Welcome to Estuaries

Estuaries are bodies of water and their surrounding coastal habitats typically found where rivers meet the sea. Estuaries harbor unique plant and animal communities because their waters are brackish—a mixture of fresh water draining from the land and salty seawater.

Estuaries are some of the most productive ecosystems in the world. Many animal species rely on estuaries for food and as places to nest and breed. Humans communities also rely on estuaries for food, recreation and jobs.

Of the 32 largest cities in the world, 22 are located on estuaries (Ross, 1995). Not surprisingly, human activities have led to a decline in the health of estuaries, making them one of the most threatened ecosystems on Earth. NOAA's National Estuarine Research Reserve System (NERRS), in partnership with coastal states, monitors the health of estuaries, educates the public about these ecosystems, and helps communities manage their coastal resources.

Estuarine habitats are typically found where rivers meet the sea. **Mouse over** the image to see some of the estuarine areas highlighted in this tutorial. **Click on image** for more details and a larger image.

Estuaries are both beautiful and ecologically bountiful. Their natural expanses provide habitats for a wide range of animal and plant species. **Click on image** for more details and a larger image. (Photo: Old Woman Creek NEERS site)

New York City, with a population of over eight million people, is one example of a major urban area located on an estuary. **Click on image** for more details and a larger image. (Photo: Stanne/NYSDEC)

In this Discovery Kit, you will find three sections devoted to learning about estuaries: an online tutorial, an educational roadmap to resources, and formal lesson plans for educators.

The Estuaries Tutorial is an overview of estuarine habitats, the threats facing them, and

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efforts to monitor and protect estuaries nationwide. The tutorial is made up of 12 "chapters" or pages, and includes illustrations and interactive graphics to enhance the text.

The Roadmap to Resources complements the information in the tutorial by directing you to specific online estuary-related offerings from NOAA and other reputable resourses.

The Lesson Plans integrate information presented in the tutorial with the offerings from the roadmap. These lesson plans are developed for students in grades 9–12 and focus on monitoring living resources and physical factors in estuaries, how estuaries vary over time, and how even slight variations in physical factors can affect an estuary's living resources.

Selected by Science Educators from NSTA

The National Science Teachers Association (NSTA) has included this online resource in its *SciLinks* database.
SciLinks provide students and teachers access to Web-based, educationally appropriate science content that has been formally evaluated by master teachers.

For more information about the *SciLinks* evaluation criteria, click here: http://www.scilinks.org/certificate.asp.

To go directly to the *SciLinks* log-on page, click here: http://www.scilinks.org/.

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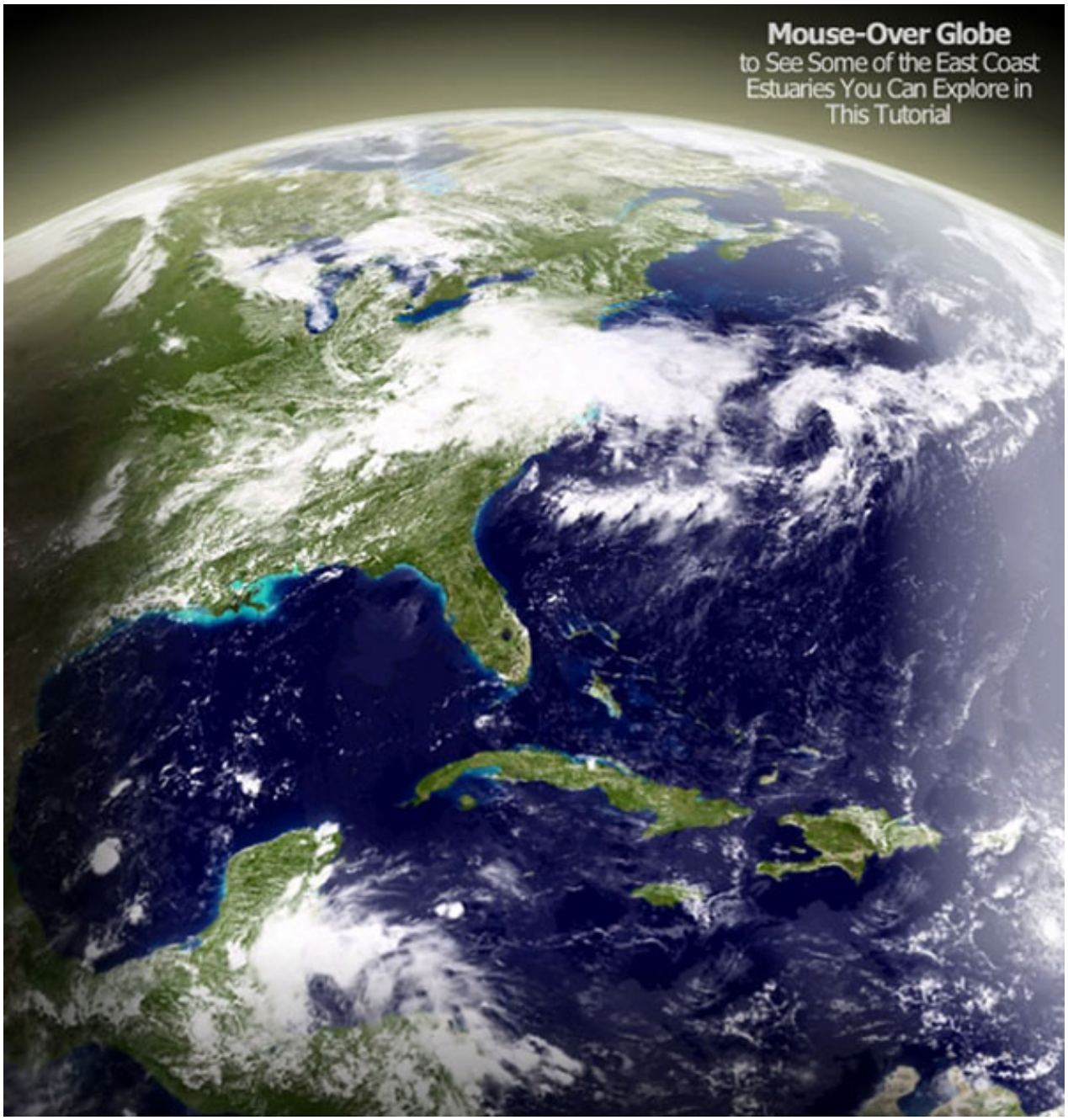
This image shows the eastern half of North America as viewed from space. If you **roll over the image with your mouse**, you can see that most of the land area drains into three major bodies of water, the Great Lakes, the Atlantic Ocean, and the Gulf of Mexico. Wherever freshwater rivers drain into these larger bodies of water, estuarine habitats are found.

The yellow squares in the image indicate some of the North American estuaries that contain NOAA's National Estuarine Research Reserves.



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Estuaries are both beautiful and ecologically bountiful. Their natural expanses provide habitats for a wide range of animal and plant species. This is an image of the Old Woman Creek National Estuarine Research Reserve. It is located on the south-central shore of Lake Erie in Erie County, Ohio, three miles east of Huron. It is the only "Great Lakes-type" freshwater estuary in the National Estuarine Research Reserve System, and features freshwater marshes, swamp forests, a barrier beach, an upland forest, and a portion of near-shore Lake Erie. (Photo: Old Woman Creek NEERS site)

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New York City, with a population of over eight million people, is located at the mouth of the Hudson River Estuary which stretches 153 miles inland from the Atlantic ocean and includes a wide range of wetland habitats. Home to more than 200 species of fish, the Hudson River Estuary serves as a nursery ground for sturgeon, striped bass and American shad. It also supports an abundance of other river-dependent wildlife, especially birds. (Photo: Stanne/NYSDEC)

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What is an Estuary?

An estuary is a partially enclosed body of water, and its surrounding coastal habitats, where saltwater from the ocean mixes with fresh water from rivers or streams. In fresh water the concentration of salts, or salinity, is nearly zero. The salinity of water in the ocean averages about 35 parts per thousand (ppt). The mixture of seawater and fresh water in estuaries is called brackish water and its salinity can range from 0.5 to 35 ppt. The salinity of estuarine water varies from estuary to estuary, and can change from one day to the next depending on the tides, weather, or other factors (Levinton, 1995.)

The daily tides experienced by coastal areas can have dramatic effects on an estuarine ecosystem. These images show the remarkable daily rise of waters at the Elkhorn Slough National Estuarine Research Reserve in California. **Click here** for more details. (Photo: Elkhorn Slough NERRS site)

Estuaries are transitional areas that straddle the land and the sea, as well as freshwater and saltwater habitats. The daily tides (the regular rise and fall of the sea's surface) are a major influence on many of these dynamic environments. Most areas of the Earth experience two high and two low tides each day. Some areas, like the Gulf of Mexico, have only one high and one low tide each day. The tidal pattern in an estuary depends on its geographic location, the shape of the coastline and ocean floor, the depth of the water, local winds, and any restrictions to water flow. For example, tides at the end of a long, narrow inlet might be amplified because a large volume of water is being forced into a very small space. However, the tides in wetlands composed of broad mud flats might appear to be rather small. With the variety of conditions across the Earth, each estuary displays a tidal pattern unique to its location (Niesen 1982).

While strongly affected by tides and tidal cycles, many estuaries are protected from the full force of ocean waves, winds, and storms by reefs, barrier islands, or fingers of land, mud, or sand that surround them. The characteristics of each estuary depend upon the local climate, freshwater input, tidal patterns, and currents. Truly, no two estuaries are the same.
Yet they are typically classified based on two characteristics: their geology and how saltwater and fresh water mix in them.

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However, not all estuaries contain brackish waters. There are a small number of ecosystems classified as freshwater estuaries. These estuaries occur where massive freshwater systems, such as the Great Lakes in the United States, are diluted by river or stream waters draining from adjacent lands.

Click on image to see a movie of a daily tidal cycle near Anchorage, Alaska.

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The daily tides experienced by coastal areas can have a dramatic effect on estuarine ecosystems. This series of images shows the remarkable daily rise of waters at the Elkhorn Slough National Estuarine Research Reserve in California. Elkhorn Slough is a tidally flushed seasonal estuary with little freshwater input. Strong tidal currents scour every major wetland habitat within the estuary, transporting large quantities of sediment into Monterey Bay during each low tide. At low tides, a muddy plume reaches a mile or more into Monterey Bay. The black and white-striped stick held in the images is meant to convey a sense of scale, and is approximately eight feet high. You can see at the tides highest point, the man has to wear a mask and snorkle just to be able to stand in the same spot. (Photo: Elkhorn Slough NERRS site)

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This video was created from a series of still photographs taken over the course of a single daily tidal cycle near Anchorage, Alaska. In some areas of Alaska daily tides can exceed 15 meters (45 feet!) This video gives some perspective of the changes in water level experienced at the Kachemak Bay National Estuarine Research Reserve, located on the western coast of the Kenai Peninsula, about 150 miles south of Anchorage.

In addition to effecting the distribution and abundance of plants and animals in the estuary, the daily tides effect the movement of all types of water-borne vessels, ranging from recreational fishers, to commercial transportation. (Video: Kachemak Bay NERRS site)

View Video Clip in Windows Media Player
You may need to download:
Quicktime | Windows Media

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Why Are Estuaries Important? The Economy and Environment

Healthy estuaries are critical for the continued survival of many species of fish and other aquatic life, birds, mammals, and reptiles. All of the animals pictured above live in the Rookery Bay National Estuarine Research Reserve. Located on the gulf coast of Florida, Rookery Bay represents one of the few remaining undisturbed mangrove estuaries in North America. (Images: Rookery Bay NERRS site)

Estuaries are important natural places. They provide goods and services that are economically and ecologically indispensable. Often called nurseries of the sea (USEPA, 1993), estuaries provide vital nesting and feeding habitats for many aquatic plants and animals. Most fish and shellfish eaten in the United States, including salmon, herring, and oysters, complete at least part of their life cycles in estuaries. Estuaries also help to maintain healthy ocean environments. They filter out sediments and pollutants from rivers and streams before they flow into the oceans, providing cleaner waters for marine life.

Environmental Benefits

Estuaries provide critical habitat for species that are valued commercially, recreationally, and culturally. Birds, fish, amphibians, insects, and other wildlife depend on estuaries to live, feed, nest, and reproduce. Some organisms, like oysters, make estuaries their permanent home; others, like horseshoe crabs, use them to complete only part of their life cycle (Sumich, 1996). Estuaries provide stopovers for migratory bird species such as mallard and canvasback ducks. Many fish,

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including American shad, Atlantic menhaden and striped bass, spend most of their lives in the ocean, but return to the brackish waters of estuaries to spawn.

Economic Benefits

Estuaries are often the economic centers of coastal communities. Estuaries provide habitat for more than 75 percent of the U.S. commercial fish catch, and an even greater percentage of the recreational fish catch (National Safety Council's Environmental Center, 1998). The total fish catch in estuaries contributes $4.3 billion a year to the U.S. economy (ANEP, 1998).

Many estuaries support healthy recreational fisheries. This, in turn, provides financial security for communities that rely on tourists to support their economies. **Click on image** for a larger view. (Photo: Rookery Bay NERRS site)

Estuaries are also important recreational areas. Millions of people visit estuaries each year to boat, swim, watch birds and other wildlife, and fish. Coastal recreation and tourism generate from $8-$12 billion per year in the United States alone (National Safety Council's Environmental Center, 1998).

The fishing industry depends on healthy estuaries to provide essential nursery areas for many commercially important fish and shellfish species. **Click on image** for more details and larger view. (Photo: Apalachicola NERRS site)

Many estuaries are important centers of transportation and international commerce. In 1997, commercial shipping employed over 50,000 people in the United States (National Safety Council's Environmental Center, 1998). Many of the products you use every day pass through one or more estuaries on a commercial shipping vessel before ever reaching your home.

The continuing prosperity many coastal communities reap from transportation, fishing and tourism is clearly linked to the health of their estuaries. The economy and the environment are completely intertwined.

