

Appendix 1.

Extent of the range of marine habitat types in Puget Sound (1)

By Bryan Palmer and Scott Stcherbinine

Sub-Step 1A

The primary conceptual framework we used to identify the major structural elements and processes of the state of the Puget Sound social-ecological system and to identify its key attributes was the Heinz Center 2008 framework noted Table 1 in the (WSAS 2012). We selected this conceptual framework instead of other options because it most closely resembled our initial brainstorm ideas concerning our geodesign goals.

Washington State Academy of Sciences. (2012). Sound Indicators: A Review for the Puget Sound Partnership. p.17. http://www.washacad.org/about/files/WSAS_Sound_Indicators_wv1.pdf.

Heinz Center, The H. John. (2008). The state of the nation's ecosystems 2008: measuring the lands, waters, and living resources of the United States. Island Press.

Sub-Step 1B

Other conceptual frameworks we reviewed were the SAB framework (WSAS 2012) and NRC (2000) framework (WSAS 2012). We were very impressed by the detail of the biotic condition section of the SAB framework. We were also impressed with the level of detail provided by the section in the NRC framework titled 'extent and status of ecosystems' on the diversity of total species and native species.

Washington State Academy of Sciences. (2012). Sound Indicators: A Review for the Puget Sound Partnership. p.17. http://www.washacad.org/about/files/WSAS_Sound_Indicators_wv1.pdf.

U.S. Environmental Protection Agency. (2002). A framework for assessing and reporting on ecological condition: An SAB report. U.S. Environmental Protection Agency Science Advisory Board, Washington, D. C. (Eds.) Young, T. F., & Sanzone, S. EPA-SAB- EPEC-02-009.

National Research Council. (2000). Ecological indicators for the nation. Washington, D. C.: National Academies Press.

Sub-Step 1C

The key attributes we chose to focus on for our indicator was Estuarine habitat types in the Puget Sound region, Estuarine Intertidal habitats, Estuarine Subtidal habitats, and Estuarine Deep Water habitats.

Sub-Step 2A

Our key attributes are the Puget Sound estuarine habitats as described by MN Dethier in 1990 and 1992. Our intertidal and subtidal indicators are selected from the diagnostic species documented by Dethier. We decided to select our deep-water indicators based on the recommendations in the Washington State Academy of Sciences Committee Review. "Orcas, Salmon (Chinook Salmon) and Pacific Herring – all are predators but occupy different levels in the food chain. Southern Resident Orcas prey primarily on Chinook Salmon and the salmon prey on Herring. Herring in turn prey on smaller zooplankton such as Copepods" (WSAS 2012).

Washington State Academy of Sciences. (2012). Sound Indicators: A Review for the Puget Sound Partnership, III. D. 3. Marine and Terrestrial Species Indicators, p. 54.
http://www.washacad.org/about/files/WSAS_Sound_Indicators_wv1.pdf

Sub-Step 2B

The current estuarine (marine) extent indicators are based on the absence/presence of just a few species such as 'eel grass'. The Puget Sound shoreline is a collection of many very unique and separate habitats as outlined by Megan N. Dethier in 1990 and 1992. To accurately portray the entire Puget Sound assortment of habitats it is necessary to select an appropriate indicator species for each. Eel grass is not a primary indicator species to represent all of them. Our conceptual framework will encompass a unique set of indicator species for each habitat. We embraced the classification system described in the white papers listed below by Megan N. Dethier.

Dethier, M.N. (1992). Classifying marine and estuarine natural communities: an alternative to the Cowardin system. *Natural Areas Journal* 12(2):90-100.

Dethier, M.N. (1990). A Marine and Estuarine Habitat Classification System for Washington State, WASHINGTON STATE DEPARTMENT OF Natural Resources. http://www.dnr.wa.gov/Publications/aqr_nrsh_marine_class.pdf

Sub-Step 3A

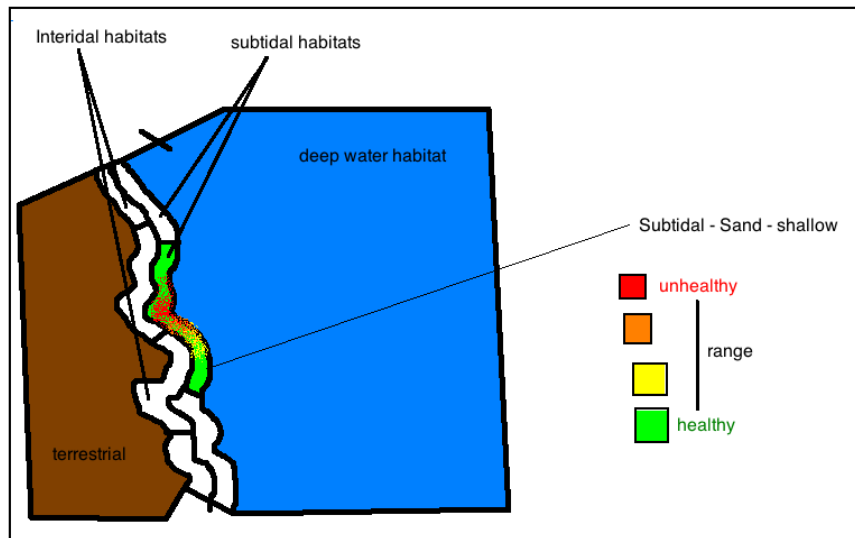
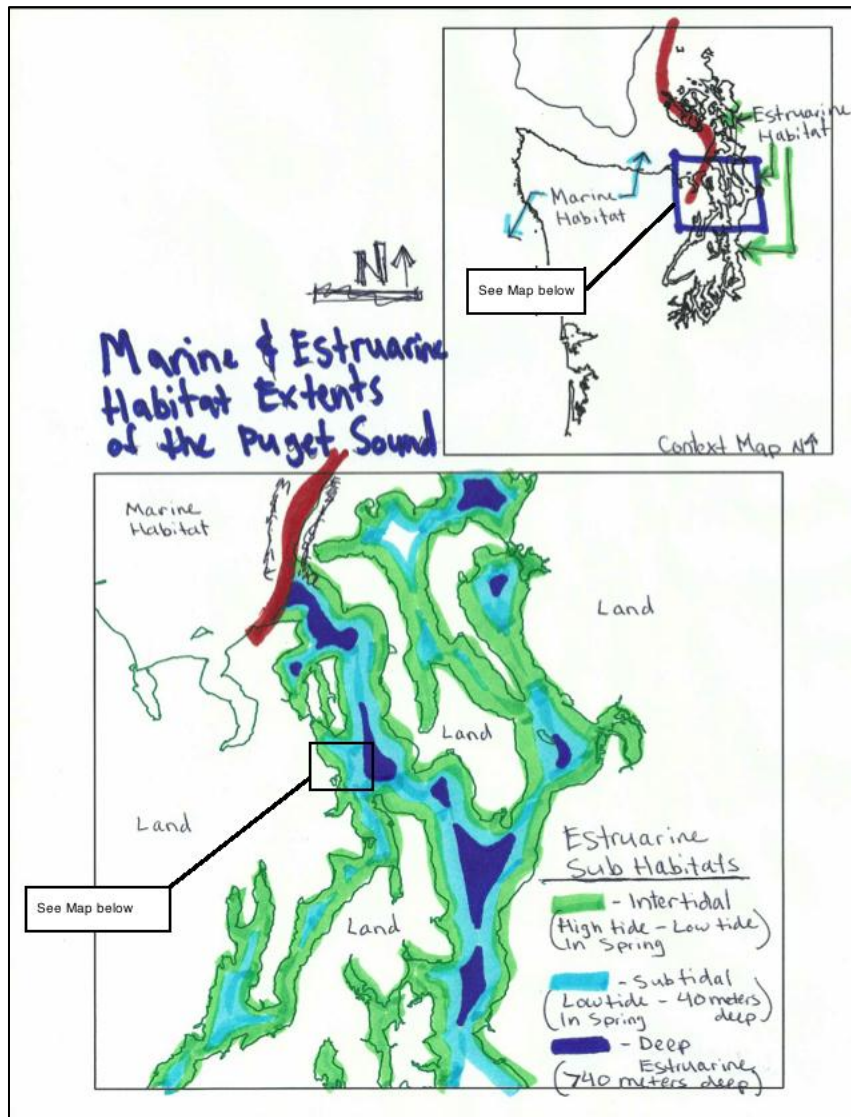
It is important to understand that each habitat has its own species indicators. The metric we are using for relevant measures are presence/absence, abundance, and/or health of the indicator species within these habitats. All of these metrics can be used to represent the state of these habitats. Surrounding natural phenomena and human activity (*drivers*) of the Pacific Northwest are constantly impacting the water quality, air quality, and sediment quality (*pressures*) in these habitats positively and negatively (*state*). Our conceptual framework (*response*) could help the Puget Sound Partnership develop a more appropriate strategy to monitor this complex social-ecological system.

Sub-Step 3B

It is our recommendation that each unique habitat be given its own relevant measure as described by scientists and professional researchers. Each habitat needs to be analyzed exclusively as its own niche in nature. MN Dethier's papers from 1990 and 1992 are exhaustive classifications of the Puget Sound region. It was recommended in the Washington State Academy of Sciences Review that the MN Dethier 1992 white paper be used as a baseline for creating a better indicator set for estuarine (marine) extent. It was realized early on in our research that these papers are ideal in scope with their level of detail. We believe the current indicators chosen by the Puget Sound Partnership lacks an understanding of the complexity of the Puget Sound intertidal and subtidal environments.

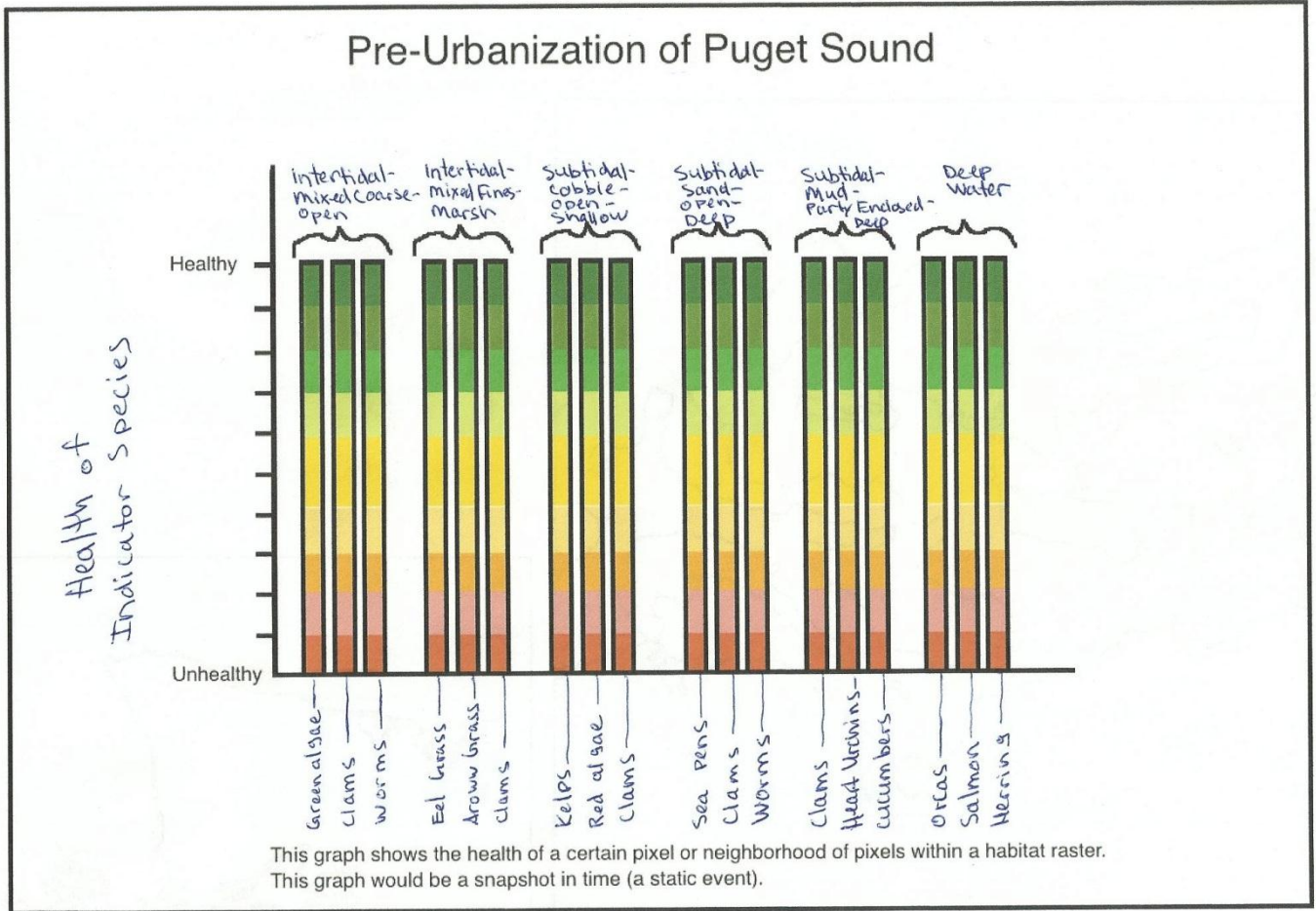
Sub-Step 3C

The hand drawn maps and digital paintbrush sketch below is an example of how our conceptual framework would depict a single habitat 'end product' from an ArcGIS computation. The first two map sketches show the dividing line between the two main habitat extent classifications, marine and estuarine. (Dethier 1990) The Puget Sound estuarine habitat classifications intertidal, subtidal, and deep marine are shown as green, light blue, and dark blue respectively. The digital paintbrush sketch is a close-up of the shoreline illustrating intertidal and subtidal polygon boundaries. One habitat shows a color ramp reflecting the health of its unique species indicators pixel by pixel.

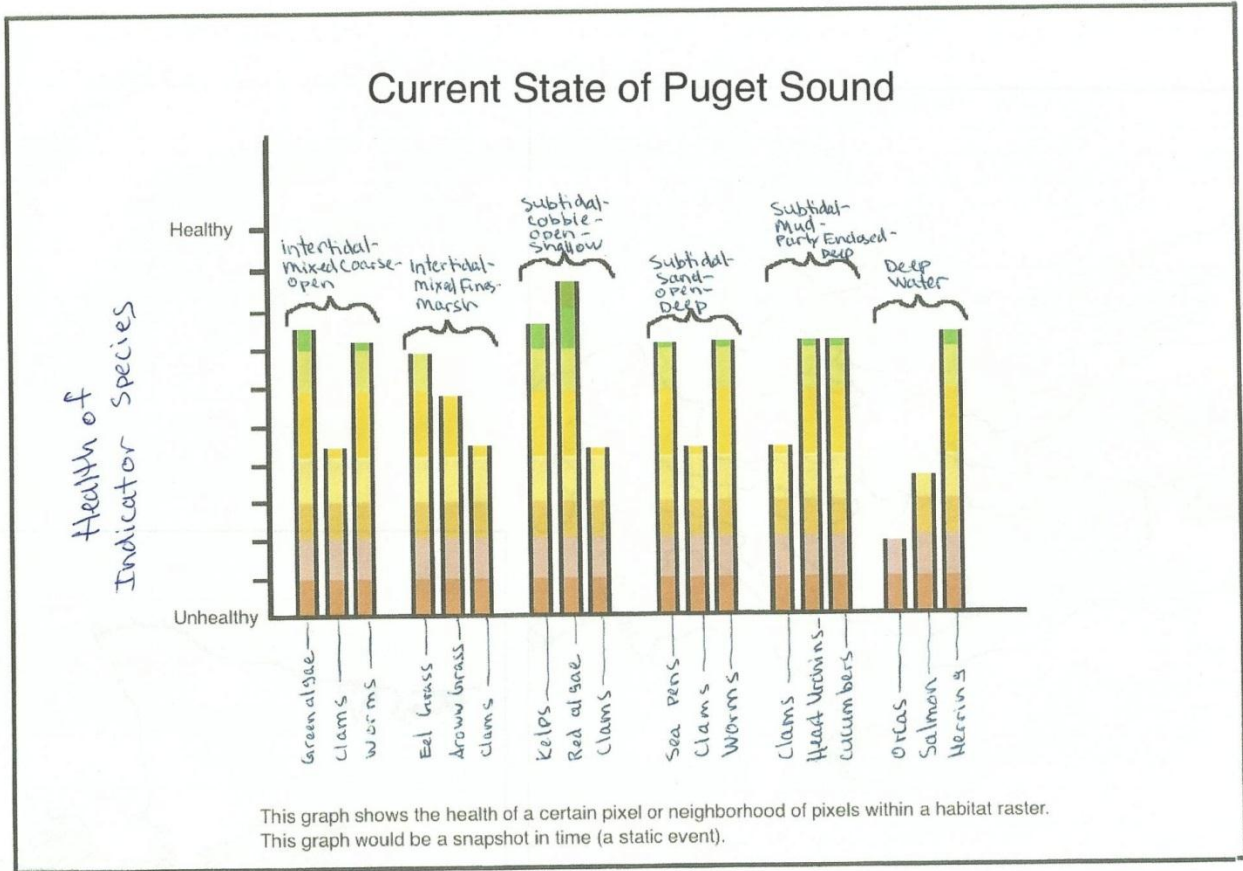


Sub-Step 3D

We created a multi-bar graph showing the selected indicator species health for each habitat for two different snapshots in time representing past historical condition and present context (pre-urbanization



and current state).



Sub-Step 3E

The representations that we have created to implement our solution was conceptual. In the maps and graphs we have provided we show a sample area of the Puget Sound region and how it would look after running it through our computational solution. For our computational solution to work properly we would need extensive and comprehensive data sets.

The datasets that our conceptual framework would require for a computational solution within in a GIS change model are listed as follows:

- 1) Indicator species extents/health polygons or rasters
 - collection from federal, state, local, tribal, educational institutions, and private agencies
- 2) Habitat classification polygons
 - a) created from buffers of DNR shorezone classifications and/or USGS DEMs
 - b) subtidal dataset polygons/rasters from SONAR/LIDAR Batelle Science lab maps
- 3) Habitat air, water, and sediment quality attributes
 - collection from federal, state, local, tribal, educational institutions, and private agencies

We created our sample area Map 1B using the geographic extent of certain estuarine habitat classifications that we created for our conceptual framework shown in Table 1 and illustrated in Figure 1 and Map 1A . The first step of our computational solution would require polygons representing the geographic extent of each estuarine habitat of Puget Sound. We would then need to convert these shapefiles to rasters. In the second step we would use extensive and comprehensive species indicator

rasters depicting their health. We illustrate this with a present context polygon map (Map 1C) of our sample area in the Puget Sound showing shellfish health. In the third step we would reclassify (Spatial Analyst tools-Reclass) the habitat raster pixels with the most sensitive indicator species either for the whole habitat area or for individual pixels dependent on the complexity of the indicator (Figure 2). A red/green color ramp on the raster would show the *health* of each pixel within the Puget Sound Estuarine habitats. In the final step our end product would be a mosaic of rasters that would contain a green/red color ramp of pixels representing the health of the estuarine habitat indicators (Figure 3). We illustrate this with our sample area of the Puget Sound in Map 1D.

