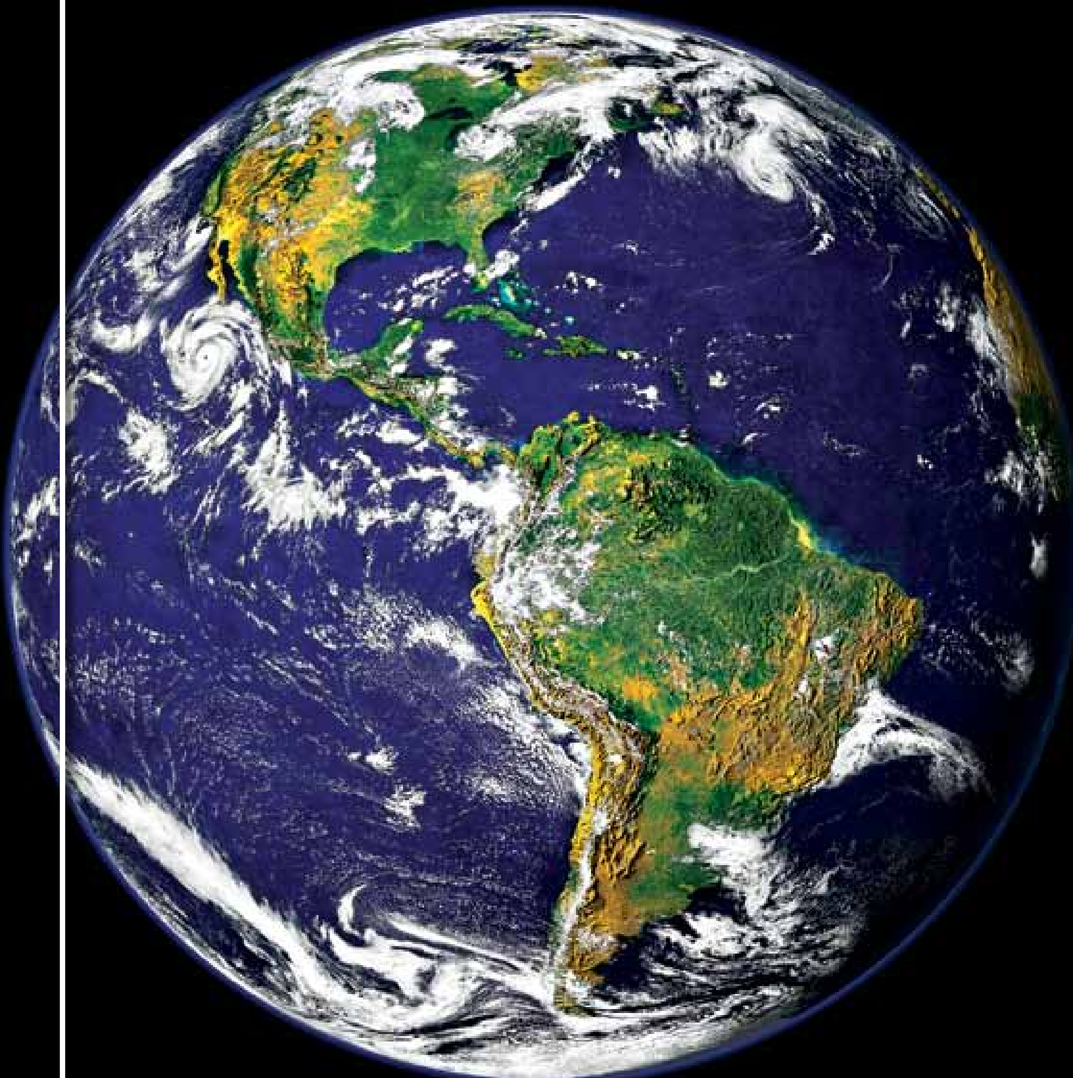
11. The Coastal Bays in Context



Suzanne B. Bricker,

William C. Dennison, Kenneth H. Dunton, João G. Ferreira, Matthew R. Hall, Jorge A. Herrera-Silveira, Ben J. Longstaff, Sara Morales-Ojeda, Christopher P. Onuf, Roberto Pastres, Jane E. Thomas, & Catherine E. Wazniak

COASTAL LAGOONS

Coastal lagoons are unique coastal features

Coastal lagoons are a significant feature of coastlines throughout the world, making up 13% of the world's coastline.[37] Lagoons are generally shallow—the depth of U.S. lagoons averages 1.6 m (5.2 ft). Lagoons are coastal waterbodies that are oriented parallel to the coast and separated from the ocean by a strip of low land such as a barrier island or sand spit. They usually have low freshwater inflow and, in most U.S. lagoons, tidal range is small, averaging 0.5 m (1.6 ft). The shallow nature of coastal lagoons means that water is generally well-mixed vertically by winds in comparison to other types of coastal waterbodies.

The area of water in coastal lagoons is generally small when compared to drowned river-valley estuaries, such as Chesapeake Bay, and the ratio of watershed area to lagoon area is small (median of 11), about half the average ratio of other types of estuaries (median of 28).[5] The small volume of water in coastal lagoons limits dilution, so they are particularly sensitive to any increase of nutrient inputs and tend to accumulate nutrients.

Most lagoons have relatively low freshwater inflow and exchange with the ocean is limited, occurring through only one or a few narrow inlets. This 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, in these settings, stabilization or permanent opening of inlets may actually decrease average salinity. For more information on inlets and barrier islands, see Chapter 12—*Dynamic Systems at the Land–Sea Interface*.

Coastal waterways may be classified according to the forces that shaped them during their evolution—river flow, wave

JANE THOMAS

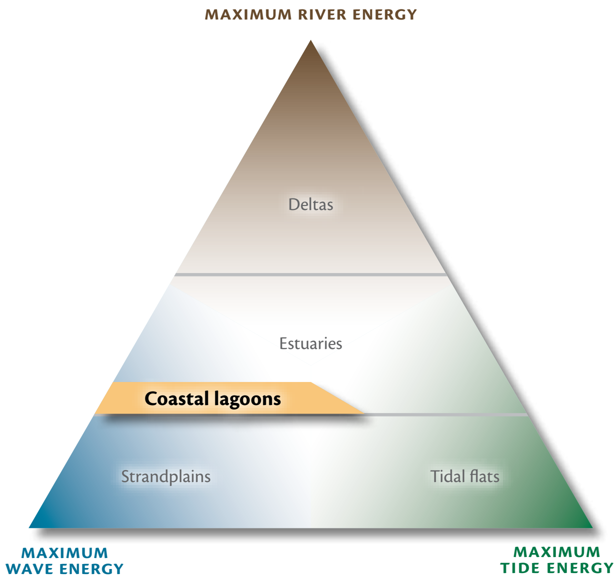
Coastal lagoons, such as the Maryland Coastal Bays, usually occur behind narrow barrier islands and are connected to the ocean through tidal inlets.

action, and tidal movement.[48] Coastal lagoons occur most commonly in wave-dominated systems, as they usually have minimal river input and are typically microtidal.

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. Benthic microalgae and macroalgae can be important in lagoons where shallow waters allow light to penetrate to the bottom. Seagrass meadows, a typical benthic habitat within coastal lagoons—along with macroalgae and benthic microalgae—dominate primary production in lagoons. Retention of nutrients in the biomass of benthic primary producers during the growing season produces relatively high apparent water quality even when nutrient loading rates are high.[33] The predominance of benthic productivity makes lagoons very susceptible to eutrophication, when bloom-forming algae become prevalent, increasing turbidity and reducing light penetration which causes losses of benthic producers and release of nutrients into the water column. Long residence times and localized nutrient inputs in many lagoons provide opportunities for phytoplankton and slower-growing harmful algae species to bloom.[17]

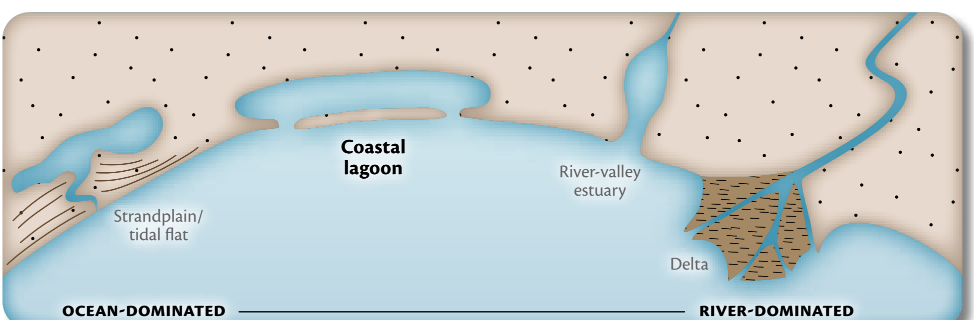
Lagoons are often fringed by wetlands such as salt marsh (temperate lagoons) or mangroves (tropical lagoons), which serve as habitat for a

Classification of estuaries & coastal waterways



Estuaries and coastal waterways can be classified according to the relative influence of rivers, waves, and tides.[48]

Types of coastal waterways



There is a continuum of coastal waterways, from strandplains/tidal flats and lagoons to estuaries and deltas[11,12] variety of organisms including wading birds, finfish, and shellfish. Living resources found in coastal lagoons include many filter feeders (oysters, clams, scallops, and mussels), finfish, and migratory birds. When intact, lagoons are highly productive. Some unpolluted lagoons yield greater numbers of fish per unit area than well-known fishing grounds such as the Peruvian upwelling.[37]