Healthy estuaries provide tranquil oases where canoists, kayakers, sailors, fishers, and many others can appreciate nature. Coastal recreation and tourism generate from $8-$12 billion per year in the United States alone. **Click on image** for larger view. (Photo: Rookery Bay NERRS site)

Birdwatching is a hobby enjoyed by millions of Americans. Healthy estuarine ecosystems provide excellent opportunities for birders to see diverse avian species in their native surroundings. **Click on image** for larger view. (Photo: Rookery Bay NERRS site)

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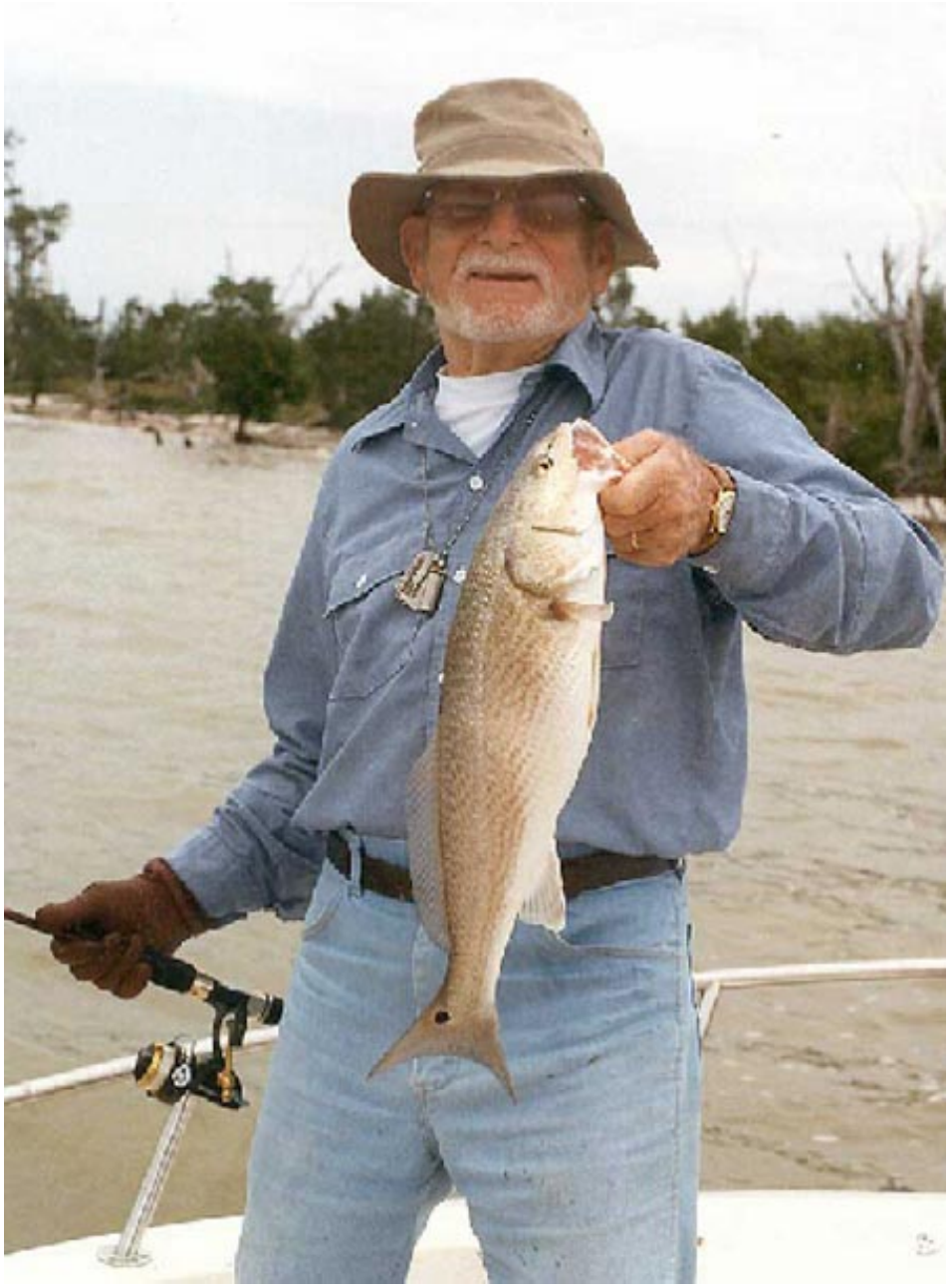
Many estuaries support healthy recreational fisheries. This, in turn, provides financial security for communities that rely on tourists to support their economies. (Photo: Rookery Bay NERRS site)



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The fishing industry depends on healthy estuaries to provide essential nursery areas for many commercially important fish and shellfish species. In Apalachacola Bay, Florida, about 60-85% of local residents make their living directly from the fishing industry, most of which is done in National Estuarine Research Reserve waters. Seafood landings from the Apalachicola Reserve are worth $14-$16 million dockside annually. At the consumer level, this represents a $70-$80 million industry. (Photo: Apalachicola NERRS site)

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Healthy estuaries provide tranquil oases where canoists, kayakers, sailors, fishers, and many others can appreciate nature. Coastal recreation and tourism generate from $8-$12 billion per year in the United States alone. (Photo: Rookery Bay NERRS site)

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Birdwatching is a hobby enjoyed by millions of Americans. Healthy estuarine ecosystems provide an excellent opportunity for birders to see diverse avian species in their native surroundings. (Photo: Rookery Bay NERRS site)

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Why Are Estuaries Important? Ecosystem Services

In addition to providing economic, cultural and ecological benefits to communities, estuaries deliver invaluable ecosystem services. Ecosystem services are fundamental life-support processes upon which all organisms depend (Daily et al., 1997). Two ecosystem services that estuaries provide are water filtration and habitat protection.

Many estuarine habitats filter pollutants such as herbicides, pesticides, and heavy metals out of the water flowing through them. **Click the image** to see a large animation of this process.

Habitats associated with estuaries, such as salt marshes and mangrove forests, act like enormous filters. As water flows through a salt marsh, marsh grasses and peat (a spongy matrix of live roots, decomposing organic material, and soil) filter pollutants such as herbicides, pesticides, and heavy metals out of the water, as well as excess sediments and nutrients (USEPA, 1993).

One reason that estuaries are such productive ecosystems is that the water filtering through them brings in nutrients from the surrounding watershed. A watershed, or drainage basin, is the entire land area that drains into a particular body of water, like a lake, river or estuary. In addition to nutrients, that same water often brings with it all of the pollutants that were applied to the lands in the watershed. For this reason, estuaries are some of the most fertile ecosystems on Earth, yet they may also be some of the most polluted.

Estuaries and their surrounding wetlands are also buffer zones. They stabilize shorelines and protect coastal areas, inland habitats and human communities from floods and storm surges from hurricanes. When flooding does occur, estuaries often act like huge sponges, soaking up the excess water. Estuarine habitats also protect streams, river channels and coastal shores from excessive erosion caused by wind, water and ice.

Unlike economic services, ecosystem services are difficult to put a value on, but we cannot do without them, and thus, they are essentially priceless.

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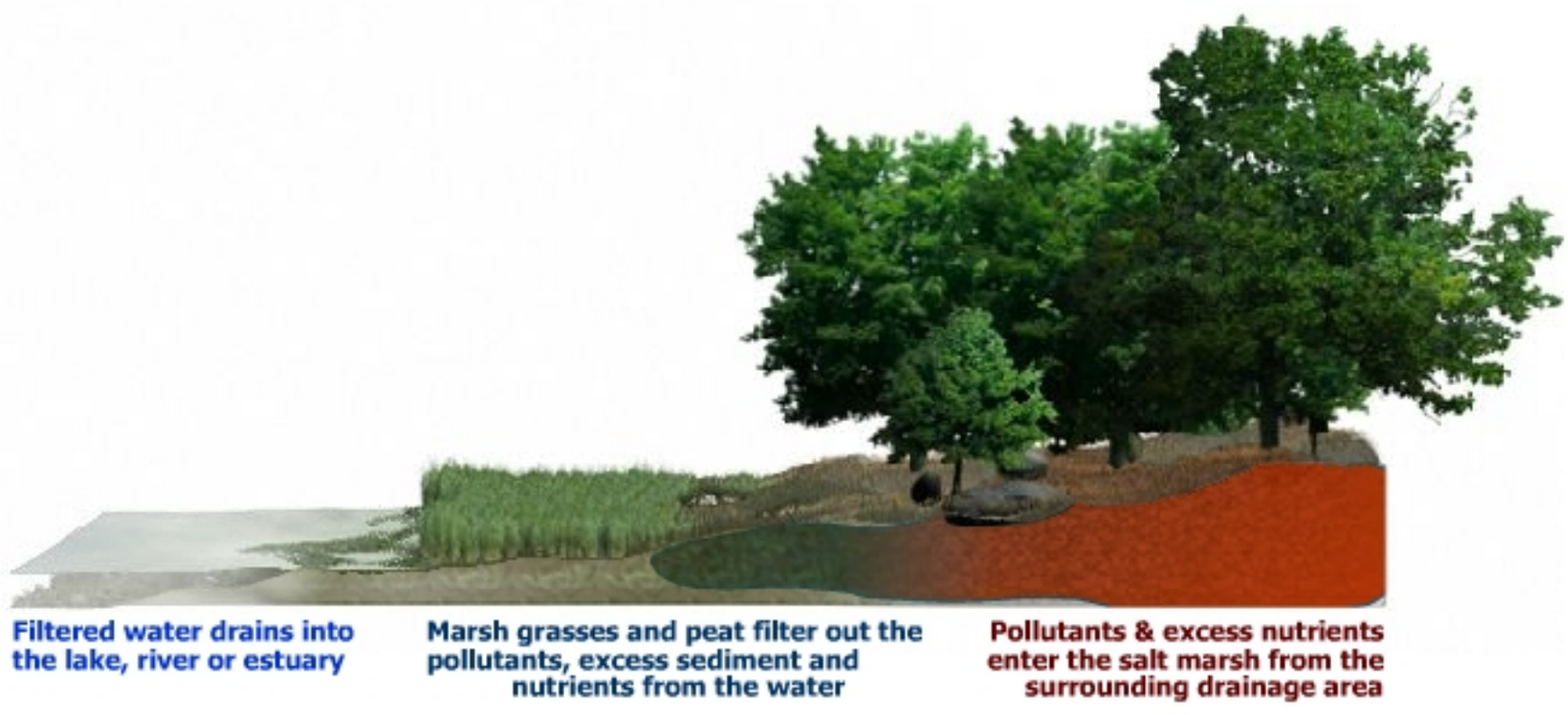
Salt marshes are one type of estuarine habitat that acts like an enormous filter, removing pollutants such as herbicides, pesticides, and heavy metals out of the water flowing through it (USEPA, 1993). In addition to pollutants, the same water often brings with it all of the nutrients from the surrounding watershed. A watershed, or drainage basin, is the entire land area that drains into a particular body of water, like a lake, river or estuary. The nutrients flowing into an estuarine habitat often provide for lush plant growth. For this reason, estuaries are some of the most fertile ecosystems on Earth. Yet, due to the pollutants they extract from waters running through them, they may also be some of the most polluted as well.

In the animation below, as groundwaters flow into the salt marsh from the surrounding drainage area, marsh grasses and the surrounding peat extract excess pollutants and nutrients from it.



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Estuaries

Classifying Estuaries - By Geology

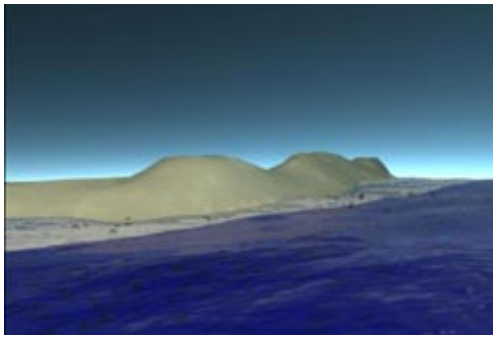
coastal plain | bar-built | deltas | tectonic | fjords

The features of an estuary are determined by a region's geology, and influenced by physical, chemical, and climatic conditions. For example, movements in the Earth's crust elevate or lower the coastline, changing the amount of seawater that enters an estuary from the ocean. The coastal elevation also determines the rate of fresh water that flows into an estuary from rivers and streams. The amounts of seawater and fresh water flowing into an estuary are never constant. The quantity of seawater in an estuary changes with the changing tides, and the quantity of fresh water flowing into an estuary increases and decreases with rainfall and snowmelt.

Mouse over the image to see how flooding waters create a coastal plain estuary. **Click the image** for more details and to view a larger animation.

Classification by Geology

Estuaries are typically classified by their existing geology or their geologic origins (in other words, how they were formed). The five major types of estuaries classified by their geology are coastal plain, bar-built, deltas, tectonic and fjords. In geologic time, which is often measured on scales of hundreds of thousands to millions of years, estuaries are often fleeting features of the landscape. In fact, most estuaries are less than 10,000 years old (Levinton, 1995).



Mouse over the image to see how bar-built estuaries are created. **Click the image** for more details and to view a larger animation.

Coastal plain estuaries, or drowned river valleys, are formed when rising sea levels flood existing river valleys. Bar-built estuaries are characterized by barrier beaches or islands that form parallel to the coastline and separate the estuary from the ocean. Barrier beaches and islands are formed by the accumulation of sand or sediments deposited by ocean waves.

A delta, characterized by large, flat, fan-shaped deposits of sediment at the mouth of a river, occurs when

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sediments accumulate more rapidly than ocean currents can carry them away. When the Earth's tectonic plates run into or fold up underneath each other, they create depressions that form tectonic estuaries. Fjords are steep-walled river valleys created by advancing glaciers, which later became flooded with seawater as the glaciers retreated.

Mouse over the image to see how a tectonic estuary is formed. **Click the image** for more details and to view a larger animation.

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Coastal Plain Estuaries

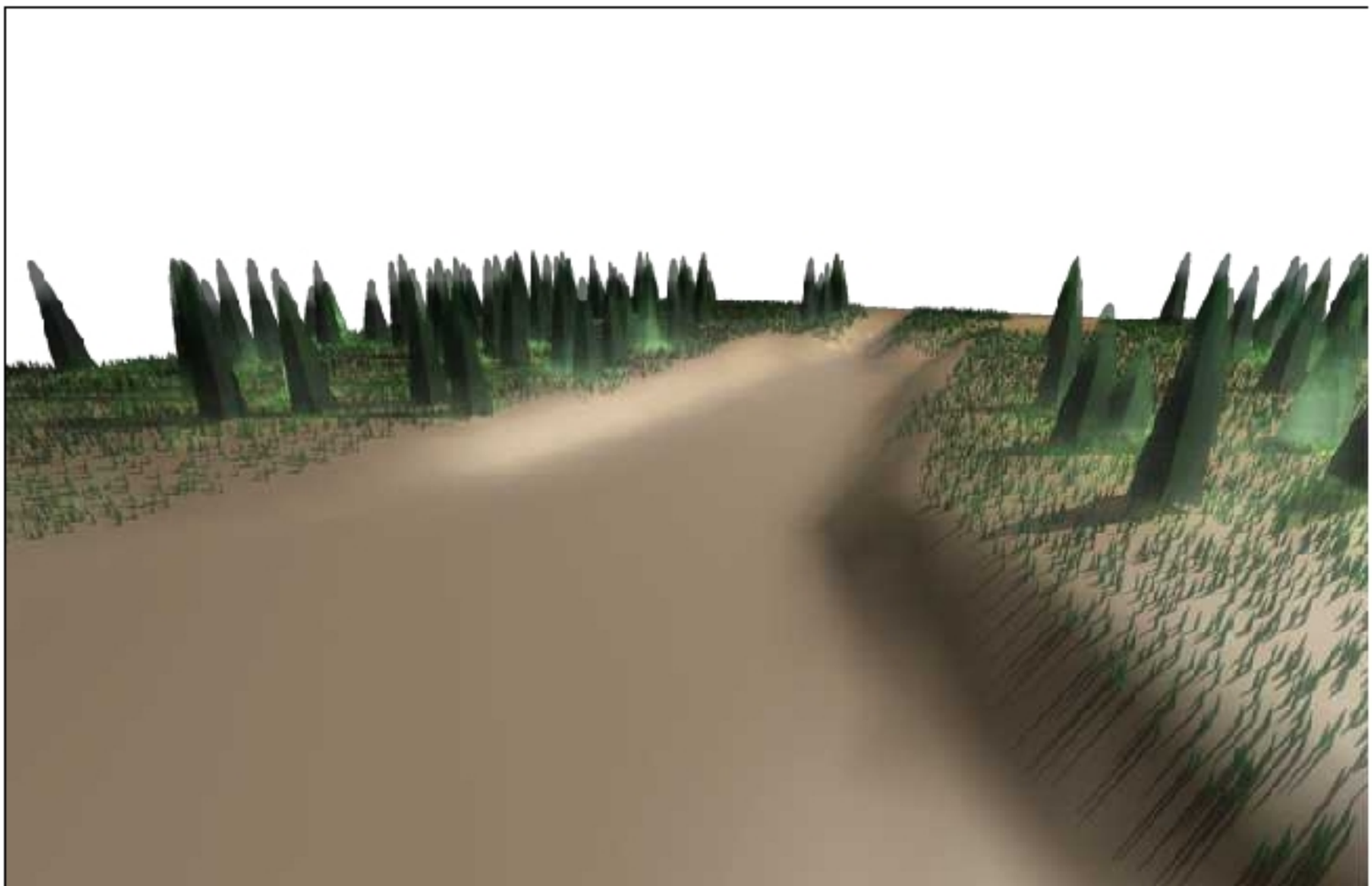
coastal plain | bar-built | deltas | tectonic | fjords

Chesapeake Bay on the East Coast of the United States and Coos Estuary on the West Coast are both coastal plain estuaries. These, and most other coastal plain estuaries in North America, were formed at the end of the last ice age between 10,000-18,000 years ago. As glaciers receded and melted, sea levels rose and inundated low-lying river valleys. Coastal plain estuaries are also called drowned river valleys.

