

What is an Estuary?



- Portion of the ocean that is semi-enclosed by land and diluted by freshwater runoff
 - All estuaries are embayments
 - But embayments without rivers \neq estuaries
- Very elastic size definition
 - Small stream mouth (Pipers Creek, N. Seattle)
 - Large river mouths (Columbia)
 - Complex embayments (Puget Sound)

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Importance of Estuaries



- Biologically important
 - Very productive
 - Habitat for wildlife & commercial species
 - Birds, mammals
 - Oysters, clams, shrimp, crab
 - Sole, flounder
 - Nursery grounds for oceanic species
 - Crab, sole, flounder, salmon, shad
 - Migratory pathway for oceanic species
 - Salmon, shad, striped bass

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Importance of Estuaries



- Economically important
 - Sites for human settlement
 - Sheltered harbors & access to rivers
 - Fishing, recreation, & aesthetic activities
 - Liquid waste disposal
 - Municipal sewage
 - Industrial effluent

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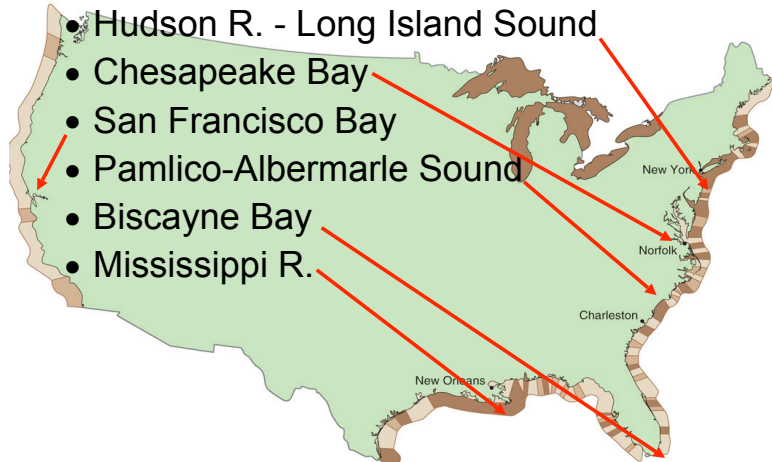
Importance of Estuaries



- Environmentally vulnerable
 - Alteration of flow (dams)
 - Habitat degradation & destruction
 - Depletion of fish and wildlife
 - Chemical contamination ("pollution")
 - Fresh/salt water boundary affects physical state and chemical reactions of pollutants

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Prominent U.S. estuaries



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Creation of Estuaries

- Shape of estuaries related to their origin
 - Broad & shallow
 - Chesapeake Bay = Drowned river valleys
 - Formed by rising sea level after Ice Age
 - Albermarle-Pamlico Sound = Bar-built
 - Enclosed by formation of barrier beach



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Creation of Estuaries

- Shape of estuaries related to their origin
 - Broad & shallow
 - Mississippi = river mouth (sediment buildout)
 - Narrow & deep
 - San Francisco Bay = Tectonic (San Andreas Fault)
 - Puget Sound = fjord
 - Carved by glaciers

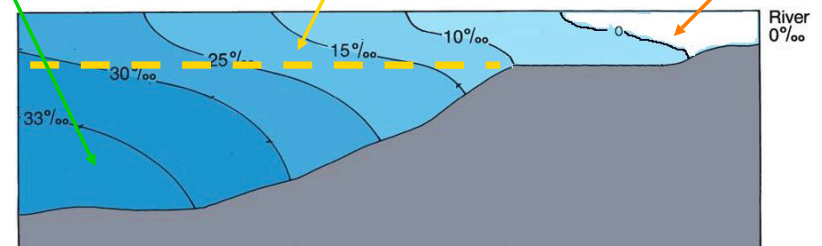


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Circulation in Estuaries

- 2-layered haline vertical stratification
- Surface low-salinity layer created by river runoff
- Deeper saltier layer originating from the ocean
- Separated by halocline

