10. The Coastal Bays in Context

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COASTAL LAGOONS

Coastal lagoons are unique coastal features

Coastal lagoons are a significant feature of coastlines throughout the world, and comprise 18% of the estuaries in the United States (Burgess et al 2004). Lagoons are shallow, coastal waterbodies (depth of U.S. lagoons averages 1.6 m [5.2 ft]), that are oriented parallel to the coast, and are separated from the ocean by a sandbank or by a strip of low land such as a barrier island. They usually have low freshwater inflow and in most U.S. lagoons, tidal range is also small (averaging 0.5 m [1.6 ft]). The shallow nature of coastal lagoons means that water is generally well mixed vertically.

The area of water in coastal lagoons is generally small when compared to drowned river valley estuaries, and the ratio of watershed area to lagoon area is also small. The small volume of water in coastal lagoons limits dilution, so they are particularly sensitive to any increase of nutrient inputs.

Exchange with the ocean is typically restricted through small inlets, which results in relatively long water residence times. Coastal lagoon inlets and barrier islands are dynamic in space and time, with sediment transport and storm events continuously changing their morphology. Lagoons with insignificant freshwater inflow and high evaporation can become hypersaline, and stabilization or permanent opening of inlets may decrease average salinity. For more information on inlets and barrier islands, see Chapter 11—*Dynamic Systems at the Land–Sea Interface*.

Coastal lagoons are very productive ecosystems, where life on the bottom (benthic) is closely linked to life in the water column (pelagic), and nutrients are efficiently recycled. Seagrass meadows are a typical habitat within coastal lagoons. Lagoons are fringed by wetlands such as salt marsh (temperate lagoons) or mangroves (tropical lagoons),

Jane Thomas.

Coastal lagoons, such as the Maryland Coastal Bays, usually occur behind narrow barrier islands and are connected to the ocean through inlets.

which serve as habitat for a variety of organisms including wading birds, finfish, and shellfish. Benthic microalgae and macroalgae can be important in lagoons where shallow waters allow light to penetrate to the bottom. Long residence times and localized nutrient inputs in many lagoons provide opportunities for phytoplankton and slower-growing harmful algae species to bloom (Ferreira et al 2005). Living resources found in coastal lagoons include many filter feeders (oysters, clams, scallops, and mussels), finfish species, and migratory birds. Sediments found in coastal lagoons are often muddier toward the mainland and sandier on the barrier island/sand spit side. For more information on water quality, living resources, and habitats in the Coastal Bays, see Chapter 12—*Water Quality Responses to Nutrients,* Chapter 13—*Diversity of Life in the Coastal Bays*, and Chapter 14—*Habitats of the Coastal Bays and Watershed*.

Threats to coastal lagoons include development, pollution, and shoreline hardening

Expanding coastal populations are putting pressure on coastal lagoon systems worldwide through increased wastewater inputs, increased development, and shoreline 'hardening', such as dead-end canals and rock walls. Atmospheric inputs of nutrients are also increasing, as are groundwater inputs which can have a delayed effect because of the lag time before groundwater reaches lagoon waters.

Joana Dilao.

Coastal lagoons are particularly vulnerable to nutrient enrichment, manifested here as excessive macroalgal growth in Ria Formosa, Portugal.

The dynamic nature of inlets and barrier islands, and increasing coastal development, often result in inlets being stabilized to prevent closure or migration. Stabilization of inlets changes circulation patterns and may also have an impact on lagoon salinity regime. Lagoons are typically not well flushed because of restricted exchange with the ocean through inlets that are sometimes only seasonally open. Increasing the tidal exchange by stabilizing inlets can decrease residence time and thus decrease susceptibility to some types of algal blooms. However, development on barrier islands may limit the formation of new inlets, increasing the residence time. Barrier islands often require sand replenishment to prevent their natural landward migration and to compensate for increased erosion caused by the stabilization of the inlet.

Coastal lagoons are expected to be strongly affected by climate change. The increase in frequency of storms that is predicted with climate change may intensify natural processes such as inlet formation, island overwash, and storm surges. In addition, lagoons are typically wave dominated and highly influenced by meterological events rather than by tides. Concurrently, sea level rise will affect coastal lagoons because of their typically low elevations.

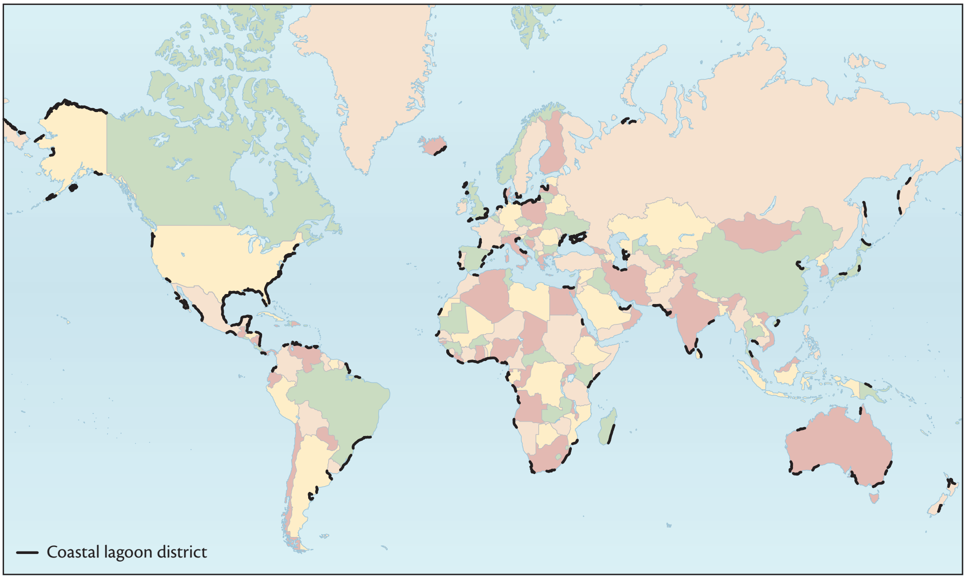
Productivity of coastal lagoons is threatened

Globally, barrier island–lagoon systems make up 7% (14,000 km [8,700 mi]) of the ocean's coastline. They occur on all continents except Antarctica (see map).

world map with distribution of coastal lagoons near here

Some lagoons have sandy beaches

Global coastal lagoon distribution



Coastal lagoons occur on all continents except Antarctica. Modified (Nichols and Boone 1994).

on the ocean side which attract heavy usage in the summer. In many countries, lagoons are used for aquaculture because they have naturally high fish productivity. These picturesque locations suffer heavy pressures from development and tourism. Many have also been altered by engineered structures such as bridges and roads that foster runoff and erosion and alter circulation patterns, leading to sedimentation and eutrophication.

Studies worldwide show that coastal lagoons have gone from highly productive recreation areas and fishing grounds to polluted ponds that no longer produce fish or shellfish. On account of this trend, there is a movement worldwide to develop management plans that will balance desired uses with preservation and conservation of these fragile systems.

Coastal lagoons are more vulnerable than other types of estuaries

To illustrate the differences between drowned river or delta estuaries and coastal lagoons, descriptions of the Maryland Coastal Bays and the nearby Chesapeake Bay and tributaries are compared below. The characteristics of other types of systems may vary, especially in terms of impacts, but this comparison is intended to provide a basic overview.

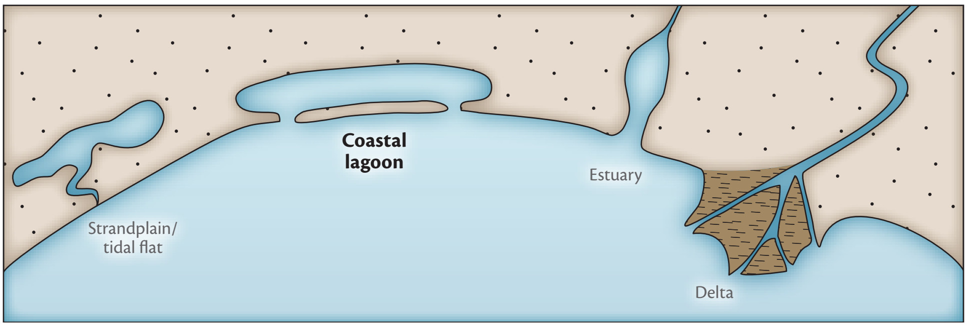
pyramid and schematic of different types of bays near here

Wind blowing across shallow coastal lagoons results in very strong mixing, meaning oxygen levels usually remain high in open areas except in late summer. Dissolved oxygen is typically not a problem in these systems (due to the well-mixed water column), but many lagoons have algal bloom problems (macroalgae, microalgae, and harmful algal blooms [HABS]) on account of long residence times.

The deeper Chesapeake Bay (averaging 21 m [70 ft]), has a large watershed (171,944 km^2 [66,388 mi^2]), high inputs of turbid river water, and a large opening to the ocean which promotes greater tidal exchange. These features provide the potential for stratification (layers of water of different salinity or temperature) that can lead to low oxygen levels, particularly when high levels of nutrients are present. The residence time of water in Chesapeake Bay (~~8–40 days.~~ ***Suzanne:*** Reference) is significantly less than in the Coastal Bays (21–~~100~~ days. ***Suzanne:*** Reference), making this system less susceptible to nutrient-related problems. However, inputs of freshwater and nutrients from the large watershed counterbalance the faster residence time, increasing the potential for problems.

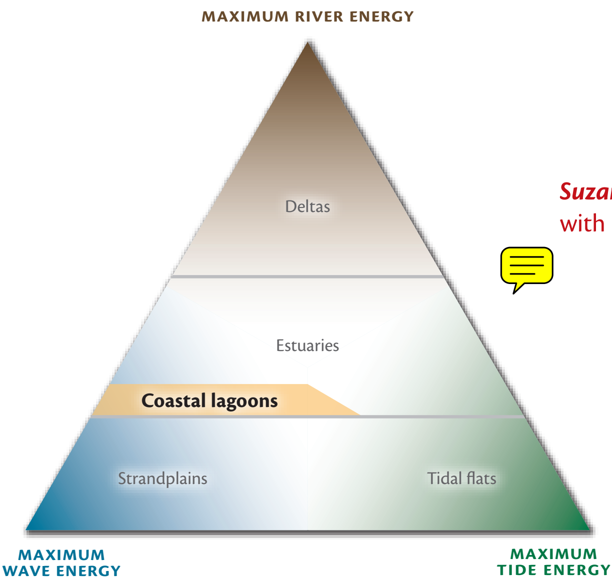
The Coastal Bays have diffuse nutrient sources, including septic systems, agricultural inputs, and atmospheric deposition, that contribute to development of problems. They are also a summertime tourist destination and the added seasonal pressure from population increases—up to 40 times the resident population—occurs

Types of coastal waterways



There is a continuum of coastal waterways, from strandplain/tidal flat to lagoon to delta. Modified (Day et al 1989, Davies 1973).

