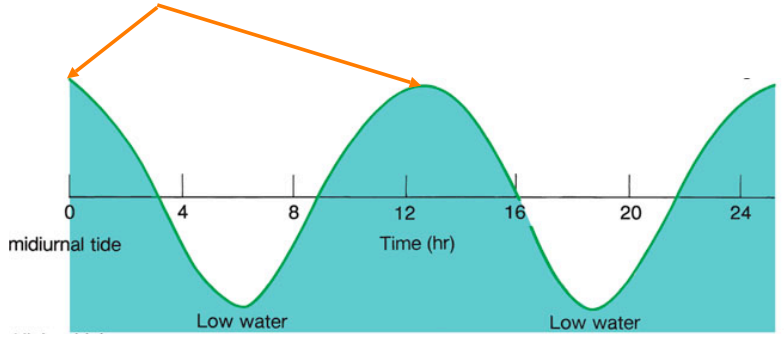
Hood Canal Oxygen

- Lesson 1: The tides

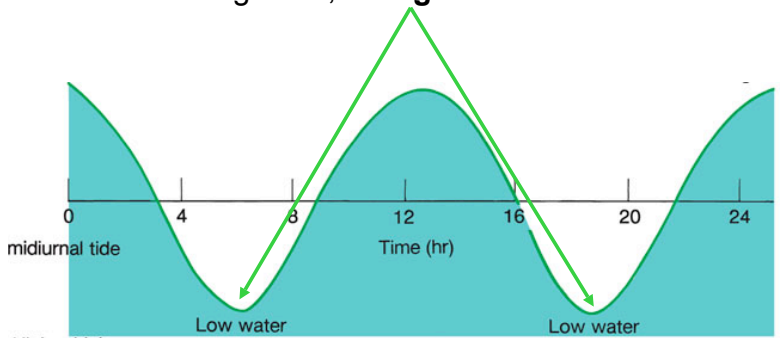
Tidal terminology

- A form of wave
  - **Crest** = high tide,



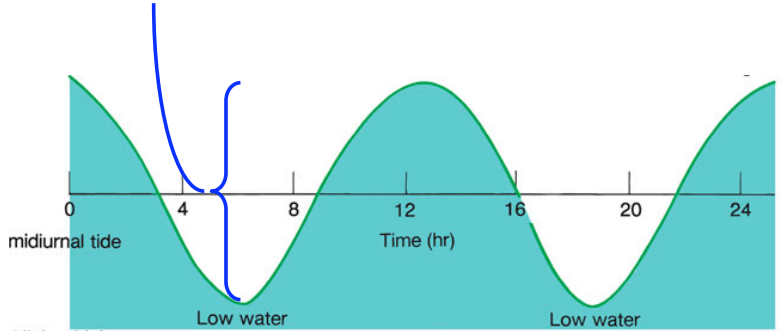
Tidal terminology

- A form of wave
  - **Crest** = high tide, **Trough** = low tide



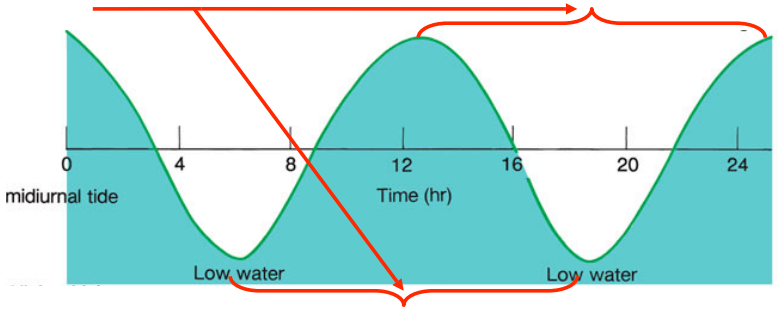
Tidal terminology

- A form of wave
  - **Tidal range** = vertical height from high to low



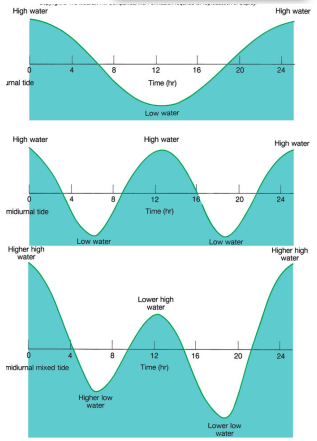
Tidal terminology

- A form of wave
  - **Tidal range** = vertical height from high to low
  - **Period** = Time between highs or lows



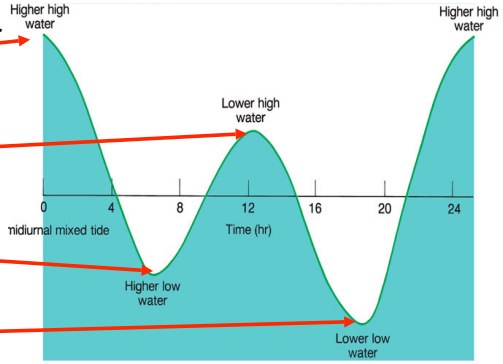
Tidal terminology

- Tidal periods (per day)
  - **Diurnal** = 1 high & low
    - Gulf of Mexico
  - **Semidiurnal** = 2 equal highs & lows
    - U.S. East Coast
  - **Mixed (semidiurnal)** = 2 unequal highs & lows
    - U.S. West Coast



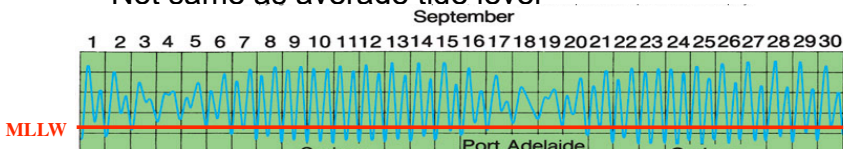
Tidal terminology

- **Mixed (semidiurnal tide)** = 2 unequal highs and lows per day
- High(er) high water (HHW)
- Low(er) high water (LHW)
- High(er) low water (HLW)
- Low(er) low water
- (LLW)



Tidal terminology

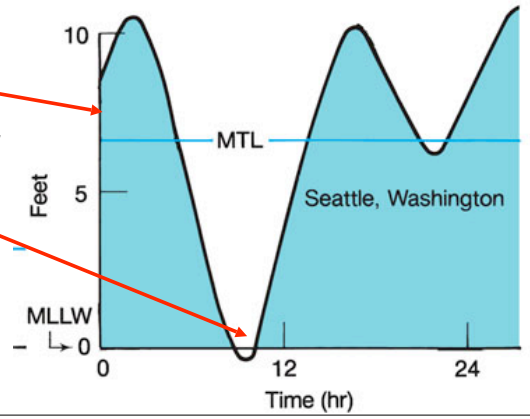
- **Tidal datum** = zero tide level
  - Mean low water (MLW) (diurnal & semidiurnal)
  - Mean lower low water (MLLW) (mixed)
  - Not same as average tide level



  - Zero depth on navigation charts & tide tables
  - Any tide below this level = a **minus tide**.