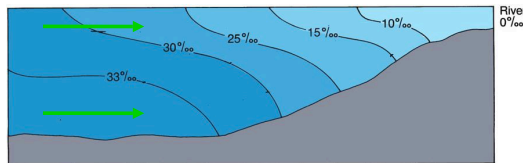


Circulation in Estuaries

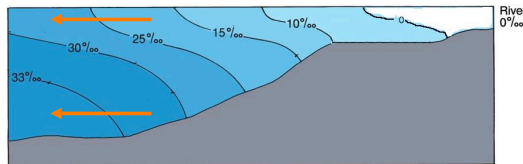


- Instantaneous tidal exchange (flood & ebb)
 - Tidal flood & ebb at all depths at (roughly) the same time

– Flood



– Ebb

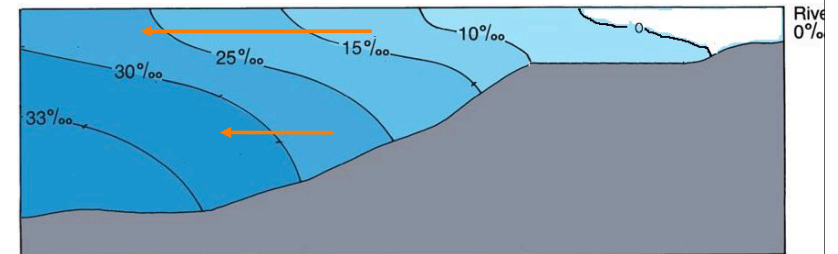


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Circulation in Estuaries



- Ebb current stage
 - Both surface (lower-S) & subsurface (higher-S) layers flow seaward
 - Surface layer flows faster (boost from river input)

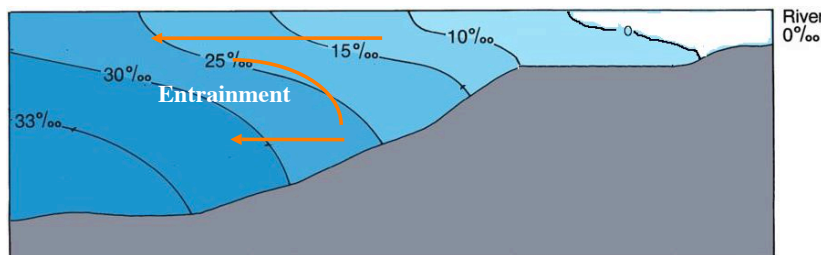


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Circulation in Estuaries



- Ebb current stage — Entrainment
 - Fast surface flow causes friction across halocline
 - Some turbulent mixing across halocline
 - Drags some subsurface water along into outflow

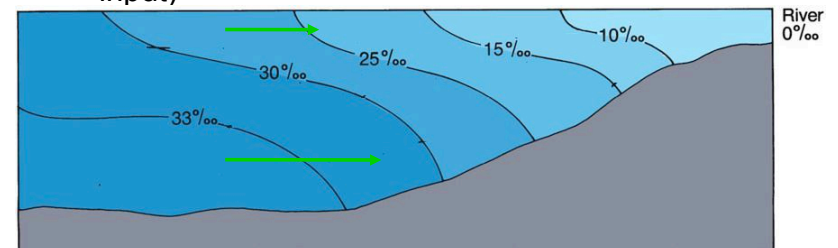


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Circulation in Estuaries



- Flood current stage
 - Both surface (lower-S) & subsurface (higher-S) layers flow landward
 - Surface layer flows slower (inhibition from river input)

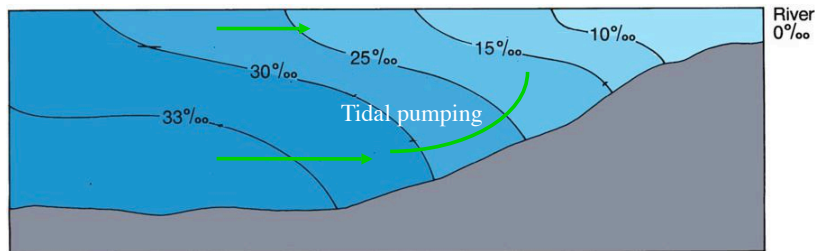


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Circulation in Estuaries



- Flood Current Stage — Tidal pumping
 - Inflowing deep water hits shallow areas
 - Water propelled upward into surface layer
 - A form of upwelling