Classification of estuaries and coastal waterways



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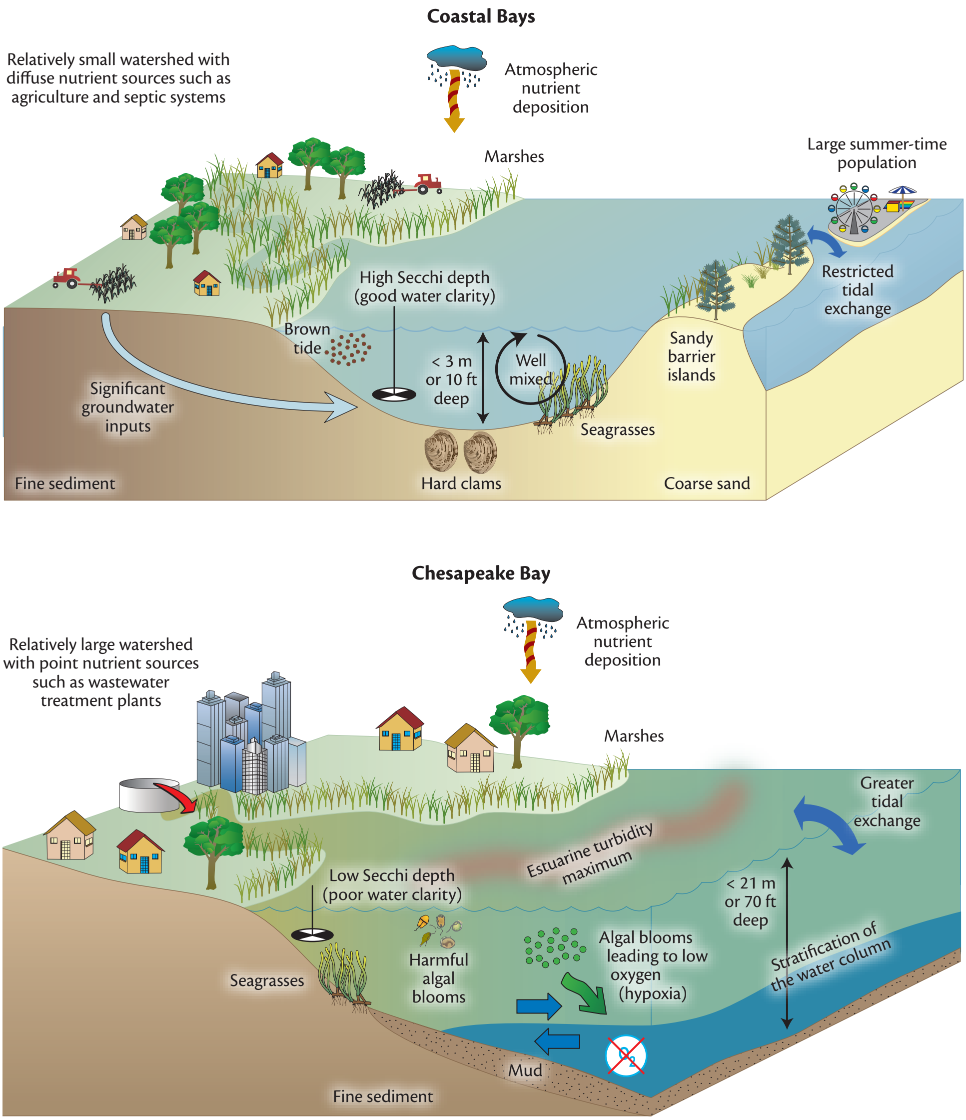
Estuaries and coastal waterways can be classified according to the relative influence of rivers, waves, and tides. Modified (Tracey et al 2004).



Coastal lagoons are different from drowned river valley estuaries such as Chesapeake Bay. These differences often make coastal lagoons more vulnerable to eutrophication.

at the most vulnerable time of year when temperatures are high and conditions for algal growth are optimal.

The Chesapeake Bay watershed includes large population centers, such as Baltimore and Washington D.C., with notable point source sewage discharges. The population is less variable seasonally, however, population density is greater—Chesapeake Bay has 83 people km^{-2} (215 people mi^{-2}), compared to the Coastal Bays resident watershed density of 27 people km^{-2} (1,887 people mi^{-2}). The larger Chesapeake Bay watershed means that much more agricultural area is present, as well as extensive heavy industry with associated toxicant discharges.

Limited water exchange, together with seasonal population pressures, makes the Coastal Bays more sensitive to nutrient inputs than Chesapeake Bay. Overall, the Coastal Bays have moderate to high level eutrophication impacts that have become worse over the past decade. These include problems with algal blooms and HABS, and there are some recent indications of dissolved oxygen issues and seagrass losses. By comparison, the larger, deeper Chesapeake Bay has had high level impacts for at least a decade, including well-established problems with low dissolved oxygen and seagrass loss, in addition to problems with algal blooms and HABS. While nutrients are the primary pollutant problem in the Coastal Bays, problems in Chesapeake Bay include additional contaminants due to the larger population and more diverse watershed activities.

conceptual diagram comparing bays and lagoons near here

COASTAL LAGOONS AROUND THE WORLD

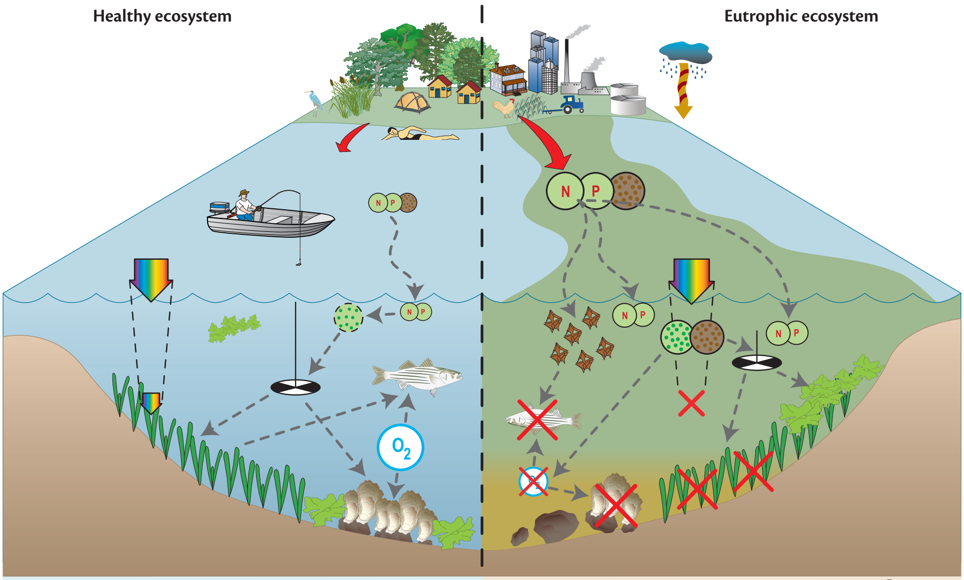
The case studies that follow are intended to highlight the different expressions of eutrophication that occur in different systems around the world. Results of the application of the Assessment of Estuarine Trophic Status (ASSETS) method (Bricker et al., 1999, 2003, 2007, Ferreira et al., 2007b) are presented for Ria Formosa (Portugal), Venice Lagoon (Italy), Lagoons of the Yucatán (Mexico), and the North and South Maryland Coastal Bays in the United States.

What is eutrophication?

Eutrophication is a process in which the addition of nutrients (largely nitrogen and phosphorus) to water bodies stimulates algal growth. Excessive nutrient inputs may lead to other more serious problems such as low dissolved oxygen and loss of submerged aquatic vegetation.

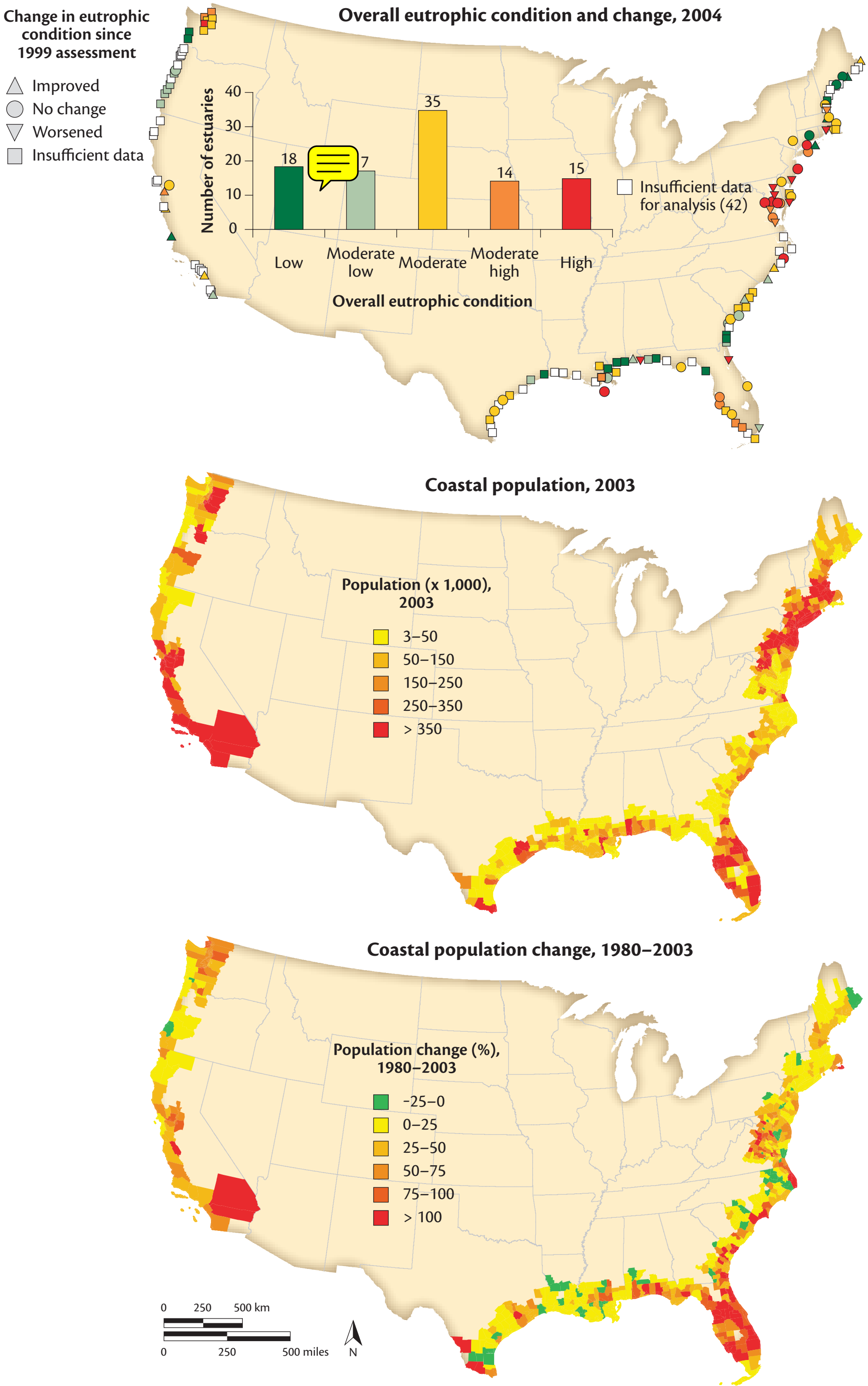
In recent decades, human activities and population growth have greatly increased nutrient inputs to systems, leading to degraded water quality and impairments of estuarine resources for human use.

Healthy and eutrophic ecosystems



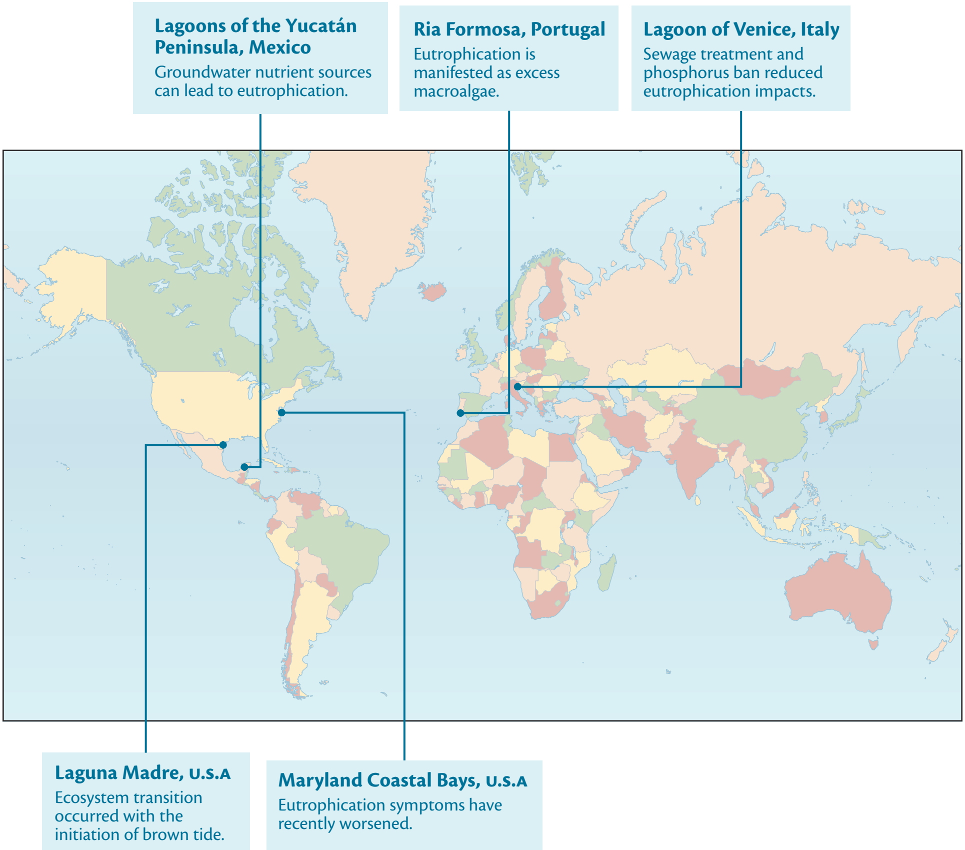
In healthy ecosystems, nutrient inputs—specifically nitrogen and phosphorus —occur at a rate that stimulates a level of macroalgal and phytoplankton (chlorophyll *a*) growth in balance with grazer biota. A low level of chlorophyll *a* in the water column helps keep water clarity high , allowing light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

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



Overall eutrophic condition for United States estuaries (top; NEEA report) shows that 78% of the assessed estuarine surface area rated as *Moderate* or *Moderate high*, mostly in the Mid-Atlantic region. U.S. coastal areas already support high human populations (middle), and population growth will continue to add pressure to coastal estuarine systems (bottom; NOAA website 2007).

