BAY, FL: Large seagrass recovery due to nitrogen load reductions*

*Holly Greening, Tampa Bay Estuary Program*

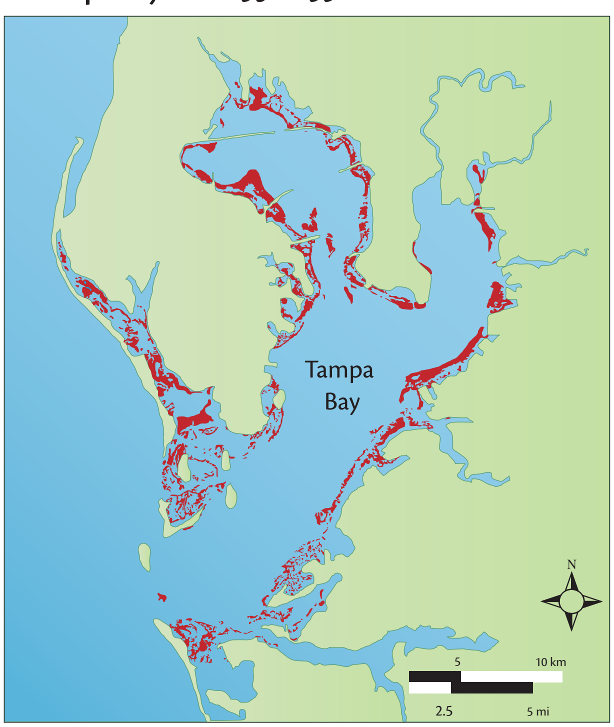
The Tampa Bay estuary is located on the eastern shore of the Gulf of Mexico in Florida, U.S. At more than 1000 $km^2$, it is Florida's largest open water estuary. More than 2.5 million people live in the 5,700 $km^2$ watershed, with a 20% increase in population projected by 2010. Land use in the watershed 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).

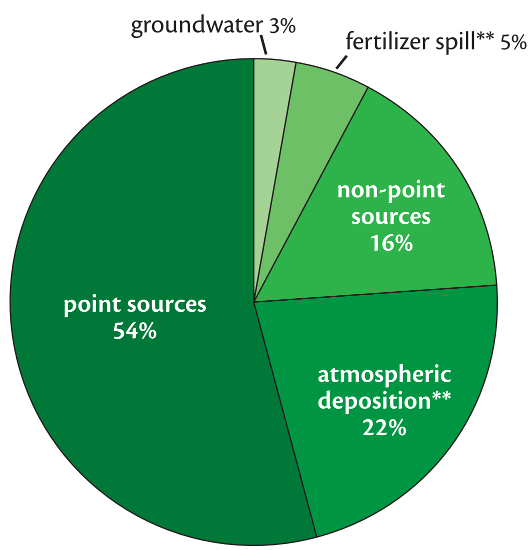
Since the mid-1970s, a number of actions were taken to address the problem of excessive nitrogen loading to Tampa Bay. First, in 1980, all municipal wastewater treatment plants were required to provide Advanced Wastewater Treatment (AWT) for discharges directly to the bay and its tributaries. AWT required 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).

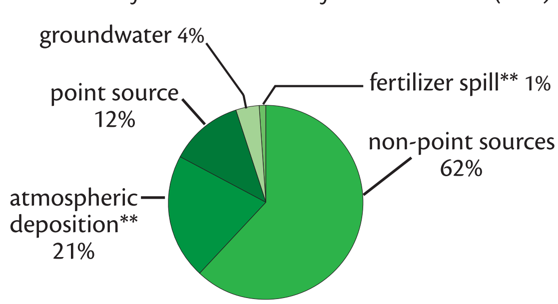
The Tampa Bay Estuary Program (TBEP), a partnership that includes three regulatory agencies and six local governments, has built on the resource-based approach initiated by earlier management efforts. The program has developed water quality models to quantify linkages between nitrogen loads and bay water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

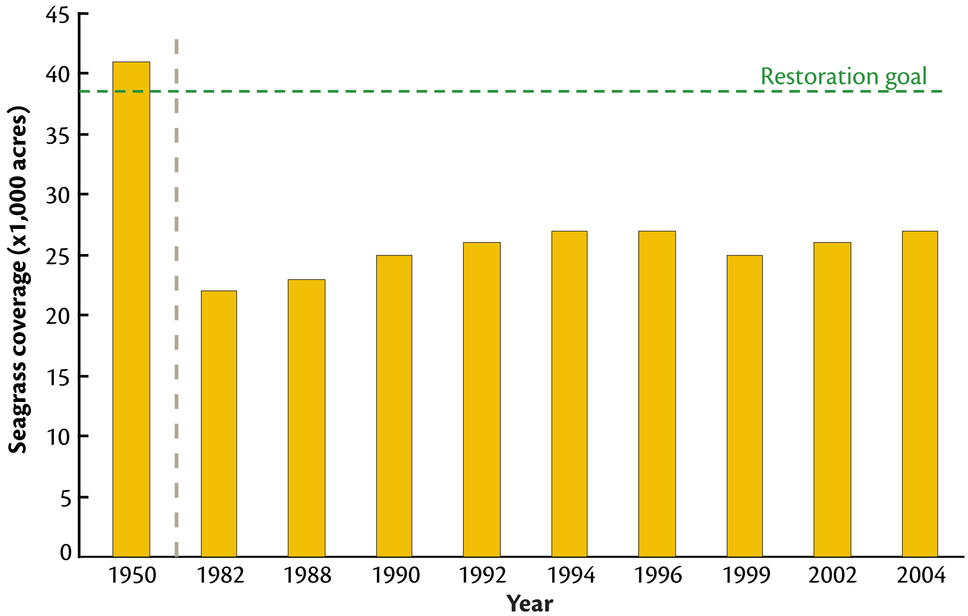
A nitrogen management strategy is being implemented by public and private entities to reduce and maintain nutrient loads to support water quality conditions necessary for submerged aquatic vegetation recovery to 1950s levels. The Tampa Bay Nitrogen Management Consortium, consisting of local electric 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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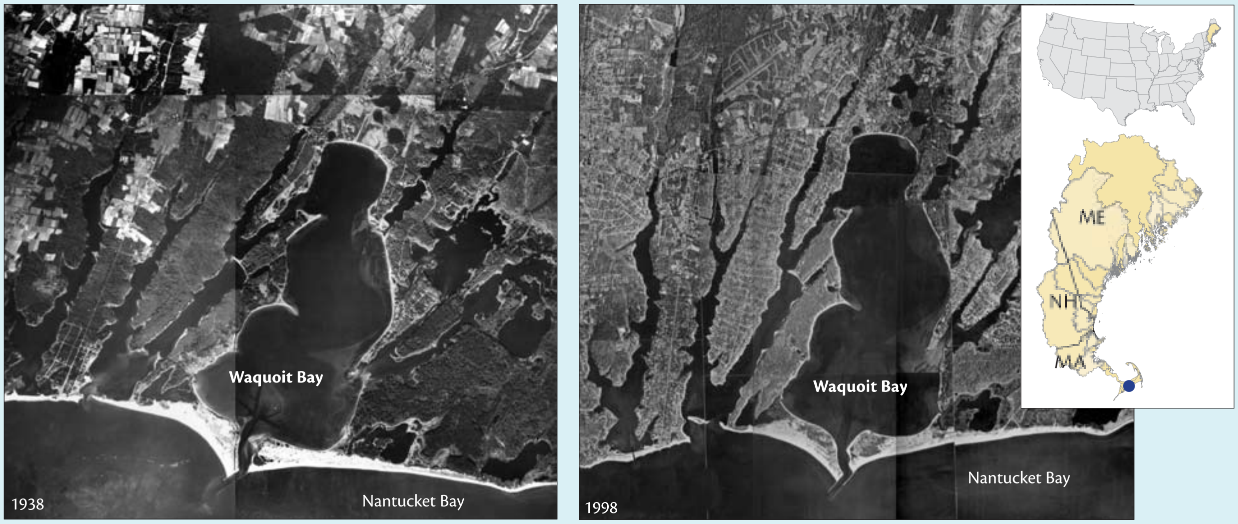
## *WAQUOIT BAY, MA: Increased nitrogen load leads to increased eutrophic symptoms*