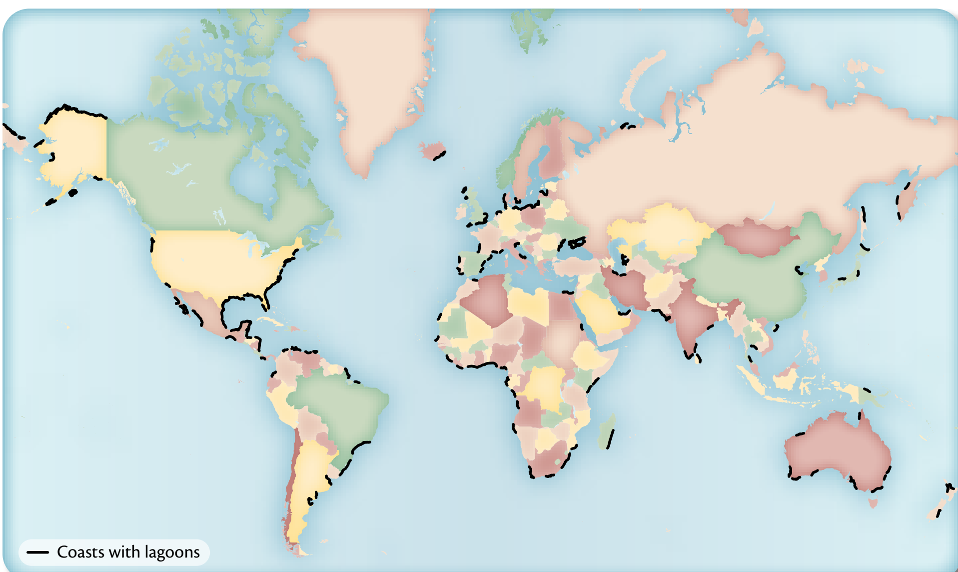
Sediments found in coastal lagoons are often muddier toward the mainland and sandier on the seaward side behind the barrier island or sand spit. For more information, see Chapter 13—*Water Quality Responses to Nutrients*, Chapter 14—*Diversity of Life in the Coastal Bays*, and Chapter 15—*Habitats of the Coastal Bays & Watershed*.

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

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

The dynamic nature of inlets and barrier islands and increasing coastal development often result in inlets being stabilized by structures such as jetties to prevent closure or migration. Stabilization of inlets changes circulation patterns and may impact the lagoon salinity regime. Lagoons are typically not well flushed because of restricted exchange with the ocean through inlets that are sometimes only open seasonally. Increasing the tidal exchange by stabilizing inlets can decrease residence time and thus decrease susceptibility to some types of algal blooms and other water quality problems. However, development on barrier islands may limit the formation of new inlets, maintaining

Global distribution of coastal lagoons



Coastal lagoons occur on all continents except Antarctica.[36]

the long residence times. Developed barrier islands often require sand replenishment to prevent their natural landward migration and to compensate for increased downdrift 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 global warming may intensify natural processes such as inlet formation, island overwash, and storm surges. In addition, lagoons are typically more highly influenced by wave mixing and meterological events than by tides. Sea level rise will also affect coastal lagoon watersheds because of their typically low elevations.

Globally, barrier island–lagoon systems make up 13% of the ocean's coastline. They occur on all continents except Antarctica (see map on facing page).

Although lagoons are sensitive ecosystems, they are increasingly impacted by development and human activities. Most lagoons have sandy beaches on the ocean side which attract heavy usage in summer. In many countries, lagoons are used for aquaculture because they have naturally high productivity. Lagoons provide picturesque locations and their watersheds 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 many coastal lagoons have gone from highly productive fishing grounds and recreation areas to polluted ponds that no longer produce fish or shellfish. Because of this trend, there is a movement worldwide to develop management plans that will balance desired uses with the preservation and conservation of these sensitive ecosystems.

Eutrophication is a key threat

Eutrophication is a natural process in which nutrients such as nitrogen and phosphorus from the watershed, ocean, and atmosphere enter coastal waterbodies. Nutrients are essential for algal growth—which supports fisheries—but they become a problem when there is an oversupply that causes excessive growth of algae. The main sources of nutrients to coastal lagoons are wastewater inputs from septic tanks and combined sewer overflow, urban or suburban development and runoff, farming, tourist activities, and atmospheric deposition. One of the main features of lagoonal systems is their attraction as summer vacation destinations, leading to extreme seasonal changes in population. The population of Ocean City, Maryland in the northern 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.[39] The increase in watershed population puts intense nutrient pressures on these sensitive ecosystems 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

What is eutrophication?

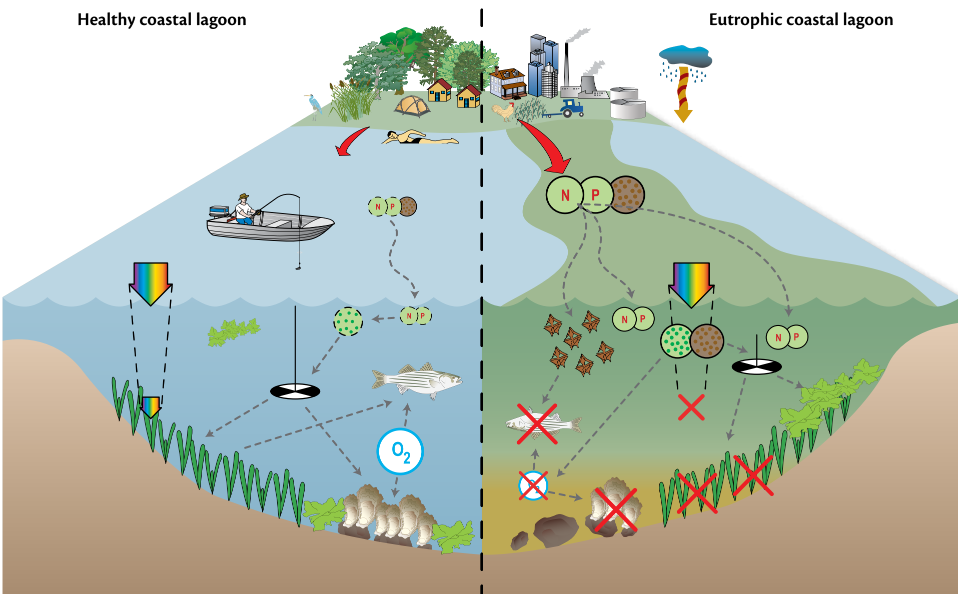
Eutrophication is the process by which the addition of nutrients (largely nitrogen and phosphorus) to waterbodies stimulates algal growth. Excessive nutrient inputs may lead to other serious problems such as low dissolved oxygen and loss of seagrasses.

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

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.[56] But in some lagoonal watersheds, past and future population increases may be even greater. For example, in the Barnegat Bay–Little Egg Harbor Estuary watershed in New Jersey, the population increased by 43% from 1980 to 2000,[25] and the coastal population in Maryland is expected to increase by 17% by 2020.

In addition to increases in total nutrient inputs, changes in the specific form of nutrients being delivered to waterbodies 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,[22,23] highlighting a need to focus on the component sources of nutrient inputs as well as the quantity of inputs. (Brown tide [*Aureococcus*

Healthy & eutrophic coastal lagoons



In healthy ecosystems, nutrient inputs—specifically nitrogen and phosphorus —occur at a rate that stimulates macroalgal and phytoplankton growth in balance with grazer biota. A low level of phytoplankton 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 suitable for healthy fish and shellfish , so that humans can enjoy the benefits that a healthy coastal environment provides.

In a eutrophic ecosystem, increased sediment and nutrient loads from farming , urban and suburban development , wastewater treatment plants , and industry , in combination with atmospheric nitrogen , help trigger both macroalgae and phytoplankton 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 , increased nuisance/toxic algal blooms , and contamination or die-off of fish and shellfish .

anophagefferens] is a bloom-forming alga which can clog the feeding siphons of filter feeders such as clams, causing death.)

The physical characteristics of lagoonal ecosystems—low freshwater inflow, shallow depth, restricted tidal exchange, and large summer populations—combine to make these systems vulnerable to eutrophication. Typical problems observed in lagoons everywhere are high levels of chlorophyll *a* (an indicator of phytoplankton), occurrences of nuisance and toxic algal blooms, and high biomass of macroalgae (i.e., seaweed).

Lagoons usually do not have significant problems with depletion of dissolved oxygen because of wind mixing of the shallow water; however, they may experience diel oxygen cycles, where oxygen levels drop to hypoxic levels in the hours before sunrise.[1] The high levels of phytoplankton and macroalgae cause losses of seagrasses which are habitat for fish, crabs, and other commercially and recreationally harvested species.

For example, in Barnegat Bay–Little Egg Harbor Estuary, long-term annual occurrences of brown tide appear to have caused declines in hard clams (*Mercenaria mercenaria*) and seagrasses (eelgrass [*Zostera marina*] and widgeon grass [*Ruppia maritima*]).[25] Surveys showed a 67% decline of hard clams from 1985 to 2001, and a 62% loss of seagrass beds between the mid-1970s and 1999.[25] The loss of seagrass is particularly problematic since they dominate primary productivity and temporarily retain nutrients during the summer period, providing good water quality despite high nutrient inputs.[33] Progressive eutrophication impacts ecosystem structure and function with shifts from benthic to pelagic productivity causing negative effects on biotic communities, essential habitat, and recreational and commercial fisheries, which lead to reduced value of these lagoons.

In addition to traditional measures to stop watershed-based inputs from reaching lagoon waters, complementary measures from within lagoonal waters can be pursued. A recent review suggests that filter feeders, through aquaculture projects or restoration of native shellfish beds, can be a cost-effective complementary addition to coastal management strategies. The review showed that bivalve harvesting removes nutrients from coastal systems and that deposition of organic particles (i.e., feces, pseudofeces) into sediments also contributes to nitrogen removal.[44] This result is demonstrated by the low level of eutrophication impacts observed in the heavily populated, high-use Jiaozhou Bay lagoon in China. The low levels of eutrophication impacts are accounted for by the intensive aquaculture activity within the system.[57]

Additionally, mussel farming is currently promoted in Sweden as a solution to address coastal eutrophication, recognizing that reduction of phytoplankton biomass by bivalves reduces the risks of anoxic conditions in waterways that can occur when plankton blooms, triggered by excessive nutrient loading into coastal waters, die off and increase biological oxygen demand.[28]

JOANA DILAO

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

Summer brown tide bloom at Public Landing in Chincoteague Bay.