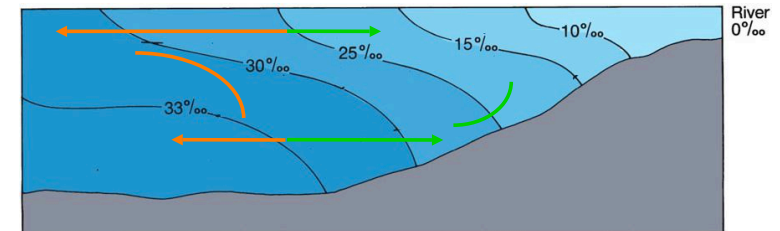


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Circulation in Estuaries



- Net circulation (mean over many tidal cycles)
 - Tidal flood & ebb average almost to zero
 - Surface layer: ebb is stronger than flood (rivers)
 - Subsurface layer: flood is stronger than ebb
 - Replace water lost to entrainment & tidal pumping

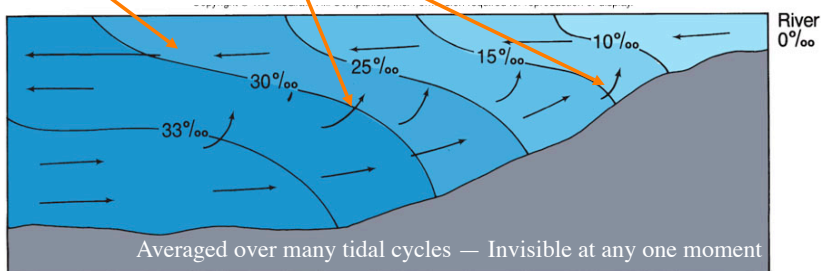


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Net Circulation in Estuaries



- 2-layered Circulation
 - Net lower-S seaward flow in surface layer
 - River input
 - Some entrained, pumped & mixed higher-S water

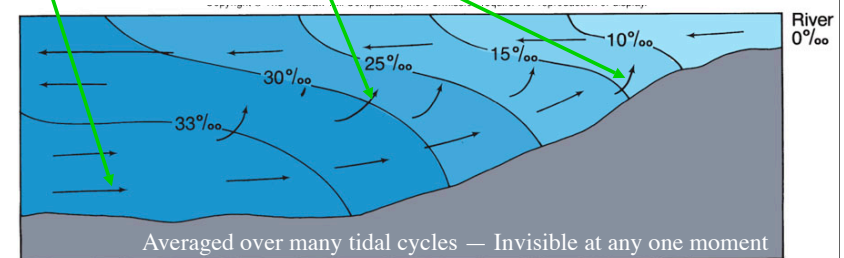


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Net Circulation in Estuaries



- 2-layered Circulation
 - Net higher-S landward flow in subsurface layer
 - Inflow from ocean along bottom
 - Replaces entrained, pumped & mixed higher-S water



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Types of Estuaries



- 4+1 types of estuaries
 - Classified by pattern of vertical stratification
 - Salinity is the most important factor
 - Unlike temperature dominance in most oceans
 - Change in salinity between upper and lower layers
- Vertical salinity gradient is a balance
 - River flow creates the stable vertical stratification
 - Mixing due to tidal action disrupts stratification.