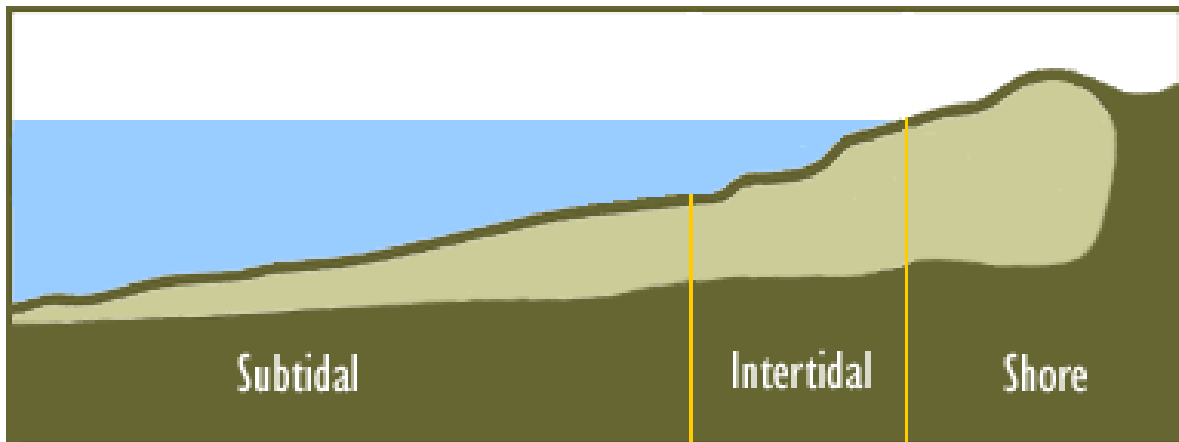
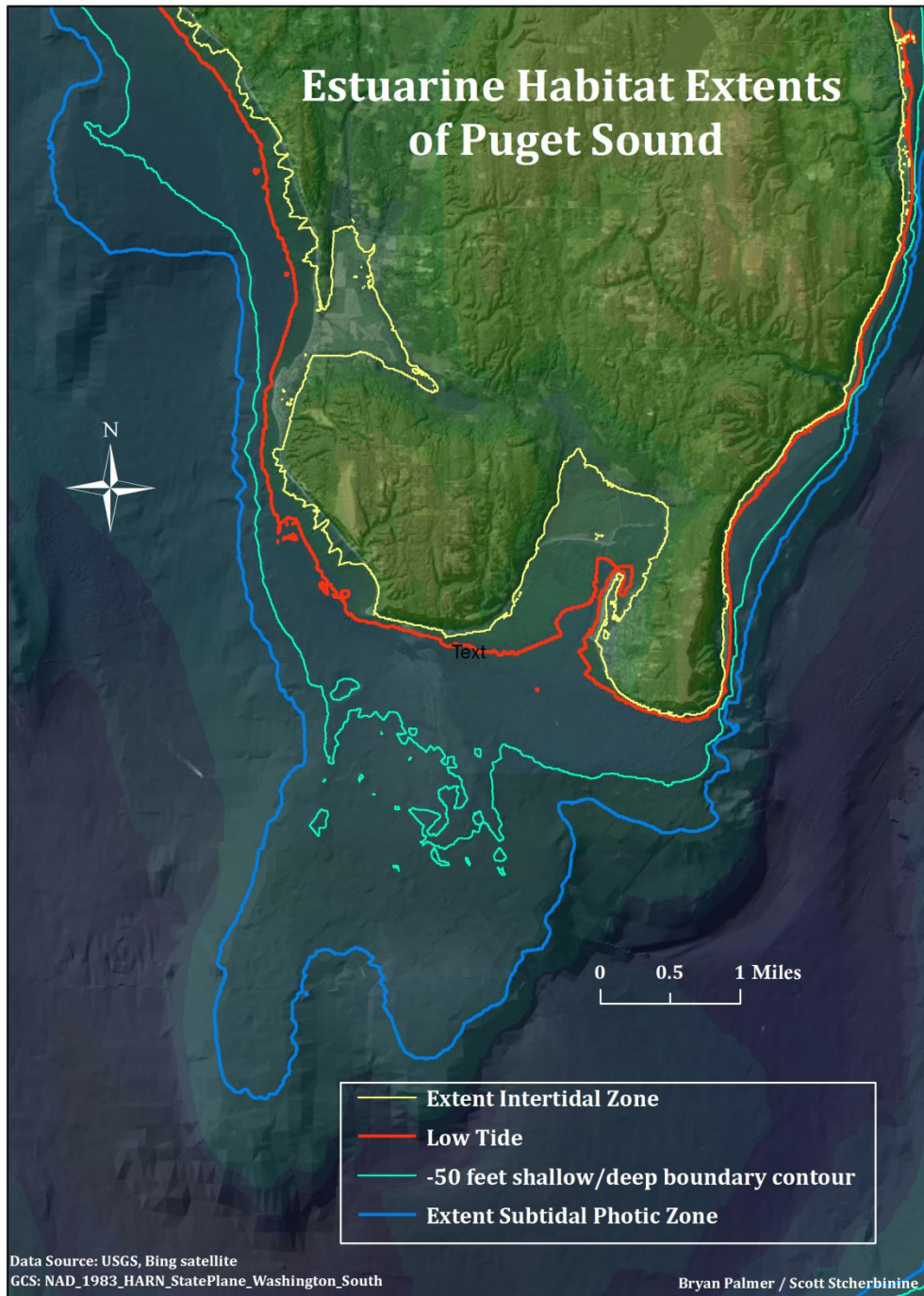
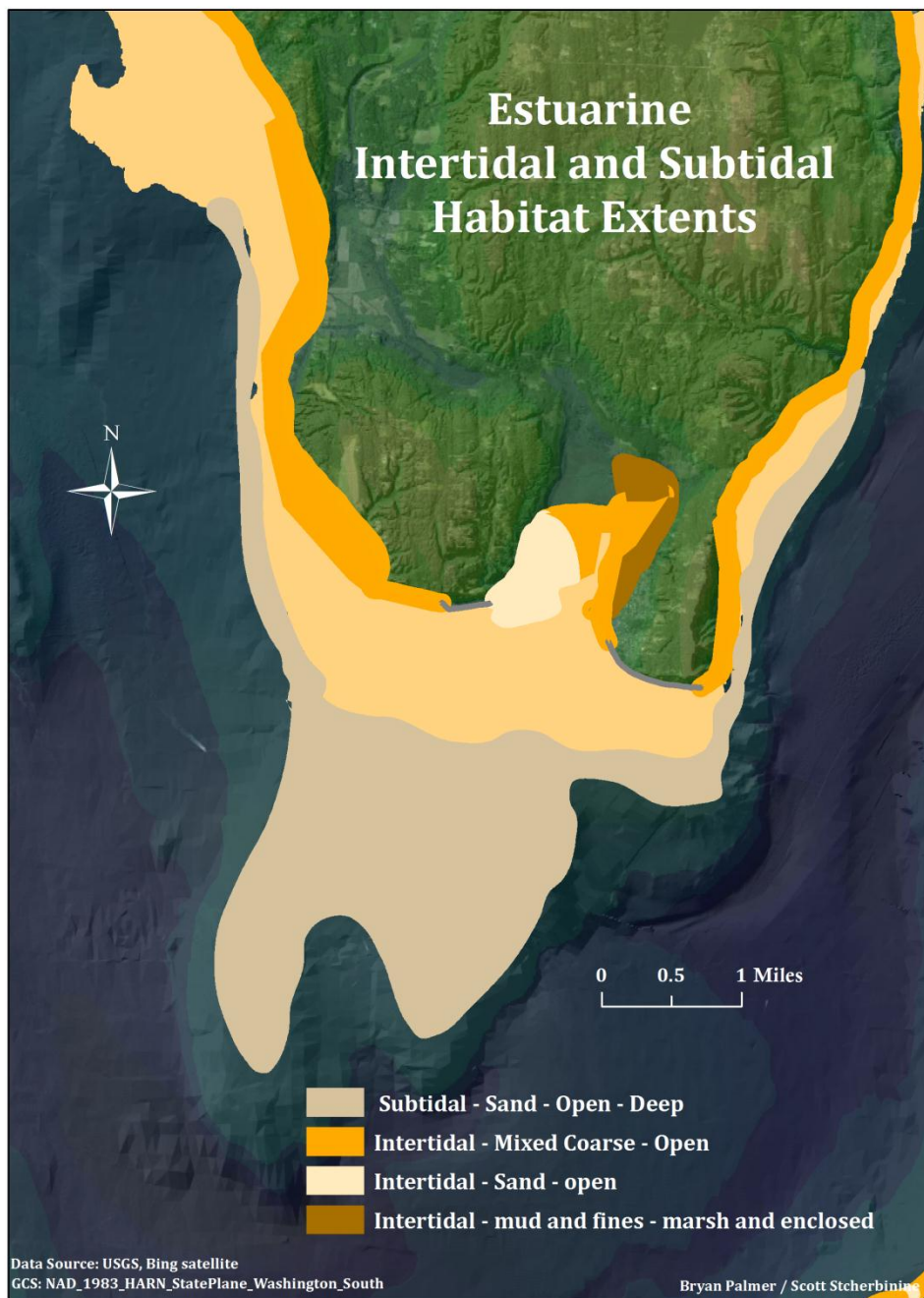


Figure 1 – Washington Department of Fish and Wildlife



Map 1A



Map 1B

Puget Sound Estuarine Extents				Indicator Species		
Habitat	Sub-habitat	Sub-sub-habitat	Sub-sub-sub-habitat	Common Name	Latin Name	
Intertidal	Rock	Open		furoid and red algae		
	Hardpan	Open		mussels		
	Mixed-Coarse	Open			clams	Petricola, Zirfaea, Platydora
					Green ulvoid algae	
	Gravel	Open			worms	Macoma inquinata, Protothaca staminea
					isopods (burrowing crustaceans)	Exosphaeroma inornata
	Sand	Open			worms	Phoronopsis harmeri, Notomastus tenuis, Mediomastus capensis, Owenia fusiformis
					isopods (burrowing crustaceans)	Exosphaeroma inornata
		Lagoon	Hyperhaline (>40 ppt) or Euhaline (30-40 ppt)		worms	Hemipodus borealis, Armandia brevis
					saltwort	Glaux maritima
	Marsh	Eulittoral			umbel	Ulvaopsis occidentalis
					clams	Macoma secta
					eelgrass	Zostera marina
					pickleweed	Salicornia virginica
	Backshore	Oligohaline (0.5-5 ppt)			marsh jaumea/pickleweed	Jaumea carnosa-Salicornia virginica
					pickleweed	Salicornia virginica
					saltgrass	Distichlis spicata
					pickleweed	Salicornia virginica
	Mixed-Fines	Marsh			bulrush	Scirpus americanus
					sedge	Carex lyngbyei
Mixed Fine/Mud	Lagoon	Hyperhaline (>40 ppt) or Euhaline (30-40 ppt)		bulrush (hard stem)	Scirpus acutus	
				cattail	Typha latifolia	
Mud	Marsh and Enclosed			eelgrass	Zostera marina	
				arrowgrass	Triglochin maritimum	
Organic	Marsh/Backshore	Mesohaline (5-18 ppt)		clams	Protothaca, Saxidomus giganteus, Protothaca staminea	
				pickleweed	Salicornia virginica	
	Backshore	Oligohaline (0.5-5 ppt)		marsh jaumea/pickleweed	Jaumea carnosa-Salicornia virginica	
				bulrush	Scirpus maritimus	
Mud	Backshore	Oligohaline (0.5-5 ppt)		arrowgrass	Triglochin maritimum	
				sedge	Carex lyngbyei	
Subtidal	Rock	Open	Shallow (ELWS and 15m)	crustaceans		
			Deep (>15m below ELWS)	eelgrass		
	Cobble	Open	Shallow (ELWS and 15m)		clams	Macoma nasuta, Macoma balthica
			Deep (>15m below ELWS)	bulrush (hard stem)	Scirpus acutus	
	Mixed-Coarse	Open	Shallow (ELWS and 15m)	cattail	Typha latifolia	
			Deep (>15m below ELWS)	gumweed	Grindelia integrifolia	
	Sand	Open	Shallow (ELWS and 15m)	saltgrass	Distichlis spicata	
			Deep (>15m below ELWS)	tufted hair-grass	Deschampsia caespitosa	
		Partly Enclosed	Deep (>15m below ELWS)		silverweed	Potentilla pacifica
					bulrush (hard stem)	Scirpus acutus
	Mixed-Fines	Open	Shallow (ELWS and 15m)	cattail	Typha latifolia	
			Deep (>15m below ELWS)	crustaceans		
	Mud	Open	Shallow (ELWS and 15m)	eelgrass	Zostera marina	
			Deep (>15m below ELWS)	seastars		
		Partly Enclosed	Deep (>15m below ELWS)		sea pens	Ptilosarcus gurneyi
					clams	Astarte sp., Nuculana minuta, Nemocardium centifilum, Megacrenella columbiana
	Deep Water	Channels			worms	Phylichaeopterus prolifica, Chaetozone setosa
					crustaceans (ostracod)	
	Deep Water	Channels			clams (small)	
					crabs (cancerid)	
Deep Water	Channels			shrimps		
				shrimps		
Deep Water	Channels			seapens		
				anemones		
Deep Water	Channels			eelgrass		
				clams		
Deep Water	Channels			snails		
				clams	Macoma nasuta, Mysella tumida	
Deep Water	Channels			worms	Armandia brevis, Glycine picta, Terebellides stroemi, Lumbrineris lutei	
				clams	Aclia castrensis	
Deep Water	Channels			heart urchins	Briaster latifrons	
				cucumbers	Molpadia intermedia	
Deep Water	Channels			crabs (cancerid)		
				shrimps		
Deep Water	Channels			herring		
				salmon		
Deep Water	Channels			orca		

Table 1

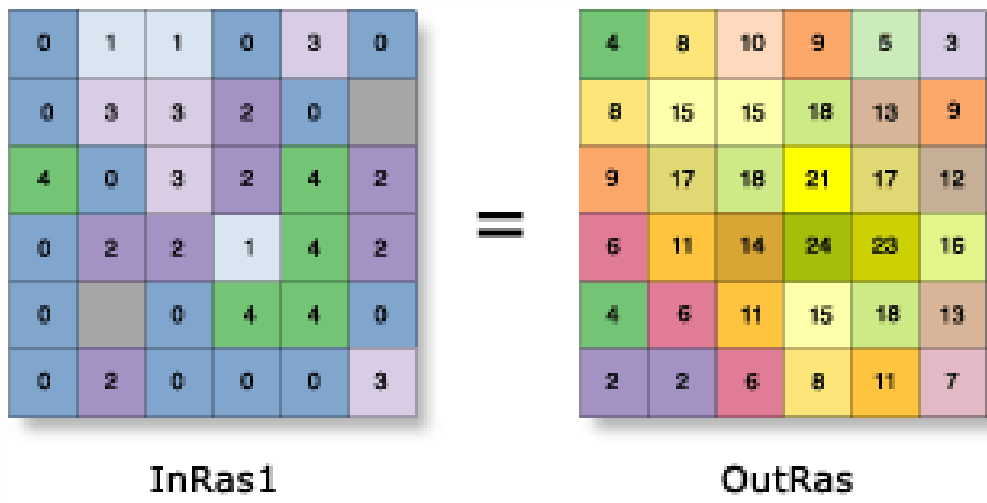


Figure 2

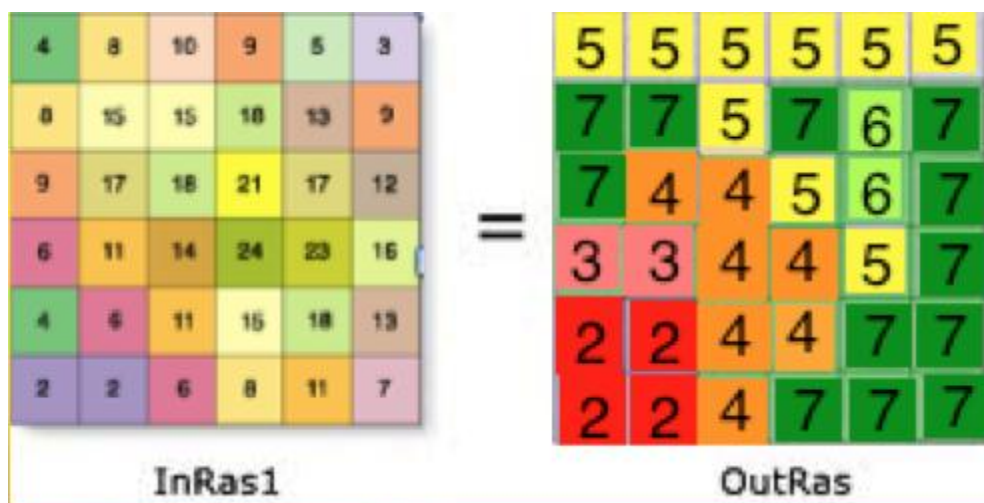
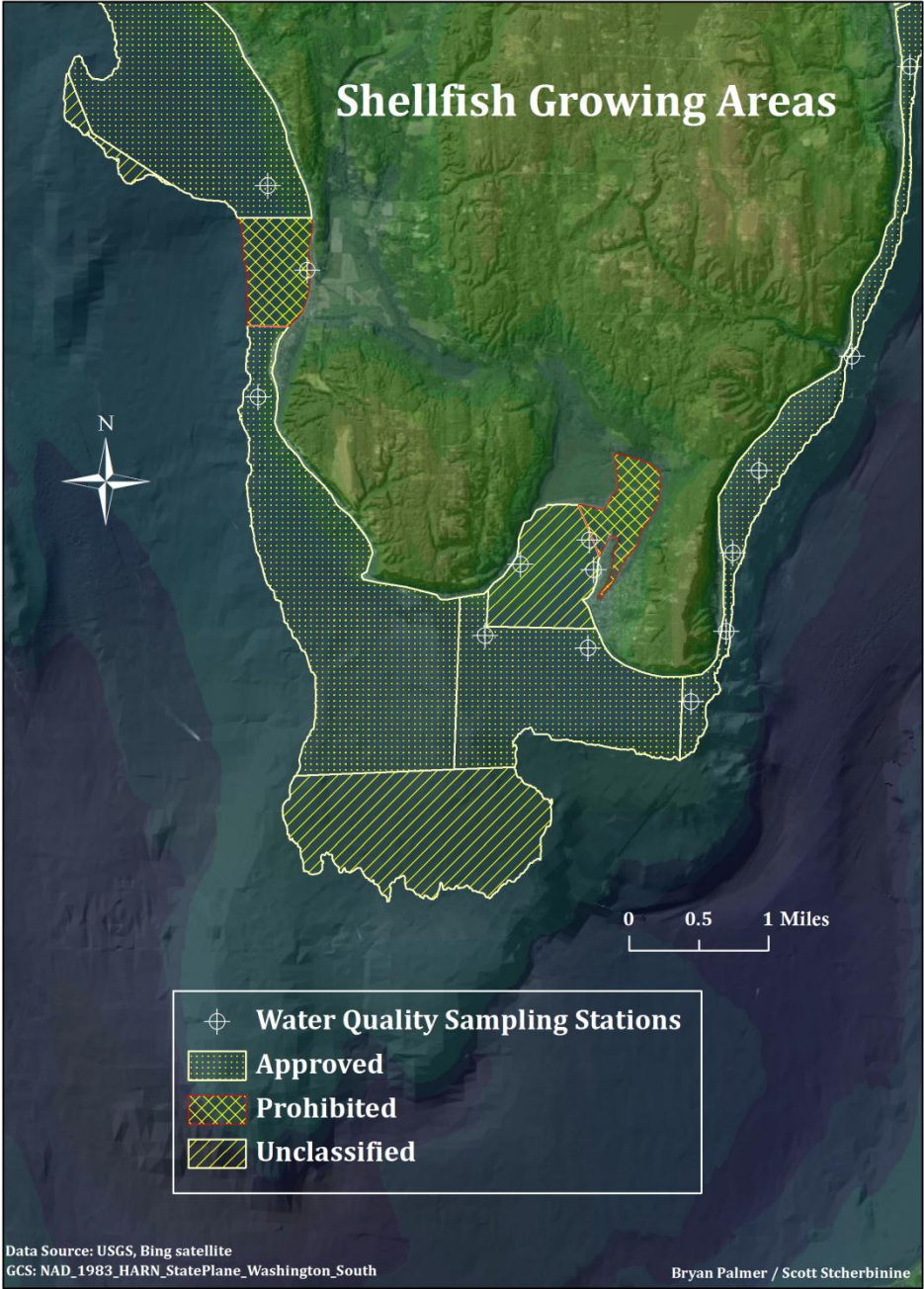
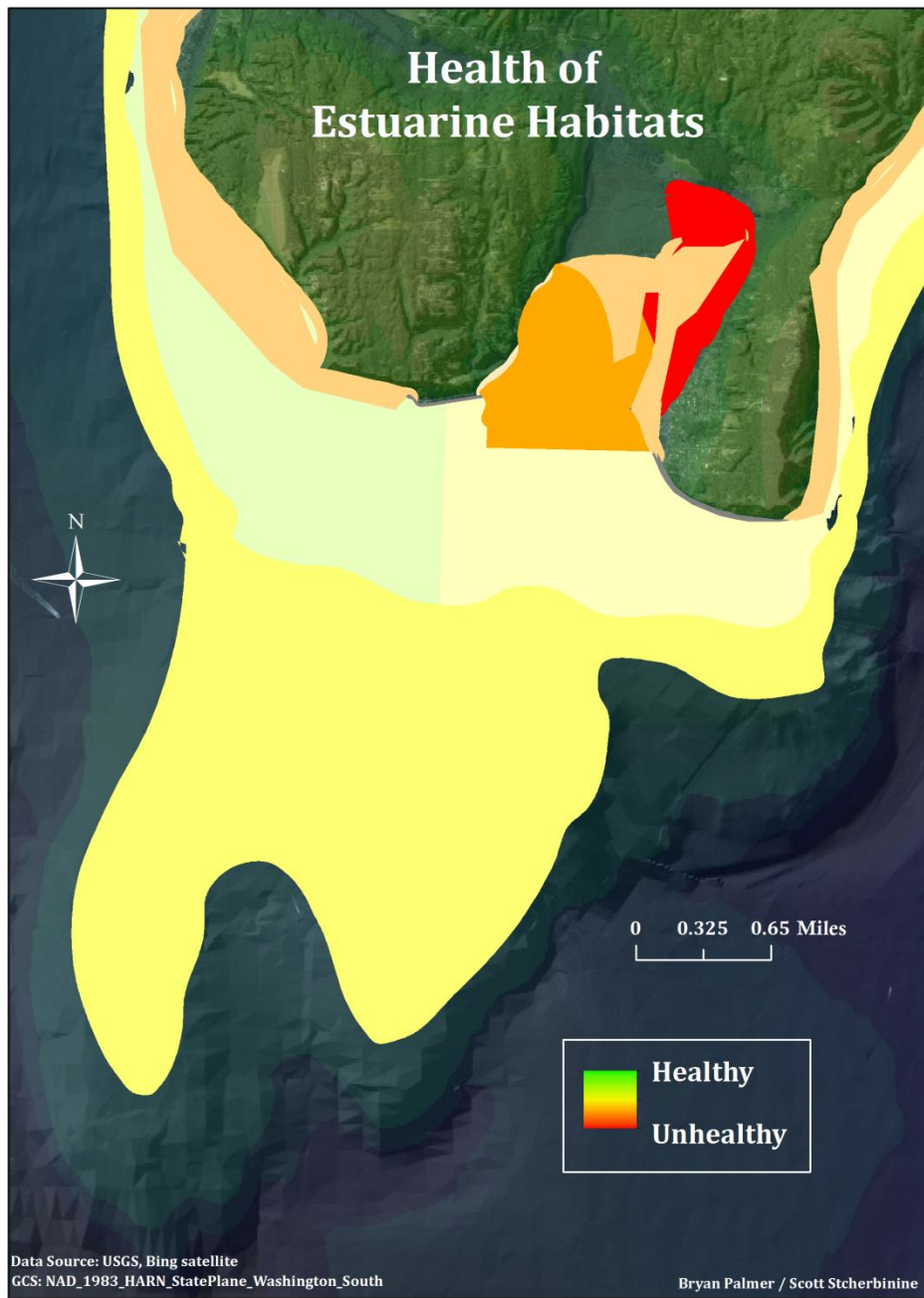