Further evidence of the benefit of aquaculture is shown in a model designed to balance aquaculture yield and profitability while minimizing nutrient-related environmental damage. The results show that farmers can potentially derive significant extra income through emissions trading since shellfish farms are nutrient sinks.[18]

One example of an effort to use this concept to improve coastal water quality is the Barnegat Bay Shellfish Restoration Program which raises seed clams to restock the system's clam population and raise awareness of the water quality benefits of filter-feeding populations (*www.reclamthebay.org*). Shellfish restoration or aquaculture projects may have greater benefit in smaller coastal waterbodies such as lagoonal systems, since a greater percentage of incoming nutrients can be removed in comparison to larger systems.[44]

Monitoring results and studies of coastal lagoons indicate that they are susceptible to nutrient-related problems. Even small inputs of nutrients can cause significant impacts, including excessive algal biomass and loss 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 afforded the best available management. This includes best management practices and sewage treatment to prevent nutrients from entering the waterbodies from the watershed, as well as complementary methods, such as aquaculture or re-establishment of native filter-feeding populations.

Eutrophication of coastal lagoons is evident at regional, national, & international scales

A recent analysis shows that eutrophication is a problem in estuaries and coastal waters in the U.S. and globally, with lagoons everywhere showing eutrophication impacts. The National Estuarine Eutrophication Assessment (NEEA) evaluated overall eutrophic condition of selected coastal systems throughout the U.S., Europe, Australia, and China using the NEEA/ASSETS (Assessment of Estuarine Trophic Status) method.[3,4,5,19] Each of the component ratings is determined using a matrix approach.

Overall eutrophic condition (OEC) is a combined assessment of five symptoms based on occurrence, spatial coverage, and frequency of problem occurrences. The rating is determined from a combination of the average scores for chlorophyll and macroalgae—primary symptoms indicating the start of eutrophication—and the worst score of the three more serious secondary symptoms (dissolved oxygen, seagrass loss, and nuisance/toxic algal blooms).

The 2007 NEEA study shows that more than half of all coastal ecosystems in the U.S. have moderate to high eutrophication (65%) but that proportionally more coastal lagoons in the U.S. are highly impacted (75%; see overall eutrophic condition results later in this chapter). Case studies highlight the similar impacts that are observed in lagoons elsewhere, such as

Primary symptoms	**Description**
Chlorophyll *a* (phytoplankton)	Chlorophyll *a* is a measure of the amount of phytoplankton (microscopic algae) growing in a waterbody. High concentrations can lead to low dissolved oxygen levels as a result of decomposition.
Macroalgal blooms	Macroalgae are large benthic algae commonly referred to as seaweed. Blooms can cause loss of submerged aquatic vegetation (seagrass) 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 symptom of eutrophication because it results from the decomposition of organic matter (from dense algal blooms). Dead algae sink to the bottom and bacterial decomposition of those cells consumes oxygen. Low dissolved oxygen can cause fish kills, habitat loss, and degraded aesthetic quality, resulting in the loss of tourism and recreational water use.
Seagrass loss	Loss of seagrass occurs when dense phytoplankton blooms caused by excess nutrient additions (and absence of grazers) decrease water clarity and light penetration. These phytoplankton may occur in the water column, or can grow directly on the seagrass blades, also blocking light. Turbidity caused by other factors (e.g., sediments resuspended by wave energy) similarly affects seagrass. The loss of seagrass can have negative effects on an estuary's function and may impact fisheries due to loss of 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. *Nuisance blooms* involve algal growth that is so rapid or extensive that it influences water clarity, decreases oxygen levels (upon decomposition), clogs filter-feeder siphons, and crowds out other organisms. *Toxic blooms* involve large growths of toxin-producing algae that directly impact the health of organisms and may also contain toxins dangerous to humans. Many nuisance/toxic blooms occur naturally—some are circulated into estuaries from the ocean, where they may be maintained by land-based sources of nutrients.

Eutrophication symptoms included in the NEEA assessment.[5]

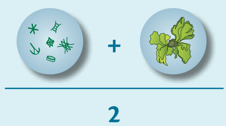
in the Lagoon of Venice, Italy, where eutrophic conditions were severe in the 1970s but have improved as a result of management measures since then. The case studies illustrate the various impacts of eutrophication and share information about successful management efforts that reduced observed problems.

A desktop application of the method was developed recently as part of the SPEAR project (Sustainable Options for People, Catchment, and Aquatic Resources; *www.biaoqiang.org*).[20] It is now available for download in English, Chinese, Portuguese, and Spanish from *www.eutro.org/register*.

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:

A.



= **Estuary-wide primary symptom value**

B.

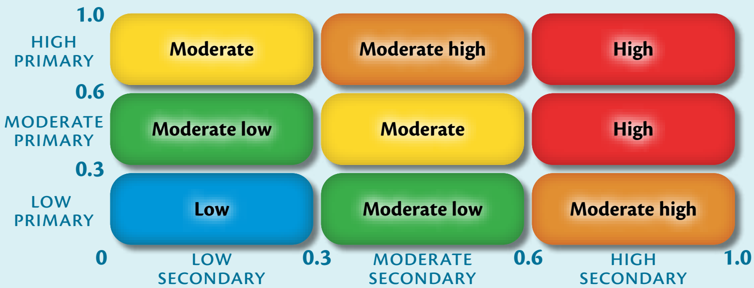
= **Estuary-wide secondary symptom value**

(Highest value is selected)

Estuary-wide symptom rating is determined:

Symptom expression value	Symptom rating
0.0–0.3	Low
0.3–0.6	Medium
0.6–1.0	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.[3]



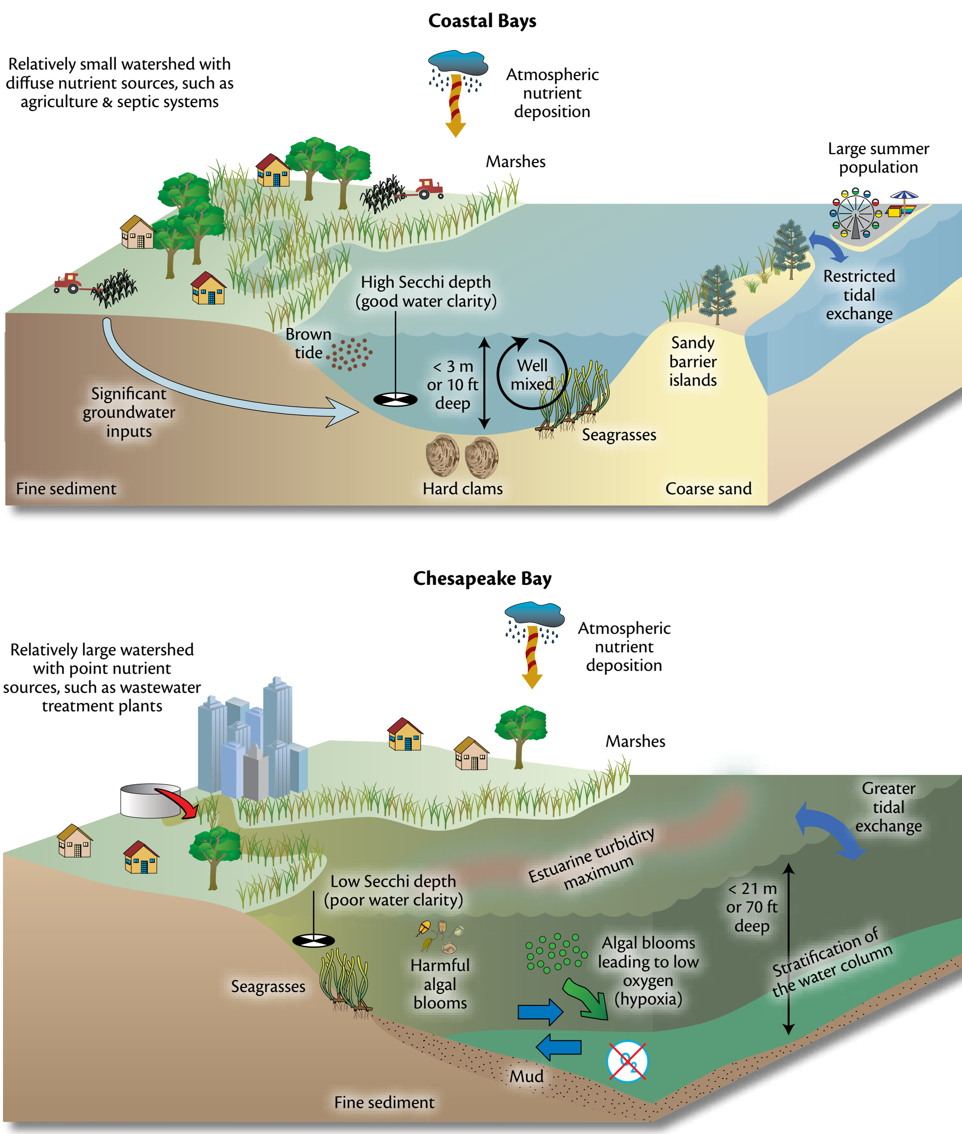
COASTAL LAGOONS IN THE UNITED STATES

Drowned river valleys are different from coastal lagoons

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

Wind blowing across shallow coastal lagoons results in strong mixing of the water column, meaning oxygen levels usually remain high in open areas except during calm days in late summer. Dissolved oxygen is typically not a problem in lagoons due to the well-mixed water column, but many lagoons have problems with algal blooms (macroalgae, microalgae, and harmful algal blooms [HABs]), which can locally deplete oxygen.