Other examples of coastal plain estuaries include the Hudson River in New York, Narragansett Bay in Rhode Island, the Thames River in England, the Ems River in Germany, the Seine River in France, the Si-Kiang River in Hong Kong, and the Murray River in Australia.

In the animation below, rising waters flood a low-lying river valley, creating a coastal plain estuary.

Click on image to PLAY



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Bar-built Estuaries

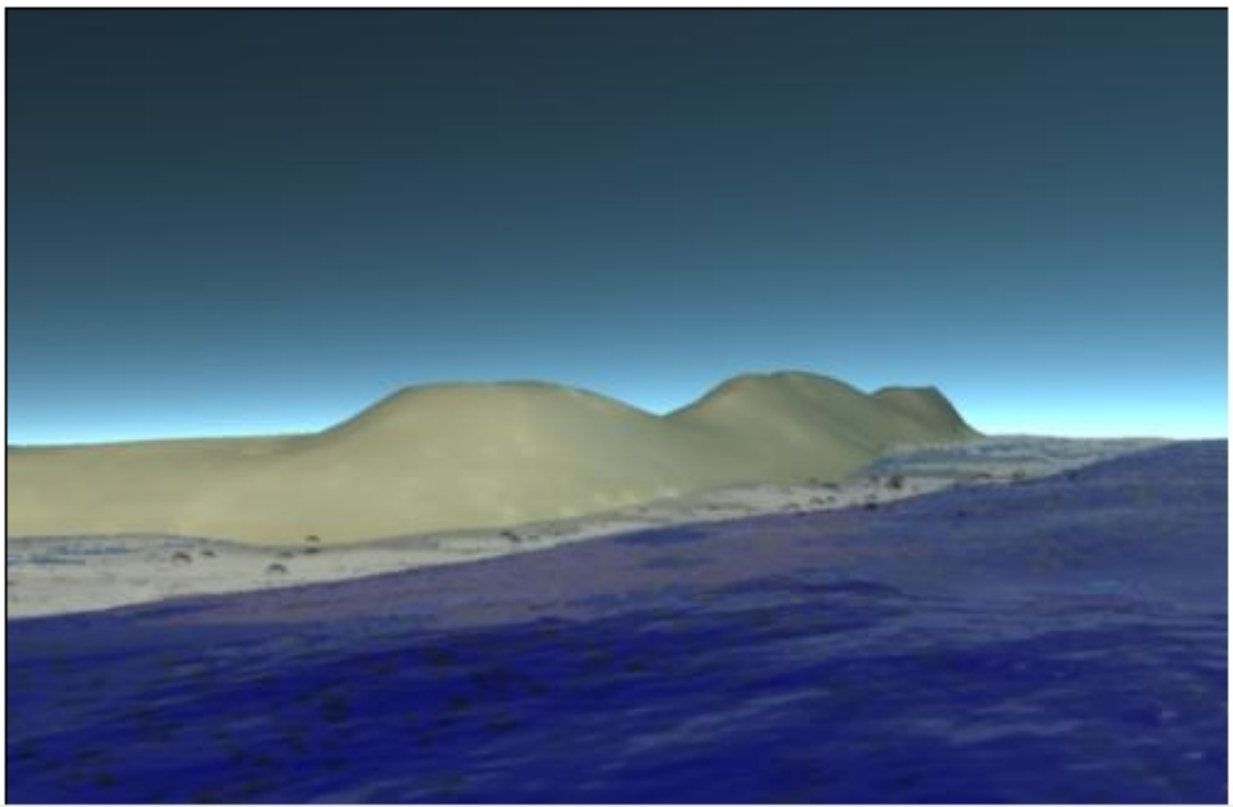
coastal plain | **bar-built** | deltas | tectonic | fjords

Bar-built or restricted-mouth estuaries occur when sandbars or barrier islands are built up by ocean waves and currents along coastal areas fed by one or more rivers or streams. The streams or rivers flowing into bar-built estuaries typically have a very low water volume during most of the year. Under these conditions, the bars may grow into barrier beaches or islands and the estuary can become permanently blocked. The area between the coast and the barrier beaches or islands are protected areas of calm water called lagoons.

Barrier beaches or islands break the impact of destructive ocean waves before they can reach the estuary and mainland, consequently protecting them. The barrier beaches take the brunt of the waves' force and are sometimes completely washed away, leaving the estuary and coast exposed and vulnerable. During heavy rains, large volumes of water flowing down the river or stream can also completely wash away small bars and reopen the mouth of the estuary (Ross, 1995; Sumich, 1996).

Bar-built estuaries are common along the Gulf Coast of Texas and Florida, in the Netherlands, and in parts of North Carolina. Good examples are Pamlico Sound in North Carolina, Matagorda Bay in Texas, and the Nauset Barrier Beach System on Cape Cod, Massachusetts.

In the animation below, ocean waves move sediments shoreward, as the sediments build up, they form sandbars. **Click on image to PLAY**



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Deltas

coastal plain | bar-built | **deltas** | tectonic | fjords

Deltas form at the mouths of large rivers, when sediments and silt accumulate rather than being washed away by currents or ocean waves. Over time, a complex set of channels, sand barriers and marshes form at the mouth of the river. As sediments continue to accumulate, the course of the river may even be changed. The name delta comes from the resemblance of the triangular fan-shaped mouth of the famous Nile River Delta to the Greek letter delta (Δ).

Bar-built estuaries and deltas both have large deposits of silt, mud and sand near their mouths, but the processes forming each of these estuaries are quite different. In deltas, sediments are carried downstream and deposited at the mouth of the river. Bar-built estuaries are formed by ocean waves and currents pushing sediments shoreward, building up sandbars and forming barrier islands (Ross, 1995; Sumich, 1996).

The image below is the Mississippi Delta as viewed from space. The city of New Orleans is in the center left-hand side of the image. The massive deposits of sand and silt that make up the delta appear light tan in color, surrounding the peninsula. (Photo: Weeks Bay NEERS site)

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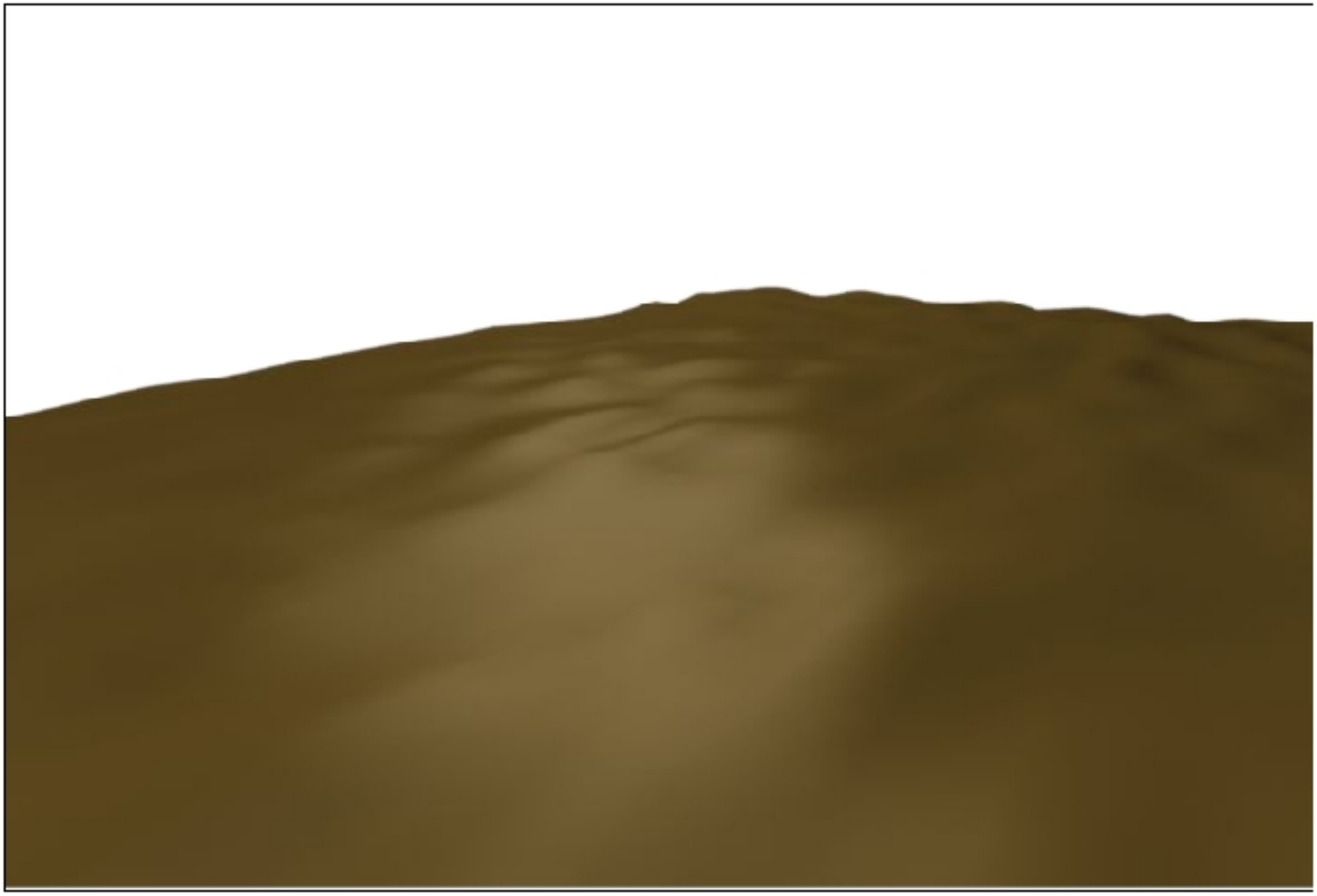
Tectonic Estuaries

coastal plain | bar-built | deltas | **tectonic** | fjords

The first stage in the formation of a tectonic estuary is when the rapid movement of the Earth's crust causes a large piece of land to sink, or subside, producing a depression or basin. These drastic changes typically occur along fault lines during earthquakes. If the depression sinks below sea level, ocean water may rush in and fill it. The same geological forces that create these depressions often form a series of natural channels that drain fresh water from nearby rivers and streams into these newly formed basins. The mixture of seawater and fresh water creates a tectonic estuary. Estuaries formed in this manner are typically very deep and surrounded by mountainous areas. San Francisco Bay, on the West Coast of the United States, is an excellent example of a tectonic estuary.

Click on image to PLAY



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Fjords

coastal plain | bar-built | deltas | tectonic | **fjords**

Fjords (pronounced fee-YORDS) are typically long, narrow valleys with steep sides that are created by advancing glaciers. The glaciers leave deep channels carved into the earth with a shallow barrier, or narrow sill, near the ocean. When the glaciers retreat, seawater floods the deeply incised valleys, creating estuaries. Fjords tend to have a moderately high input of freshwater. In comparison, very little seawater flows into the fjord because of the sill. In addition, the sill prevents deep waters in the fjord from mixing with deep waters of the sea. This poor water exchange results in stagnant, anoxic (low oxygen) water that builds up on the bottom of the fjord.

Not surprisingly, fjords are found in areas that were once covered with glaciers. Glacier Bay in Alaska and the Georgia Basin region of Puget Sound in Washington State are good examples of fjords. Fjords are also found throughout Canada, Chile, New Zealand, Greenland, Norway, Siberia, and Scotland.

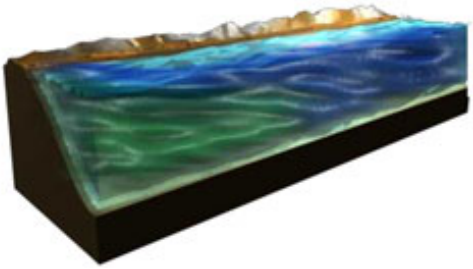
This satellite image of Glacier Bay Alaska shows many characteristic long narrow fjords that have been carved out of the surrounding terrain by advancing glaciers.

Estuaries

Classifying Estuaries - By Water Circulation

salt-wedge | fjord | slightly stratified | vertically mixed | freshwater

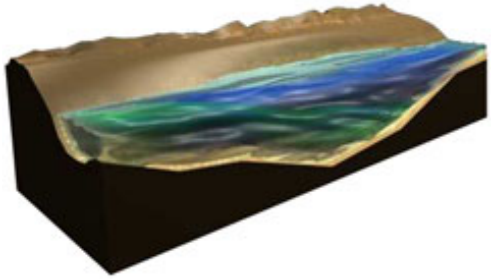
In addition to classifying estuaries based on their geology, scientists also classify estuaries based on their water circulation. The five major types of estuaries classified according to their water circulation include salt-wedge, fjord, slightly stratified, vertically mixed, and freshwater (Levinson, 1995; USEPA, 1993).



Salt-wedge estuaries are the most stratified, or least mixed, of all estuaries. **Click the image** for more details and to view a large animation.

Water movements in estuaries transport organisms, circulate nutrients and oxygen, and transport sediments and wastes. Once or twice a day, high tides create saltwater currents that move seawater up into the estuary. Low tides, also once or twice a day, reverse these currents. In some estuaries, the mixing of fresh water from rivers and saltwater from the sea is extensive; in others it is not. In the Hudson River in New York, for example, tidal currents carry saltwater over 200 km upstream.