Figure 3



Map 1C



Map 1D

Sub-Step 3F

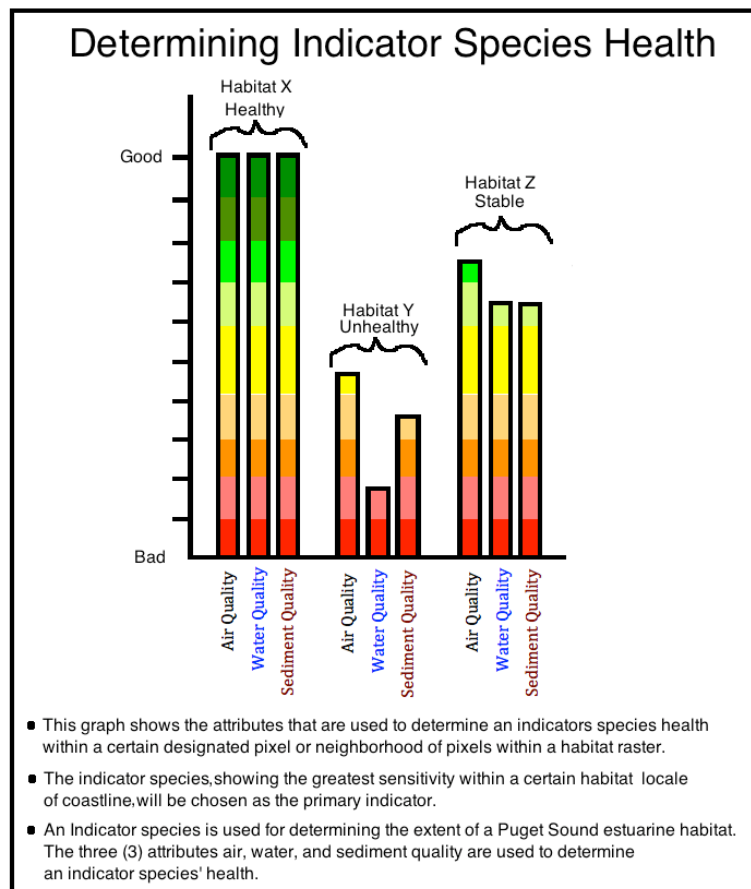
We based our project on a conceptual example area of the Puget Sound due to the lack of extensive and comprehensive datasets available. Our computational solution is a proposal for how to proceed when these datasets become available. Our temporal pattern of interest would be dependent on a pre-urbanization Puget Sound indicator species health compared to the present-day.

Step 4|5|6

Step 4: We evaluated all species within each estuarine habitat of Puget Sound as identified by M.N. Dethier. We decided that each habitat will have a list of diagnostic or common species as primary indicators. The metric for quality of our indicator was health.

Step 5: We evaluated over 200 species for the estuarine habitats of the Puget Sound and narrowed them down to two to three species for each habitat type due to economic reasons and practicality.

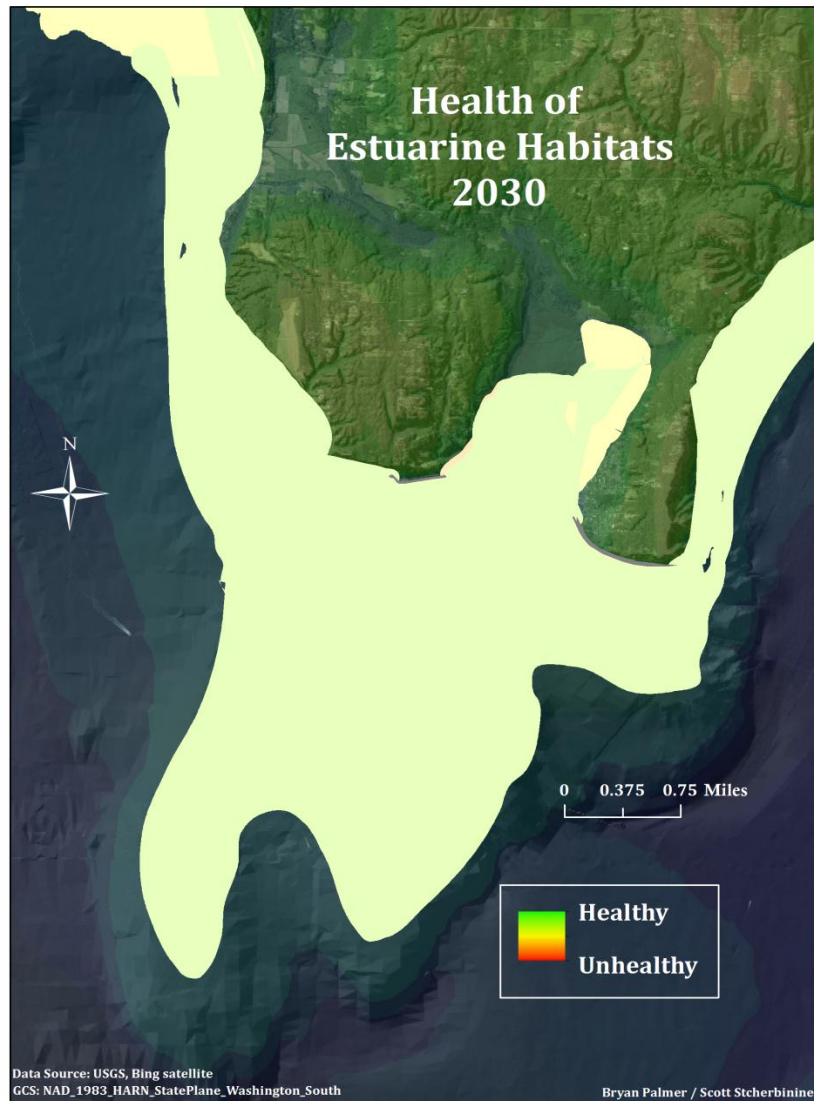
Step 6: Out of the set indicator species for each habitat our computational model depends on selecting the indicator species showing the most sensitivity. This process is very subjective and based on air, water and sediment quality attributes of the indicator species which always changes. This is shown in Graph 3 below.



Graph 3

Sub-Step 7A

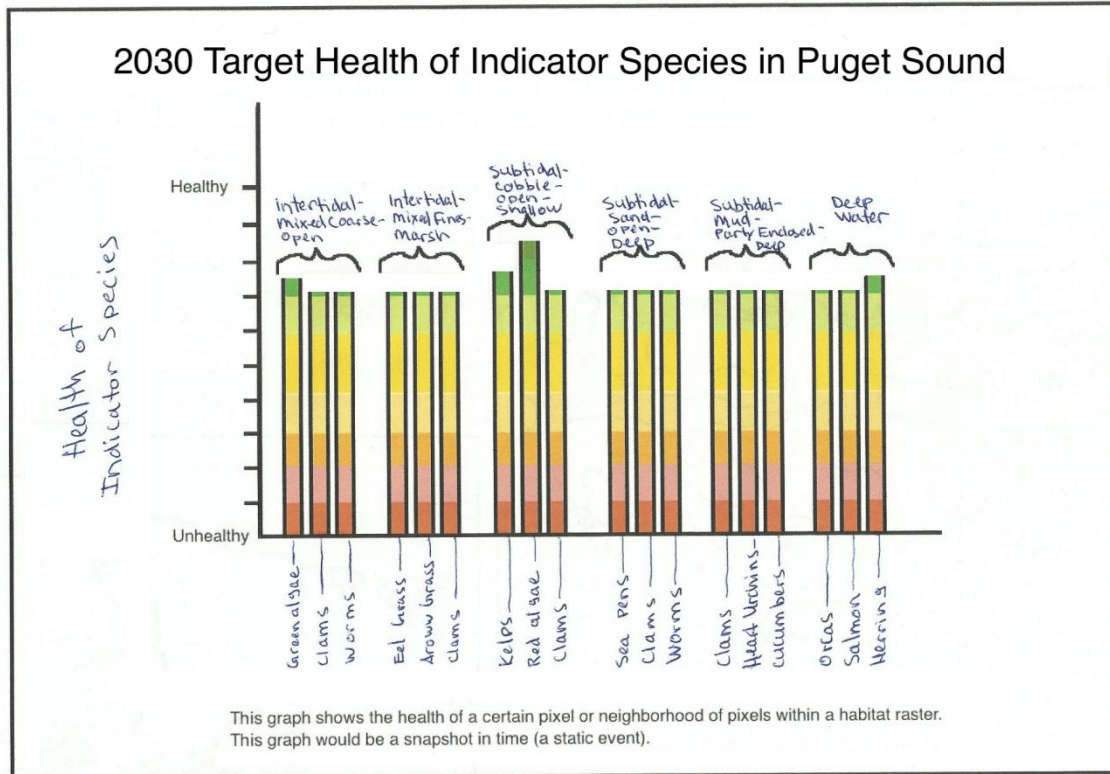
Map 2 differs from Map 1 in that intertidal and subtidal habitats of Puget Sound become healthy and productive environments. This is modeled on the pre-urbanization of the Puget Sound.



Map 2

Sub-Step 7B

The process that must occur for graph 1 to look like graph 2 is the restoration of the indicator species in unhealthy habitat areas. This is accomplished by giving more money to local agencies like the Puget Sound Partnership to develop a greater awareness of the present context concerning the Puget Sound.



Sub-Step 7C

Of the nine case studies noted in Steinitz we selected the Combinatorial Change Model as our primary “Option A” change model and the Constraining Change Model as our secondary “Option B” change model. We selected these two because we were unsure of how the future should look. We chose the Combinatorial Change Model as our primary one because it is most useful for situations where a few main objectives of similar importance are present. This geodesign process first identifies the few most significant requirements of the scenario and then lets these guide the design. This approach works well when the design team is seeking out alternative scenarios of the future and working with limited time. The Padova, Italy case study also used this approach and mirrored our project by dealing with issues of time and complex systems that needed to be condensed. Since we had no preconceptions as to how the final design was to look, we selected the Constraining Change Model as our secondary change model. This approach would be useful if our conceptual framework was to be implemented by a committee or through a participatory process which included experts in their own field with possible graduate students. The Cagliari, Sardinia, Italy case study for this change model approach was also completed in a tight time frame and set up under the structure of a five day workshop. Many variables were decided ahead of time including the decision to go with a Constraining Change model approach.

Appendix 2.

Extent of the range of marine habitat types in Puget Sound (2)

By Malena Foster and Nathan Teut

Sub-Step 1A

The conceptual framework that seems to be the most detailed while also being non-confusing is the framework proposed by Levin et al. (2011) in the Puget Sound Science Update. In this document, the authors adhere to the Drivers, Pressures, States, Impacts, and Responses (DPSIR) model originally cited by O'Neil et al. (2008). Levin attempts to use this common framework to determine indicators of the ecological system of Puget Sound through the recognition of the Puget Sound Partnership's (PSP's) stated goals, the Focal Components of those goals, and the key attributes that they determine to be of importance to the Focal Components.

The Focal Components in this conceptual framework are Species, Food Webs, Habitats, Water Quality, and Water Quantity. The Key Attributes for these Focal Components are intended to specifically describe the state of the components as follows:

Species: Population and condition

Food Webs: Composition and energy flow

Habitats: Area, condition, and patterns

Water Quality: Hydrodynamics, physical parameters, and trace chemicals

Water Quantity: Surface water, groundwater, and consumptive use and supply

This framework was selected because it focuses on ecological aspects of the social-ecological system. Although human well-being and health are important aspects of the system, identifying the ecological key attributes and focal components in the Puget Sound environment will reflect the human involvement in the focal components themselves. Levin et al. (2011) is also the most up to date description of the PSP activities and goals, and it is cited as a good start for determining indicators in the later Washington State Academy of Sciences (WSAS) Sound Indicators (2012) document, although critiqued extensively.

Sub-Step 1B

We reviewed all the indicated conceptual framework documents provided to the class (Levin et al. 2011, O'Neil et al. 2008, PSP 2008a, Neuman et al. 2009, and PSP 2009). As noted above, the Levin et al. document focuses on ecological factors as the focal components. One item of interest in these other documents describing conceptual frameworks is in the Neuman et al. document where the conceptual framework is instead referred to as the "human-biological-water framework" (pg. 8). Here, the authors report human health and well-being as the first focal component of the model as well as specify that these rely on the viability of a healthy ecosystem. They incorporate human dimensions with the biophysical dimensions and note that they are both dependent on the abundance of clean water. It is important to consider the human element in any framework adopted, including the one by Levin et al. that we have accepted here. It is also just as important to note that the human health and well-being, although discussed by the PSP in subsequent chapters of the Puget Sound Science Update, will be dependent on the functioning of the natural component of the ecosystem. Here, human activities and key attributes are viewed as the pressures (the P in DPSIR model) that act on the key attributes of the ecosystem (represented by Levin et al.'s conceptual framework).

Sub-Step 1C

The Key Attributes relevant to the “Extents of Marine Habitats” work to be done are clearly stated in the conceptual framework under the Focal Component of “Habitats”. These are the area and extent of different marine habitat types, patterns, and connectivity of habitats. These can include descriptions of specific habitat types or extents of species domains, any fractional descriptions or index values assigned to habitat types’ presence or absence, any numerical representation of increase or decrease in abundance(s), patterns of “patches” or connected zones of identical or similar habitat types.

Sub-Step 2A

The key attributes mentioned above are area extent of nearshore habitat types, patterns, and connectivity. Our indicator seeks to involve all three of those things into a single index value to better describe the health of the ecosystem. This index value will mathematically incorporate the presence or lack of several habitat types that marine species like salmon, rockfish, and marine mammals depend on in all areas of Puget Sound. This index will then be able to show what areas of the Sound have greater or lesser variability of nearshore habitat extents compared to other areas when represented in a map format. Any future change in conditions that result in expansion or contraction of habitat extents will affect the index value and demonstrate where and if progress is being made to increase the health of the ecosystem.

Sub-Step 2B

The WSAS recognized in its recommendations of the Puget Sound indicators that land cover uses are often described by percent of cover type in a given area for terrestrial environments. Their recommendation was that more marine habitat extents should be incorporated into the indicator set and an index value or composite would be far more useful than tracking the extent of a single habitat (as in eelgrass, the only habitat extent originally proposed by the PSP Indicator Dashboard)(WSAS 2012, p. 43).

An index value of multiple nearshore marine habitats as an indicator would be more appropriate than some general figure for how much of a single habitat type exists or has been observed. Although a simple increase or decrease in an extent of a marine habitat type could be represented alone, an index showing changes relative to many habitat types in the Puget Sound region would be more useful and interpretable in describing positive and negative changes relative the entire complex marine ecosystem and the region as a whole.

Focusing on one habitat type, like eelgrass, may lead to positive changes in eelgrass habitat extent. However, one must consider that increasing eelgrass extent may decrease another desirable habitat extent. Programs or policies directed at an improvement in a habitat type should take this give-and-take relationship in account. By deriving an index value for the extent and connectivity of several desirable marine habitat types, both positive and negative changes to individual habitat extents are taken into account and can better be related to the effectiveness of programs and public policy.

Sub-Step 3A

The metric for this indicator, as an index, is the known extent of different nearshore marine habitat types in terms of both habitat area coverage and simple presence of multiple varied habitat types in the

different regions and shorezones of the Puget Sound. Species that have already been measured were chosen to evaluate the current habitat conditions. The species of interest are seagrass, kelp, saltmarshes, and sargassum.

The metric will measure the average density of these species across the different shorezones by assigning a value to the presence or absence of a species along the shorezone. An average value from all species of interest given to segments along the shorezone will characterize the relative density of species across the Puget Sound. This will allow for comparison of relative densities and habitat extents of these four species in critical areas.

This measurement represents a “state” variable in the DPSIR framework. State variables represent physical, chemical, and biotic conditions within the ecosystem. The habitat extent indicator represents a physical variable which can be measured within the Puget Sound social-ecological system. Changes in these state variables can then be used to assess impacts overtime. For example, increases or decreases in the habitat extent and density of the species of interest can be measured and compared to target conditions.

Sub-Step 3B

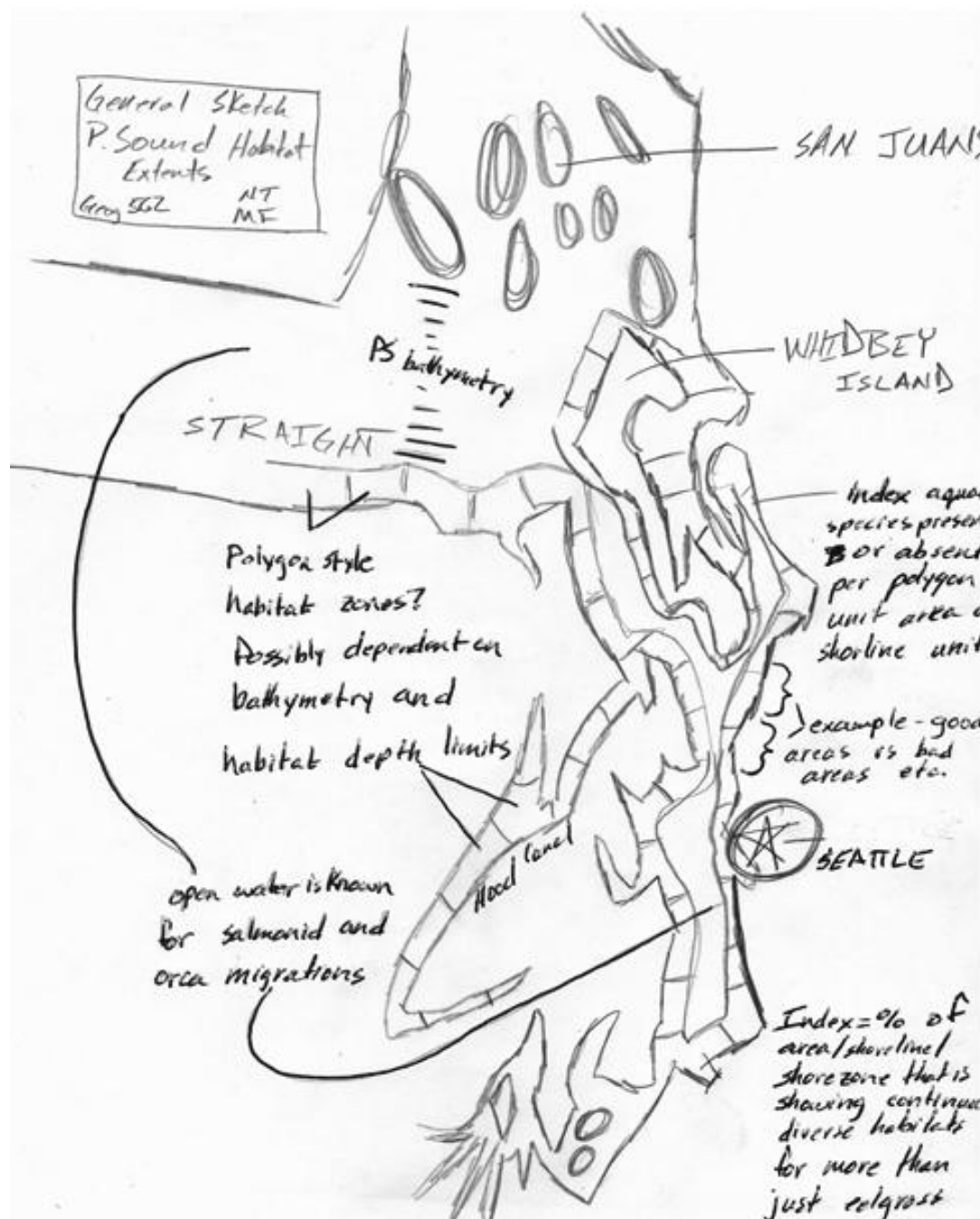
The inclusion of additional measures of nearshore habitat extent in the Puget Sound has been recommended by multiple sources (WSAS 2012, PSP 2009, and Levin et al. 2011) and has been the basis for using the abundance of other aquatic plant life as metrics for a larger variety of marine habitat types represented by an index value indicator. The PSP Action Agenda recommends using eelgrass, kelp and seaweeds, and saltmarshes as indicators of healthy marine habitats (PSP 2008a, p.15). Levin et al. also recommends using eelgrass, kelp, and macro algae as habitat area and pattern indicators (Levin et al., p. 63). The following habitats were chosen for inclusion in the metric based on these recommendations: Seagrass (which is primarily represented by eelgrass), kelp, saltmarshes, and sargassum.