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Classification of Estuaries I



- Salinity difference ΔS between surface and bottom layers at any station in the estuary
 - $\Delta S > \sim 19 \text{ g/kg}$ = Salt Wedge or Fjord (highly stratified)
 - $\sim 3 \text{ g/kg} > \Delta S > \sim 19 \text{ g/kg (PSU)}$ = Partially Mixed (moderately stratified)
 - $\Delta S < \sim 3 \text{ g/kg}$ = Well Mixed (weakly stratified or unstratified)

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Classification of Estuaries II



- Based on ratio of mean volume of river inflow (R) to mean volume of tidal prism (P) over 1 (mean) tidal cycle
 - $R/P > 1$ = Salt Wedge or Fjord (highly stratified)
 - $R/P \sim 0.25$ = Partially Mixed (moderately stratified)
 - $R/P < 0.1$ = Well Mixed (weakly stratified or unstratified)

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Salt wedge estuaries

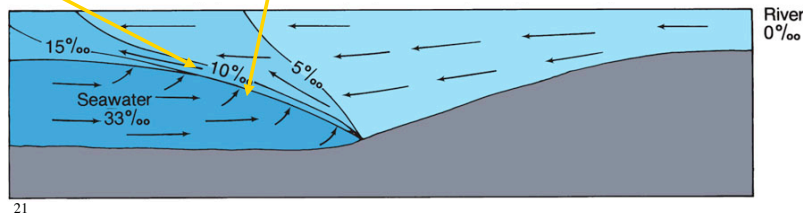


- Dominated by high river runoff
 - Large river mouths
 - Columbia & Mississippi
 - Smaller river mouths entering larger estuaries
 - Duwamish entering Puget Sound
 - Named for sharp boundary between river & sea water
 - Strong halocline moves back and forth with tides
 - Strong vertical stratification

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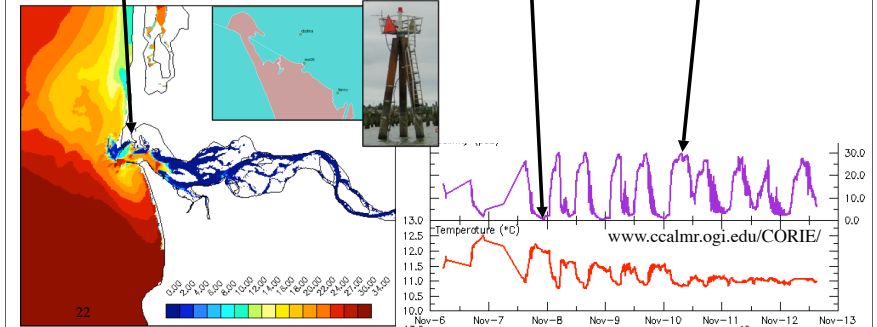
Salt wedge estuaries

- Dominated by high river runoff
 - Weak vertical mixing, strong stratification
 - Strong halocline "wedge" moves with tide
 - Moves up river channel for some distance on flood
 - Moves out into open water on flood
 - Weak entrainment of higher-S water



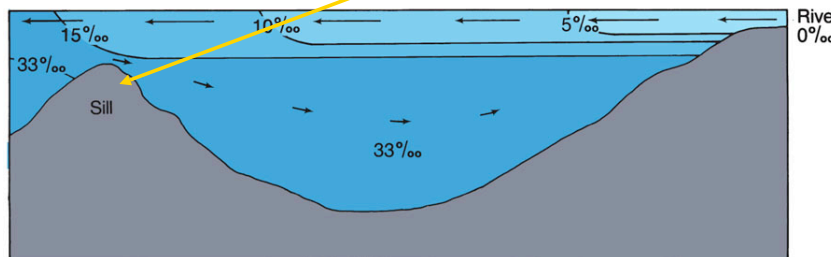
Salt wedge estuaries

- Columbia River estuary
 - Strong halocline "wedge" moves with tide
 - Moves up river channel for some distance on flood
 - Moves out into open water on ebb