The daily mixing of fresh water and saltwater in estuaries leads to variable and dynamic chemical conditions, especially salinity. When fresh water and saltwater meet in an estuary, they do not always mix very readily. Because fresh water flowing into the estuary is less salty and less dense than water from the ocean, it often floats on top of the heavier seawater. The amount of mixing between fresh water and seawater depends on the direction and speed of the wind, the tidal range (the difference between the average low tide and the average high tide), the estuary's shape, and the volume and flow rate of river water entering the estuary. These factors are different in each estuary, and often change seasonally within the same estuary. For example, a heavy spring rain, or a sustained shift in local winds, can drastically affect the salinity in different parts of an estuary (Sumich, 1996).



Fjords are typically long, narrow valleys with steep sides that were created by advancing glaciers. **Click the image** for more details and to view a large animation.

The degree to which fresh water and saltwater mix in an estuary is measured using isohalines. Isohalines are areas in the water that have equal

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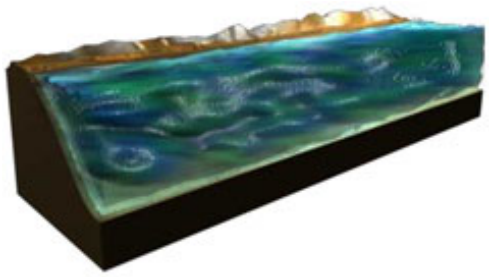
salt concentrations, or salinities. The shape of the isohalines indicates the amount of mixing that is occurring, and may provide clues about the estuary's geology (Sumich, 1996). To determine isohalines, scientists measure the water's salinity at various depths in different parts of the estuary. They record these salinity measurements as individual data points. Contour lines are drawn to connect data points that have the same salinity measurements. These contour lines show the bounderies of areas of equal salinity, or isohalines, and are then plotted onto a map of the estuary. The shape of the isohalines tells scientists about the type of water circulation in that estuary (Sumich, 1996).



The salinity of water in a **vertically mixed** estuary is the same from the water's surface to the bottom of the estuary. **Click the image** for more details and to view a large animation.

(top)

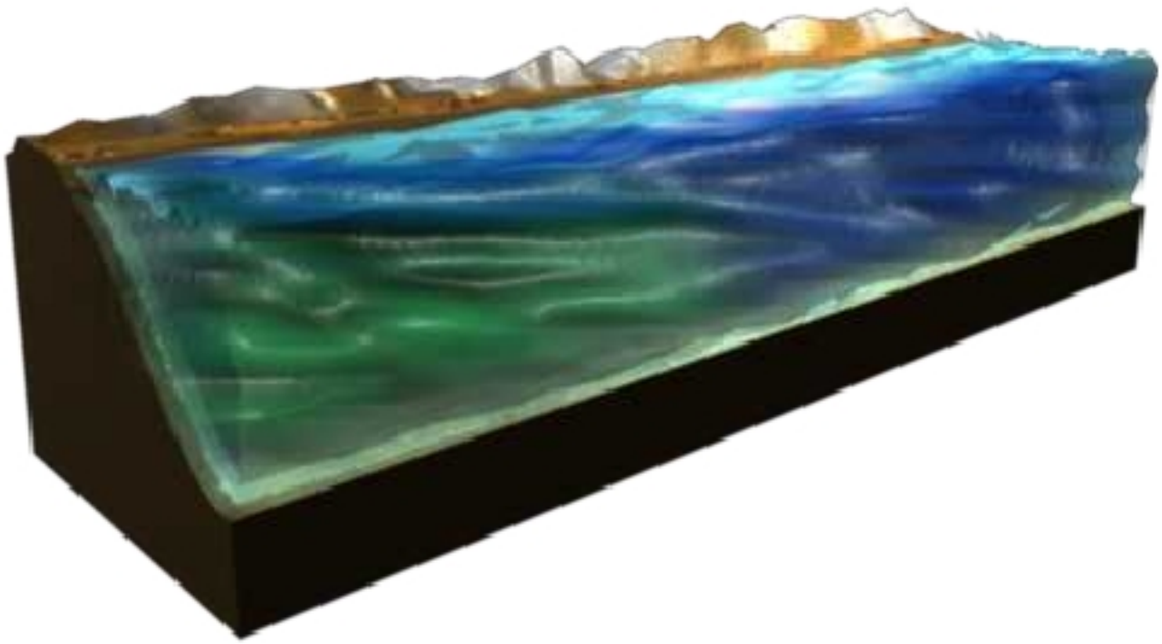
Return to Classifying Estuaries - By Water Circulation

Salt-wedge Estuaries

salt-wedge | fjord | slightly stratified | vertically mixed | freshwater

Salt-wedge estuaries are the most stratified, or least mixed, of all estuaries (Molles, 2002; Ross, 1995). They are also called highly stratified estuaries. Salt-wedge estuaries occur when a rapidly flowing river discharges into the ocean where tidal currents are weak. The force of the river pushing fresh water out to sea rather than tidal currents transporting seawater upstream determines the water circulation in these estuaries. As fresh water is less dense than saltwater, it floats above the seawater. A sharp boundary is created between the water masses, with fresh water floating on top and a wedge of saltwater on the bottom. Some mixing does occur at the boundary between the two water masses, but it is generally slight. The location of the wedge varies with the weather and tidal conditions. Examples of salt-wedge estuaries are the Columbia River in Washington and Oregon, the Hudson River in New York, and the Mississippi River in Louisiana.

In the animation below, the blue-colored fresh water flows from the river on the right-hand side of the image over a green-colored wedge of salty seawater as it moves out toward the ocean on the left-hand side of the image.



(top)

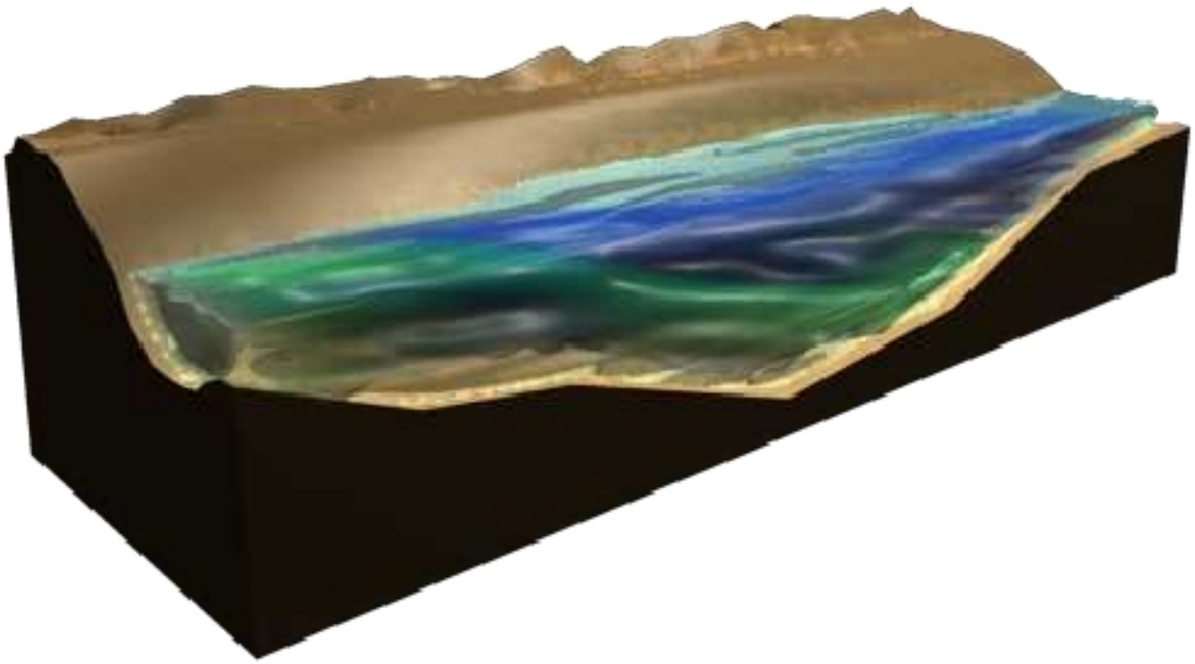
Return to Classifying Estuaries - By Water Circulation

Fjord-type Estuaries

salt-wedge | **fjord** | slightly stratified | vertically mixed | freshwater

Fjords (pronounced fee-YORDS) are typically long, narrow valleys with steep sides that were created by advancing glaciers. As the glaciers receded they left deep channels carved into the earth with a shallow barrier, or narrow sill, near the ocean. The sill restricts water circulation with the open ocean and dense seawater seldom flows up over the sill into the estuary. Typically, only the less dense fresh water near the surface flows over the sill and out toward the ocean. These factors cause fjords to experience very little tidal mixing; thus, the water remains highly stratified. Fjords are found along glaciated coastlines such as those of British Columbia, Alaska, Chile, New Zealand, and Norway.

In the animation below, the blue-colored fresh water is seen flowing over the narrow sill of the fjord on the far right-hand side of the image into the ocean. Almost none of the green-colored seawater is able to make it over the sill into the estuary.



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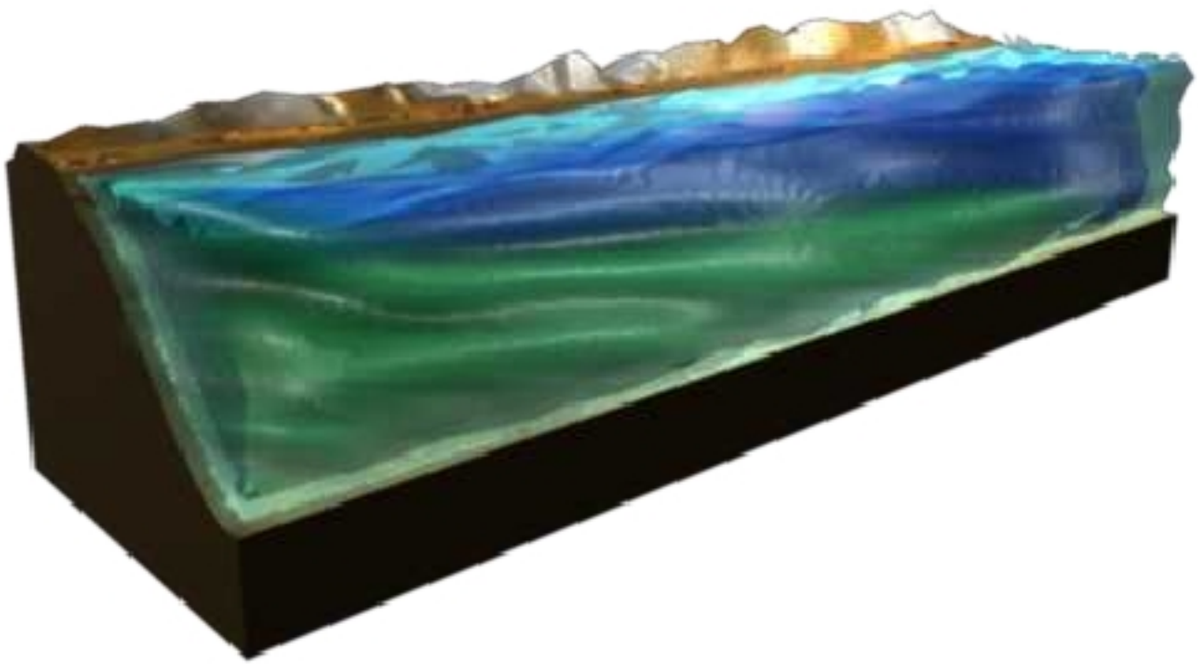
Slightly Stratified Estuaries

salt-wedge | fjord | **slightly stratified** | vertically mixed | freshwater

In slightly stratified or partially mixed estuaries, saltwater and freshwater mix at all depths; however, the lower layers of water typically remain saltier than the upper layers. Salinity is greatest at the mouth of the estuary and decreases as one moves upstream. Very deep estuaries, such as Puget Sound in Washington State and San Francisco Bay in California, are examples of slightly stratified estuaries (Ross, 1995). Even though Puget Sound is classified as a fjord in terms of its geology, it does not exhibit the characteristics of a fjord when classified by water circulation.

In this animation, you can see the slight stratification of the blue-colored freshwater flowing from the river on the right hand side of the image, and the green- colored seawater from the ocean on the left hand side of the image flowing beneath it.



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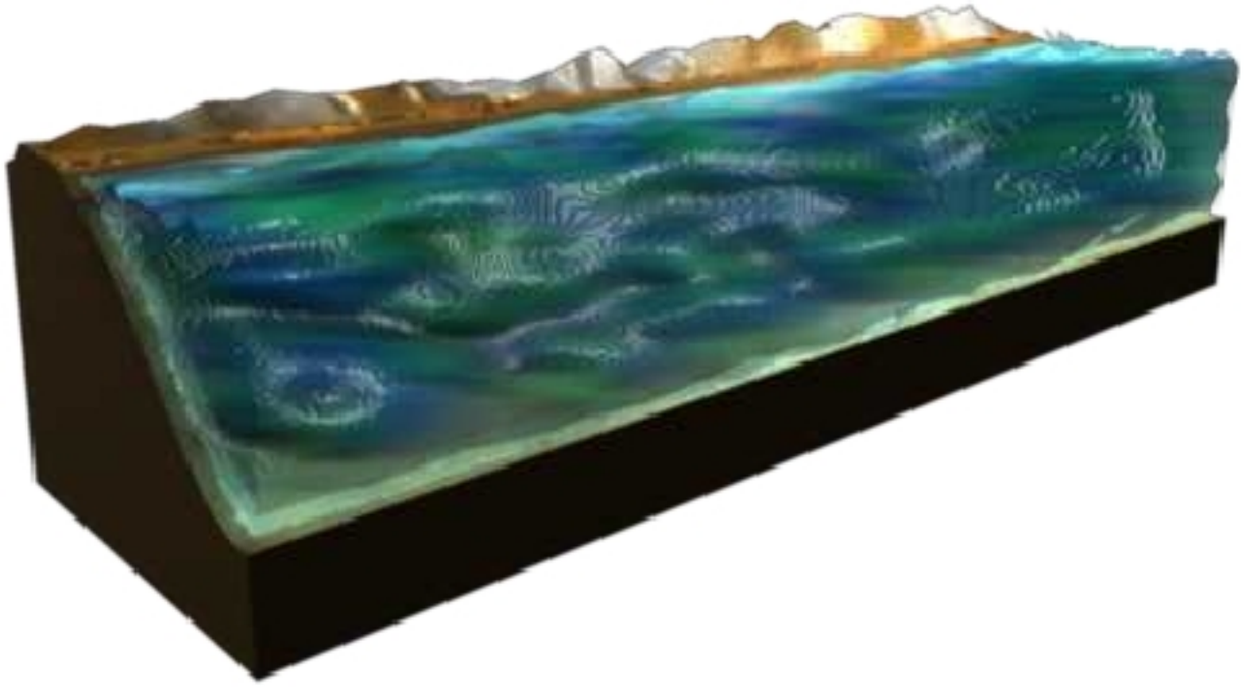
Vertically Mixed Estuary

salt-wedge | fjord | slightly stratified | **vertically mixed** | freshwater

A vertically mixed or well-mixed estuary occurs when river flow is low and tidally generated currents are moderate to strong (Ross, 1995). The salinity of water in a vertically mixed estuary is the same from the water's surface to the bottom of the estuary. Strong tidal currents eliminate the vertical layering of fresh water floating above denser seawater, and salinity is typically determined by the daily tidal stage. The estuary's salinity is highest nearest the ocean and decreases as one moves up the river. This type of water circulation is often found in large, shallow estuaries, such as Delaware Bay.



