Puget Sound basin dynamics, what a concentration represents, and mechanisms for nutrient fluxes

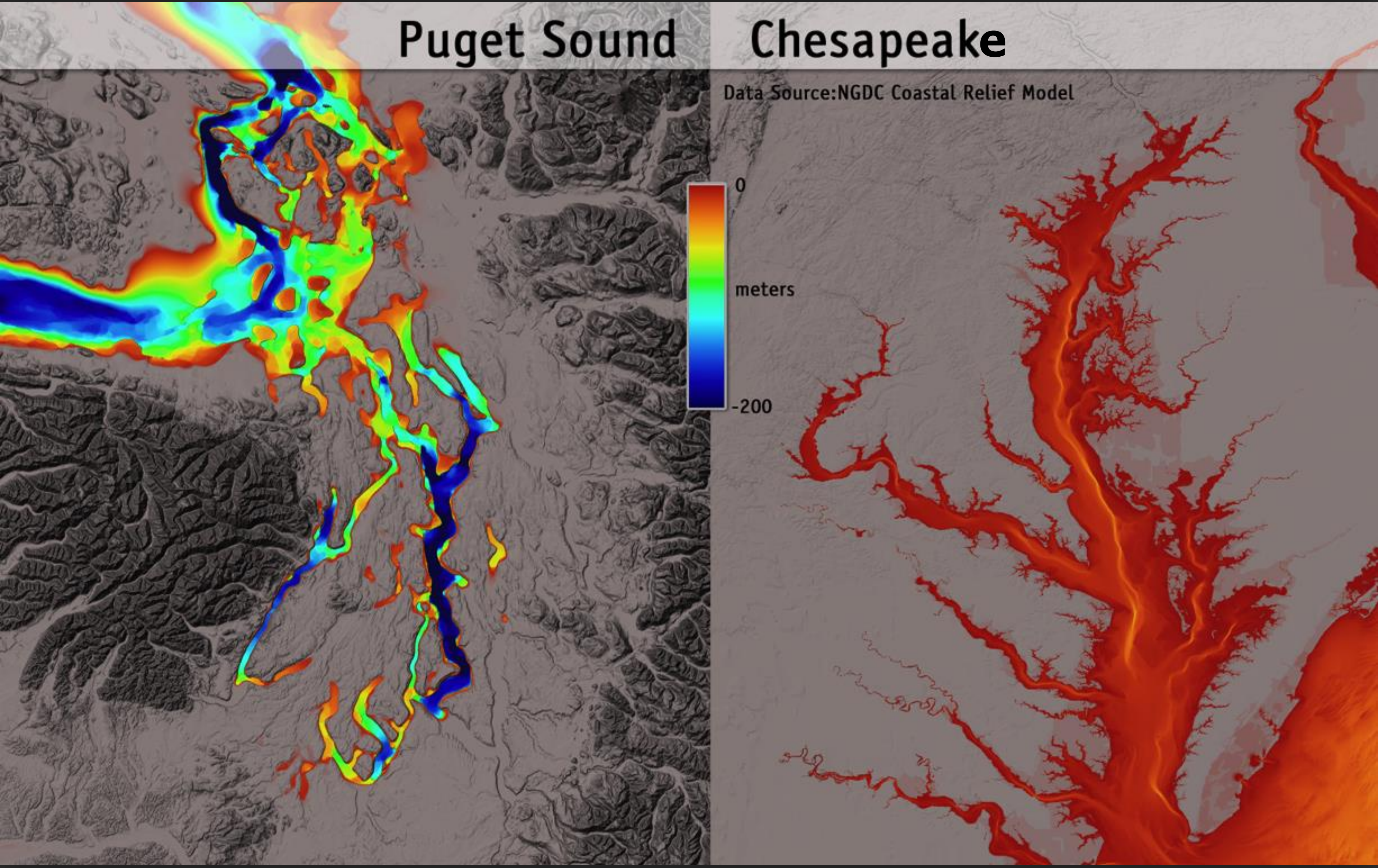
Jan Newton
University of Washington APL and WOAC

Al Devol, John Mickett, Wendi Ruef, Mark Warner,
and many technicians over the years

Puget Sound

Chesapeake Bay

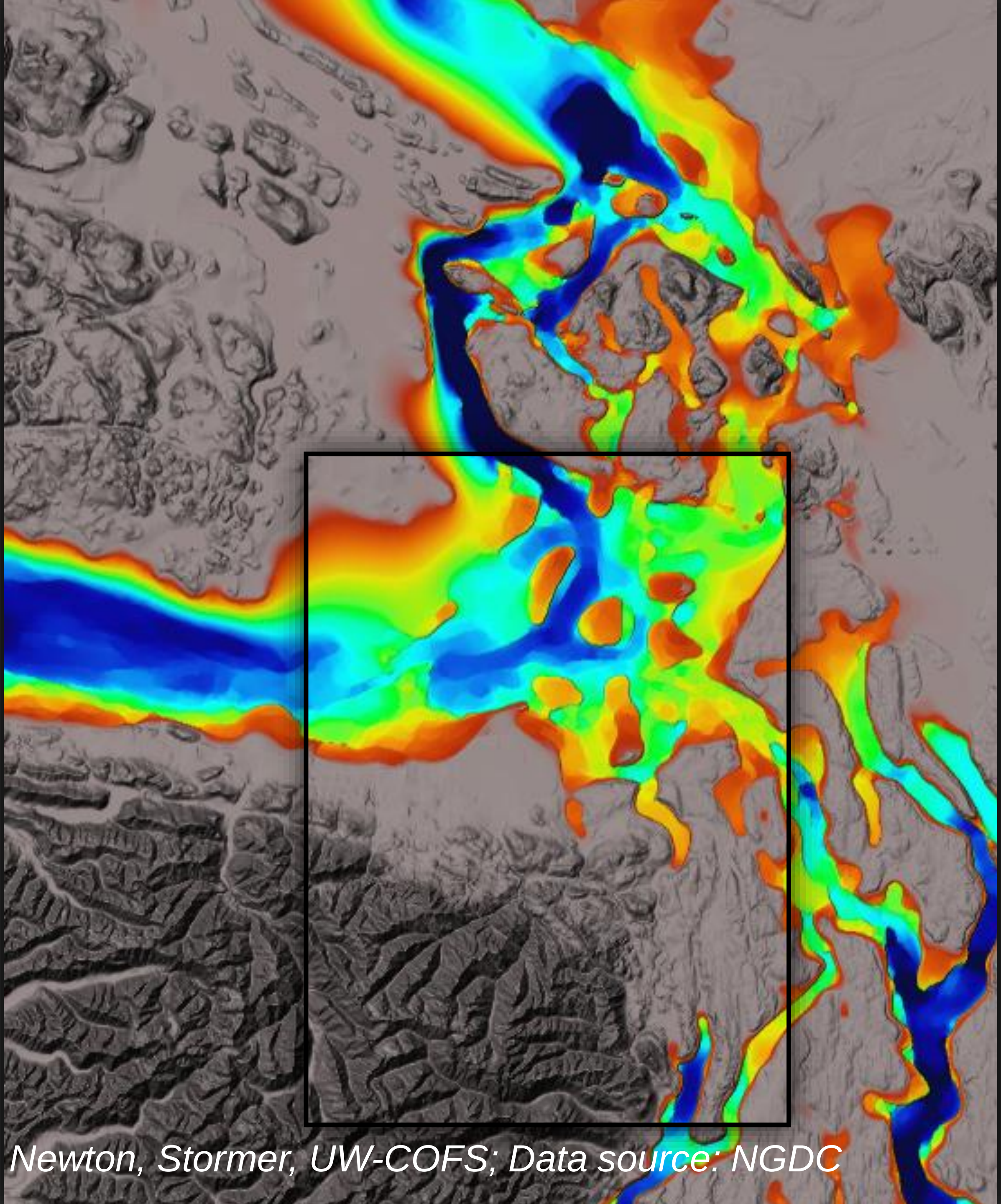
Bathymetry

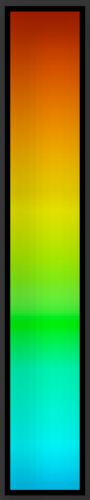


Newton, Stormer, UW-COFS; Data source: NGDC

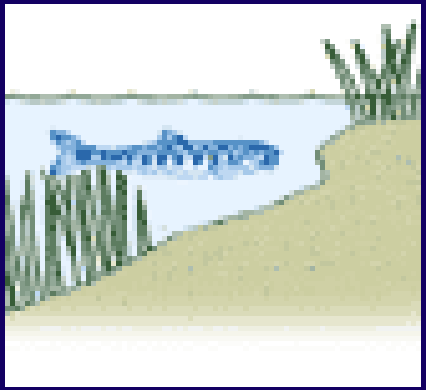
Puget Sound is fjord-like; a glacial-cut estuarine system

- It is deep
- Its nearshore is narrow





Implications of a steep nearshore for the ecosystem:



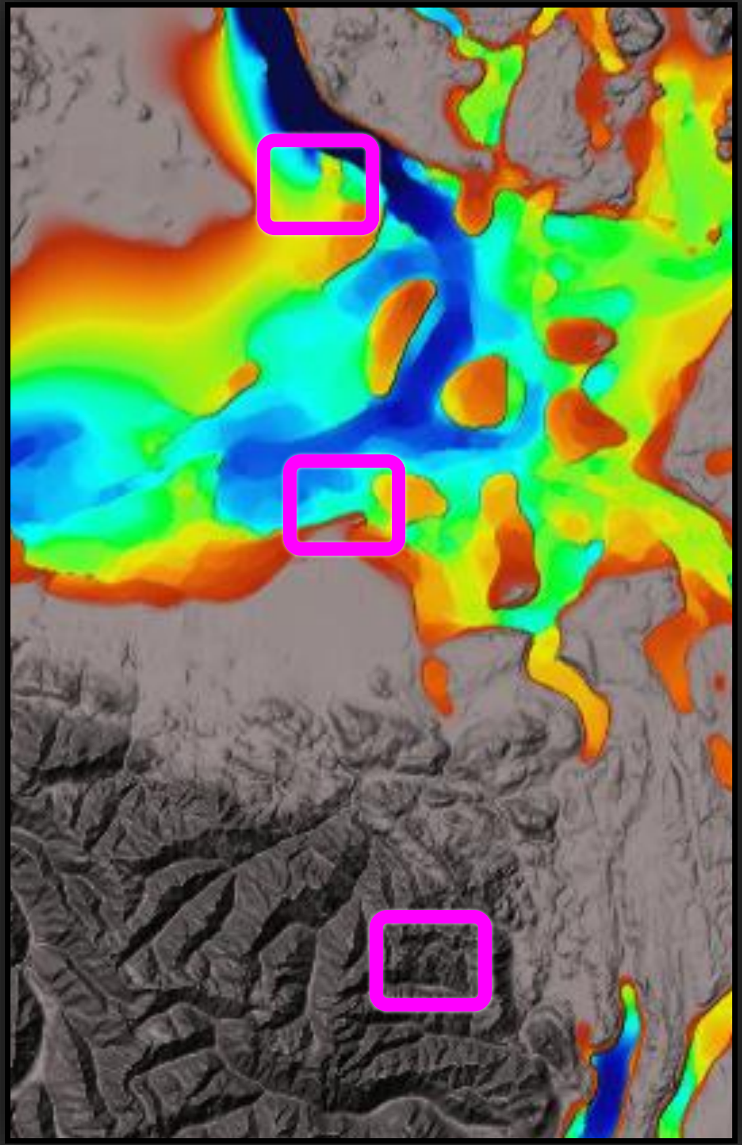
- It is only a narrow “fringe” of nearshore habitat that supports many species at some point in their life cycle

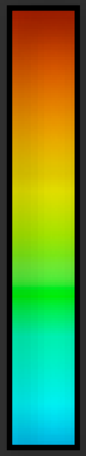
- Because narrow, we have less ‘leeway’ regarding destruction of nearshore habitat

- Removing or degrading a portion of the nearshore habitat in Puget Sound does not have the same proportional effect on the living system as in a shallow, flat estuary

Photo: PSAT 2004 State of Sound

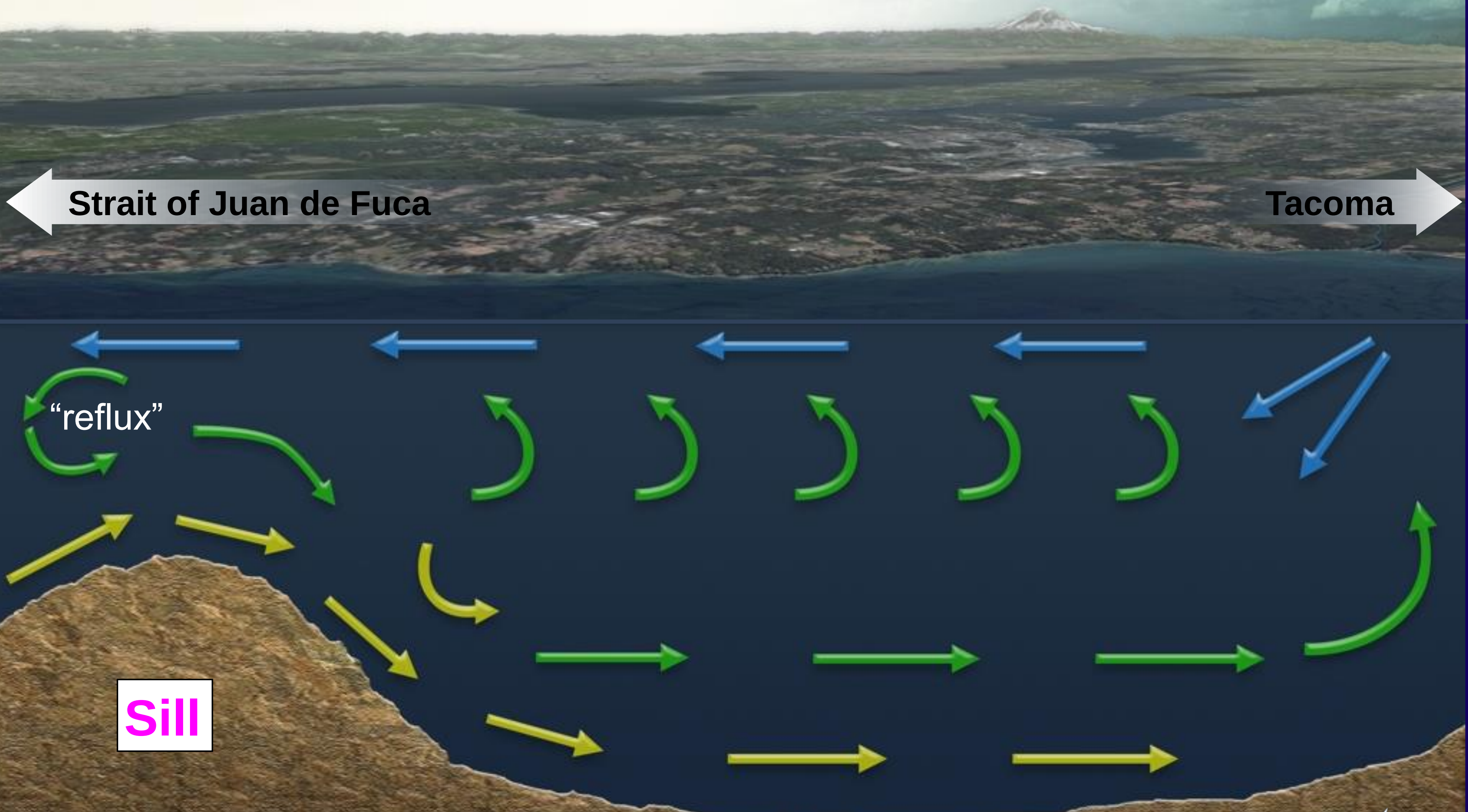
Puget Sound is deep, with strong tides, but sills too





Newton, Stormer, UW-COFS; Data source: NGDC

Puget Sound circulation is retentive



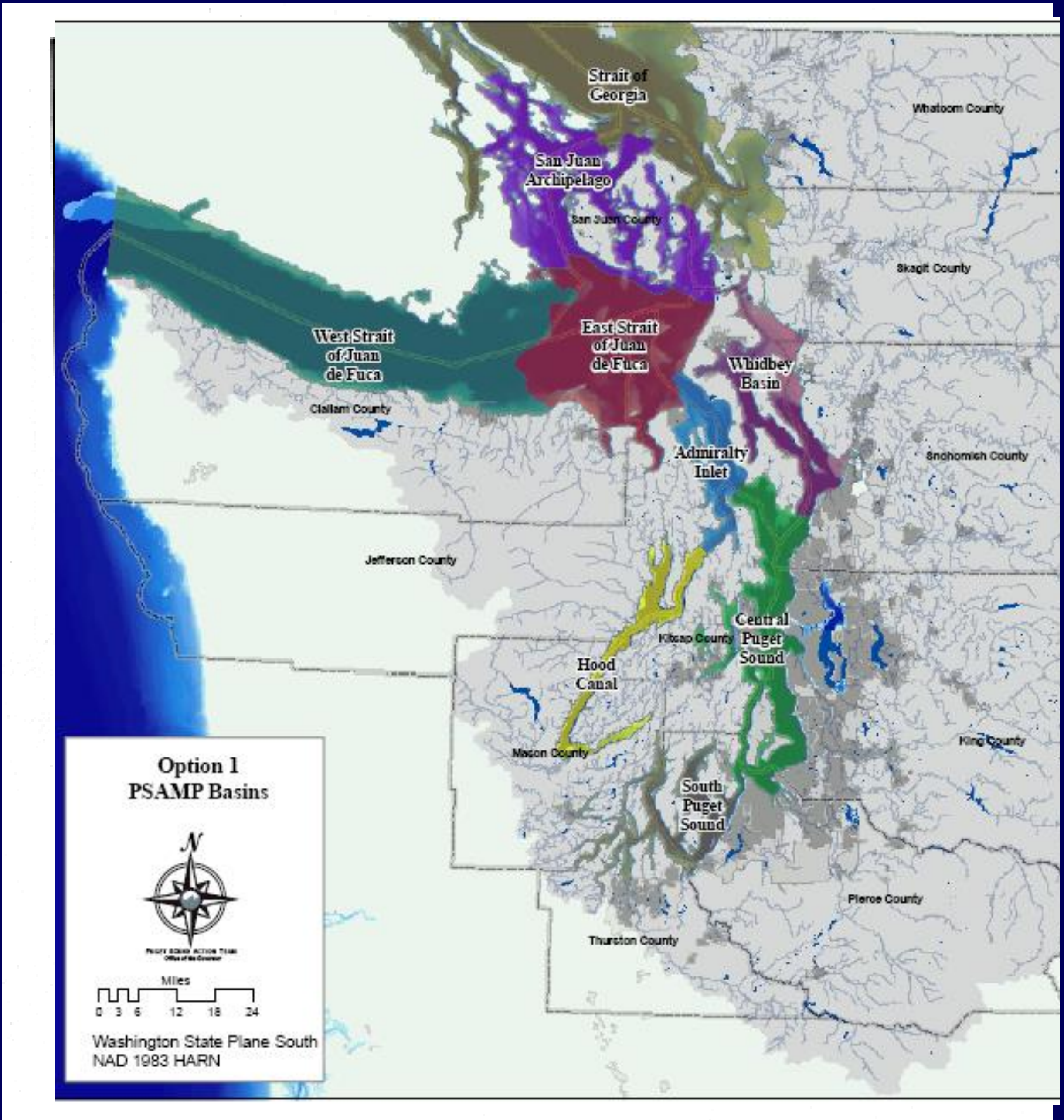
Stormer, UW; Data source: *The Sound CD-ROM” UW-APL, WA Sea Grant, 1997*

Implications of reflux for ecosystem:

- Inputs to Puget Sound stay around for a long time…
  - Long-lasting effects that can be de-coupled from source elimination
- Biota in Puget Sound have a high degree of residency
- Both good and bad: this is why Puget Sound is highly productive, but also highly retentive of contaminants

Photos: PSAT 2004 State of Sound

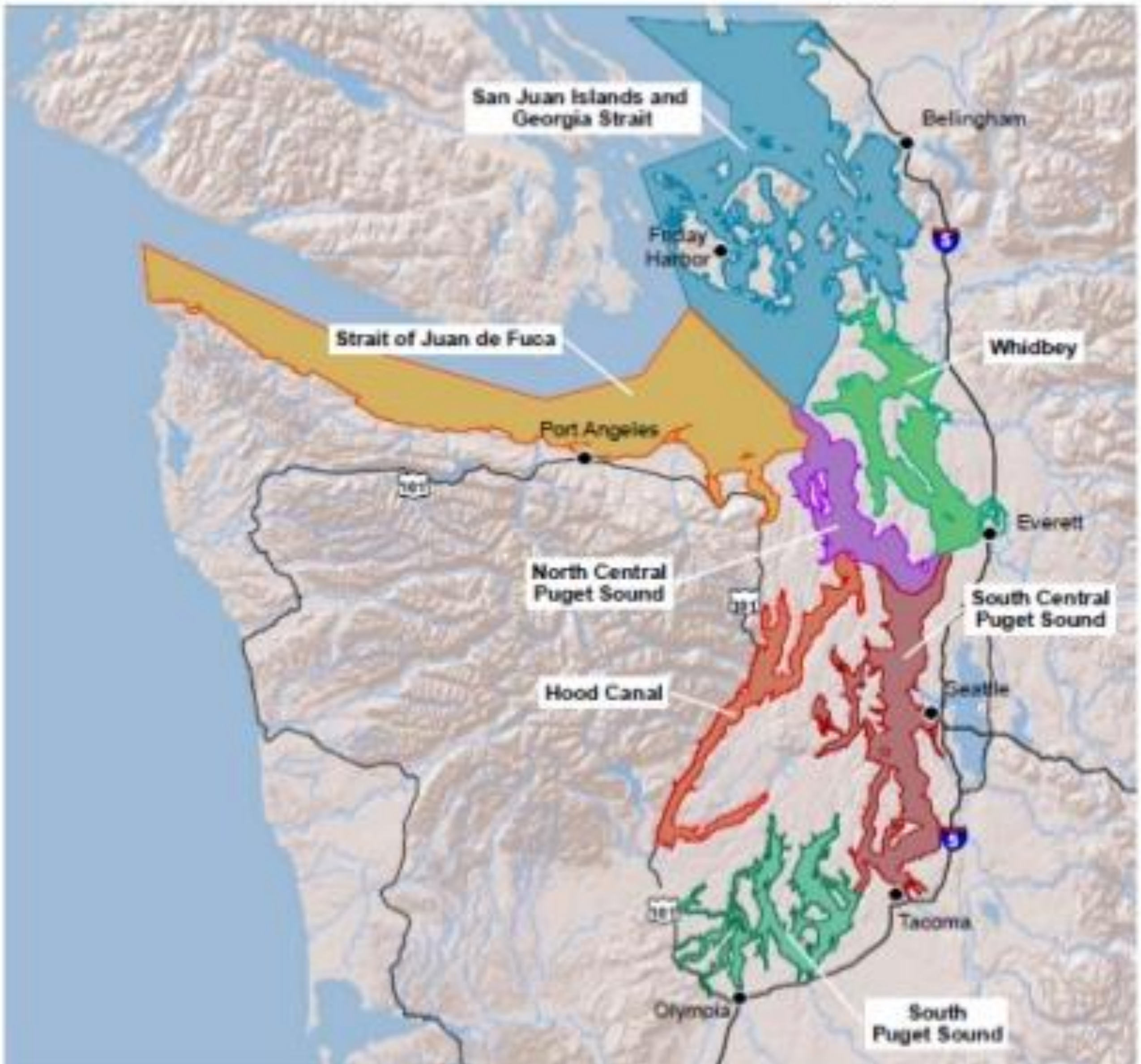
BASINS AND SILLS



PSAMP, 2002

Ebbesmeyer et al., 1984

Puget Sound Basins



Source: Puget Sound Partnership

Puget Sound Tidal Range

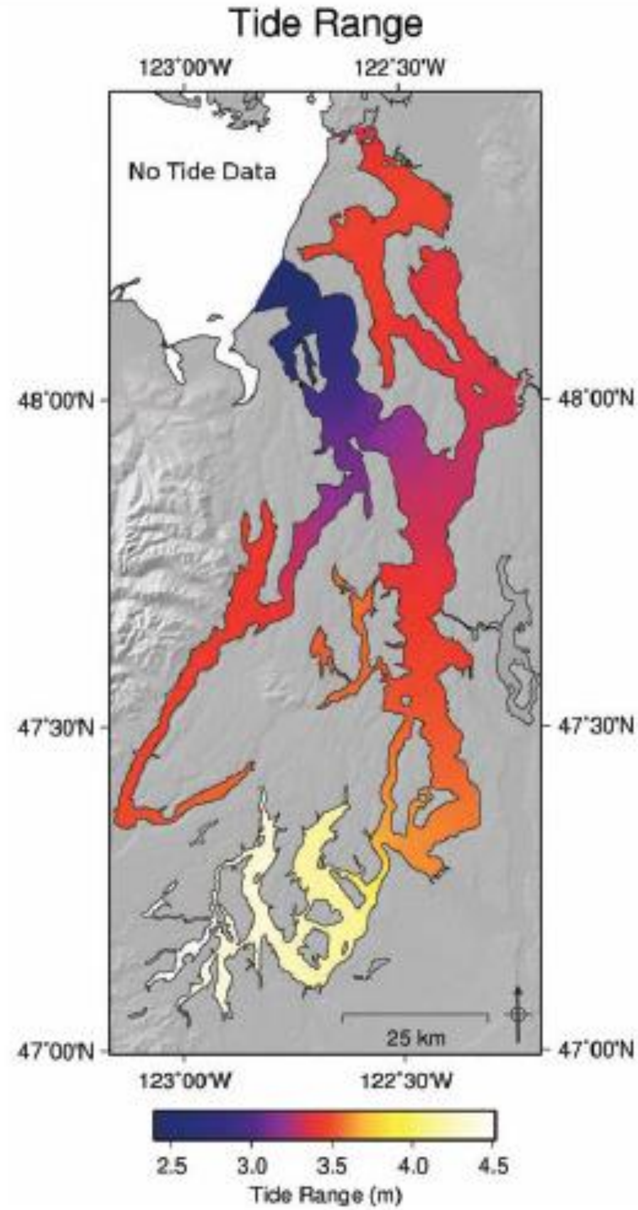


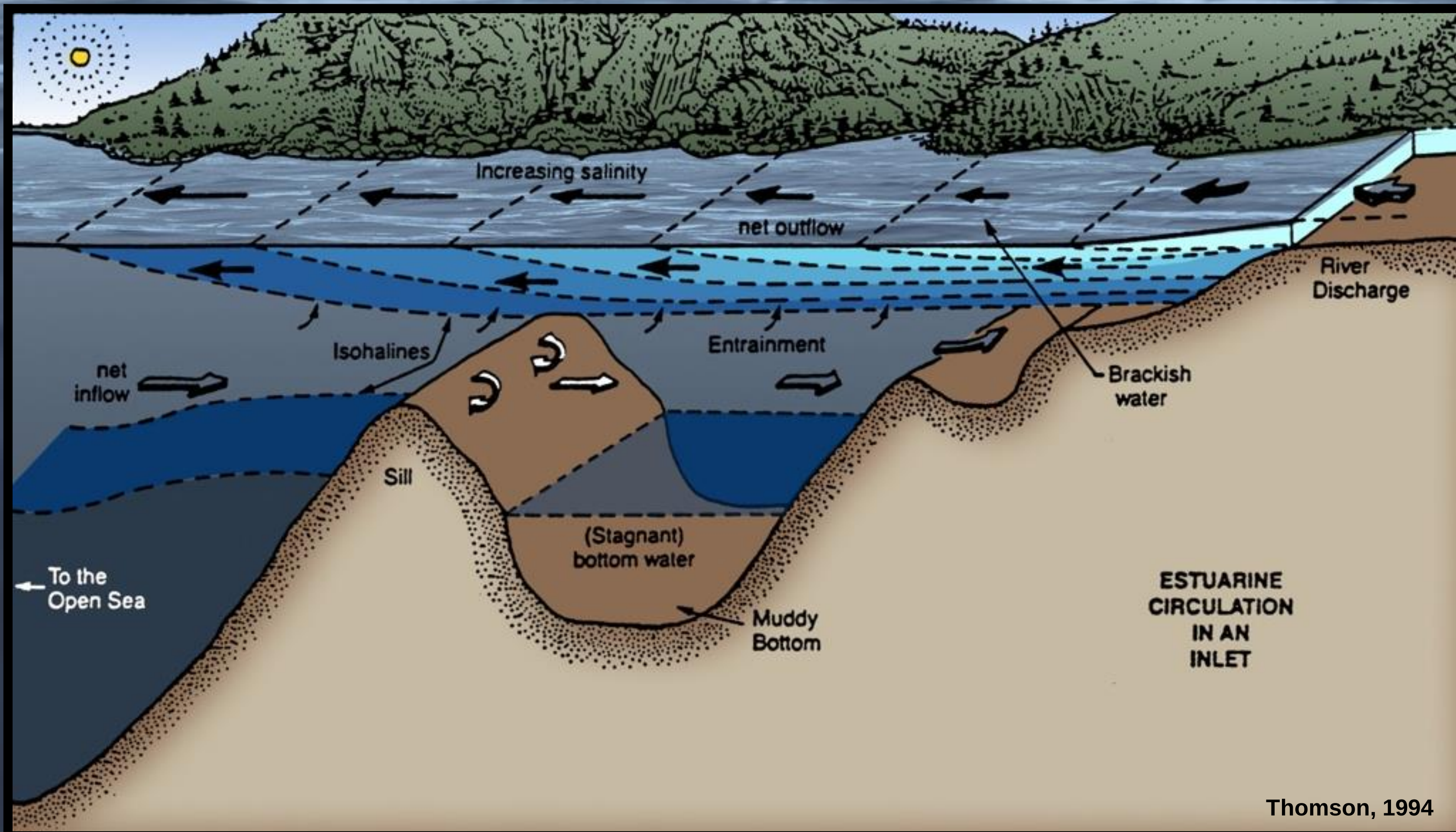
Figure 4.3. Tidal range (mean higher high water–mean lower low water) for Puget Sound and Hood Canal interpolated from the Puget Sound Tide Channel Model. Data courtesy of Mofjeld et al. (2002).