Eelgrass beds have long been noted as the dominant seagrass in Washington, which serves as shelter, food, and breeding areas for fish and wildlife species (PSP 2009) and has already been studied as an indicator by the PSP. While there has been few studies done in the Puget Sound, various kelp species (such as bull-kelp, giant kelp, and non-floating kelp) have been noted as providing an extensive amount of primary habitat in marine shores around the world, by being consumed directly, providing shelter for small organisms, and by providing a source of carbon, and thus has been recommended as an indicator by the PSNERP (Mumford, 2007). The extent of saltmarshes is also valuable here as saltmarshes are areas of marine wetlands providing yet another unique habitat opportunity in the intersection between marine and terrestrial life. Saltmarshes found near seagrass beds share plant and animal communities and have been identified as indicators of change in coastal environments in Australia (Dale et al, 2012). Sargassum has also been added to the index despite being identified as an invasive species in the Puget Sound. Sargassum was introduced in the 1920s and has slowly encroached on native seagrass and kelp beds in Puget Sound. While it is invasive, the habitat does still provide spawning habitat for Pacific Herring, grazing amphipods, and other small creatures (WCMRC, 2005). The encroachment has also become significant at an estimate 22% of the Puget Sound Shorezone based on the dataset described below. While the species is invasive, it still contributes significantly to the total nearshore marine habitat.

The additional species of plants to seagrasses will create habitat and cover for fish, invertebrates, and marine mammals. These species each provide unique cover and foraging opportunity for the other

marine life in the Sound. While the different seagrasses and macro algae will provide different habitats for some species exclusively, there will also be cross-over between species. For this reason, significance is not distinguished between individual species, but incorporated as a whole and diversity of species in an area is considered more valuable to multiple habitat needs.

The inclusion of an average-of-habitats index value as an indicator provides a baseline of multiple habitat extent and densities across Puget Sound. A higher average value denotes a more diverse and denser habitat in a given shorezone segment. Other possible measures included: determining the extent of the dominant species within a cell across a gridded area, and including the extent of individual species habitat as separate areas. The measures of a gridded index value would show the presence of a dominant species in the area but was rejected because this measure would not show continuity between habitats or the presence of multiple habitats in given area. The measure of the extent of individual species habitats would be an ideal measurement. However, since the goal was to provide a measure of the extent of all habitats of interest, the measure of an average value demonstrates the overall extent of diverse habitat versus looking at individual habitat sets at one time.

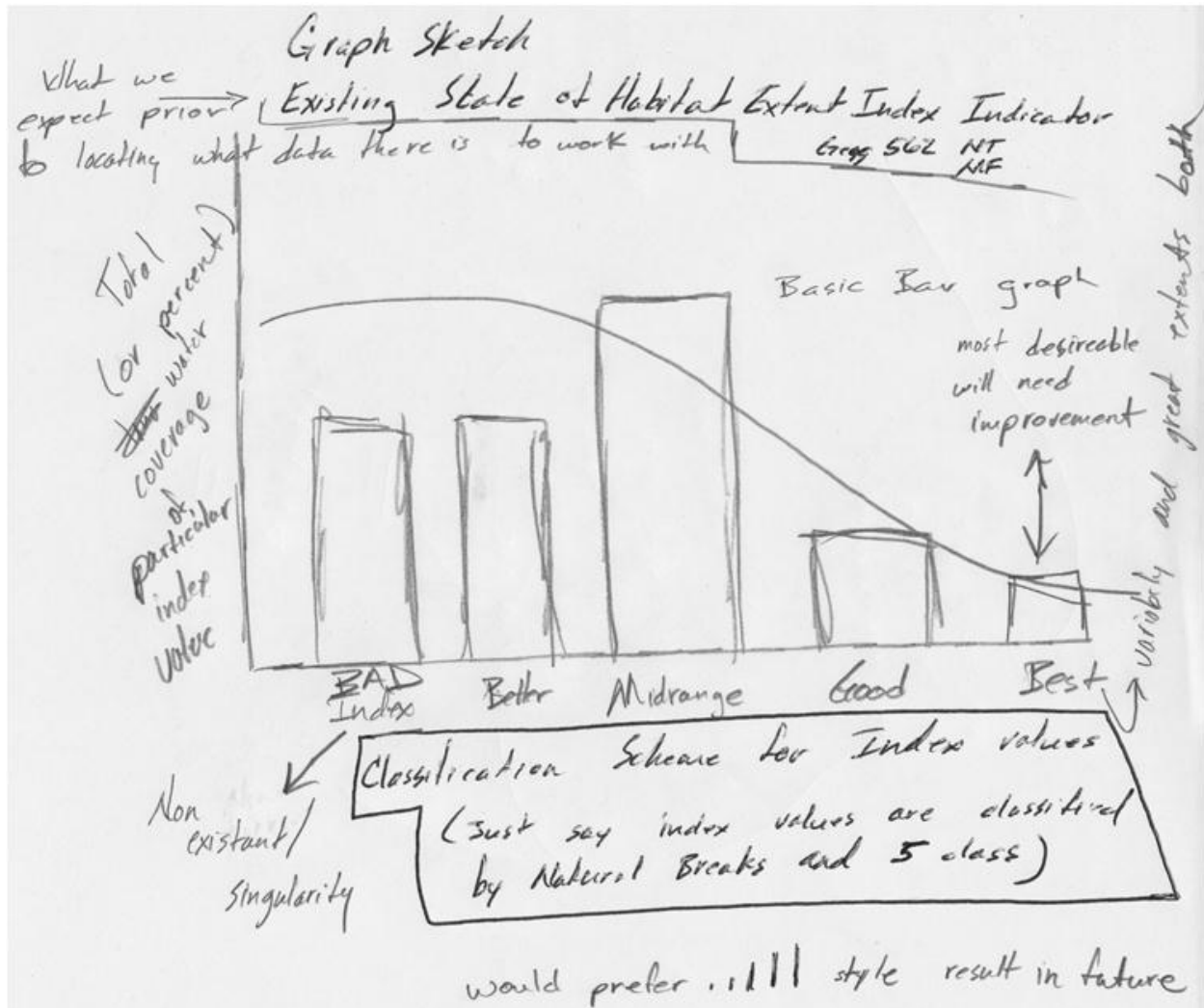


Sub-Step 3C: MAP SKETCH

The rough sketch of a habitat extent indicator shown above is meant to display how an index value can be displayed over the region. It is expected (assuming that we can find existing data) that the nearshore zones where the depths are sufficiently shallow will exhibit some extent of the different habitat types focusing on vegetation and saltmarshes. These extents can be observations or lack of observations (present or absent) and data on acreage or square miles of extent as polygon data.

This sketch is meant to demonstrate possible data without actually attempting to locate the data from sources like Dept. of Ecology and Dept. of Natural Resources yet. The indicator index values can be symbolized as categories or classes. A hypothetical example could be that the index values are calculated using presence or absence, acreage or square miles, and averaged out over the number of species and habitats included in the study. The actual index we create will be expanded on and explained in the next questions/segments of this document. Then, for each unit of area delineated, the index can be shown as classifications and displayed similarly to a choropleth map, or as units or segments of shoreline and shorezone. Logically, red colorations would be used to display areas of poor index values compared to greens for better index value areas. The final idea would be that managers and policy makers could then better gauge the health of the ecosystem by seeing an index of different habitat extents throughout Puget Sound, and subsequently use that information in deciding where and how to direct improvement programs.

Sub-Step 3D



The index value proposed as an indicator of habitat extents would be representable in a map as classifications of comparable value ranges. The ranges of the index can then be assumed to be “Bad” or “Worst” case up to “Good” or “Best” case. The graph gives the indication of just how much area or extent falls into the lower end of the index value versus the higher end desirable values. This is much more difficult to pinpoint just by examining the map. Although the graphic representation on a map may give the viewer the impression that a certain class grouping might dominate over the others, the graph is where one can see the actually quantified comparison where ‘x’ percent of areas surveys score a “Bad” value whereas ‘y’ percent of areas surveys score a “Good” value.

In a perfect world, with lots of available data, the ideal graph could show a temporal change along the lines of having a bar for many successive time periods or decades. This would show change over time, which could be alarming or more subdued than one might expect. Currently, this in depth historical data is probably not available; however, this temporal change idea can be carried into the future to show improvements or degradations over time. For example, a graph could have this index value

information presented here as “year 1” and over the next ten or twenty years, add bars, and gradually create meaningful temporal changes. With the Puget Sound Partnerships general goals for improvement by 2020, the temporal scale here would yearly if data can be collected that fast and display any meaningful changes.

Sub-Step 3E

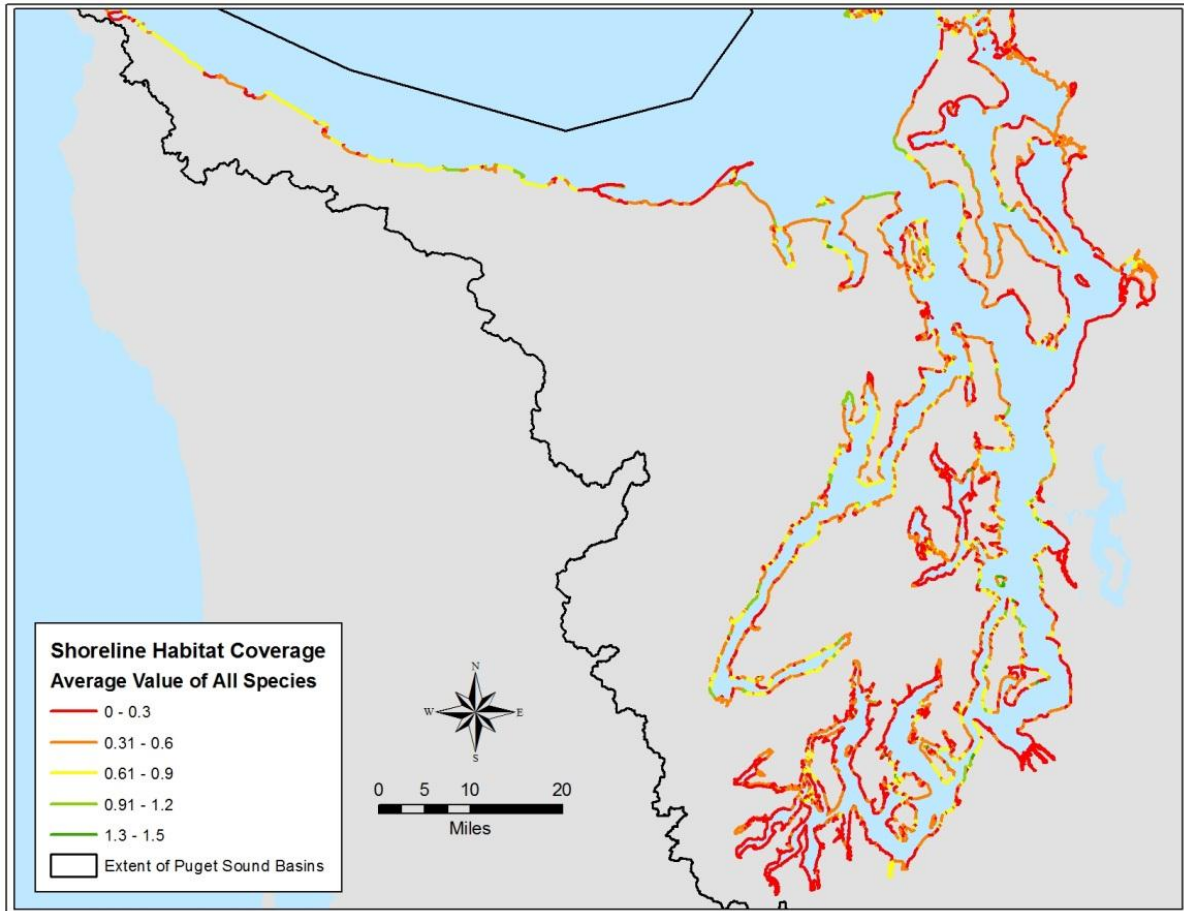
Due to the lack of surveyed extent data, data from the Washington Department of Natural Resources ShoreZone program was used, represented as lines along the shoreline of the Puget Sound. The lines were clipped to the Puget Sound region as defined by Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). In order to calculate the index value, attribute operations were performed to combine the four habitat types. Each line segment had a corresponding habitat represented as either “absent”, “patchy”, or “continuous”, which were assigned the values of 0, 1, or 2, respectively, as shown in the table below:

Original Designation	Value
Absent	0
Patchy	1
Continuous	2

Each value was averaged across the four species of interest for each line segment and a final index value was calculated based on the following equation:

$$\text{Index Value} = (\text{SeagrassValue} + \text{KelpValue} + \text{SargassumValue} + \text{SaltmarshValue})/4$$

Where each “HabitatValue” is either a 0, 1, or 2 based on how the representation of the original line segments. For example, if all species were present in a given line segment with a “continuous” value of 2, the resulting average would be a 2. This would be an ideal but hardly likely situation given that one species may crowd out another species. If no species were present, the resulting average would be 0. The results of the index calculation are shown in the Map Figure below.

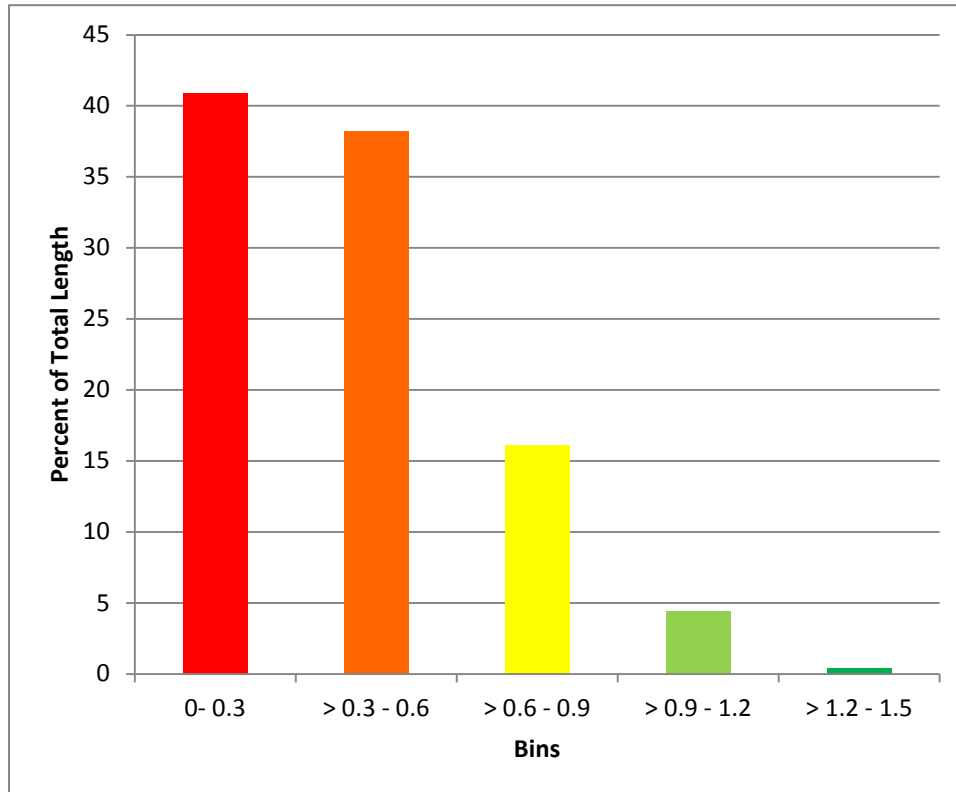


The average values index computed range from 0 to 1.5, with 0 being where no species are present, and 1.5 being the most diverse extent of habitat species in the Puget Sound. The ranges are represented in five equal interval bins in the figure above. The green bins shown segments with an index measure of greater species diversity and density and the red bins showing little or no habitat presence.

The spatial patterns show that the current condition of Puget Sound primarily has lesser species habitat and diversity as described by the index value. This is particularly represented in the southern regions of Puget Sound and many other smaller regions (such as Elliott Bay and Commencement Bay) where industrial activities are heavily present and expected to have an impact on habitats.

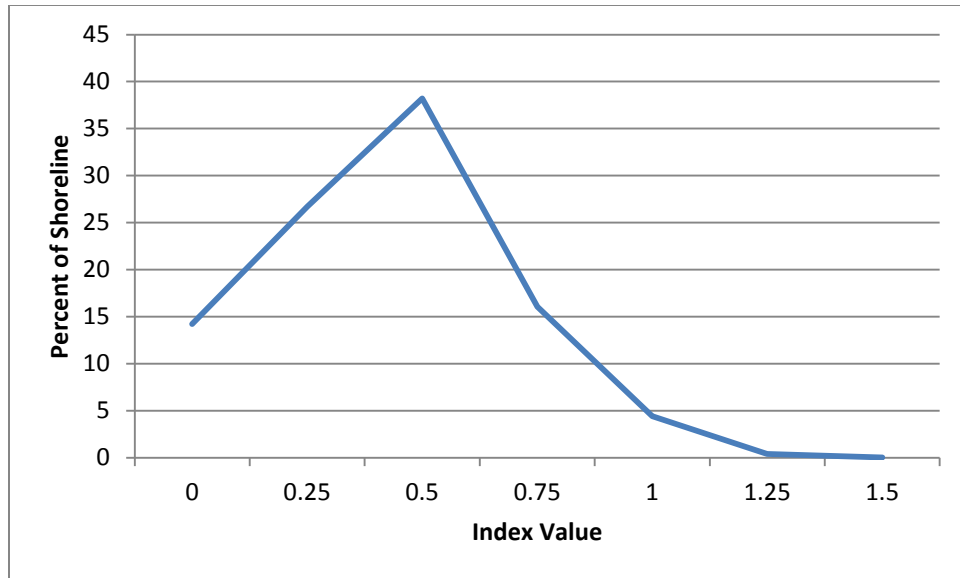
Sub-Step 3F

The graph below represents the percent of the total shoreline for each of the five index value bins as represented in the map. The existing state has predominantly little or sparse habitat along the shoreline as shown by the higher percentages of the lower index values. There is very little shoreline represented with the higher index value (less than 1%). While it is expected that some regions would simply not be able to support the vegetation habitat (such as areas with steep slopes that do not provide shallow water depths with enough light for the vegetation to grow), there is a general lack of diversity and density in habitat extents as represented by the index indicator.



Graph 1. Graph representing the percentage of total Puget Sound shoreline length for each bin.

Another graph representation of the data is shown in the line graph below. This more clearly shows how the index values are distributed across the sound and that the highest percentage of values is 0.5, which can either represent at least one species is present with continuous habitat or at two species are present with sparse habitat. The graphs still demonstrate a lack of diversity and continuous habitats in general within the Puget Sound.



Graph 2. Graph representing the change across all index values calculated in the Puget Sound.

Step 4|5|6

The results of assessing habitat extents in a computational environment are good considering the data that was found and utilized. WSAS recommended an indicator that used more species data incorporated into an index value that can better represent what is going on in the Puget Sound. They noted that a healthy Sound will have more habitat extents than just the eelgrass extents that have been greatly emphasized and studied by the DNR and others. This habitat extent index does exactly that, describing the presence of multiple habitat types and accounting for connectivity on an averaged basis throughout the shorezone of Puget Sound. The key attributes for the extent of marine habitats are area, patterns, and connectivity. Although a measure of areal extent (such as hectares of eelgrass) are not presented here (but is advocated for future determination of that data) the index is valid for the entire shorezone and displayed in the Graph 1 as a percentage of the shoreline length as a substitute for true areal descriptions. Using available data, and numerically coding for 'absent', 'patchy', and 'continuous' demonstrates the patterns and connectivity key attributes.

The index created has several pros and cons to consider for whether or not a public agency should use the index in policy making. The pros include that the index is simple to calculate as well as understand the logic behind the averaging out the presence and absence of habitat types. The data the index is based on is also complete and easily available. Finally, the index can be mapped and color coded such that one can visualize shoreline characteristics and can change classifications as desired to represent the shorezone in new ways (e.g. look at only three index classes rather than five or base values on set goals). The index is not without faults. The cons to this index include the fact that area data is not used.

Ideally, a complete vision of this index in future trials and uses would be more insightful with incorporated areal extent and overlay analysis of interconnected habitat zones when and if that data can be derived. This may be too expensive or time consuming of a process to be realistic; however, remote sensing techniques could supplement surveyed data across the Puget Sound. The index also does not account for substrate types at the bottom. In shallower zones that harbor aquatic vegetation, differences in substrate will be apparent. Accounting for this could be appropriate when considering other Puget Sound remediation activities that may change the substrate of an area, such as attempting to curb excess sedimentation delivery.

