The Coastal Zone - Coastal Ocean extends from the high-tide line to the shelf break

This region is responsible for nearly 30% of the total net oceanic primary production and nearly 90% of the global fish catch

**Estuaries**

- Estuary is derived from the Latin word for tide - “aestus”
  - Aestuarium – low ground covered by the sea at high water
- Estuaries and lagoons comprise 80-90% of coastline along Atlantic & Gulf Coast and 10-20% on Pacific Coast
- Nearly 900 individual estuaries in the continental US
- Atlantic & Gulf Coasts - border broad continental shelf - have extensive marshes - older
- Pacific Coast - formed by tectonic activity, deep, narrow shelf, salt marshes small or absent - younger
Definitions of “Estuary”

Two major components involved:

• Transition from fresh (river) water to saline (ocean) water
• Tidal influence

One definition:

“An estuary is a semi-enclosed coastal water body that extends to the effective limit of tidal influence, within which sea water is significantly diluted with freshwater from land drainage”

Why are features covering such a small portion of the ocean of importance?

• high primary production
• fishing, shipping, recreation, aquaculture, etc.
• most materials entering the ocean from land do so through estuaries
• population centers
• most human perturbation of the ocean (pollution, over-exploitation, dredging, etc.) occurs in estuaries
Transition zones (ecotones) occur between two or more diverse communities or habitats.

Species that have highest abundance in ecotones are called “edge species”

Odum (1971) - estuaries are ecotones between freshwater and marine habitats

Estuaries can be conceptualized as physical and biological mixing zones

The shallow and intertidal areas are usually bordered by salt marsh or mangrove vegetation (in the tropics)

Estuaries are very efficient “traps” for nutrients, sediments, and pollutants - Usually present in high concentrations

High socio-economic relevance
Salt marsh vegetation exists in dynamic equilibrium between rate of sediment accumulation and rate of coastal subsidence, or sea level rise.
- As deposits accumulate, erosion and OM oxidation increase, slowing rate of further accumulation.
- As sea level rises, marsh is inundated more frequently, and accumulation rate of sediment and peat increases.
- When rate of sedimentation does not keep up with subsidence, marshland is lost.
- Sea level rise due to global warming could accelerate loss of marshland.

Salt marsh soils undergo daily cycle of changing aeration and, thus, redox state.
- High tide: soils are inundated, anaerobic conditions may develop.
- Low tide: soils drain, high redox potential re-established in surface layers.

Tide-induced flushing, combined with groundwater flow from land, leads to large amounts of import/export from/to tidal creeks.
- Low tide: low salinity due to flushing of marsh by freshwater runoff from land.
- High tide: marsh is inundated with seawater, highest salinities observed.
**Continental Margins**

*Passive (Atlantic-type) Margins*

Atlantic coast and shelf is subsiding because it is a passive margin

The lithospheric plate cools and thickens with age and distance from the spreading center and sinks (subsides)

Isostatic sinking occurs as sediment accumulates on the shelf and sediment layer thickens (GOM)

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*Tectonic Margin Diagram* (From Pinet 2003)

---

**Active (Pacific-type) Margins**

Tectonic activity occurs along the margin

The lithospheric plate is subducted beneath the continental plate

Crust is pushed upward to produce an emergent coast

Active continental margins usually have narrow shelves.....Passive margins have wide shelves

---

*Active Margin Diagram* (From Pinet 2003)
Shelf Sediments

Sediment grain size decreases as you go further offshore due to wave energy and currents

From Pinet 2003

Shelf Sediments

Sediment grain size and feeding strategies

(a) BOTTOM ENERGY BANDS

(b) BENTHOES AND SUBSTRATE TYPE

From Pinet 2003
Major Factors that Determine Processes on Shelves

- Presence or absence of large rivers
- Presence or absence of upwelling
- Location of ocean boundaries
- Shelf width

All of these factors are influenced by climate, hurricanes, El Niño, La Niña, global weather patterns

Based on Geomorphology

Drowned River Valleys or Coastal Plain estuaries (most common)

- Formed by sea level rise during the Holocene
- Tide and river dominated

Examples: Chesapeake Bay, Delaware Bay, Charleston Harbor
Coastal Plain, Bar-Built Estuaries

longshore currents form a sand bar or sand spit across an embayment

Lack a major river source

These estuaries are usually shallow (<2 m) and wind-dominated

Example: Galveston Bay, Albemarle-Pamlico Sound

Fjord-Type Estuaries

deep (>100 m), built by glaciers, shallow sill (terminal moraine)

sill may trap bottom water that may be anoxic

Examples: Puget Sound, coasts of Norway and British Columbia
Tectonically-Produced Estuaries

formed by earthquakes and block faulting

common on active coasts

creates basins that become filled with water

*Examples: San Francisco Bay, Tomales Bay*

---

**Based on Physiography**

Fairbridge Classification (1980)