Finlayson, 2006

Estuarine circulation

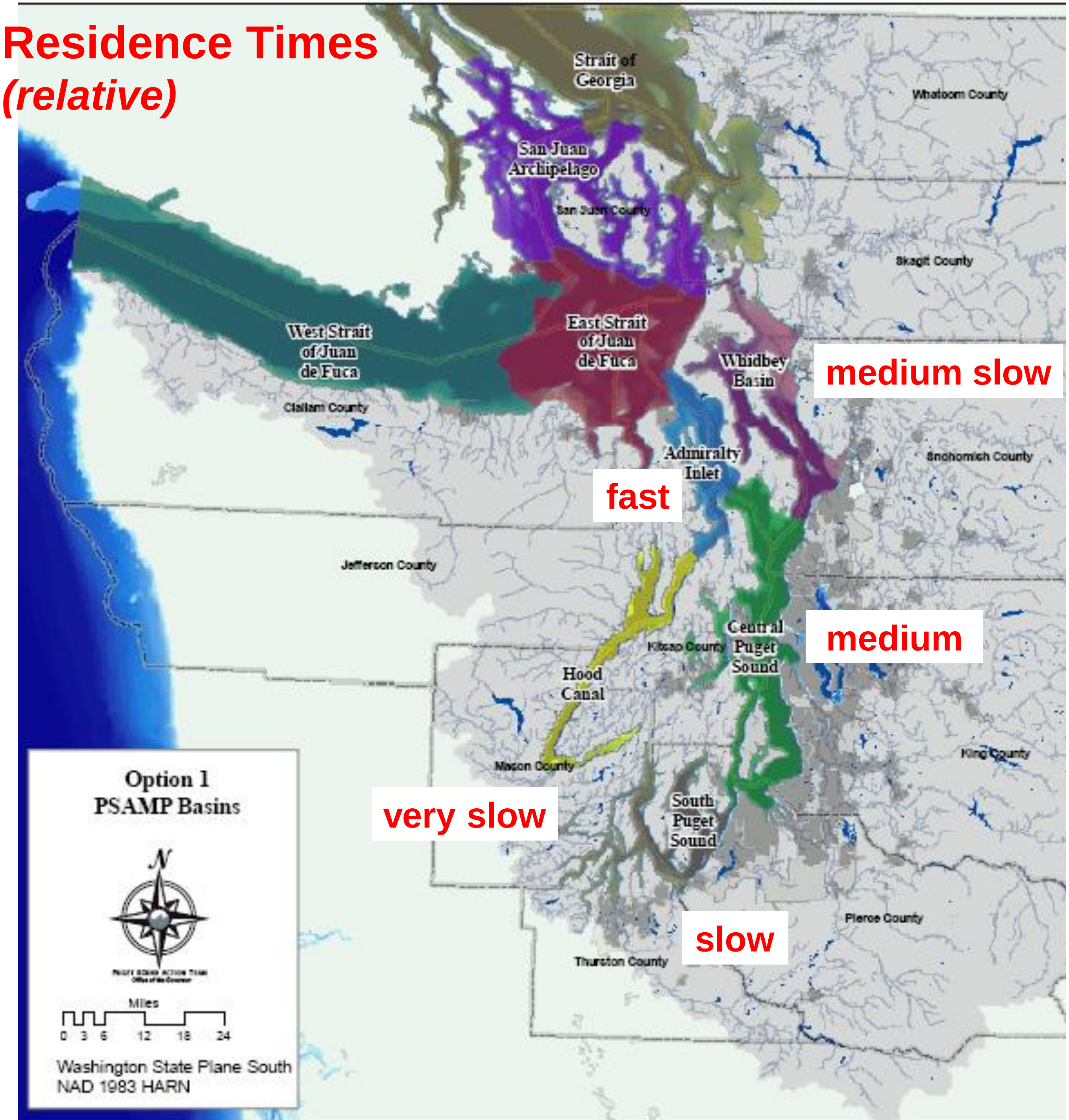
ocean

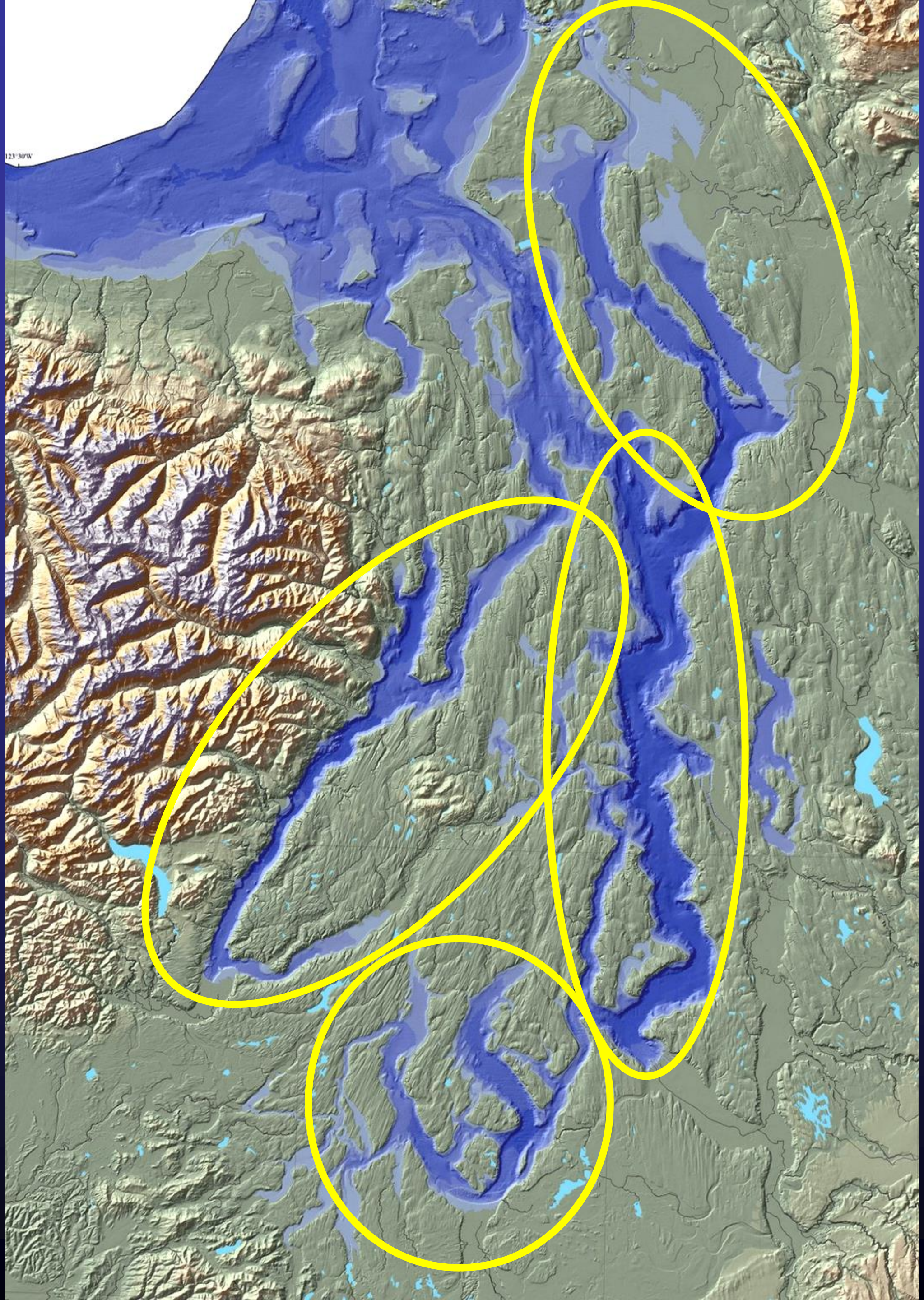
river



Buoyant river water flows out of an estuary on surface, dense ocean water flows in at depth, but there is mixing, and sills cause “reflux” of water back in to an estuary.

Residence Times
(relative)





Basins

- Hood Canal: slow circulation, strong stratification
- Main Basin: fastest circulation, strong mixing
- Whidbey Basin: most freshwater input
- South Sound: strong mixing in some locations, slower circulation

“The many faces of Puget Sound”

By Eric Sorensen

Seattle Times science reporter; Monday, June 25, 2001

“Here's how some of the Sound's personalities work:

• The South Sound is so dynamic, with channels and inlets of varying depth, that different samplings show wildly different profiles.

• The Whidbey Basin off Everett is wonderfully productive in its top layer to the point where the phytoplankton below 30 feet is shaded out by the phytoplankton above and the incoming sediment of the many rivers. In the lower levels, ocean water can linger and last as long as a year.

• The north part of the Sound's main basin is well-mixed, with strong tides and sills turning the water regularly.

• The southern part of the basin is more stable, letting phytoplankton develop more easily.

• Hood Canal has so much phytoplankton that it goes off the researchers' graphs. It's also less turbulent, with upper layers letting the waters warm so much that by midsummer temperatures can top 70º F. By comparison, what's 48º F in Friday Harbor in November will be 48º F in June.”

http://community.seattletimes.nwsource.com/archive/?date=20010625&slug=pugetsound25m0

Some characteristic features of the three main basins of the Georgia-Fuca system. HS = Haro Strait; RS = Rosario Strait; AI = Admiralty Inlet; V-GP = Victoria-Green Point.

	Strait of Georgia	*Puget Sound*	*Juan de Fuca Strait*
Type of estuary	Partially-mixed	Partially-mixed	Well-mixed
Area (km^2)	6,800	2,330[a]	3,700
Volume (km^3)	1,050	169[a]	402
Mean depth (m)	155	62[d]	200
Maximum depth (m)	420 Texada Is.	284[d] Pt. Jefferson	300+ (at mouth)
Yearly Mean Runoff (m^3/s)	5,800[b]	2,200[b]	500[b]
Drainage Area (km^2)	286,890[b]	40,327[b]	7,420[b]
Sill Depths (m)	90 (HS); 50 (RS)	65; 105 (AI)	130 (V-GP)
Basin flushing time, summer	50–75 days	120–140[c] days	30–60 days
Basin flushing time, winter	100–200 days	120–140[c] days	30–60 days
Transport ($\times 10^6$ m^3/s)	variable/ill-defined	0.01–0.10	0.10–0.90

Oceanic control is strong

Thomson, 1994

Estuaries Vol. 23, No. 6, p. 765-792

Geographic Signatures of North American West Coast Estuaries

Robert Emmett[1,*], Roberto Llansó[2,†], Jan Newton[2], Ron Thom[3], Michelle Hornberger[4], Cheryl Morgan[5], Colin Levings[6], Andrea Copping[7], and Paul Fishman[8]

[1] *National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, 2030 South Marine Science Drive, Newport, Oregon 97330*
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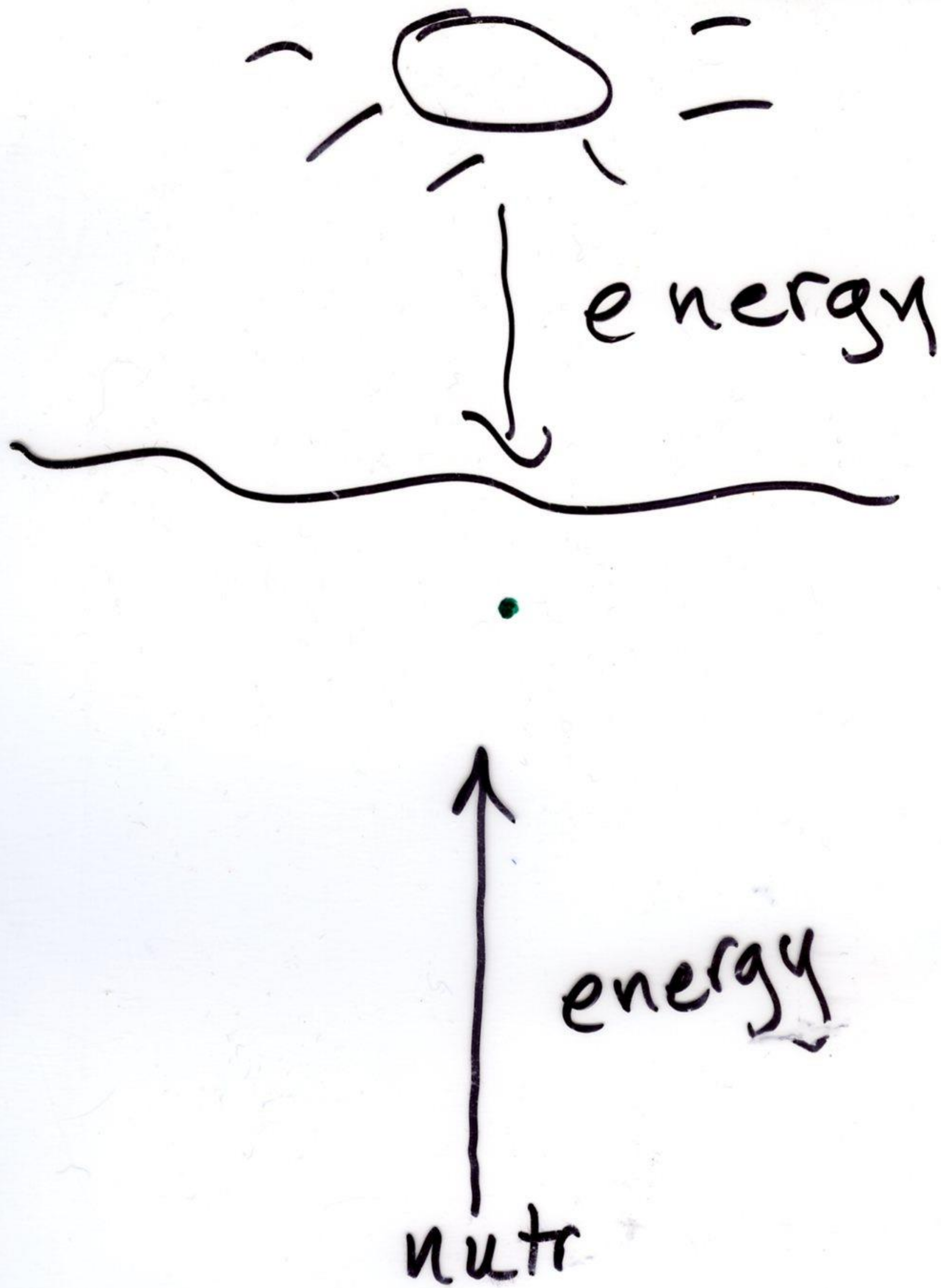
[7] *Washington Sea Grant Program, University of Washington, 3716 Brooklyn Avenue Northeast, Seattle, Washington 98105*
[8] *Fishman Environmental Services, 434 NW Sixth Avenue, Suite 304, Portland, Oregon 97209-3600*

Emmett, et al., 2000

TABLE 3. Estimates of net primary production (gC m^{-2} yr^{-1}) from West Coast estuaries from five different habitat types. Conversion, 1 g dry wt = 0.4 gC.

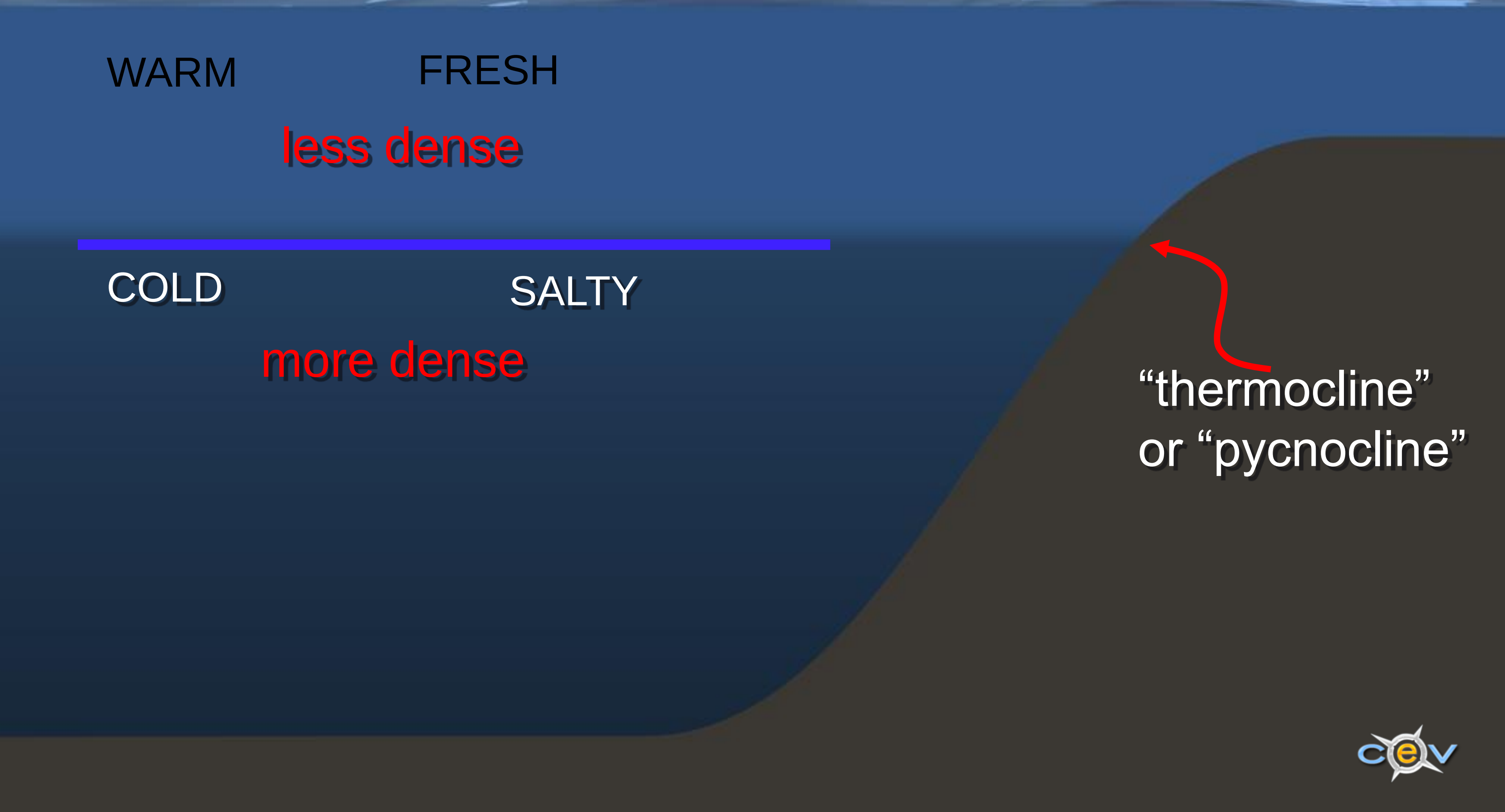
Estuary	Annual Plankton Primary Production	Aerial Annual Tidal Marsh npp	Aerial Annual Eelgrass npp	Annual seaweed npp	Annual Tideflat npp	Reference
Cowichan River		492				Kennedy 1982
Qualicum River		607–698				Dawe and White 1982; Kennedy 1982 in Hutchinson 1986
Nanaimo River		17–203				Kennedy 1982
Salmon River, British Columbia		474				Kennedy 1982
Campbell River, British Columbia		489				Kistritz and Yesaki 1979
Fraser River		275–718				Yamanaka 1975
Nisqually River		363–556				Burg et al. 1975
Nooksack River		680				Disraeli and Fonda 1979
Padilla Bay			351	296	148	Thom 1990, 1989
Strait of Georgia	300					Harrison et al. 1994; Harrison and Kedong 1998
Puget Sound	500		84–480			in Philips 1984
Puget Sound			1,355	4,185	1,285	Thom et al. 1984
Skagit River		112–521				in Hutchinson 1986
Squamish River		24–213			100	in Hutchinson 1986
Grays Harbor	9–110	196–280	322	8–503	26–234	in Thom 1981
Columbia River		432–1,501				Macdonald 1984
Nehalem River		350–702				Eilers 1975
Netarts Bay			737	1,120	12	McIntire et al. 1983
Selitz River		480–800				Gallagher and Kibby 1981
Yaquina Bay					3	McIntire et al. 1983
Coos Bay		123–480				Taylor and Frenkel 1979; Hoffnagle 1980
Oregon Estuaries		180–740				Kibby et al. 1980
Humboldt Bay			266			in Philips 1984
San Francisco Bay		110–1,264				in Josselyn 1983
Mugu Lagoon		80				Zedler 1982
Upper Newport Bay		240				Zedler 1982
San Diego Bay		240				Zedler 1982
Sweetwater River		440				Zedler 1982
Tijuana River		164–340		34–253		Zedler et al. 1992

Emmett, et al., 2000


energy
energy
nutr

Water Structure

temperature + salinity determine density



Density structure can be two different ways:

"stratified"

WARM

FRESH

COLD

SALTY

"mixed"

And more things vary than just temp. and salinity:

Lo nutrient Hi oxygen

Phytoplankton present

Hi nutrient Lo oxygen

No phytoplankton

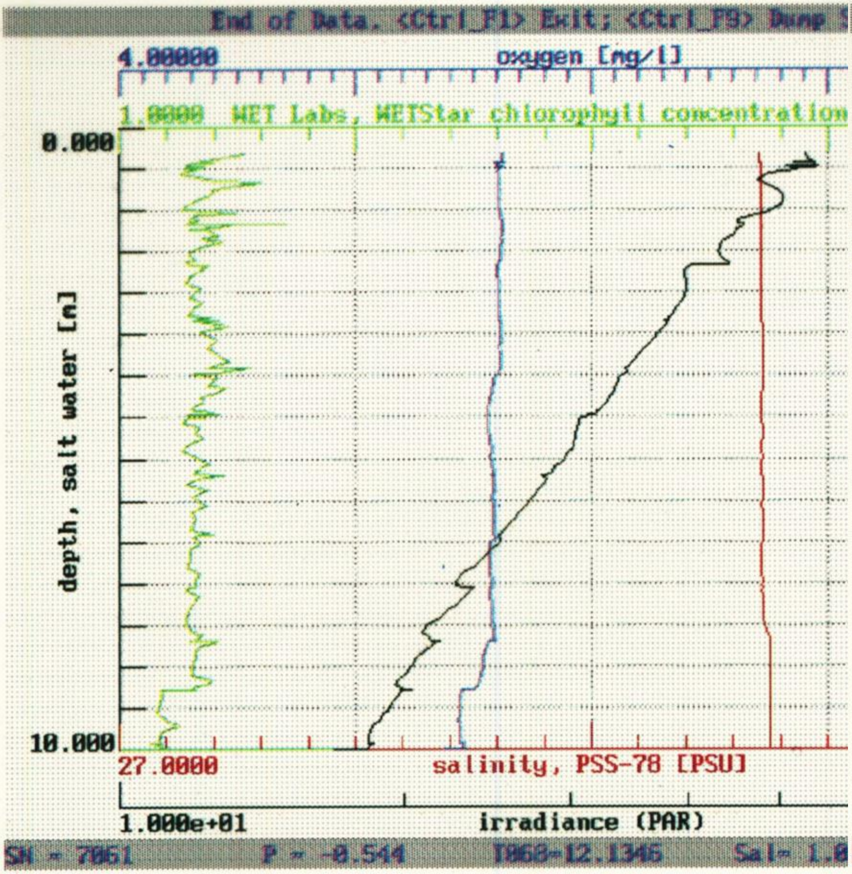
Respiration

$$\{ CO_2 + H_2O \leftrightarrow C(H_2O) + O_2 \}$$

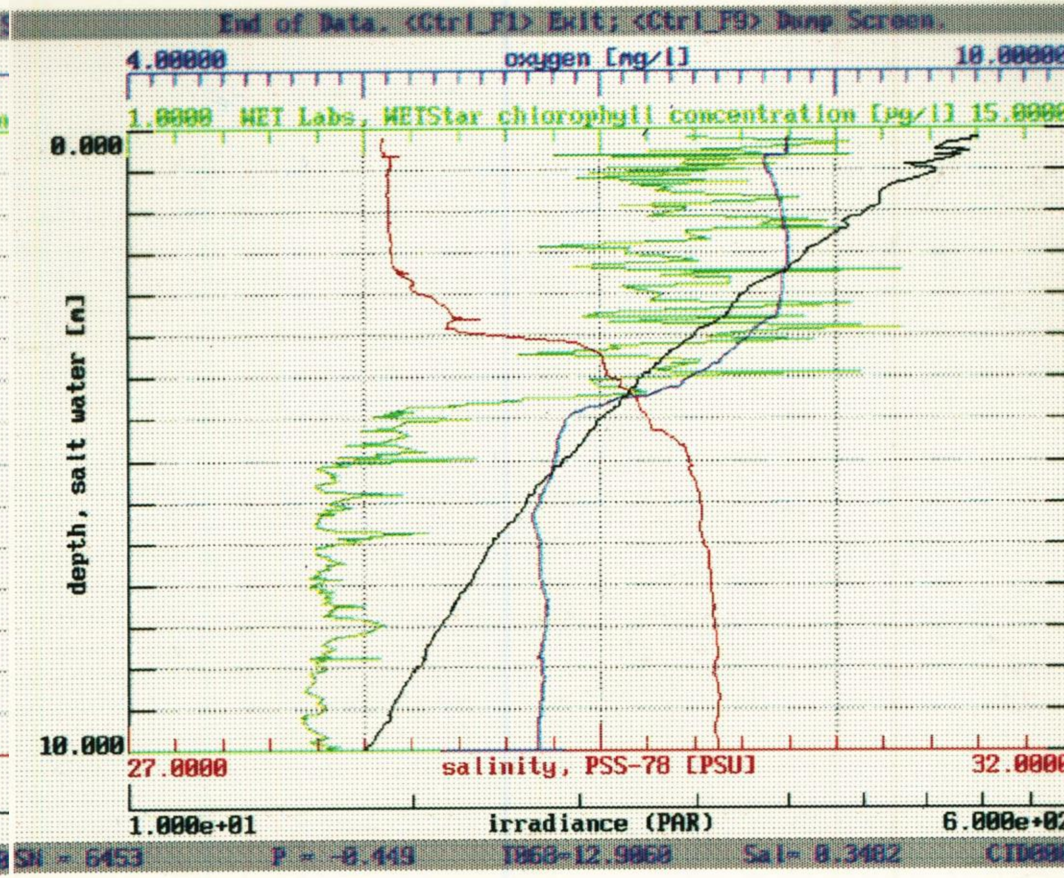
sunlight
nutrients

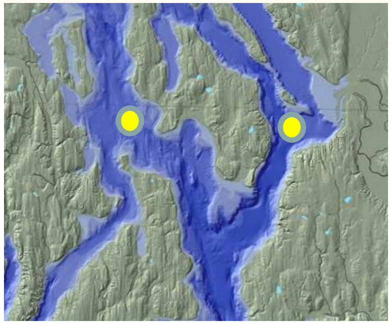
Photosynthesis

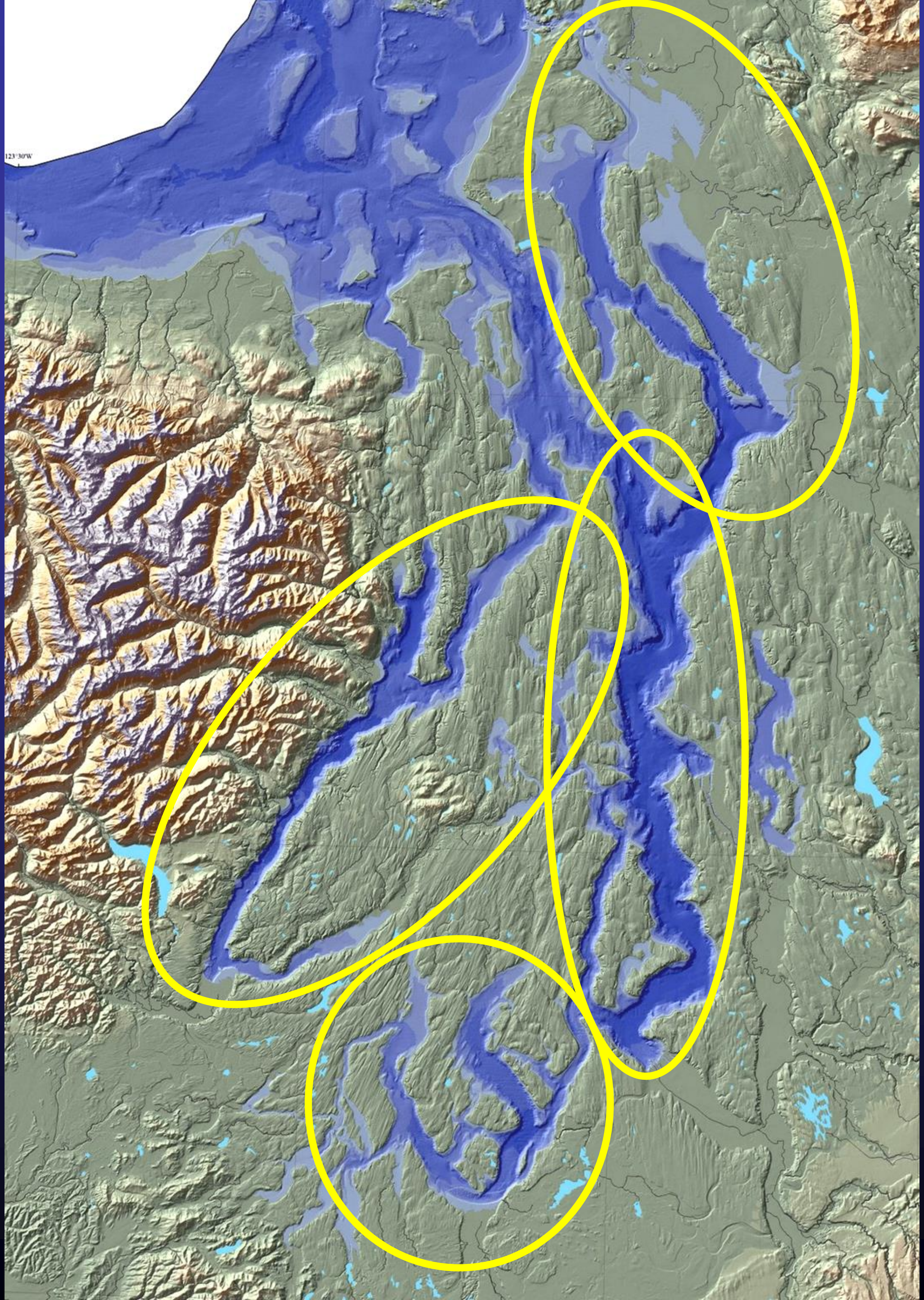
Admiralty Inlet C-14 Cruise October, 27, 1998



Possession Sound C-14 Cruise October 27, 1998







Basins

- **Hood Canal: slow circulation, strong stratification**
- **Main Basin: fastest circulation, strong mixing**
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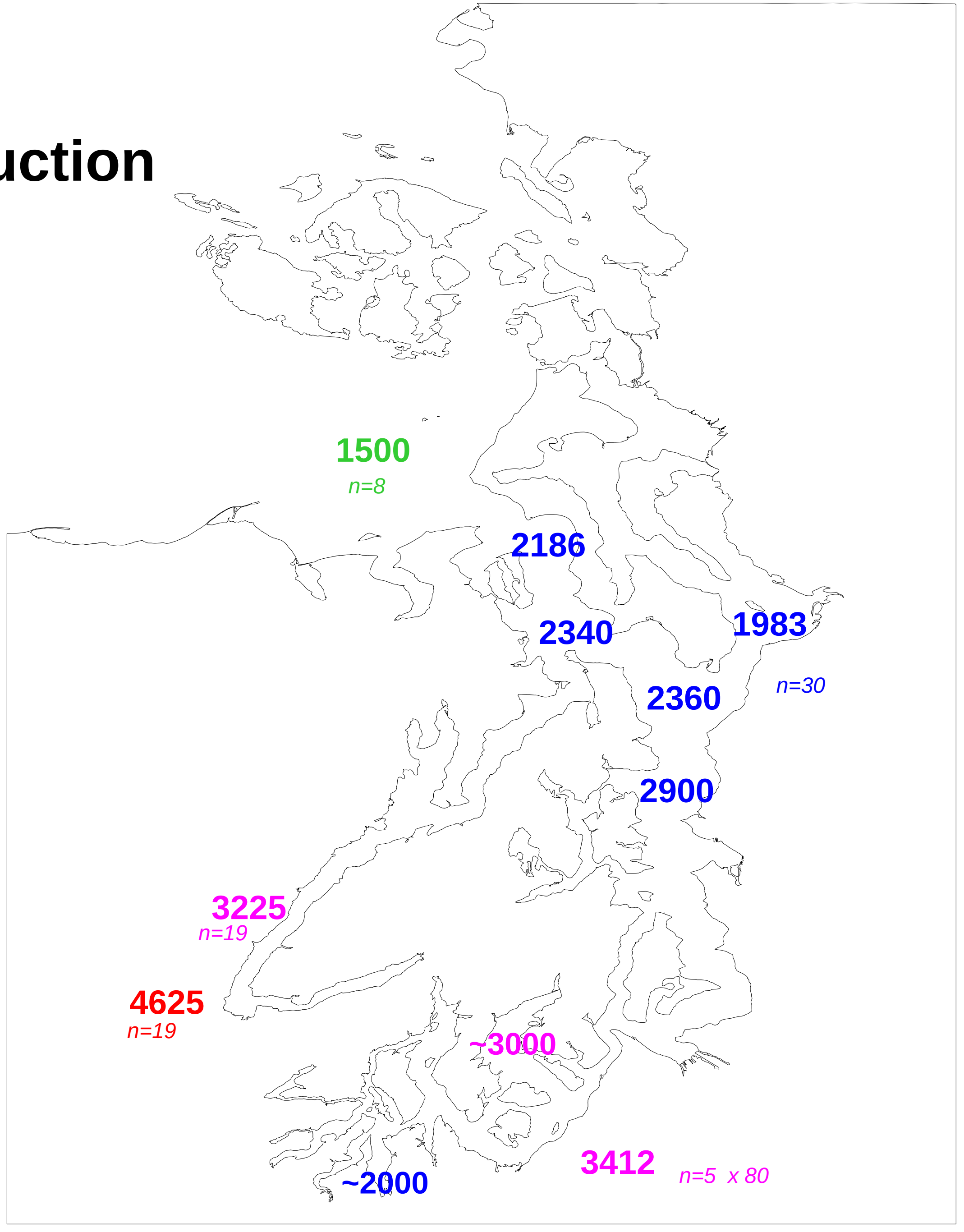
Primary Production
(mg C m^{-2} d^{-1})

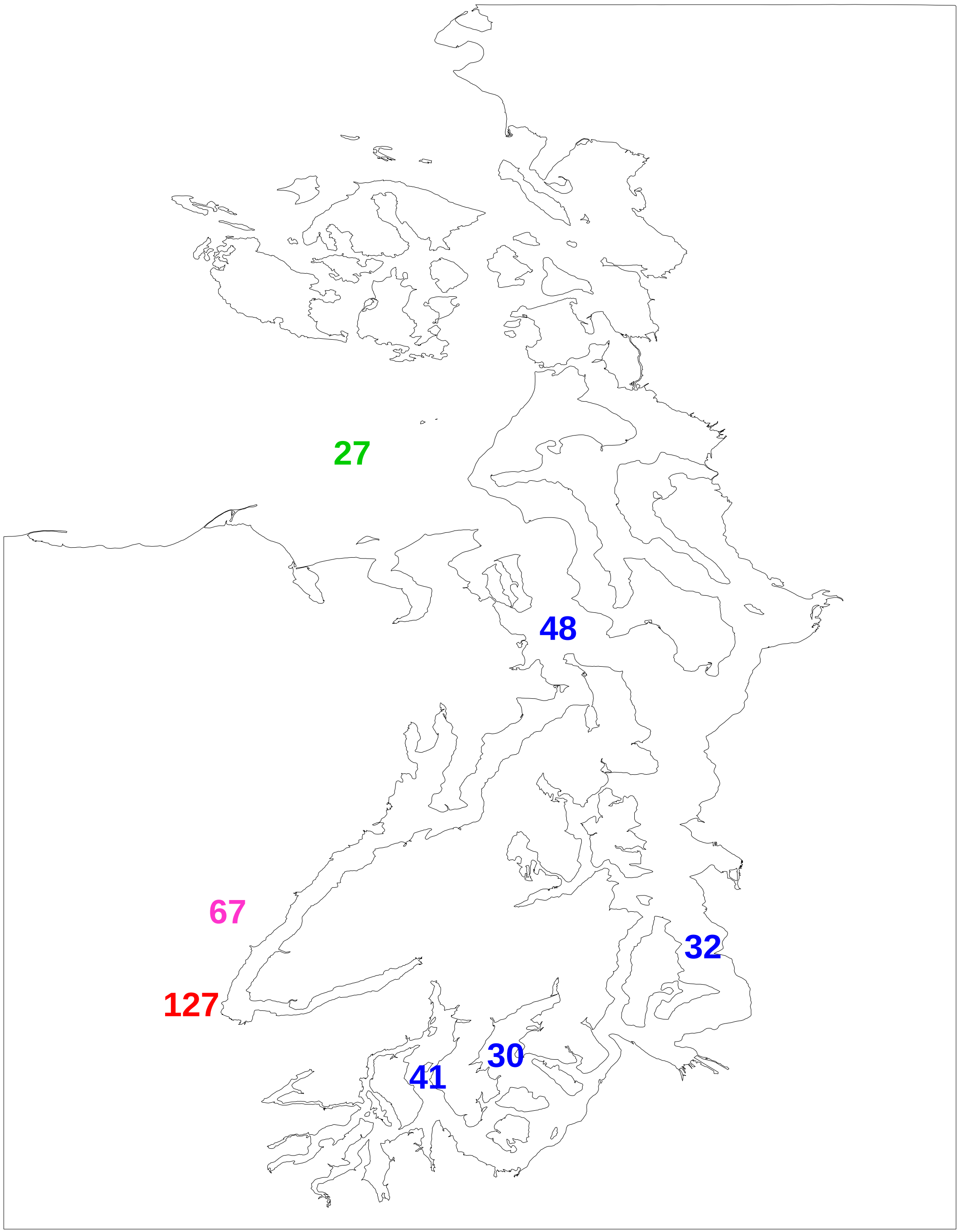
>1000-2000
>2000-3000
>3000-4000
>4000-5000



Newton et al., 2000

Chlorophyll *a*
(mg chl m^{-2})

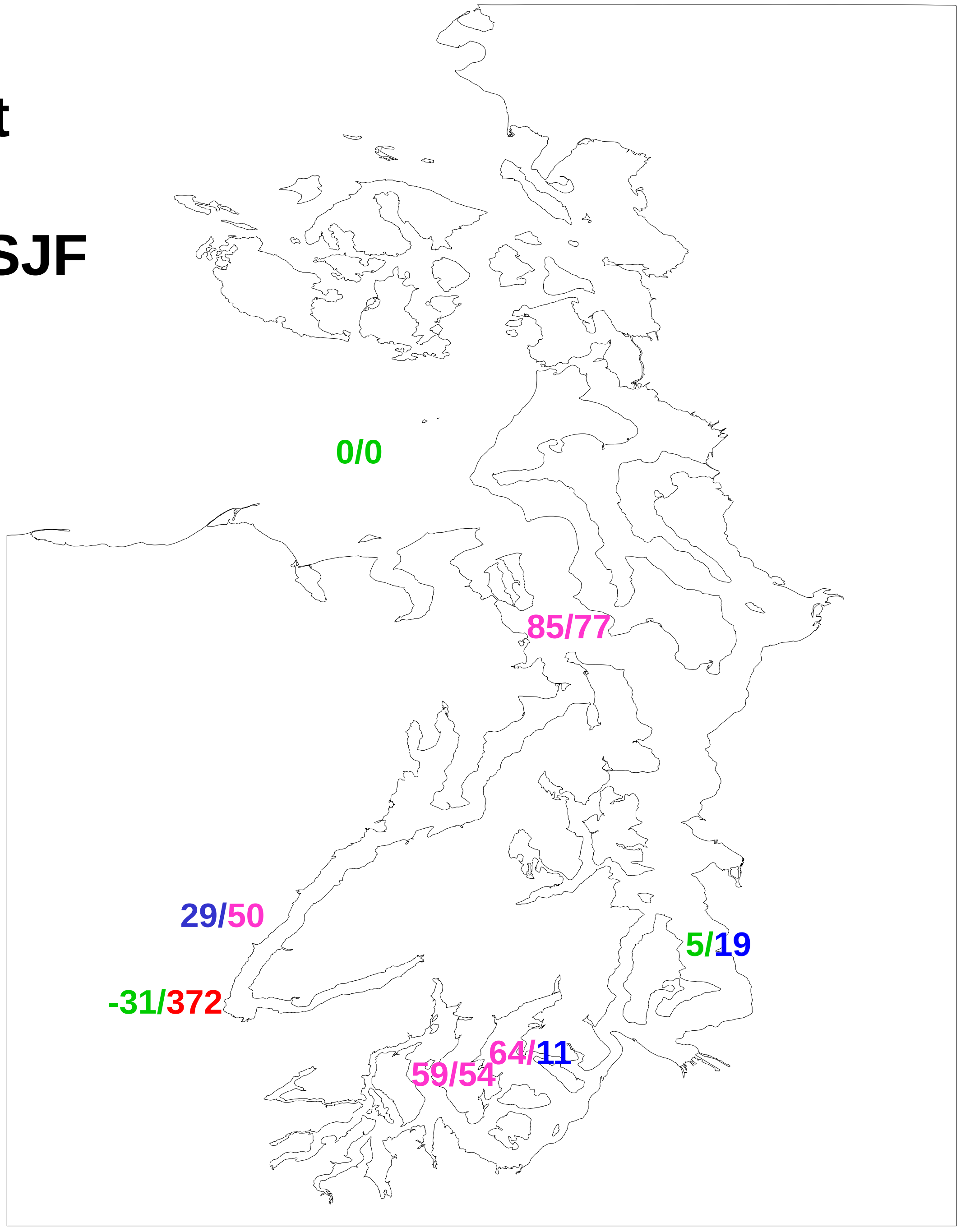
<30
>30-50
>50-70
>70



Newton et al., 2000

(P / B) percent increase compared to SJF

<10
>10-50
>50-100
>100



Newton et al., 2000

What makes Puget Sound unique?

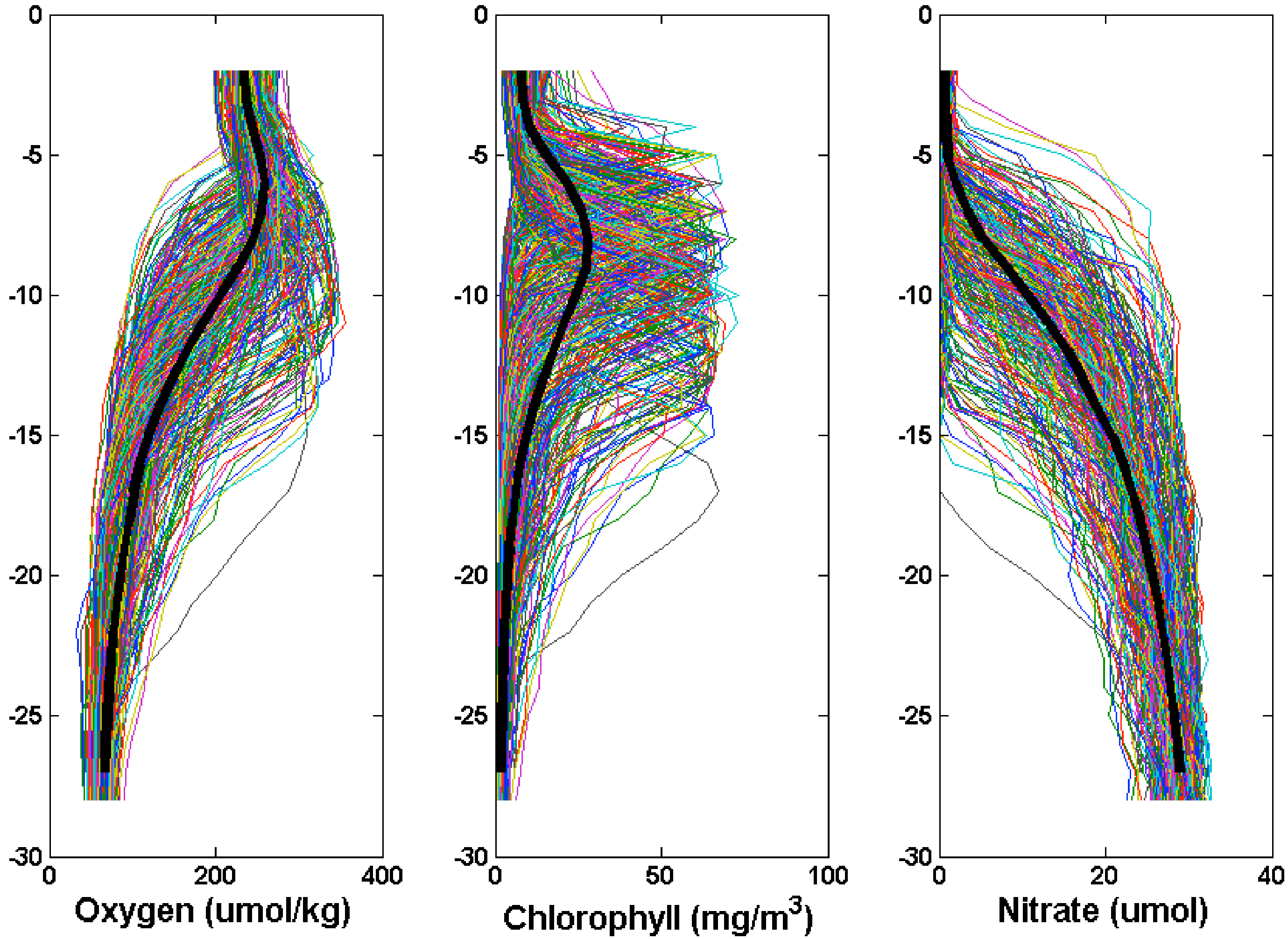
- 2nd largest estuary in the US, one of most productive in the world
- Deep, glacial fjord average depth 62.5m, max ~280m:
  - Chesapeake Bay average depth 6.4m
  - San Francisco Bay average 7.6 m, max 30.5m
- Large tidal exchange: 3-4m
- Ocean-dominated salinity: Puget Sound 83% seawater vs 50% seawater for Chesapeake Bay
- Distinct basins

Source: Puget Sound 2015 Fact book, Puget Sound Institute

Problems

- Not all basins work the same, so our monitoring needs to be distributed.
- Within a basin, there can be strong spatial variation
- Can be strong temporal variation

High variability



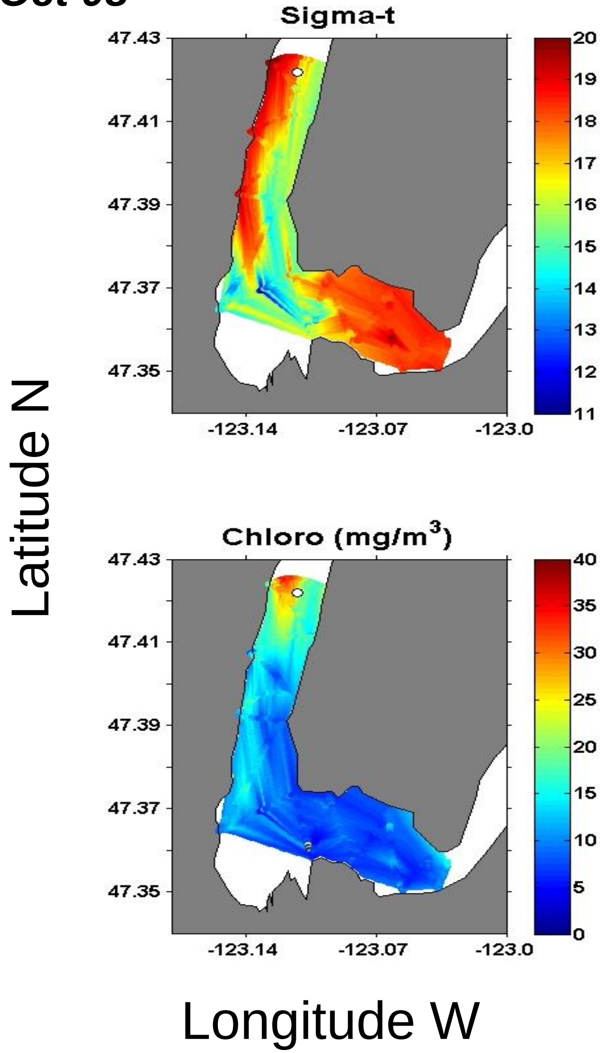
370 profiles in July 2008

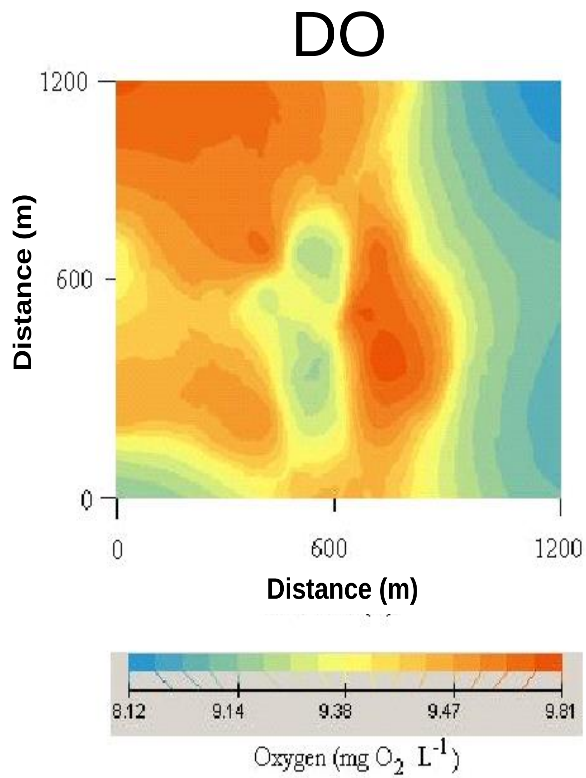
Representativeness critical to understanding change in highly dynamic environment. Sensor drift was found to vary 10% for the ORCA buoy oxygen sensors over one month. Using samples from monthly versus every 6 hours intervals was found to account for 50-300% variation or error, based on Monte Carlo sub-sampling simulations of 6-h frequency data (Devol et al.2007).