Coastal lagoon case studies



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

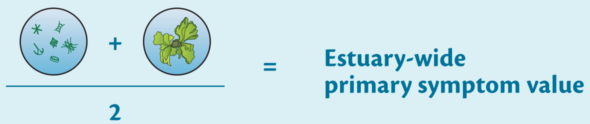
Calculating overall eutrophic condition

1. Assign categories for primary and secondary symptoms

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

Primary and secondary estuary-wide symptom expression values are determined in a two-step process:

1.



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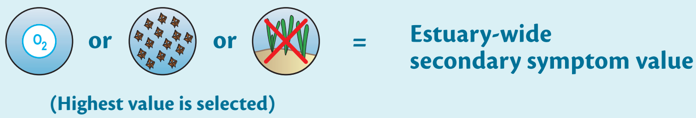


Estuary-wide symptom rating is determined:

Symptom expression value	Symptom rating
0–0.3	Low
0.3–0.6	Medium
0.6–1	High

2. Determine overall eutrophic condition

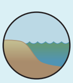
A matrix is used to combine the estuary-wide primary and secondary symptom values into an overall eutrophic condition rating according to the categories below. Thresholds between rating categories were agreed on by the scientific advisory committee and participants from the 1999 assessment (Bricker et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

	LOW SECONDARY (0–0.3)	MODERATE SECONDARY (0.3–0.6)	HIGH SECONDARY (0.6–1.0)
HIGH PRIMARY (0.6–1.0)	Moderate	Moderate high	High
MODERATE PRIMARY (0.3–0.6)	Moderate low	Moderate	High
LOW PRIMARY (0–0.3)	Low	Moderate low	Moderate high

How is an ASSETS rating evaluated?

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

- **Influencing factors.** The influencing factors for a system take into account both the natural characteristics of, and human impacts to systems. They are determined by calculating susceptibility and nitrogen load. Susceptibility is a measure of a system's nutrient retention based upon flushing and dilution. Nitrogen loads are the amount of nitrogen input to a system. For influencing factors, nitrogen loads are estimated as a ratio between ocean and land inputs.



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

- **Future outlook.** Like influencing factors and overall eutrophic condition, the future outlook for an estuary is ultimately determined by a matrix. This matrix combines two factors: system susceptibility and predicted future loads to the system. The future outlook is designed to estimate future changes in eutrophic condition based on expected changes in nutrient inputs to a system.

Ria Formosa, Portugal—Eutrophication is manifested as excess macroalgae

Ria Formosa is a shallow (averaging 1.5 m [5 ft]), small (49 km² [19 mi²]) lagoon located in a sheltered coastal area in southern Portugal, southwestern Europe. It is a hypersaline barrier island lagoon system connected to the ocean by six inlets—five natural and one artificial. The semi-diurnal tidal exchange (average tidal height of 2 m [6.6 ft]) is significantly greater than the residual volume, and freshwater inputs are negligible, leading to

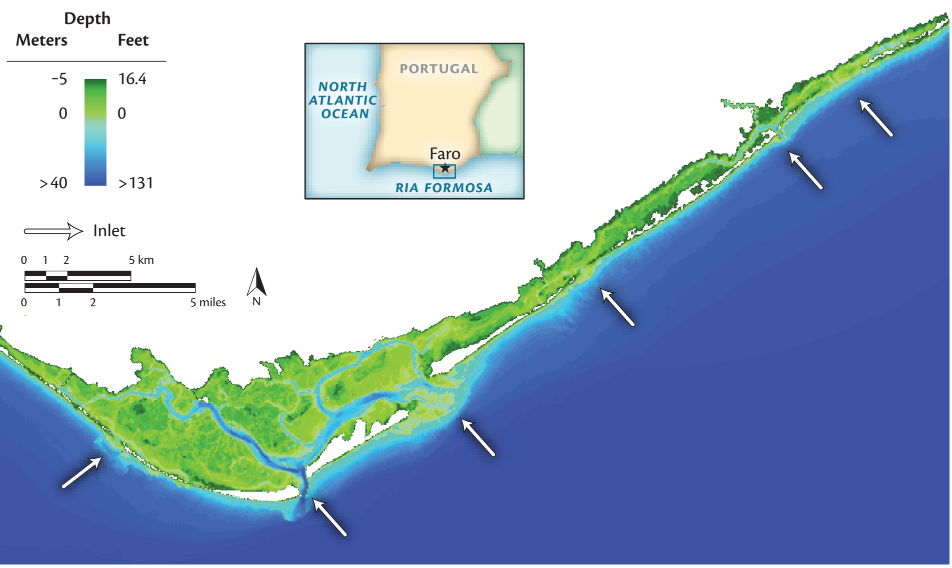
Species	March 1993	June/July 1993
Ulva lactuca	1,350	100
Enteromorpha ramulosa	700	200
Gracilaria verrucosa	140	18
Fucus spiralis	335	75
Total macroalgae biomass	**2,250**	**520**

Maximum biomass (g dry weight m^{-2}) of macroalgae in the Faro–Olhã . Note: values taken from graphical information. *Suzanne:* Source/reference?

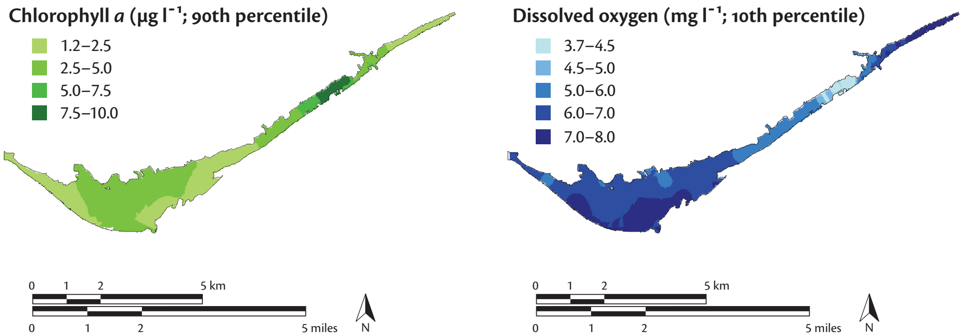
Joana Dilao & Tim Carruthers.

Ria Formosa has extensive intertidal areas (left), which support hard clam populations (middle). Eutrophication symptoms are manifested as excessive macroalgal growth, such as this *Enteromorpha* bloom (right).

Location and bathymetry of Ria Formosa, Portugal



Ria Formosa general view, showing bathymetry and inlets. Depths are referenced to a tidal datum (negative values are intertidal). The eastern end of the lagoon was not included as it is a distinct hydrographic area.



Interpolated surfaces for chlorophyll *a* (left) and dissolved oxygen (right) in the Ria Formosa.

high average salinities (36 ppt). The lagoon has several channels and an extensive intertidal area covered by sand, muddy sand flats, and salt marshes.

The main sources of nutrients are point source discharges from a population of 150,000 inhabitants. Ria Formosa has a wide range of uses, including tourism, extraction of salt and sand, fisheries, and aquaculture. Clam (*Ruditapes decussatus*) aquaculture provides a yield of 8,000 metric tonnes (8,800 U.S. tons) total fresh weight per year.

Figures for Ria Formosa near here.

Pelagic primary production within the lagoon is strongly limited by fast water turnover (Ketchum 1954, Le Pape & Menesguen 1997, Valiela et al 1997). The combination of nutrient peaks, shallow water, large intertidal area, and short water residence time (approximately one day) results in benthic eutrophication symptoms such as intense macroalgal blooms (Coffaro & Sfriso 1997, Deegan et al 2002). The maximum values of macroalgal biomass observed in Ria Formosa reach about 2 kg dry weight m^{-2} (0.41 lb ft^{-2}).

The ASSETS screening model (Bricker et al 2003) was chosen as an integrated approach for eutrophication assessment in Ria Formosa. This system is *Moderately influenced*, due to *Moderate* susceptibility (based on a high dilution but low flushing capacity) combined with *Moderate* nutrient loads.

The 90th percentile value for chlorophyll *a* (5 µg chl *a* l^{-1}) resulted in a rating of *Low*. The macroalgal component of the model shows that parts of the system are impaired, particularly in the western end, due to excessive blooms of *Enteromorpha*, which locally cause oxygen problems and increased mortality of benthic bivalves. The combination of *Low* chlorophyll and *High* macroalgal symptoms give a *High* primary symptom rating. Dissolved oxygen is generally above the 5 mg l^{-1} threshold, indicating no oxygen problems, and there are no significant problems with losses of seagrasses or occurrences of nuisance and toxic blooms. The secondary symptom rating for Ria Formosa is *Low*, which, combined with the *High* primary symptom rating, gives a *Moderate* overall eutrophic condition.

Nutrient loads in this system are expected to decrease significantly in the future due to improvements and increased capacity of sewage treatment, including construction of 10 new wastewater treatment plants within the next decade. This system is expected to show a *Small improvement* in the future.

The overall ASSETS grade for Ria Formosa is *Moderate*, based on the *Moderately influenced* system, *Moderate* overall eutrophic condition, and the *Small improvement* expected in the future.