7 Categories based on relative relief and degree of blocking at the mouth of the estuary

- Fjord (fjärd)
- Ria
- Coastal Plain
- Bar-built
- Blind
- Delta front
- Tectonic
**Based on Circulation and Hydrography**

Water circulation and stratification influence chemistry and biology

For most estuaries, NET flow is **OUT** at the surface and **IN** along the bottom

Two-layered circulation

Longitudinal, lateral, and vertical circulation patterns are important

---

**Estuarine Classification Based on Circulation**

Type A - Highly stratified, salt wedge estuary - river discharge dominates over tidal action
Salt exchange by vertical advection across the fw/sw interface (halocline). *Example: Mississippi River*
**Estuarine Classification Based on Circulation**

Type B - Partially mixed, moderately stratified - tidal flow increases relative to river discharge
Vertical advection and turbulence mix the system
Example: Chesapeake Bay

![Diagram of partially mixed estuary](From Garrison 2002)

**Estuarine Classification Based on Circulation**

Type C - Vertically homogeneous and well-mixed
Intense tidal flow and strong turbulent mixing, lateral heterogeneity sometimes caused by strong winds
e.g., Delaware Bay

![Diagram of well-mixed estuary](From Garrison 2002)
**Estuarine Classification Based on Circulation**

Type D - Fjord - sill results in “stagnant” bottom waters
Usually highly-stratified

![Diagram of Fjord estuary](From: Garrison 2002)

**Estuarine Classification Based on Circulation**

<table>
<thead>
<tr>
<th>FACTORS AFFECTING ESTUARIES</th>
<th>TYPE</th>
<th>SALINITY PROFILES</th>
<th>NET CIRCULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>![Diagram](From: Pinet 2003)</td>
<td></td>
</tr>
</tbody>
</table>
Many ways to classify an estuary…

- Geomorphology
- Physiography
- Circulation and Hydrography
- Salinity and Tidal Characteristics
- Sedimentation
- Ecosystem Energetics

Estuaries are dynamic in space and time, highly influenced by meteorology (precipitation, hurricanes, El Niño, etc.)

Are a continuum - come in a variety of sizes and shapes

What are the implications for systems ecology and ecosystem processes?

**Mixing Processes**

Estuaries are “mixing zones” where freshwater is combined with saltwater

Mixing - the process whereby a water parcel or water mass is diluted by, or redistributed within, other water masses (Kjerfve 1989)

- **Sloshing** - time-averaged flux of particles by oscillatory tidal currents - is a dominant longitudinal mixing process.

- **Shear Effect** - mixing over a tidal cycle due to systematic covariations of velocity and particle concentrations. Shear results from different velocities of parallel currents.
  
  Also known as *Shear-Induced Mixing*
Mixing Processes

**Advection** – the water mass remains intact, but is transported

**Diffusion** - random scattering of water parcels or particles by either random molecular or eddy (turbulent) motions - molecular diffusion usually much less than eddy diffusion

Important at the sediment/water interface

**Dispersive Mixing** - the scattering of water parcels or particles dissolved in the estuary due to tidal sloshing, shear effects, eddy (turbulent) diffusion, or tidal trapping

Estuarine Fronts

Boundary between two dissimilar water masses. Commonly form at freshwater/saltwater interface of estuaries and plumes

Surface convergence and advection downward - accumulate particulates at the surface (flotsam & foam lines)

Are different from Langmuir circulation cells - which are driven by friction between wind and water surface
Nutrients are different!