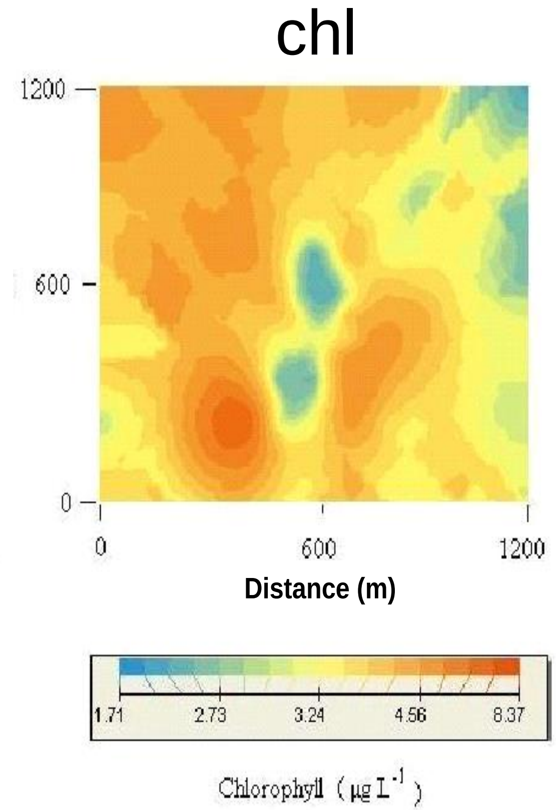
Devol & Ruef

Strong spatial variation

Oct 08







Surface maps of dissolved oxygen and chlorophyll concentrations around the ORCA mooring in April 2007.
Note correlations of concentration fields.

Devol & Ruef

Problems

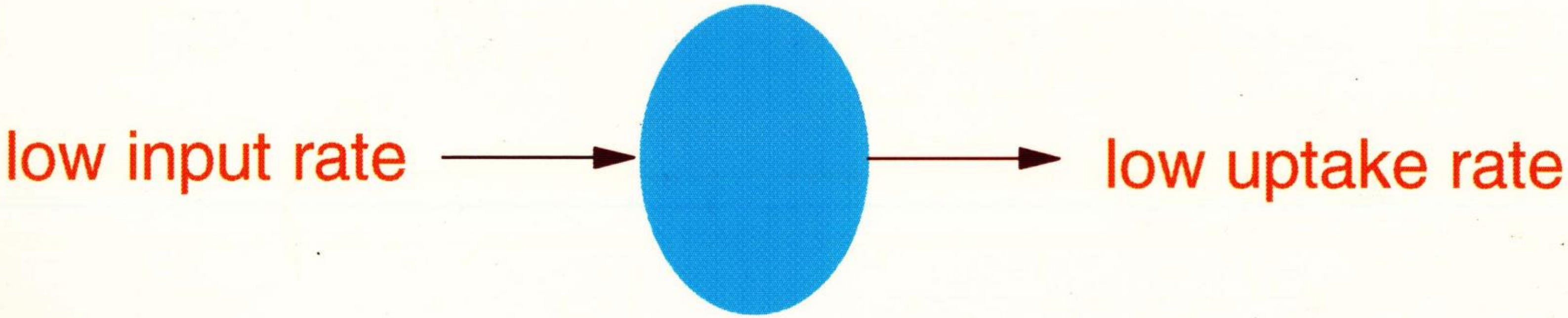
- Not all basins work the same, so our monitoring needs to be distributed.
- Within a basin, there can be strong spatial variation
- Can be strong temporal variation
- What does a nutrient concentration really mean?

for a given

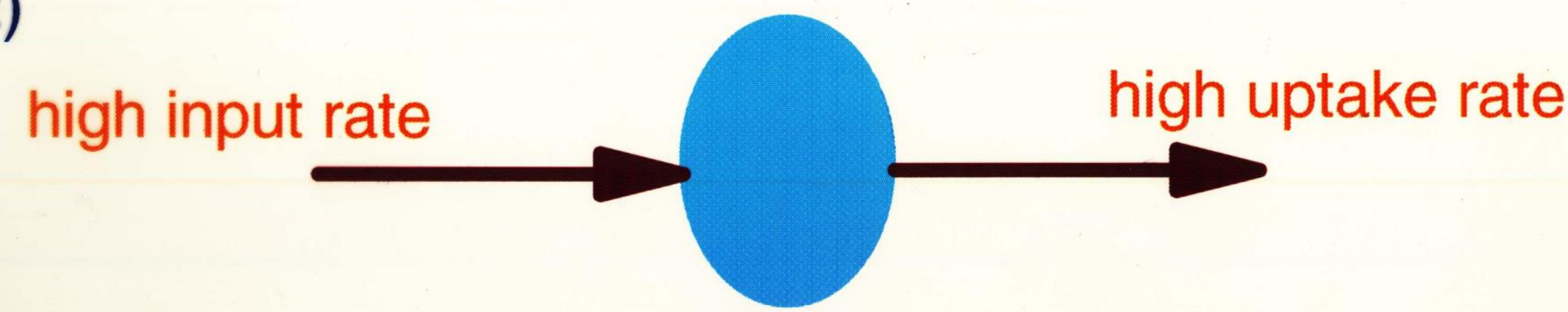
NUTRIENT CONCENTRATION

two possible scenarios:

1)



2)



Nutrients & Chlorophyll

- Low nutrients could indicate lack of phytoplankton (persistence of lack of nutrients, thus low biomass)
- Low nutrients could indicate a bloom (sudden uptake of nutrients with high biomass)
- High nutrients could indicate eutrophication
- High nutrients could indicate upwelling
- High nutrients could indicate lack of sunlight and slow growth

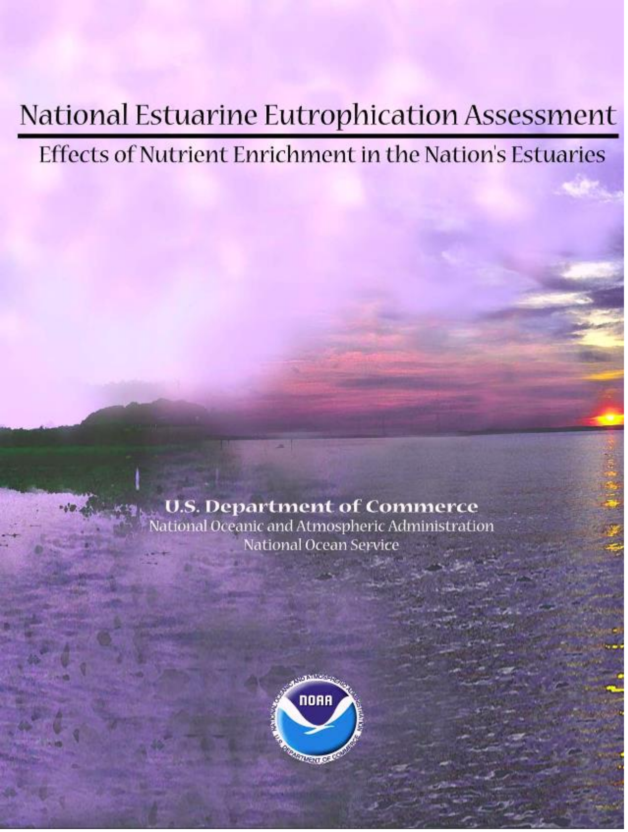
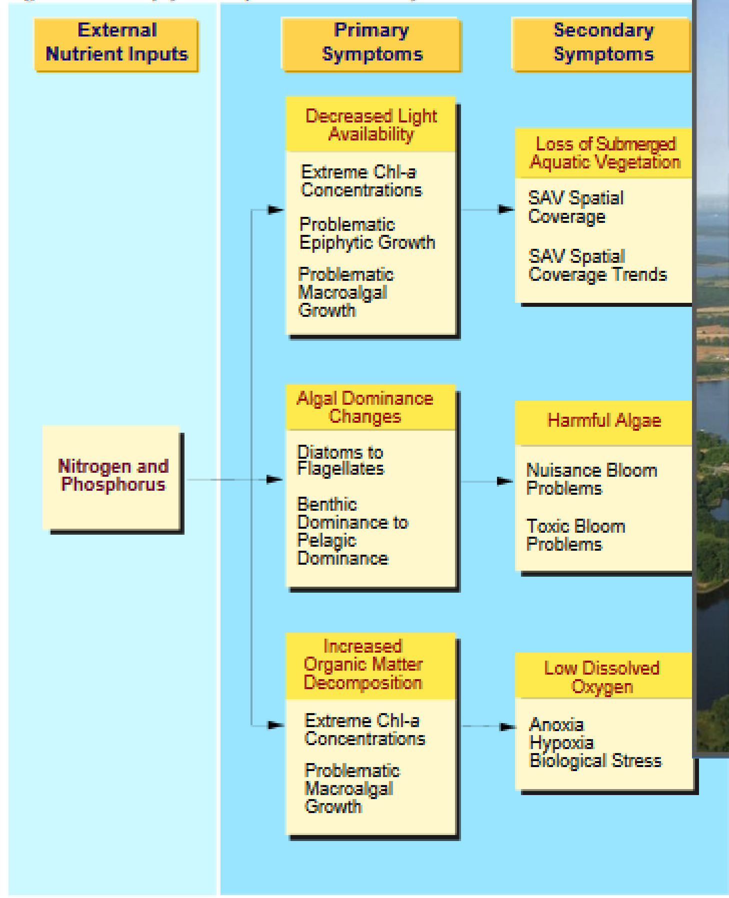
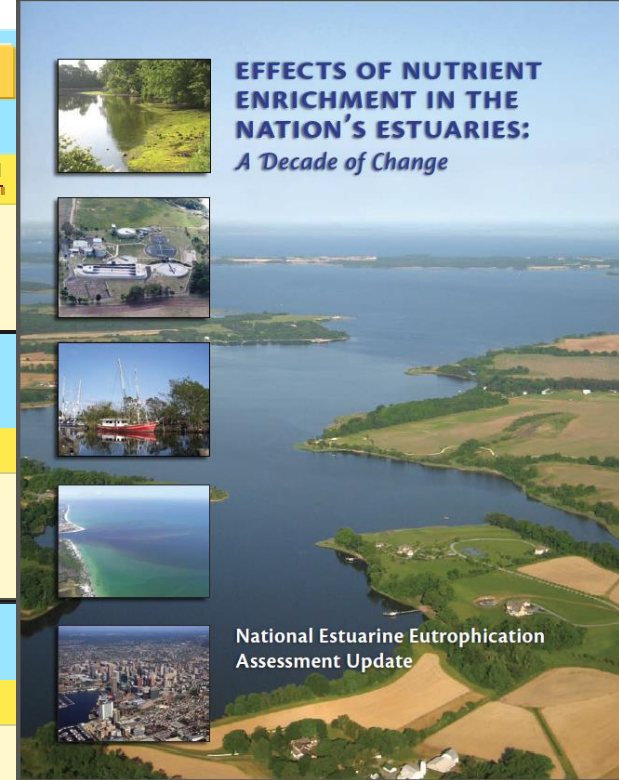


Figure 2. The simplified eutrophication model used for the National Assessment



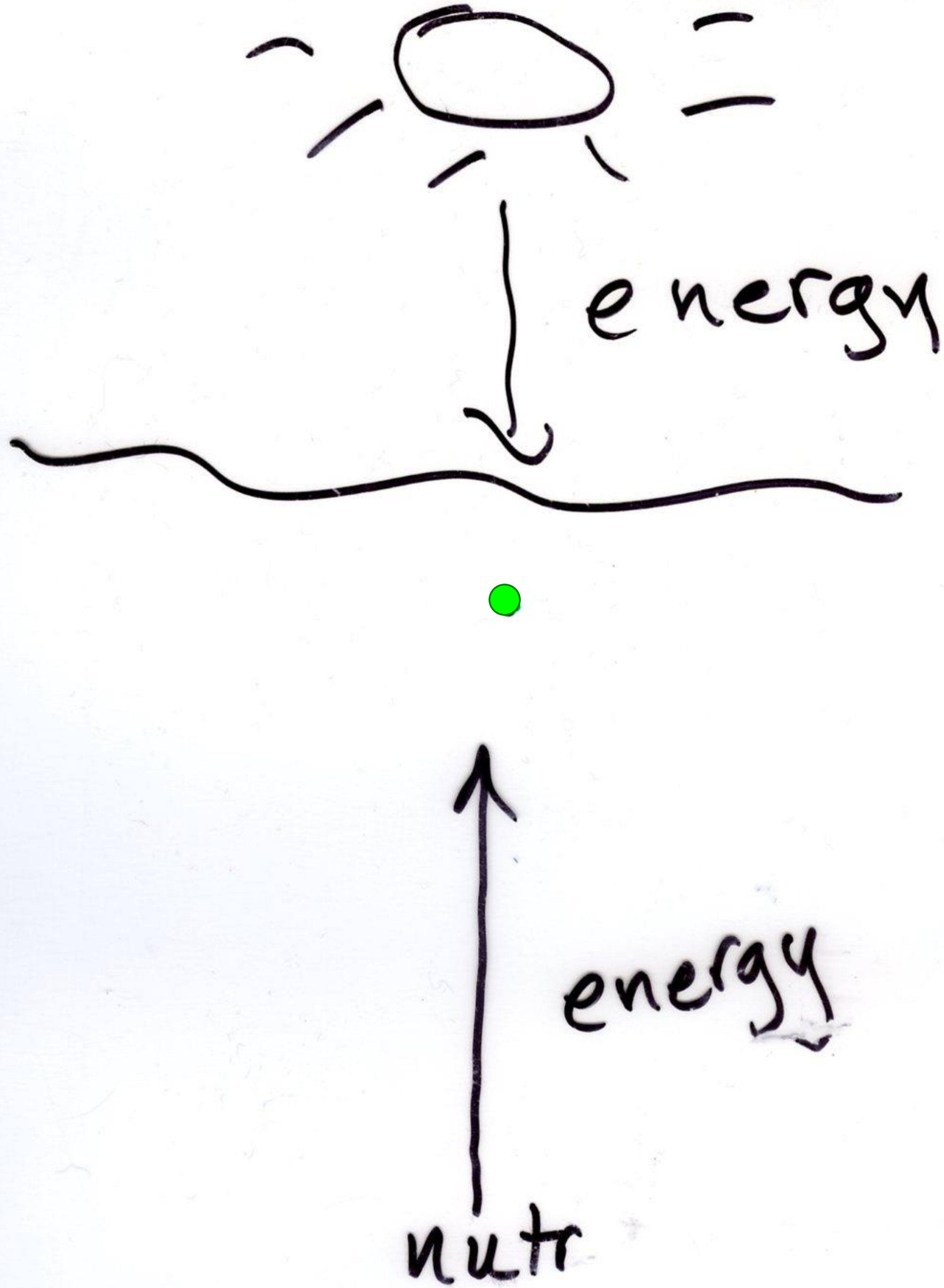


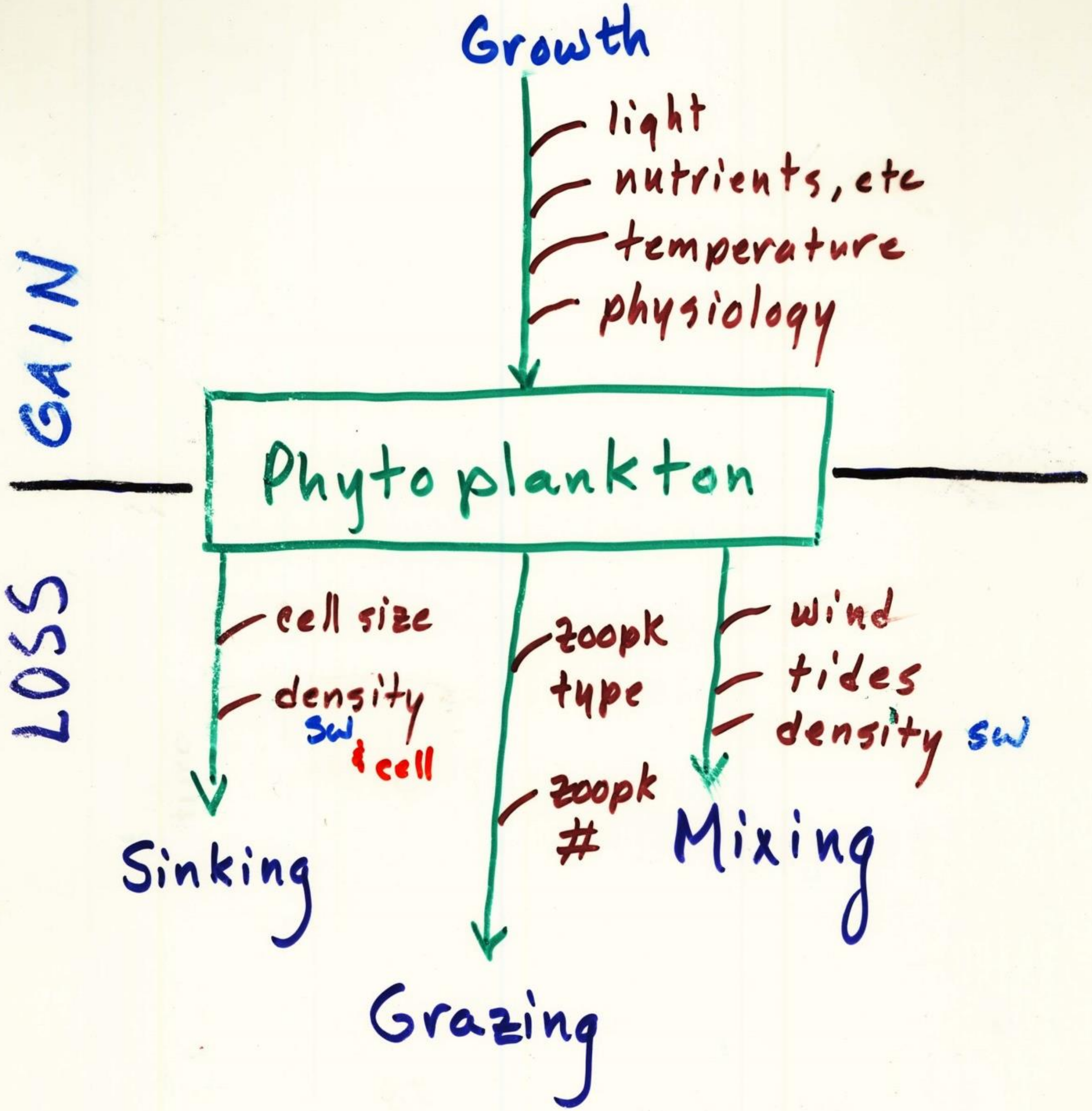
"In general, the symptoms contributing most to high eutrophic conditions were elevated levels of chlorophyll a, coupled with various combinations of macroalgal abundance, nuisance/toxic algal blooms, and low dissolved oxygen. High chlorophyll a concentrations is also a fairly common natural condition in some North Pacific estuaries due to naturally occurring seasonal blooms."

Bricker, S.B., et al., 1999

"These particular systems are influenced by inflows of upwelled oceanic water which is low in dissolved oxygen, and therefore contributes to dissolved oxygen problems which might otherwise be attributed to human influence."

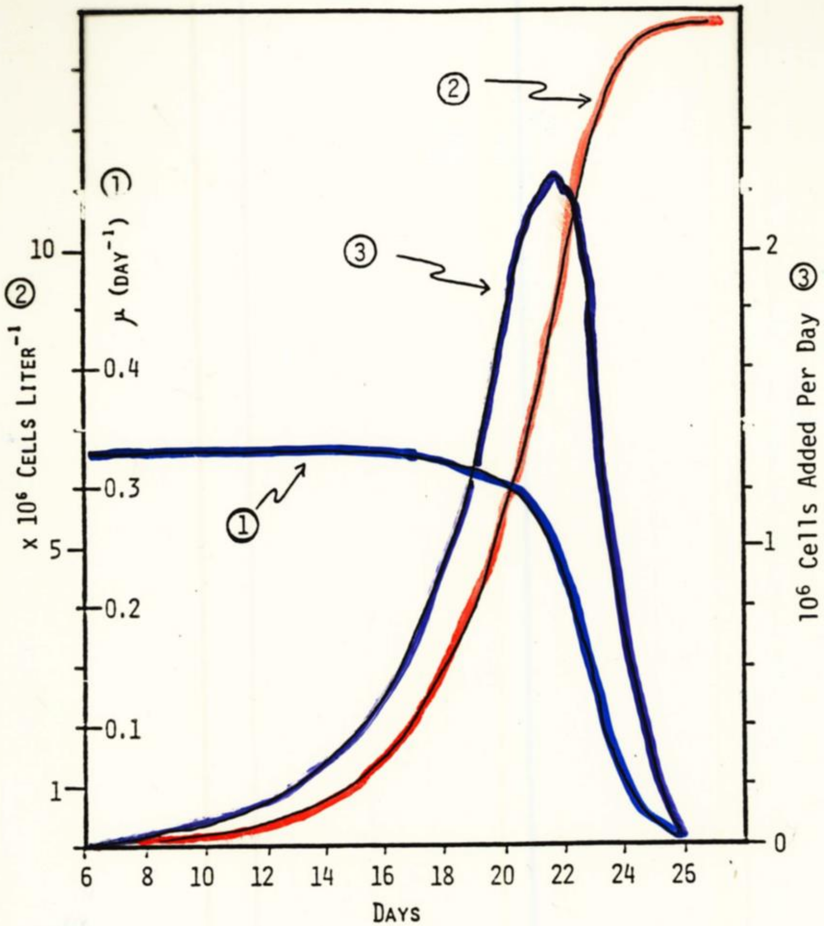
Bricker et al., 2007


energy
energy
nutr



$$\frac{\Delta \text{phyto}}{\Delta t} = [\text{phyto}]\,(\underbrace{\mu}_{\text{growth}} - \overbrace{d}^{\text{loss}})$$

Primary production in 1983:



Example of Growth of a Resource-Limited Microbial Culture

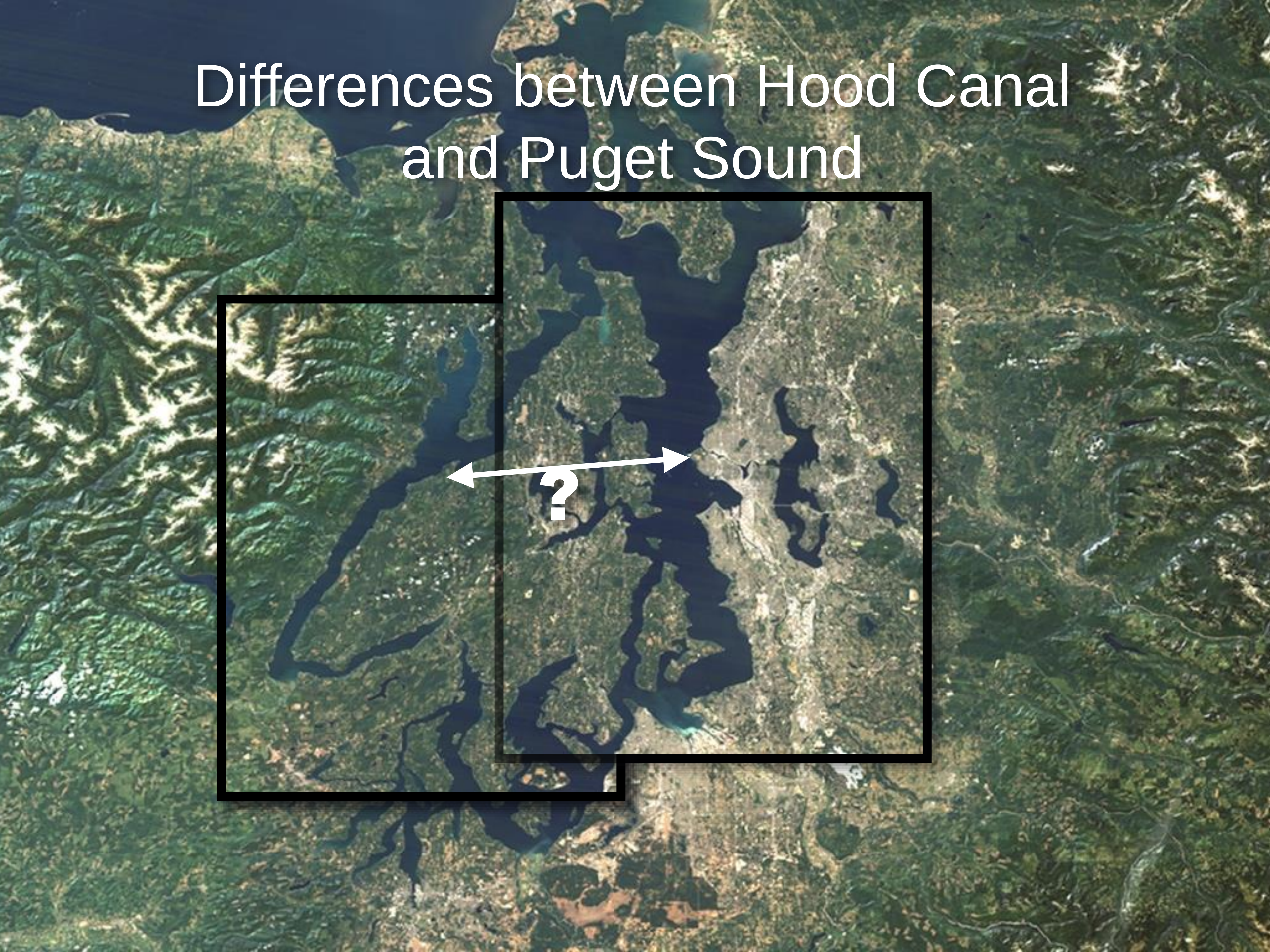
μ (1) Instantaneous growth rate μ (= 1/N dN/dt) vs. time; μ is another term for r, the intrinsic growth rate in ecological literature; here, at day 6 taken as 95% of 0.347 day^{-1}, (i.e., generation time of two days),

(B) #/l (2) Concentration N vs. time (= cumulative population growth);

(3) Population growth vs. time (finite growth, from multiplying (1) by mean concentration over daily intervals, from (2)).

productivity (P)

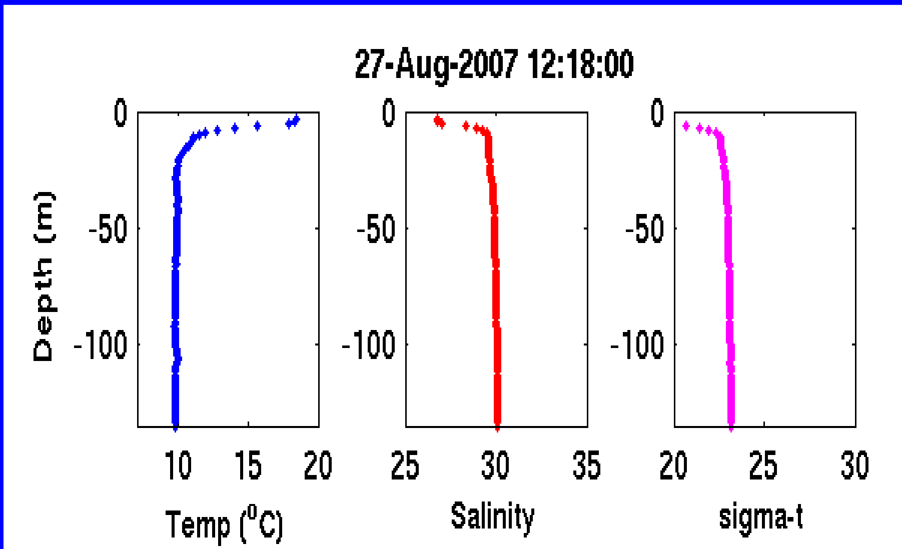
Differences between Hood Canal and Puget Sound