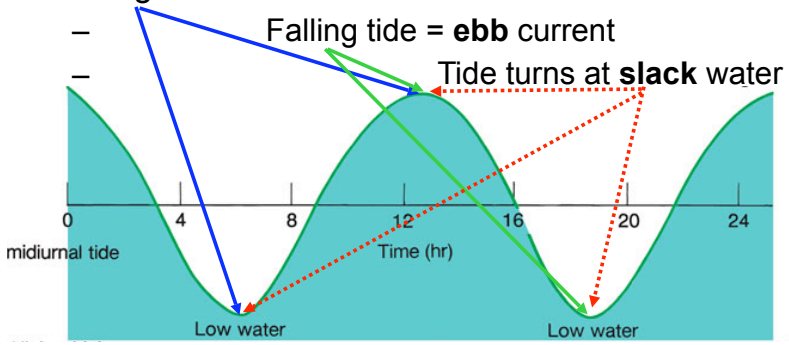
Tidal terminology

- **Tidal datum** = zero tide level
  - MLLW ≠ average tide level (MTL)
  - Any tide below MLLW = **minus tide**



Tidal Currents

- As tide rises & falls, water moves laterally
- Rising tide = **flood** current
  - Falling tide = **ebb** current
  - Tide turns at **slack** water

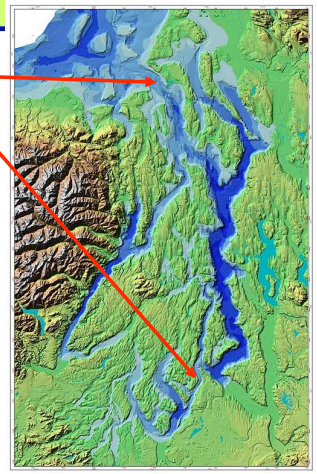


Tidal Currents

- **Flood** current flows landward until HW
  - Slack water corresponds to high water
  - Point at which current slows to zero & reverses
- **Ebb** current flows seaward until LW
  - Slack water corresponds to low water
  - Point at which current slows to zero & reverses
- Maximum speed halfway between slacks
  - Speed proportional to range (spring vs. neap)
  - Volume of water transported in 6 hrs. 12 min.

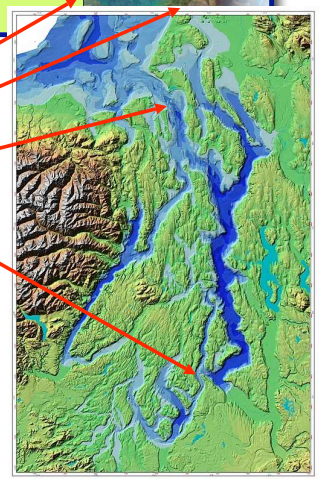
Tidal Currents

- Currents in inland passages
  - Large volume of water squeezing into a narrow shallow channel
  - Amount of water exchange reduced
  - Speed of water exchange increased
  - Lag between the times of HW & LW and those of slack



Tidal Currents

- Currents in inland passages
  - San Juan Islands 4 knots
  - Deception Pass 8 kt
  - Admiralty Inlet 4 kt
  - Tacoma Narrows 6 kt
  - Sechelt rapids, BC coast ("Skookumchuck", Indian for "strong salt water") 12 kt



Hood Canal Oxygen

• Lesson 2: Density

Density

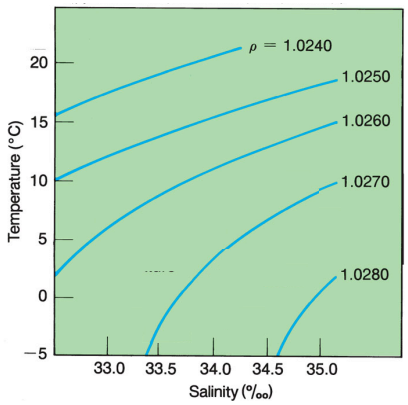
- Definition: mass of substance per unit volume
  - Grams per cm^3 (=cc, =ml)
  - Symbol = ρ
- ρ of pure water at 4˚C = 1.0 g/ cm^3

Density of Sea Water

- Salts make water more dense
  - In 35 g/kg seawater (at 4˚C) density = 1.028
- Temperature also affects density
  - Warm water expands, density decreases
  - Cold water contracts, density increases

T-S Diagrams

- Density is calculated from T & S
  - Uses a complex formula
  - Results printed in tables
  - Easier to use is a T-S diagram



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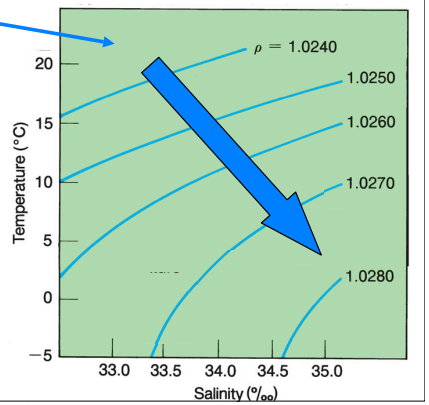
T-S Diagrams

- Density is calculated from T & S
  - Isopycnals = lines of constant density
  - Density increases from upper left to lower right



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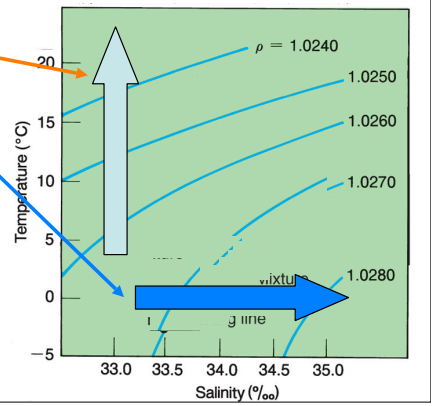
T-S Diagrams

- T&S have opposite effects on ρ
  - ⇑T = ⇓ρ
  - but ⇑ S = ⇑ ρ
  - ⇓S = ⇓ρ
  - but ⇓T = ⇑ ρ



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T-S Diagrams

- T&S have opposite effects on ρ
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  - ⇓T = ⇑ ρ
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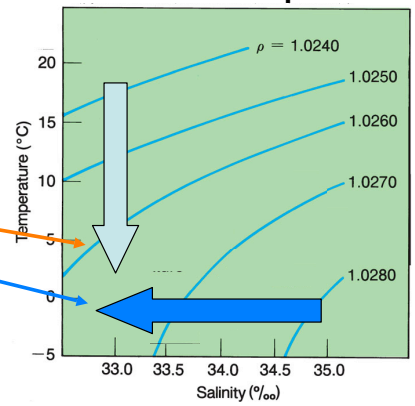
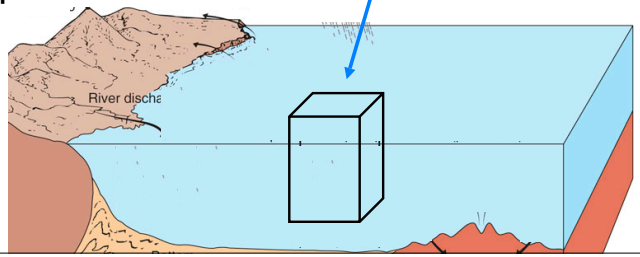