Last, all indexes are based on assumptions. For this index, the main assumption is that aquatic vegetation can be used to display different habitat types. It is assumed that different groups of plants will thrive in different conditions (depth, temperature, substrate, etc.), but will also have significant overlap in the healthiest state of the ecosystem.

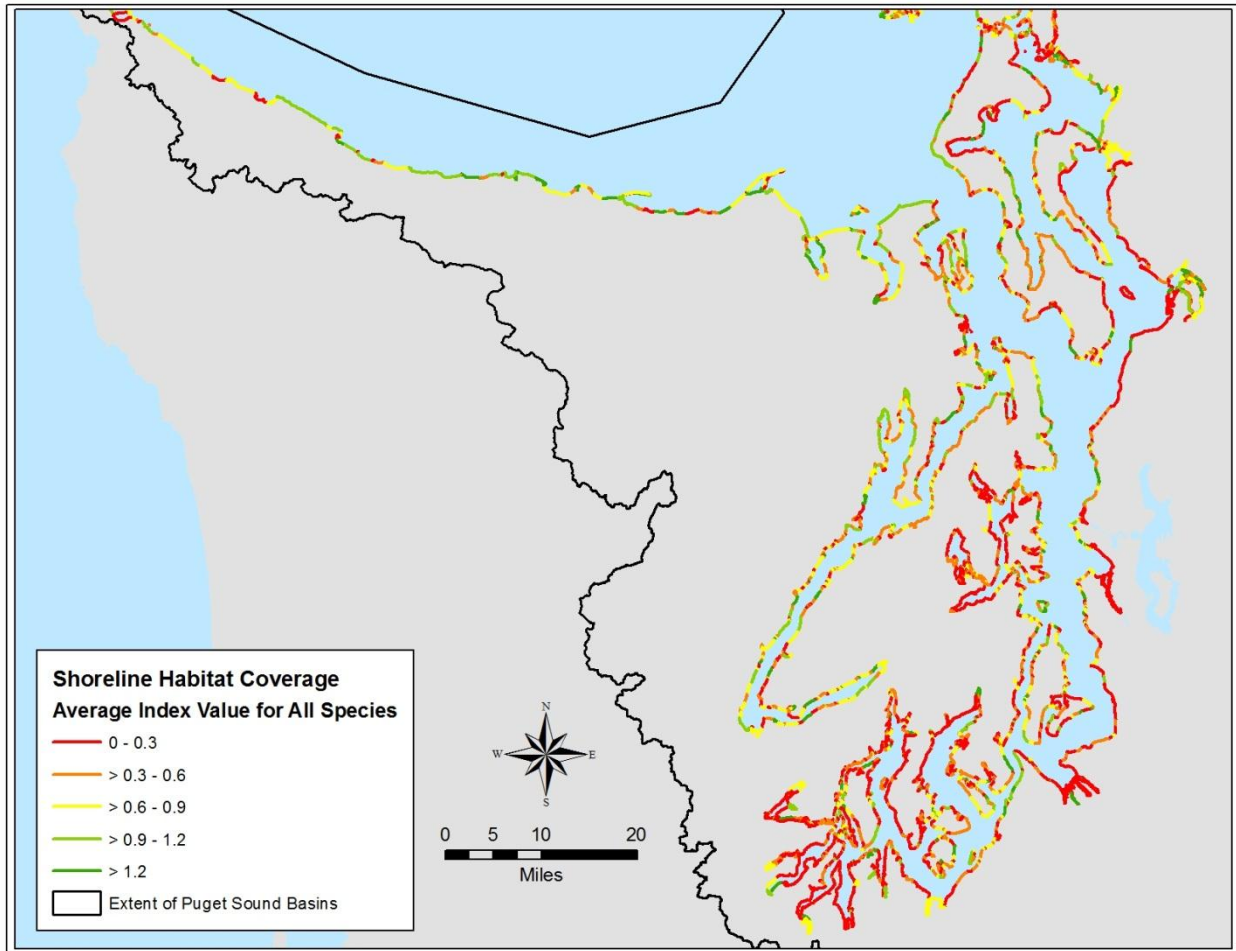
Even though the index is not perfect, there are still a lot of positive aspects of its development and use. We would advocate that it is usable at the minimum as a template or model for future investigation. Ecological experts involved in the Puget Sound Partnership should be able to expand on and improve this index, especially if more sound and complete data is surveyed or otherwise made available.

Sub-step 7A

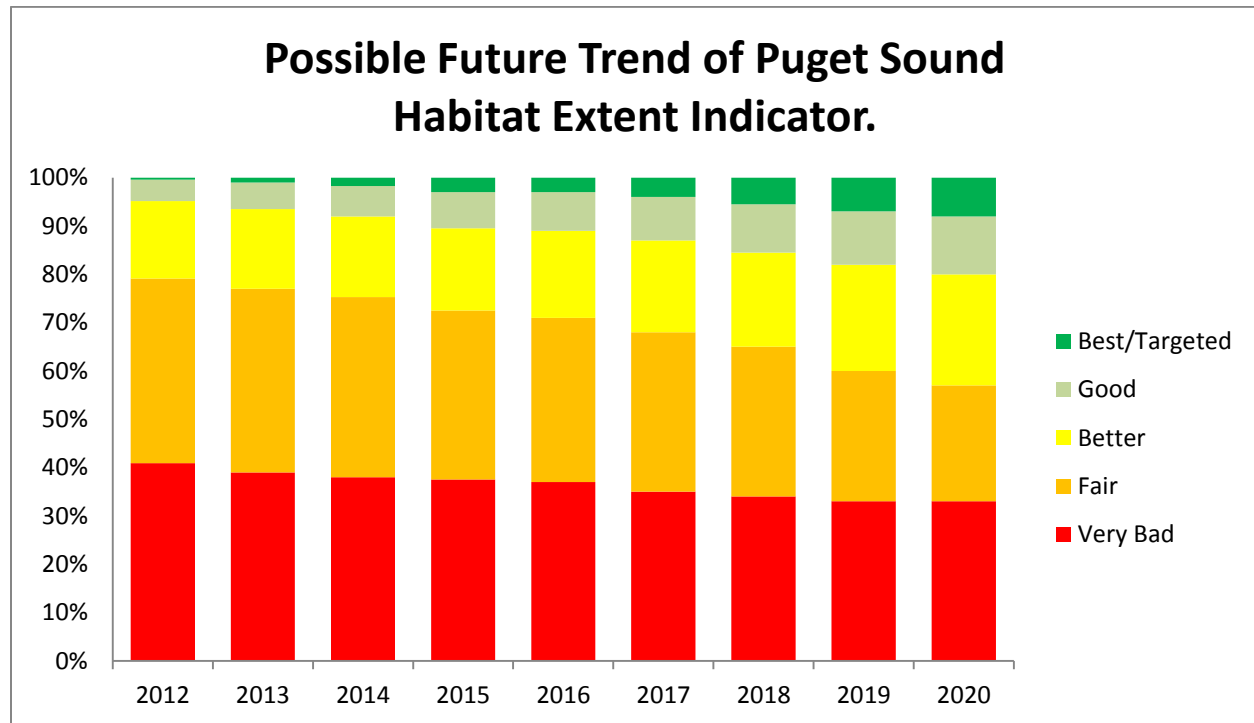
Currently, there are no target metrics for the four nearshore species of marine habitat within the Puget Sound. However, the Washington Department of Natural Resources has proposed a target of a 20% increase in eelgrass area in the Puget Sound by 2020, based on other case studies around the country (Dowty et al 2010). However, no specific targets have been set for shoreline length and both the Puget

Sound Partnership Action Agenda and the 2009 Supplemental state that more analysis is needed for historic conditions. The 2009 Supplemental states that the ideal situation would be a stable or increasing eelgrass abundance and distribution (PSP 2009, p. 95). While habitat indicators of eelgrass, kelp, and marine macro algae are generally considered theoretically sound, it has been difficult to pinpoint a direct link variation in habitat area (Levin et al. 2011, p. 61). No documents have been found with targets for any of the other species investigated.

While an ideal of a 20% increase could be projected, there have been no specific values determined for all habitats, so a general representation of the ideal situation is shown below in which there is an overall increase in the presence of habitats in the area. While there is still a lack of habitat in industrial areas, this ideal future shows a general increase to the mid and higher range index values in the future. The range of habitat values should be tracked into the future to establish base values and determine overall changes across the sound. A compilation of historical data may lead to a better determination of preferred situation in each Puget Sound region.



Sub-step 7B



Graph 2 is a possible future state of the Puget Sound habitat extent indicator. It is a reorganization of Graph 1 above such that each category of index value ranges are now a stacked column representing the complete percentages of the different categories. The data in column 1, for 2012, is the same data as is in Graph 1 showing the current state of the habitat extents index in Puget Sound. The index is then extrapolated out to the 2020 goal of the Puget Sound Partnership with improvements that have been made. The trend shown is a hypothetical estimation; however, realistic achievements are kept in mind. Thus, the trend is only a modest increase in the “Best” index values from about a half percent in 2012 to about six percent in 2020. We feel even this much progress would be difficult to attain in reality, but the goal and trend towards improvement is important and demonstrated. The 2020 values of the Graph 2 are approximately the same as what is demonstrated in Map 2 above for a future state of the Sound where more shoreline is represented in green index category representations.

The process to achieve such a graph would be extremely complicated. To attain a better index value as it is calculated in this project, there would have to be simultaneous increases in frequency and connectivity of habitat types (presence and continuity rather than sparse and disconnected), as well as an increase in the number of habitat types observed. It is only sensible to recognize that even though a goal of a more diverse habitat extent ecosystem is desired, it is unlikely to if not impossible to have a “continuous” condition of all the species categories represented in all shoreline segments. However, general improvements in the Puget Sound shorezone conditions should lead to increasing diversity and connectivity when considering that the segments of shoreline studies will most likely have at least some variability in water column depths and sediment types. Index values can increase also with more complete surveying such that there are not “holes” in the data for missed habitat type observations. Increasing index values will depend on many improvement programs and policies that are themselves studied by looking at other indicators given by the PSP and / or the WSAS recommendations. These include general water quality improvement, shoreline armoring, and sedimentation and turbidity aspects. Sedimentation and turbidity are major contributors here because the index value is highly

dependent on the presence of aquatic vegetation types as determinates of habitat type extents. A main determinate in extent of aquatic vegetation is the availability of light to penetrate the water column. Increases in turbidity reduce light penetration into the water column thereby reducing the available area for habitat extents derived by aquatic plants. Although many factors are involved in overall habitat extent improvement, general water quality and turbidity may be the most pivotal for improving the index indicator.

Sub-step 7C

The nine different change models proposed by Steinitz each have a different way about achieving a change in the state of a study or study area. The one that stands out for being compatible with the work on the index value indicator for marine habitat extents is the Optimized Change Model. This model is defined by Steinitz as attempting to use only a single metric in judging and influencing decisions about the ultimate change. In the book, the optimized change model is delivered through a discussion about the Telluride region of Colorado. There, the geodesign of the region's expansion is centered on the housing market (second homes) and decisions were made in relation to optimizing that industry and the economy it supports.

The optimized change model would be applied the same way in this example. While recognizing the fact the Puget Sound region is large and there are many indicators that are also being developed to monitor the system, when looking only at habitat extents decisions and potential actions in policy can be related directly to the index value. The goal would be to establish a "Green-light" index value, and pursue activities and change that optimize the index value in more areas of the Puget Sound. Such activities could include sedimentation control through riparian buffer zones and increasing wetland delineations, reduction or improvement in quality of wastewater and industrial effluents, and the control of all manner of nonpoint source pollutions like urban runoff entering the waters of the Puget Sound basin at large.

Clearly, activities like these would be affected by if not instigated by studying and working with other indicators of the health of the social-ecological system. The cyclical nature behind indicators that relate to, and are affected by, other indicators' processes means that there is any number of change models that could be pursued. As such, the second most logical change model to pursue would be the Combination change model. Here, the change model recognizes uncertainties in the appropriate choices among all the options for change. In a complex system such as the Puget Sound, with targets that will be set for many indicators, this model can seek to investigate alternative solutions and scenarios based on what would be determined as the most important requirements of the system. The social-economic conceptual framework, no matter how it is perceived by different groups, must result in indicators that affect each other. Therefore, when considering the system as a whole, envisioning many scenarios by accounting for the interactions between indicators like sedimentation and habitat extents together should bring to light the good and the not-as-good processes towards a positive desirable change in the system.

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Appendix 3.

Extent of the range of marine habitat types in Puget Sound (3)

By Nicolas Eckhardt and Donald McAuslan

Sub-Step 1A

There are several conceptual frameworks that were looked at the beginning of this project. After careful consideration and thought over the pros and cons of each conceptual framework, it was decided that the DPSIR framework, as stated in O'Neill's article *Environmental Indicators for the Puget Sound Partnership: A Regional Effort to Select Provisional Indicators (Phase 1)*: 2008, was the most appropriate framework to use given the choice of indicators that will be evaluated. The DPSIR framework acronym stands for drivers, pressures, states, impacts, and responses. These elements can be considered a set of cause and effect relationships that are part of the "process", which is the dynamic interaction of the elements that make up the conceptual framework.

The DPSIR framework is "a framework that clearly defines the causal links or relationships between ecosystem attributes we can measure and aspects of the ecosystem that have high relevance to humans (i.e. potential indicators for the Action Agenda. Specifically, the DPSIR framework defines the causal links between human activities (i.e. drivers), the stress or pressures they can put on the ecosystem, that cause changes in the state of ecosystem components, resulting in negative impacts to other ecosystem components. Ultimately, society can react (i.e. show a response), often with management actions that can regulate the driver, the pressure, state, or impact. An existing Puget Sound Assessment and Monitoring Program (PSAMP) conceptual model was modified to fit the DPSIR framework. The resulting component-based DPSIR models will eventually need to be linked into a whole-ecosystem based conceptual model that denotes the inter-connections among these components" (O'Neill et al. 2008).

Using this framework we had to make sure that our indicator was relevant to the Puget Sound Partnership's (PSP) goals. The goals identified by the PSP for conceptual model were listed in Table 1 of O'Neill (O'Neill et al. 2008). The framework was broken up into ecosystem components of which each has a goal. The ecosystem components include Water Quality, Human Health, Species and Food Webs, Habitat, and Water Quantity. Each of the ecosystem components have goals that improve upon the current state of the Puget Sound and desired outcomes by 2020 of how each of these ecosystem components and goals should be. In this project, we will be focusing on the Habitat ecosystem component, specifically looking at the extent of marine habitat types as the indicator with the goal of being able to show the current extent of marine habitat types and to come up with a standard by which we would like to see this indicator to be at in the future and which will accomplish the goals set up by the PSP.

There are several reasons why we chose the DPSIR conceptual framework over other potential frameworks. One reason is that the Puget Sound is made up of a variety of dynamic processes. While all of the frameworks illustrate the links between attributes, the DPSIR framework clearly demonstrates the causal effects of these links. The DPSIR framework also divided up the ecosystem components in to individual conceptual models which allows for clearly defined efforts to be focused. This makes the framework a more focused option but an obvious flaw is the lack of attention spent looking at relationships between individual conceptual models. This did not, in our mind, hinder the use DPSIR framework to a point that it could not be considered. Another reason why we chose to use this framework was that it was tied to be overarching and specific goals as stated in Table 1 of O'Neill (O'Neill et al. 2008). This made it clear that the framework was considering the outcomes of the actions and indicators at different scale levels. This made it an attractive framework to use. Also another reason

why this framework was chosen was that the Puget Sound Assessment and Monitoring Program (PSAMP) conceptual model was using a modified DPSIR framework model. This shows that this framework is important and is being used currently to monitor other facets of the ecosystem. This will allow us to have an easier time integrating our indicator and data into a data model that encompasses many more factors.

Sub-Step 1B

During our selection process for a conceptual framework we looked at many different options. Ultimately these were all eliminated except for the DPSIR framework. However, all of looked at framework models did have some elements that was worth considering even though it was not chosen. The reports *Identification of Ecosystem Components and Their Indicators and Targets* by Neuman et al. and the *Puget Sound Science Update* by Levin et al., both discussed the Open Standard conceptual framework. This framework is a set of adaptive management steps developed by the Conservation Measures Partnership as a framework for planning and implementing conservation action (Levin et al. 2011, p. 7). While it is a good conceptual framework we ultimately decided not to use it. The suggestion as a possible relevant measure in Table 3 regarding the fractal dimension (i.e. habitat complexity) of habitat types is a worthwhile consideration that could be reviewed within the conceptual framework but for our purposes we decided to exclude this on the basis that it would be difficult to construct given our time constrains. In addition, it would have required us to come up with methods to design and implement the indicator for which there is no time and limited resources and also no guarantee of being a better indicator than marine habitat extent which we are currently going to use.

The other conceptual frameworks looked at come from the Washington State Academy of Sciences *Sound Indicators: A review for the Puget Sound Partnership*. This report discuss three conceptual frameworks that could be applicable to our efforts in this project. These frameworks are: the SAB framework, the NRC framework, and the Heinz Center framework. Each of these frameworks were looked at individually and analyzed to see if they met our goals. While in the end they did not meet our goals, elements of each of these frameworks were important to consider. For example, NRC framework and the Heinz Center framework have a more simple design than the SAB framework. This makes it appealing as it is possible to address a wide range of issues and not overly complicate the issue and things. This makes it easier for the user to understand and will make it easier to convey information to participants and shareholders.

The SAB framework is the only framework that explicitly lists the dynamic attributes of hydrology and geomorphology, which are critical for understanding ecosystems like Puget Sound (WSAS 2012). This is important because the Puget Sound is a complex mixture of different hydrology and geomorphology types that interact in many different ways. Many of these interactions are dynamic and can change over time and space. It is important to consider these elements in our framework because of their potential influences on the whole ecosystem. This is an important consideration to consider even though the SAB framework is not our chosen framework to use.

Sub-Step 1C

The key attributes that are the focus of our indicator will be the habitat area, extent, and pattern/structure as specified by the *Puget Sound Science Update* (Levin et al. 2011, p. 35) as well as Table 1 of the *Indicator Summary Report* (O'Neill 2008, p. 11).

Sub-Step 2A

Our indicator is a composite of the linear extent of different marine habitats, including eelgrass, kelp, saltmarsh, intertidal wetlands, and oyster or clam beds. From the above list, after careful research and discussion we have narrowed our indicator to only include eelgrass, kelp, and saltmarsh. We derived this indicator from Tables 1 and 5 of O'Neill (O'Neill 2008, p. 13 & 25), while also utilizing the suggestions made by WSAS (WSAS 2012, p. 61), Levin (Levin et al. 2011, p. 35) and PSP Ecosystem Status and Trends: A 2009 Supplement to State of the Sound Reporting (Redman et al. 2011, p. 80-82). As discussed in Sub-step 1A, O'Neill's framework breaks the Puget Sound up into different ecosystem components, each that has an individual conceptual framework. Table 1 of O'Neill details these ecosystem components and the specific PSP goals each one addresses. The ecosystem component "Habitat" supports the goal, "A healthy Puget Sound where freshwater, estuary, nearshore, marine, and upland habitats are protected, restored and sustained." This goal has a series of sub-goals that lead to a series of desired outcomes for the year 2020. Our indicator of habitat extent is derived from the italicized text in sub-goal HB-1: "The *amount*, quality and *location* of *marine*, nearshore, freshwater, and upland *habitats* sustain the diverse species and food webs of Puget Sound lands and waters."

Sub-Step 2B

In determining whether or not the indicators we selected accurately represent the key attributes that were selected in Step 1 we did some research and looked at papers that dealt with the subject. Regarding using eelgrass as an indicator we looked at a document entitled "*Developing Indicators and Targets for Eelgrass in Puget Sound: A Science Assessment*". This document discussed the developing of the indicator and the specific targets for recovery for eelgrass. The document stated the various ecological benefits that eelgrass provides. In the Puget Sound specifically, eelgrass provides spawning grounds for Pacific herring, out-migrating corridors for juvenile salmon and important feeding and foraging habitats for waterbirds such as the Black and Great Blue Heron (Dowty 2010, p. 3). Eelgrass also improves water quality by reducing particle loads, acts as a sink for nutrients, and stabilizes sediment, thus counteracting erosion processes (Dowty 2010, p.3). As can be seen, eelgrass provides many important habitat functions and is essential to having a healthy ecosystem. It is important to protect these types of habitats and incorporate them into an extent of marine habitat type indicator. However, the WSAS does advise that eelgrass not be the only marine habitat type to be used to show this indicator. Although the attribute 'habitat area' is identified, the indicator chosen to represent the habitat area in the marine system-extent of eelgrass-is only one habitat type among many important habitat types for which extent information will be valuable. (WSAS 2012, p. 43). An index or composite indicator of extent would be far more useful than tracking extent of a single habitat (WSAS 2012, p. 43).