*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.

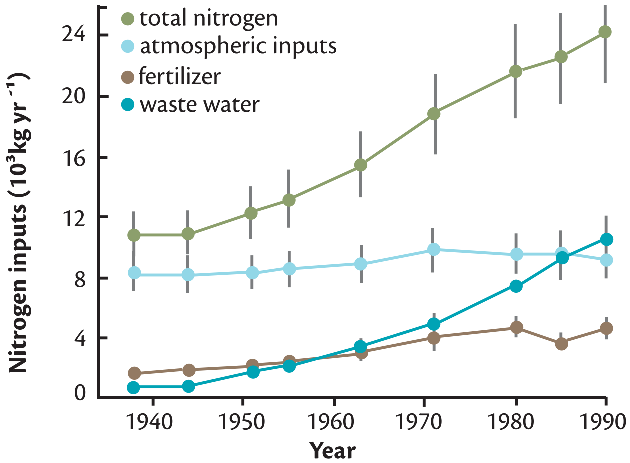
Different estuaries within the Waquoit estuarine system are subject to different loads; comparisons among these estuaries provided compelling inferential evidence that increased nitrogen loads were the agents of change that restructured

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).**




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).

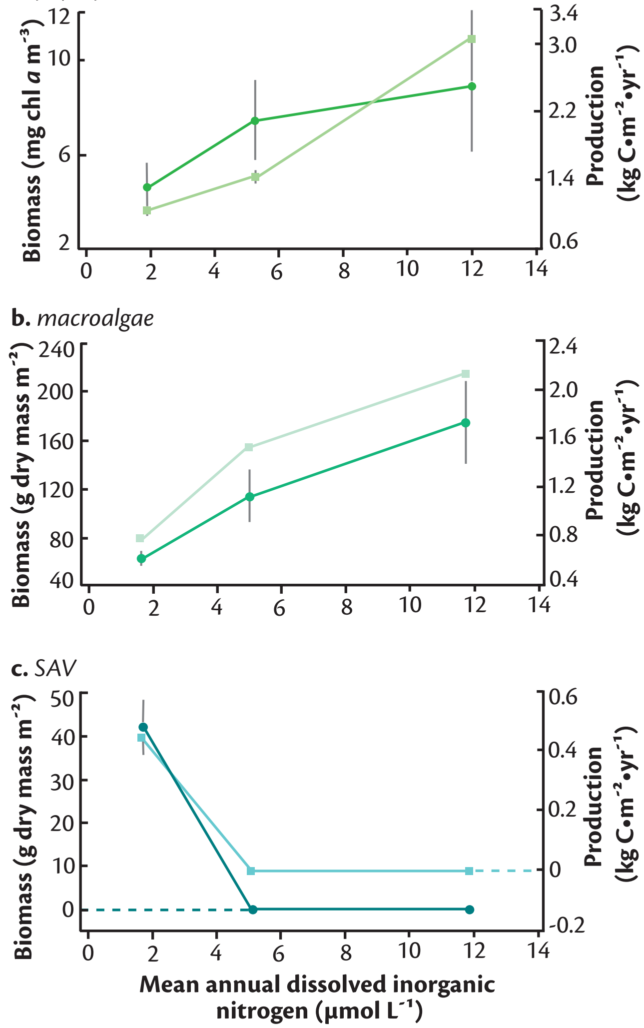
## Future outlook

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

**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).

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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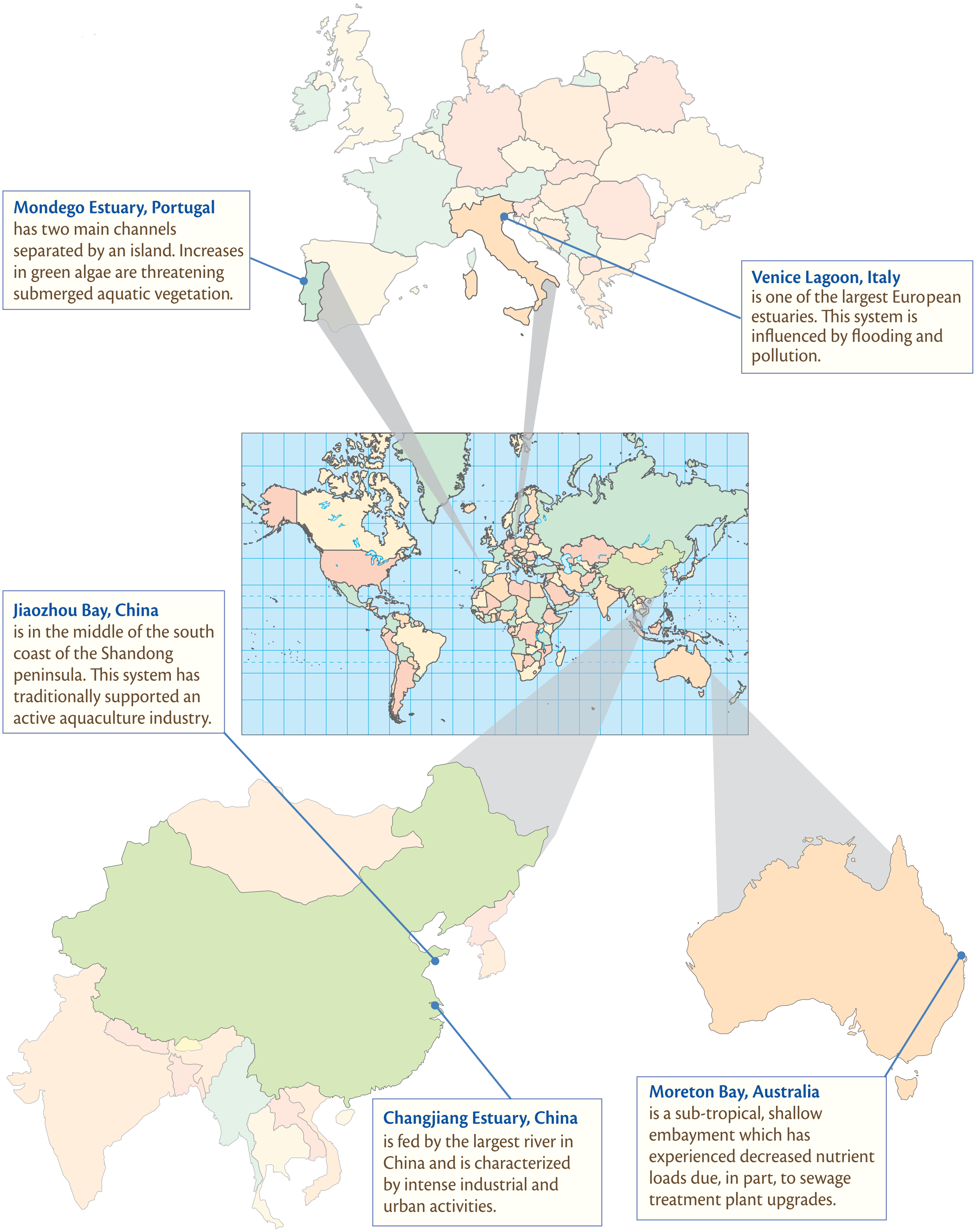
## International case study maps



## 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 $1.94 \times 10^6$ $km^2$ 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.

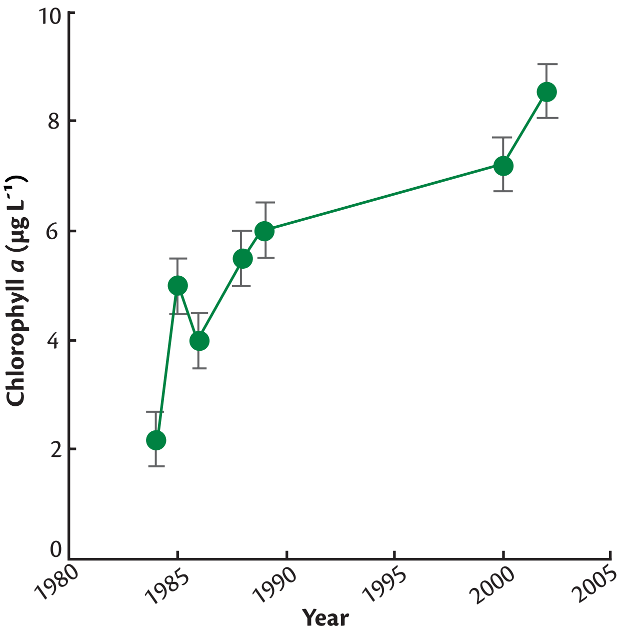
Due to the differences in sampling time, place, methods of analysis, and annual and seasonal variations, there are some uncertainties in the nutrient fluxes of the Changjiang. According