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Freshwater Estuaries

salt-wedge | fjord | slightly stratified | vertically mixed | **freshwater**

We normally think of estuaries as places where rivers meet the sea, but this is not always the case. Freshwater or Great Lakes-type estuaries do not fit the definition of a brackish water estuary where freshwater and seawater mix.

Freshwater estuaries are semi-enclosed areas of the Great Lakes in which the waters become mixed with waters from rivers or streams. Although these freshwater estuaries do not contain saltwater, they are unique combinations of river and lake water, which are chemically distinct. Unlike brackish estuaries that are tidally driven, freshwater estuaries are storm-driven. In freshwater estuaries the composition of the water is often regulated by storm surges and subsequent seiches (vertical oscillations, or sloshing, of lake water). While the Great Lakes do exhibit tides, they are extremely small. Most changes in the water level are due to seiches, which act like tides, exchanging water between the river and the lake.

Old Woman Creek is a freshwater estuary located on the south-central shore of Lake Erie in Ohio. Tidal changes in water level only average about 3 cm. As a storm-driven estuary system, during periods of low water flow, a barrier sand beach will often close the mouth of the estuary, isolating it from Lake Erie. Water movement through the sand barrier beach is generally very limited. (Photo: Old Woman Creek NERRS site)

Estuaries

Estuarine Habitats

salt marshes | mangrove forests

A rich array of habitats surround estuaries. The type of habitat is usually determined by the local geology and climate. Habitats associated with estuaries include salt marshes, mangrove forests, mud flats, tidal streams, rocky intertidal shores, reefs, and barrier beaches.

<< Lower Tide | Play - Stop | Higher Tide >>

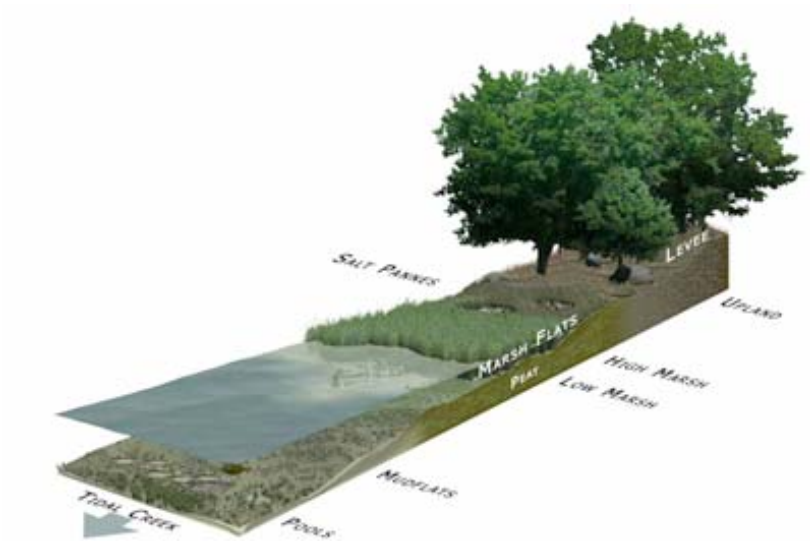

Image: 3 of 4- High Tide

Click here to read more about salt-marsh habitats and to view a large slideshow.

Examples of nearly every type of estuarine habitat exist along the coastline of the United States. In New England, salt-tolerant grasses fill salt marshes along the shores of tidal rivers. As one travels further south, the Atlantic Coast becomes much sandier, and barrier beaches enclose huge bays or sounds. In this region, estuarine habitats cover large areas along tidal rivers, and salt marshes reach far inland. Along the southern coast of Florida and lining the Gulf of Mexico are extensive mazes of mangrove forests, also called mangals.

From northwestern Florida to the Texas coast are long, narrow, sandy barrier islands and shallow estuaries lined with marshes. Along the Texas coast, barrier islands protect estuaries that have formed narrow lagoons with small openings to the Gulf of Mexico. In these areas, estuaries with very little freshwater input often become

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hypersaline or super salty.

Along the Pacific Coast of the United States, from northern California to Alaska, coastal rivers flow quickly out of the mountains and into very small estuaries. San Francisco Bay is one of the largest estuaries on the U.S. West Coast, and one of only a few that is similar in size to those found on the East Coast.

Mangrove forests line about two-thirds of the coastlines in tropical areas of the world. They can be recognized by their dense tangle of prop roots that make the trees appear to be standing on stilts above the water. **Click on image** to read more about mangroves and for a larger view. (Photo: Rookery Bay NERRS site)

(top)

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Salt Marshes

salt marshes | mangrove forests

Scroll down to read detailed information about salt marshes

<< Lower Tide | Play - Stop | Higher Tide >>

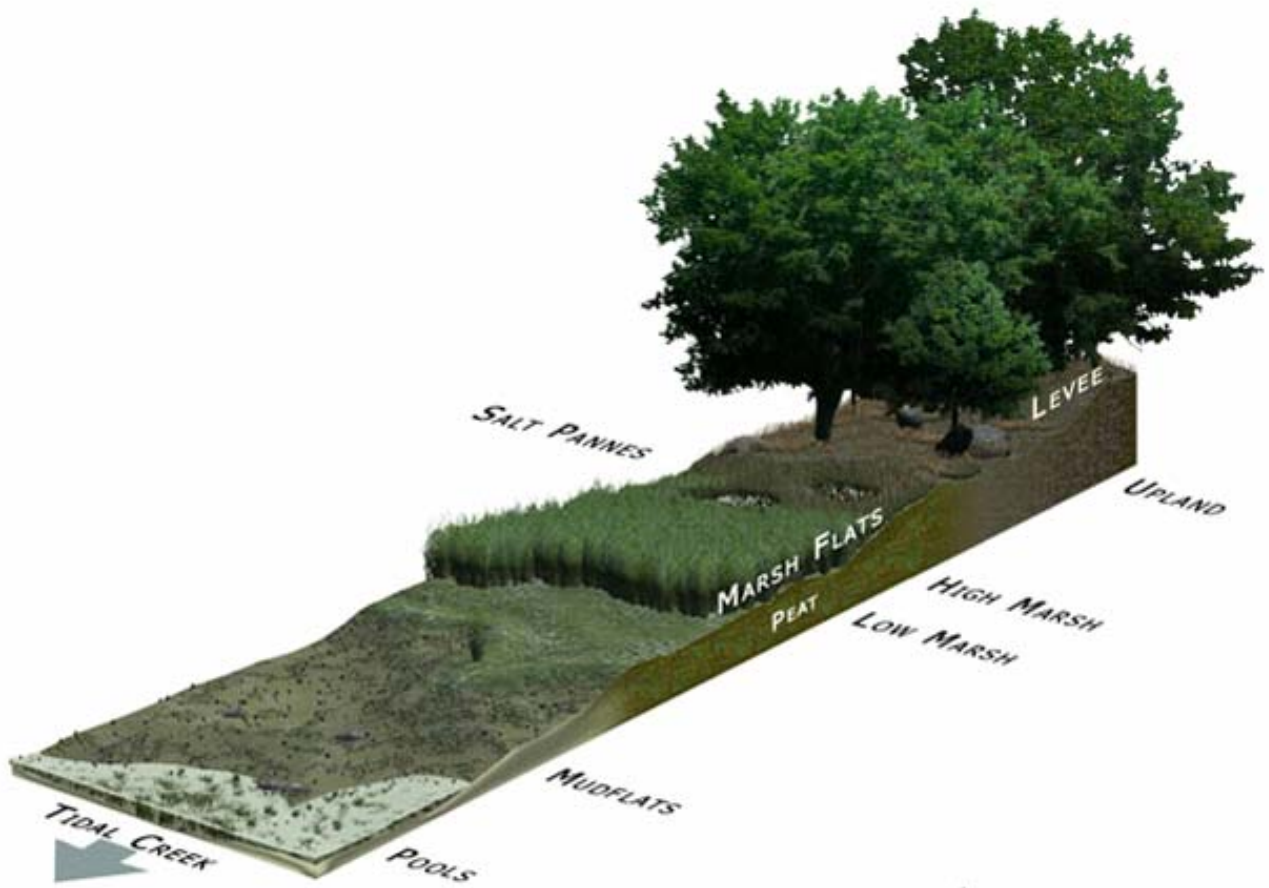

Image: 1 of 4- Low Tide

Salt marshes are a mosaic of snaking channels called tidal creeks that fill with seawater during high tides and drain during low tides. Fish species including flounder and mullet live most of their lives in marsh creeks.

(top)

Levees are areas of higher ground that border the marsh creeks. Between the levees and tidal creeks are marsh flats, which contain pools and salt pannes. Salt pannes are shallow depressions that contain very high concentrations of salt. Pannes retain seawater for very short periods of time. When the seawater evaporates, the salts remain and accumulate over many tidal cycles. Glasswort, a plant tolerant to very high salt concentrations, is one of the only organisms able to survive in salt pannes. Pools are generally deeper than pannes, and retain water all year long (Molles, 2002). Salt-marsh snails and green crabs are some of the creatures found in pools scattered across the marsh.

Low-lying areas of the marsh are often covered with large, flat expanses of mud called mud flats (Bertness, 1999; Smith and Smith, 2000). Composed of fine silts and clays, mud flats harbor burrowing creatures including clams, mussels, oysters, fiddler crabs, sand shrimp, and bloodworms.

Salt marshes are salty because they are flooded by seawater every day. They are marshy because their ground is composed of peat. Peat is made of decomposing plant matter that is often several feet thick. Peat is waterlogged, root-filled, and very spongy. Because salt marshes are waterlogged and contain lots of decomposing plant material, oxygen levels in the peat are extremely low—a condition called hypoxia. Hypoxia promotes the growth of bacteria which produce the rotten-egg smell that is attributed to marshes and mud flats.

Salt marshes are covered with salt-tolerant plants, or halophytes, like salt hay, black rush, and smooth cordgrass. However, these plants do not grow together in the same area. Marshes are divided into distinct zones, the high marsh and the low marsh. The difference in elevation between these two areas is usually only a few centimeters, but for the plants that inhabit each of these zones, a few centimeters makes a world of difference. The low marsh floods daily at high tide. The high marsh usually floods about twice a month during very high tides associated with new and full moons. The more often an area is flooded, the more saline it is. Plants living in salt marshes have different tolerances to salt. Those with higher tolerances are found in the low marsh, and those with lower tolerances to salt are found in the high marsh zones. Plants from one marsh zone are never found in the other.

(top)

Smooth cordgrass *(Spartina alterniflora)* dominates the low marsh all the way down to the estuary's edge. It is tall, sturdy, broad-leaved, and one of the main components of peat. As one moves toward the high marsh, salt hay *(Spartina patens),* a very fine-leaved grass about 1-2 feet tall, and spike grass *(Distichlis spicata)* dominate the area. The highest parts of the marsh are characterized by black rush *(Juncus gerardii),* which grows in dense swaths.

Surrounding the high marsh are the upland habitats. Uplands are rarely, if ever, flooded with saltwater.

(top)

Return to Estuarine Habitats

Mangrove Forests

salt marshes | **mangrove forests**

Scroll down to read detailed information about mangrove forests

Mangrove forests or mangals grow at tropical and subtropical latitudes near the equator where the sea surface temperatures never fall below 16°C. Mangals line about two-thirds of the coastlines in tropical areas of the world.

There are about 80 species of mangrove trees, all of which grow in hypoxic (oxygen poor) soils where slow-moving waters allow fine sediments to accumulate (Florida Department of Environmental Protection, 2000). Many mangrove forests can be recognized by their dense tangle of prop roots that make the trees appear to be standing on stilts above the water. This tangle of roots helps to slow the movement of tidal waters, causing even more sediments to settle out of the water and build up the muddy bottom. Mangrove forests stabilize the coastline, reducing erosion from storm surges, currents, waves and tides.

Just like the high and low areas of salt marshes where specific types of grasses are found, mangals have distinct zones characterized by the species of mangrove tree that grows there. Where a species of

mangrove tree exists depends on its tolerance for tidal flooding, soil salinity, and the availability of nutrients. Three dominant species of mangrove tree are found Florida mangals. The red mangrove (*Rhizophora mangle*) colonizes the seaward side of the mangal, so it receives the greatest amount of tidal flooding. Further inland and at a slightly higher elevation, black mangroves *(Avicennia germinanas)* grow. The zone in which black mangrove trees are found is only shallowly flooded during high tides. White mangrove *(Laguncularia racemosa)* and buttonwood trees *(Conocarpus erectus),* a non-mangrove species (Florida Department of Environmental Protection, 2000), face inland and dominate the highest parts of the mangal. The zone where white mangrove and buttonwood trees grow is almost never flooded by tidal waters.

A unique mix of marine and terrestrial species lives in mangal ecosystems. The still, sheltered waters among the mangrove roots provide protective breeding, feeding, and nursery areas for snapper, tarpon, oysters, crabs, shrimp and other species important to commercial and recreational fisheries. Herons, brown pelicans, and spoonbills all make their nests in the upper branches of mangrove trees. (Florida Department of Environmental Protection, 2000). (Photo: Rookery Bay NERRS site)

(top)

Estuaries

Adaptations to Life in the Estuary

mangrove trees | blue crabs

Mangrove trees and blue crabs are some of the estuarine species that have adapted to unique environmental conditions. In almost all estuaries the salinity of the water changes constantly over the tidal cycle. To survive in these conditions, plants and animals living in estuaries must be able to respond quickly to drastic changes in salinity.

Pickleweed (*Salicornia sp.*) is an edible halophylic (salt-loving) plant that tolerates the unique and constantly changing environment of the salt-marsh estuary. **Click on image** for more details and a larger view.

Plants and animals that can tolerate only slight changes in salinity are called stenohaline (Sumich, 1996). These organisms usually live in either freshwater or saltwater environments. Most stenohaline organisms cannot tolerate the rapid changes in salinity that occur during each tidal cycle in an estuary.

Plants and animals that can tolerate a wide range of salinities are called euryhaline. These are the plants and animals most often found in the brackish waters of estuaries. There are far fewer euryhaline than stenohaline organisms because it requires a lot of energy to adapt to constantly changing salinities. Organisms that can do this are rare and special. Some organisms have evolved special physical structures to cope with changing salinity. The smooth cordgrass *(Spartina alterniflora)* found in salt marshes, for example, has special filters on its roots to remove salts from the water it absorbs. This plant also expels excess salt through its leaves.

Unlike plants, which typically live their whole lives rooted to one spot, many animals that live in estuaries must change their behavior according to the surrounding waters' salinity in order to survive. Oysters and blue crabs are good examples of animals that do this.