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, heavy nutrient load, and a large opening to the ocean which promotes greater tidal exchange in the lower bay. These features provide the potential for water-column stratification



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

(layers of water of different salinity or temperature) that can lead to low oxygen levels, particularly with high nutrient levels.

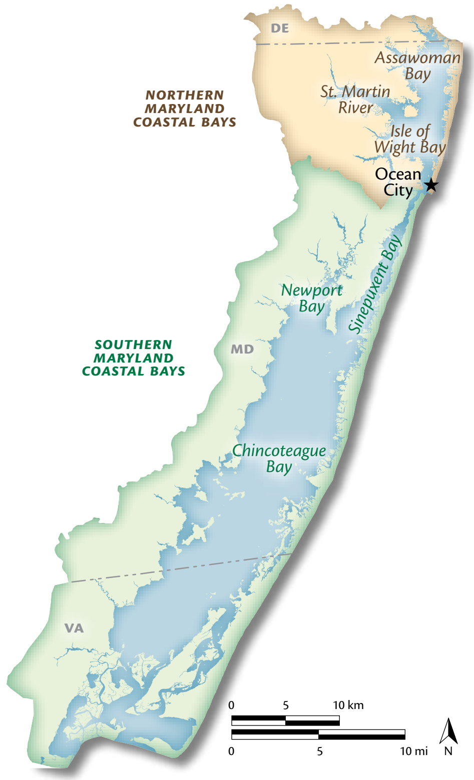
The Chesapeake Bay watershed includes large population centers, such as Baltimore and Washington, D.C., with notable point-source sewage discharges. The population is less variable seasonally; however, population density is greater—Chesapeake Bay has 83 people km^{-2} (215 people mi^{-2}), compared to the resident density in the Coastal Bays watershed of 27 people km^{-2} (70 people mi^{-2}). The larger Chesapeake Bay watershed means that much more agricultural area is present, as well as extensive heavy industry with associated contaminant discharges.

The shallow nature of lagoons limits dilution which, together with long residence times, seasonal population pressures, and benthic-dominated primary productivity, makes the Coastal Bays more sensitive to nutrient inputs than Chesapeake Bay. The problems that develop include algal blooms (microalgae and macroalgae) which cloud the water column, causing losses of seagrasses and other benthic primary producers, and occurrences of HABs. There are also recent indications of dissolved oxygen issues. By comparison, the larger, deeper Chesapeake Bay has had high-level impacts for several decades, including well-established problems with low dissolved oxygen in the deep channels and seagrass loss along the shallow flanks, in addition to increasing 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 land use within the watershed.

Eutrophication was assessed in the Maryland Coastal Bays

Overall eutrophic conditions in the Maryland Coastal Bays were determined from primary (increased chl *a* and

Northern & southern Maryland Coastal Bays



Location of the northern and southern Maryland Coastal Bays and watersheds.

macroalgae) and secondary (dissolved oxygen problems, seagrass loss, and occurrence of nuisance/toxic blooms) symptoms, using the most recent available data (see table on page 190). Water quality data was 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 Coastal Bays and 34 in the southern Coastal Bays) during 2004 and data concerning the spatial distribution of macroalgae was collected in 2003 and seagrasses in 2004.[32,53]

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

Primary symptoms in the northern Maryland Coastal Bays indicated

JANE THOMAS

The Ocean City Inlet forms the boundary between the northern and southern Maryland Coastal Bays.

eutrophication impacts, with hyper-eutrophic chlorophyll *a* concentrations and some areas with harmful concentrations 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 an overall *Moderate* primary symptom expression. *Low* incidences of secondary symptoms (10th-percentile dissolved oxygen value was 3.5 mg L^{-1} in the mixed zone and 4.8 mg L^{-1} in the seawater zone) resulted in *Low* secondary symptom expression.

Although several species of harmful and toxic algae are known to occur in the northern Maryland Coastal Bays, including the potentially toxic dinoflagellates *Prorocentrum minimum* and *Chattonella cf. verruculosa*, and the toxic *Pfiesteria piscicida*, there is no evidence of toxic episodes in the Maryland Coastal Bays.[47] A nuisance species that has increased in abundance since it was first identified in this system in 1999 is brown tide, which bloomed at low concentrations in the northern Maryland Coastal Bays during 2004, coincident with 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.[3]

JOANNA WOERNER

The northern Maryland Coastal Bays are influenced by large developed areas, including Ocean City and Fenwick Island.

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

Primary conditions in the southern Maryland Coastal Bays were similar to those in the northern bays with *High* chlorophyll *a* (90th percentile was 33 µg L^{-1}) and *Moderate* macroalgal abundances, resulting in *High* primary symptom expression. There were *Low* incidences of dissolved oxygen problems

The southern Maryland Coastal Bays benefit from the Assateague Island National Seashore.

(10th percentile value was 5.2 mg L^{-1}) and seagrass coverage increased in the early 2000s.[30,31] However, there were *High* nuisance/toxic blooms—intense annual blooms of brown tide at Category 3 levels (the highest of three categories; > 200,000 cells L^{-1}), which are known to seriously impact mussels, scallops, hard clams, seagrasses, and copepods.[21,52] This resulted in a *High* secondary symptom rating.

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 have worsened since the early 1990s when the overall eutrophic condition was *Moderate low*,[3] because of increasing frequency of brown tide events and high chlorophyll *a*.[54]

Maryland's Coastal Bays share characteristics with other Mid-Atlantic coastal lagoons

The lagoons of the Mid-Atlantic (i.e., Cape Cod, Massachusetts south to the Maryland Coastal Bays) are of particular interest because they are located in one of the most densely populated regions of the country and are therefore subject to more intense pressures than lagoons in other regions. The six lagoon systems in this region are Great South Bay, Barnegat Bay–Little Egg Harbor Estuary, 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 lagoons are less than 2 m (6.6 ft) deep on average (see table on page 190). 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 shown signs of oxygen depletion in the late summer, even to the point where crab jubilees have been observed—when the waters that are home to crabs become so depleted of oxygen that the crabs crawl up on land in search of oxygen to breathe.

Mid-Atlantic coastal lagoons have moderate to high levels of macroalgae, (primarily *Enteromorpha* and *Ulva*), which are known to smother seagrasses and bivalves,[2,14] and can cause low dissolved oxygen events. In some shallow lagoonal systems, additional nutrients will result in increased macroalgal abundance rather than high concentrations of chlorophyll *a*.[37] However, in these Mid-Atlantic lagoons, chlorophyll *a* impacts are moderate to high in all except the New Jersey Inland Bays. Macroalgal impacts in the New Jersey Inland Bays have worsened since the early 1990s.

A symptom of eutrophication typical of lagoons is the occurrence of nuisance or toxic algal blooms, due in part to 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 lagoons have high level nuisance/toxic bloom impacts—Great South Bay, Barnegat Bay–Little Egg Harbor Estuary, and the southern Maryland Coastal Bays. However, the other three—the New Jersey Inland Bays, Delaware Inland Bays, and the northern Maryland Coastal Bays—are rated as low, meaning that there are some nuisance and/or toxic bloom occurrences in all of these lagoons. In Barnegat Bay–Little

Barnegat Bay–Little Egg Harbor Estuary

Small tidal range, low tributary inflow, and limited ocean exchange with high nutrient inputs led to *High* eutrophic conditions. Chlorophyll *a* concentrations were high with blooms of brown tide and other harmful algal blooms, there was seagrass loss, and fisheries were highly reduced.

SCOTT HAAG

Mid-Atlantic coastal lagoons overall eutrophic condition, 2004

Great South Bay

Moderate dilution and low flushing led to high levels of chlorophyll *a* and macroalgae, although oxygen depletion was not a problem. Some nuisance/toxic and brown tide blooms occurred in this system. Overall eutrophic conditions were *Moderate high*.

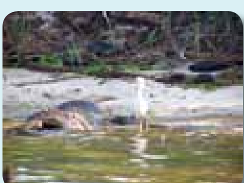
DODSON ASSOCIATES, LTD

Northern Maryland Coastal Bays

Shallow depth, small tidal range, and small freshwater inflow combined with high summer population led to *Moderate* eutrophic conditions. Chlorophyll *a* concentrations were very high and macroalgal abundances were moderate but there were no problems with nuisance/toxic blooms, low dissolved oxygen, or seagrass loss.

New Jersey Inland Bays

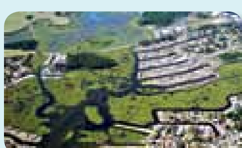
The high susceptibility of these bays is due to moderate dilution and low flushing. Chlorophyll *a* concentrations were low but brown tide blooms were a problem. Macroalgae blooms caused significant die-off of seagrass but there were no dissolved oxygen problems. Eutrophic conditions were *High*.



TRACY KIRWAN

Delaware Inland Bays

Low freshwater input and small tidal range led to *Moderate* eutrophic conditions. Severe hypoxia was observed in parts of the bays and seagrass was limited by excessive macroalgal growth. Chlorophyll *a* concentrations were moderate and some nuisance/toxic blooms occurred.



CHRIS BASON

Southern Maryland Coastal Bays

Low flushing and dilution capabilities led to *High* eutrophic conditions which have worsened in the past decade. Chlorophyll *a* concentrations were high and nuisance/toxic blooms, especially brown tide, were observed. Dissolved oxygen was not a problem.