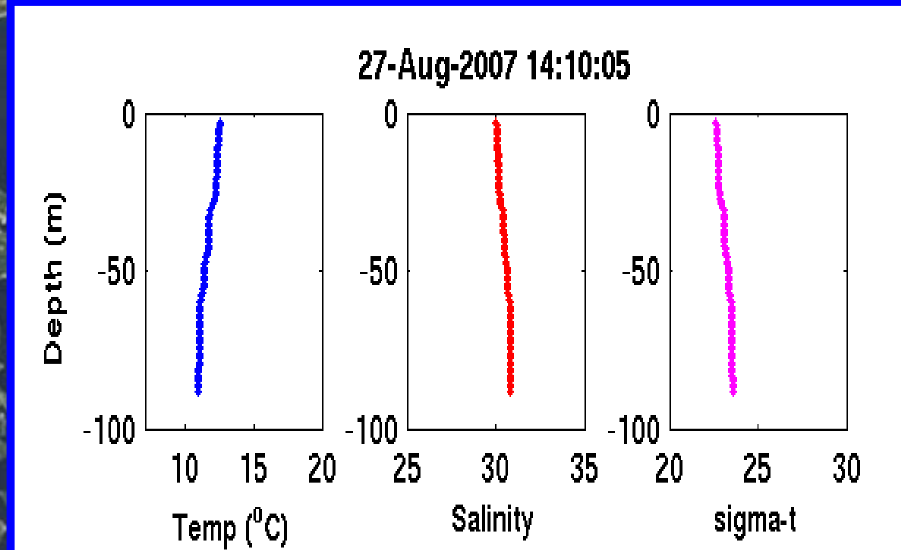
“ORCA” buoy data
Devol, Ruef (UW)

HCDOP

Within Hood Canal

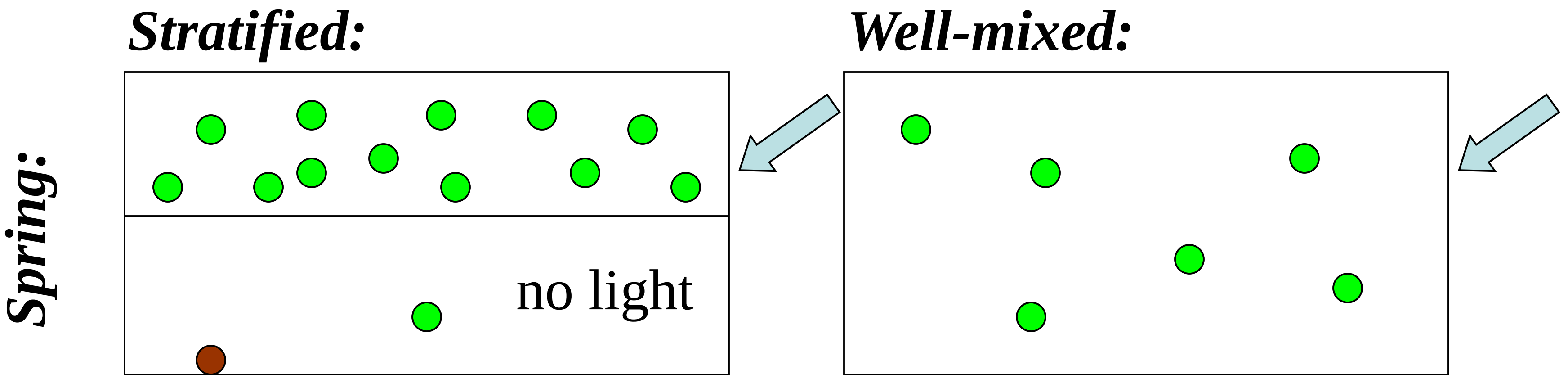


Near Admiralty Inlet



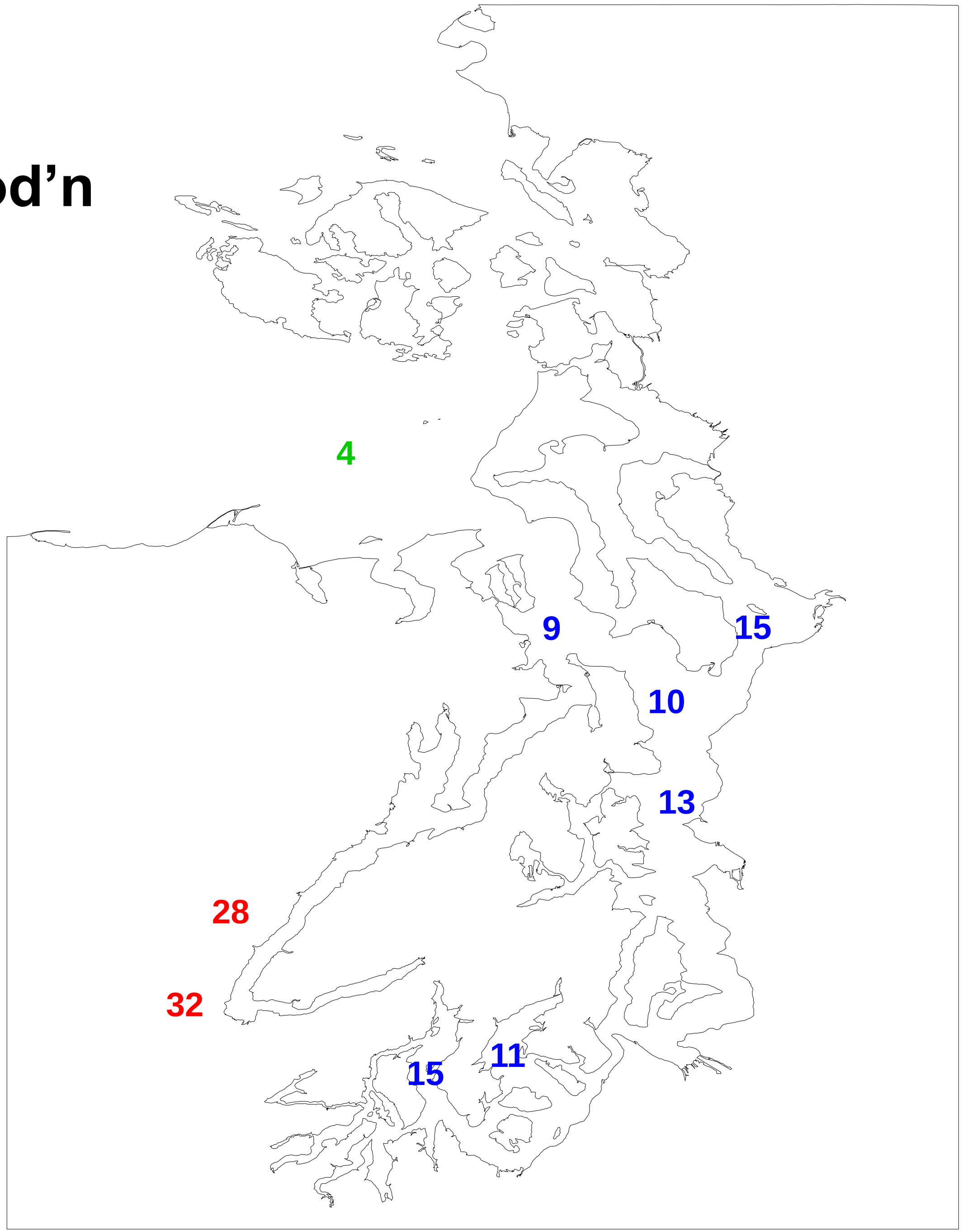
Water quality impacts from eutrophication

- Dependent on stratification



% increase in integrated prod'n

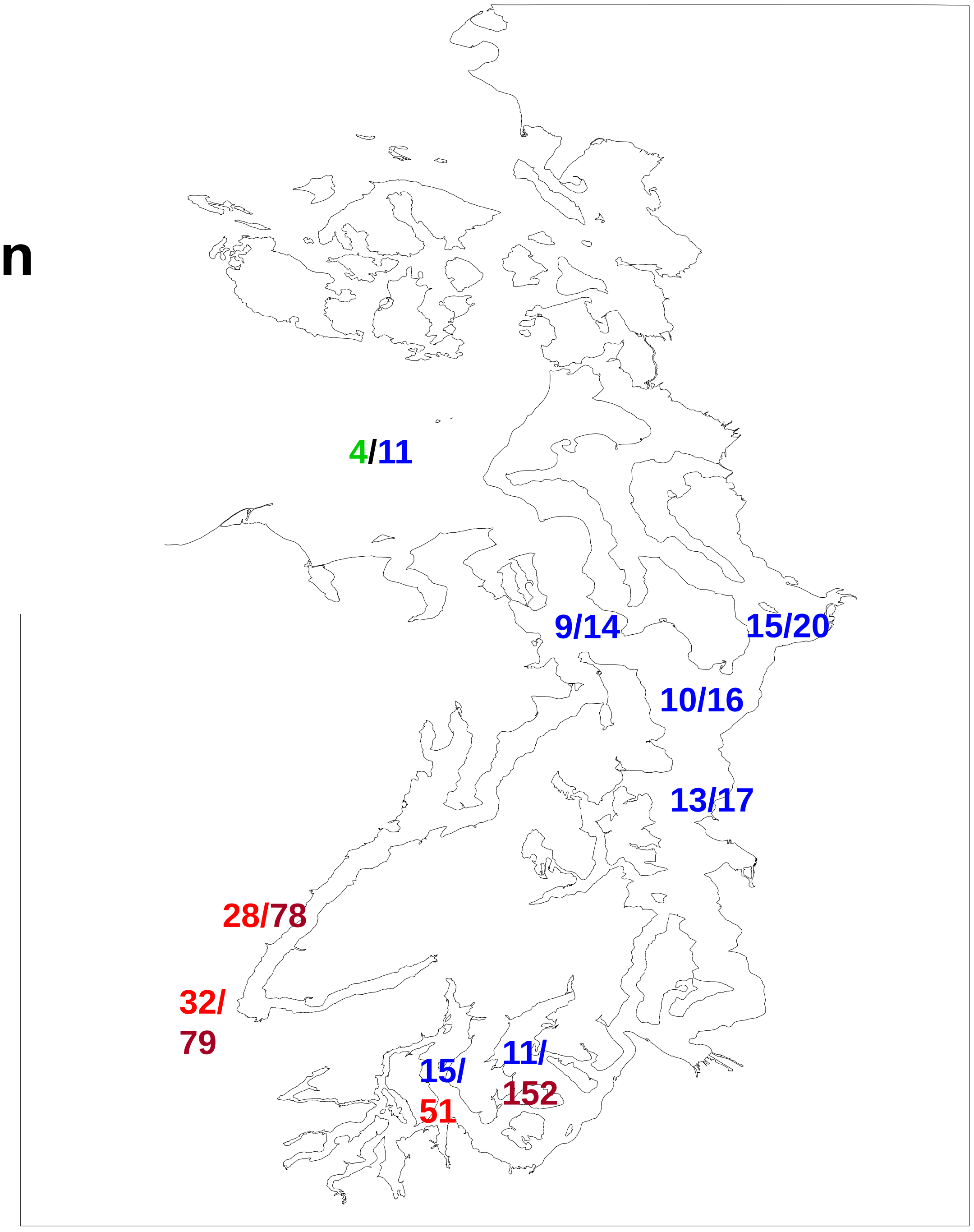
<5
>5-15
>15-25
>25-35



Newton et al., 2000

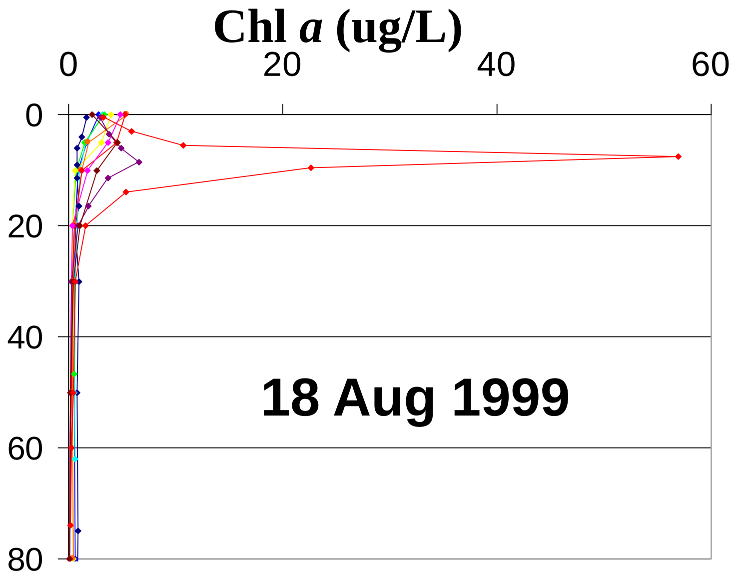
% increase in integrated / surface prod'n

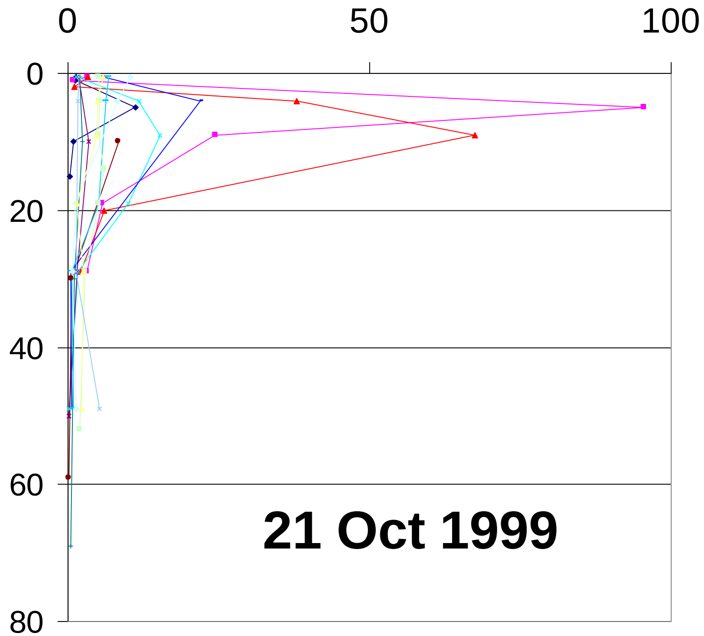
<5 / <10
>5-15 / >10-30
>15-25 / >30-50
>25-35 / >50-70
>35 / >70

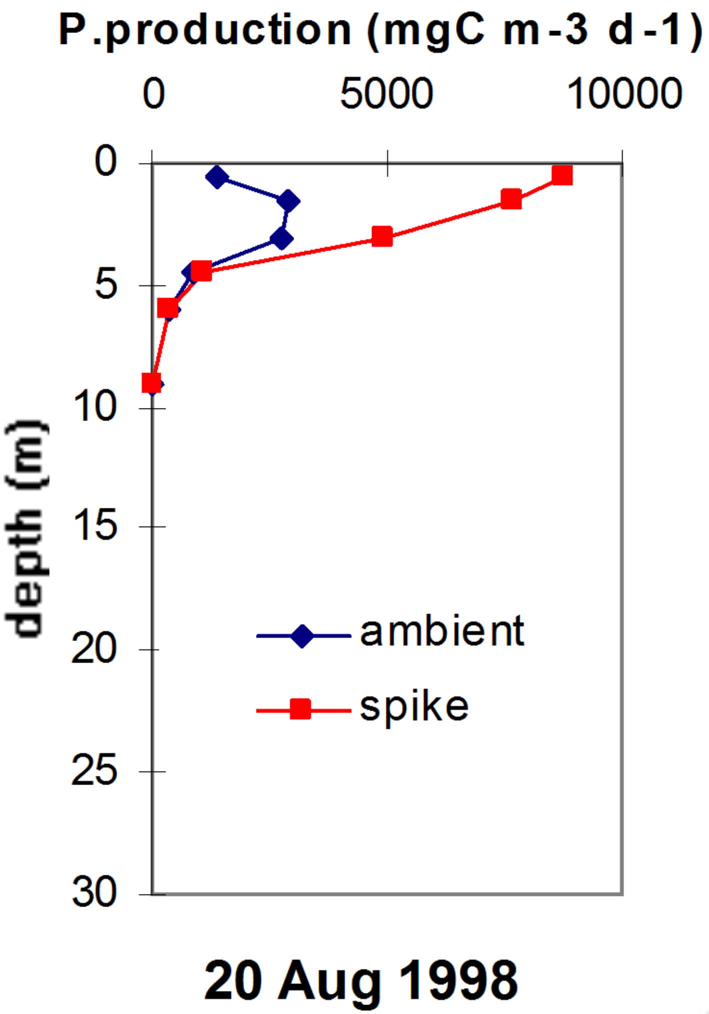


Newton et al., 2000

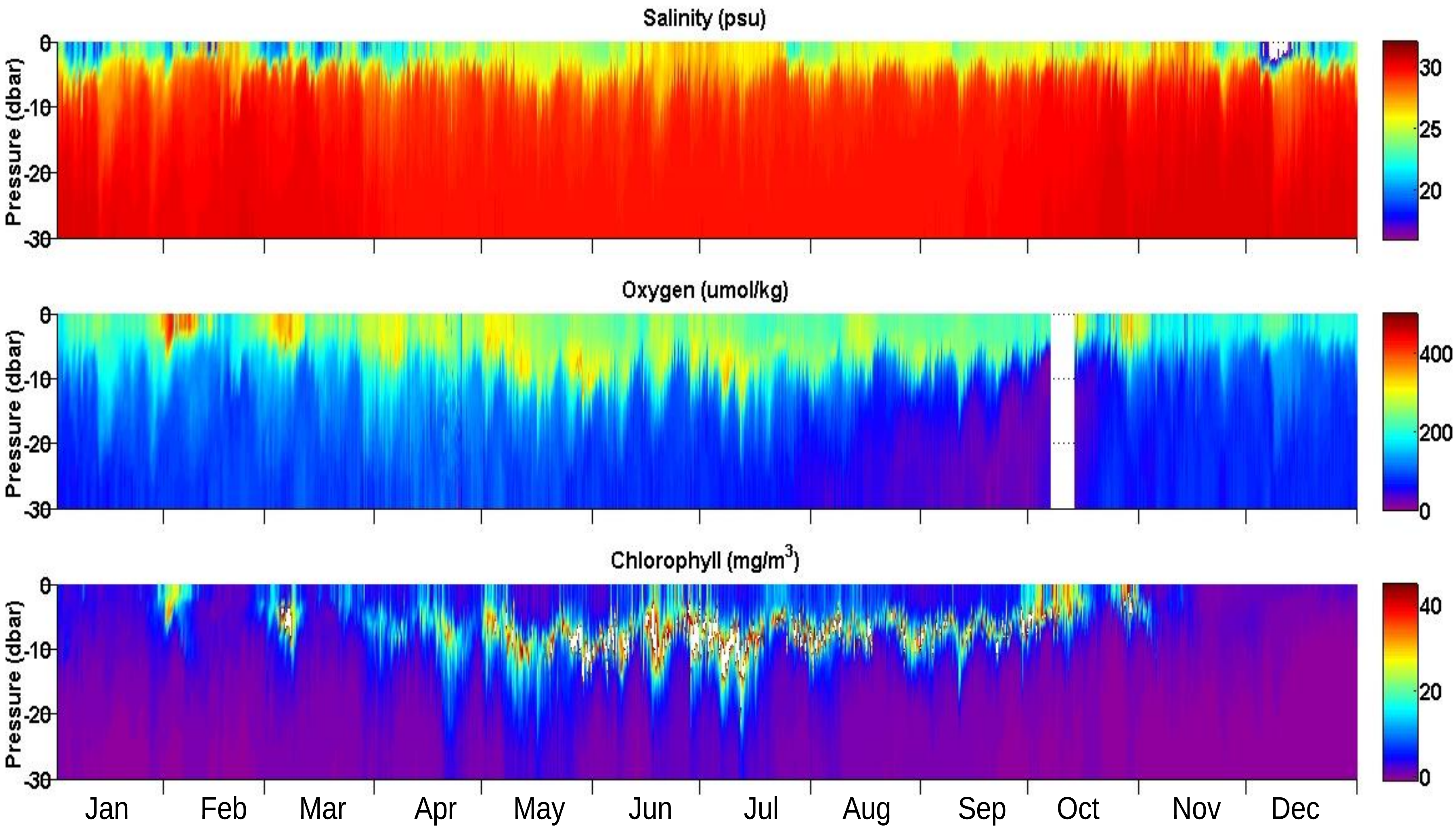
Hood Canal Vertical stratification strong





