Estuaries are regions where rivers meet the coastal ocean.

They are biologically unique because these are the only water bodies where salinity values take all intermediate values, from zero upstream in the river to that of the ocean.

A number of organisms (plants and shellfish) can only live at those intermediate salinities. Hence, estuaries have peculiar ecosystems.
A prime example in the United States: The Chesapeake Bay

Estuarine Dynamics

Complex interaction of
- river inflow (gravity driven)
- density-driven salinity intrusion (buoyancy induced)
- tidal motions (water pumping from open sea)
- surface wind stress (if bay wide enough)
- instabilities and entrainment between surface and bottom layers.

Schematic diagram of two-dimensional estuarine circulation.
(Schroor, 1996, page 284)
For animation, see [http://www.vims.edu/physical/WEB/PRESNT/bsalt.htm](http://www.vims.edu/physical/WEB/PRESNT/bsalt.htm)

Traditional classification of estuaries

Estuaries come in a diversity of sizes and shapes and are fed by rivers of various strengths. In some, the river flow is powerful enough to keep the seawater literally “at bay”, while some other estuaries have weak rivers or are deep enough to allow upstream intrusion of seawater along the bottom of the river channel.

Finally, some estuaries are wide enough to feel the effect of the rotation of the earth, skewing their circulation (tendency of flow to be concentrated to the right in the Northern Hemisphere).

- Salt-wedge estuaries
  Example: Mississippi River
  ![Salt-wedge estuaries](https://www.msci.sc.edu/seas/estuaries.html)

- Partially stratified estuaries
  Examples: Chesapeake Bay
  ![Partially stratified estuaries](https://www.msci.sc.edu/seas/estuaries.html)

- Well mixed estuaries
  Example: Delaware Bay
  ![Well mixed estuaries](https://www.msci.sc.edu/seas/estuaries.html)

- Fjord-type estuaries
  Example: Norwegian fjords
  ![Fjord-type estuaries](https://www.msci.sc.edu/seas/estuaries.html)
To classify the various types of estuaries, one defines the Estuarine Richardson Number as

\[ R = \frac{g \Delta \rho Q_{\text{river}}}{\rho_W W u_{\text{tide}}} \]

in which:
- \( Q_{\text{river}} \) = the volumetric flowrate of the feeding river
- \( W \) = width of river
- \( u_{\text{tide}} \) = rms tidal velocity = 0.71 \( u_{\text{max}} \).

This can be recast in terms of velocities:

\[ R = \frac{u_{\text{river}}^2 u_{\text{density}}^2}{u_{\text{tide}}^2} \]

in which:
- \( u_{\text{river}} = \frac{Q_{\text{river}}}{W h} \) = incoming river velocity
- \( u_{\text{density}} = \sqrt{g (\Delta \rho / \rho_W) h} = \sqrt{g h} \)
- \( u_{\text{tide}} \) = rms tidal velocity = 0.71 \( u_{\text{max}} \).

- Salt-wedge estuaries (0.8 < \( R \))

**Structure:** Sharp salinity gradient in the vertical reaching surface toward the sea

**Dynamics:** Deeper basins, large rivers, weak tides

**Examples:** Mississippi River, Silver Bay (Alaska), Teign River Estuary (England)

Many river estuaries during wet season

As freshwater meets seawater, the former begins to float over the latter. The velocity shear created at the interface of the two waters generates billowing and vertical mixing. The salt and water thus entrained upward gradually increases the salinity of the upper layer. The incoming salinity must be provided by an upstream flow at depth, which is driven by negative buoyancy.

The salinity gradient is relatively sharp. Sailing on the surface of the water, one notices an almost abrupt change in salinity and water color.
River Teign estuary in southwestern England

Note the color contrast in the offshore waters is due to tides

Note: Arrows are for mariners and have no scientific meaning.
Partially stratified estuaries ($0.08 < R < 0.8$)

*Structure:* Tidal flow comparable to river flow

*Dynamics:* Relatively vigorous mixing in vertical smearing the salinity gradient
The salinity now varies as much horizontally as vertically

*Example:* Chesapeake Bay, Hudson River

![Diagram of isohalines in a typical partially stratified estuary.](image)

(Fischer et al., 1979, page 244)

Surface salinity distribution in Chesapeake Bay

![Map of Chesapeake Bay](image)

Note how gradual is the surface salinity variation. There is only one sharp gradient, in the James River (southwestern tributary, at bottom of map), which has a significantly higher flowrate than the other rivers.

*(From McIlgach, 1990.)*
- Well mixed estuaries ($R < 0.08$)

**Structure:** Salinity homogeneous in vertical, gradually varying in horizontal

**Dynamics:** Tidal pumping is so vigorous that waters are well mixed throughout the vertical, and the salinity varies strictly in the horizontal, with or without sharp gradient

**Examples:** Delaware Bay, Fitzroy Estuary

Fitzroy Estuary and Keppel Bay in Central Queensland, Australia

Longitudinal dispersion in an estuary

\[
\frac{u}{D_x} = 3.17 \times 10^{-5} \quad m \quad \rightarrow \quad D_s = 1058 \quad m^2/s
\]
Turbidity in an estuary

Case of the Seine River, France

The Seine River (France) is highly contaminated by industrial waste. Some of it has found its way into bottom sediments, which are lifted and re-deposited with every tidal cycle, and thus progressing very slowly downstream.