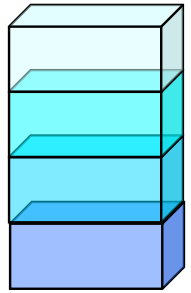
Vertical Stratification

- **Water column**
  - Hypothetical vertical section of water from surface to bottom
    - Square cross-section



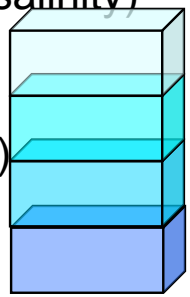
Vertical Stratification

- **Stratification** is the vertical density layering of water column
  - Waters of different density at different depths
  - Buoyancy — less dense water tends to float atop more dense



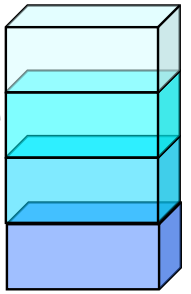
Vertical Stratification

- Density stratification
  - Warmer water floats & cooler water sinks (constant salinity)
  - Fresher water floats & saltier water sinks (constant temperature)



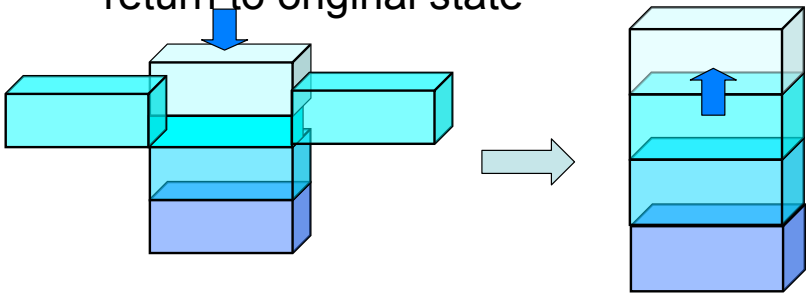
Vertical Stability

- **Stability** of stratified water column
  - Depends on relative density of layers
  - Less dense water atop more dense water = **stable**
    - It will persist until disturbed



Vertical Stability

- **Stable** stratification
  - Resists disturbance & tends to return to original state



Examples: Stability

- **Thermal**—Lake Washington
  - Surface warms in summer
  - Warm (lower-density) water lies atop cool (higher-density) water
  - Lower density atop higher density

Examples: Stability

- **Thermal**
  - **Thermocline**: boundary between layers of different temperature
  - Rapid change in temperature with depth

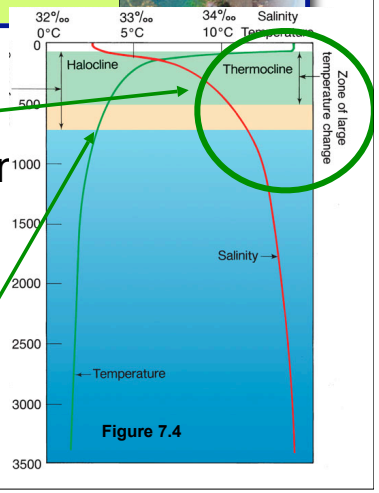


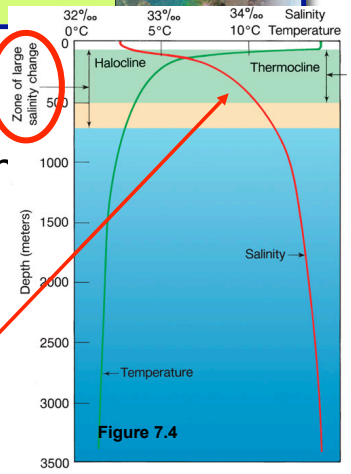
Figure 7.4

Examples: Stability

- **Haline**—Puget Sound
  - River **runoff** meets sea water at the river mouths
  - Fresh or **brackish** (low-salinity) water lies atop higher-salinity water
  - Lower density atop higher density

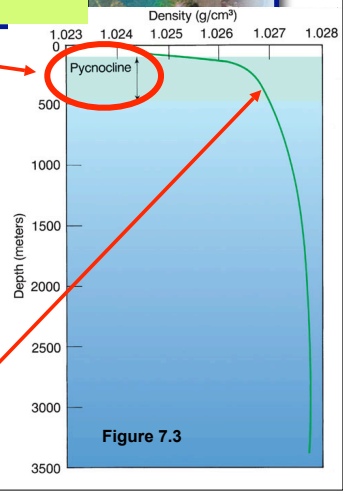
Examples: Stability

- **Haline**
  - **Halocline**: boundary between layers of different salinity
  - Rapid change in salinity with depth



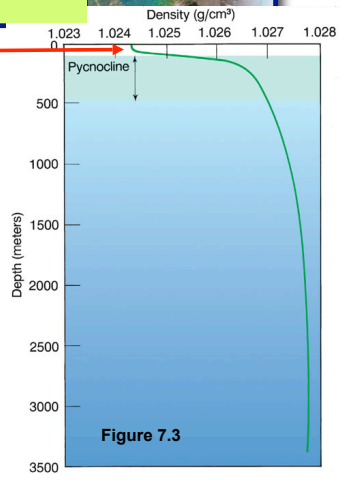
Examples: Stability

- **Pycnocline**
  - Boundary between 2 layers of different density
  - If there is a thermocline or halocline, there is also a pycnocline.



Examples: Stability

- **Mixed layer**
  - Layer above the pycnocline
  - Homogenized by wind mixing
  - Nearly uniform properties over depth.



Stratifying processes

- What external natural processes affect stratification?
  - Anything that changes density
    - Heating & cooling
    - Freshwater runoff
    - Evaporation & precipitation

Stabilizing processes

- What external natural processes enhance vertical stratification & stability?
  - Surface solar heating (T)
  - Freshwater runoff (S)
  - Rain (S)

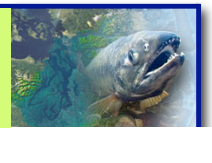
Hood Canal Oxygen

- Lesson 3: Estuaries

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 ≠ estuaries
- Very elastic size definition
  - Small stream mouth (Pipers Creek, N. Seattle)
  - Large river mouths (Columbia)
  - Complex embayments (Puget Sound)

Prominent U.S. estuaries

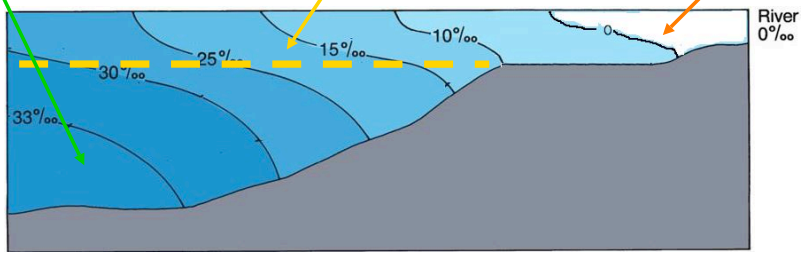


Puget Sound

- Low salinity
  - Surface salinity away from river mouths ranges from 28-29
    - At river mouths or in very sheltered inlets of the south Sound, salinity can be very low (**brackish**, 10 or less) depending on season
  - Subsurface salinity 30 - 31, depending on season
  - Inflowing ocean water salinity ~32