Coastal lagoon	Watershed area (km²)	Pop'n (× 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	1,733	2,084	383	5,441	1.10	0.57	16	199
Barnegat Bay–Little Egg Harbor Estuary	1,730	520	280	2,211	1.5	0.75	20	74
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**	**42**
—Northern	**283**	**15**	**54**	**281**	**1.92**	**0.67**	**28**	**21**
—Southern	**487**	**6**	**335**	**17**	**1.94**	**0.50**	**29**	**63**

NATIONAL ESTUARINE EUTROPHICATION ASSESSMENT DATABASE

Characteristics of the Mid-Atlantic coastal lagoons, early 2000s. 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, although summer populations may increase to nearly 40 times the resident year-round population.[6,29,43,46,54]

Egg Harbor Estuary, nuisance/toxic blooms have been reported for more than a decade.[5,25] In the southern Maryland Coastal Bays, data show that these blooms have become worse during the past decade.[5,23,49]

Brown tide bloom events have been recorded in Barnegat Bay–Little Egg Harbor Estuary in 1995, 1997, and 1999–2002, with bloom cell concentrations exceeding two million cells L^{-1} in 2000.[25,40] Brown tide has also been observed in Great South Bay, where brown tide was first observed and identified in 1985.[9] In the 1999 NEEA, the rating for nuisance/toxic blooms for the southern Maryland Coastal Bays was "no problem,"[3,49] meaning that there has been significant worsening of bloom conditions since then, while conditions have remained at moderate levels in Great South Bay and at high levels in Barnegat Bay–Little Egg Harbor Estuary during the same time period.

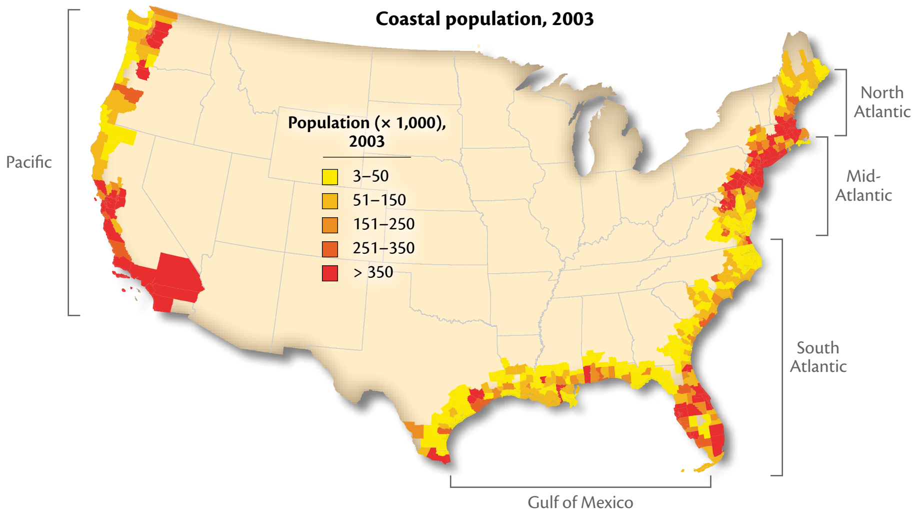
In both Barnegat Bay–Little Egg Harbor Estuary and the southern Maryland Coastal Bays, several toxic and non-toxic HAB species have been observed but the most noted HAB is brown tide.[22,23,25,40,47,49] In both lagoonal systems, blooms commonly occur at Category 3 levels (>200,000 cells mL^{-1})—concentrations which may cause severe impacts on mortality of shellfish and reductions in seagrasses.[21,49] There is also evidence that the frequency, duration, and intensity of blooms has increased in the past decade in the southern Maryland Coastal Bays.[49] Although troubling, these increases are consistent with observed population increases in coastal watersheds. The population in the southern Maryland Coastal Bays watershed doubled and has increased more than 40% in the Barnegat Bay—Little Egg Harbor Estuary watershed between 1980 and 2000.[25,54]

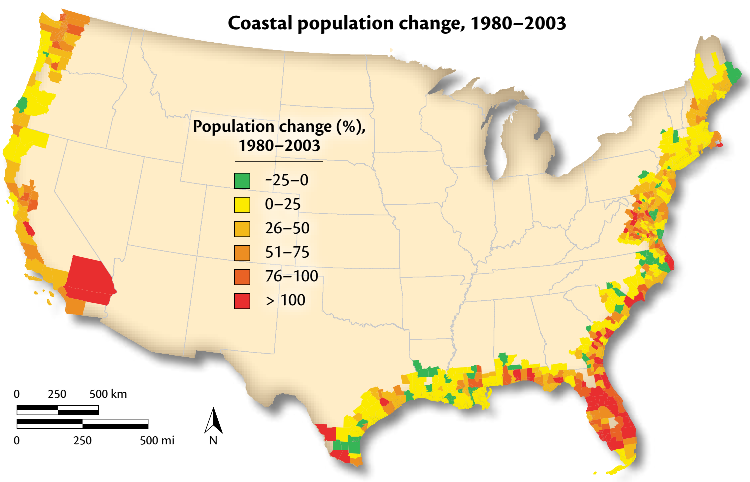
Nutrient loads have also increased with measured dissolved organic nitrogen concentrations doubling in the southern Maryland Coastal Bays.[23] Recent results have shown that brown tide favors organic nitrogen, increases of which have contributed to the proliferation of brown tides in the southern Maryland Coastal Bays.[23] This highlights that the composition of nutrients, in addition to the amounts entering a lagoon are important factors influencing the species that are able to grow and bloom and suggests that management measures must be attentive to the forms of nutrients that are being targeted for reduction.

Different regions have differing pressures & susceptibility

Over half of the nation's population lives on the coastal fringe of the contiguous United States, an area only one-fifth of the land area.[50] This large population has significantly increased the amount of nutrients entering the nation's coastal waterways, including coastal lagoons.

Population density within the coastal fringe varies greatly between regions. Some areas are under intense pressure, such as the North and Mid-Atlantic and Florida coasts, where very high densities occur, while other areas have relatively low population densities such as parts of the South Atlantic and Gulf of Mexico coasts. Coastal populations are increasing rapidly, with the majority of regions recording





Coastal areas in the contiguous United States already support high human populations (top), and population growth continues to add pressure to coastal estuarine systems (bottom).[35] There are 30 coastal states in the United States containing a total of 673 coastal counties, boroughs, parishes, or county equivalents. NOAA's Special Projects office defines a county as coastal if one of the following criteria is met: (1) at a minimum, 15% of the county's total land area is located within a coastal watershed or (2) a portion of or an entire county accounts for at least 15% of a coastal cataloging unit. For the purposes of this book, coastal states and counties are grouped into five regions: North Atlantic, Mid-Atlantic, South Atlantic, Gulf of Mexico, and Pacific.[10]

at least a 25–50% increase between 1980 and 2003,[35] although some areas, such as Florida, experienced increases over 100%. The coastal population increase is also projected to continue for at least the next decade.[34]

Differing climate conditions, freshwater inflow, number of tides per day, and oceanic exchange all contribute to the susceptibility of coastal lagoons to eutrophication. For example, the lagoons along the Gulf of Mexico coast are more vulnerable than those on the temperate Mid-Atlantic coast because of the warmer climate and longer growing season.

The North Atlantic region (Maine to Cape Cod, Massachusetts) of New England 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 in part to the large tidal range in the Gulf of Maine.

The Mid-Atlantic region (Cape Cod south to the Maryland Coastal Bays) is characterized by sandy beaches, numerous barrier islands, and extensive salt marshes. Water depths are shallower in this region (averaging 4.7 m [15.5 ft]). Tidal flushing (averaging 0.8 m [2.6 ft]) is dominant in northern ecosystems, 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 mi^{-2}).

The South Atlantic region (Maryland Coastal Bays south to Florida) is comprised of extensive barrier island–lagoon–salt marsh systems. Depths are shallow (averaging 3 m [9.8 ft]) and tides are variable, averaging 0.6 m (1.9 ft) in North Carolina systems, 1.8 m (5.9 ft) in South Carolina and Georgia ecosystems, and 0.5 m (1.6 ft) in Florida. Circulation is dominated by wind and seasonal freshwater inflow in the north, and by freshwater inflow and tides in the south. The warmer climate and low water exchange makes these ecosystems, especially the lagoons, susceptible to development of nutrient-related problems.

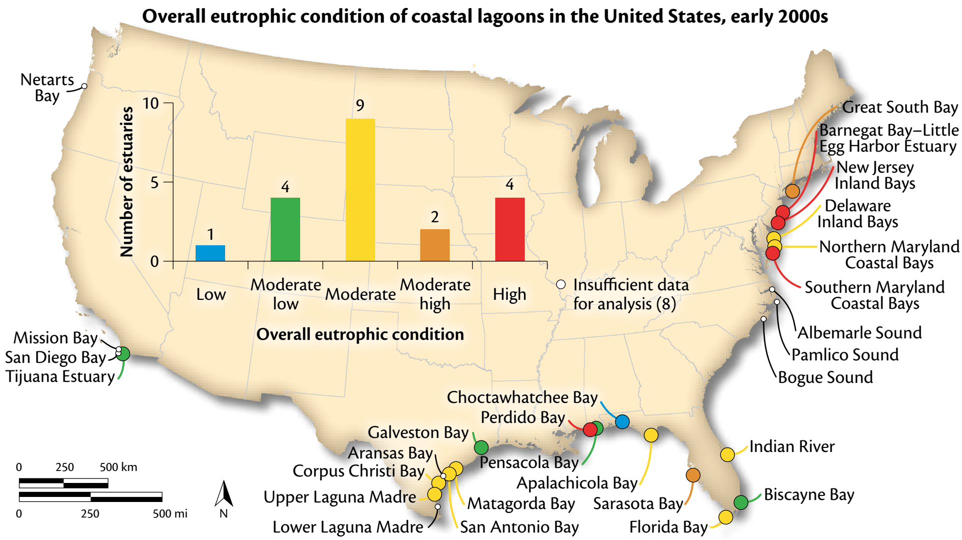
The Gulf of Mexico (Florida west to Texas) has the most lagoons of any region but also has open bays and tidal marsh–delta complexes. This region has the lowest tidal ranges (averaging 0.4 m [1.3 ft]) and the shallowest depths (averaging 1.9 m [6.2 ft]) of all regions. Freshwater inflow is highly variable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

The Pacific coast region (Washington, Oregon, and California) 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 to longer residence times, warmer climate, and location of large population centers.