As a result of the WSAS recommendation, we have decided to incorporate the extent of saltmarsh habitat and the extent of kelp habitat into the indicator. After much research it was determined that these two marine habitat types also play an important role in maintaining a healthy ecosystem and should be included in the indicator in order to help monitor and assess the state of the Puget Sound. These two marine habitat types are found throughout the Puget Sound and are home to many species of organisms. "Fast-growing salt marsh grass species, called *Spartina*, form the base of a highly productive food web- more productive than the most fertile mid-western farmland. A diverse community of mammals, birds, finfish, and shellfish use these grasses for food, shelter, spawning, nursery areas and refuge from predators" (Dionne et al., p.3).

Not only do salt marshes provide habitat for various marine and land species they also provide many important natural processes functions that contribute to the overall health of the surrounding

landscape. These functions are important as they help to maintain the surrounding landscape and help to preserve ecological functions. “Marsh vegetation helps shield the upland from erosion by waves and currents. In addition, the marsh can absorb and moderate much of the impact of floods. As the marsh slows down and retains water, it also filters pollutants. Pollutants are often carried by sediment particles that settles and stay buried in the marsh, which limits the pollutants' impact on humans, animals and other ecosystems. Marsh plants can absorb excess nutrients, reducing the likelihood of nuisance algal blooms in coastal waters” (Dionne et al., p.4). The various processes listed above are all important in maintaining a healthy ecosystem and because of this it is important to include salt marshes as an indicator. The *Puget Sound Science Update* states in Table 22 that saltmarshes are “Overall good indicator – total area often used as integrative assessment of ecosystem health. May best be used as part of an integrative assessment of habitat change in the region.” (Levin et al., p. 69). Their status and trends have peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria and have been documented numerous times as being sound and relevant indicator for management. As a result it was decided to include saltmarsh as an indicator of the extent of marine habitat types.

In addition to eelgrass and saltmarshes being used as indicators of the extent of marine habitat type it was determined that we should also include kelp as an indicator. Kelp habitats provide many of the same benefits that eelgrass beds and saltmarshes provide. It has been shown that kelp is highly productive, annually producing large amounts of carbon that fuel nearshore food webs, principally through detritus pathways (Mumford 2007, p. 5). Many fish species and crustaceans use kelp beds as habitat similarly to eelgrass beds. Kelp is found distributed throughout the Puget Sound and is primarily found in the shallow subtidal zone in areas where there is a lot of water movement. Kelp is also impacted by many human activities. Human impacts on kelps consist largely of processes that increase sedimentation in shallow waters (Mumford 2007, p. 5). In addition, the building of docks, which shade the bottom, increases in nutrients due to runoff, toxics chemicals, and low oxygen impact both kelp and eelgrass and threatens the overall health of the Puget Sound. Therefore this is an important marine habitat type that needs to be monitored and can be used as an indicator to determine the state of the Puget Sound. It is also important to consider the impacts of not having this type of habitat would have on the rest of the Puget Sound. Therefore, it needs to be included in the indicator for extent of marine habitat type as it will provide much insight into the current state of the ecosystem.

Sub-Step 3A

The indicators that we have selected in Step 2 are extent of eelgrass, kelp, and saltmarshes. Given these indicators we have come up with a metric that deals with the linear extent of the data for which we have obtained. We have come up with a classification based off of how the obtained WA DNR ShoreZone GIS data is stored. In this dataset the linear extent of these feature is recorded as Continuous, Patchy, or Absent. This is the metric that we have adopted for our work as well. It will work well to depict the type of cover for each habitat within a given linear extent. Having the data divided into three categories simplifies the geoprocessing process yet still retains enough data for which we can conduct analysis. It will also help make it easier to understand to both the user as well as interested third parties.

In the context of driver, pressure, state, impact, or response our measurements represent the state of the indicator. Our measurement categories are representative of the structure of the marine habitat at a given point in time. Therefore, our measurement represents the state. Having the state expressed and recorded is important in order to determine if the specified habitat is in a form that helps to determine the current health of the Puget Sound.

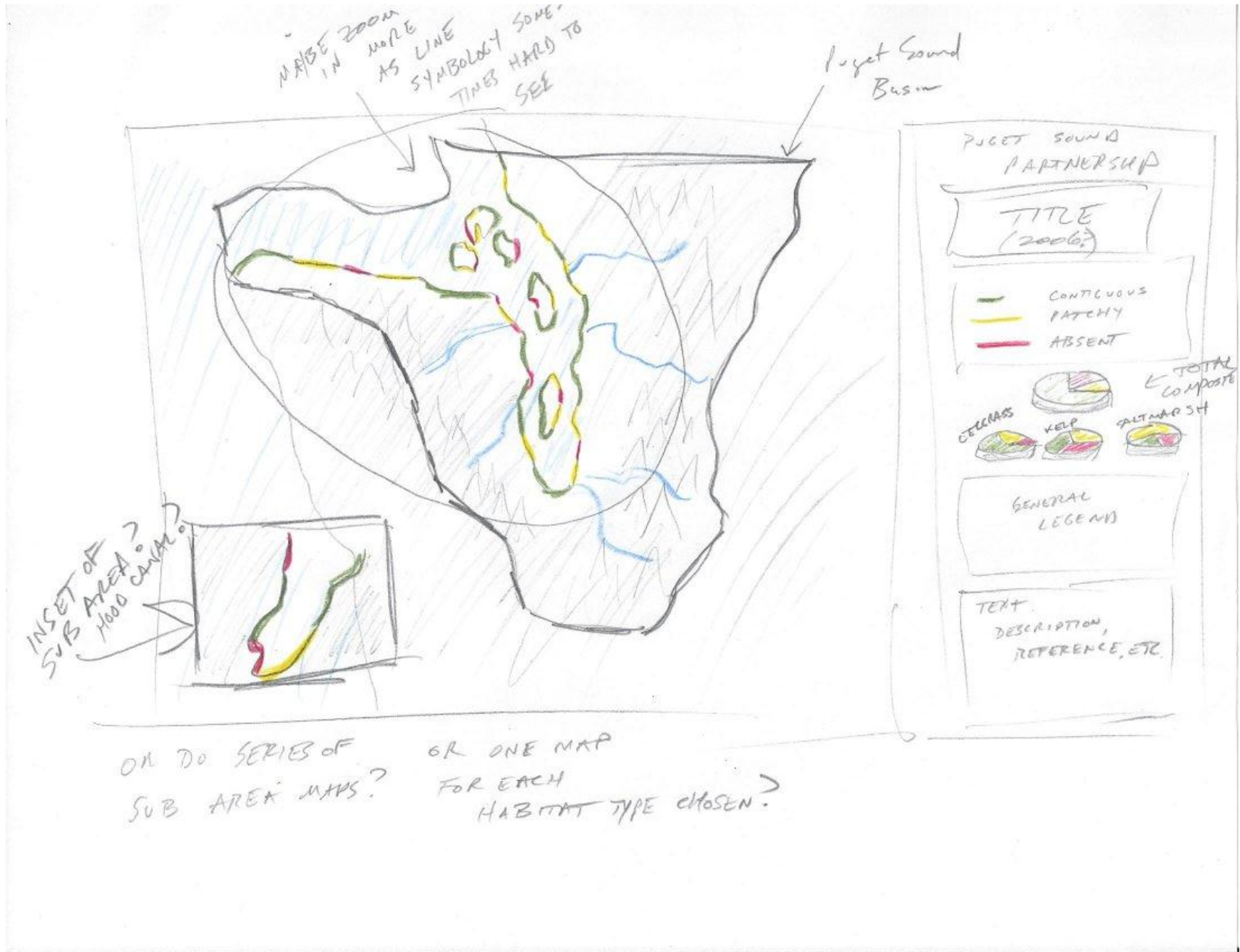
Sub-Step 3B

During our reading of the *Puget Sound Science Update* by Levin et al., we came across Table 3 on page 27 which listed selected key attributes for each goal. For the goal of Habitats some of the relevant measures listed are area or extent. This led us to feel that the linear extent of the selected marine habitat types accurately represents the indicators we selected. Many different ecological attributes may be used to describe habitat status and determine whether or not it is “healthy” including, as the U.S. EPA identified, various attributes of habitats including extent, composition, and pattern/structure; other attributes of habitats included dynamic structural characteristics and physical structure (Levin et al. 2011, p. 34). Therefore we decided that it was appropriate to use the linear extent of the different habitats as a measure for the indicators. This was the best way of performing this operation given the available data and time we had to complete this process.

We did look at other relevant measures before deciding on the linear extent of marine habitat types. We did look at using area as the relevant measure for marine habitat types extent. Areal extent of marine habitat types would have been an excellent measure to use because then we would be able to calculate the amount of acreage of each habitat type. This would be useful in determining if these habitat types were healthy or not. Areal extent would have been the preferred measure. However there is a lack of data sources which provide marine habitat types in a polygon format which is needed to produce area. This type of data does not exist on a Puget Sound wide scale although we did locate datasets on a smaller spatial scale. Having marine habitat type extents on an areal extent has several benefits which would make data analysis and interpretation easier to perform. It is much easier to use an acreage calculation and visualize an areal extent than a linear extent. Areal extent may also provide a more accurate account of the state of the indicator than a linear extent can. However due to the fact that this type of data does not exist for the entire Puget Sound we were not able to use areal extent and therefore chose to use linear extent.

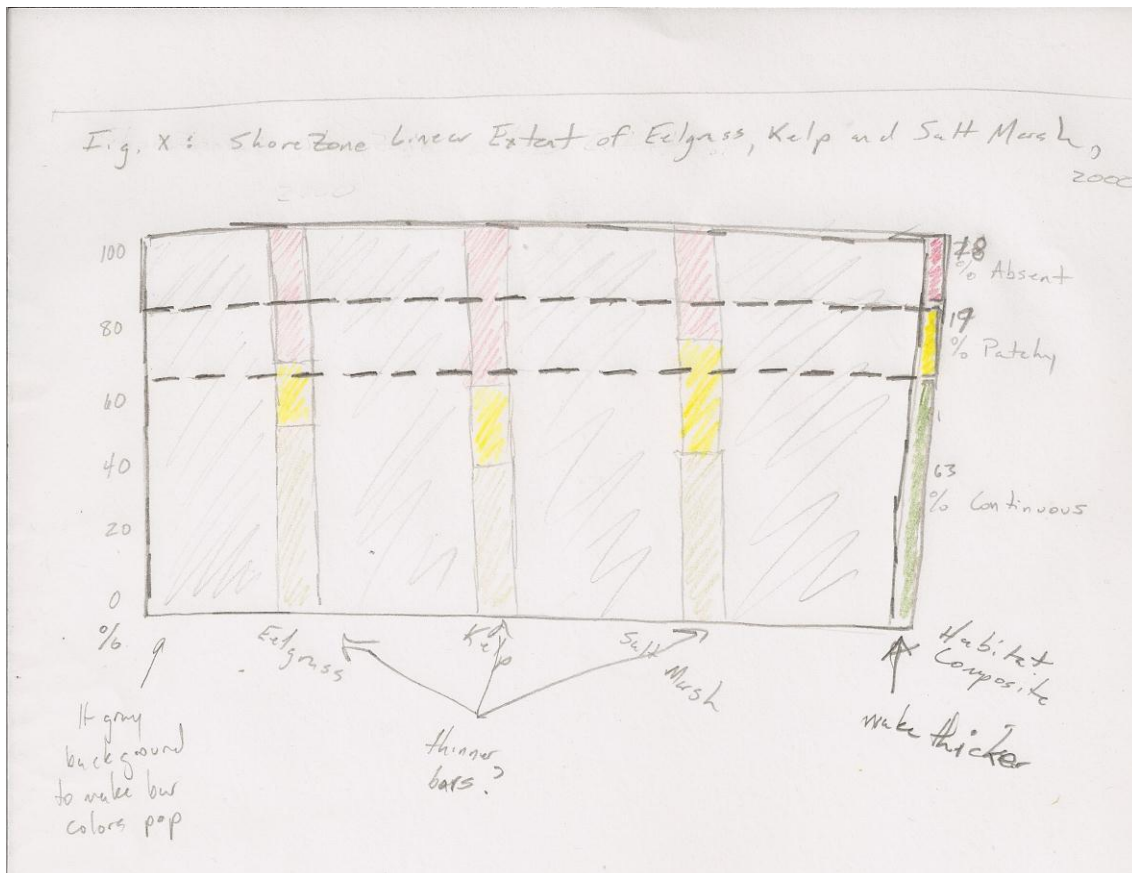
Although there is no example of areal extent data for Puget Sound wide marine habitat type extents in either polygon or raster format that would allow for area calculations to be easily conducted we did find a data source for parts of the Hood Canal which used remote sensed data to classify marine vegetation and habitat in both raster and polygon formats that would be useful. The Point No Point Treaty Council (http://www.pnptc.org/nearshore_habitat_images_&_report.html) conducted a Nearshore Habitat Imagery project using a Compact Airborne Spectrographic Imager (CSAI) to map out 547km of Puget Sound in order to map eelgrass beds and seven other habitat types at a spatial resolution of 4 meters (Garono et al. 2002, p. 8). The data collected during this project is very detailed, having identified many different marine vegetation and several habitat types. This data, if it had been conducted at a Puget Sound wide scale would have been perfect for our indicators and would have made the indicators much more useful. However, the data extent is only limited to certain sections of the Hood Canal and did not cover enough area to be of any use for our project. It is an example of a dataset that may potentially be the solution to coming up with the perfect dataset for the marine habitat type extent indicator and because of this we wanted to make everyone aware of its existence so that others may access it and see if it will help them.

Sub-Step 3C



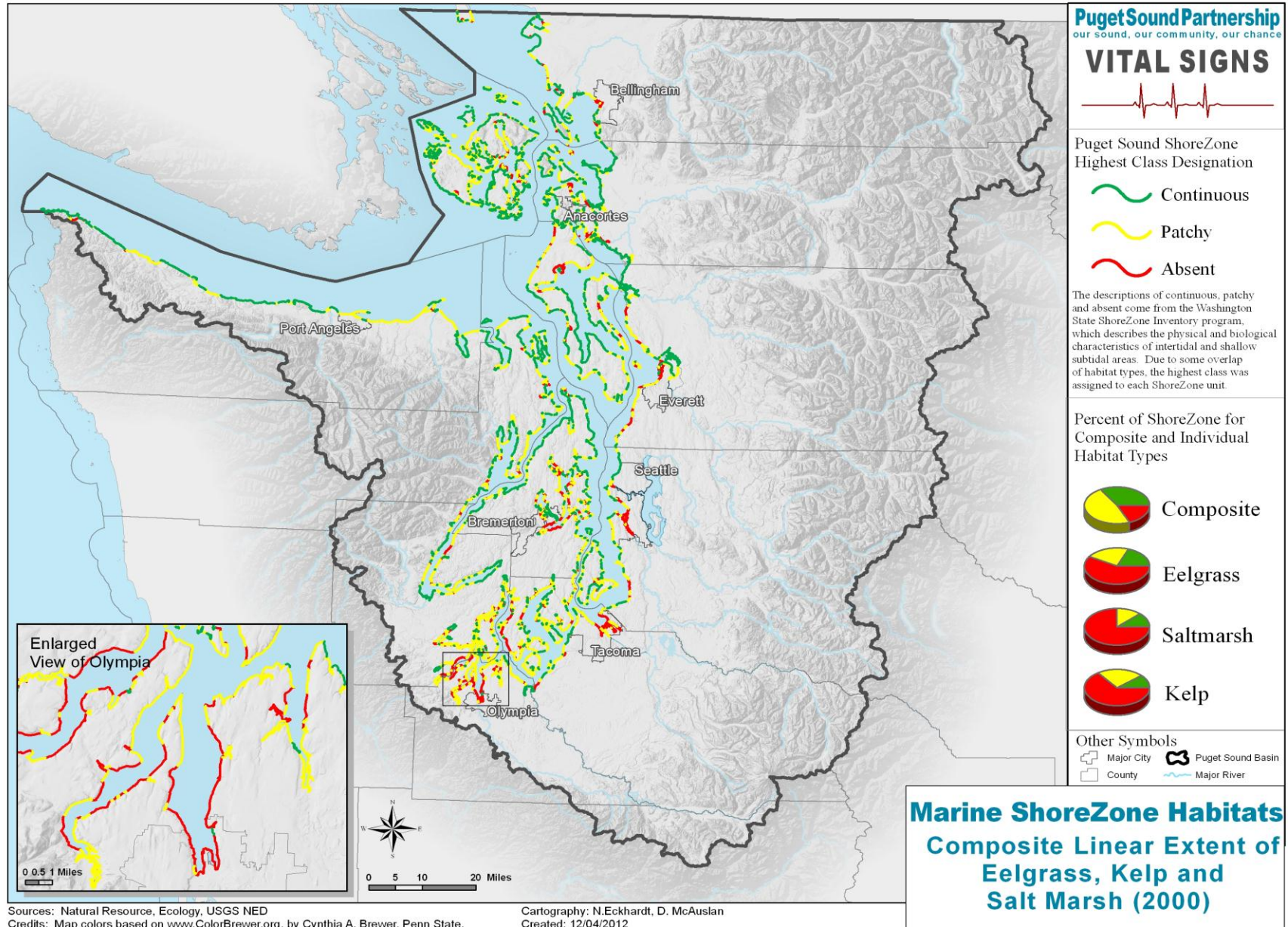
As referenced above, our indicator for our attribute is the shorezone linear extent of marine habitat types. The submitted sketch is a representation of the percent of shorezone that is either continuous, patchy, or absent of a composite of the three habitats of saltmarsh, eelgrass, and kelp. Primary colors of green (continuous), yellow (patchy) and red (absent) were chosen to represent the three states as they are bold colors that come to the forefront. This current sketch is at a scale that represents the entire Puget Sound basin, however, a decision may be made to zoom in to the areas of the shorezone and forego displaying as much of the interior areas of the basin. We may do this because it is quite possible that the vector polyline file that we create may not stand out well enough at this scale. Although the indicator itself can simply be reflected by a percentage, our hope is that this visual representation will allow analysis of specific sub-area patterns. Analyzing the map might allow for areas to be selected for investigation and/or restoration. For example, an abundance of green continuous lines interspersed periodically with smaller patchy or absent areas might represent areas that should be restored because of the possibility of increasing the connectivity of habitat types. As of yet, we have not determined where (or even if) there are areas of specific interest. Because we are using a vector polyline data format to represent our indicator we do not need to make determinations about line 'resolution'. However, we do need to carefully consider the width of our lines and the perception that width will generate. If the line is thin, we may not truly be able to 'see' any patterns. But if the line is thick, there may be confusion because it may appear as if the line looks like an area.

Sub-Step 3D



The hand-drawn graph attempts to represent not only the percentage of shorezones in 2000 that are 'continuous', 'patchy' and 'absent' for a composite of our habitat types, but it also represents each habitat individually. Because of the "limited availability of historical data," we are unable to do more than just present a baseline year (Redman et al. 2009, p.89). Although this graph represents one point in time, future representations should have measurements as frequently as possible. Every two years in perpetuity would be ideal, but assessments every five to ten years would be more realistic due to financial and time constraints for measurements. A bold dotted line runs across the graph denoting the percentage increments for each category of the habitat composite. At the terminus of the line along the right hand side of the graph are 'blocks' of color for each percentage. In order to provide consistency and facility comprehension, these colors mirror the colors used in the hand-drawn sketch of the map referenced above. Bar charts are overlaid in the body of the graph for each individual habitat type and are broken up based upon their percentages of the three categories as well. By superimposing these charts on the composite chart we can more easily educate the reader about both composite and individual habitats at once.

Sub-Step 3E



A lot of work was put into creating the above map. We had to answer many questions regarding the measurements, representations, operations, and transformations in order to implement our solution to the extent of marine habitat type indicator. In order to accomplish this we encountered and manipulated each of the above operations. For our solution we had to measure the length of shoreline that was in the Puget Sound. Based on this measurement we then had to determine the total length of continuous, patchy, and absent habitat for eelgrass, saltmarshes, and kelp. This measurement was split into a composite measurement for continuous, patchy, and absent for all three habitat types together and also for each individual habitat type. The length measurement was a key factor in being able to create the necessary data to represent the indicator. After the total length for the Puget Sound and all the composite and individual habitat type lengths were calculated, we were able to determine the percentages of each habitat type individually and as a composite for the entire Puget Sound. This allowed us to determine the percentage of eelgrass, saltmarsh, and kelp present for each of the three individual conditions.

The data we used for this indicator came from the DNR ShoreZone GIS data. This data was in a vector data model, specifically as a polyline feature. This gave us the linear extent of each of the individual habitat types. The vector polyline feature also allowed us to be able to represent the individual habitat conditions: continuous, patchy, and absent, as different colors and in different layers. We were able to store multiple different attributes of habitat type in the same dataset which cannot easily be done using a raster. Using this vector dataset allowed us to successfully display this indicator.