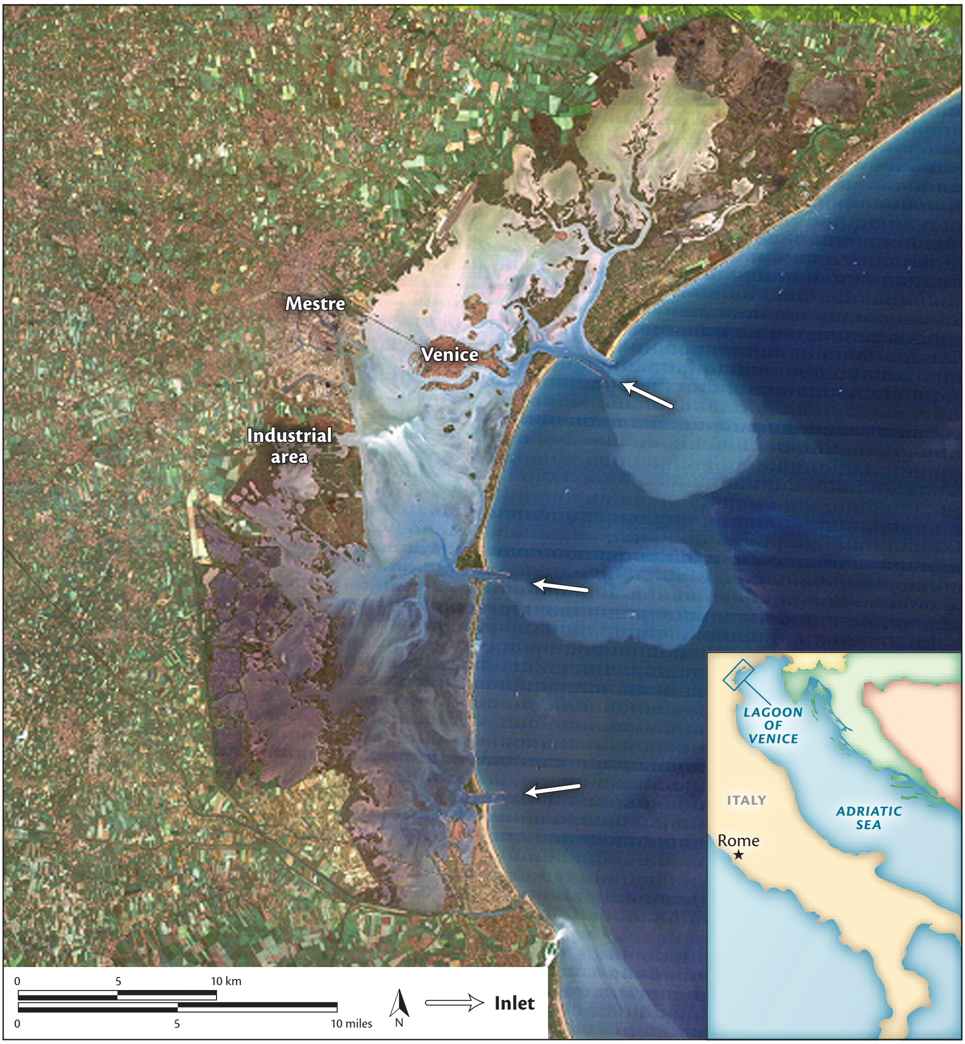
For the summary of the case studies, see the table at the end of this chapter.

Lagoon of Venice, Italy—Sewage treatment and phosphorus ban reduced eutrophication impacts

The Lagoon of Venice is one of the largest lagoon systems in Europe, with a total surface of 550 km² (212 mi²), of which 360 km² (139 mi²) are open to tidal exchanges. The lagoon is located along the northeast coast of the Adriatic Sea in Italy. It is a shallow water basin (averaging 1.5 m [5 ft]), connected to the sea by three inlets. The semi-diurnal tide (average tidal height of 1.9 m [6.2 ft]) drives exchanges of water volumes which are, on average, equivalent to the volume of the entire lagoon and comparable to the yearly freshwater inputs. The average annual salinity is higher than 25 ppt.

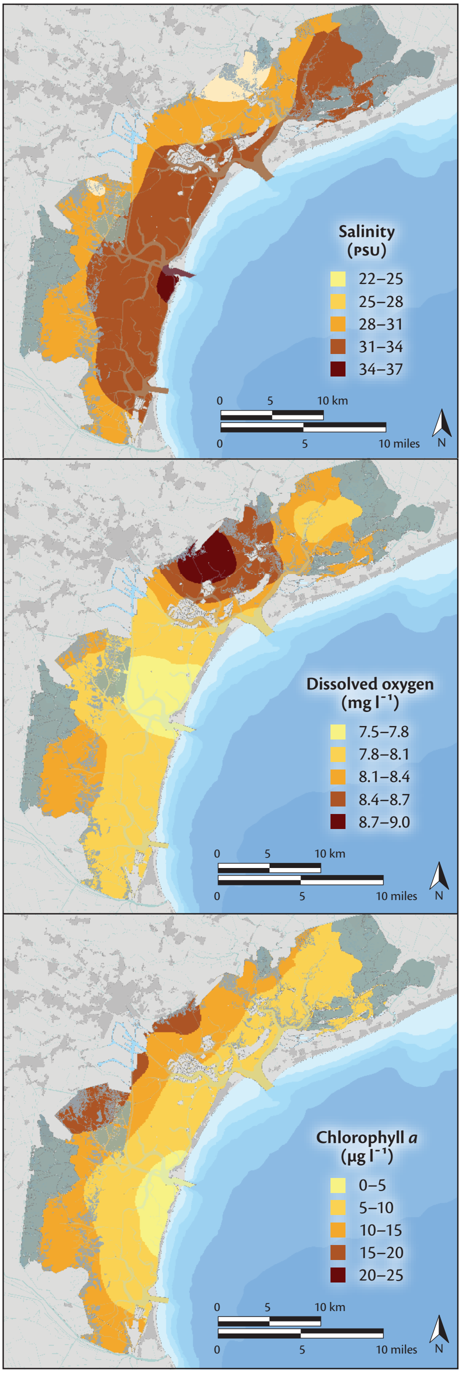
Seven main tributaries and several minor canals carry the wastewaters of this densely populated drainage basin, which hosts agricultural and industrial activities, into the lagoon. Other relevant nutrient

Location of the Lagoon of Venice



The Lagoon of Venice is located in the northwestern Adriatic Sea.

Salinity, dissolved oxygen, and chlorophyll in the Lagoon of Venice



Interpolated surfaces for the salinity (top), dissolved oxygen (middle), and chlorophyll *a* (bottom) average concentrations in the years 2001–2003.

and pollutant sources are the chemical industrial area of Porto Marghera, located on the edge of the lagoon in front of the city of Venice, the city of Venice itself, and other small islands (Murano, Burano, Lido, etc.).

Locator and surface maps near here

The uncontrolled discharges of nutrients during the 1960s and 1970s contributed to hypereutrophic conditions, which were evident during the 1980s, when the density of macroalgae (*Ulva rigida*) reached values as high as 20 kg m^{-2} (4.1 lb per ft^{-2}) of fresh weight in large areas of the central part of the lagoon. In order to reduce the loads of nitrogen and phosphorus, in the 1980s, wastewater treatment plants were built and phosphorus was banned from detergents. These actions, together with other restoration activities aimed at lowering the unpleasant effects of acute eutrophication, lead to a marked decrease in the concentration of soluble reactive phosphorus. During the last 15 years, macroalgae biomass has markedly decreased, while seagrass meadows (mainly *Zostera marina* and *Cymodocea nodosa*) have progressively recolonized large areas in the central and southern part of the lagoon.

The ASSETS screening model (Bricker et al 2003) was applied in order to assess the present eutrophication status of the Lagoon of Venice. To this aim, the most recent available data were used, including nutrient input measurements collected in 1999 (Collavini et al., 2005), water quality data collected monthly at 30 lagoon sites during 2001–2003 (Pastres et al., 2004), and seagrass spatial distribution data from 2002 (Rismondo et al., 2003).

This system is rated as *Moderately influenced*, due to *Moderate* susceptibility and nutrient loads. The 90th percentile value for chlorophyll *a* (24.4 µg chl *a* l^{-1}) is high, but spatial coverage is low, resulting in a *Low* rating. Macroalgae biomass is also *Low*, resulting in a *Low* primary

IN CONTEXT

symptom rating. The dissolved oxygen 10th percentile (6 mg l^{-1}) indicated *Low* oxygen problems. The biomass level of macroalgae at present does not represent a problem for the lagoon, and recent increases in spatial coverage of seagrasses also indicates no problems. As a result, the secondary symptom rating is *Low*, which, combined with the *Low* primary symptom rating, gives a *Low* overall eutrophic condition classification.

The future outlook is for conditions to show a *Small improvement*. In fact, even though the watershed population of the lagoon is likely to increase in the near future, the construction of new wastewater treatment plants, the decommissioning of factories in the industrial area, and other interventions aimed at controlling nitrogen and phosphorus loads have already been planned by the stakeholders and should result in decreased future nutrient loads.

The overall ASSETS grade for the Lagoon of Venice is *Good*, based on the *Moderately influenced* system, *Low* overall eutrophic condition, and the *Small improvement* expected in the future.

For the summary of the case studies, see the table at the end of this chapter.

Stefano Ciavatta & Ilaria Beiso.

Venice's waterways are a large part of the city's charm (traffic jam in the Grand Canal; left. The church of Santa Maria della Salute at the entrance of the Grand Canal; middle). Rising sea level has necessitated the construction of flood protection infrastructure to protect against 'acqua alta', or high water, a regular occurrence in Piazza San Marco (right). Such flood protection measures can unintentionally enhance eutrophication symptoms. ***Suzanne:*** now that we've removed reference to flood protection, I don't know that the right-hand photo is relevant.

Yucatán Peninsula, Mexico—Groundwater nutrient sources can lead to eutrophication

Coastal lagoons are distributed along the Gulf of Mexico and Caribbean coastlines of the Yucatán Peninsula, a 400,000 km^2 (150,000 mi^2) flat, limestone terrace located in southeast Mexico, with 1,250 km (780 mi) of shoreline. These lagoons provide a variety of socioeconomic services such as fisheries, port facilities, and low and high density recreational activities that support important urban areas such as Progreso and Cancún. The ecological and socioeconomic importance of these ecosystems and perceived threats to coastal water quality resulted in their inclusion in ECOPEY (Ecosistemas Costeros de la Peninsula de Yucatán [Coastal Ecosystems of the Yucatán Peninsula]), a long-term ecosystem research and management program of the Mex-LTER program (*www.mexlter.org.mx*) that began in 1994.

Yucatan locator map near here

The coastal lagoons of the Yucatán are variable in size—the 11 lagoonal systems range from 3 km^2 (1.2 mi^2) to almost 1,500 km^2 (580 mi^2, Table 1) of water area. The physical characteristics are consistent with lagoons elsewhere. They are very shallow (averaging 1.2 m [3.9 ft]), with a small tidal range (averaging 0.65 m [2.1 ft]), are surrounded by mangrove vegetation, and are covered with seagrasses. Many have limited connectivity to the ocean and the most important source of freshwater is through groundwater discharges (nine million m^{-3} yr^{-1} km^{-1} of coastline [11 million yd^{-3} yr^{-1} mi^{-1} of coastline]), which are characteristic of this area of karstic soils where rivers are almost absent. Restricted tidal exchange and variable groundwater discharge lead to water residence times from weeks to years. As a result of variable freshwater inputs, lagoonal salinity varies from oligohaline (low salinity; inner zone of Celestún and Ascensión) to mesohaline (moderately brackish; middle zone of Celestún), euhaline (ocean-strength salinity; Chelem and Bojórquez), and hypersaline (more saline than ocean water; inner zones of Chelem). Circulation is dominated by wind–tides and seasonal freshwater inflow, and is also influenced by changes in land use of the surrounding watersheds and from circulation pattern modification.

The ecological functioning of the coastal lagoons of the Yucatán Peninsula is strongly influenced by local and regional forcing functions such as the Yucatán coastal current, Cabo Catoche upwelling, and runoff, as well as by pulse events such as hurricanes, groundwater discharge, and cold fronts. The main sources of nutrients to Yucatán coastal waters are from manure, fertilizer, and sewage. Tourism is a major feature of this area (there were about eight million visitors in 2000 to Cancún, Playa del Carmen, and Cozumel. OCDE 2001) and there are four million Yucatán residents, greater than 50% of whom

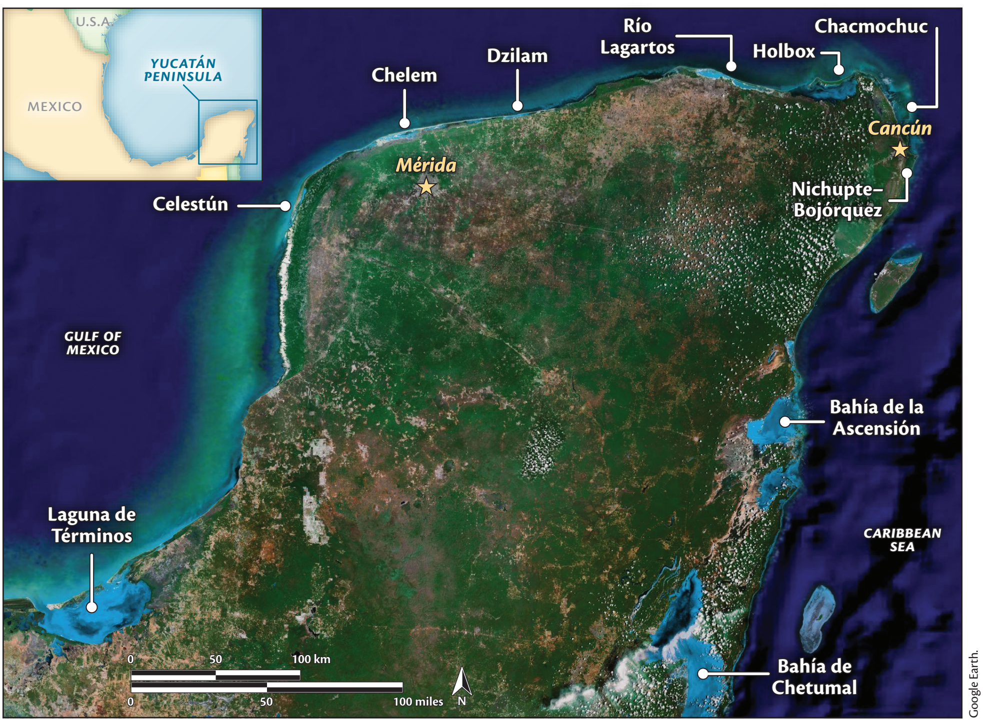
IN CONTEXT

live within the coastal zone, and future increases are expected. The extent of past growth is evident from the total load of nitrogen and phosphorus to Yucatán coastal waters, which has approximately doubled during each of the past two decades (Table XX). However, the primary source of nutrients is from agricultural activities, most notably pig farms which sell primarily to the U.S. market. In total, manure accounts for 40–50% of the total nitrogen loads and 75–80% of phosphorus loads during the last two decades.