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Oysters can live in the brackish waters of estuaries by adapting their behavior to the constantly changing environment. **Click on image** for more details and a larger view. (Photo: Apalachicola NERRS site)

Return to Adaptations to Life in the Estuary

Adaptations of Mangrove Trees

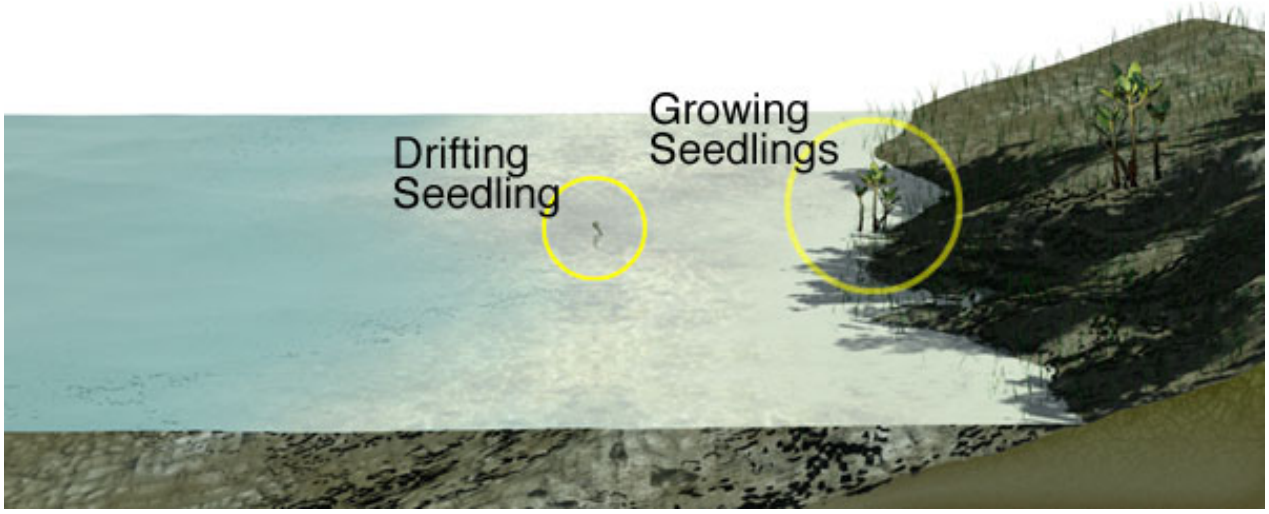
mangrove trees | blue crabs

Mangrove trees have become specialized to survive in the extreme conditions of estuaries. Two key adaptations they have are the ability to survive in waterlogged and anoxic (no oxygen) soil, and the ability to tolerate brackish waters.

Some mangroves remove salt from brackish estuarine waters through ultra-filtration in their roots. Other species have special glands on their leaves that actively secrete salt, a process that leaves visible salt crystals on the upper surface of the leaves.

All mangrove species have laterally spreading roots with attached vertical anchor roots. These roots are very shallow. Because the soil in shallow areas of mangal forests is typically flooded during high tides, many species of mangrove trees have aerial roots, called pneumatophores, that take up oxygen from the air for the roots. Some species also have prop roots or stilt roots extending from the trunk or other roots that help them withstand the destructive action of tides, waves, and storm surges (Smith and Smith, 2000).

Many mangrove trees also have a unique method of reproduction. Instead of forming seeds that fall to the soil below and begin growing, mangrove seeds begin growing while still attached to the parent plant. These seedlings, called propagules, even grow roots. After a period of growth, these seedlings drop to the water below and float upright until they reach water that is shallow enough for their roots to take hold in the mud (Northern Territory Government, 2000).



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Adaptations of Blue Crabs

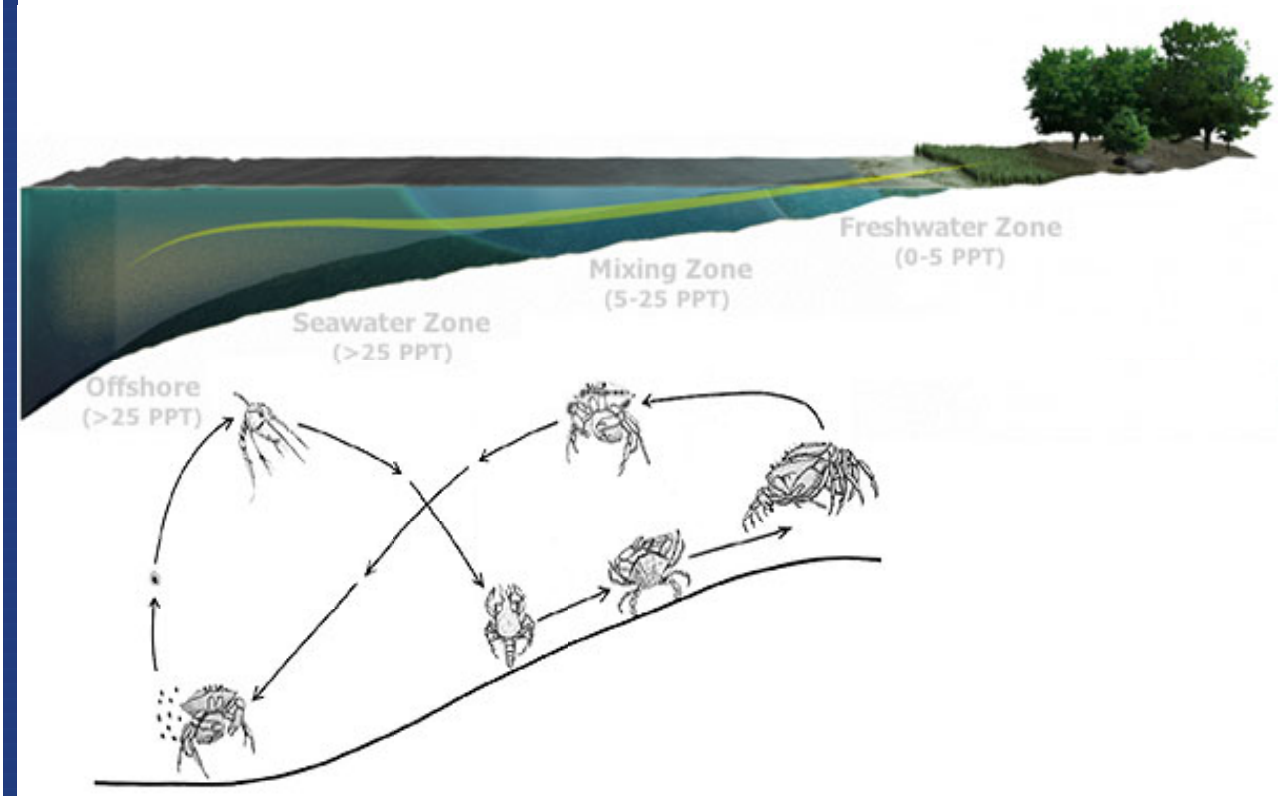
mangrove trees | **blue crabs**

Blue crabs live in estuaries along the United States' Atlantic and Gulf coasts. They are mobile predators whose salinity requirements change at different stages in their lives.

Adult male crabs live in the low-salinity waters upstream, while adult female crabs live in the higher-salinity waters near the mouth of the estuary. During the crabs' mating season (May to October), the high-salinity preference of the female overlaps with the lower-salinity preference of the male (Zinski, 2003). After mating, female crabs migrate offshore, sometimes up to 200 km, to high-salinity waters to incubate their eggs. The females release their larvae, called zoeae, during spring high tides. The zoeae, resembling tiny shrimp, develop in the coastal waters. Zoeae require water with a salinity over 30 ppt (parts per thousand) for optimal development, which is only found in the ocean. Winds and coastal currents keep the larvae near the ocean shore, until they return to the estuary as young crabs, called megalops.

When the megalops return to the estuary, they swim up and down in the water in response to light and tides. This is called vertical migration (Zinski, 2003). The young crabs use nighttime flood tides to move upriver into the shallow parts of the estuary. Eventually, the young crabs take up life on the bottom of the estuary, seeking out shallow-water habitats like seagrass beds and submerged aquatic vegetation (SAV), where they feed and gain protection from predators.

MouseOver the crabs for details of the blue crab's life cycle.



Estuaries

Natural Disturbances to Estuaries

This pair of images illustrates the destructive power that hurricanes can have on estuarine environments. This barrier island in Pine Beach, Alabama, was severed following hurricane Ivan's landfall in late 2004. The image on the left was taken on July 17, 2001. The image on the right was taken on September 17, 2004, soon after Hurricane Ivan reached the Alabama mainland. **Click on either image** for a larger view.

Estuaries are fragile ecosystems that are very susceptible to disturbances. Natural disturbances are caused by the forces of nature, while anthropogenic disturbances are caused by people. Natural disturbances include winds, tidal currents, waves, and ice. Anthropogenic disturbances include pollution, coastal development, and the introduction of non-native species to an area.

We like to think of natural places as being stable over time, but, in fact, they are not. Natural habitats are continually disturbed by natural processes, followed by periods of recovery. When a natural disturbance is followed by an anthropogenic disturbance or vice versa, a habitat may become so damaged that it never recovers.

Dead floating plant material, called wrack, is often deposited on salt marshes by high spring tides, smothering all of the plant life beneath it. **Click on image** for more details and a larger view. (Photo: Weeks Bay NERRS site)

One type of natural disturbance is the continual pounding of ocean waves. In many estuaries, barrier beaches protect inland habitats from wave erosion. If these beaches are destroyed, salt marshes and inland habitats adjacent to the estuary may become permanently damaged. Waves can also dislodge plants and animals, or bury them with sediments, while objects carried by the water can crush them. Large storms are especially destructive to estuaries, particularly in areas like Florida and the Carolinas, where barrier beaches are common.

A common disturbance to estuaries in nontropical regions is winter ice

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(Bertness, 1999). Ice can freeze on an estuary's shoreline, or float freely in the water. When slabs of free-floating ice make contact with the shore, they have a scouring effect, dislodging and killing the plants and shoreline animals that lie in their path. When sheets of ice form on the shore, especially in salt marshes, they can trap plants and grass stalks inside them. During high tides, these ice sheets are lifted up, or rafted, inland to the high marsh. These rafts carry both ice and tufts of plants inshore. When the rafts settle down at low tide, they can smother inshore vegetation or scrape it from the soil. Further damage is caused as these sheets of ice and vegetation are rafted and dragged across the marsh with the ebb and flow of the daily tides.

Another natural disturbance in salt marshes is the burial of vegetation by rafts of dead floating plant material, called wrack. Wracks can be quite large—up to hundreds of square meters, and up to 30 centimeters thick. The spring high tides often move these wracks into the high marsh, where they become stranded (Bertness, 1999).

(top)

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This pair of images iillustrates the destructive power that hurricanes can have on estuarine environments. This barrier island in Pine Beach, Alabama, was severed following Hurricane Ivan's landfall in late 2004. The image on the left was taken on July 17, 2001. The image on the right was taken on September 17, 2004, soon after Hurricane Ivan reached the Alabama mainland.

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Dead floating plant material, called wrack, is often deposited on salt marshes by high spring tides. Wracks can be quite large—up to hundreds of square meters, and up to 30 centimeters thick. If these wracks are deposited in the high marsh, they often become stranded (Bertness, 1999), smothering all of the plant life beneath them. (Photo: Weeks Bay NERRS site)

(top)

Estuaries

Human Disturbances to Estuaries

toxic substances | nutrient pollution | pathogens | invasive species

Because they are transitional areas between the land and the sea, and between freshwater and saltwater environments, estuaries can be seriously impacted by any number of human, or anthropogenic, activities.

Construction projects like this housing development can cause major damage to estuaries through a variety of mechanisms. **Click on image** for more details and a larger view. (Photo: Bernz/Clearwater)

The greatest threat to estuaries is, by far, their large-scale conversion by draining, filling, damming or dredging. These activities result in the immediate destruction and loss of estuarine habitats. Until the last few decades, many estuary habitats in North America were drained and converted into agricultural areas; others were filled to create shipping ports and expand urban areas. In the United States, 38 percent of the wetlands associated with coastal areas have been lost to these types of activities (Good et al., 1998). In some areas, the estuarine habitat loss is as high as 60 percent.

Of the remaining estuaries around the world, many are seriously degraded by pollution. People have historically viewed estuaries and waterways as places to discard the unwanted by-products of civilization. Pollution is probably the most important threat to water quality in estuaries. Poor water quality affects most estuarine organisms, including commercially important fish and shellfish.

The pollutants that have the greatest impact on the health of estuaries include toxic substances like chemicals and heavy metals, nutrient pollution (or eutrophication), and pathogens such as bacteria or viruses.

Another, less widely discussed human-caused disturbance is the introduction of non-native or invasive species into estuarine environments.

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Toxic Substances

toxic substances | nutrient pollution | pathogens | invasive species

Toxic substances are chemicals and metals that can cause serious illness or death. They may be poisonous, carcinogenic (cancer-causing) or harmful in other ways to living things. Pesticides, automobile fluids like antifreeze, oil or grease, and metals such as mercury or lead have all been found to pollute estuaries. These substances can enter an estuary through industrial discharges, yard runoff, streets, agricultural lands, and storm drains.

Once consumed by plants and animals, some toxic substances can accumulate in these organisms' tissues. This process is called biomagnification. The insecticide DDT, and the metal mercury, are known to progressively accumulate or build up in the tissues of organisms as they make their way from the bottom of the food web (algae, shrimp, oysters, fish) to the top (osprey, eagles, bears, people).

Sometimes, toxic substances become attached to sediments (sand or mud) that flow down rivers and get deposited in estuaries. Toxic substances that enter the estuary this way often contaminate bottom-dwelling animals like oysters or clams, making them a serious health risk to people who eat them. (USEPA, 1993; USEPA, date unknown).

(top)

Toxic substances that find their way into estuaries cause severe harm not only to the native plant and animal species that live there, but also to people who may consume them. **Click on image** for further detail and larger view. (Photo: Stanne/NYSDEC)

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Return to Human Disturbances to Estuaries - Toxic Substances

Toxic substances that find their way into estuaries cause severe harm not only to the native plant and animal species that live there, but also to people who may consume them. People who eat plants or animals contaminated with high levels of toxic substances can contract many terrible diseases, including cancer. In addition to being directly harmful to plants, animals, and people, toxic substances can cause great economic damage to communities that depend on healthy recreational and commercial fisheries for their livelihoods. Toxic pollutants may originate many miles away and be transported by groundwater or sediments to the estuaries where they are eventually found. (Photo: Stanne/NYSDEC)

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Nutrient Pollution - Eutrophication

toxic substances | **nutrient pollution** | pathogens | invasive species

Nitrates and phosphates are nutrients that plants need to grow. In small amounts they are beneficial to many ecosystems. In excessive amounts, however, nutrients cause a type of pollution called eutrophication. Eutrophication stimulates an explosive growth of algae (algal blooms) that depletes the water of oxygen when the the algae die and are eaten by bacteria. Estuarine waters may become hypoxic (oxygen poor) or anoxic (completely depleted of oxygen) from algal blooms. While hypoxia may cause animals in estuaries to become physically stressed, anoxic conditions can kill them.