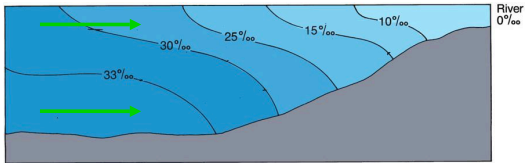
Circulation in Estuaries

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

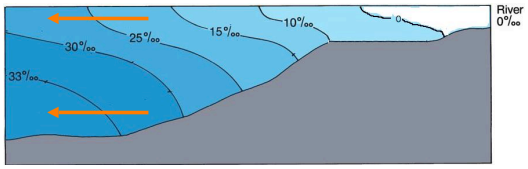


Circulation in Estuaries

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

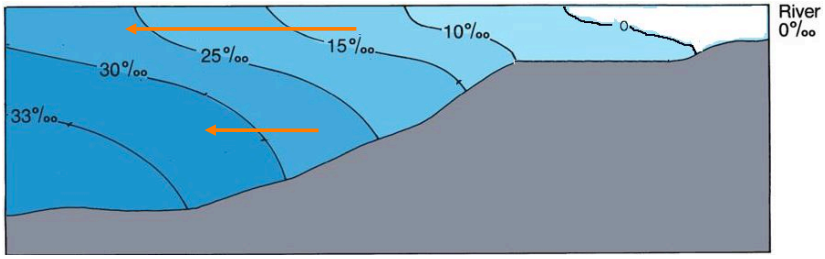


  - Ebb



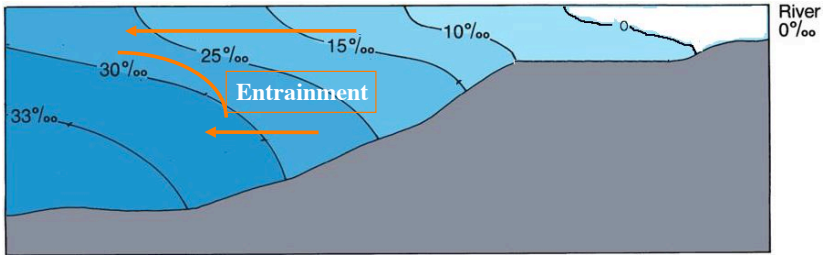
Circulation in Estuaries

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



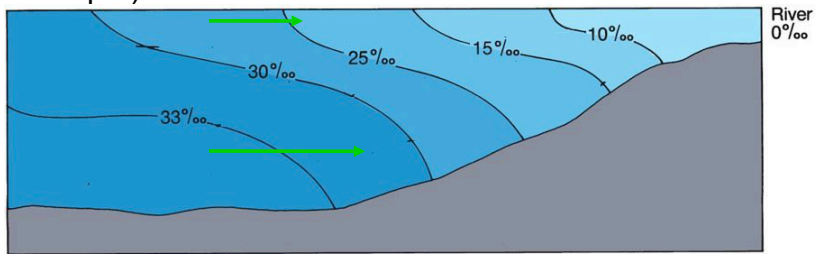
Circulation in Estuaries

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



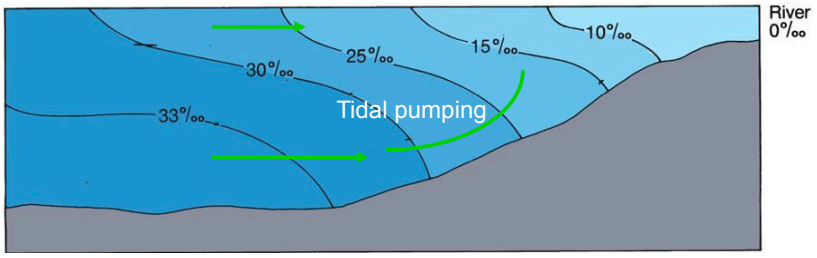
Circulation in Estuaries

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



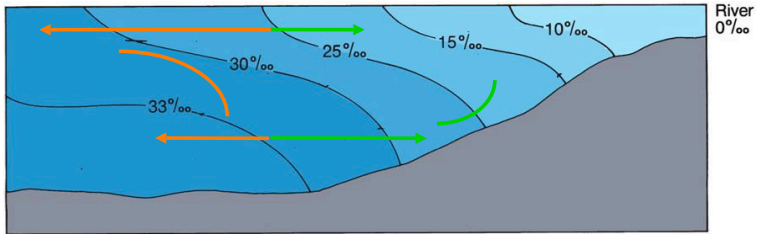
Circulation in Estuaries

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



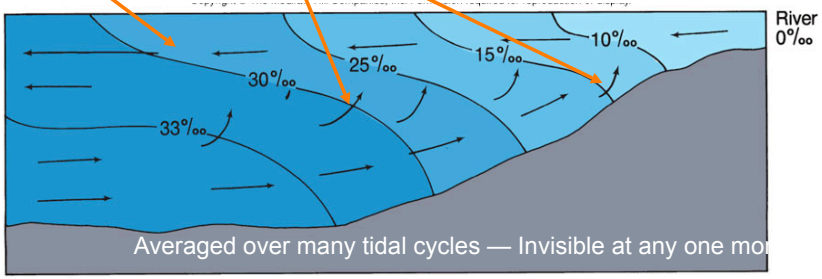
Circulation in Estuaries

- 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



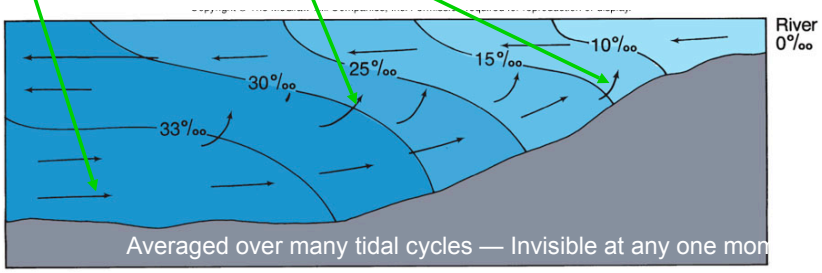
Net Circulation in Estuaries

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



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



Types of Estuaries

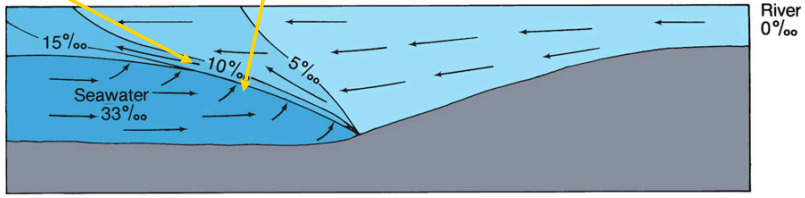
- 4 types of estuaries
  - Classified by pattern of vertical stratification
  - Salinity is the most important factor
    - Unlike temperature dominance in most oceans
    - Change in salinity between upper and lower layers
      - See table in lab manual p. 38.
  - Vertical salinity gradient is a balance
    - River flow creates the stable vertical stratification
    - Mixing due to tidal action disrupts stratification.