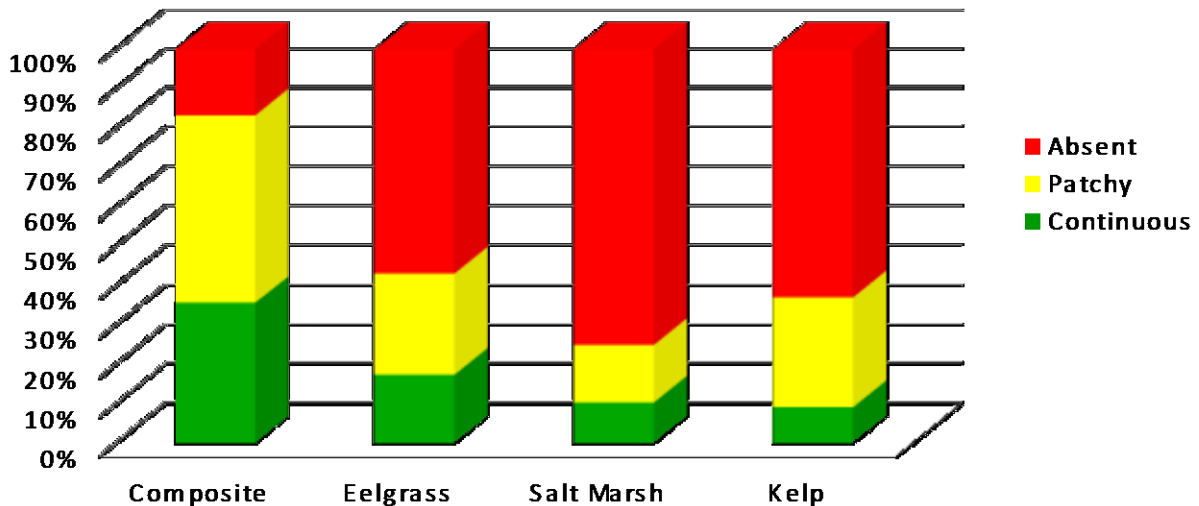
In order to come up with the final indicator data there had to be several operations performed on the data in order to have it in the format that would sufficiently show the indicator. One of the first operations that we had to perform on the data was clipping the data to the extent of the Puget Sound. This was done in order to get the most accurate length of shoreline for only the Puget Sound. In ArcGIS the tool that was used to carry out this operation was the Clipping tool that can be found in the Data Management Toolbox. This tool clips any input data based on specified parameters such as an area of interest. Since we had multiple layers to clip the clipping operation was done using the batch clipping option which clipped as many specified layers as possible at the same time. In addition we had to calculate the length of each subunit corresponding to the habitat conditions of continuous, patchy, and absent. This was accomplished using the calculate length tool in the Xtools toolbox. This tool allowed us to calculate the length of each line segment. We could then determine the total length of a habitat condition by selecting those attribute records containing a selected habitat condition and using the 'Statistics' tool to obtain the sum of the lengths. This tool can be accessed via the attribute table by right-clicking the attribute column header and selecting 'Statistics'. A dialog window will appear and the user can see the sum of all the segment lengths. With the length value we were then able to divide it against the total shoreline length for the Puget Sound in order to come up with a percentage. That data was used to create Graph 1.

Finally there were some transformations that occurred to the shoreline data in order for it to be used to represent the indicator. In order to create the composite indicator of continuous, patchy, and absent for all three habitat types we needed to determine which out of the three attributes to use for a specific line segment when one or more different habitat conditions were present. It was determined that the highest habitat class would be used in these situations. We determined the order to be continuous as the highest and absent as the lowest. For example, if a line segment had patchy eelgrass but continuous kelp in the composite data the line segment was changed to being continuous since continuous is the higher of the two habitat classes. This made sure that we used the best type of habitat condition when coming up with the composite habitat types. This transformation was not used often as it appeared that

many of the habitats did not occur at the same location and line segment. Although the occurrences of overlap were fewer than expected, there were enough overlaps to justify doing this transformation.

Sub-Step 3F

Percent of ShoreZone for Composite and Individual Habitat Types (2000)



During our time searching for data and researching this topic we found that there is not real historical data that can be used to create a temporal pattern from some distant past to the present. A lack of historical data is especially true to the eelgrass extent. There is anecdotal evidence but nothing freely available or in GIS format that represents eelgrass from the past. Therefore our data represents the state of these habitats in 2000, which one could supposedly consider the past but in this case we will use it as the current state as we do not have any other data to go on. Therefore our temporal pattern will show the state of habitat types in 2000 and we will observe some interesting phenomena.

One noticeable phenomenon is the fact that all three of the habitat types are absent over 50% of the length of shoreline within the Puget Sound. This is represented by the red color. Evidently much of the Puget Sound is absent of each of these habitat types. However once you combine the continuous and the patchy habitat conditions together for each habitat type there is still a good portion of the Puget Sound that has these at least one of these habitats. It is evident that there is a need in 2000 to increase the amount of these individual habitat types in order to create a healthier state for the Puget Sound.

Another interesting phenomena is that although individually the percentages of continuous and patchy habitat conditions for each is low, the composite for all the habitat conditions has a much higher percentage for continuous and patchy habitats. In this situation, close to 80% of the Puget Sound is covered by either continuous or patchy habitat type of at least one of the three habitat types. This shows that there is a lot of shoreline that does have one of these three habitat types present. However this does not mean that the state of these habitat types within the Puget Sound in 2000 is at an adequate level for a healthy condition. There is really no way for us to know exactly as there is no historical data to compare it to. If we had historical data we would be able to make a determination as

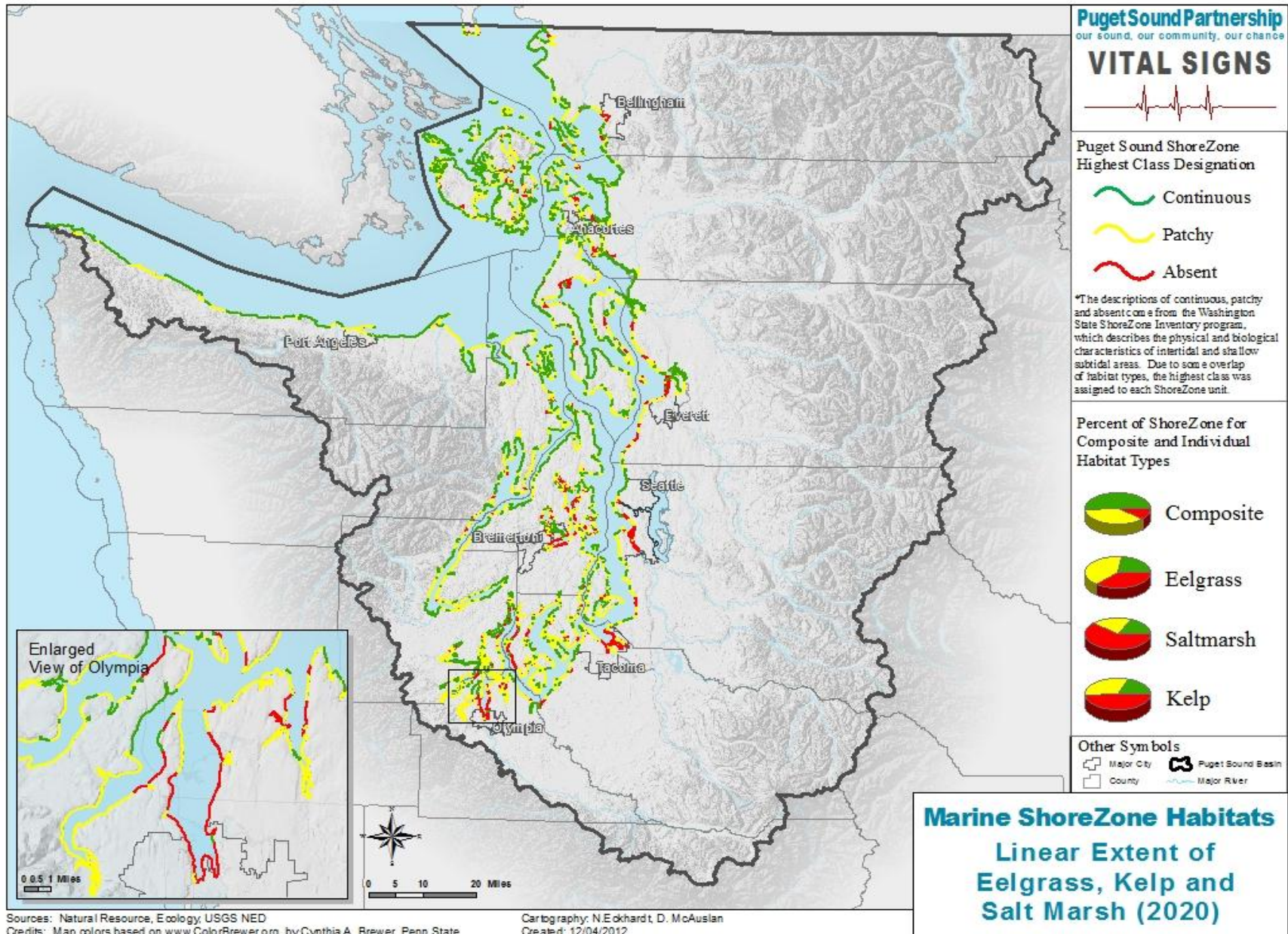
to whether there has been an increase or decrease in the percentages of these habitat types and this would help us to determine the state of the Puget Sound.

Step 4|5|6

The maps and graphs that we have designed to ultimately represent the relevant measures, indicator, and key attributes have been able to succeed in their intentions of displaying this information. Given the available data that we had to work with we were able to create maps and graphs that showed both the current state and a potential future state of our selected indicator. We were able to do this without having the best possible data available. The ideal dataset would be having an area based polygon dataset of the three habitat types. In our case we only had polyline data that gave us the linear extent of the habitat types. This was not the ideal situation but we were able to use this data to adequately represent the indicator. Using linear data did make it possible to represent the data at a Sound-wide scale. Also, although we only have data from the one year, it appears that the data is easily replicated and could be done again and used to create similar maps of future states. Using linear data made it so that our map is not as cluttered as it could potentially be if we were using polygons. Our map made it possible to show spatial patterns at the Sound-wide scale and have it easily interpreted. We are able to see locations where continuous, patchy, and absent habitat type conditions exist and to see this distribution throughout the Puget Sound. This simplifies interpretation and allows us to better communicate our message regarding the indicator.

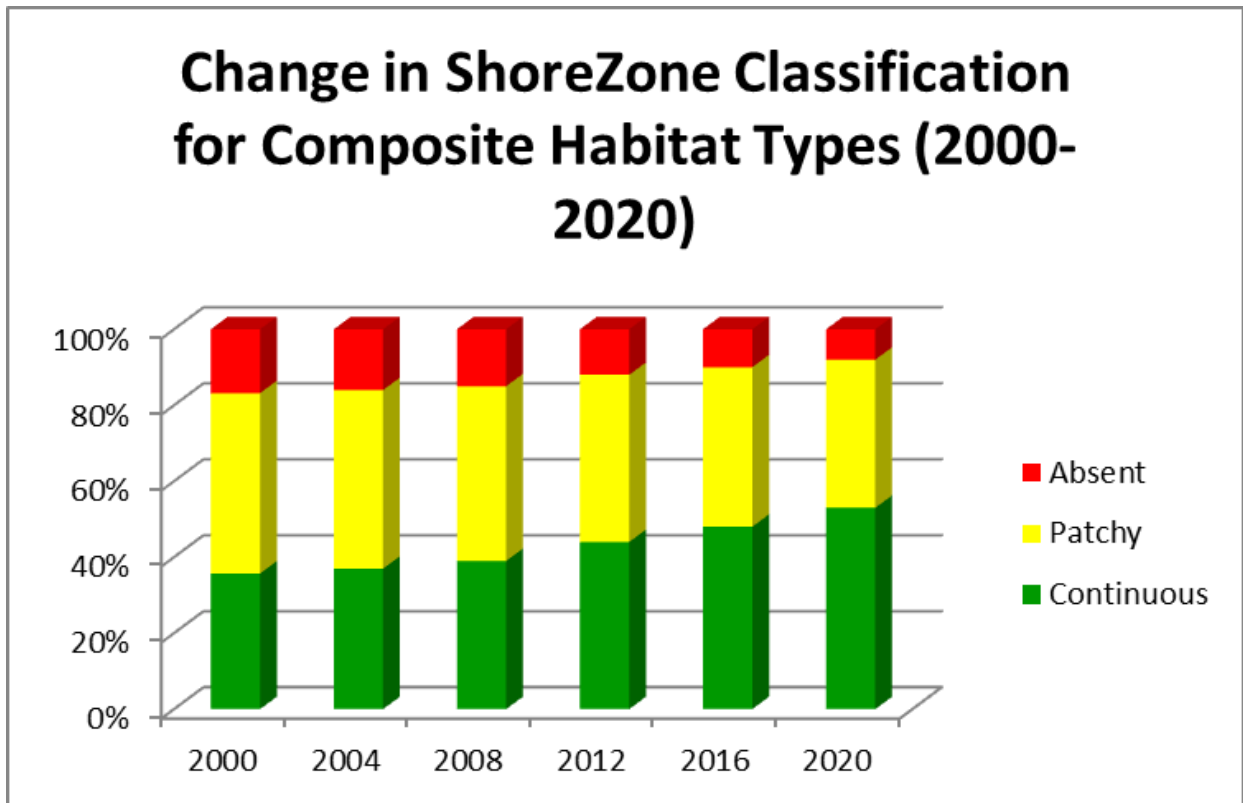
If a public agency were to consider using our maps to act upon this information for some policy intervention the indicators and the maps that we have created would be an acceptable source of information to use as a first step. It should not be used as the final informative step as we do not have habitat suitability data available which would enhance the indicator and make it more accurate. In addition the lack of data from multiple year's worth of habitat extent data is a limiting factor in the usability of the indicator. However, it is a good starting point and allows for the initial understanding of what is going on in the environment. An agency could use this data and indicator to determine what needs to be accomplished and in which direction they should proceed. Although limited in some aspects this information would prove useful and should be considered by agencies planning on tackling this complex issue.

Sub-step 7A



As stated above, the spatial pattern of shorezone vegetation for the current state shows a distinct absence of our indicator species in the larger urban areas, as well as the southern portion of the Hood Canal. Our approach to a future state map was to demonstrate a “what if” type map had we used a rule-based change model for scenario analysis. This hypothetical map for the year 2020 shows some marked improvement in the amount of shorezone now classified as continuous and patchy, while also showing some reductions in the areas that are absent. The improvements shown occur mostly in the southern portion of the Hood Canal, the west coast of Whidbey Island, and the area between Port Angeles and Sequim. We felt that these areas were ripe for growth in the eelgrass, kelp and/or salt marsh habitats because they are not as developed as the larger urban areas. Because of this, these areas should not struggle with managing what population growth that will occur over the foreseeable future. Because our time frame was relatively short to represent any change, we felt that the change would be more localized rather than improvements everywhere in the sound. As an example, we did not feel that ten to twenty years was enough time to truly make improvements in those urban areas that showed significant amounts of absent. Additionally, we did not feel a future state would show improvements everywhere because we wanted to acknowledge that some areas probably are not suitable environments for our indicator species to occupy.

Sub-step 7B



According to the Puget Sound Partnership’s Dashboard, eelgrass has remained relatively stable throughout the sound recently. Localized areas have shown sharp decreases while many others have shown slight increases. Our future state graph attempts to not only reflect a significant positive change

over the course of twenty years, but also the relative stability in the near term. We believe that the pattern displayed in this graph is possible because it will be difficult to see marked improvements in the short term. Only after interventions are in place for a significant amount of time will we begin to see larger increases in our indicator species. Specifically, policies need to be established to decrease turbidity in the waters. Better stormwater management and construction site management needs to be in place to decrease the amount of sedimentation. Additionally, the land needed for development needs to occur outside of the shorezone, thereby minimizing shoreline alterations. Smart growth policies need to be strengthened in some areas and created in others to minimize shore area growth. Additionally, a decrease in pollutants and toxics in the water needs to occur to facilitate growth. Increased funding for DNR's Creosote Removal Program would help in this regard. This program removes older, derelict docks, piers, bulkheads, etc. that are made from wood treated with creosote. The creosote in the wood is harmful to both plants and animals. Furthermore, areas need to be determined for restoration projects based on the suitability requirements for each type of vegetation. Marine preserves can be established through the DNR's Aquatic Habitat Conservation Plan program. Education efforts need to be established to teach motorized boat operators to avoid eelgrass and kelp areas so as to avoid chopping up the vegetation with their propellers. Part of this education effort would also be to encourage boaters to avoid high-energy wakes near the shore. Aside from minimizing pollutants and sedimentation, salt marsh habitats can benefit from a reestablishment of tidal hydrodynamics. Where possible, shoreline armoring needs to be removed in order to allow for natural wave action to occur. These are just some of the many policies that need to be in place in order to see an upward trend in "continuous" shorezone vegetation.

Sub-step 7C

Of the different change models presented as case studies by Steinitz (2012), we have chosen the rule-based change model. We believe this model is appropriate for a variety of reasons. The model is spatially sophisticated, allowing for different areas to behave differently depending on the influences placed upon them in the model. The rules for area change are strict and deterministic once locational conditions are exerted upon those areas. The rule-based model requires a significant amount of work up front when determining the rules and what the behaviors will be. But once these rules are established is where we truly see the model shine. This model is particularly useful with sensitivity analysis. So if a desired future state is mapped or graphed, the inputs to a rule-based model can continually be tweaked to arrive at that future state. To affect change in eelgrass, kelp and salt marsh, we may have inputs for the following: current habitat conditions, salinity levels, temperature changes, restoration projects, policy changes, population and economic growth forecasts, etc. By adjusting these and other inputs, the model will provide different results. This will allow public agencies and interested parties to discover what measures need to be taken to arrive at a desired future state. However, the rule-based model can be utilized differently, but no less meaningfully. For the vegetation chosen as our indicator, there currently are no set goals or targets for future states, other than a "no net loss" or "improved" policy. The rule-based model can be used to illustrate what possible future states could occur depending on different input tweaks. These possible scenarios could then be used by public agencies or interested parties to choose what that desired future state might be. Additionally, as we learn more and more about our indicator and attributes, we can continue to adjust the model to account for that new knowledge.

Another option for a change model would be an agent-based change model. This is a form of rule-based change model that allows for individual behaviors. If we had been able to utilize area instead of linear measurements, our data representation might have been in a raster format. The vastness of the Puget Sound combined with a small cell size would allow for enough individual records to determine how

individual cells would act. Each individual cell would not only be subject to the general rules and behaviors created in the model, but would also be influenced by those cells immediately surrounding it. Marine habitats are often complex environments and this agent-based model might better account for this complexity.

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Appendix 4.

Extent of the range of marine habitat types in Puget Sound (4)

By Grant Novak

Sub-Step 1A

My conceptual framework analyzes a DEM of estuarine bathymetry using process described by Hammond (1964) and ESRI's ArcHydro tools to determine the extent of intertidal habitat adjacent to secondary estuarine drainage channels.

ArcHydro is used to construct the drainage network. Strahler stream order is assigned to drainage channels to define primary vs. secondary drainage channels. By measuring and analyzing neighborhood statistics in the DEM describing relief, profile, and slope we are able to delineate tidal flats. By converting the raster tidal flats to vector representations and using proximity analysis, we are able to define and measure the acreage of tidal flats in close proximity to secondary drainage channels.

I settled upon this framework for several reasons:

- 1) Bathymetry elevation models are currently available for assessment in order to make proof-of-concept analyses.
- 2) Because the input to our assessment is a single raster dataset we have a simplified and easily updated single input.
- 3) With the advent of water penetrating LiDAR along with decreasing LiDAR collection costs, using raster elevation datasets as input is a cost-effective and viable solution.

Sub-Step 1B

I originally considered conducting an assessment of water quality using an ArcHydro network and proximity of dairy farms (and manure-producing cows) to the streams. The complexity of determining water quality due to cow proximity, dilution based on flows, and degradation of pollutants led me to decide that the amount of effort involved in constructing the model would not be outweighed by the benefit of the assessment output. The pollutant load outputs would be open to suspicion because of the many assumptions used in the computations. I believe that it is important to assess potential water quality based on proximity and density of dairy herds to streams, I believe that my earlier ArcHydroManure model provides an adequate index by which to measure potential impacts and make qualitative comparisons of change without adding a level of detail that leads to increased skepticism.

Sub-Step 1C

Acreage of intertidal flats adjacent to secondary estuarine drainage channels.

Sub-Step 2A

Measures of slope, relief, and profile lead to delineation of flats. Using an elevation dataset and ArcHydro processes, a drainage network is constructed and Strahler stream order is designated for the drainage network in order to define secondary drainage channels.

Sub-Step 2B

Armstrong, D.A., C. Rooper, and D.R. Gunderson. 2003. Estuarine Production of juvenile Dungeness crab (*Cancer magister*) and contribution to the Oregon-Washington coastal fishery. *Estuaries* 26:1174-1188.

A simplified approach would be to delineate all intertidal area within an estuary as tidal flats but, because Armstrong et al have pointed to the increased importance of intertidal flats immediately adjacent to **secondary** drainage channels relative to tidal flats that are not adjacent to tidal flats, I felt it was important to differentiate between intertidal flat types.

Sub-Step 3A

My measure is the acreage of intertidal flats adjacent to secondary estuarine drainage channels. The intent is to be able to measure change in this metric based on the restoration of currently diked tidal flats.

My measure represents a state as well as an impact. The current situation is a state while the future situation is both a state and an impact depending upon the frame of reference of the individual making the assessment.