All U.S. coastal lagoons show signs of eutrophication

In the United States, there are coastal lagoons distributed along the Atlantic, Gulf of Mexico, and Pacific coastlines. They are variable in size—the 28 lagoons included in NOAA's NEEA 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).[3,5] However, they are more similar in most other physical characteristics. Most are very shallow (averaging 1.6 m [5.2 ft]) with a small tidal range (averaging 0.54 m [1.8 ft]).

There are moderate to high levels of eutrophication observed in 15 of 20 of the



Overall eutrophic condition for United States coastal lagoons shows that most lagoons are rated as *Moderate*. However, many of the lagoons that are rated as *Moderate high* or *High* are located in the Mid-Atlantic region.[5]

NEEA lagoons (for eight lagoons, data were inadequate for assessment). All but one (Indian River Lagoon, Florida) of the most impacted lagoons are located along the Gulf of Mexico and Mid-Atlantic coasts.

Upper Laguna Madre—Ecosystem transition occurred with the initiation of brown tides

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 lagoon. Annually, evaporation is approximately twice precipitation, and no permanent streams discharge into the lagoon. As a result, the waters of the lagoon are hypersaline during the summer (annual average salinity >37 ppt). Seagrass meadows cover approximately two-thirds of the bottom. The surrounding watershed includes a National Park, a National Wildlife Refuge, and very large cattle ranches. The extreme northern end of the watershed is becoming increasingly urbanized.

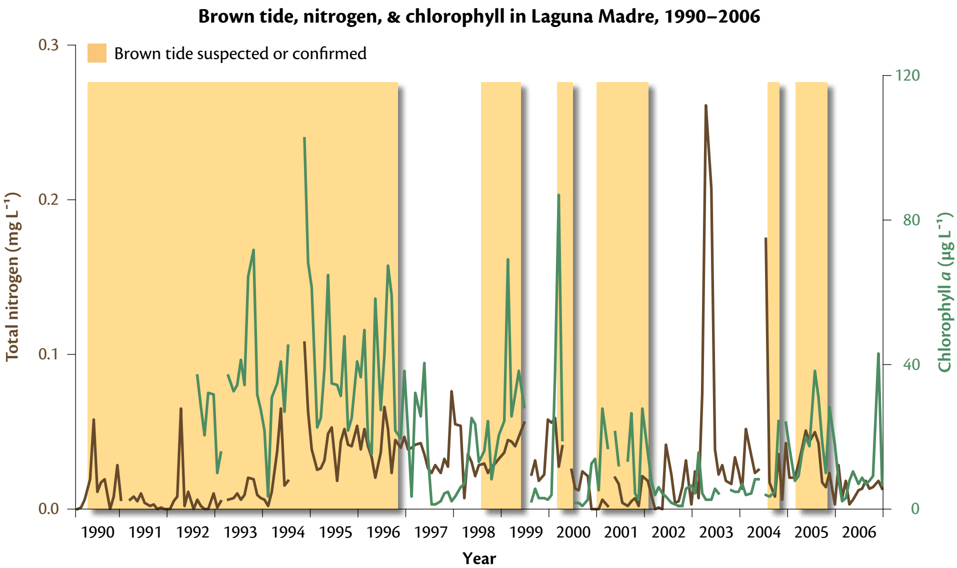
Upper Laguna Madre was known for its clear water until a phytoplankton bloom (*Aureoumbra lagunensis*) developed in the spring of 1990 and persisted long enough to earn its own name—Texas brown tide.[55] The first episode lasted until October 1996, with a few brief blooms since then, including one as recently as August 2007. 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

KEN DUNTON

Seagrasses in Upper Laguna Madre have been negatively affected by the Texas brown tide.

Location of Upper Laguna Madre

Location of Upper Laguna Madre on the Gulf of Mexico coast of Texas.



Nitrogen, chlorophyll *a*, and brown tide occurrence in Laguna Madre between 1990–2006. Note: prior to April 1994, total dissolved nitrogen only included measurements of nitrate (NO_3) and nitrite (NO_2).

historically clear-water system has been converted abruptly to one that supports algal blooms much of the time without an obvious cause.

A retrospective analysis of the algal bloom established that the 1990 bloom initiated in Baffin Bay, a tributary of Upper Laguna Madre.[15,55] The initiation of the bloom is suspected to be linked to a variety of unusual circumstances preceding the bloom, including a long drought 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 the unpalatability of *A. lagunensis* cells (i.e., 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 dormant cells in the sediments.

This system was characterized by *Moderate* symptom expressions for chlorophyll *a* and nuisance/toxic blooms, resulting in a *Moderate* overall eutrophic condition.

COASTAL LAGOONS AROUND THE WORLD

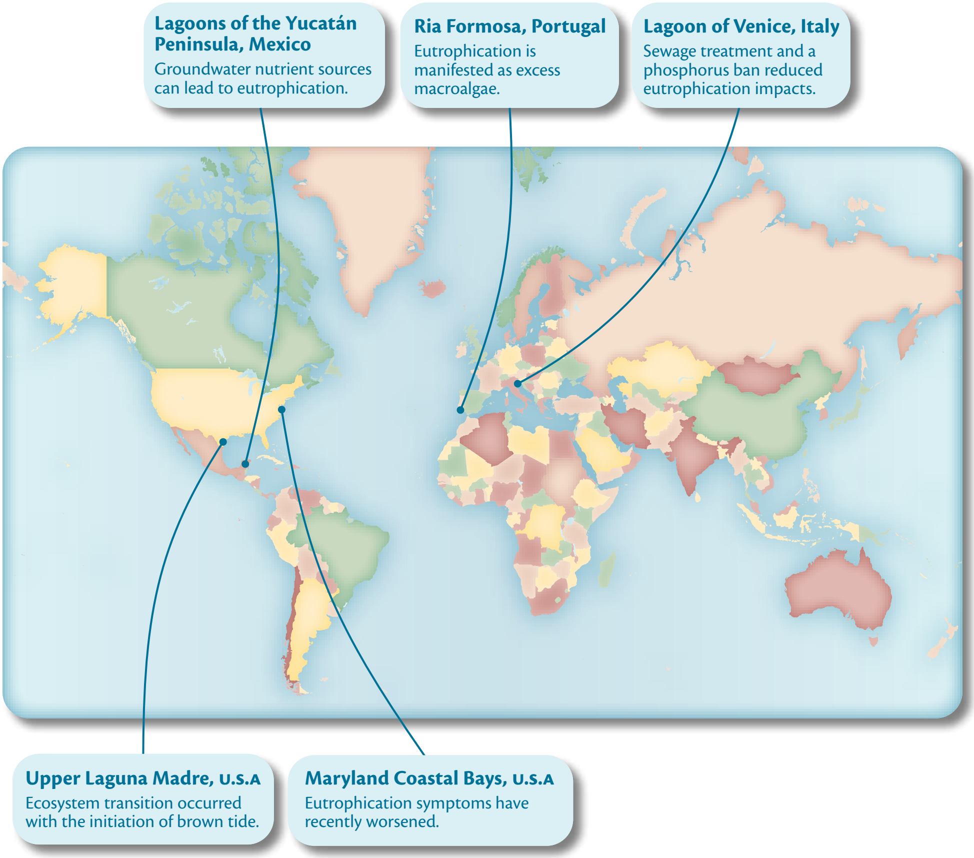
Similar symptoms & progression of eutrophication are seen globally

Research and monitoring in the past decade have revealed that eutrophication impacts have been observed in estuaries and coastal waterbodies around the world. In most cases, the progression of symptoms and the symptoms themselves are similar, often beginning with high chlorophyll *a* or macroalgae. Low dissolved oxygen, seagrass loss, and occurrences of harmful algal blooms are also observed. Though not all symptoms are observed in all estuaries and different

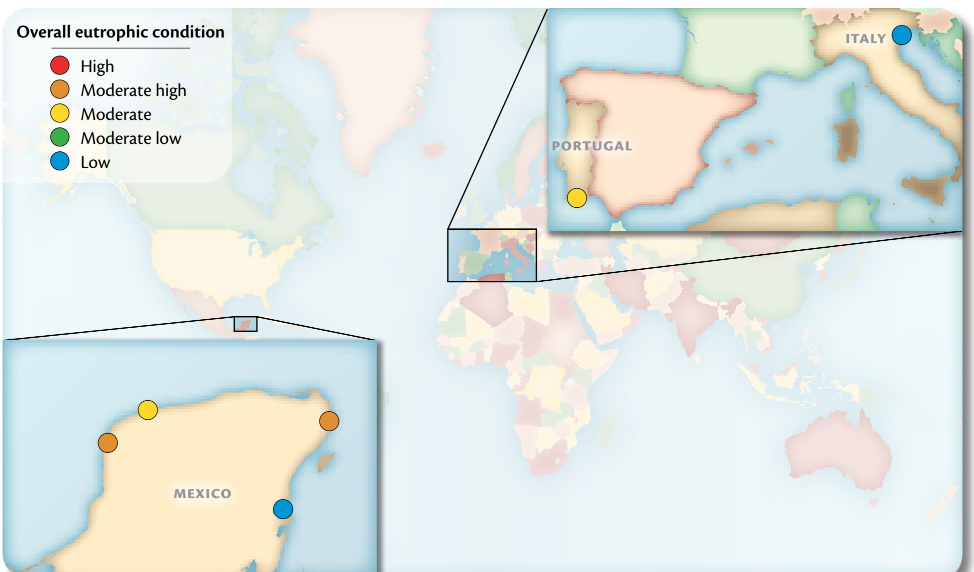
DATA COURTESY MARC IMHOFF (NASA/GSFC) AND CHRISTOPHER ELVIDGE (NOAA/NGDC). IMAGE BY CRAIG MAYHEW (NASA/GSFC) AND ROBERT SIMMON (NASA/GSFC)

This night view of the city lights of Earth shows the global extent of human population pressures in the coastal zone.