to a survey by Liu et al. (2002), the concentration of dissolved inorganic nitrogen increased from 15 μmol $L^{-1}$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

Dilution volume in Changjiang Estuary was estimated as approximately $6.375 \times 10^{11}$ $m^3$ 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 $925 \times 10^{11}$ $m^3 y^{-1}$ (Che et al. 2003), Changjiang Estuary falls into the moderate category in flushing potential.

### Characteristic eutrophic symptoms

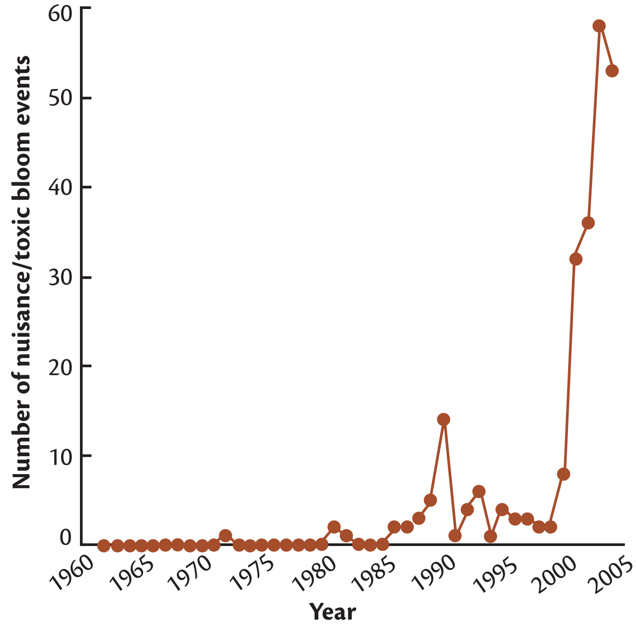
During the last two decades, chlorophyll *a* concentrations increased by four times (Figure 5.31). The 90th percentile value for chlorophyll *a* is 15 μg $L^{-1}$, which in Assessment of Estuarine Trophic Status (ASSETS), is considered medium (5–20 μg $L^{-1}$). The elevated phytoplankton biomass, as 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 $4.06 \times 10^6$ 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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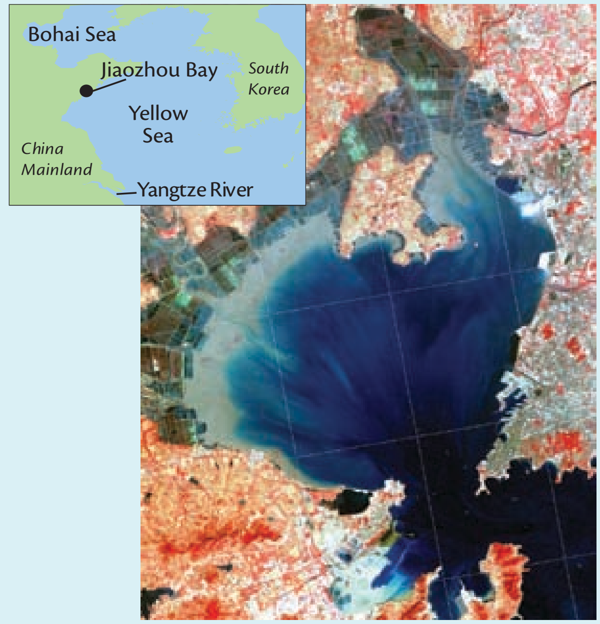
## *JIAOZHOU BAY, CHINA: Threats from eutrophication to large scale aquaculture stimulate nutrient management*