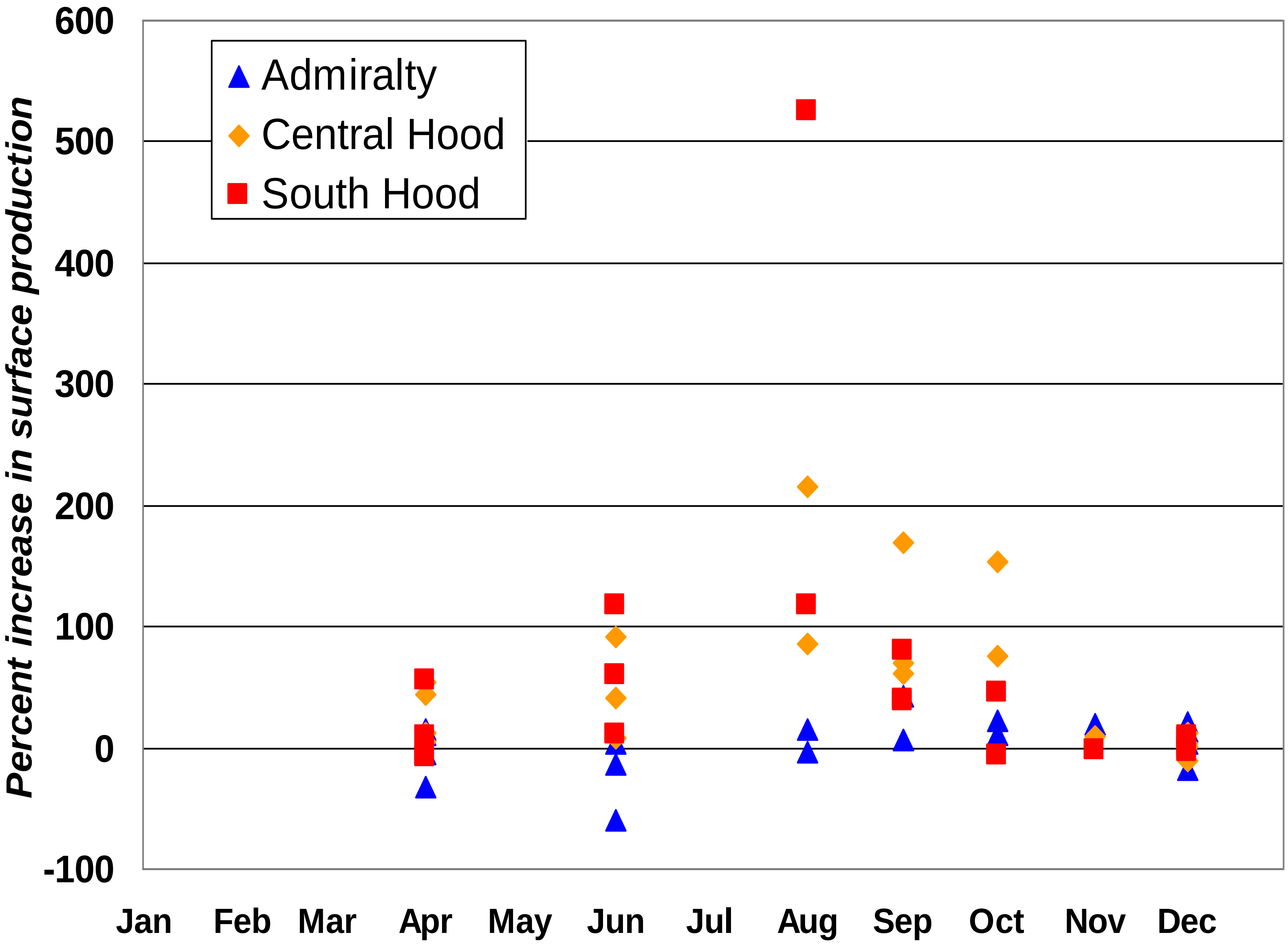


Annual cycle



2006

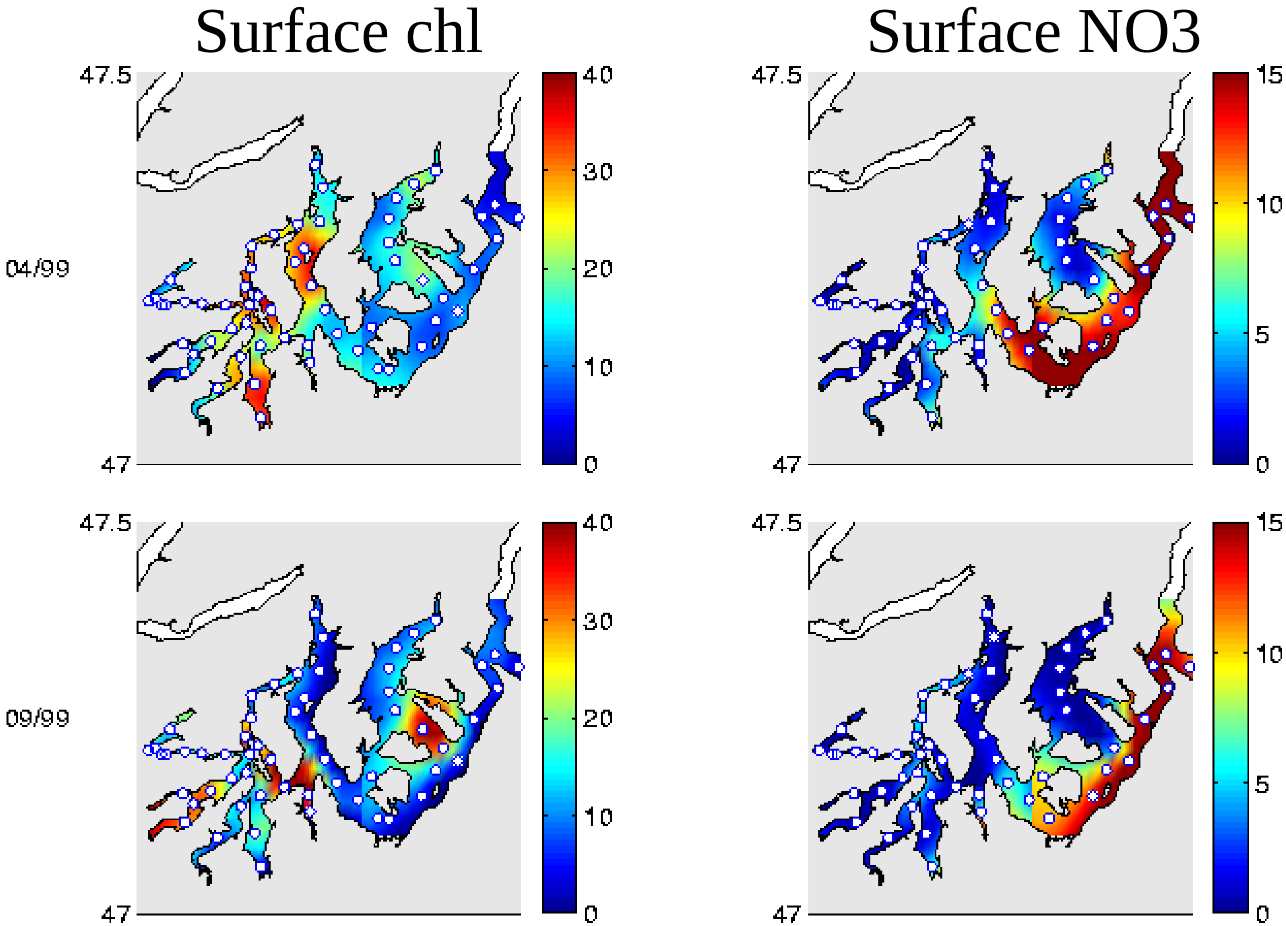
Hood Canal



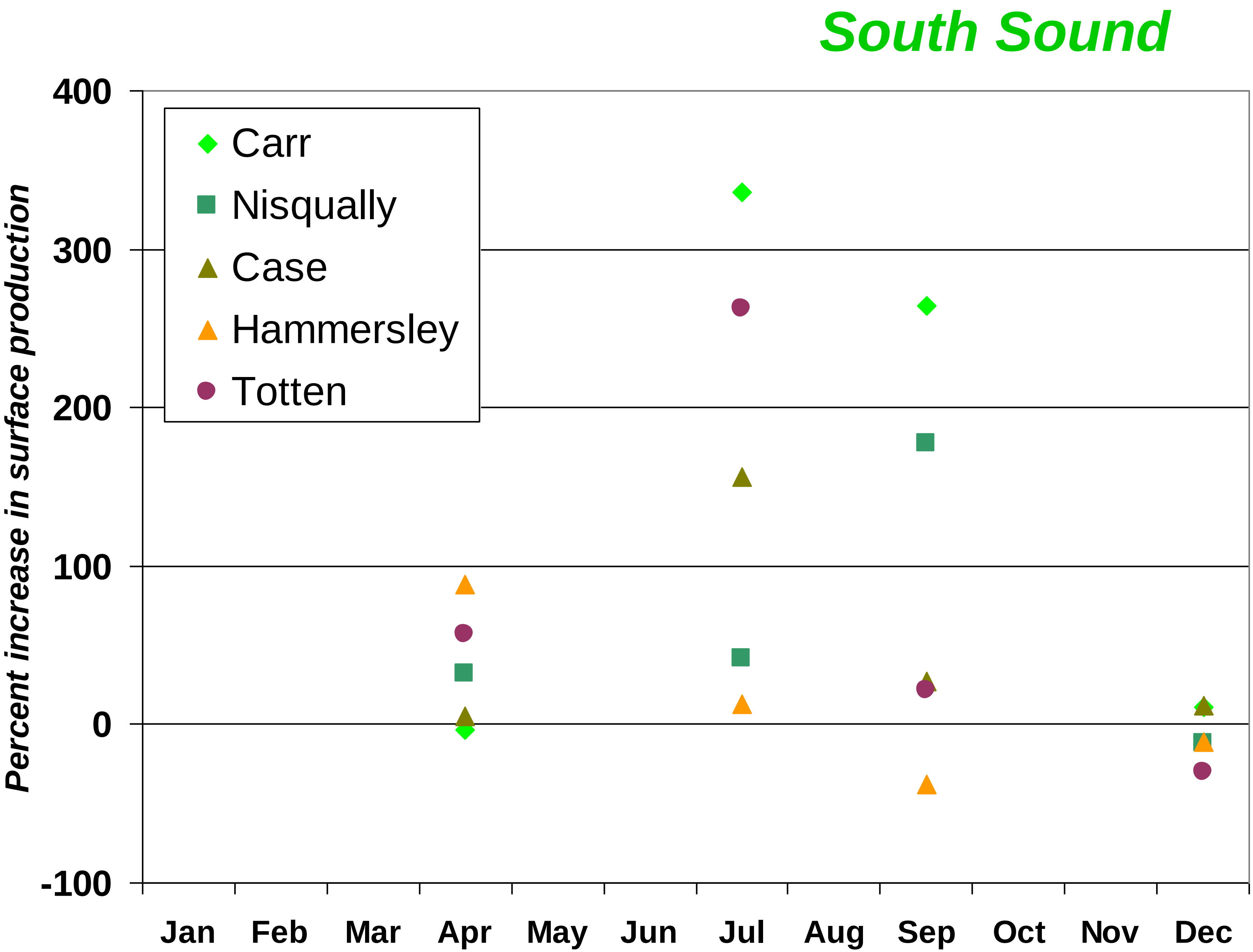
Newton et al., 2000

South Sound

Phytoplankton blooms appear spatially variable and dynamic

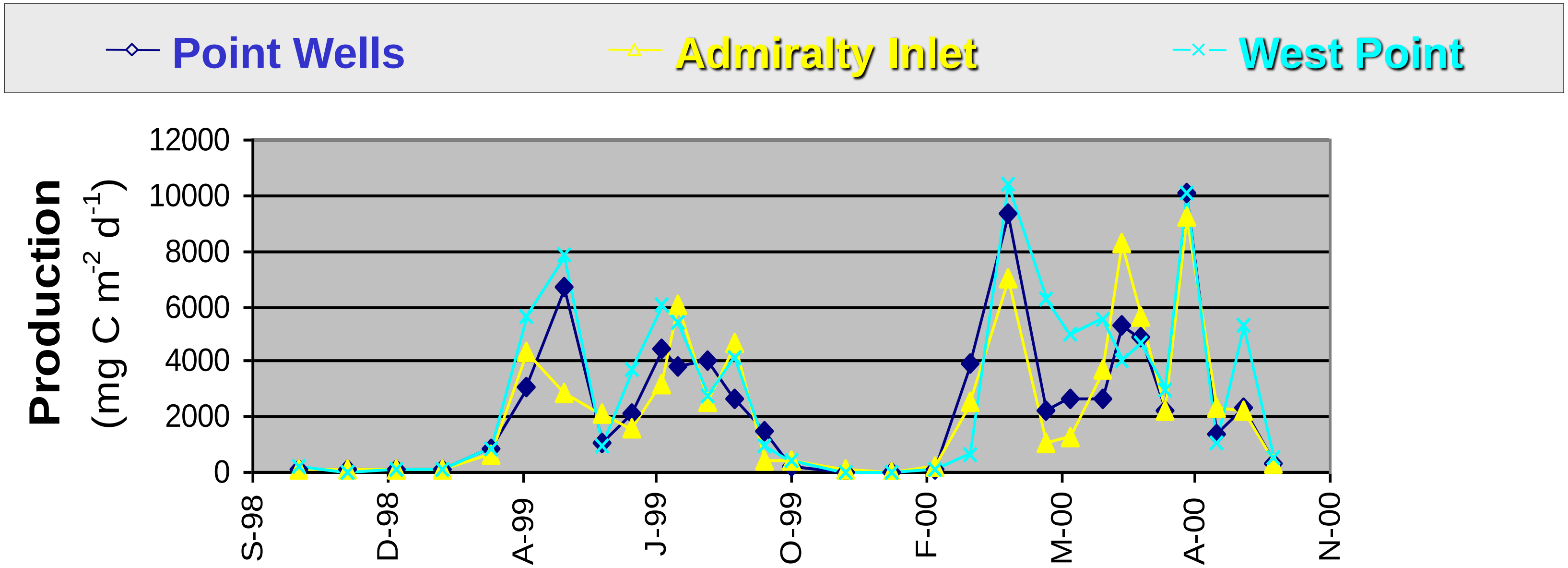


Albertson et al., 2002

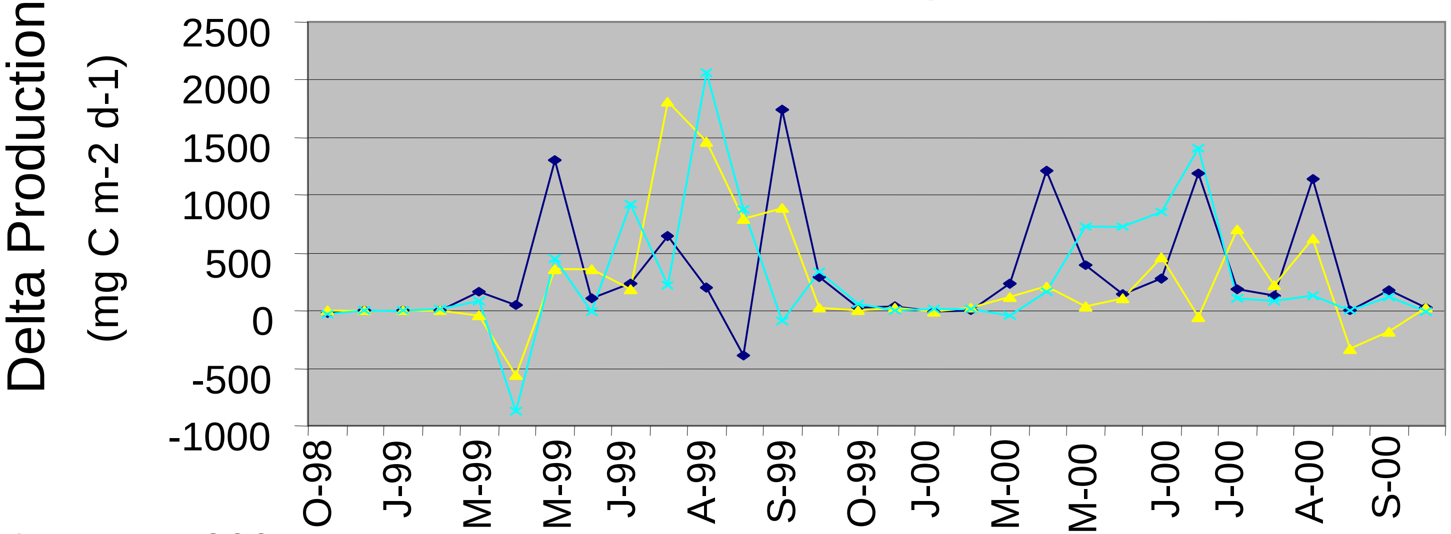


Newton et al., 2000

Main Basin Strong temporal variability

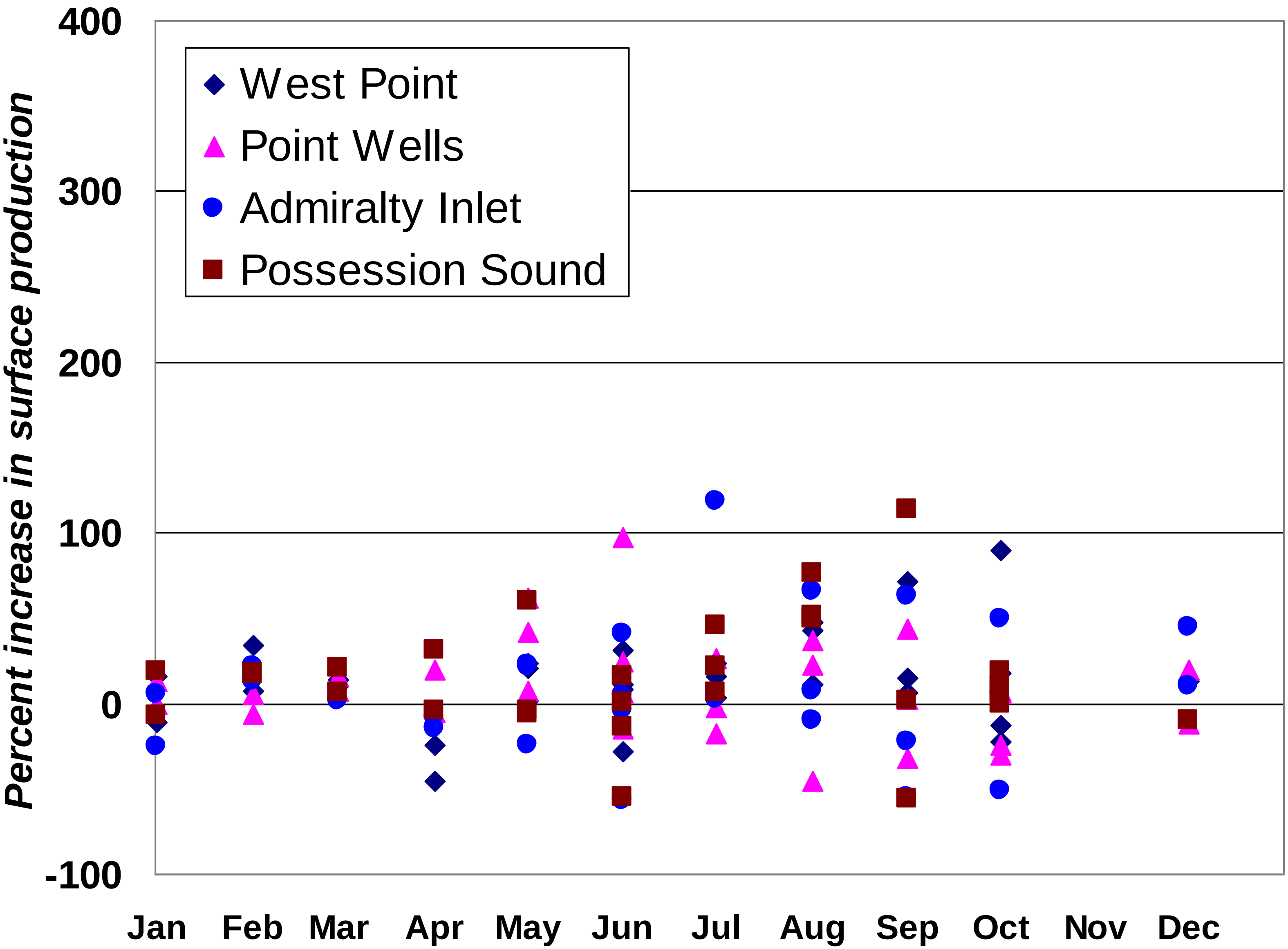


Effect of nutrient spike



Nakata & Newton 2004

Main Basin



Newton et al., 2000

Regional patterns

- ***Hood Canal: 1.0 - 1.5 kg C m^{-2} y^{-1}***
  - highest P, B, ~ constant nutrient sensitivity
- ***South Sound: 0.7 - 1.1 kg C m^{-2} y^{-1}***
  - high and variable P, B, nutrient sensitivity
- ***Main Basin: 0.8 kg C m^{-2} y^{-1}***
  - dynamic and moderate P, B, variable nutrient sensitivity
- ***Strait of Juan de Fuca: 0.5 kg C m^{-2} y^{-1}***
  - lowest P, B, strong ocean influence

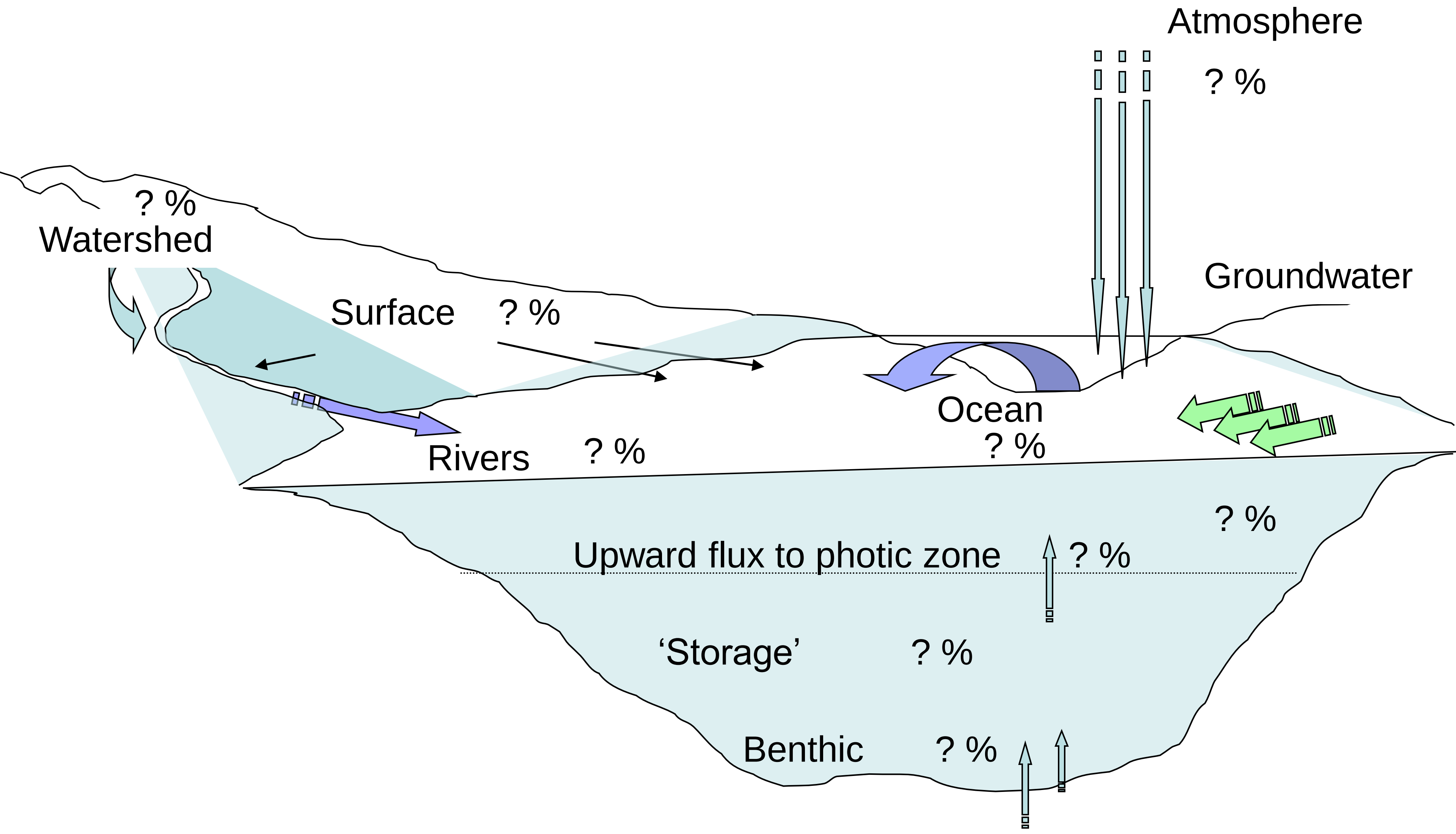
Problems

- Not all basins work the same, so our monitoring needs to be distributed.
- Within a basin, there can be strong spatial variation
- Can be strong temporal variation
- What does a nutrient concentration really mean?
- Do we understand the system?

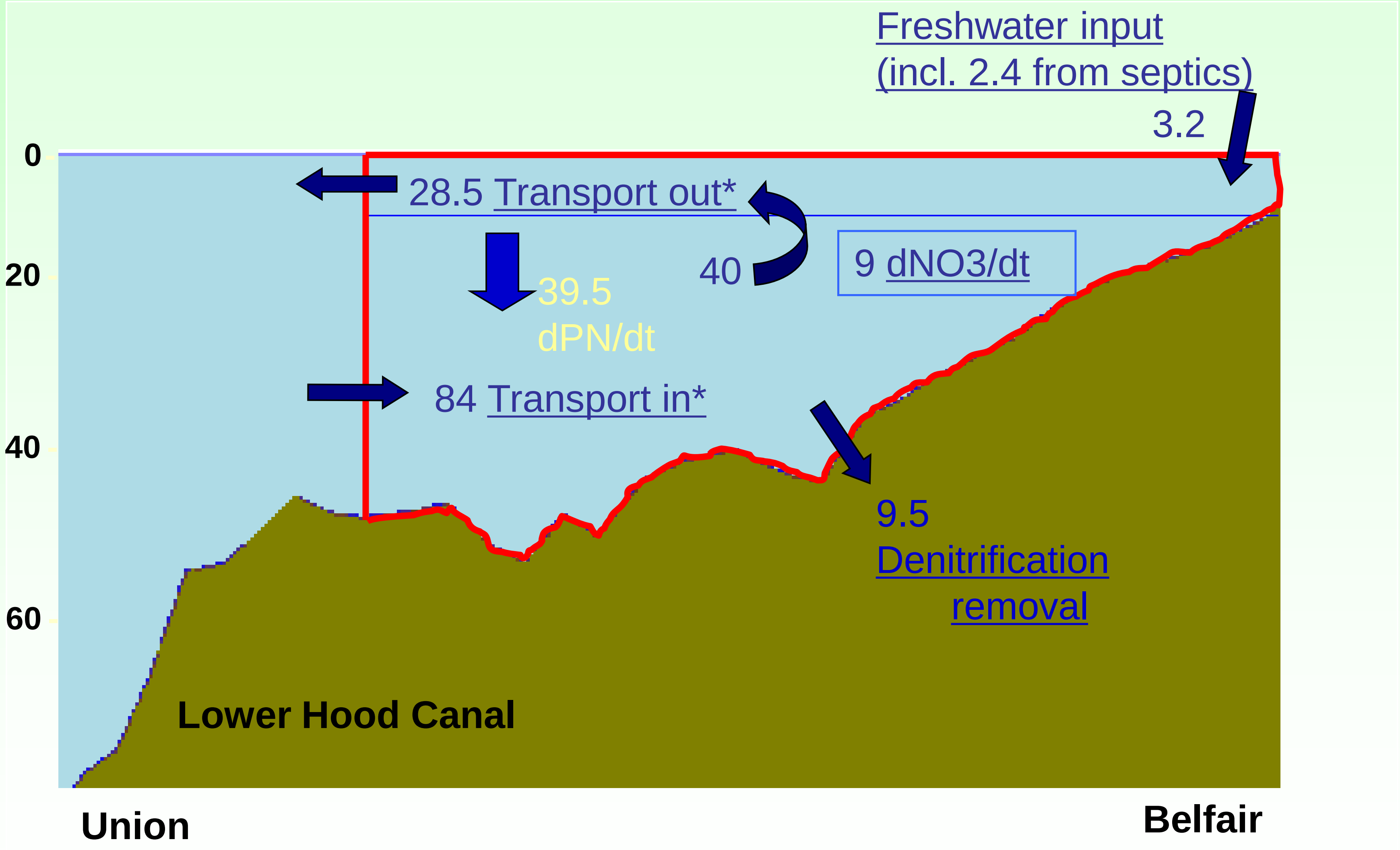
Sources of N to Puget Sound

- **Land**
  - ground water
  - surface water: rivers, streams, storm water, etc.
  - point sources: sewage, industrial
- **Water**
  - recycled from consumers: zpk, fish, benthos, etc.
  - flux from marine sediments
  - import from other marine areas: ocean, etc.
- **Air**
  - atmospheric nitrogen equilibrium with water
  - rain
  - fallout of particles

Load estimates:

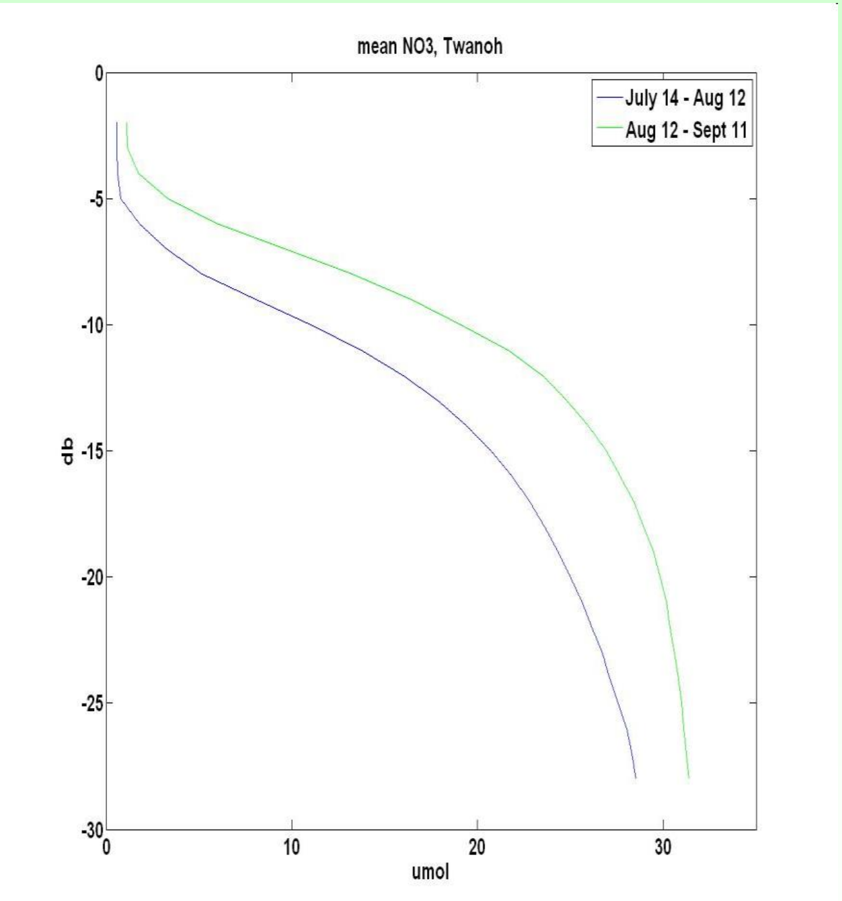


Lower Hood Canal N-Budget (Mt/mo; JJAS):

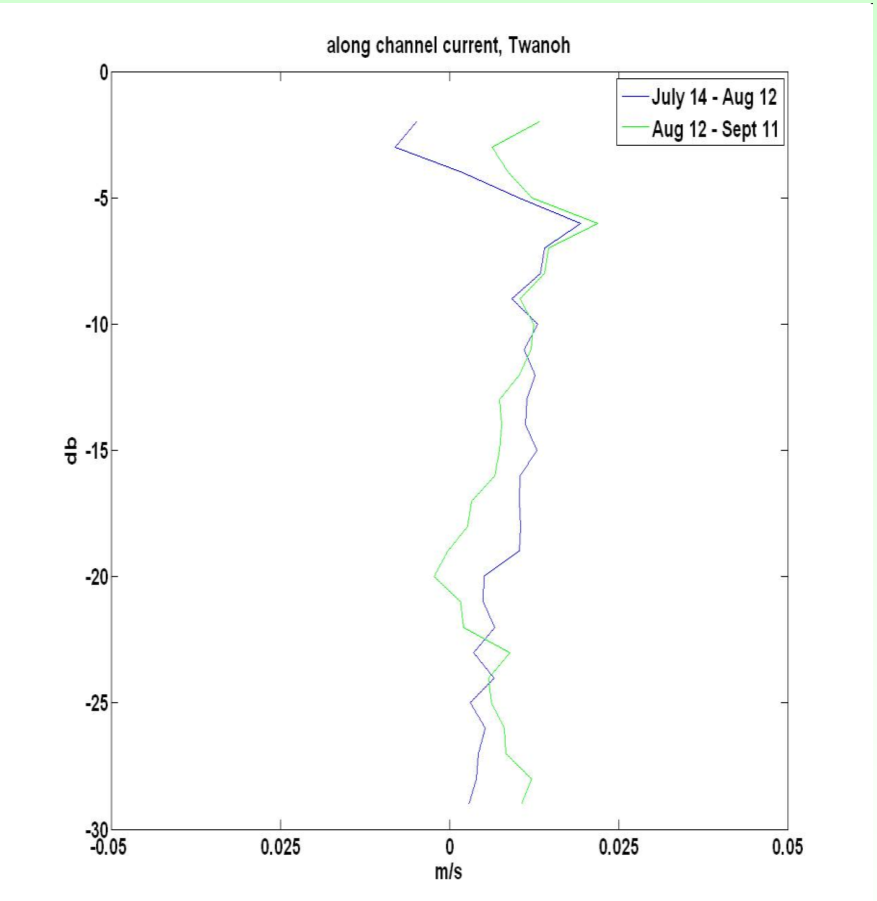


Concentration x flow = flux !