Preliminary results show that on account of high nutrient inputs and long residence times, more than half of the Yucatán coastal lagoons show signs of eutrophication. Under natural conditions, nitrate and silicate concentrations are high in areas with groundwater influence, while phosphate concentrations are low. However, in places such as the Yucatán Peninsula, the disposal of wastewater through septic tanks (90%) causes significant increases in ammonium, nitrate, and phosphate concentrations in groundwater, impacting the lagoons. Observed problems include dinoflagellate blooms—though it should be noted that HAB events are less common in the lagoons than in the coastal sea—and high chlorophyll *a* concentrations that together discolor the water to the extent that tourism has declined. There has been a decrease in spatial coverage of seagrasses (mostly *Halodule wrightii* and *Thalassia testudinum*) in some lagoons (e.g., Chelem and Celestún Lagoons) and changes in composition in others (e.g., Nichupté–Bojórquez). There is also sediment and nutrient export to the coastal sea, expanding eutrophic influences beyond lagoonal waters.

A more detailed analysis of eutrophic conditions was done for four coastal lagoons from Yucatán Peninsula (Chelem,

Location of the Yucatán Peninsula coastal lagoons



Location of coastal lagoons of the Yucatán Peninsula.

Celestún, Nichupté–Bojórquez, and Ascensión Lagoons) using the ASSETS model, which combines elements of pressure, state, and response.

Chelem Lagoon

Chelem Lagoon has an area of 14 km^2 (5.4 mi^2) and average depth of 0.8 m (2.6 ft). It is a euhaline system (30–40 ppt) and is vertically homogeneous and microtidal, with a tidal range of 0.6 m (2 ft). This system is highly susceptible to eutrophication processes due to long water residence times (50 days) and the fact that the watershed is characterized by the highest human population density of the north coast of the Yucatán Peninsula. Additionally, this system receives groundwater nutrient inputs from a polluted aquifer. The most important human activities are tourism, fishing, and urban development.

Despite the high population density, nutrient inputs are *Low*, but combined with *High* susceptibility, this system is *Moderately influenced*. *Moderate* chlorophyll *a* and macroalgae result in *Moderate* primary symptom expression. *Low* dissolved oxygen problems combined with *Moderate* seagrass loss and nuisance and toxic blooms result in *Moderate* secondary symptom expression. These symptom expression ratings result in *Moderate* overall eutrophic condition.

In systems such as this, even a small nutrient load can cause significant problems because of the long water residence times. The future outlook in this system is that conditions will undergo a *Large deterioration* due to the continued increase in population and continued development of the watershed.

The overall ASSETS rating for Chelem Lagoon is *Poor*, based on the *Moderately influenced* system, *Moderate* overall eutrophic condition, and the *Large deterioration* expected in the future.

Celestún Lagoon

Celestún Lagoon comprises an area of

Nutrient loads	1980	1990	2000
Nitrogen	[illegible],100	169,203	309,378
Phosphorus	24,838	64,059	115,580

Estimated loads (metric tons yr^{-1}) to Yucatán State in 1980, 1990, and 2000. ***Suzanne:*** source/reference? Is it loads *from* Yucatan State?

Coastal lagoon	Surface area (km^2)	Avg. depth (m)	Salinity range (ppt)	Avg. residence time (days)	Chl *a* conc.[1] Annual avg. bloom conc.[2] (µg chl *a* l^{-1})
Celestún	28	1.2	5–37	20	6 30
Chelem	14	1	20–44	50	4 20
Nichupté	41	2	16–36	100	1 10
Bojórquez	3	1.5	23–34	400	0.8 10
Bahía de la Ascensión	740	2.5	3–33	100	0.5 5

Characteristics of the Yucatán coastal lagoons discussed in this chapter. All these lagoons have groundwater as their freshwater source.

1. Chlorophyll *a* concentrations (Averaged? 90th percentile???).
2. Annual annual bloom chlorophyll *a* concentrations (again, how calculated?).

IN CONTEXT

28 km^2 (10.8 mi^2), with a average depth of 1.2 m (3.9 ft). It is an estuarine system (5–39 ppt), vertically homogeneous in the main body and stratified in the tidal channel, and is microtidal with a tidal range of around 0.6 m (2 ft). This system has a high susceptibility to development of eutrophication problems due to long water residence times (20 days) of the inner zone and the high nitrate inputs (5.7 mg l^{-1} [80 μM]) from groundwater springs that are polluted with waste from pig farms located in the watershed.

In spite of the *High* susceptibility and *Low* nutrient loads, water quality is not significantly impacted. The lagoon is part of a Biosphere Reserve, where human density is low and the system supports such activities as tourism, fishing, and salt extraction. This system is *Moderately influenced*.

Moderate chlorophyll *a* and *High* macroalgae result in a *Moderate* primary symptom expression. *Low* dissolved oxygen problems combined with *Moderate* seagrass loss and *Low* nuisance and toxic blooms result in *Low* secondary symptom expression. These symptom expression ratings result in *Moderate low* overall eutrophic condition, indicating no significant impacts. Nutrient loads are not expected to increase in the future and it is expected that there will be *No change* in conditions.

The overall ASSETS rating for Celestún Lagoon is *Good*, based on the *Moderately influenced* system, *Moderate* low overall eutrophic condition, and the *No change* expected in the future.

Nichupté–Bojórquez

Nichupté–Bojórquez is a lagoon system comprising an area of 50 km^2 (19.3 mi^2) with an average depth of 0.8 m (2.6 ft). It is a polyhaline system (16–36 ppt) and is vertically homogeneous and microtidal, with a tidal range of 0.3 m (1 ft). This system is highly susceptible to the eutrophication process due to intense Cancún tourism, development within the watershed, and long water residence times (100–400 days). Although there are seagrasses covering the lagoon bottom, the leaves are covered with epiphytes which is strong evidence of eutrophic impact.

High susceptibility combined with *Low* loads means this system is *Moderately influenced*. *Low* chlorophyll *a* and *High* macroalgae result in *High* primary symptom expression. *Moderate* dissolved oxygen problems combined with *Moderate* seagrass loss and *Low* nuisance and toxic blooms result in *Moderate* secondary symptom expression. These symptom expression ratings result in *Moderate high* overall eutrophic condition.

This suggests that even small nutrient loads into long residence time lagoons can cause significant impacts. The future outlook for this system is that conditions will undergo a *Large deterioration* as a result of increased nutrient loads due to continued increases in development and tourism.

The overall ASSETS rating for Nichupté–Bojórquez is *Poor*, based on the *Moderately influenced* system, *Moderate high* overall eutrophic condition, and the *Large deterioration* expected in the future.

Bahía de la Ascensión

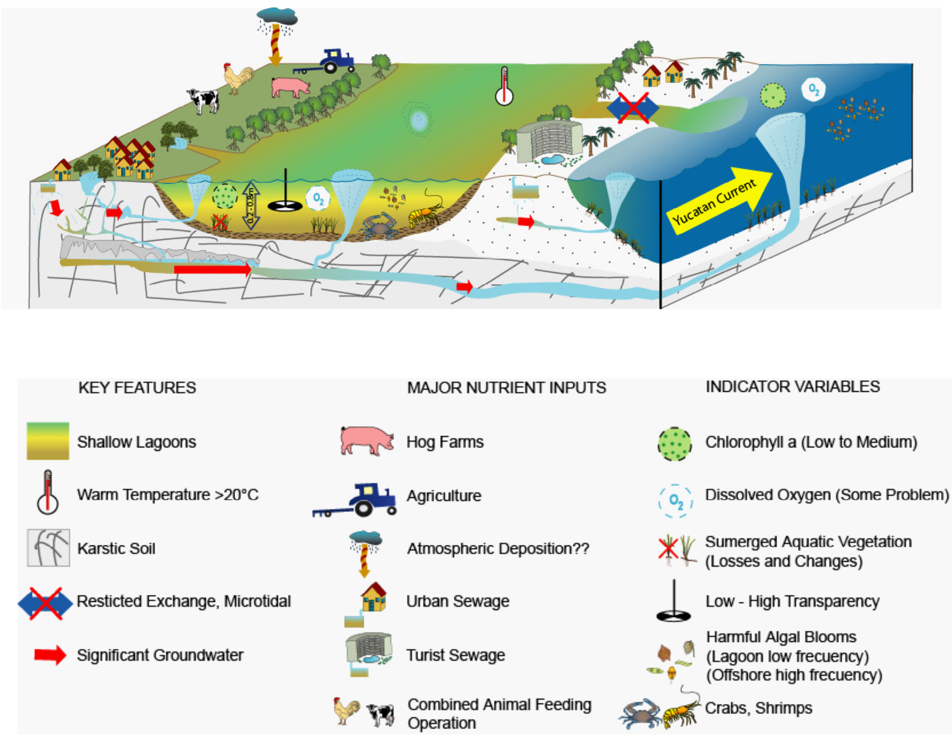
Bahía de la Ascensión, located inside the Biosphere Reserve Sian Ka'an, comprises an area of 740 km^2 (286 mi^2), with an average depth of 2.5 m (8.2 ft) and estuarine salinity (3–33 ppt). This system is vertically homogeneous and microtidal, with a tidal range of 0.5 m (1.6 ft). This system has a *Low* susceptibility to eutrophication due the high exchange with the ocean water through a wide inlet, despite long water residence times (100 days). The human population density in the surrounding watershed is very low and the main activities are ecotourism and fishing.

Low susceptibility combined with

Jorge Herrera-Silveira.

The coastal lagoons of the Yucatán Peninsula show varying signs of eutrophication. Celestún Lagoon (left) shows few signs of eutrophication, while Chelem Lagoon (middle) shows many eutrophication symptoms and is expected to worsen. Nichupté Lagoon, with the adjacent tourist center of Cancún (right), also shows eutrophication signs and is expected to deteriorate further.

Jane:*I get original from Jorge. Make sure to emphasize cenotes.*



Relevant characteristics of the coastal lagoons of Yucatán considered for the condition assessment.

Low loads means this system is *Slightly influenced*. *Low* chlorophyll *a* and *Moderate* macroalgae result in *Low* primary symptom expression. *Low* dissolved oxygen problems, seagrass loss, and nuisance and toxic blooms result in *Low* secondary symptom expression. These symptom expression ratings result in *Low* overall eutrophic condition, likely the result of low population density. The future outlook is that there will be *No change* in conditions.

The overall ASSETS rating for Bahía de la Ascensión is *High*, based on the *Slightly influenced* system, *Low* overall eutrophic condition, and the *No change* expected in the future.