*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 x $10^9$ $m^3$, 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 x $10^8$ $m^3$ $y^{-1}$. 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.

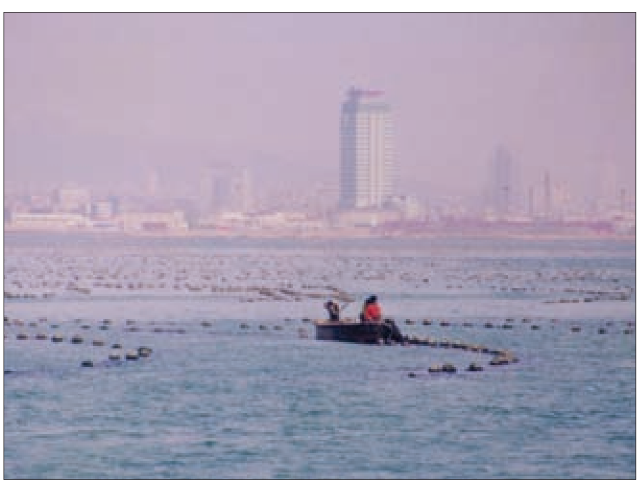



### Issue of concern: nuisance/toxic blooms

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.**

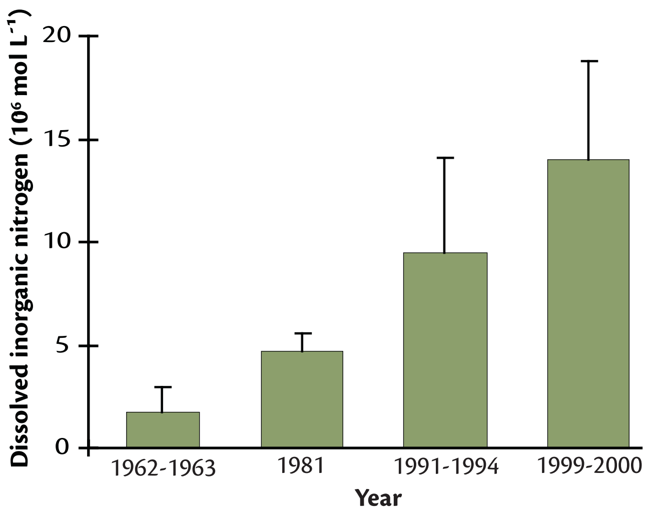



**Figure 5.35. Phosphate concentrations in Jiaozhou Bay.**

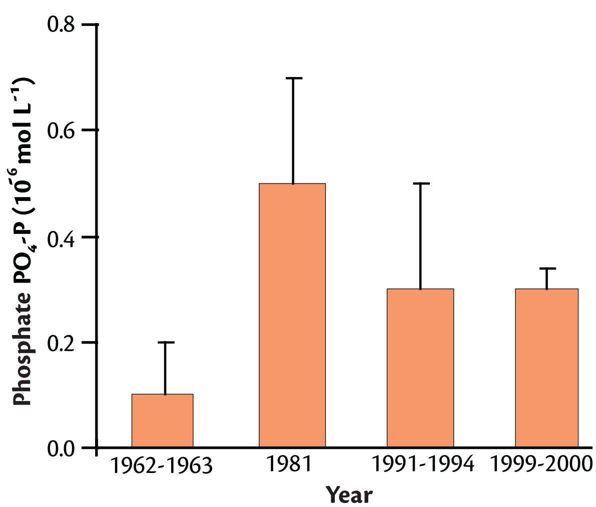



**Figure 5.36. Nitrogen to phosphate ratios in the Bay.**

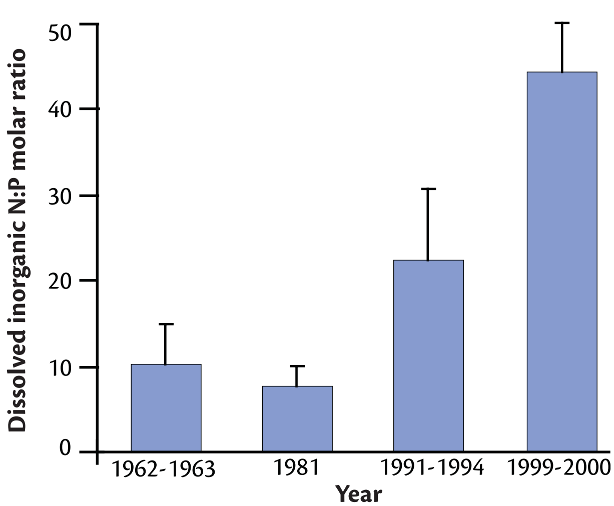



**Figure 5.37. The shellfish aquaculture areas in Jiaozhou Bay in the late 1990s.**


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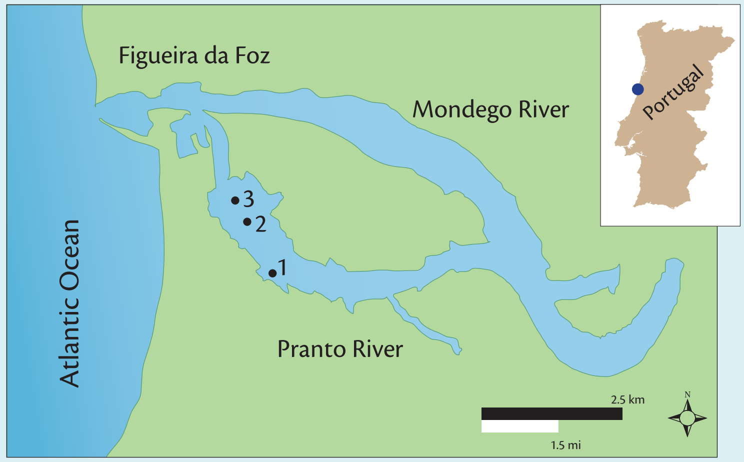