Nutrient pollution often causes explosive algal growth, which depletes the water of oxygen when the algae die. Toxic and foul-smelling compounds may also be produced through this process. **Click on image** for a larger view. (Photo: Weeks Bay NERRS site)

Eutrophication may also trigger toxic algal blooms like red tides, brown tides, and the growth of *Pfiesteria. Pfiesteria* is a single-celled organism that can release very powerful toxins into the water, causing bleeding sores on fish, and even killing them. Although consuming fish affected by this toxin is not harmful to humans, exposure to waters where *Pfisteria* blooms occur can cause serious health problems (USEPA, 1998; Howarth et al., 2000).

Eutrophication is often devastating to animals and plants in estuaries as well as the economies of communities surrounding estuaries. Toxic algal blooms disrupt tourism due to foul odors and unsightly views, and poisoned fish and shellfish adversely affect recreational and commercial fisheries (Carpenter, 1998; Howarth et al., 2000).

Nutrient pollution is the single largest pollution problem affecting coastal waters of the United States (Howarth et al., 2000). Most excess nutrients come from discharges of sewage treatment plants and septic tanks, stormwater runoff from overfertilized lawns, golf courses and agricultural fields. Over 60 percent of the coastal rivers and bays in the United States are moderately to severely affected by nutrient pollution (Howarth et al., 2000).

(top)

Return to Human Disturbances to Estuaries - Nutrient Pollution

Nutrient pollution often causes explosive algal growth which depletes waters of oxygen when the algae die. Toxic and foul smelling compounds may also be produced through this process. Nutrient pollution is the single largest pollution problem effecting coastal waters of the United States (Howarth et al., 2000). Most excess nutrients come from discharges of sewage treatment plants and septic tanks, storm-water runoff from overfertilized lawns, golf courses and agricultural fields. Over 60 percent of the coastal rivers and bays in the United States are moderately to severely affected by nutrient pollution (Howarth et al., 2000). (Photo: Weeks Bay NERRS site)

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Pathogens

toxic substances | nutrient pollution | **pathogens** | invasive species

Pathogens are disease-causing organisms. They include bacteria, viruses and other parasites. Pathogens pose a major health threat to people who swim, fish, or boat in estuaries, as well as to filter-feeding animals, like oysters, mussels and clams. These animals concentrate the pathogens in their tissues, making them dangerous for humans to eat.

Pathogens can come from many sources, including sewage treatment plants, leaky septic systems, pet, livestock, or wildlife wastes, and combined sewage overflows (CSOs). CSOs are probably the largest contributor of bacteria and viruses in most estuaries. They carry the combined sewage from residential, industrial and commercial wastes in the form of sewage solids, metals, oils, grease and bacteria. During heavy rains, CSOs combine with storm water and overwhelm sewage treatment plants. The result is that untreated or partially treated waste flows directly into the estuary.

Contamination by pathogens can result in the temporary or permanent closure of beaches and shellfishing areas. In some cases, health officials may warn citizens that they should restrict the amount of fish and shellfish that they eat.

(top)

Pathogens can enter estuaries from many different sources. Storm-water runoff and improper or inadequate sewage treatment may all allow disease-causing organisms to enter estuaries, affecting the plants and animals that live there, as well as the people who may consume them. **Click on image** for a larger view. (Photo: Stanne/NYSDEC)

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Pathogens can enter estuaries from many different sources. Storm-water runoff and improper or inadequate sewage treatment may allow disease-causing organisms to enter estuaries, affecting the plants and animals that live there, as well as the people who may consume them. (Photo:Stanne/ NYSDEC)

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Invasive Species

toxic substances | nutrient pollution | pathogens | **invasive species**

Invasive species, or invasives, are plants and animals that have found their way into areas outside their normal geographic range. In many cases, humans have transported them to their new homes. Invasive species have been called a type of biological pollution (University of Rhode Island, 2001; Mack et al., 2000). Unlike pesticides or sewage, invasive species do not dissipate over time. With no natural enemies in their new habitat, invasive species often grow, reproduce and spread quickly.

Purple loosestrife *(Lythrum salicaria)* is one of many wetland plants that has invaded estuarine ecosystems in North America. If left unchecked, invasive species can cause tremendous ecological damage and economic losses in areas where they are introduced. (Photo: Washington State Department of Ecology)

Non-native species are often introduced to estuaries in the ballast water of ships. When ships are empty, they take in water to help keep them balanced. When cargo is loaded onto the ships, they release the ballast water. In addition to water, aquatic organisms are sucked into the ships' ballast tanks. When ships take on water in one part of the world and release it in another, aquatic plants and animals are transported along with the water and introduced into foreign estuaries. The San Francisco Bay estuary is probably the most invaded estuary in the world. Over 230 non-native species now live there; so many, in fact, that they now dominate the ecosystem. Over 160 invasive species are now found in the Chesapeake Bay, and their numbers are growing.

Invasives often cause ecological damage and economic losses where they are introduced. Competing with native species for food, or preying upon native species, invasive species have drastically reduced the populations of native species and have, in some cases, caused their extinction. Purple loosestrife, for example, was introduced to the United States from Europe as an ornamental plant in the early 1800s. Today it has invaded estuaries in 48 states, crowding out 44 species of native plants. Controlling purple loosestrife costs about $45 million a year (Pimentel et al., 1999).

(top)

Estuaries

Monitoring Estuaries

temperature | depth | salinity | dissolved oxygen | turbidity | pH | nutrients | chlorophyll

The National Estuarine Research Reserve System or NERRS is a partnership program between NOAA and U.S. coastal states that protects more than one million acres of estuarine land and water. These estuarine reserves provide essential habitat for wildlife; offer educational opportunities for students, teachers and the public; and serve as living laboratories for scientists.

The health of every reserve is continuously monitored by the NERRS System-wide Monitoring Program or SWMP (pronounced “swamp”). SWMP measures changes in estuarine waters to record how human activities and natural events affect coastal habitats.

The NERRS SWMP uses automated data loggers to monitor the temperature, depth, salinity, dissolved oxygen, turbidity, and pH of each estuary’s water. These variables are recorded every 30 minutes at four stations in each of the 26 NERRS sites. They are key indicators of water quality and environmental conditions for the plants and animals that live in or use the estuary. The reserves also sample the water for nutrients (nitrogen and phosphorus) and chlorophyll on a monthly basis.

Weather can have a major impact on water quality in estuaries. For example, rainfall can increase sediment runoff, which, in turn, influences dissolved oxygen, turbidity, pH and temperature. As part of SWMP, every reserve has a weather station that collects data every 15 minutes on temperature, relative humidity, atmospheric pressure, rainfall, wind speed and direction. Several reserves are able to send real-time data as they are collected

This is a YSI 6000 UPG Multi-Parameter Water Quality Monitor. This particular model measures dissolved oxygen, salinity, temperature, pH, depth, and turbidity. **Click on image** for more details. (Photo: North Carolina NERRS site)

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directly to Web sites on the Internet.

These data have already helped scientists gain a better understanding of how environmental conditions fluctuate in estuaries. The SWMP data have been used to detect conditions related to oyster diseases, measure the recovery of estuaries after hurricanes, and evaluate restoration projects in estuaries.

(top)

Return to Monitoring Estuaries

The image on the left is a YSI 6000 UPG Multi-Parameter Water Quality Monitor. This particular model measures dissolved oxygen, salinity, temperature, pH, depth, and turbidity.

The image on the right shows a UT3 Campbell scientific weather station. Sensors on the weather station include an anemometer and vane to measure the horizontal wind speed and wind direction, a quantum sensor to measure solar radiation, a temperature and relative humidity probe, a barometric pressure sensor, and a rain gauge. (Photos: North Carolina NERRS site)

(top)

Return to Monitoring Estuaries

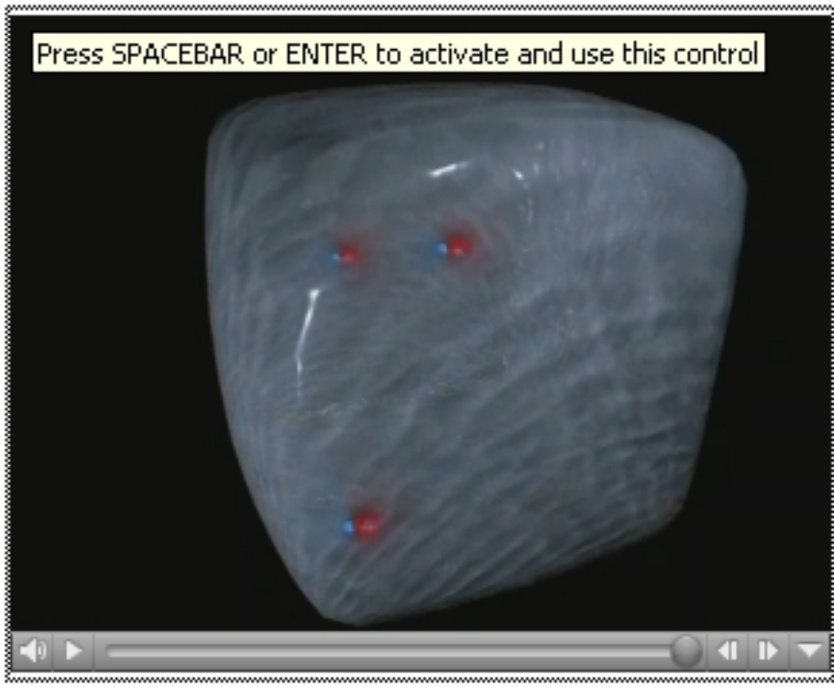
Water Temperature

temperature | depth | salinity | dissolved oxygen | turbidity | pH | nutrients | chlorophyll

Just knowing the temperature of the water in an estuary can give us a pretty good idea of how healthy it is. One important thing we can tell from water temperature is how much oxygen can be dissolved into the water.

Dissolved oxygen is critical for the survival of animals and plants that live in the water. The more oxygen there is in the water, the healthier the ecosystem is. As the water temperature increases, the amount of oxygen that can dissolve in the water decreases. For example, fresh water at 0°C can contain up to 14.6 mg of oxygen per liter of water, but at 20°C, it can only hold 9.2 mg of oxygen per liter. Thus, seasonal water temperature (and dissolved oxygen) is an important indicator of habitat quality for many estuarine species.

The temperature of the water also tells us what types of plants and animals are able to live in the estuary. All plants and animals have a range of temperatures in which they thrive. If the water in the estuary is outside the normal seasonal temperature range in which most estuarine organisms can comfortably live, it is probably an indication that something is adversely affecting the health of the estuary.



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This animation shows how increasing temperature affects the concentration of oxygen in water. When the animation starts, the temperature of the water cube is very low. At low temperatures the molecules move slowly, and a lot of oxygen can be dissolved into the water. As the animation progresses, the temperature of the water increases. With increasing temperature the molecules' movement increases, and most of the oxygen escapes into the atmosphere.

(top)

Return to Monitoring Estuaries

Depth

temperature | **depth** | salinity | dissolved oxygen | turbidity | pH | nutrients | chlorophyll

Water levels in an estuary typically rise and fall with the daily tides, but they are also affected by the weather. Periods of drought or excessive rainfall affect the amount of fresh water entering the estuary from rivers or runoff, and can easily change the physical, chemical and biological conditions in an estuary.

Depending on the source of pollution, the levels of toxins, bacteria, or nutrients may rise as runoff increases due to heavy rainfall. The concentration of dissolved and suspended materials in the water, or turbidity, may increase with runoff due to storms, or during periods of drought when there is a low volume of water in the estuary and winds and waves stir up the muddy bottom at low tide. In general, when water levels are too high or too low in an estuary for prolonged periods of time, the health of the estuary, and the plants and animals that live in it, are vulnerable to damage.

The NERRS SWMP uses electronic depth gauges to determine estuarine water levels throughout the year. To verify the accuracy of these sophisticated devices, researchers often go out and take measurements the old-fashioned way, by hand. (Photo: Hudson River NERRS site)

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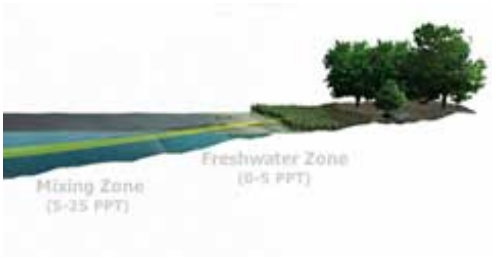
Salinity

temperature | depth | **salinity** | dissolved oxygen | turbidity | pH | nutrients | chlorophyll

Under laboratory conditions, pure water contains only oxygen and hydrogen atoms, but in the real world, many substances are often dissolved in water, like salt. Salinity is the concentration of salt in water, usually measured in parts per thousand (ppt). The salinity of seawater in the open ocean is remarkably constant at about 35 ppt. Salinity in an estuary varies according to one's location in the estuary, the daily tides, and the volume of fresh water flowing into the estuary.



In estuaries, salinity levels are generally highest near the mouth of a river where the ocean water enters, and lowest upstream where fresh water flows in. **Click on image** for more details and a larger image.

In estuaries, salinity levels are generally highest near the mouth of a river where the ocean water enters, and lowest upstream where freshwater flows in. Actual salinities vary throughout the tidal cycle, however. Salinity levels in estuaries typically decline in the spring when snowmelt and rain increase the freshwater flow from streams and groundwater. Salinity levels usually rise during the summer when higher temperatures increase levels of evaporation in the estuary.

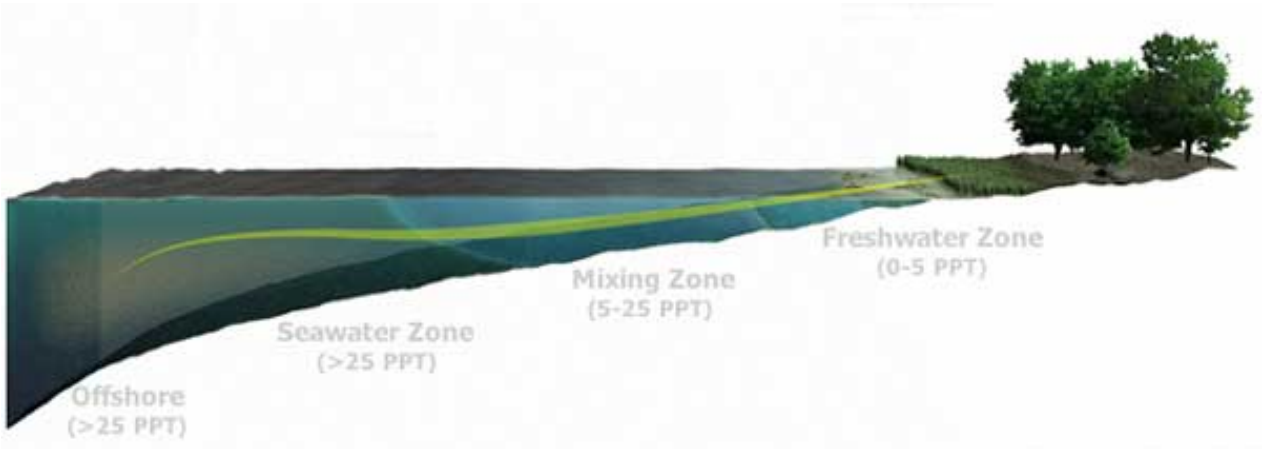
Estuarine organisms have different tolerances and responses to salinity changes. Many bottom-dwelling animals, like oysters and crabs, can tolerate some change in salinity, but salinities outside an acceptable range will negatively affect their growth and reproduction, and ultimately, their survival.