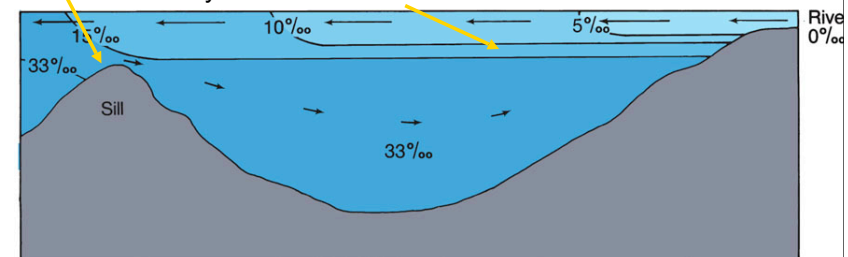
Fjord estuaries

- Like a salt wedge but some special traits
 - Carved by glacier: Deep, narrow, straight
 - U-shaped cross section vs. V-shaped river valleys
 - Shallow area called a sill at the mouth



Fjord estuaries

- Sill blocks exchange of deep water with ocean
 - Little water movement below sill depth
- Strong vertical stratification
 - River water runs off with little mixing
 - Nearly horizontal isohalines



Fjord estuaries

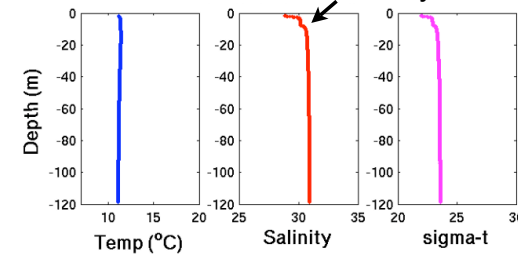
- Found in B.C., S.E. Alaska, Chile, Norway, Scotland, New Zealand
 - Puget Sound has fjord-like properties
 - Carved by a glacier
 - But one moving from mouth to head
 - Several sills
 - Mixing strong enough that the deep water is replaced
 - Potential for oxygen depletion in places



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Fjord estuaries

- Hood Canal the most fjord-like in Puget Sound
 - Data from Hoodspout 11-4-06
 - Continuous monitoring buoy
 - Thin low-S surface layer



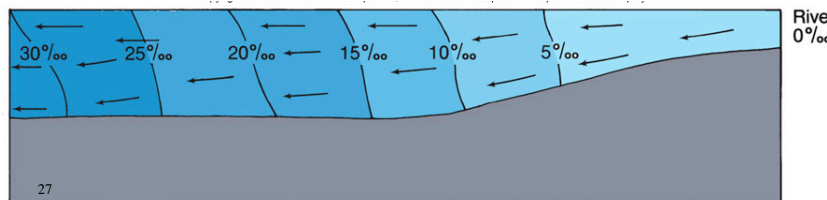
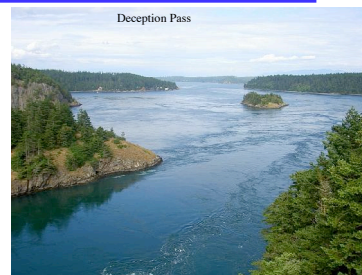
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Well-mixed estuaries

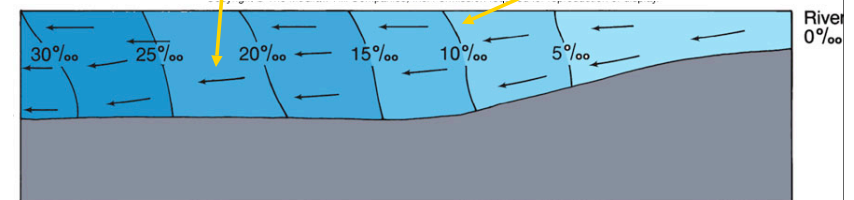
- Low river input & strong tidal mixing
 - Far from river mouth
 - In areas of large tidal exchange, fast tidal currents, and/or turbulence



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Well-mixed estuaries

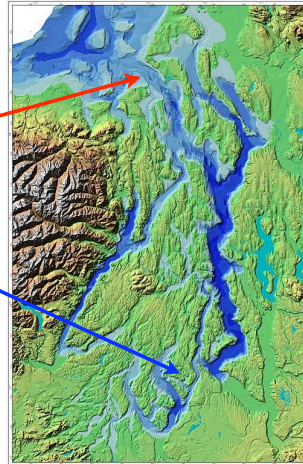
- Weak vertical stratification & halocline
 - Isohalines almost vertical
 - Move back & forth with tide
- No 2-layered net circulation
 - Net outflow at all depths