## MONDEGO RIVER, PORTUGAL: *Seasonal macroalgae blooms lead to seagrass loss*

*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

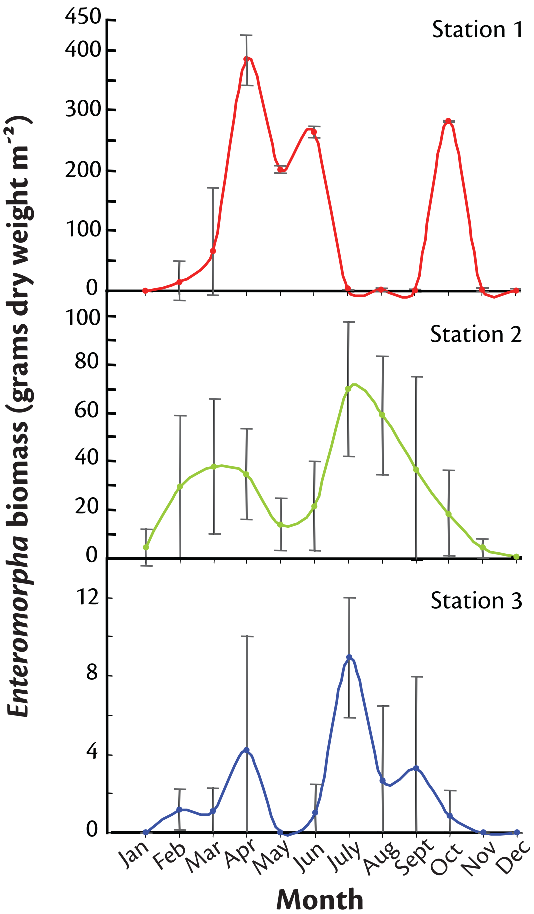
Nutrients from domestic sources come primarily from the population of Figueira da Foz and the Mondego River discharge. The sewage of about 90% of the population is discharged to the system without treatment. No data on nutrient inputs from industry and agriculture on the shores of the estuary were available. 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.**

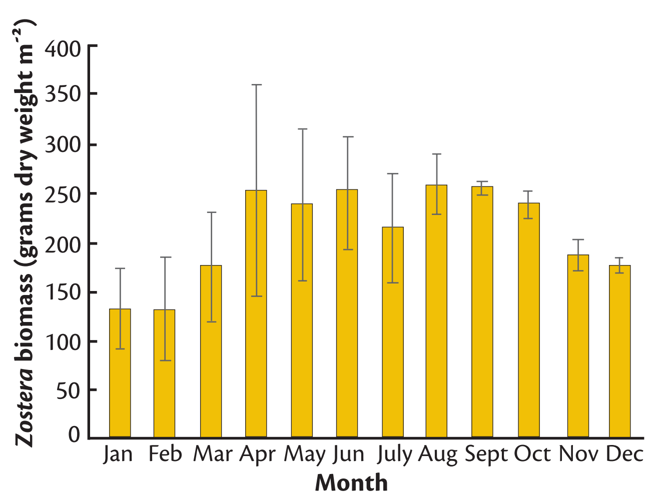
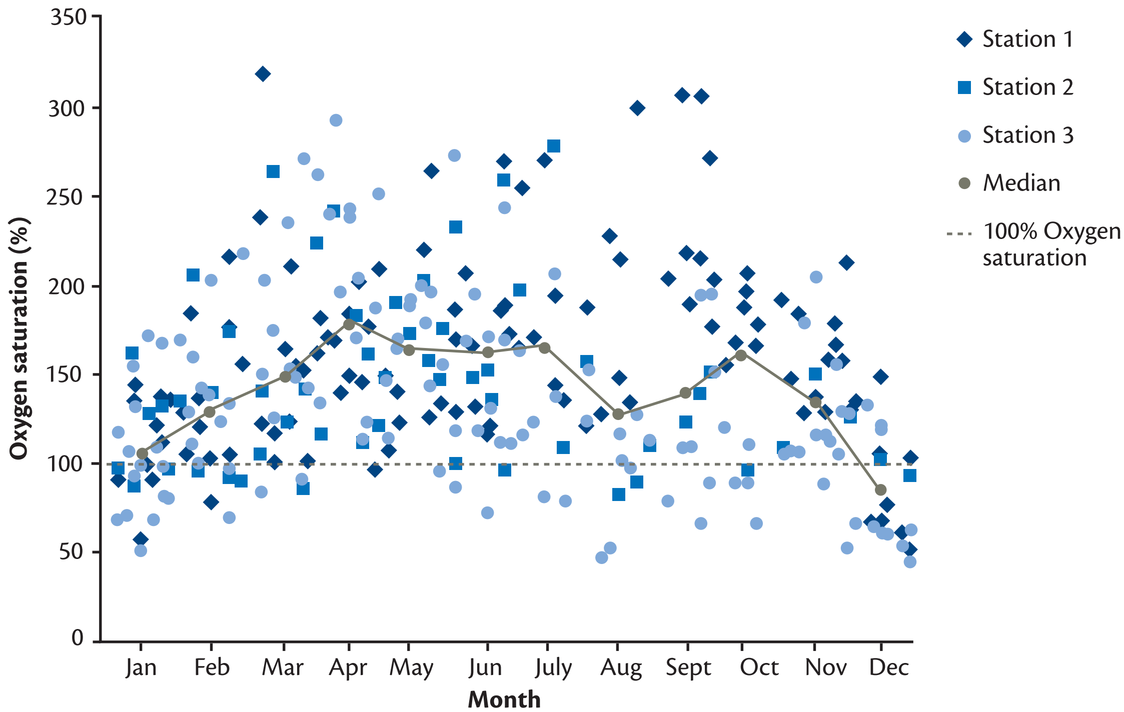