For the summary of the case studies, see the table at the end of this chapter.

The results of the application of the ASSETS assessment method are useful in advancing the understanding of the processes related to the ecosystem health of the Yucatán coastal lagoons. The high susceptibility of the lagoons and expected future trends of eutrophication are of major concern. Among the analyzed variables, salinity changes, nitrate, ammonium, silicate, chlorophyll *a*, macroalgal abundances, seagrass coverage changes, and the abundance of harmful phytoplankton species should provide a strong basis for determination of the health of the coastal lagoons. However, variables such as the nitrogen:phosphorus ratio, N^{15}, and heavy metals in seagrass leaves and rhizomes should also be good indicators of the environmental conditions in these systems. Measurement of these indicators should be incorporated into monitoring programs of the Yucatán coastal condition assessment. Equally important are measurements or estimates of the load sources and amounts so that appropriate management measures can be planned. The main threats to the Yucatán coastal lagoons are wastewater inputs from urban development, farming, and tourist activities and changes in hydrodynamics (***Jorge:*** is this from water extraction? or from engineering water structures of some kind?) which affect water residence times. Together, these results suggest that management actions should focus on conserving or rehabilitating water fluxes and reducing nutrient inputs to the aquifer through wastewater treatment systems using tertiary level treatment and constructed wetlands. Consequently, the legal framework of protection and conservation of the Yucatán coastal ecosystems should be adjusted at least to State level.

Conceptual diagram of Yucatán lagoons near here

Upper Laguna Madre, U.S.A.—Ecosystem transition occurred with the initiation of brown tides

Send to Ken Dunton to check.

Need “g[illegible] & “bad” photos for photo strip, and a satellite image for the locator map. Some data maps/tables would be good too.

Upper Laguna Madre, along the southeast Texas coast, has an area of 591 km^2 (228 mi^2), average depth of 0.3 m (1 ft), and is microtidal, with a tidal range of 0.15 m (0.5 ft). Seasonally and meteorologically influenced changes in water level are more important than lunar tides in driving water exchange in this system. Annually, evaporation is approximately twice precipitation, and no permanent stream discharges into the lagoon. As a result, the waters of the lagoon are hypersaline (annual average salinity > 29 ppt). Seagrass meadows cover approximately two-thirds of the bottom. The surrounding watershed includes a national park, a wildlife refuge, and very large ranches and the extreme northern end is becoming increasingly urbanized.

Upper Laguna Madre was known for its clear water until a phytoplankton bloom (*Aureoumbra lagunensis*) developed in the spring of 1990 and persisted long enough to earn its own name—Texas brown tide. The first episode lasted until 1997, and others of shorter duration have occurred since, including one as recently as December 2005. Although not acutely toxic to most biota, the bloom reduced light reaching the bottom long enough to eliminate 12 km^2 (4.6 mi^2) of seagrass 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.

A retrospective analysis of the algal bloom conducted primarily by scientists at the University of Texas Marine Science Institute (reference?) has demonstrated that the 1990 bloom initiated in Baffin Bay, a tributary of Upper Laguna Madre. The initiation of the bloom is suspected to be linked to a variety of unusual circumstances preceding the bloom, including a long drought period culminating in high salinities, and a hard freeze coinciding with extremely low water. The high salinity eliminated most species of phytoplankton and grazers, but high salinity is tolerated by *A. lagunensis*, which was able to bloom. Despite being a relatively slow-growing organism that cannot assimilate nitrate, the bloom achieved densities exceeding one million cells ml^{-1}, which was attributed to a lack of grazing pressure and availability of ammonium released from decaying fish and invertebrates killed by the hard freeze. Other factors that contributed to the long persistence of the bloom include unpalatability or a feeding-depressant effect on most grazers, the low flushing rate, and a nutrient subsidy from the gradual die-back of seagrasses. 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 nitrogen and may be kick-started from resting stages in the sediments.

High nutrient loads combined with *High* susceptibility has led to Upper Laguna Madre being *Highly influenced*. This system is characterized by *Moderate* symptom expressions for chlorophyll *a* and nuisance/toxic blooms, resulting in a *Moderate* overall eutrophic condition. A watershed management plan associated with a Total Maximum Daily Load (TMDL) process for the main agricultural drainage area may counteract some of the effects of continuing development in the watershed, so *No change* to Upper Laguna Madre is expected in the future. What is the overall ASSETS rating? For the summary of the case studies, see the table at the end of this chapter.

COASTAL LAGOONS IN THE UNITED STATES

There is evidence of eutrophication in all U.S. coastal lagoons

In the United States, there are coastal lagoons distributed along the Atlantic, Gulf of Mexico, and Pacific coastlines. These systems are variable in size—the 28 lagoonal systems included in NOAA's NEEA (National Estuarine Eutrophication Assessment) (Bricker et al 1999) range from 1 km^2 (0.4 mi^2) of water area to almost 5,000 km^2 (1,930 mi^2), averaging 709 km^2 (274 mi^2). However, in most other physical characteristics they are more similar. Most are very shallow (averaging 1.6 m [5.2 ft]) with a small tidal range (averaging 0.54 m [1.8 ft]).

Most have relatively low freshwater inflow and oceanic exchange is limited, occurring through one (e.g., Tijuana Estuary, Netarts Bay) or multiple (e.g., New Jersey Inland Bays, Sarasota Bay) narrow inlets. The restricted exchange with the ocean and relatively low freshwater inflow leads to residence times of days to months. This makes lagoons susceptible to development of eutrophic symptoms. Because these watersheds are typically well-developed with higher summer-time populations, the nutrients discharged to the lagoons often lead to water quality problems which is evidenced by the moderate to high levels of eutrophication observed in 15 of 20 of the NEEA lagoons (for eight lagoons, data were inadequate for assessment). All but one of the impacted lagoons are located along the Gulf of Mexico and Mid-Atlantic coasts. The Gulf of Mexico region has a warmer climate and single tidal excursion per day (for the western lagoons), which combine to make them much more sensitive than the lagoons located in cooler climates. The Mid-Atlantic region is the most densely populated of all regions, contributing to the higher level of impacts noted for lagoons (and also estuaries) in this region.

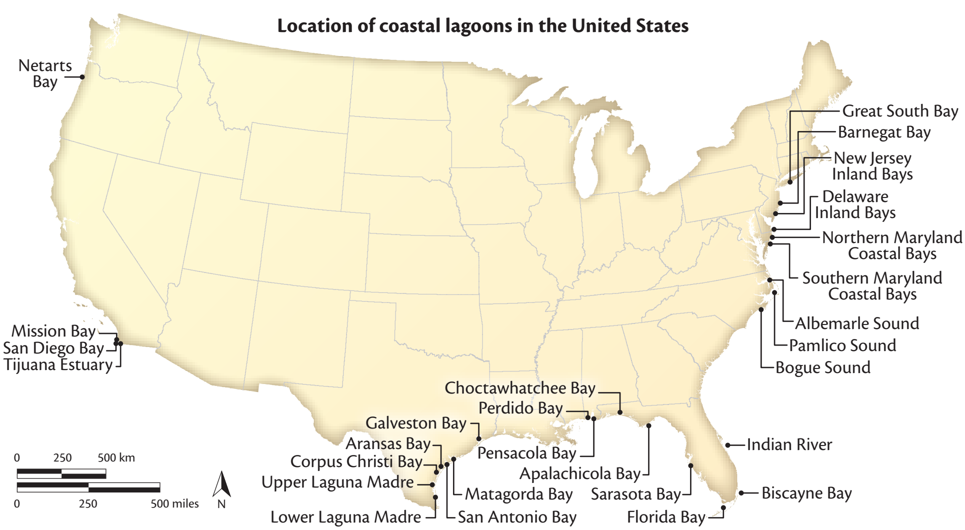
US map of lagoons near here

Different regions have different pressures and susceptibility

Differing climate conditions, freshwater inflow, number of tides per day, and oceanic exchange all contribute to the susceptibility of a system to development of eutrophic conditions. The level of nutrient inputs also influences development of these conditions. As noted, the Gulf of Mexico systems are more vulnerable on account of the warmer climate and longer growing season. Each region has a different combination of physical and hydrologic characteristics that contribute to the susceptibility and different levels and sources of nutrients.

The North Atlantic region has a rocky shoreline and wave-cut cliffs in the north, while to the south there are cobble, gravel, and sand beaches with extensive marshes. There are no lagoons in this region due to the deeper depths (averaging 12.9 m [42.3 ft]) and high tidal range (averaging 2.8 m [9.1 ft]). Although there is low freshwater input, the high tidal action and cooler climate combined with low population makes these systems less susceptible to nutrient-related problems.

The Mid-Atlantic region is characterized by sandy beaches, numerous barrier islands, and extensive salt marshes. Depths are shallower in this region (averaging 4.7 m [15.5 ft]). Tidal flushing (averaging



There are coastal lagoons along all U.S. coastlines—Atlantic, Gulf of Mexico, and Pacific.

0.8 m [2.6 ft]) is dominant in northern systems, while freshwater inflow is more important in the southern part of the region. This is the most densely populated of all regions with an average of 156 people km^{-2} (404 people per mi^{-2}).

conceptual diagrams near here

The South Atlantic region is comprised of extensive barrier island–lagoon–salt marsh systems. Depths are shallow in this region (averaging 3 m [9.8 ft]) and tides are small (averaging 1.2 m [4 ft]). Circulation is dominated by wind and seasonal freshwater inflow in the north, and by freshwater inflow and tides to the south. The warmer climate and low water exchange makes these systems, especially the lagoons, susceptible to development of nutrient-related problems.

The Gulf of Mexico has the most lagoons of any region but also has open bays and tidal marsh–delta complexes. This region has the lowest tidal ranges (averaging 0.4 m [1.3 ft]) and the shallowest depths (averaging 1.9 m [6.2 ft]) of all regions. Freshwater inflow is highly variable with seasonal rains dominant in the western systems. Circulation patterns are mostly wind-driven and coastal waters are warmest of all regions due to the subtropical climate. Long water residence times and high temperatures make these the most susceptible systems among all the regions.

The Pacific coast region is highly variable with rocky shores, sandy beaches, and river outlets, with a few lagoonal systems in the south where population density is highest. Circulation is dominated by seasonal freshwater inflow to the south and freshwater inflow and tides to the north. Water depths (averaging 14.4 m [47.2 ft]) and tidal heights (averaging 1.5 m [4.9 ft]) are highly variable along this coastline. Susceptibility is also variable, with higher susceptibility in the south, due longer residence times, warmer climate, and location of large population centers. For several systems in the north (mostly in Oregon), there are inadequate data to evaluate eutrophic conditions.

The Mid-Atlantic is the most densely populated U.S. region

The lagoons of the Mid-Atlantic are of particular interest because they are located in the most densely populated region of the country and are therefore subject to more intense pressures than lagoons in other regions (Figure 10). The six lagoons in this region are Great South Bay, Barnegat Bay, New Jersey Inland Bays, Delaware Inland Bays, Northern Maryland Coastal Bays, and Southern Maryland Coastal Bays. Residence times vary from 21–100 days (averaging about 50 days), highest tidal height is 1 m (3.3 ft), and all systems are less than 2 m (6.6 ft) deep on average (Figure 9). There are only low level impacts of dissolved oxygen depletion in all of these systems, a result of their characteristically shallow nature that allows for wind mixing. However, some lagoons (e.g., Maryland Coastal Bays) have recently showed signs of oxygen depletion in the late summer, even to the point there crab jubilees have been observed.

table of Mid-Atlantic lagoon

IN CONTEXT

characteristics near here

map of east coast system locations here

Despite the lack of sustained problems with dissolved oxygen, all have moderate to high levels of macroalgae, (*Enteromorpha* and *Ulva*), which are known to smother seagrasses (Dennison et al 1989), can cause low dissolved oxygen events, and may smother bivalves (Bricelj and Lonsdale 1997). In some shallow lagoonal systems, additional nutrients will result in increased macroalgal abundance rather than high concentrations of chlorophyll *a* (Nobre et al. 2005), although in these systems, chlorophyll *a* impacts are also moderate to high in all except New Jersey Inland Bays (Figure 11). Macroalgal impacts in the New Jersey Inland Bays have worsened in the decade since the early 1990s (Figure 11).