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

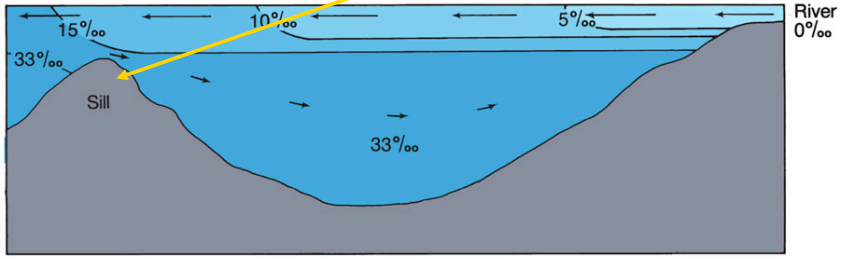
Salt wedge estuaries

- 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



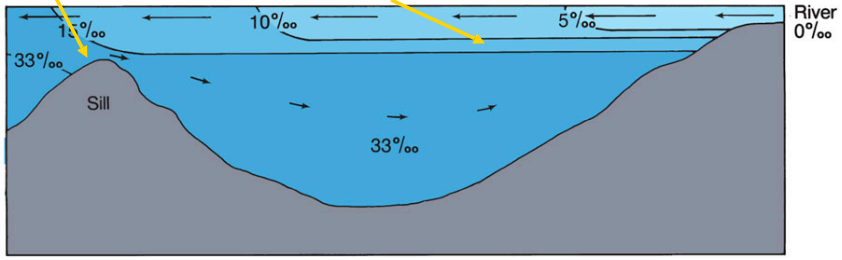
Fjord estuaries

- 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

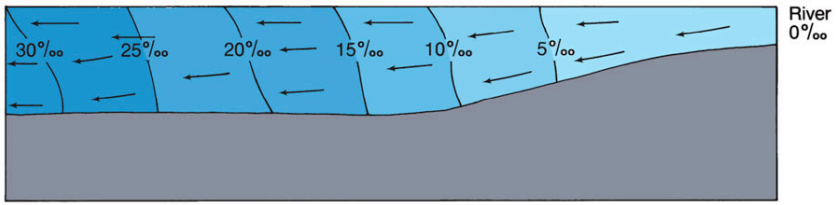


Fjord estuaries

- 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
  - Saanich Inlet (Vancouver Island) anoxic fjord
    - No oxygen below ~ 80 m (sill depth ~60 m)

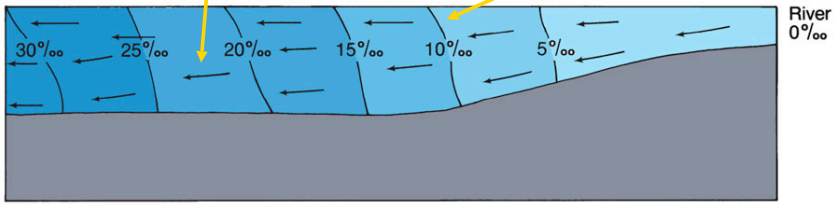
Well-mixed estuaries

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



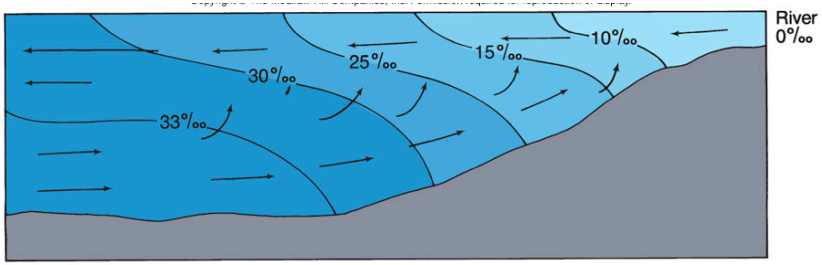
Well-mixed estuaries

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



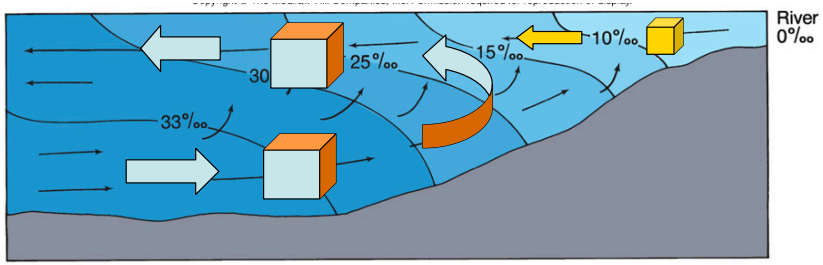
Partially-mixed estuaries

- **Rough balance between rivers & mixing**
  - 2 layers & 2-layered circulation
    - Halocline weaker & broader than salt wedge or fjord
    - Mixing, entrainment, tidal pumping stronger



Flushing in Estuaries

- Gradual replacement of water in estuary
  - Inflowing river & ocean waters flushed to sea
  - Removes pollutants, replaces nutrients & O_2

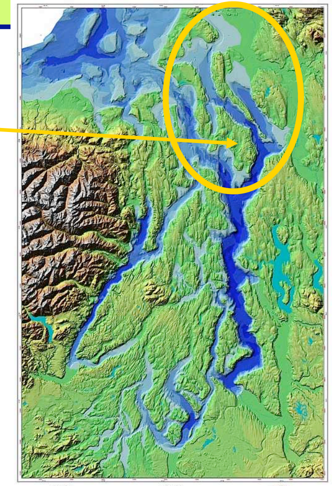


Flushing in Estuaries

- Flushing time = time to 100% replace volume
  - (**Inter)tidal prism** = average volume entering & leaving over tidal cycle
  - Average volume of estuary ÷ **prism =** # tidal cycles to flush total volume of estuary
    - Use tidal period (diurnal or semidiurnal) to convert to time in hours and minutes.

Puget Sound

- Puget Sound a complex of sub-basins:
  - Whidbey Basin (no sill)
  - Hood Canal (sill under bridge)
  - Main basin (sill at Admiralty Inlet)
  - South Sound (sill at Tacoma Narrows)



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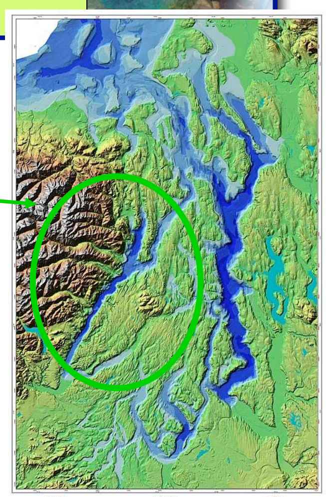

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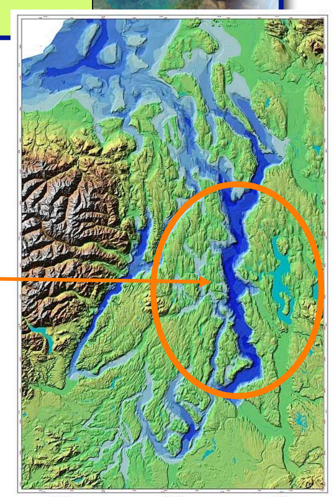