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Well-mixed estuaries

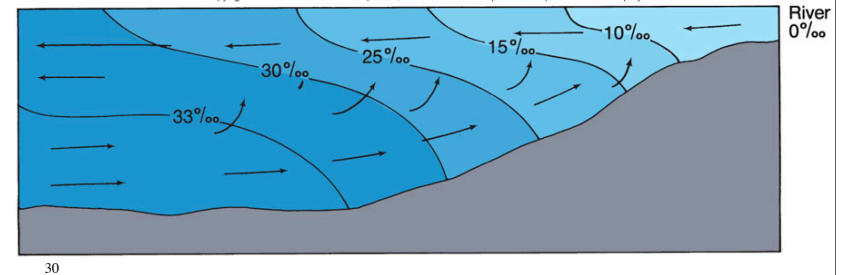
- Currents in inland passages
 - Large volume of water squeezing into a narrow shallow channel
 - Admiralty Inlet
 - Tacoma Narrows
 - Speed of current & rough bottom topography
 - Strong vertical mixing
 - Breaks down stratification



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Partially-mixed estuaries

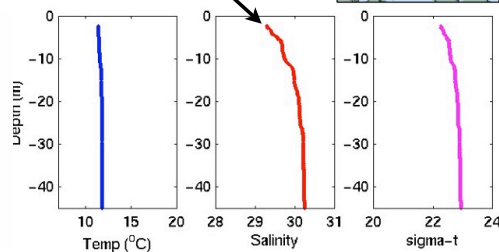
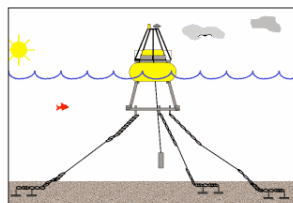
- Rough balance between rivers & mixing
 - 2 layers & 2-layered circulation
 - Halocline weaker & broader than salt wedge or fjord
 - Mixing, entrainment, tidal pumping stronger
 - Example: Puget Sound Main Basin off Seattle area



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Partially-mixed estuaries

- Halocline weaker & broader than salt wedge or fjord
 - UW ORCA buoy moored off Edmonds
 - Data from Nov. 7 2004
 - More gradual change in S with depth



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"Reverse" estuaries

- Not really estuaries
 - Semi-enclosed evaporative basins
 - Arid, subtropical latitudes
 - Fresh water gain from rivers much less than loss to evaporation
 - Mediterranean & Red Seas
- Vertically instability & convection
 - Evaporation increases surface salinity
 - Surface water more dense despite temperature

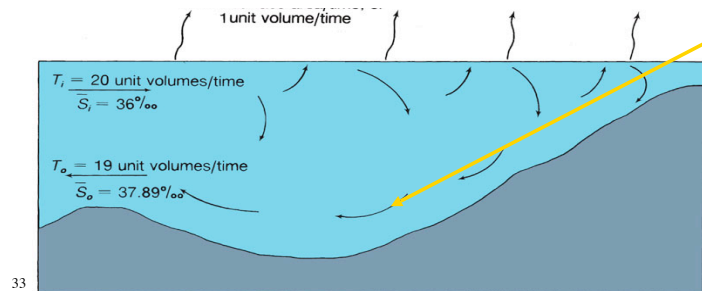


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"Reverse" estuaries



- Inverse circulation (Mediterranean)
 - Net subsurface seaward higher-S outflow
 - Dense bottom water flows over Gibraltar "sill"
 - Sinks to a depth of about 1000 m in Atlantic



"Reverse" estuaries



- Inverse circulation (Mediterranean)
 - Net surface landward inflow from Atlantic
 - Replaces evaporating and sinking water
 - Surface inflow lower-S than water it replaces