A symptom of eutrophication typical of lagoons is occurrence of nuisance and toxic algal blooms (sometimes called harmful algal blooms [HABS]) because of long water residence times. Many HABS are slow-growing and thus may not be able to bloom in systems with shorter residence times. Three of these systems have high level nuisance/toxic bloom impacts—Great South Bay, Barnegat Bay, and Southern Maryland Coastal Bays. However, the other three— New Jersey Inland Bays, Delaware Inland Bays, and Northern Maryland Coastal Bays—are rated as low, meaning that there are nuisance and/or toxic bloom occurrences in all of these lagoons (Figure 11). In Barnegat Bay, nuisance/toxic blooms have been at a high level for more than a decade (Bricker et al., 2007; Kennish et al., 2007). In the Southern Maryland Coastal Bays, data show that these blooms have become worse during the past decade—in the early 1990s (Bricker et al 1999, 2007; Trice et al 2004; Glibert et al 2007) the rating for HABS was 'no problem', meaning that there has been significant worsening of bloom conditions since then in the Southern Maryland Coastal Bays. The worsening is accounted for by the occurrence of the brown tide organism (*Aureococcus anaphagefferens*), which is also seen Great South Bay and Barnegat Bay. In the Southern Maryland Coastal Bays between 1980 and 2000, the increase of these blooms coincided with the doubling of dissolved organic nitrogen inputs, which promotes *Aureococcus* growth more than inorganic forms (Wazniak et al., 2007; Glibert et al., 2007). Annual bloom events have been recorded in Barnegat Bay since 1995, with some recent bloom concentrations reaching 106 cells l^{-1} (Kennish et al., 2007; Olsen and Mahoney, 2001). This brown tide organism

Barnegat Bay

Small tidal height, low tributary inflow, and limited ocean exchange with high nutrient inputs leads to high eutrophic impacts. Chlorophyll *a* concentrations are high with blooms of brown tide and other harmful algal blooms, loss of SAV, and highly reduced fisheries. Conditions are expected to improve.

Scott Haag.

Mid-Atlantic coastal lagoons

Great South Bay

Moderate dilution and low flushing capability lead to high levels of chlorophyll *a* and macroalgae, although dissolved oxygen depletion is not a problem. Some nuisance/toxic and brown tide blooms occur in this system. Overall eutrophic conditions are moderate high and are expected to remain the same.

Suzanne: we need a photo

Delaware Inland Bays

Low freshwater input and small tidal height lead to moderate eutrophic impacts. Severe hypoxia is observed in part of the bay and SAV is limited by excessive macroalgal growth. Chlorophyll *a* concentrations are moderate and some nuisance/toxic blooms occur. Conditions are expected to remain the same.

Suzanne: we need a photo

Southern Maryland Coastal Bays

(Sinepuxent, Newport, and Chincoteague Bays)

Low flushing and dilution capabilities lead to high level eutrophic impacts which have worsened in the past decade. Chlorophyll *a* concentrations are high and nuisance/toxic blooms, especially brown tide, are observed. Dissolved oxygen is not a problem. Conditions are expected to worsen.

Joanna Woerner.

New Jersey Inland Bays

The high susceptibility of these bays is due to moderate dilution and low flushing capability. Chlorophyll *a* concentrations are low but brown tide blooms are a problem. Macroalgae blooms cause significant dieoff of SAV but there are no dissolved oxygen problems. Eutrophic conditions are high and are expected to worsen.

Tracy Kirwan.

IN CONTEXT

Coastal lagoon	Watershed area (km²)	Pop'n (x 1,000)	Lagoon area (km²)	People per km² of lagoon	Avg. depth (m)	Tide height (m)	Avg. salinity (ppt)	Exchange time (days)
Great South Bay (New York)	1,733	2,084	383	5,441	1.10	0.57	16	199
Barnegat Bay (New Jersey)	1,399	402	182	2,211	0.65	0.24	20	29
New Jersey Inland Bays	3,431	330	278	1,188	1.11	1.00	28	27
Delaware Inland Bays	560	27	72	374	1.39	0.53	26	61
MD Coastal Bays	***770***	***21***	***389***	***54***	***1.93***	***0.59***	***29***	***218***
—Northern	*283*	*15*	*54*	*281*	*1.92*	*0.67*	*28*	*253*
—Southern	*487*	*6*	*335*	*17*	*1.94*	*0.50*	*29*	*183*
Albemarle Sound (North Carolina)	45,036	1,275	2,497	510	2.50	0.58	10	140
Pamlico Sound (North Carolina)	26,841	1,378	5,588	247	2.47	0.22	13	378

National Estuarine Eutrophication Assessment database.

Characteristics of the Mid-Atlantic coastal lagoons. Long exchange times in the Maryland Coastal Bays are balanced by some of the lowest population densities (per area of lagoon) of all the lagoons. ***Suzanne:*** should we remove the NC lagoons to be consistent with the Mid-Atlantic?

has also been observed in Great South Bay.

Eutrophication symptoms have recently worsened in the Maryland Coastal Bays

Like many lagoons, these systems have very little freshwater inflow and limited connection with the ocean and thus have long water residence times which contributes to their sensitivity to nutrient inputs. However, the long residence times are balanced by their watersheds and population densities, which are relatively small by comparison to other Mid-Atlantic lagoons (See Table XX).

The ASSETS screening model was applied to both the Northern and Southern Maryland Coastal Bays using the most recent available data, including water quality data collected monthly (by Maryland Department of Natural Resources and Assateague Island National Seashore water quality monitoring program) at 60 lagoon sites (26 in the Northern Bays and 34 in the Southern Bays) during 2004, as well as data concerning the spatial distribution of macroalgae in 2003 (McGinty et al. 2002) and seagrasses in 2004 (Wazniak et al. 2004b). Physical and hydrologic data from Coastal Assessment and Data Synthesis (CADS; *cads.nos.noaa.gov*) and the USGS SPARROW (Spatially Referenced Regressions on Watershed Attributes) model (Smith et al., 1997) were used, as well as land use and loading data (for 1997) from Maryland Department of the Environment (2002).

Application of the modified Influencing Factor model for determination of the magnitude of load (Bricker et al., 2003; Ferreira et al., 2007b), which includes a conservative re-entrainment estimate of 50% was used in combination with the susceptibility to determine the overall Influencing Factor rating. In both systems, the most important agricultural use is animal feeding operations which are the largest contributors of nitrogen and phosphorus to these systems (Boynton et al., 1996). Since summertime watershed population is orders of magnitude (~40 times) higher than in winter, there is a significant seasonal difference in input, with higher inputs during the growing season when the waterbody is most susceptible.

Overall Eutrophic Conditions were determined from primary (chlorophyll *a* and macroalgae) and secondary (loss of seagrass, dissolved oxygen, and occurrence of HABs) symptoms. The expected response, or Future Outlook, of the Coastal Bays was examined by considering future changes in watershed population growth, potential management measures that will be implemented, and other land use changes which will influence nutrient loads to these systems.

The watershed population of Maryland and Virginia coastal counties is cted to increase by 17% by 2020 (reference?), which will increase nutrient pressures to these systems. There are also plans for nutrient management measures such as implementation of waste load allocations through the Total Maximum Daily Load process (USEPA, 1991) and required implementation of nutrient management plans for all agricultural lands through Maryland which should result in decreased loads. The limitation of nutrient loads from agricultural uses will be especially important given their significant contribution to the total load. One problem that has yet to be formally addressed is the discharge of nutrients through septic systems.

Results of the assessment for the Northern and Southern Maryland Coastal Bays are described below.

Figures 7 for MD Inland Bays near here.

Northern Maryland Coastal Bays (Assawoman and Isle of Wight Bays and St. Martin River)

Land use in the Northern Coastal Bays watershed is about 40% developed, 33% mixed agriculture, with the remainder in forest ar etlands (Boynton et al., 1996) ***Suzanne:*** data from MD Dept Planning says wetlands 6.5%, developed 25%, forest 33%, agriculture 32%. A total nitrogen load of 528 metric tonnes yr^{-1} (Boynton et al 1996) was calculated. Boynton et al 1995 & Boynton et al in press: Isle of Wight Bay 2.6 g N m^{-2} yr^{-1}; St. Martin River 39.7 g N m^{-2} yr^{-1}.

The modified Influencing Factor model gives a result of 92% for the Northern Maryland Coastal Bays, which falls within the *High* category, meaning that this system is highly impacted by land-based, human-related nutrient loads. The combination of *High* loading and *High* susceptibility means this system is *Highly*

Northern and Southern Maryland Coastal Bays

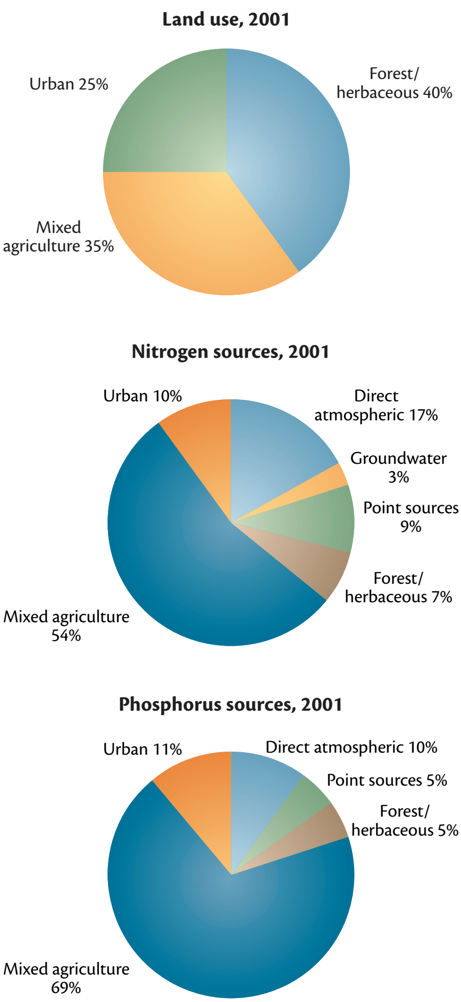
Location of the Northern and Southern Maryland Coastal Bays and watersheds.

influenced.

Primary symptoms in the Northern Maryland Coastal Bays indicate eutrophication impacts with hyper-eutrophic chlorophyll levels and some areas with harmful levels of macroalgae. Chlorophyll *a* was *High* (90th percentile value was 91.95 µg l^{-1} in the mixed zone and 22.8 µg l^{-1} in the seawater zone), and macroalgal biomass was *Moderate*, resulting in *Moderate* primary symptom expression. *Low* dissolved oxygen problems (10th percentile value was 3.5 mg l^{-1} in the mixed zone and 4.8 mg l^{-1} in the seawater zone), seagrass loss, and nuisance/toxic blooms resulted in *Low* secondary symptom expression. However, there have been recent indications of more serious dissolved oxygen problems, with dissolved oxygen less than 5 mg l^{-1} 27–66% of the time at selected sites. There are no problems with seagrass loss—seagrass actually increased in spatial coverage from the early 1990s until analysis was completed in 2004 (Orth 2002, MDNR, 2007). Recent large-scale losses in 2005 may be related to episodic temperature fluctuations, rather than to nutrients. For more information on seagrasses in the Coastal Bays, see Chapter 14—*Habitats of the Coastal Bays and Watershed*.

Although several species of harmful and toxic blooms are known to occur in the Northern Maryland Coastal Bays, including the potentially toxic organisms *Prorocentrum minimum*, *Chattonella cf. verruculosa*, and the toxic *Pfiesteria piscicida*, there is no evidence of toxic episodes in the Maryland Coastal Bays (Tango et al 2004). A nuisance species that has increased in abundance since first appearing in this system in 1999 is brown tide, which bloomed at low levels in the Northern Maryland Coastal Bays during 2004 as a result of decreased rainfall during that year. *High* primary symptom expression and *Low* secondary symptom expression resulted in *Moderate* overall eutrophic condition for the Northern Maryland Coastal Bays, and the rating has not changed since the early 1990s (Bricker et al., 1999).