Case studies of coastal lagoons globally



Global case studies—overall eutrophic condition



combinations of symptoms occur, there are commonalities, particularly in coastal ecosystems of the same geomorphological type. For example, macroalgal problems are observed in coastal lagoons more than in fjords or drowned river valleys, which seem to have more dissolved oxygen problems than are observed in coastal lagoons.

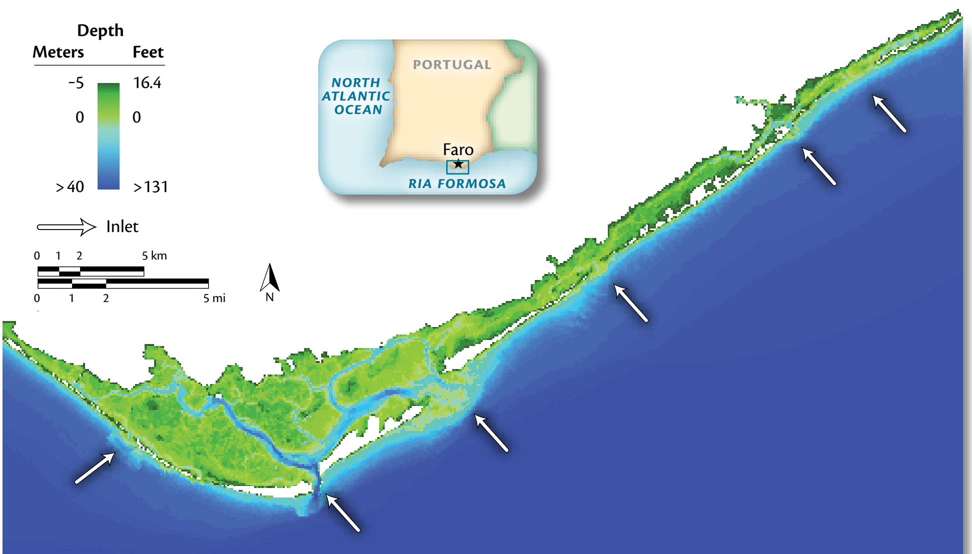
The case studies that follow are intended to highlight the different expressions of eutrophication that occur in different lagoon systems around the world. The case studies include Ria Formosa (Portugal), Lagoon of Venice (Italy), and lagoons of the Yucatán Peninsula (Mexico), in addition to those already presented—Upper Laguna Madre (Texas) and the northern and southern Maryland Coastal Bays. The Lagoon of Venice study also illustrates how the application of carefully planned management measures has relieved eutrophication. The success of these management measures should be used to encourage and promote management elsewhere to prevent future degradation and relieve impacts in lagoons elsewhere.

Ria Formosa, Portugal—Eutrophication is manifested as excess macroalgae

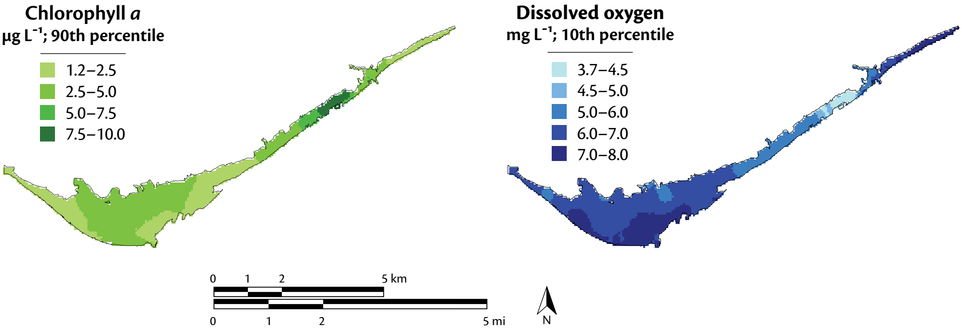
Ria Formosa is a shallow (averaging 1.5 m [5 ft]), small (49 km² [19 mi²]) lagoon located in a sheltered coastal area in southern Portugal, southwestern Europe. It is a hypersaline barrier island–lagoon system connected to the ocean by six inlets—five natural and one artificial. The semi-diurnal tidal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

Location & 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 Ria Formosa.

(*Ruditapes decussatus*) aquaculture provides a yield of 8,000 metric tonnes (8,800 U.S. tons) total fresh weight per year.

Pelagic primary production within the lagoon is strongly limited by rapid water turnover.[26,27,51] 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.[7,13] The maximum values of macroalgal biomass observed in Ria Formosa reach about 2 kg dry weight m^{-2} (0.41 lb ft^{-2}).

Species	Spring	Summer
Ulva lactuca	1,350	100
Enteromorpha ramulosa	700	200
Gracilaria verrucosa	140	18
Fucus spiralis	335	75
Total macroalgae biomass	**2,525**	**393**

Maximum biomass (g dry weight m^{-2}) of macroalgae in the Faro–Olhão area in 1993. Note: values taken from graphical information.[16]

The 90th percentile value for chlorophyll *a* (5 µg L^{-1}) resulted in a rating of *Low*. The macroalgal component of the model showed 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 gave a *High* primary symptom rating. Dissolved oxygen was generally above the 5 mg L^{-1} threshold, indicating no oxygen problems, and there were no significant problems with losses of seagrasses or occurrences of nuisance or toxic blooms. The secondary symptom rating for Ria Formosa was *Low*, which, combined with the *High* primary symptom rating, gave a *Moderate* overall eutrophic condition.

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* and *Ulva* bloom (right).

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

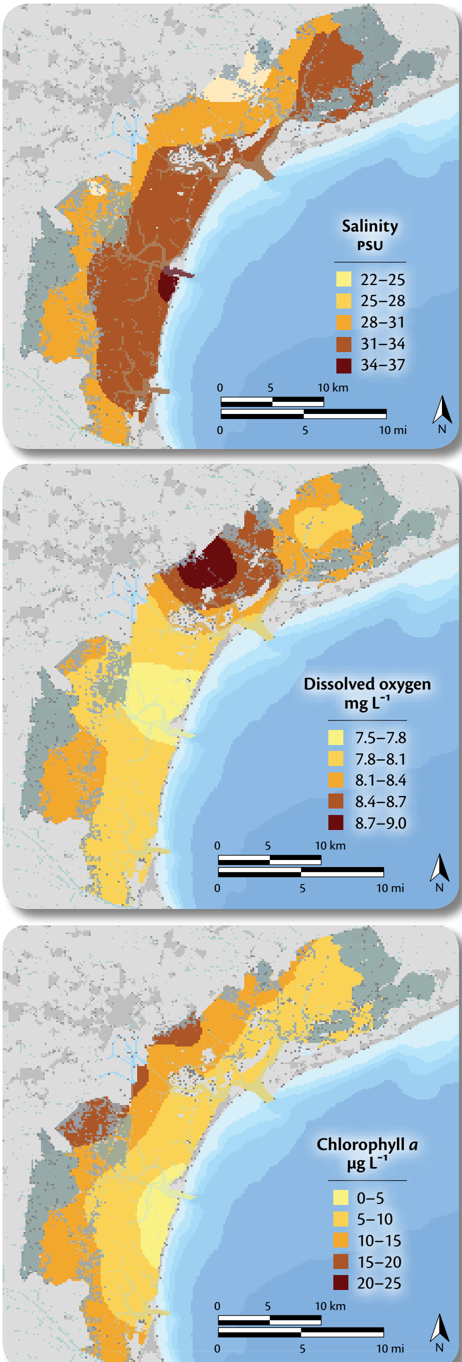
The Lagoon of Venice is one of the largest lagoon systems in Europe, with a total surface of 550 km² (212 mi²), of which 360 km² (139 mi²) are open to tidal exchanges. The lagoon is located along the northeast coast of the Adriatic Sea in Italy. It is a shallow water basin (averaging 1.5 m [5 ft]), connected 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 >25 ppt.

Seven main tributaries and several minor canals carry the wastewater 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 along the northeast coast of the Adriatic Sea.

Salinity, dissolved oxygen, & chlorophyll in the Lagoon of Venice, 2001–2003



VENICE WATER AUTHORITY & CA' FOSCARI UNIVERSITY OF VENICE

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

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, and others).

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, wastewater treatment plants were built and phosphorus was banned from detergents in the 1980s. These actions, together with other restoration activities (e.g., planting of buffer strips to prevent nutrient inputs from runoff) aimed at lowering the unpleasant effects of acute eutrophication, led 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 most recent available data were used to calculate eutrophic condition, including nutrient input measurements collected in 1999,[8] water quality data collected monthly at 30 lagoon sites during 2001–2003,[42] and seagrass spatial distribution data from 2002.[45] The 90th percentile value for chlorophyll *a* (24.4 µg L^{-1}) was high but spatial coverage was low, resulting in a *Low* rating. Macroalgae biomass was also *Low*, resulting in a *Low* primary symptom rating. The dissolved oxygen 10th percentile (6 mg L^{-1}) indicated *Low* problems with oxygen. The biomass level of macroalgae did not represent a problem for the lagoon, and recent increases in the spatial coverage of seagrasses also indicated no problems. As

STEFANO CIAVATTA & ILARIA BEISO

Venice's waterways are a large part of the city's charm (left). The church of Santa Maria della Salute is at the entrance of the Grand Canal (middle). Rising sea level often results in *acqua alta*, or high water—a regular occurrence in Piazza San Marco (right).

a result, the secondary symptom rating was *Low*, which, combined with the *Low* primary symptom rating, gave a *Low* overall eutrophic condition classification.

Even though the watershed population of the lagoon is likely to increase in the near future, the construction of new wastewater treatment plants, decommissioning of factories in the industrial area, and other interventions aimed at controlling nitrogen and phosphorus loads have already been planned and should result in decreased future nutrient loads.