**Figure 5.40. Oxygen saturation in the south channel of the Mondego estuary 1993–1997.**




**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 90$^{th}$ 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** | | moderate low |
| chlorophyll *a* | moderate | |
| macroalgae | moderate | |
| dissolved oxygen | 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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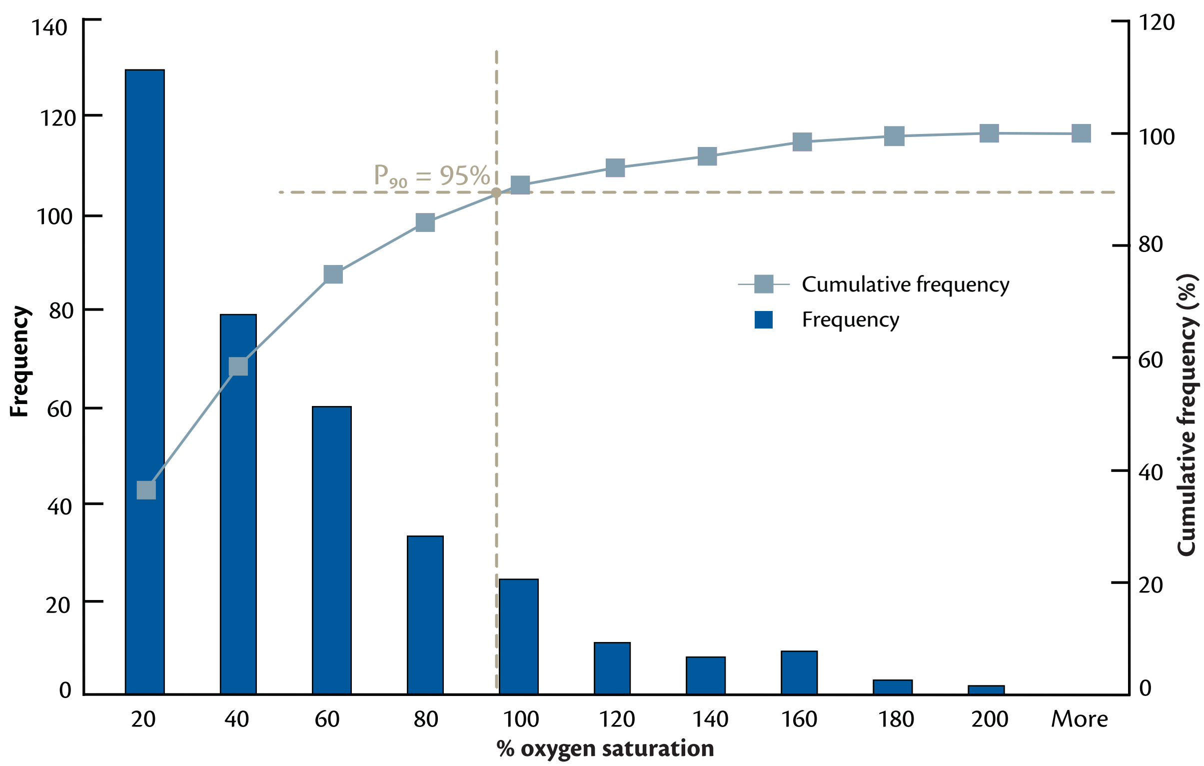
**Figure 5.41. Absolute deviation from full oxygen saturation in the south channel of Mondego estuary, 1993–1997.**



# **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 x $10^3$ km$^2$) located halfway along the east coast of Australia. Its drainage watershed (2.1 x $10^4$ 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.**

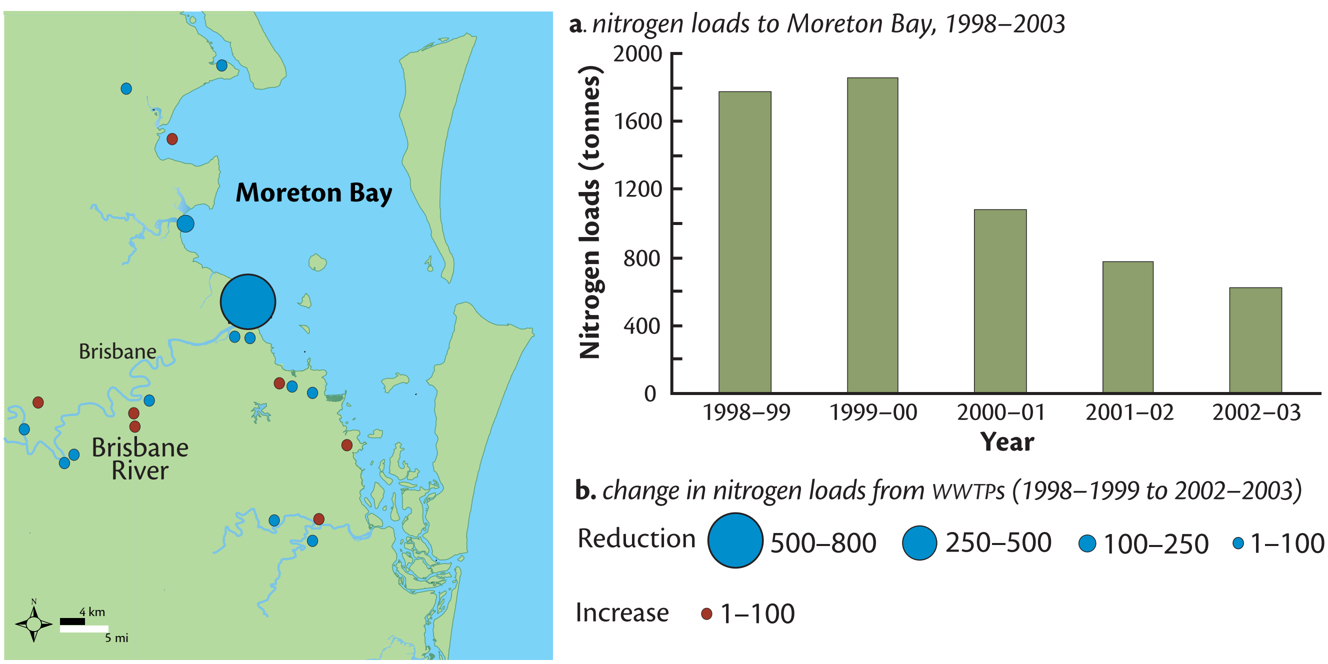
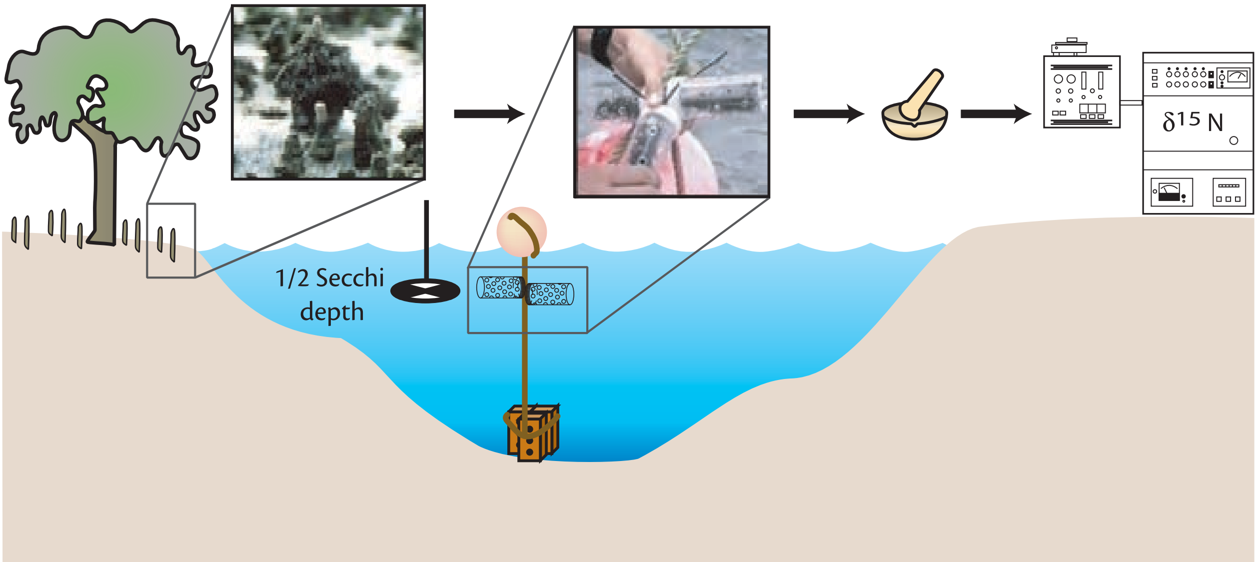