A *Large deterioration* of conditions is expected in the future as population in the watershed continues to increase. This rating was determined by considering future changes in watershed, population growth, potential management measures that will be implemented, and other land use changes which will influence nutrient loads to these systems. Despite plans for nutrient reductions, nutrient loads will likely increase.



Land use (top), nitrogen sources (middle), and phosphorus sources (bottom) in the Northern Maryland Coastal Bays. MDE 2001

Figure 7a summarizes the results obtained in the ASSETS application to the Northern Maryland Coastal Bays . This system was given an overall classification of *Poor* which reflects a range of undesirable pressure and state conditions with the recognition that future pressure increases and worsening conditions are expected.

The overall ASSETS rating for the Northern Maryland Coastal Bays is *Poor*, based on the *Highly influenced* system, *Moderate* overall eutrophic condition, and the *Large deterioration* expected in the future.

Southern Maryland Coastal Bays (Sinepuxent, Newport, and Chincoteague Bays)

The Southern Maryland Coastal Bays watershed is about one-third developed and one-third forested, with the remainder almost equally split between wetlands and agriculture (Boynton et al., 1996). ***Suzanne:*** MD Dept Planning says developed 7% wetlands 19%, agriculture 32%, forest 40%. The most important agricultural use is animal feeding operations which are the largest contributors of nitrogen and phosphorus to these systems (Boynton et al., 1996). A total nitrogen load of 908 metric tonnes yr^{-1} (Boynton et al 1996) was calculated.

Boynton et al 1995 & Boynton et al in press: Sinepuxent Bay 1.8 g N m^{-2} yr^{-1}; Chincoteague Bay 3.2 g N m^{-2} yr^{-1}. Newport Bay 17.5 g N m^{-2} yr^{-1}

The modified Influencing Factor model gives a result of 100% for the Southern Maryland Coastal Bays, meaning that this system is highly impacted by land-based human related nutrient loads. The combination of *High* loading and *High* susceptibility means this system is *Highly influenced*.

Primary conditions in the Southern Maryland Coastal Bays are similar to those in the Northern Bays with *High* chlorophyll *a* (90th percentile is 33 µg l^{-1}) and *Moderate* macroalgal abundances, resulting in *High* primary symptom expression. There were *Low* dissolved oxygen problems (10th percentile value was 5.2 mg l^{-1}) and seagrass coverage increased (MD DNR 2004, 2007). However, there are *High* nuisance/toxic blooms—intense annual blooms of brown tide at category 3 levels (i.e., > 200,000 cells l^{-1}), which are known to cause serious impacts on mussels, scallops, hard clams, seagrasses, and copepods (Wazniak et al 2004a; Gastrich and Wazniak, 2002).

High primary symptom expression and *High* secondary symptom expression resulted in *High* overall eutrophic condition for the Southern Maryland Coastal Bays, indicating significant eutrophication problems. In this system, conditions are known to have worsened since the early 1990s when the overall eutrophic condition was *Moderate low* (Bricker et al., 1999), because of increasing frequency of brown tide events and high chlorophyll *a* (Wazniak et al. 2007). Despite plans for nutrient reductions, nutrient loads will likely increase, resulting in a *Small deterioration* of conditions in the Southern Maryland Coastal Bays, but

Joanna Woerner & Jane Thomas.

The Northern Maryland Coastal Bays are influenced by large developed areas, including Ocean City and Fenwick Island (left), while the Southern Maryland Coastal Bays benefit from the Assateague Island National Seashore (right).


Jane Thomas.

The Ocean City Inlet forms the boundary between the Northern and Southern Maryland Coastal Bays.

not to the degree of the Northern Bays.

Figure 7b summarizes the results obtained in the ASSETS application to the Southern Maryland Coastal Bays. This system was given overall classification of *Bad* which both reflect a range of undesirable pressure and state conditions, with the recognition that future pressure increases, and worsening conditions, are expected.

The overall ASSETS rating for the Southern Maryland Coastal Bays is *Bad*, based on the *Highly influenced* system, *High* overall eutrophic condition, and the *Small deterioration* expected in the future.

For the summary of the case studies, see the table at the end of this chapter.

EUTROPHICATION AND COASTAL LAGOONS

Nutrient loads are greatest during the most vulnerable season

The main sources of nutrients to coastal lagoons are wastewater inputs from septic tanks and combined sewer overflow, urban development and runoff, farming, tourist activities, and atmospheric deposition. One of the main features of lagoonal systems is their attraction as summertime vacation destinations, leading to extreme seasonal changes in population. The population of Ocean City, Maryland in the Northern Maryland Coastal Bays watershed increases to almost 40 times the resident population during the summer months (around 7,000 year-round residents compared with the average summer population of around 264,000; Ocean City 2006). While this is a city population, the watershed population typically increases by a factor of nearly 10, which puts intense nutrient pressures on these fragile systems at the most vulnerable time of the year—when temperatures are high and wind mixing is typically at a minimum.

Of great concern is the increase in nutrient inputs that is expected to continue as coastal populations increase. The U.S. coastal population increased by 27% between 1980 and 2003 and is expected to increase an additional 12% by 2020 (K. Crossett, pers. comm.). But in some lagoonal watersheds, past and future increases may be even greater. For example, the Barnegat Bay watershed population increased by 43% from 1980 to 2000 (Kennish et al., 2007), and the Maryland coastal population is expected

Lagoon	*Susceptibility* +	*Loads* =	Influencing factors	*Primary symptom expression* +	*Secondary symptom expression* =	Overall eutrophic condition +	Future outlook =	ASSETS RATING	
Ria Formosa	Yellow	Yellow	Yellow	[illegible]	Dark green	Yellow	Light green	Yellow	
Lagoon of Venice	Yellow	Yellow	Yellow	Dark green	Dark green	Dark green	Light green	Light green	
Upper Laguna Madre	Red	Red	Red	Yellow	Yellow	Yellow	Yellow	Brown	????
Celestún	Red	Dark green	Yellow	Yellow	Dark green	Light green	Yellow	Light green	
Chelem	Red	Dark green	Yellow	Yellow	Yellow	Yellow	Red	Orange	
Nichupté–Bojórquez	Red	Dark green	Yellow	Red	Yellow	Orange	Red	Orange	
Bahía de la Ascensión	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Yellow	Dark green	
Northern MD Coastal Bays	Red	Red	Red	Red	Dark green	Yellow	Red	Orange	
Southern MD Coastal Bays	Red	Red	Red	Red	Red	Red	Orange	Red	

Influencing factors, susceptibility, & loads

- Red: High
- Yellow: Moderate
- Dark green: Low

Primary & secondary symptom expression

- Red: High
- Yellow: Moderate
- Dark green: Low

Overall eutrophic condition

- Red: High
- Orange: Moderate high
- Yellow: Moderate
- Light green: Moderate low
- Dark green: Low

Future outlook

- Red: Large deterioration
- Orange: Small deterioration
- Yellow: No change
- Light green: Small improvement
- Dark green: Large improvement

ASSETS rating

- Red: Bad
- Orange: Poor
- Yellow: Moderate
- Light green: Good
- Dark green: High

This table summarizes the influencing factors, overall eutrophic condition, future outlook, and ASSETS rating for the coastal lagoon case studies discussed in this chapter.

IN CONTEXT

to increase by 17% by 2020. In addition to increases in total nutrient input, changes in the specific form of nutrients being delivered to water bodies is also of concern. Increasing occurrences of brown tide in the Maryland Coastal Bays have been related to the increase in dissolved organic nitrogen, rather than inorganic nitrogen (Glibert et al., 2007, 2001), highlighting a need to focus on the component sources of nutrient inputs as well as the quantity of inputs.

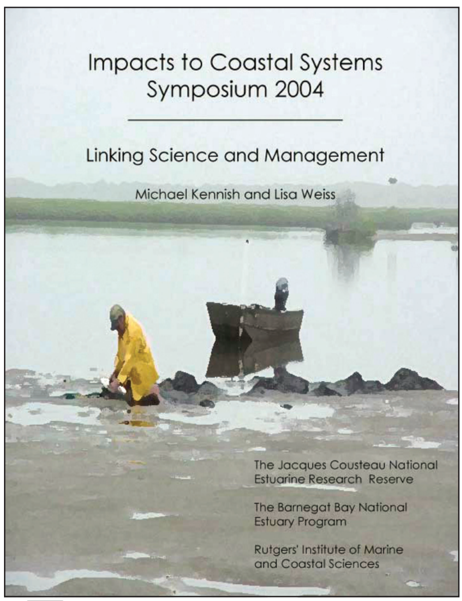
Physical characteristics and seasonal population promote eutrophication

The physical characteristics of lagoonal systems, low freshwater inflow, shallow depth, restricted tidal exchange, and large summertime populations combine to make these systems vulnerable to development of eutrophic problems. Typical problems observed in lagoons everywhere are high levels of chlorophyll *a*, occurrences of nuisance and toxic algal blooms, and high macroalgae biomass. They usually do not have significant problems with depletion of dissolved oxygen. The high levels of chlorophyll *a* and macroalgae cause losses of seagrasses which are habitat for fish, crabs, and other recreationally and commercially sought species. For example, in Barnegat Bay, long-term occurrences of brown tide has caused declines in hard clams (*Mercenaria mercenaria*) and submerged aquatic vegetation (*Zostera marina* and *Ruppia maritima*; Kennish et al., 2007). State surveys showed a 67% decline of hard clam stock levels from 1985 to 2001, and a 62% loss of seagrass beds between the mid-1970s and 1999 (Kennish et al., 2007). Progressive eutrophication impacts alter the ecosystem structure and function with negative effects on biotic communities, essential habitat, and recreational and commercial fisheries, which lead to losses of human uses of these lagoonal systems.

Protective management action is needed for coastal lagoons

A management strategy has been proposed for Barnegat Bay which could be used as a model for application to other lagoonal systems. The plan includes the implementation of four major measures: 1) low impact (smart development and best management practices [BMPS] in the watershed); 2) upgrade of storm water controls; 3) open space preservation; and 4) total maximum daily loads (TMDLS) for nutrient limitation in the estuary (Kennish et al., 2007). For more information about BMPS and TMDLS, see Chapter 2—*Management of the Coastal Bays and Watershed.*

The use of BMPS in the Barnegat Bay watershed is critical to the long-term improvement of water quality and habitat conditions within the bay, because



Cover of the proceedings from the *Impacts to Coastal Systems Symposium 2004: Linking science and management*. ***Suzanne:*** The symposium is not mentioned in the text.

urban runoff is one of the major sources of nitrogen—as it is for other lagoons. Implementation of management measures is important given the high level of detrimental impacts on this system, but management of this and other lagoons will become more difficult in the future, given expected population increases that will tax the existing infrastructure.

In addition to traditional measures to stop watershed-based inputs from reaching lagoon waters, complementary measures from within lagoonal waters should also be pursued. The Barnegat Bay Shellfish Restoration Program raises seed clams to repopulate the Barnegat Bay clam population (*www.reclamthebay.org*), which, by the early 2000s, had decreased to numbers low enough that a commercial fishery was not supportable. Clams filter estuarine waters and improve water quality which has proven to be a beneficial side benefit of aquaculture (Ferreira et al., 2007a) and has led to surprisingly low impacts in systems of heavy use such as Jiaozhou Bay, China (Xiao et al., 2007). Alternative management measures such as these should be encouraged to complement more traditional management measures for maximum nutrient impact reduction.

Studies of coastal lagoons and monitoring results show that this type of system is fragile and susceptibile to development of nutrient-related problems. Even small inputs of nutrients can cause significant impacts, including excessive algal biomass and losses of fisheries because of the long residence times of water. Because of their potential for highly productive fisheries and their use as vacation destinations, coastal lagoons should be protected by appropriate management measures. These should include traditional measures such as best management practices and sewage treatment to prevent nutrients from entering the waterbodies from the watershed, but complementary methods, such as aquaculture or re-establishment of native filter-feeding populations, should also be pursued to ensure the protection of these waterbodies for future generations.

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Suzan ny people to put here?

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