Estuaries are regions where rivers meet the coastal ocean. They are biologically unique because they 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.
The biological importance of salinity gradients in estuaries

A prime example in the United States: The Chesapeake Bay

(www.noaanews.noaa.gov)
Estuarine dynamics:

Complex interaction of
- river inflow (see hydraulics)
- tidal motions
- density-driven salinity intrusion (buoyancy induced)

Schematic diagram of two-dimensional estuarine circulation.
(Schoor, 1990, page 264)

Tidal currents and salinity distribution in Chesapeake Bay

For animation, see 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).

- Sharply stratified estuaries
  Example: salt-wedge estuaries

- Partially stratified estuaries
  Examples: Chesapeake Bay

- Well mixed estuaries
  Example: Delaware Bay

(http://www.msci.sc.edu/seas/estuaries.html)

Define: Flow ratio = $\frac{u_{\text{tide}}}{u_{\text{river}}}$

- Sharply stratified estuaries (Flow ratio < 0.1)
  
  Structure: Sharp salinity gradient in the vertical reaching surface toward the sea
  Dynamics: Deeper basins, large rivers, weak tides
  Examples: Fjords (drowned glacial valleys) and salt-wedge estuaries

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

Color contrast in the offshore waters is due to tides

Note: Arrows are for mariners and have no scientific meaning.
- Partially stratified estuaries (0.1 < Flow ratio < 10)

**Structure:** Tidal flow comparable to river flow

**Dynamics:** Relatively vigorous mixing in vertical smearing the salinity gradient

The salinity now varies as much horizontal as vertically

**Example:** Chesapeake Bay

![Isohalines in a typical partially stratified estuary.](image)

*(Fischer et al., 1979, page 244)*

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Surface salinity distribution in Chesapeake Bay

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 McPhieh, 1966)*
- Well mixed estuaries ($10 < \text{Flow ratio}$)

**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

(http://www.ozcoasts.org.au/indicators/salinity.jsp)

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Longitudinal dispersion in an estuary

\[
\frac{u}{D_c} = 3.17 \times 10^{-5} \text{ m} \quad \rightarrow \quad D_c = 1058 \text{ m}^2 / \text{s}
\]

Salinity in James River (Prichard, 1952)

![High water](image1.png) ![Low water](image2.png)

Longitudinal dispersion plot of salinity versus distance is determined, $S$, the longitudinal dispersion coefficient $D_c$ is equal to $5805$.
\[ \frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} = D \frac{\partial^2 c}{\partial x^2} - Kc \]
\[ c = \frac{M}{\sqrt{4\pi D_{t} t}} \exp \left[ -\frac{(x-ut)^2}{4D_{t} t} - Kt \right] \]

Figure 7.24 Longitudinal concentration distributions for Example 7.5: --- discharge 30 km from the mouth; ---- discharge 5 km from the mouth. (Fischer et al., 1979, page 273)
Tidal trapping

A mechanism creating additional dispersion along an estuary:

\[ D_z = \frac{D_{\text{main channel}}}{1 + r} + \frac{ru_0}{2k(1+r)(1+r+\sigma/k)} \]

with
- \( r \) = ratio of trapped volume to main-channel volume
- \( 1/k \) = characteristic exchange time
- \( \sigma \) = tidal frequency, \( u_0 \) = tidal velocity

(Fischer et al., 1979, page 242)

Figure 7.9 The phase effect in a branching channel. (a) A cloud of tracer being carried upstream on a flooding tide. (b) At high water some of the particles are trapped in the branch. (c) During the early stages of the receding tide the flow in the main channel is still upstream. The particles trapped in the branch reenter the main channel, but are separated from their previous neighbors.

Turbidity in an estuary

Case of the Seine River

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.