**Figure 5.43. Sewage plume mapping process for Moreton Bay.**



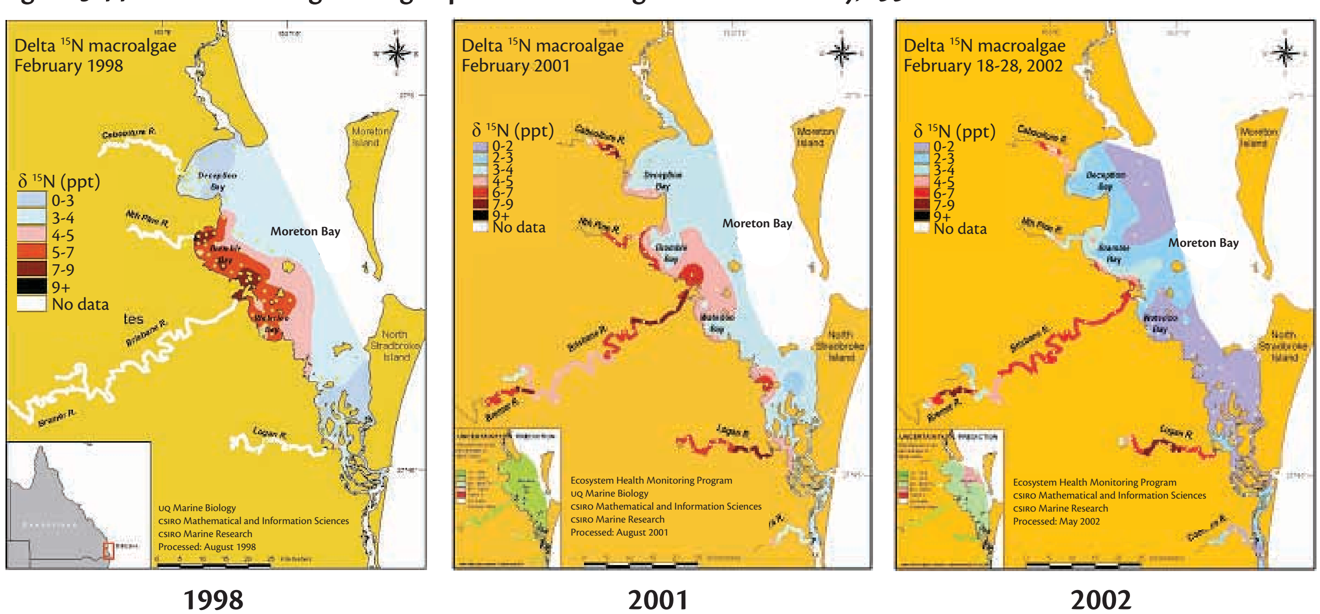

**Collect macroalgae (or other indicator organisms such as oysters or submerged aquatic vegetation) from a site distant from nutrient sources, incubate *in situ*, then dry, grind, and analyze on a stable isotope mass spectrometer for determination of δ $^{15}$N.**

of smaller WWTP continued through 2000–2003, resulting in a smaller overall reduction. Sewage nitrogen was mapped using nitrogen stable isotope ratio (δ $^{15}$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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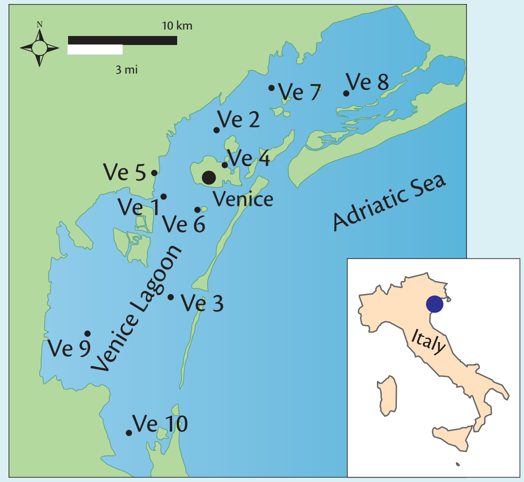
## VENICE LAGOON, ITALY: *Flood protection measure can accentuate eutrophication*

*Roberto Pastres and Stefano Ciavatta, Department of Physical Chemistry, University of Venice*

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.)