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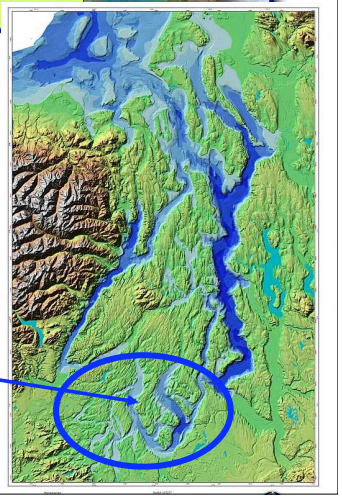

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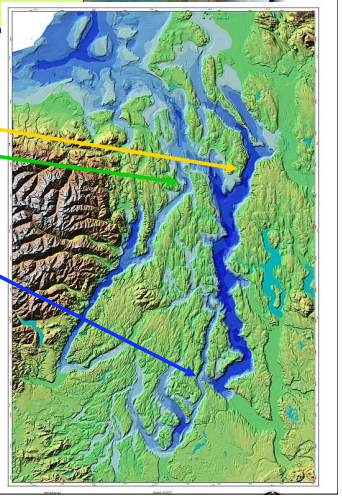
Puget Sound

- Basins are connected
  - Whidbey
    Hood Canal,
    south Sound
    connect to
    ocean via Main basin
    & Juan de Fuca Strait
  - Longer flushing time than one large basin



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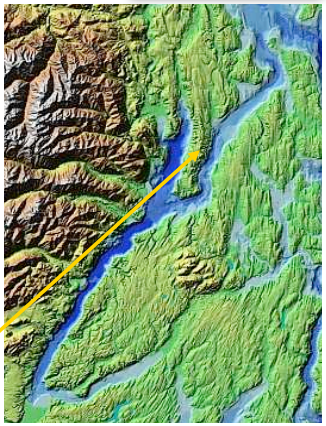
Hood Canal Flushing

- Water takes one year or more to flush out of Hood Canal
  - Compare to 2-3 months in Main Basin
  - Very slow replenishment of deep water
  - Allows O2 to be used up
  - Canal is long, narrow, deep, & blocked by sill



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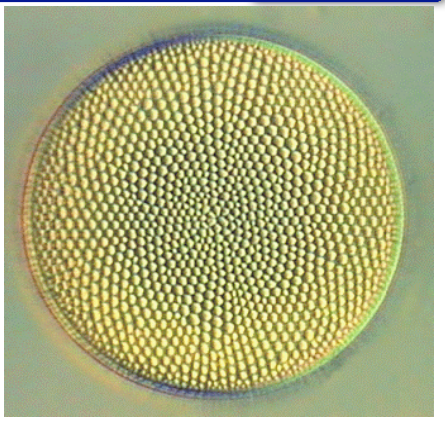
Hood Canal Oxygen

- Lesson 4: Biology

Puget Sound phytoplankton

Coscinodiscus sp., a solitary centric diatom
http://www.biol.tsukuba.ac.jp/ino/st/baci/coscino.gif



Source: Jan Rines' East Sound Page http://thalassa.gso.uri.edu/Esphyto/list/ppllist.htm

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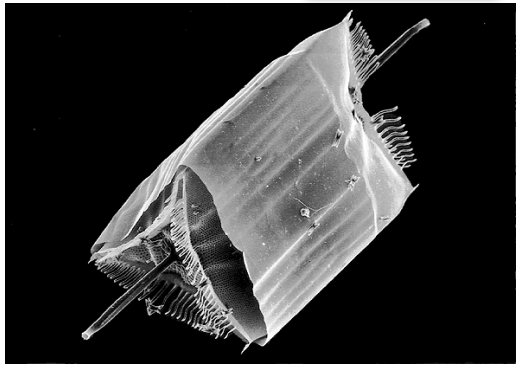
Puget Sound phytoplankton

Ditylum brightwellii, a (usually) solitary centric diatom
http://www.biol.tsukuba.ac.jp/ino/st/baci/Ditylum.GIF



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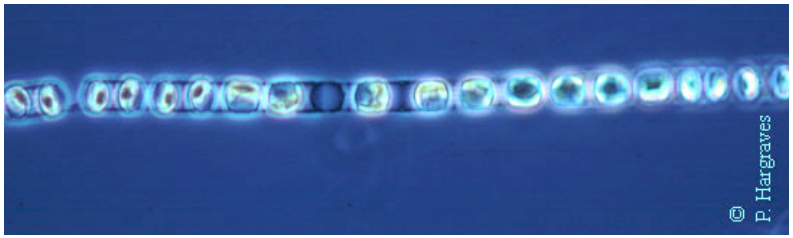
Puget Sound phytoplankton



Skeletonema costatum, a common chain-forming centric diatom

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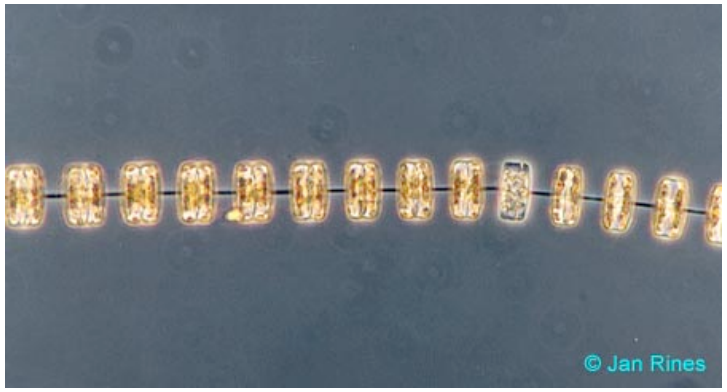
Puget Sound phytoplankton

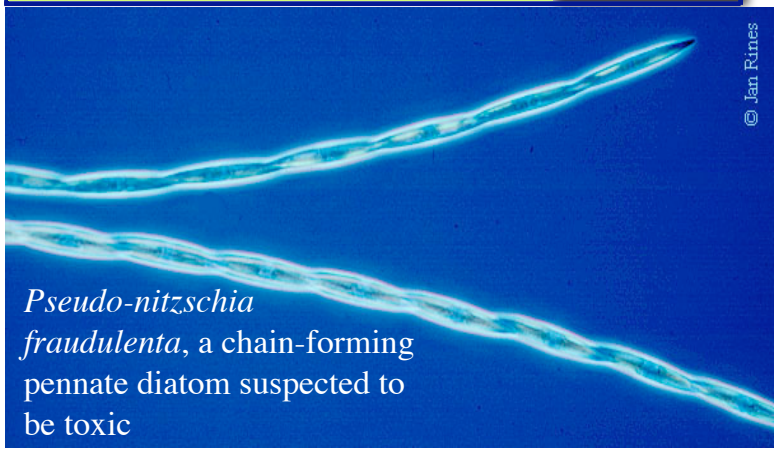
Thalassiosira sp., a chain-forming centric diatom