Salinity also affects chemical conditions within the estuary, particularly levels of dissolved oxygen in the water. The amount of oxygen that can dissolve in water, or solubility, decreases as salinity increases. The solubility of oxygen in seawater is about 20 percent less than it is in fresh water at the same temperature.

(top)

Return to Monitoring Estuaries - Salinity

The degree to which fresh water and saltwater mix in an estuary is measured using isohalines. Isohalines are areas in the water that have equal salt concentrations, or salinities. In estuaries, salinity levels are generally highest near the mouth of a river where the ocean water enters, and lowest upstream where fresh water flows in. To determine isohalines, scientists measure the water's salinity at various depths in different parts of the estuary. They record these salinity measurements as individual data points. Contour lines are drawn connecting data points that have the same salinity measurements. These contour lines showing the boundaries of areas of equal salinity, or isohalines, are then plotted onto a map of the estuary. The shape of the isohalines tells scientists about the type of water circulation in that estuary.



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Dissolved Oxygen

temperature | depth | salinity | **dissolved oxygen** | turbidity | pH | nutrients | chlorophyll

To survive, fish, crabs, oysters and other aquatic animals must have sufficient levels of dissolved oxygen (DO) in the water. The amount of dissolved oxygen in an estuary's water is the major factor that determines the type and abundance of organisms that can live there.

Low levels of dissolved oxygen in the water can cause marine life to become very lethargic. Along the eastern shore of Mobile Bay, Alabama, many aquatic animals move into shallow waters to try to get more oxygen. Local communities refer to this phenomenon as "Jubilee." During a Jubilee, residents walk along the shore and fill their ice chests with crabs and flounders. **Click on image** for a larger view.

Oxygen enters the water through two natural processes: (1) diffusion from the atmosphere and (2) photosynthesis by aquatic plants. The mixing of surface waters by wind and waves increases the rate at which oxygen from the air can be dissolved or absorbed into the water.

DO levels are influenced by temperature and salinity. The solubility of oxygen, or its ability to dissolve in water, decreases as the water's temperature and salinity increase. DO levels in an estuary also vary seasonally, with the lowest levels occurring during the late summer months when temperatures are highest.

Bacteria, fungi, and other decomposer organisms reduce DO levels in estuaries because they consume oxygen while breaking down organic matter.

Oxygen depletion may occur in estuaries when many plants die and decompose, or when wastewater with large amounts of organic material enters the estuary. In some estuaries, large nutrient inputs, typically from sewage, stimulate algal blooms. When the algae die, they begin to decompose. The process of decomposition depletes the surrounding water of oxygen and, in severe cases, leads to hypoxic (very low oxygen) conditions that kill aquatic animals. Shallow, well-mixed estuaries are less susceptible to this phenomenon because wave action and circulation patterns supply the waters with plentiful oxygen.

(top)

Return to Monitoring Estuaries - Dissolved Oxygen

Low levels of dissolved oxygen in the water can cause marine life to become very lethargic. Along the eastern shore of Mobile Bay, Alabama, many aquatic animals move into shallow waters to try to get more oxygen. Local communities refer to this phenomenon as "Jubilee." During a Jubilee, residents walk along the shore and fill their ice chests with crabs and flounders. (Photo: Weeks Bay NERRS site)

(top)

Return to Monitoring Estuaries

Turbidity

temperature | depth | salinity | dissolved oxygen | **turbidity** | pH | nutrients | chlorophyll

Turbidity is essentially a measurement of how cloudy or clear the water is, or, in other words, how easily light can be transmitted through it. As sediments and other suspended solids increase in the water, the amount of light that can pass through the water decreases. Thus, the cloudier the water, the greater the turbidity. As algae, sediments, or solid wastes increase in the water, so does turbidity.

Turbidity affects organisms that are directly dependent on light, like aquatic plants, because it limits their ability to carry out photosynthesis. This, in turn, affects other organisms that depend on these plants for food and oxygen.

Scientists often consider turbidity of the water in connection with other factors to get a better understanding of its causes and consequences. For example, high levels of turbidity can identify problems with shoreline erosion, or sewage processing facilities not functioning properly.

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Turbidity is measured at many NERRS sites using an electronic monitor. Another way to measure turbidity is to lower a device called a Secci (pronounced seh-key) Disc into the water. A Secci Disc has black-and-white elements. As the disc is lowered into the water, increasing turbidity will cause the black-and-white areas to fade into one another, and the disc will slowly disappear from sight. To determine the turbidity of the water, a mathematical calculation is performed based on the depth of water at which the Secci Disc "disappeared."

(top)

Return to Monitoring Estuaries

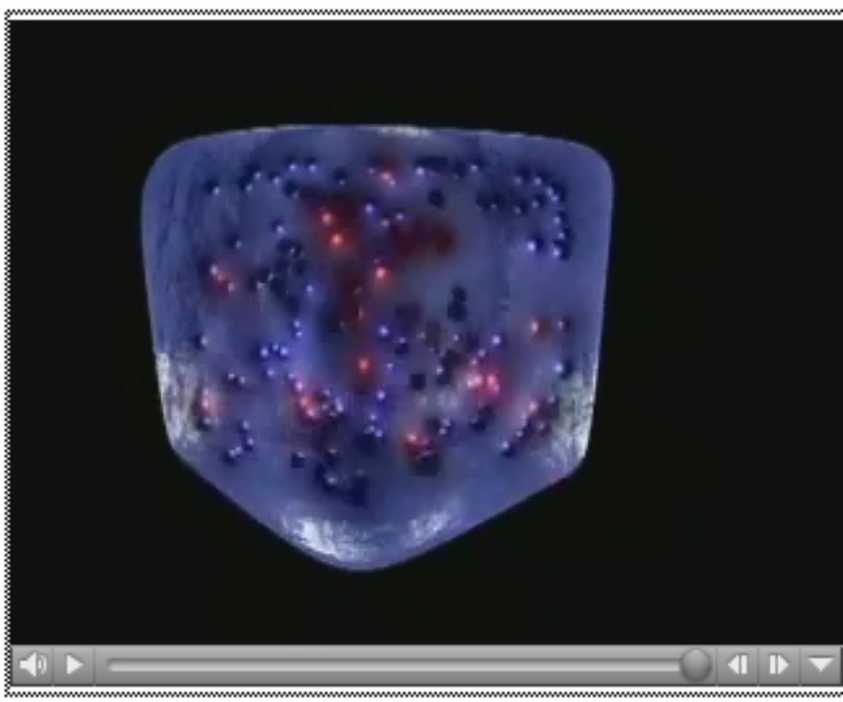
pH

temperature | depth | salinity | dissolved oxygen | turbidity | **pH** | nutrients | chlorophyll

pH is a measure of how acidic a solution is. The pH scale ranges from 0 to 14. Solutions with a pH of less than 7 are acidic, and those with a pH greater than 7 are basic (or alkaline). Distilled water is neutral and has a pH of 7.

Knowledge of pH is important because most aquatic organisms are adapted to live in solutions with a pH between 5.0 and 9.0. The pH in an estuary tends to remain constant because the chemical components in seawater resist large changes to pH. Biological activity, however, may significantly alter pH in an estuary.

Through a process called photosynthesis, plants remove carbon dioxide (CO_2) from the water and expel oxygen (O_2). Since CO_2 becomes carbonic acid when it dissolves in water, the removal of CO_2 results in a higher pH, and the water becomes more alkaline, or basic. When algae naturally begin to increase in estuaries during the spring, pH levels tend to rise. An overabundance of algae (called an algal bloom) may cause pH levels in an estuary to rise significantly, and this can be lethal to aquatic animals.



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This animation shows a parcel of water as its pH changes from acidic to alkaline. As the animation begins, the water appears red because it contains many hydrogen ions (H+), represented by red particles. As the animation progresses, the number of hydronium ions (-OH), represented by blue particles, increases. Soon they outnumber the hydrogen ions, and the water turns alkaline (blue in color).

(top)

Return to Monitoring Estuaries

Nutrients

temperature | depth | salinity | dissolved oxygen | turbidity | pH | **nutrients** | chlorophyll

Nutrients, especially nitrogen and phosphorus, are key indicators of water quality in estuaries. Plants require many nutrients (e.g., carbon, nitrogen, phosphorus, oxygen, silica, magnesium, potassium, calcium, iron, zinc, copper) to grow and reproduce. Of these, nitrogen and phosphorus are the most essential for aquatic plants.

Nitrogen and phosphorus naturally enter estuarine waters when freshwater runoff passes over geologic formations rich in phosphate or nitrate, or when decomposing organic matter and wildlife waste get flushed into rivers and streams. Manmade sources of nutrients entering estuaries include sewage treatment plants, leaky septic tanks, industrial wastewater, acid rain, and fertilizer runoff from agricultural, residential and urban areas. Too much nitrogen and phosphorus acts as a pollutant in the water. This leads to explosive blooms in algae that cloud the water and deplete it of the oxygen that is critical for aquatic animals. This is called eutrophication.

Excessive nutrient concentrations have been linked to hypoxic (very low oxygen) conditions in more than 50 percent of U.S. estuaries. Under the worst conditions, the waters of an estuary can become anoxic (having no oxygen). High nutrient concentrations have also been linked to algal blooms such as red and brown tides, some of which produce harmful toxins. Nutrients are also believed to cause the growth of the potentially toxic organism *Pfiesteria* (USGS, 1999). Red and brown algal tides and *Pfiesteria* have been linked to fish and shellfish kills, and may be harmful to human health. The image below illustrates what an estuary with a healthy input of nutrients looks like—lush and vibrant.

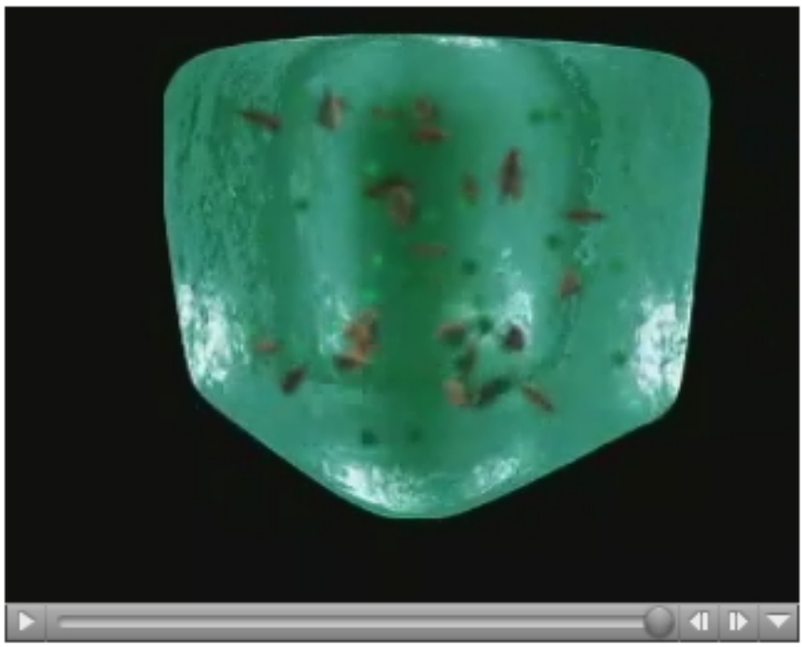
Return to Monitoring Estuaries

Chlorophyll

temperature | depth | salinity | dissolved oxygen | turbidity | pH | nutrients | **chlorophyll**

Chlorophyll is a green pigment in plants that turns light energy into food and allows plants to grow, and releases oxygen in a process called photosynthesis. The microscopic one-celled plants that float in healthy waters are called phytoplankton. By measuring the amount of chlorophyll in the water, scientists can determine the density of phytoplankton in an estuary, and the amount of primary productivity (the conversion of light energy into plant material) taking place as well.

Phytoplankton forms the base of the aquatic food web in an estuary. It is eaten by zooplankton (microscopic animals) and small fish, which, in turn, are eaten by larger creatures. The abundance of healthy animals in an estuary often depends on the amount of phytoplankton and primary productivity taking place.



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This animation represents what happens when the concentration of microscopic green algae, and therefore chlorophyll, increases in a body of water. As the amount of green algae in the water increases, the water turns greener in color. The increase in algae provides more food for the zooplankon, whose numbers and activity increase as well.

(top)

Estuaries

The Future: Managing, Protecting and Restoring Estuaries

Estuaries are biologically and economically invaluable natural resources. Assaulted by natural and anthropogenic disturbances, estuaries, and the plants and animals that call them home, are in danger of disappearing if actions are not taken to protect them.

During the last century, millions of acres of estuarine habitats have been destroyed; many more are in poor health and in danger of being lost. In 1996, 62% of estuaries had good water quality (USEPA, 1996). By 2000, only 49% of estuaries had good water quality (USEPA, 2000). How we choose to treat our estuaries today will have an enormous impact on their existence in the future.

Through research, monitoring, education, and enforcement, the National Estuarine Research Reserve Program and its many partners work to preserve essential estuarine ecosystems for future generations. **Click on image** for a larger view.

Recognizing the value and importance of estuaries and the dangers facing them, Congress created the National Estuarine Research Reserve System (NERRS) in 1972. NERRS is dedicated to protecting a system of estuaries that represent the range of coastal estuarine habitats in the United States and its territories. The system protects more than one million acres of estuarine land and water in 17 states and Puerto Rico. NEERS sites serve as laboratories and classrooms where the effects of natural and human activities on estuaries can be monitored and studied by scientists and students. In addition, all estuaries, whether or not they are in the National Estuarine Research Reserve System, are protected under every U.S. state's coastal zone management program. Many states have designated estuaries as areas to preserve or restore for their conservation, recreational, ecological, historical, and aesthetic values.

When we have failed to protect estuaries, another course of action is to restore them. Restoring habitats involves removing pollutants and invasive species from the water and surrounding lands, reestablishing natural ecosystem processes, and reintroducing native plants and animals. The goal is to rebuild the estuary to a healthy, natural ecosystem that works like it did before it was polluted or destroyed.

In November 2000, the Estuary

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Restoration Act (ERA) was signed into law. It makes restoring our nation's estuaries a national priority, with a goal of restoring one million acres of estuarine habitat by 2010. NOAA is providing the necessary data, science, tools and long-term monitoring efforts to help reach the ERA's million-acre goal.

(top)

Many species, like these great egrets, nest and breed in estuaries around the world. If estuarine habitats are not protected, these magnificent birds, and many other species, may face extinction as their habitats disappear. **Click on image** for a larger view.

Return to The Future: Managing, Protecting, and Restoring Estuaries

Through research, monitoring, education, and enforcement, the National Estuarine Research Reserve Program and its many partners work to preserve beautiful and essential estuarine ecosystems for future generations.

(top)

Return to The Future: Managing, Protecting, and Restoring Estuaries

Many species, like these Great Egrets, nest and breed in estuaries around the world. If estuarine habitats are not protected, these magnificent birds, and many other species, may face extinction as their habitats disappear.

(top)

Estuaries

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