Nitrate

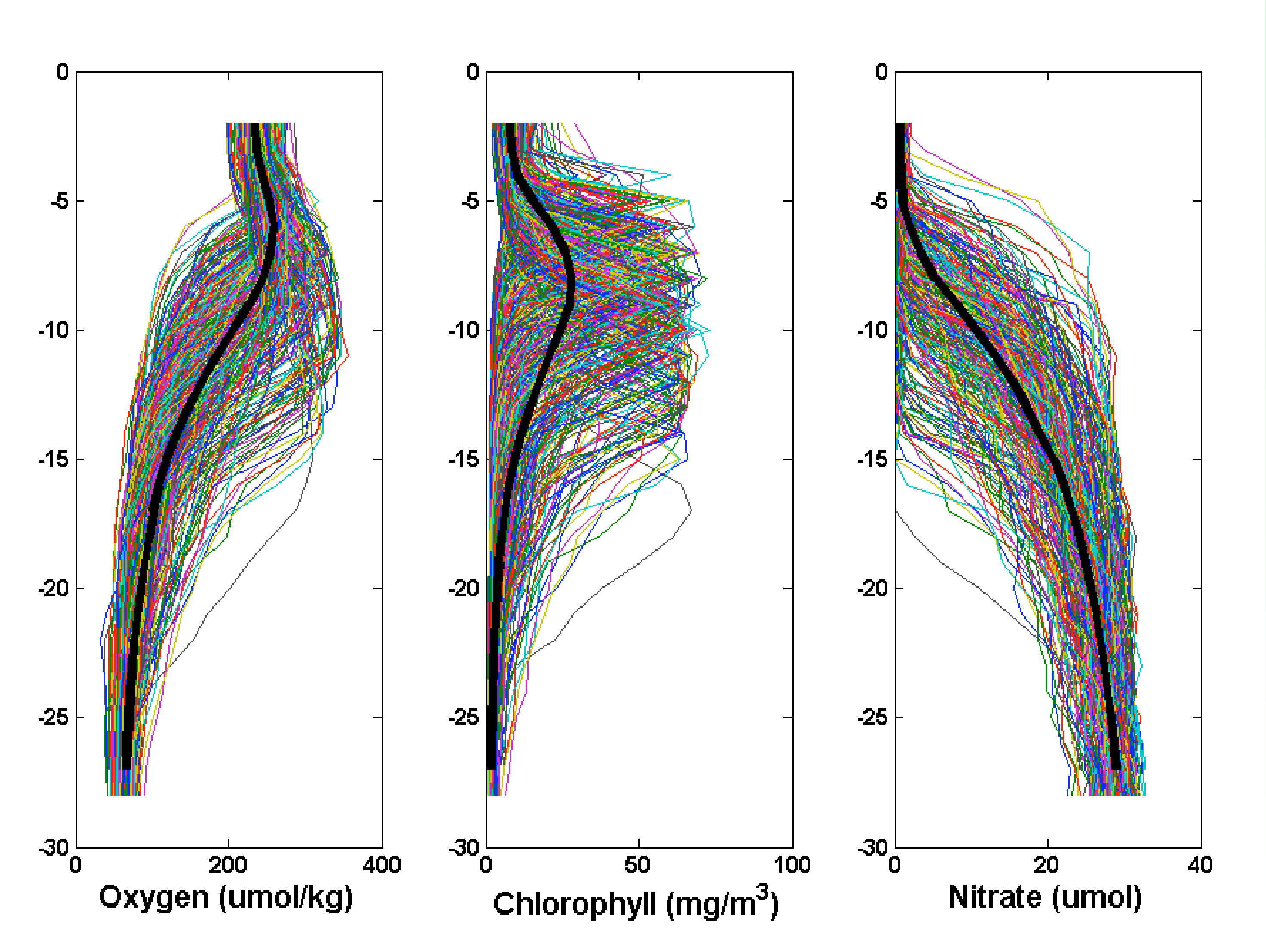


Currents

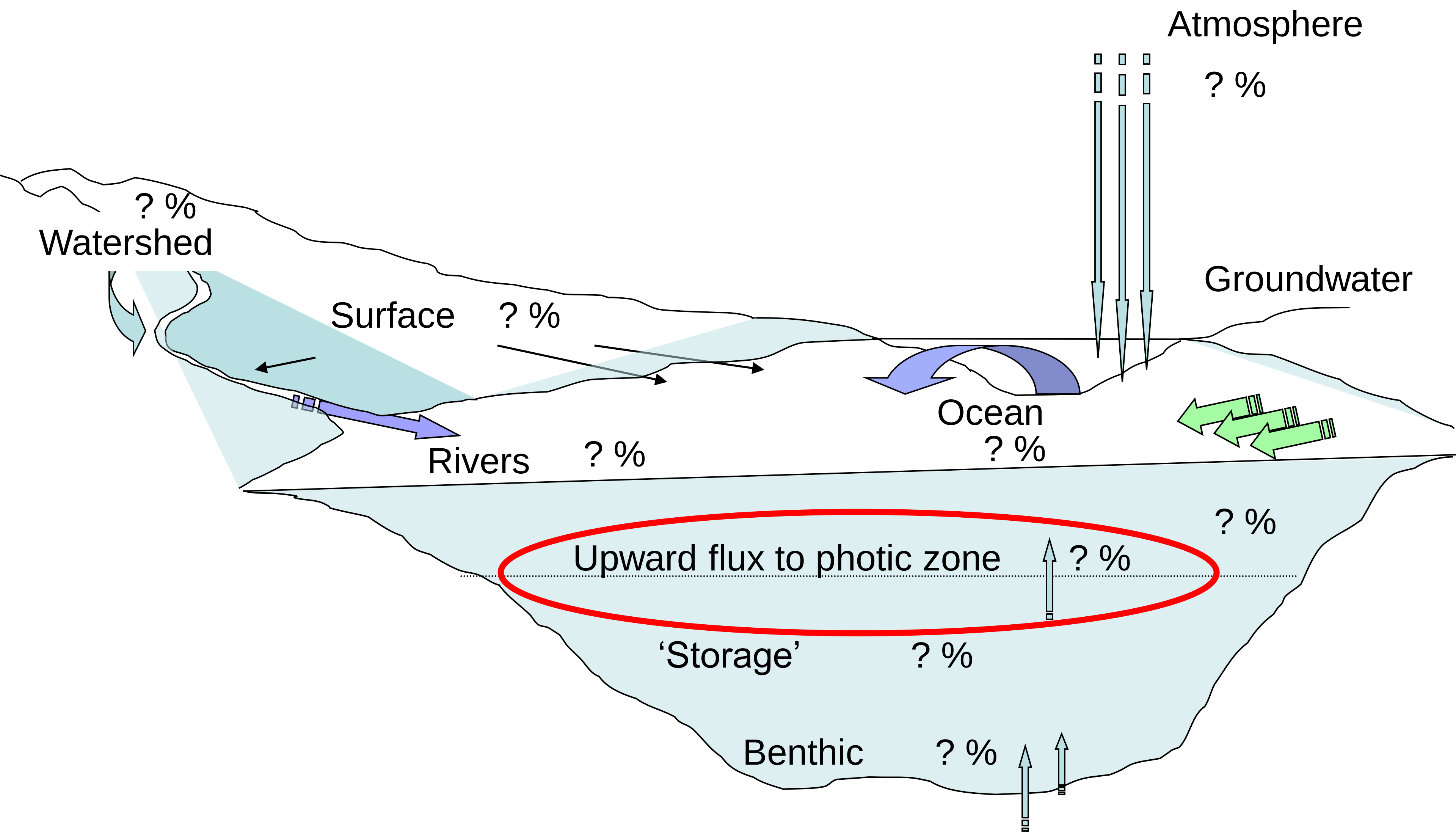


-

The answer you get depends on how you sample…



Load estimates:



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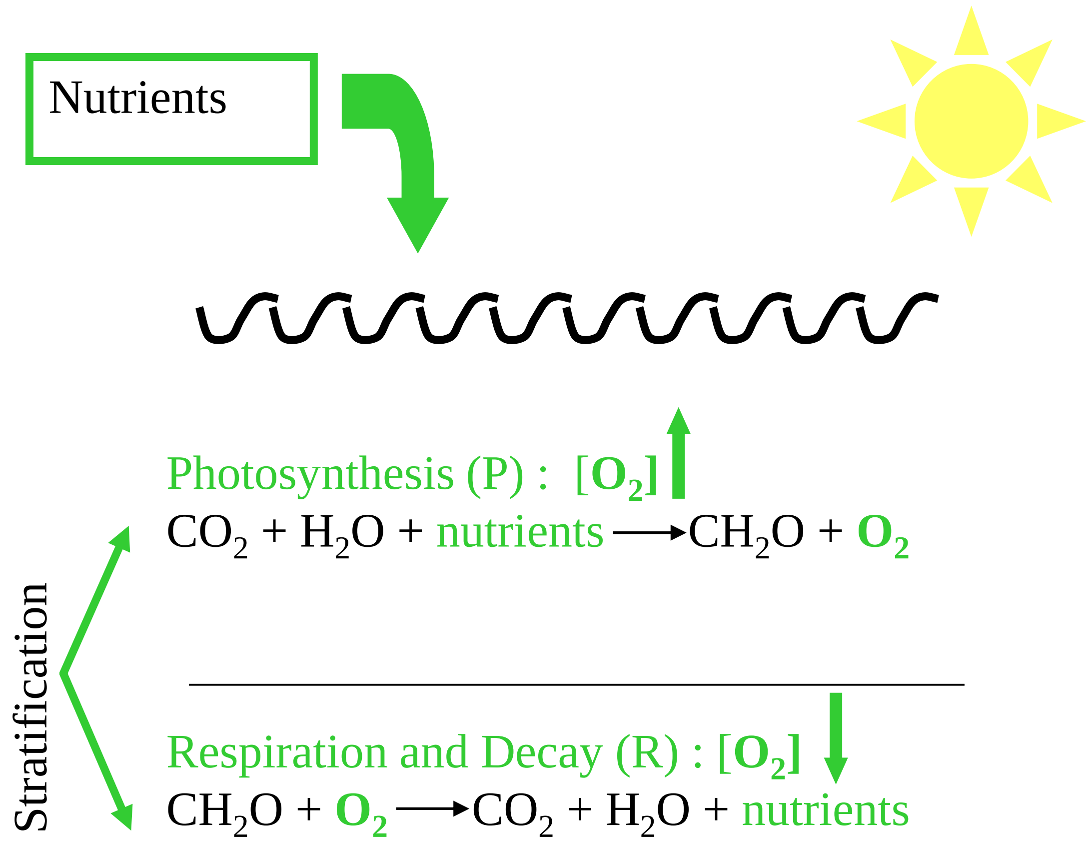
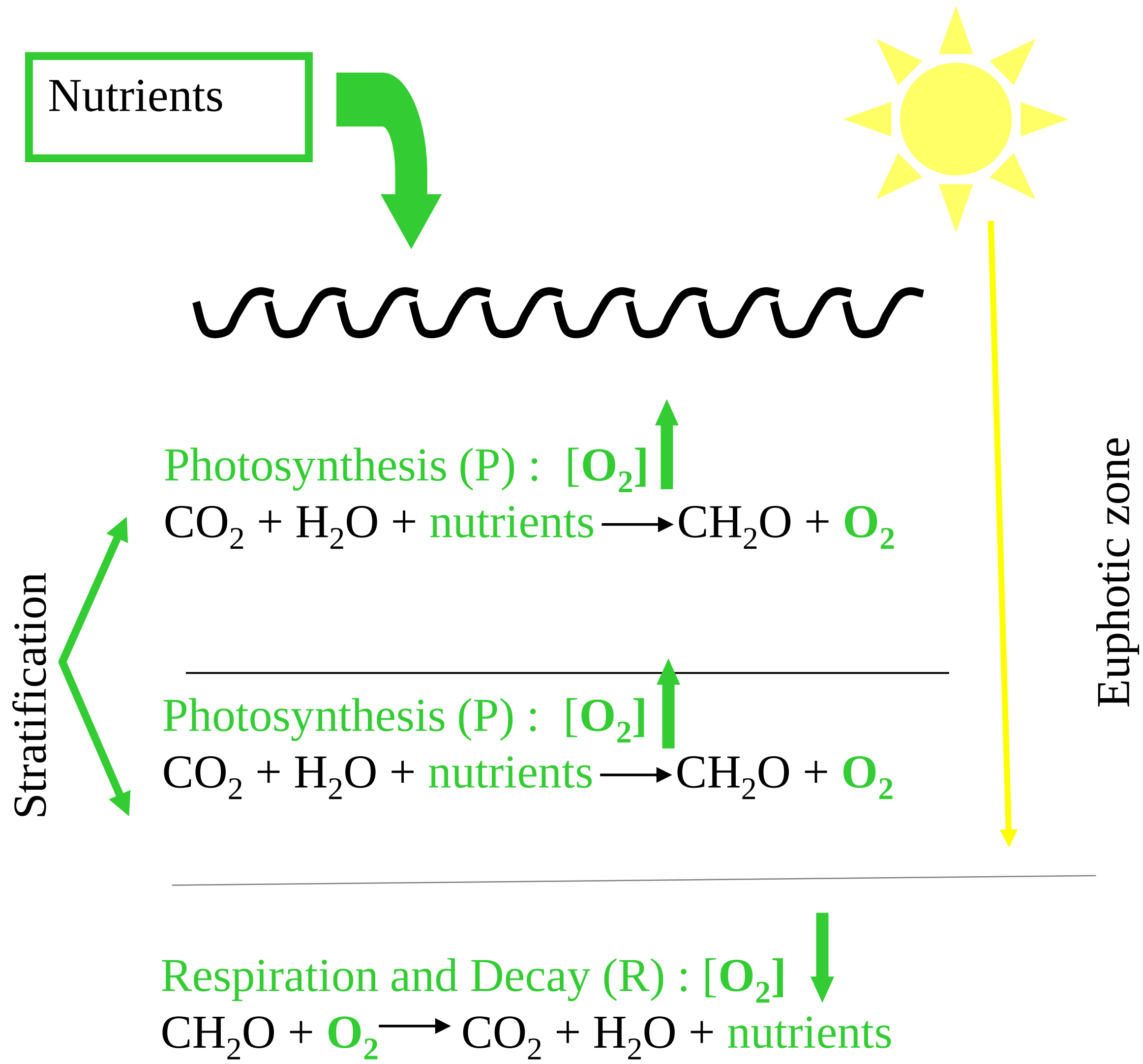

Nutrients
Photosynthesis (P) : [O_2]
$CO_2 + H_2O +$ nutrients $\longrightarrow CH_2O + O_2$
Stratification
Respiration and Decay (R) : [O_2]
$CH_2O + O_2 \longrightarrow CO_2 + H_2O +$ nutrients

Devol 2003

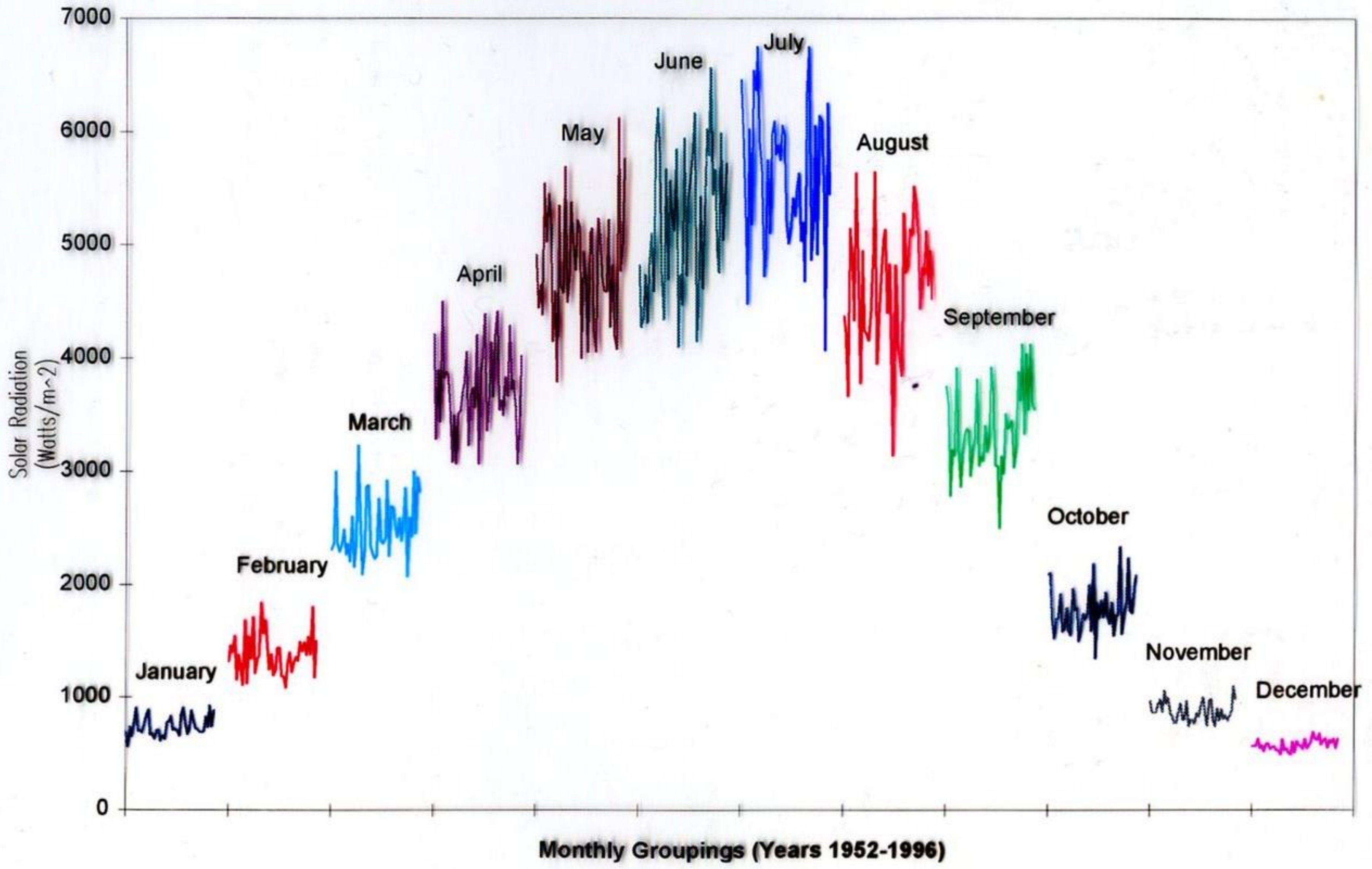

Nutrients
Photosynthesis (P) : [O_2]
CO_2 + H_2O + nutrients → CH_2O + O_2
Photosynthesis (P) : [O_2]
CO_2 + H_2O + nutrients → CH_2O + O_2
Stratification
Euphotic zone
Respiration and Decay (R) : [O_2]
CH_2O + O_2 → CO_2 + H_2O + nutrients

Devol 2003

Problems

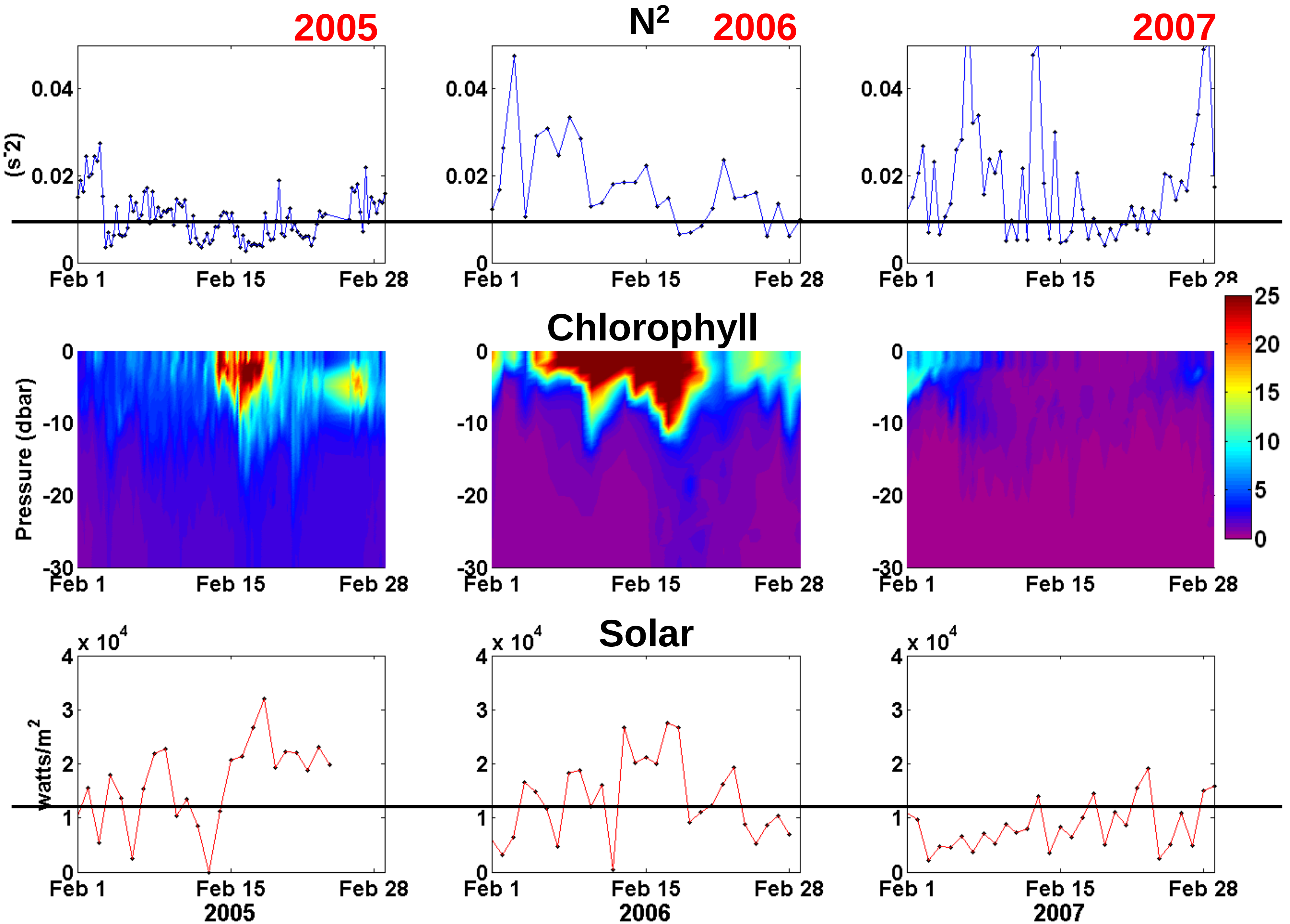
- Not all basins work the same, so our monitoring needs to be distributed.
- Within a basin, there can be strong spatial variation
- Can be strong temporal variation
- What does a nutrient concentration really mean?
- Do we understand the system?
- How will things be changing?

Monthly solar radiation SeaTac airport (48N)



Ebbesmeyer

Variation in spring bloom



Ruef

Interannual variation

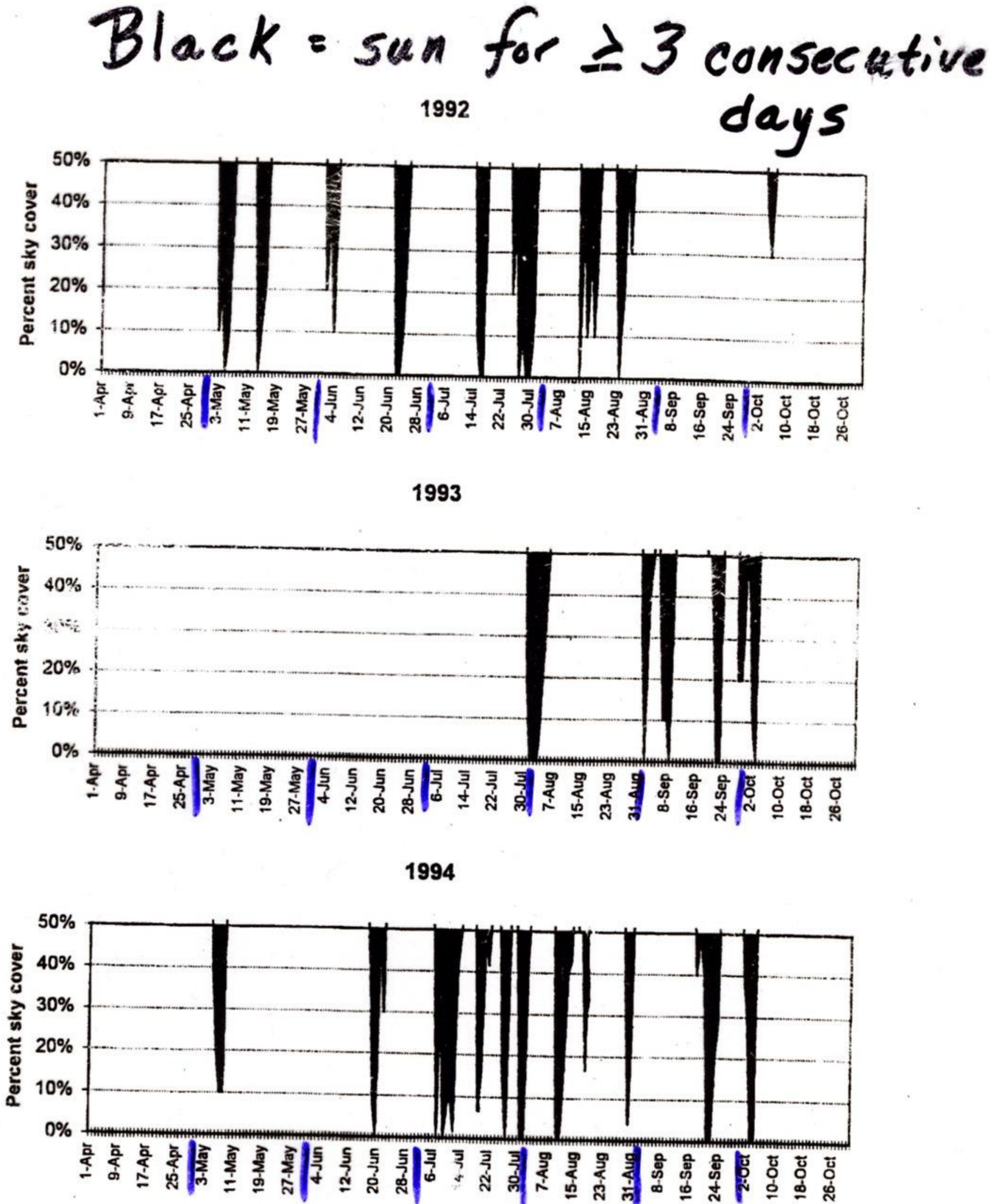


Figure 6. Periods of sun for 3 or more days as indicated by mean daily sky cover values of 50% or less. Mean daily sky cover was determined from observations made from sunrise to sunset at hourly intervals except for June to October 1994 when observations were made every 3 hours.