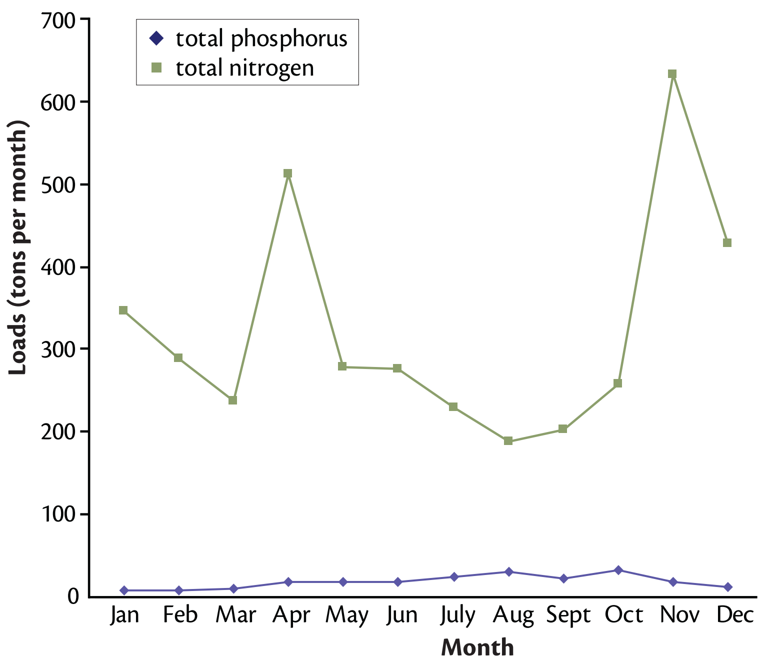

### Issue of concern: flood & pollution management

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.**



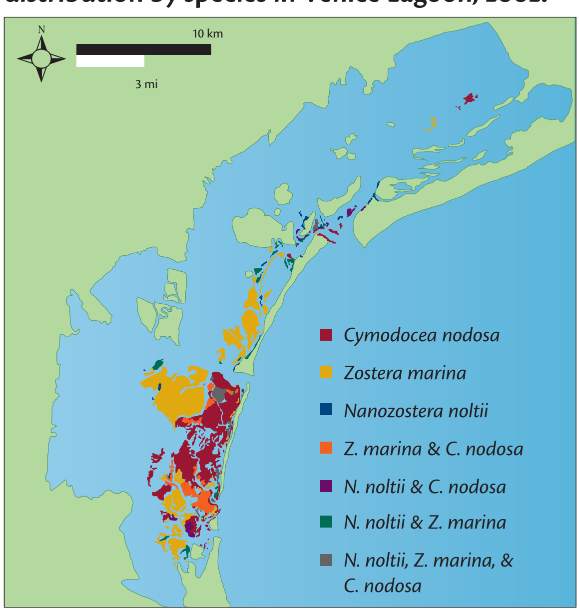
Stefano Ciavatta, University of Venice

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 (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.

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




## 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

Emily Benson, University of Maryland Center for Env. Science

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*.

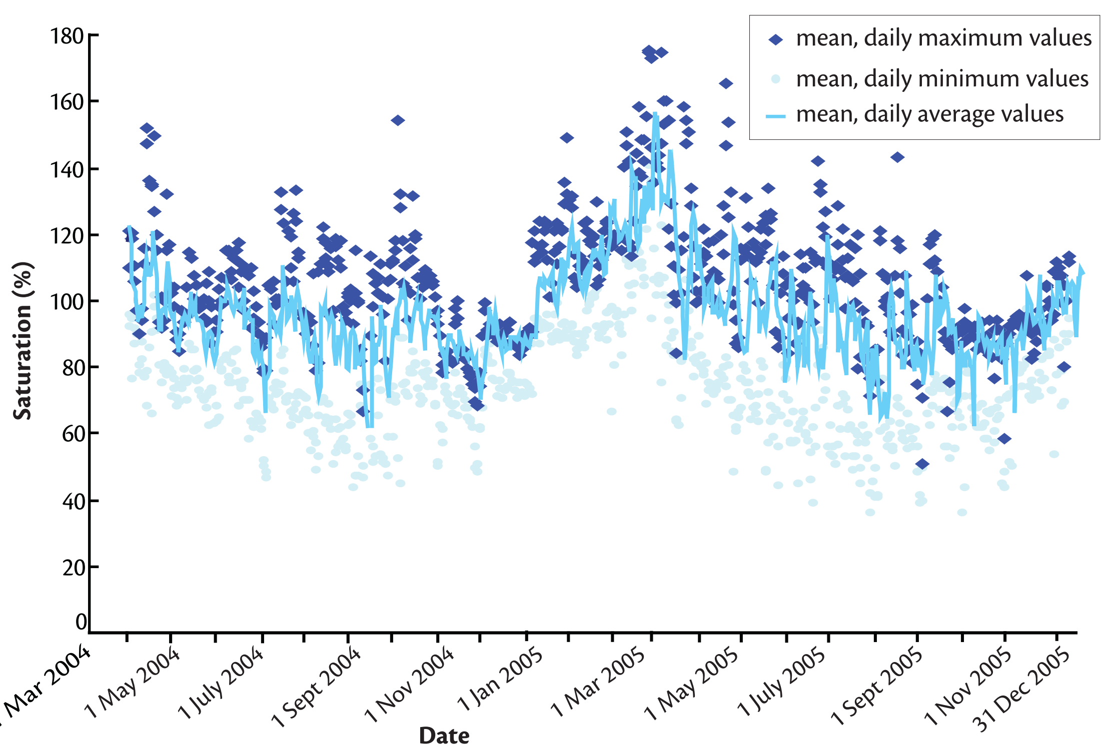
### Dissolved oxygen

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.

Emily Benson, University of Maryland Center for Environmental Science

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 90$^{th}$ percentile value for chlorophyll *a* (24.4 g chl *a* $L^{-1}$) was determined to be high, while the dissolved oxygen 10$^{th}$ 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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