Puget Sound phytoplankton

Chaetoceros decipiens, a common chain-forming spiny centric diatom

Puget Sound phytoplankton

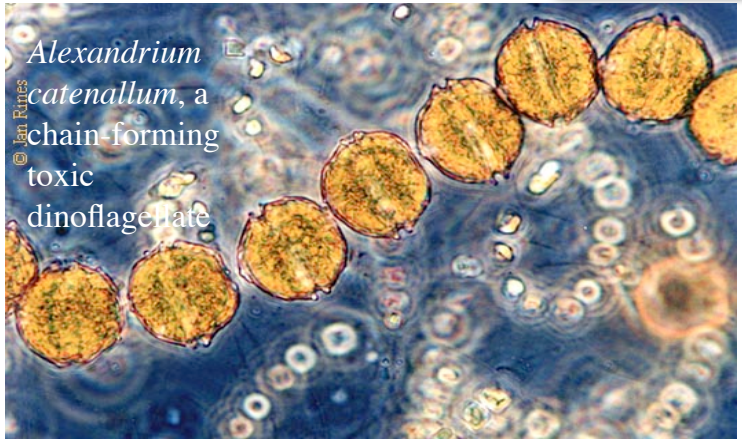


Pseudo-nitzschia fraudulenta, a chain-forming pennate diatom suspected to be toxic

Puget Sound phytoplankton

Ceratium fusus, a solitary dinoflagellate

Puget Sound phytoplankton



Alexandrium catenallum, a chain-forming toxic dinoflagellate

Limits on Primary Production

- Light is limiting below the sea surface and in winter.
  - Phytoplankton have strategies to remain at or near the surface
    - Slow sinking
    - Swimming
  - Often become dormant during winter

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Limits on Primary Production

- Nutrients become depleted at the surface due to sinking organic matter
  - Depletion caused by strong stable stratification
    - Phytoplankton sink when nutrients are scarce
  - Replenished by vertical water movement
    - Estuarine flushing
      - Entrainment & tidal pumping
    - Vertical mixing by winds & strong currents

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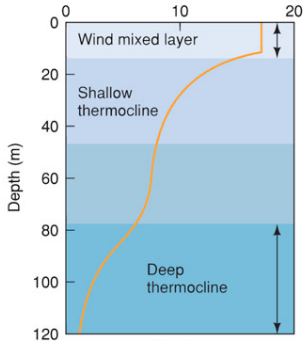
Stratification vs. Mixing

- Vertical stability—Effects
  - Allows phytoplankton to remain near surface
    - Enhanced light availability
  - But reduces nutrient supply to surface
    - Allows nutrients to become exhausted



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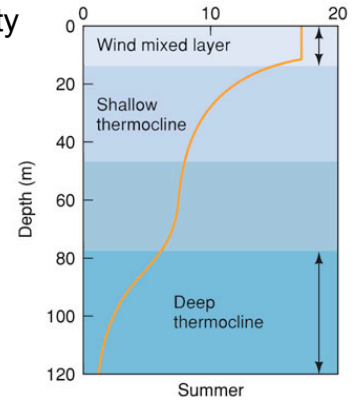
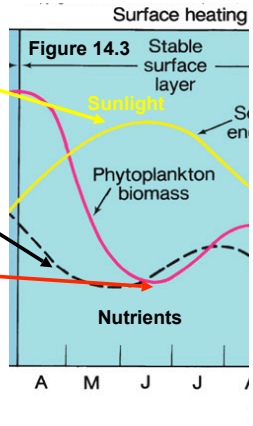
Temperate latitude Summer

- High surface light intensity
  - Strong stratification & stability
    - Shallow mixed layer
    - Enhanced light availability
  - But little mixing
    - Surface nutrient supply low
    - Surface nutrients used up
  - Phytoplankton sink



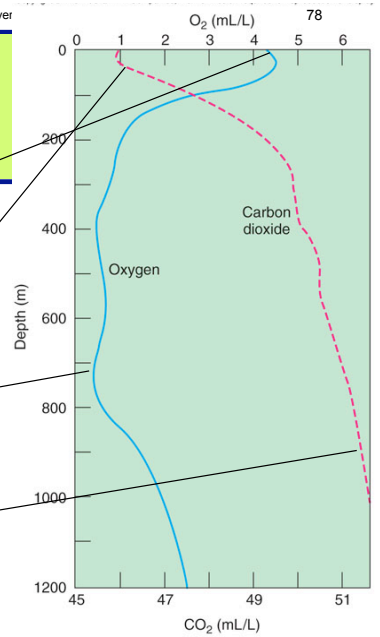
Temperate latitude Summer

- Enhanced light availablility
- Low surface nutrient availability
- Result is a summer decline in phytoplankton



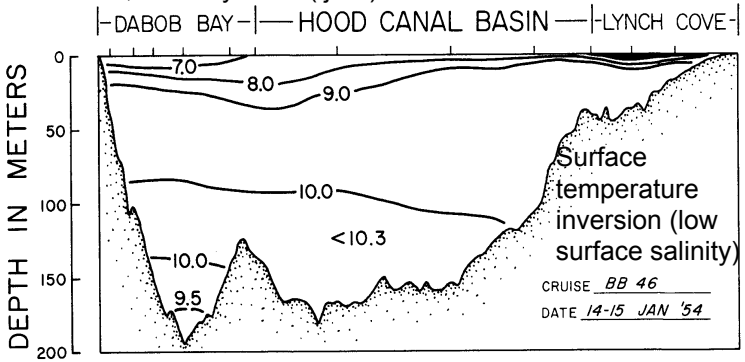
Dissolved Gases

- O2 high at surface (photosynthesis)
- CO2 low at surface (photosynthesis)
- O2 low at depth (respiration & decay)
- CO2 high at depth (respiration & decay)



Basin Temperature

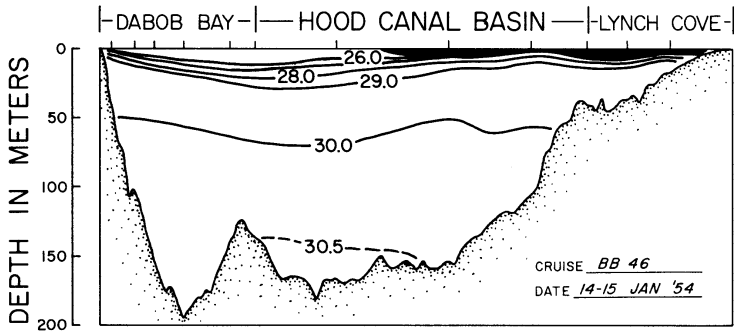
Hood Canal, January 1954 (fjord)



(Source: Collias, McGary, & Barnes 1974)

Basin Salinity

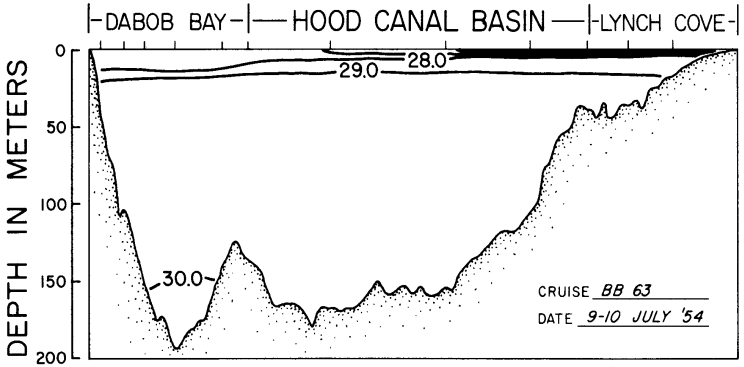
Hood Canal, January 1954 (fjord)