A future challenge for the Lagoon of Venice will be the storm surge flood gates currently being constructed at each inlet. Relative sea level rise has made Venice highly susceptible to flooding. The reduced exchange with the Adriatic Sea will make the lagoon more susceptible to eutrophication symptoms. These flood gates will effectively shut the lagoon off from the Adriatic Sea during periods of high water level to reduce flooding in the city of Venice.

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.

The coastal lagoons of the Yucatán are variable in size—the 11 lagoons range from 3 km^2 (1.2 mi^2) to almost 1,500 km^2 (580 mi^2) 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]), surrounded by mangrove vegetation, and 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 is characteristic of this area of karstic limestone 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, the salinity of individual lagoons 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).[41] There are four million Yucatán residents, more than half of whom 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 (see table, above). However, the primary source of nutrients is from agricultural activities, most notably pig farms which sell primarily to the U.S. market. Manure accounted for

Nutrient loads	1980	1990	2000
Nitrogen	79,100	169,200	309,400
Phosphorus	24,800	64,100	115,600

Estimated loads (metric tonnes yr^{-1}) from Yucatán State in 1980, 1990, and 2000.[24]

Location of the Yucatán Peninsula coastal lagoons

Location of coastal lagoons of the Yucatán Peninsula.

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 typically 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, which discharges into and impacts the lagoons. Observed problems include dinoflagellate blooms and high chlorophyll *a* concentrations that discolor the water to the extent that tourism has declined. The spatial coverage of seagrasses (mostly *Halodule wrightii* and *Thalassia testudinum*) has decreased in some lagoons (e.g., Celestún and Chelem Lagoons) and the species composition has changed in others (e.g., Nichupté–Bojórquez). Sediment and nutrient exports to the coastal sea have expanded eutrophic influences beyond lagoonal waters.

A more detailed analysis of eutrophic conditions was done for four coastal lagoons from Yucatán Peninsula (Chelem, Celestún, Nichupté–Bojórquez, and Ascensión Lagoons).

Celestún Lagoon—Groundwater impacts even protected lagoons

Celestún Lagoon comprises an area of 28 km² (10.8 mi²), with a average depth of 1.2 m (3.9 ft). It is an estuarine lagoon (averaging 22 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 lagoon is highly susceptible to development of eutrophication problems due to moderately long water residence times

JORGE HERRERA-SILVEIRA

Celestún Lagoon shows few signs of eutrophication.

(20 days) in 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. The lagoon is part of a Biosphere Reserve, where human density is low, and the lagoon supports such activities as tourism, fishing, and salt extraction.

High chlorophyll *a* and macroalgae resulted in a *High* primary symptom expression. *Low* dissolved oxygen problems combined with *Moderate* seagrass loss and *Low* nuisance and toxic blooms resulted in *Moderate* secondary symptom expression. These symptom expression ratings resulted in *Moderate high* overall eutrophic condition.

Chelem Lagoon— Highly impacted lagoons are eutrophic

Chelem Lagoon has an area of 14 km² (5.4 mi²) and average depth of 0.8 m

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Chelem Lagoon shows many eutrophication symptoms.

(2.6 ft). It is a euhaline system (averaging 35 ppt) and is vertically homogeneous and microtidal with a tidal range of 0.6 m (2 ft). This lagoon 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 lagoon receives groundwater nutrient inputs from a polluted aquifer. The most important human activities are tourism, fishing, and urban development.

Moderate chlorophyll *a* and macroalgae resulted in *Moderate* primary symptom expression. *Low* incidences of dissolved oxygen problems combined with *Moderate* seagrass loss and nuisance/toxic blooms resulted in *Moderate* secondary symptom expression. These symptom expression ratings resulted in *Moderate* overall eutrophic condition.

Nichupté–Bojórquez—Small nutrient loads into susceptible lagoons can lead to eutrophication

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 lagoon (16–36 ppt) and is vertically homogeneous and microtidal with a tidal range of 0.3 m (1 ft). Long water residence times (100–400 days) make this lagoon highly susceptible to the eutrophication process due to intense Cancún tourism and development within the watershed. Although there are seagrasses covering the lagoon bottom, the leaves are covered with epiphytes which is strong evidence of eutrophic impact.

Moderate chlorophyll *a* and *High* macroalgae resulted in *High* primary symptom expression. *Moderate* dissolved oxygen problems combined with *Moderate* seagrass loss and *Low* nuisance and toxic blooms resulted in *Moderate* secondary symptom expression. These symptom

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Nichupté Lagoon, with the adjacent tourist center of Cancún, shows eutrophication signs.

expression ratings resulted in *Moderate high* overall eutrophic condition. This suggests that even small nutrient loads into lagoons with long residence times can have significant impacts.

Bahía de la Ascensión—Protected lagoons are less eutrophic

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 lagoon is vertically homogeneous and microtidal with a tidal range of 0.5 m (1.6 ft). This system has moderate susceptibility to eutrophication due to long residence times (100 days), despite high exchange with the ocean through a wide inlet. The human population density in the surrounding watershed is very low and the main activities are ecotourism and fishing.

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Bahía de la Ascensión has low overall eutrophic condition, likely a result of low population density.

Low chlorophyll *a* and *Moderate* macroalgae resulted in *Low* primary symptom expression. *Low* occurrences of dissolved oxygen problems, seagrass loss, and nuisance and toxic blooms resulted in *Low* secondary symptom expression. These symptom expression ratings resulted in *Low* overall eutrophic condition, likely the result of low population density and thus low associated nutrient loads.

Lagoons are unique coastal features that are found along coastlines all over the world, parallel to the coast but separated from the ocean by a barrier island or sand spit. They are usually shallow and well mixed with restricted connectivity to ocean waters and often have limited freshwater inflow. They support very productive fisheries and their attraction as summer destinations results in seasonal watershed population increases of many times the resident population.

Natural characteristics, particularly the long water residence times, make these systems sensitive to nutrient inputs from human-related activities

Coastal lagoon	Surface area (km^2)	Avg. depth (m)	Salinity range (ppt)[1]	Avg. residence time (days)	Chl *a* conc.[2] Annual avg. bloom conc.[3] ($\mu g\ L^{-1}$)
Celestún	28	1.2	5–39	20	6 30
Chelem	14	0.8	20–44	50	4 20
Nichupté	48	2.0	16–36	100	1 10
Bojórquez	2.5	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 the primary freshwater source.

1. Minimum–maximum salinity range.
2. Chlorophyll *a* concentrations (annual average).
3. Annual bloom chlorophyll *a* concentrations (annual average).

Lagoon	Overall eutrophic condition	Primary symptoms: Chlorophyll *a*	Primary symptoms: Macroalgae	Secondary symptoms: Dissolved oxygen	Secondary symptoms: Nuisance/toxic blooms	Secondary symptoms: Seagrass loss
Great South Bay	Moderate high	High	High	Low	Moderate	Unknown
Barnegat Bay	High	High	High	Low	High	Moderate low
New Jersey Inland Bays	High	Low	High	Low	Low	High
Delaware Inland Bays	Moderate	Moderate	High	Low	Low	Low
Northern MD Coastal Bays	Moderate	High	Moderate	Low	Low	Low
Southern MD Coastal Bays	High	High	Moderate	Low	High	Low
Indian River	Moderate	Low	Moderate	Low	Moderate	Low
Biscayne Bay	Moderate low	Low	Low	Moderate	Low	Low
Florida Bay	Moderate	High	Unknown	Low	Unknown	Unknown
Sarasota Bay	Moderate high	High	High	Low	Moderate	Low
Apalachicola Bay	Moderate	Moderate	Low	Low	Moderate	Low
Choctawhatchee Bay	Low	Low	Unknown	Low	Unknown	Unknown
Pensacola Bay	Moderate low	Moderate	Unknown	Low	Unknown	Unknown
Perdido Bay	High	Low	Moderate	High	Low	Low
Galveston Bay	Moderate low	High	Low	Low	Low	Low
Matagorda Bay	Moderate	High	Low	Low	Low	Low
San Antonio Bay	Moderate	High	Unknown	Low	Unknown	Unknown
Corpus Christi Bay	Moderate	High	High	Unknown	Low	Unknown
Upper Laguna Madre	Moderate	Moderate	Unknown	Unknown	Moderate	Unknown
Tijuana Estuary	Moderate low	Moderate	Moderate	Low	Low	Low
Ria Formosa	Moderate	Low	High	Low	Low	Low
Lagoon of Venice	Low	Low	Low	Low	Low	Low
Celesún Lagoon	Moderate high	High	High	Low	Low	Moderate
Chelem Lagoon	Moderate	Moderate	Moderate	Low	Moderate	Moderate
Nichupté–Bojórquez Lagoon	Moderate high	Moderate	High	Moderate	Low	Moderate
Bahía de la Ascensión	Low	Low	Moderate	Low	Low	Low

Overall eutrophic condition

- High
- Moderate high
- Moderate
- Moderate low
- Low

Primary & secondary symptom expression

- High
- Moderate
- Low
- Unknown

This table summarizes the early-2000s overall eutrophic condition, including primary and secondary symptoms, for the 20 coastal lagoons in the United States with sufficient data for analysis, and the global case studies considered in this chapter.

and modifications of the watershed. The symptoms and progression of eutrophication is similar among lagoons globally, as are the impacts to water quality and human uses. While relatively unimpacted lagoons are known to support fisheries that rival those of known fishing areas (e.g., Georges Bank and the Peruvian Upwelling), productivity in lagoons around the globe has declined as a result of nutrient increases that have caused excessive macroalgal blooms, occurrences of nuisance and toxic algal blooms, losses of seagrasses, and there is some evidence that dissolved oxygen is an emerging problem in some lagoons despite the well-mixed water column.

Measures to protect lagoons from further degradation include limiting nutrient inputs through traditional management strategies such as sewage treatment and agricultural best management practices. Traditional measures may be complemented by alternative measures within the waterbody such as the restoration of shellfish beds or implementation of aquaculture projects.

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