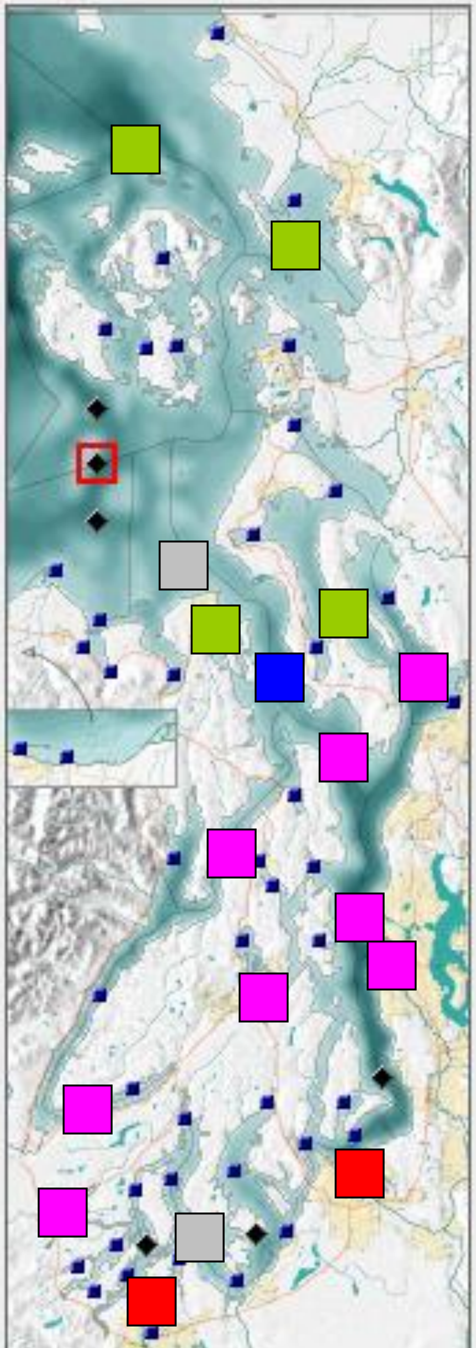
Eisner et al., 1997

PNW estuaries have strong influence from climate

Global influence on:

ocean conditions
watershed conditions
local weather

NASA SeaWiFS Image



Oceanographic Changes in Puget Sound

and the Strait of Juan de Fuca during the 2000–01 Drought

Jan A. Newton[1,2], Eric Siegel[1] and Skip L. Albertson[1]

Canadian Water Resources Journal
Vol. 28, No. 4, 2003

Percent change in stratification

(10-y mean – Oct 00-Sep 01/10-y mean)

<0%

0-30%

30-49%

50-69%

≥70%

Mean = 56%

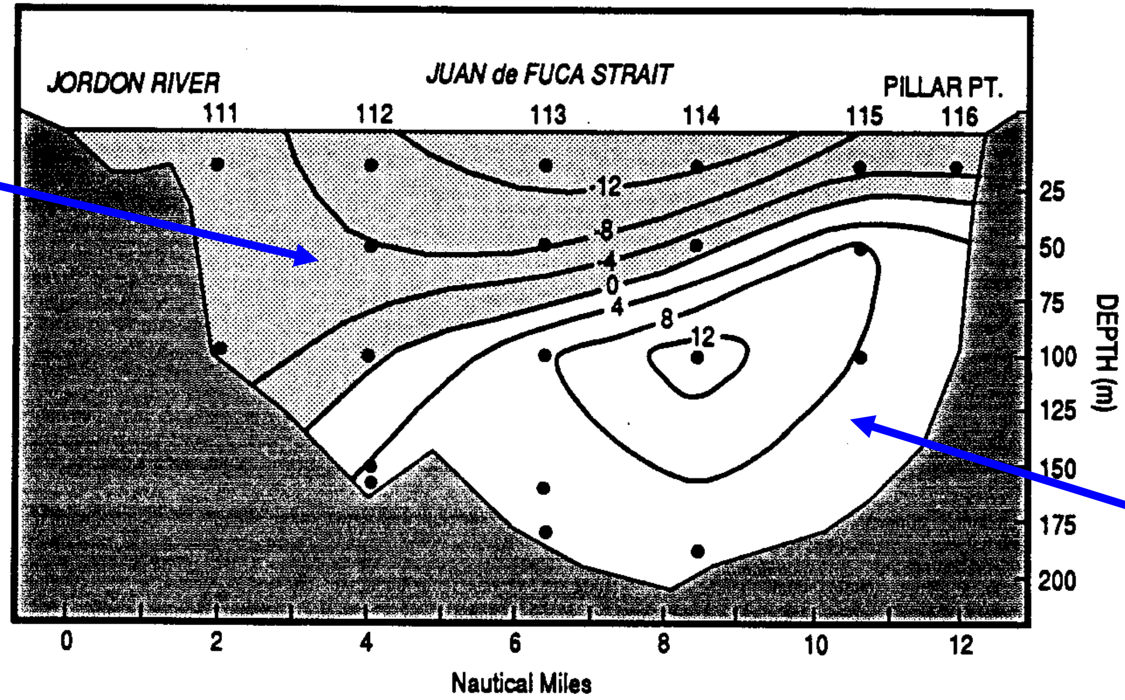
Joint Effort to Monitor the Strait (JEMS)

Flow in Strait of Juan de Fuca:

North
Canada

South
U.S.A.

fresher, warmer water from Puget Sound and Georgia Basin flowing out



colder, salty water from Pacific Ocean flowing in

Figure 10. Cross-section of residual along-channel flow in the central portion of Juan de Fuca Strait for the period 6 March–14 June 1973 (speeds in cm/s). The view is up-strait toward the east. Negative values (shaded) are seaward and positive values are landward. The transport in each layer is about 0.1×10^6 m^3/s. (Adapted from Godin et al. 1980)

Thomson, 1994

Low River Flow

↓

Weak Density Gradient

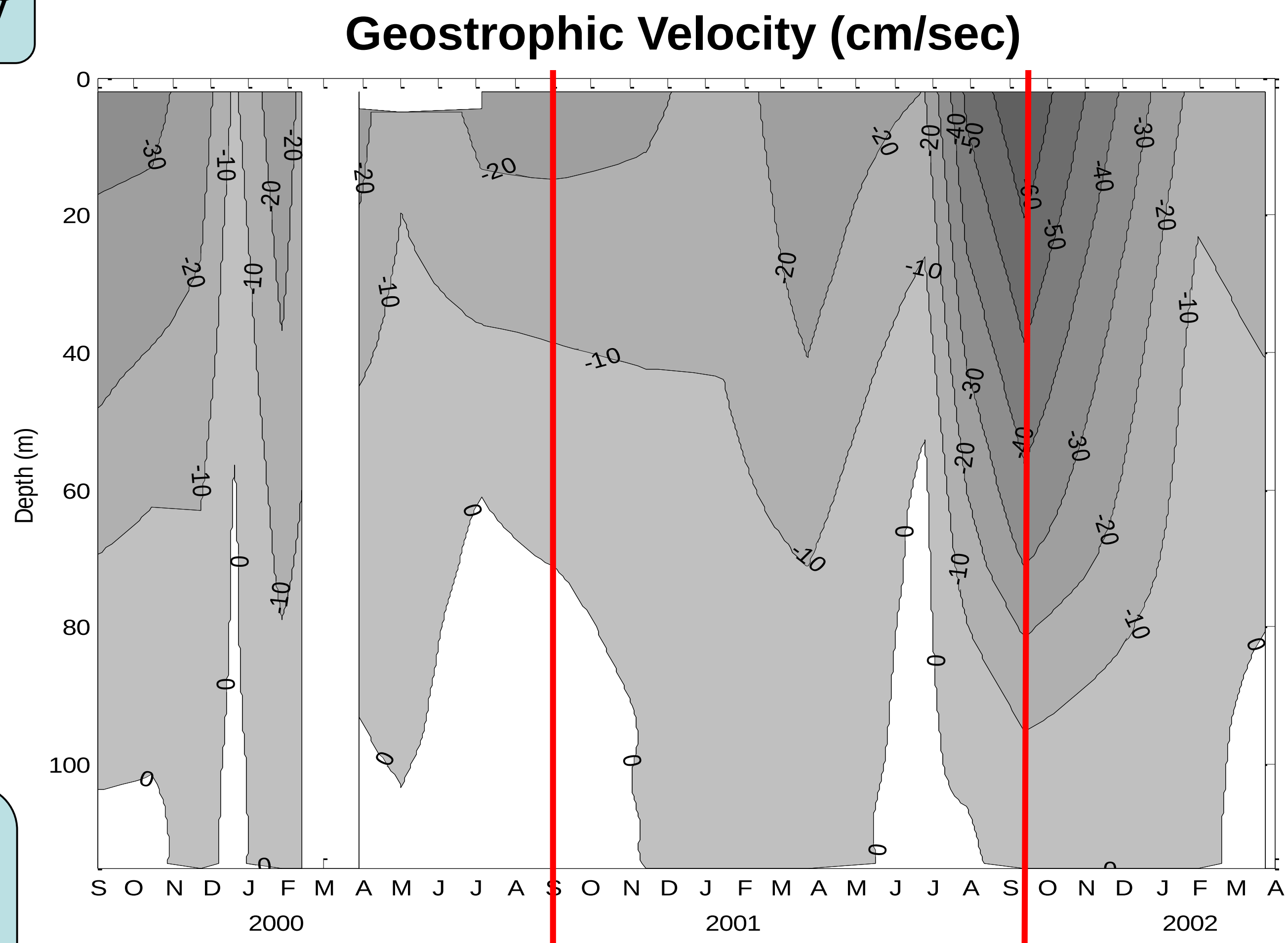
↓

Decreased Outflow Velocity

↓

Water stays in Puget Sound longer

(this means how fast the water flows out the Strait)



Four-fold difference in speed of inland water outflow.

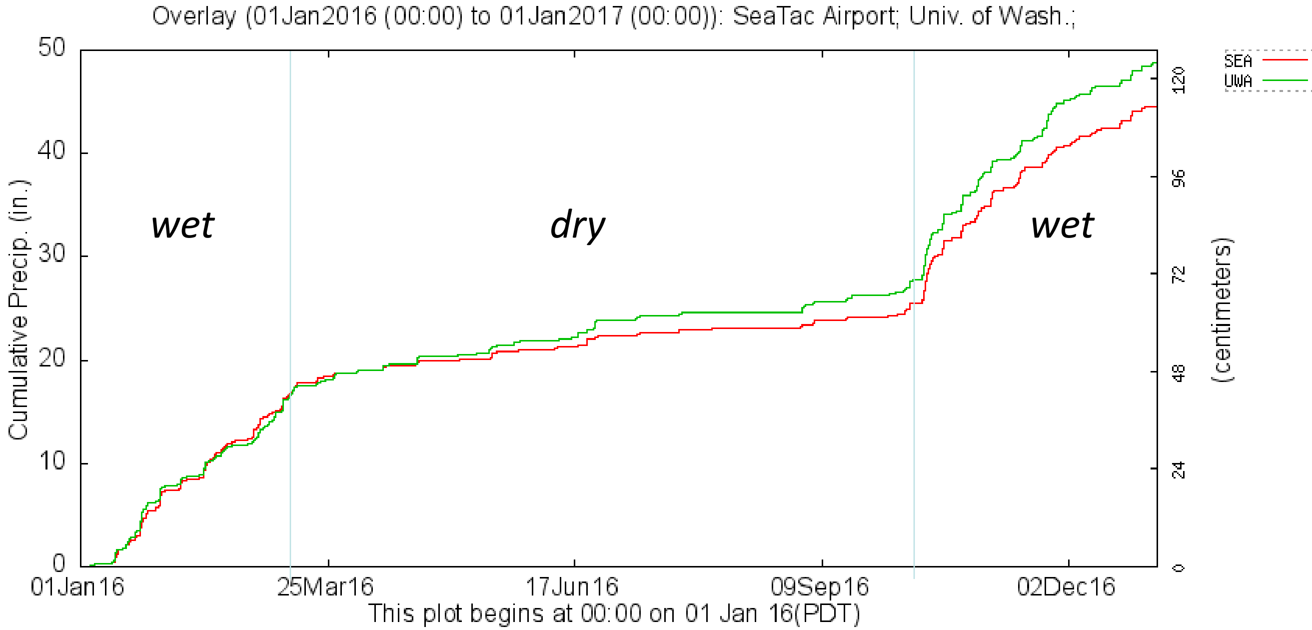
Newton et al., 2003

Conclusions

- Drought period increased the salinity of estuarine waters, leading to higher density surface layer and **weaker stratification**.
- Higher salinity surface waters with weaker vertical density gradient result in decreased outflow velocity and **longer residence time** in estuary.
- **Implications** for oxygen, phytoplankton blooms, trophic transfer, and transport or retention of larvae, species, and pollutants need further investigation.

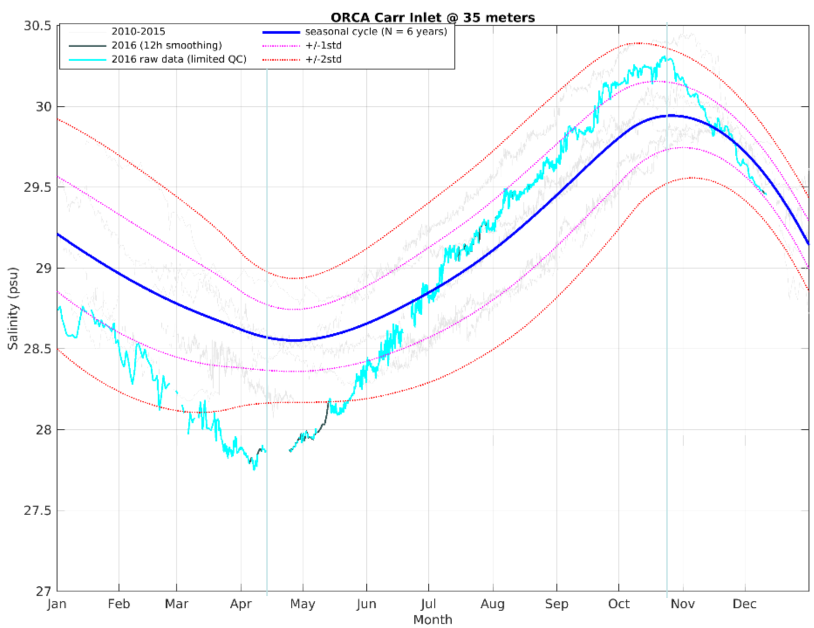
Precipitation:

Ruef et al., 2017 Marine Waters Overview

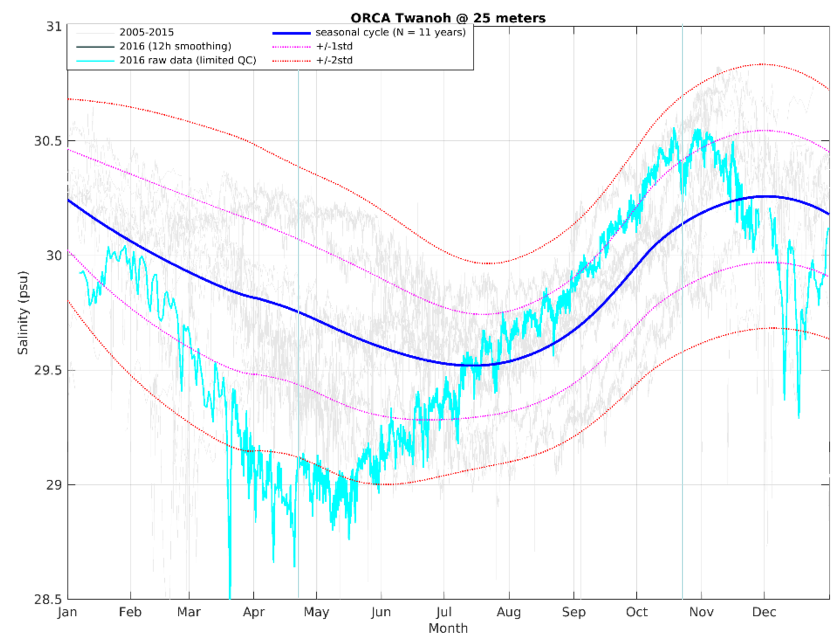


Deep Salinity:

Carr @ 35 m

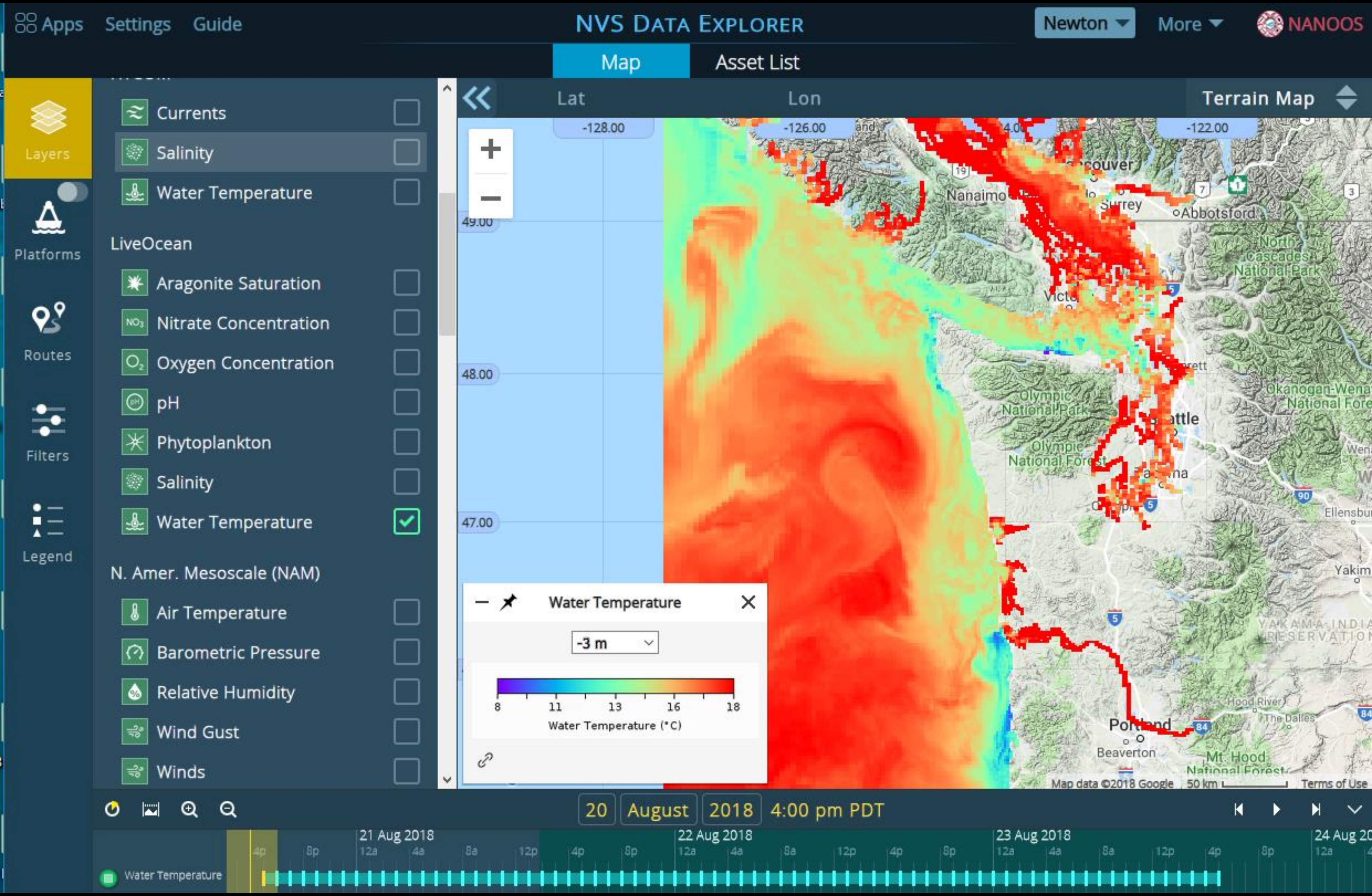


Twanoh @ 25 m



Solutions?

- More focus on mechanisms
  - Fluxes
- Sustain long-term monitoring
  - Plankton, rates
- Keep finding time for analysis
  - Including models



Apps
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NVS DATA EXPLORER
Newton
More
NANOOS
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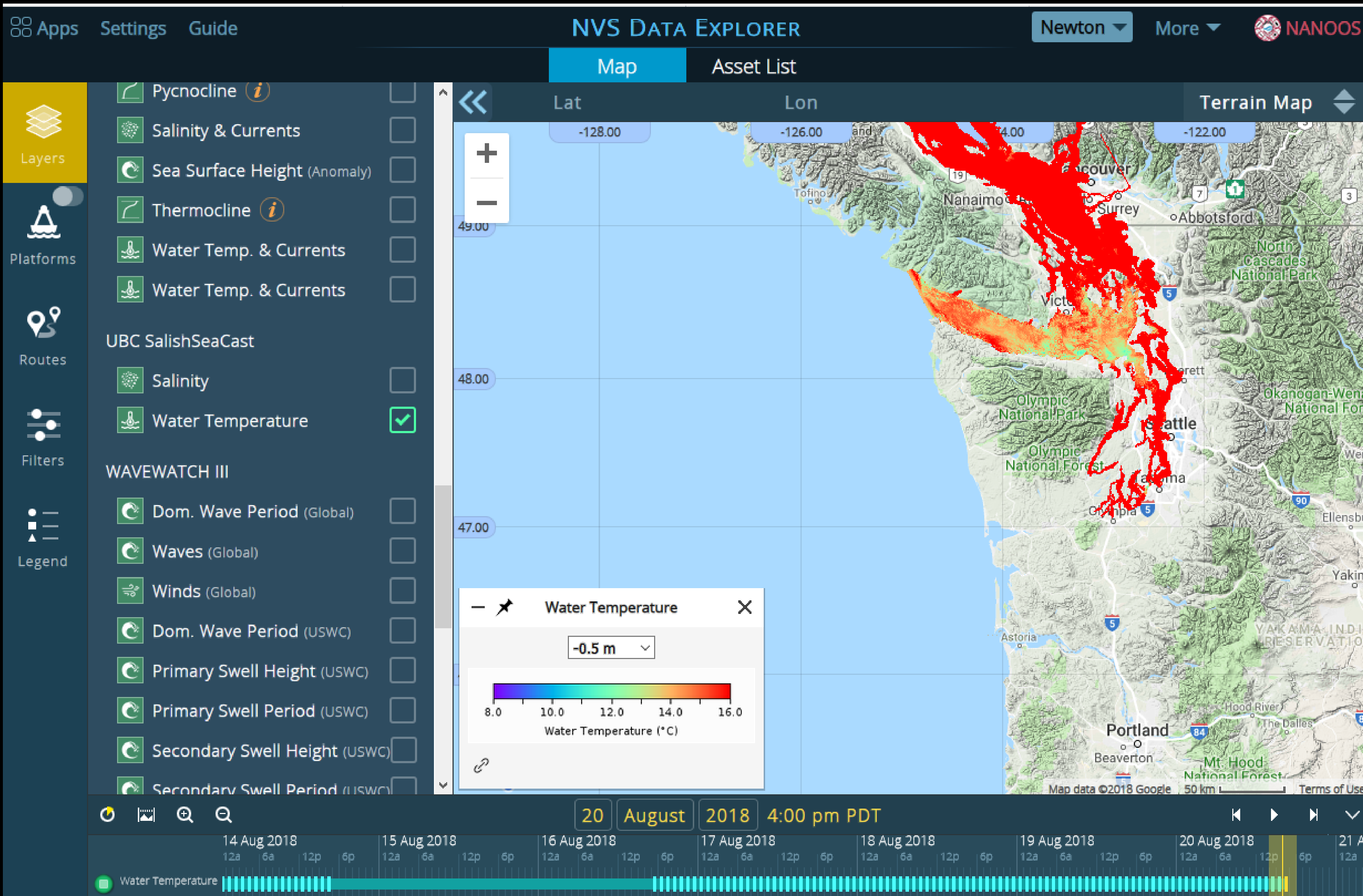
Platforms
Routes
Filters
Legend
Currents
Salinity
Water Temperature
LiveOcean
Aragonite Saturation
Nitrate Concentration
Oxygen Concentration
pH
Phytoplankton
Salinity
Water Temperature
N. Amer. Mesoscale (NAM)
Air Temperature
Barometric Pressure
Relative Humidity
Wind Gust
Winds
Lat
Lon
Terrain Map
-128.00
-126.00
-122.00
49.00
48.00
47.00
Water Temperature
-3 m
8
11
13
16
18
Water Temperature (°C)
Nanaimo
Surrey
Abbotsford
Olympic National Park
Olympic National Forest
Portland
Beaverton
Mt. Hood National Forest
Map data ©2018 Google
50 km
Terms of Use
20
August
2018
4:00 pm PDT
21 Aug 2018
22 Aug 2018
23 Aug 2018
Water Temperature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Legend
Pycnocline
Salinity & Currents
Sea Surface Height (Anomaly)
Thermocline
Water Temp. & Currents
Water Temp. & Currents
UBC SalishSeaCast
Salinity
Water Temperature
WAVEWATCH III
Dom. Wave Period (Global)
Waves (Global)
Winds (Global)
Dom. Wave Period (USWC)
Primary Swell Height (USWC)
Primary Swell Period (USWC)
Secondary Swell Height (USWC)
Secondary Swell Period (USWC)
Lat
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Terrain Map
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Nanaimo
Surrey
Abbotsford
Tofino
North Cascades National Park
Olympic National Park
Olympic National Forest
Seattle
Okanogan-Wenatchee National Forest
Ellensburg
Yakima
Astoria
Yakama Indian Reservation
Hood River
The Dalles
Portland
Beaverton
Mt. Hood National Forest
Water Temperature
-0.5 m
8.0
10.0
12.0
14.0
16.0
Water Temperature (°C)
Map data ©2018 Google
50 km
Terms of Use
20
August
2018
4:00 pm PDT
14 Aug 2018
15 Aug 2018
16 Aug 2018
17 Aug 2018
18 Aug 2018
19 Aug 2018
20 Aug 2018
Water Temperature


Thank you !