**River-water and Sea-water Concentrations**

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration in river-water (µg l⁻¹)</th>
<th>Concentration in sea-water (µg l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>8 x 10⁵</td>
<td>1.987 x 10⁷</td>
</tr>
<tr>
<td>S</td>
<td>3.7 x 10³</td>
<td>9.28 x 10⁴</td>
</tr>
<tr>
<td>Br</td>
<td>20</td>
<td>6.8 x 10⁴</td>
</tr>
<tr>
<td>F</td>
<td>100</td>
<td>4 x 10⁴</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>4.5 x 10⁴</td>
</tr>
<tr>
<td>Na</td>
<td>9 x 10²</td>
<td>1.105 x 10⁶</td>
</tr>
<tr>
<td>Mg</td>
<td>4.1 x 10³</td>
<td>1.326 x 10⁶</td>
</tr>
<tr>
<td>Ca</td>
<td>1.5 x 10⁶</td>
<td>4.22 x 10⁶</td>
</tr>
<tr>
<td>K</td>
<td>2.3 x 10⁷</td>
<td>4.16 x 10⁷</td>
</tr>
<tr>
<td>Sr</td>
<td>50</td>
<td>8.5 x 10⁴</td>
</tr>
<tr>
<td>N</td>
<td>2.5 x 10²</td>
<td>500</td>
</tr>
<tr>
<td>P</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>Si</td>
<td>6.1 x 10⁵</td>
<td>1000</td>
</tr>
</tbody>
</table>

* Data from Riley and Chester (1971).

**River-water / Sea-water Ion Ratios**

**TABLE 21.12**

Comparison of the Major Ion Ratios in River Water and Seawater

<table>
<thead>
<tr>
<th>Ion Ratio</th>
<th>River Water</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺/K⁺</td>
<td>2.5</td>
<td>50</td>
</tr>
<tr>
<td>Na⁺/Mg²⁺</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Na⁺/Ca²⁺</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>K⁺/Mg²⁺</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>K⁺/Ca²⁺</td>
<td>4.5</td>
<td>10</td>
</tr>
<tr>
<td>Ca²⁺/Mg²⁺</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Two major factors:

- Na⁺/K⁺ difference reflects lower affinity of marine rocks for sodium, as compared to potassium (ocean is a less effective sink for sodium)

- Ca²⁺/Mg²⁺ difference reflects preferential removal of calcium in the ocean as biogenic calcite (ocean is a more effective sink for calcium)
Salinity is a conservative constituent in estuaries and is a good indicator of mixing.

Constituent plotted against salinity to determine if distribution is attributable to mixing processes (as opposed to non-conservative processes; nutrient uptake, flocculation, biodegradation, etc.)

If concentration vs. salinity is LINEAR, then the chemical/particle exhibits conservative behavior.

If plot of concentration vs. salinity is NOT LINEAR, then the chemical/particle exhibits NON-conservative behavior.

Assumes end-members are constant over the flushing time of the estuary.

Mixing Diagram Examples

(from Day et al. 1989)
Salt Marshes as Filters & Transformers of Nutrients

• Salt marshes receive NO$_3$ from rivers and groundwaters, and convert it to DON, PON, and NH$_4$.
• Despite long-term storage of OM, salt marshes are a source of N and P to estuaries.

Nitrogen Cycling in Salt Marshes

• Flooded, anaerobic sediments of salt marshes allow significant rates of denitrification.
• In most salt marshes, NH$_4$ is the dominant N-form, since nitrification rates are low, and denitrifiers remove much of the NO$_3$.
• Contribution of new inputs and recycled N in salt marshes are about equal; different from upland ecosystems where new inputs are much lower (≈10%).
• Salt marshes are often N-limited.
• N-fixation by blue-green algae and soil bacteria may contribute significantly to the salt marsh N-budget.
Sulfur Cycling in Salt Marshes

- Salt marsh sediments have high SO$_4^-$ reduction rates, due to high OM, high seawater SO$_4^-$, and frequent anaerobic conditions.
- Over 50% of the CO$_2$ respired may be due SO$_4^-$ reduction.
- SO$_4^-$ reduction produces H$_2$S, which can then be transformed to pyrite (FeS$_2$) and organic-S.
- Alternatively, H$_2$S can diffuse upward out of the anaerobic zone and be re-oxidized, so that net < gross SO$_4^-$ reduction.

Permanent burial of sulfide minerals and dissolved sulfate in marsh sediment.

Table 1.3. Factors which impose temporal variability on the composition of water at a fixed geographical position in an estuary