(Source: Collias, McGary, & Barnes 1974)

Basin Salinity

Hood Canal, July 1954 (fjord)



(Source: Collias, McGary, & Barnes 1974)

Basin Temperature

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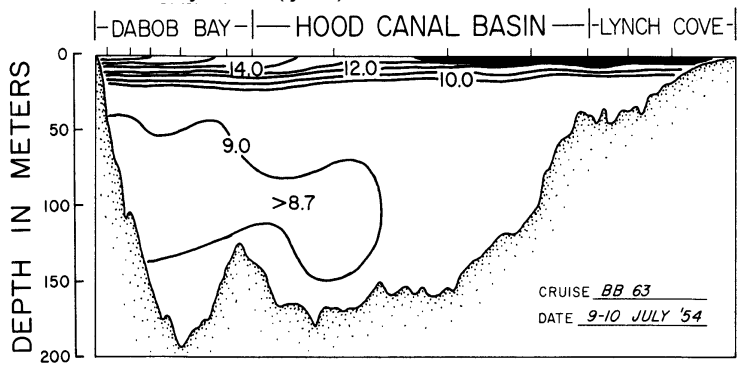
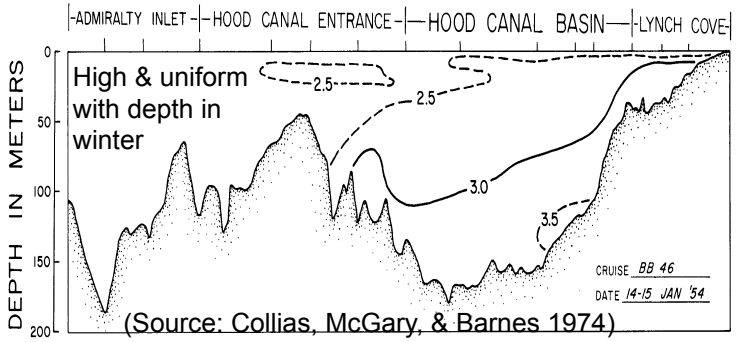


(Source: Collias, McGary, & Barnes 1974)

Puget Sound Nutrients

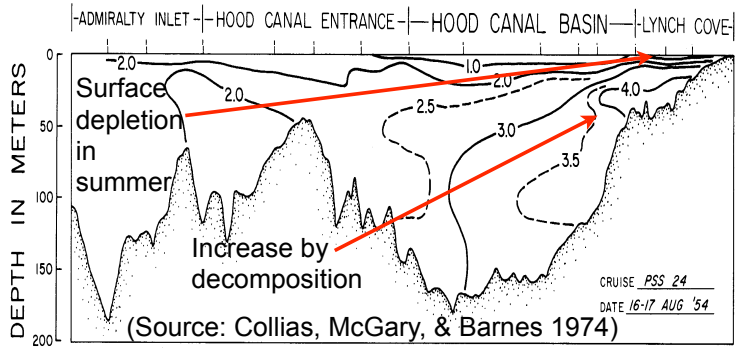
Hood Canal January 1954 (μM PO4 x 16 = NO3)



(Source: Collias, McGary, & Barnes 1974)

Puget Sound Nutrients

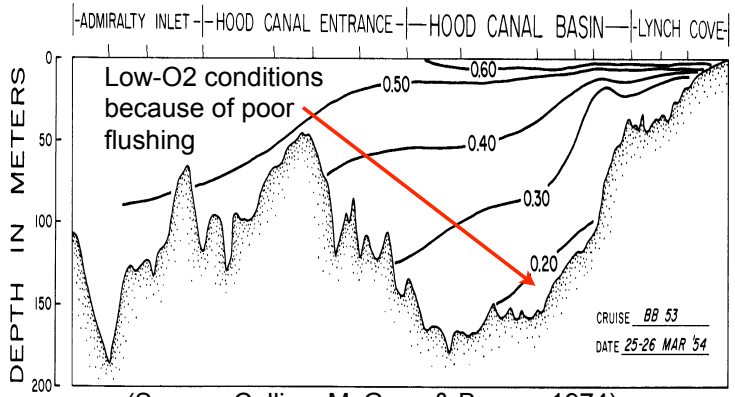
Hood Canal August 1954
(μg-at/l phosphate; multiply by ~6 = nitrate)



(Source: Collias, McGary, & Barnes 1974)

Puget Sound Oxygen

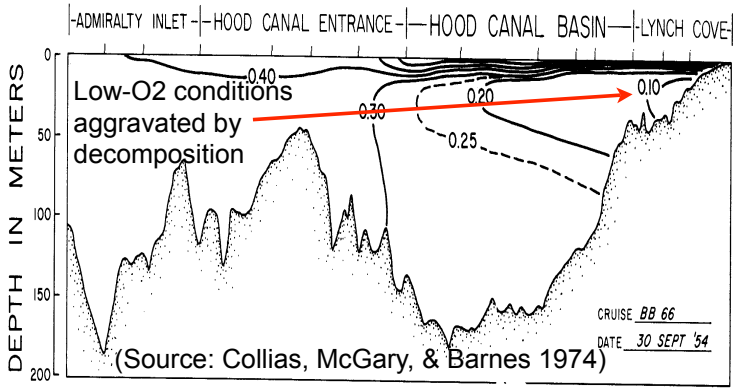
Hood Canal March 1954 (mg-at/l x 18 = mg/l)



(Source: Collias, McGary, & Barnes 1974)

Puget Sound Oxygen

Hood Canal Sept. 1954 (mg-at/l x 18 = mg/l)

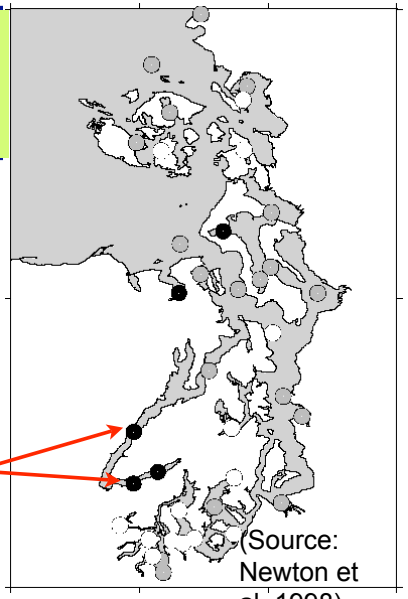


(Source: Collias, McGary, & Barnes 1974)

Oxygen

Seasonal subsurface O2 minima of concern occur where vertical stratification is strongest and most persistent (1990-97).

- Near-anoxic (<3 mg/l)
- Low (<5 mg/l)
- Adequate (>5 mg/l)



(Source: Newton et al. 1998)