<table>
<thead>
<tr>
<th>Form of variability</th>
<th>Frequency</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclic fluctuations about average conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Small scale random fluctuations about mean level or trend</td>
<td>&lt; Seconds to minutes</td>
<td>Turbulent eddy structure of water in mixing regime</td>
</tr>
<tr>
<td>2. Variability around mean level or trend</td>
<td>Minutes to hours</td>
<td>Eddying; incompletely mixed inputs; temporary isolation of water, e.g. in bays or over mud flats</td>
</tr>
<tr>
<td>3. Regular interruptions to mean level or trend</td>
<td>Often tidal</td>
<td>Intermittent discharge</td>
</tr>
<tr>
<td>4. Regularly cyclic</td>
<td>Usually 12+ hours, with spring/summer variations in amplitude</td>
<td>Tidal advection</td>
</tr>
<tr>
<td>5. Regularly cyclic</td>
<td>Annual</td>
<td>Biological and/or climatic cycles</td>
</tr>
<tr>
<td>Intermittent fluctuations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Irregular interruptions to mean level or trend</td>
<td>—</td>
<td>Irregular discharge</td>
</tr>
<tr>
<td>2. Intermittent significant change in water characteristics</td>
<td>Often annual, i.e. more probable at certain times of year</td>
<td>Climatic effects, e.g. exceptionally high or low fresh water run-off; storm surges; biological instability (plankton blooms)</td>
</tr>
<tr>
<td>3. Permanent discontinuity in water characteristics</td>
<td></td>
<td>Change in exploitation, e.g. new discharge, natural phenomena, e.g. morphological adjustment to estuarine bed form, rechanneling</td>
</tr>
<tr>
<td>Trend</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Persistent year to year trend</td>
<td>—</td>
<td>Change in exploitation, e.g. continuous increase or decrease in discharge; Natural estuarine evolution, e.g. continuing situation</td>
</tr>
</tbody>
</table>
The Mid-estuary Turbidity Maximum

Expected:
Turbidity max is due to both 1) chemical flocculation and 2) sediment resuspension

Measured:

A Mid-estuary Trap for Riverborne Material

Fig. 115. Example of the non-conservative behaviour of suspended matter in estuaries and the formation of a turbidity maximum at the fresh-sea water interface (Meade, 1972)
Particle Distribution vs. Estuary Type

Note tidal asymmetries

Fig. 113. Schematic presentation of types of estuaries. The dots indicate sediment concentration and the arrows the net water movements over ebb and flood (Preston, 1990). 0-35 are % Salinity (S) isolines. For explanation see the text.

Effects Of The Mid-estuary Particle Maximum

1. Scavenging of surface-active materials
   • 70-100% of riverine Fe is removed (most at low salinity)
   • 60-80% of humic acids are removed
   • 5% of total DOM is removed

2. Increased turbidity
   • Lower primary production
   • Reduction of photochemical reaction rates

3. Enhanced transport rates downstream / offshore
   • Enhanced sedimentation rates downstream / offshore
Water moving down the estuary at velocity $u$ is in geostrophic balance.

The sides of the estuary counteract the Coriolis force but the water surface is tilted to balance the pressure gradient.

The Coriolis force balances the pressure gradient.

In the open ocean, the flow is NOT in geostrophic balance.

Once the buoyant plume flows out onto the shelf, the surface slope is missing and cannot provide pressure to balance the Coriolis force.

In the northern hemisphere, the Coriolis force causes the flow to turn to the right and flow along the coast.

As the Coriolis force pushes water to the right, the blocking coastline causes an opposing pressure gradient in the form of a slight slope in sea level.

The plume of buoyant water continues as a coastal current in geostrophic balance parallel to the coast.

---

**Surface Slope Across an Estuary**

(the pressure gradient balancing Coriolis)

$$dh = \frac{fuW}{g}$$

$dh$ = height difference from one side of the estuary to the other

$u$ = flow rate = 0.50 m s$^{-1}$

$W$ = width of estuary = 200 m

$f$ = Coriolis parameter = $10^{-4}$ s$^{-1}$ (at 45º N)

$g$ = acceleration due to gravity = 10 m s$^{-2}$

$$dh = \left(\frac{10^{-4}}{1}\right)\left(0.50\right)\left(200\right)\frac{1}{10} = 0.001 \text{ m}$$

Thus, the change in height of the water surface across the estuary is 1 mm.
An Estuarine Summary

River | Estuary | Shelf
--- | --- | ---
Turbidity maximum | Chl a maximum | Zooplankton maximum
Mouth | Estuarine fronts | plume

Net seaward flow | Estuarine outwelling
Floculation

River input | Shelf input
Net landward flow
Upper limit of salt wedge
Active phytoplankton growth and riverine nutrient uptake
Development of stable stratification
Net heterotrophy | Net autotrophy

Figure 8.13 Conceptual model of the chemical and biological structure in estuaries. As the suspended load settles from the entering river waters and nutrients are made available, phytoplankton production increases, fueling an increase in zooplankton production and higher trophic levels. From Fisher et al. (1988).