Sub-Step 3B

Dikau, R. 1989. The application of a digital relief model to landform analysis. In *Three Dimensional Applications in Geographical Information Systems*, ed. J. F. Raper, 51-77. London: Taylor and Francis.

Dikau, R., E. E. Brabb, and R. M. Mark. 1991. Landform classification of New Mexico by Computer. U.S. Geological Survey Open File Report 91-634.

Hammond, E. H. 1954. Small scale continental landform maps. *Annals of the Association of American Geographers* 44: 32-42.

Hammond, E. H. 1964a. Analysis of properties in landform geography: An application to broadscale landform mapping. *Annals of the Association of American Geographers* 54(1):11-19.

Hammond, E. H. 1964b. Classes of land surface form in the forty-eight states, U.S.A. *Annals of the Association of American Geographers* 54(1): map supplement

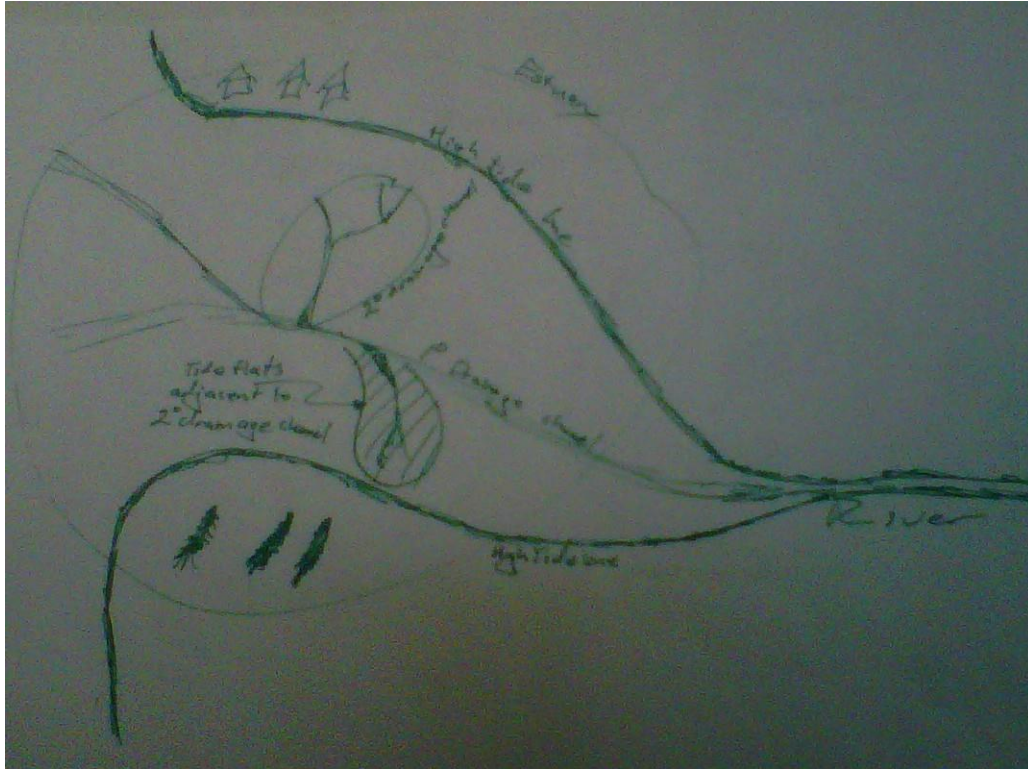
True, C. D., T. Gordon, and D. Diamond. n.d. How the size of a sliding window impacts the generation of landforms. PowerPoint presentation on the Missouri Resource Assessment

The above citations describe the measurement of slope, relief, and profile to make determinations of landform. I used methods described in these citations to delineate intertidal flats. While I used the methods in the citations as a basis, I did modify some of the analysis steps. Namely, I adjusted the analysis neighborhood sizes, as well as some of the reclassification values to better fit the elevations, profile, and relief measures found in the dataset I used in my primary assessment (Willapa Bay estuary).

Strahler, A. N. (1957), "Quantitative analysis of watershed geomorphology", *Transactions of the American Geophysical Union* 8 (6): 913-920.

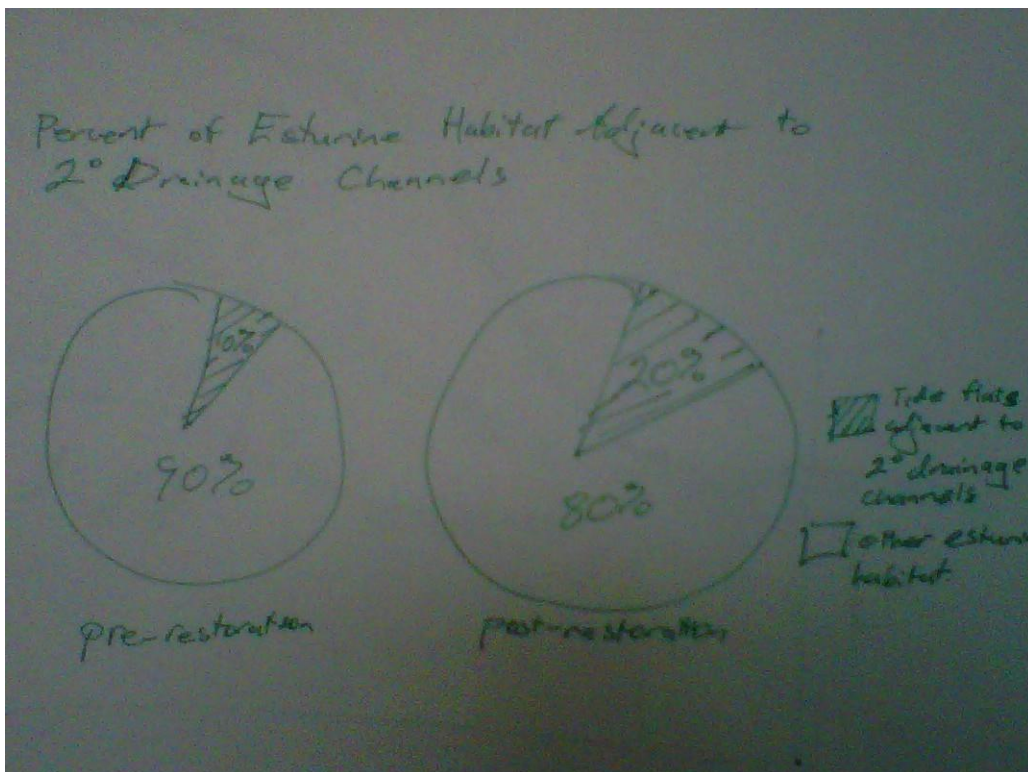
In order to determine primary channels vs. secondary, tertiary, etc. channels, I used the ArcGIS Spatial Analyst tool 'Stream Order'. Another option would be to use the Shreve method of ordering stream reaches but this was not as applicable as the Strahler order to determining secondary vs. primary reaches in the drainage network.

Sub-Step 3C



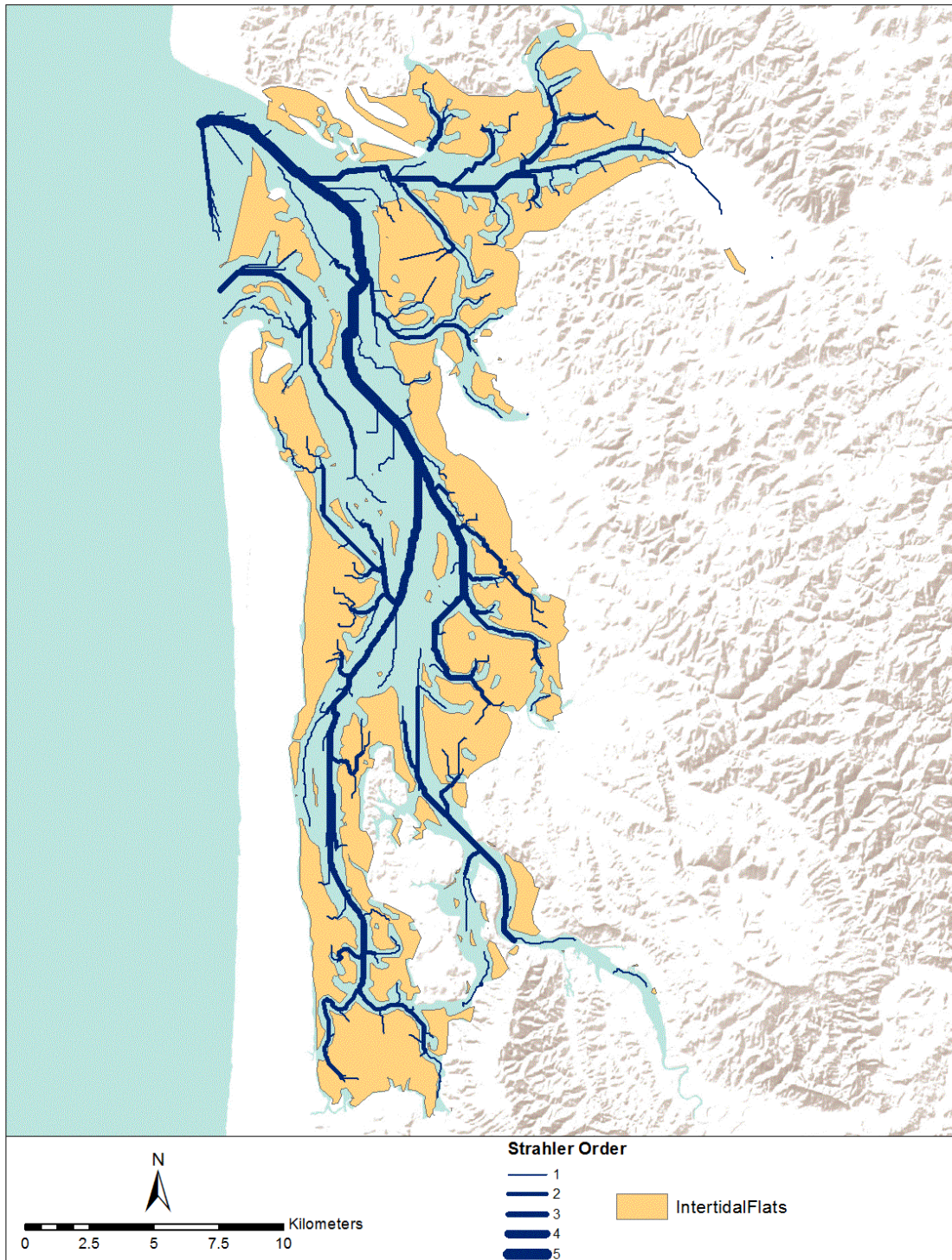
The above map is a representation of a dendritic estuarine drainage network. The intertidal flats adjacent to secondary drainage channels are known to be high quality foraging habitat for juvenile Dungeness crab. By removing dikes and restoring channel forming processes it is believed that a benefit may be realized to Dungeness crab populations.

Sub-Step 3D



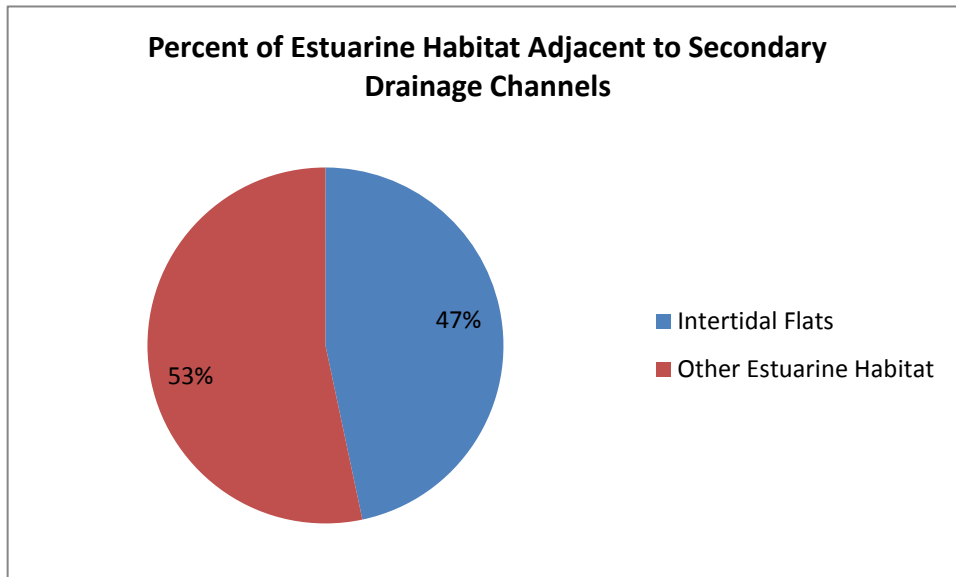
Charts of the percentage of estuarine habitat that is intertidal flat adjacent to secondary drainage channels vs. other habitat in pre- and post-restoration points in time. The change in percentage over time could also be representative of channel forming processes, sea level rise, or anthropogenic alterations.

Sub-Step 3E



By implementing methodology described by Hammond (1957), and Dikau (1991) I was able to assess landform within the Willapa Bay estuary using a digital elevation model describing bathymetry. Using the landform assessment and a polygon of the extreme low tide elevation (created by selecting DEM elevations greater than extreme lower low water and converting to a polygon) I was able to delineate intertidal flats within the estuary. I originally intended to determine the acreage of intertidal flats adjacent to only secondary drainage channels. I used ArcHydro to create a drainage network and used the stream order tool to determine Strahler stream order which was to allow me to determine secondary vs. primary channels but time (lack thereof) and complexity of the effort (increasing amount) did not allow me to complete this line of analysis. Instead, my analysis ended with the delineation and calculation of acres of intertidal flats. Future iterations of the model will include stream order of drainage channels. As can clearly be seen in the above figure there are intertidal flats that do not have associated nearby channels which are important for juvenile Dungeness crab as they provide subtidal refugia when the tide ebbs.

Sub-Step 3F



This chart shows that there is a very large portion of the Willapa Bay estuary that is intertidal mud flats which are very important to rearing juvenile Dungeness crab.

Step 4|5|6

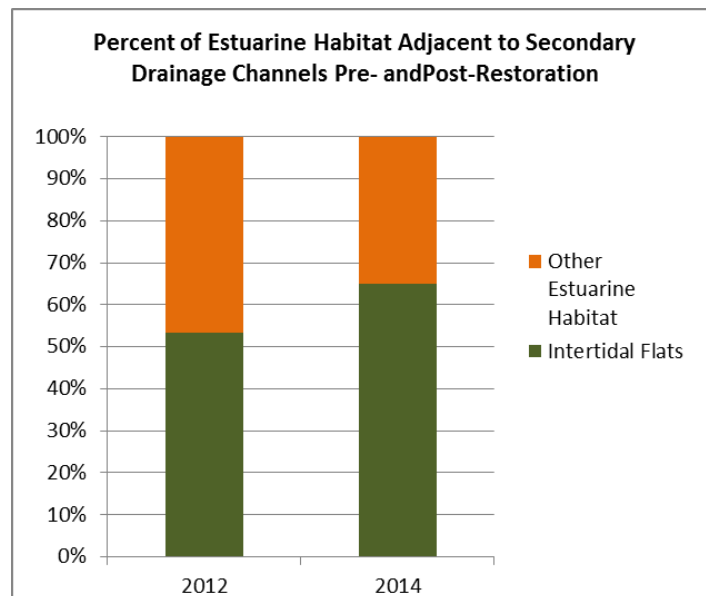
Overall the methodology that I have described and begun to implement is sound and relevant. If implemented as I have described the methodology would give a valid representation of the amount of intertidal estuarine habitat adjacent to secondary drainage channels. Unfortunately time did not allow for some of the finer details of the methodology to be implemented. Had I able to finalize the assessment to refine the acreage calculation and limit it only to those intertidal flats adjacent to secondary channels then we would have a much stronger argument for using the acreage as a measure of available prime rearing habitat. That said, I have begun to wonder about the distance that a juvenile crab might be expected to travel during a single tidal exchange. Because intertidal habitat is adjacent to a secondary channel does not make the entire flat available to foraging by juvenile crab during flood tides. If the flat is too large for the crab to travel across the entire flat then the entire flat should not be included in the acreage calculation. It seems that weighting available habitat by Euclidean distance may help us to arrive at a more valid determination of available habitat acreage.

Sub-step 7A

I do not have the layers in hand so I will describe map 2 using text.

In their paper [Geospatial Habitat Change Analysis in Pacific Northwest Coastal Estuaries](#), Borde et al (2003) show mapped estuarine habitat that has been modified by human development. It is not perfectly clear but it appears based on the location and extent of the impacted habitat that these are diked areas that could be restored and made available to rearing juvenile Dungeness crab. My map 2 would include this additional habitat. One deficiency of including this additional habitat would be the altered nature of the elevation profile. Because diked areas in Willapa Bay are typically cow pastures they have been smoothed and the drainage channels have been removed. It is expected that any restoration project would include conceptual designs from which elevation models could be created and included in the current bathymetry representation. This would allow for an increasingly refined assessment of the additional intertidal habitat provided by removal of the dikes and restoration of the intertidal habitat.

Sub-step 7B



In order for graph 2 to look like graph 1 a considerable amount of intertidal restoration must occur to reconnect diked areas to the effects of tidal habitat forming processes.

Sub-step 7C

I believe the rule-based change model to be the most appropriate for this situation. Because the changes and implementation to move the estuary from situation 1 to situation 2 require a great deal of specialized local knowledge and input from overseeing agencies, the rule-base model , which assumes that the geodesign team is knowledgeable and confident enough to specify a formal set of rules for developing the design, would be a very good choice.

An alternative option would be to use the anticipatory change model. Similar to the rule-based model, the anticipatory model assumes that the geodesign team are knowledgeable enough to arrive at a design that is a best fit for the situation.

Appendix 5.

Freshwater quality in lakes as well as streams, and primary organic productivity in freshwater habitats

By Joel Perkins

Sub-Step 1A

I used conceptual frameworks from a couple of different sources. I used the Washington State Academy of Sciences' framework of including lakes in PSP's dashboard of indicators and also including primary productivity as an indicator of the key attribute lake trophic status.

I also drew from O'Neill's 2008 (NOAA Northwest Fisheries Phase I Environmental Indicators for the PSP: A Regional Effort to Select Provisional Indicators) report. This framework goes a step further and identifies phosphorus as the measurement that defines the indicator (primary productivity) of the key attribute (lake trophic status).

I tweaked these frameworks to also include the measurements Chlorophyll – A and Secchi Disc readings (in addition to the aforementioned Total Phosphorus) as part of a Trophic Status Index that was created by scientist Robert Carlson in 1977).

I selected this framework because my researched revealed to me that TSI scores were a robust and fairly accurate way of measuring primary productivity in lakes and this method has been around for over 30+ years, and during this time has performed quite well as a measurement (and predictor) of trophic lake status.

Sub-Step 1B

I did look at only including phosphorous (instead of adding CH-A and SD) as O'Neill et al recommends and I also took a look at the framework from the PSP entitled Ecosystem Status & Trends 2009 which includes a framework of using a water quality index to measure water quality.

In this document, the PSP makes the statement that “stations with the lowest scores tended to have high nitrogen concentrations”, which seems to be consistent with the rationale behind O'Neil's recommendation of only including phosphorus as an indicator attribute. So I do think that was something to consider (and I did consider just sticking with phosphorus instead of adding in CH-A and SD). But in the end, I think its easy enough to incorporate the three biological measurements and also, I like the fact that Carlson's TSI is a scientific approach whereas the water quality index is more of a subjective index (good, bad, OK, etc).

Sub-Step 1C

As mentioned above, water quality in freshwater lakes and specifically trophic lake status (as a means to track eutrophication) are my key attributes.

Sub-Step 2A

Primary productivity in freshwater lakes is my indicator that represents these attributes.

Sub-Step 2B

Primary productivity refers to the rate at which organic matter is created by producers in an ecosystem. When primary productivity increases (thus more organic matter is created), the result will be an increase in algal biomass. An increase in algal biomass will change a lake's trophic status (ex. from mesotrophic to eutrophic). Therefore, I think primary productivity is the best way to represent the key attribute of trophic lake status (eutrophication).

There are other possible indicators that might represent trophic lake status, one of them being soils for instance. I looked at a study that examined possible phosphorus buildup in lake soils that were associated with dairy farms. Even though we know phosphorus does correlate with trophic state, according to this study "Overall, there was no spatial or temporal buildup of soil P and other crop nutrients despite the annual application of fertilizers and daily in-field loading of animal waste."

Now that might be just one area – but it would appear that soils aren't the best indicator for trophic status and that is why I stuck with primary productivity as a more reliable option.

Sub-Step 3A

The metric is a TSI score and its methodology is documented below.

Total Phosphorus – measured in micrograms at surface

$$TSI(TP) = 14.42 (\ln TP) + 4.15$$

Chlorophyll A – measured in micrograms at surface

$$TSI(CH) = 9.81 (\ln \text{Chl } a) + 30.6$$

Secchi Disc Transparency – measured in meters.

$$TSI(SD) = 60 - 14.41 (\ln SD)$$

To get a complete TSI, you would take the 3 individual TSI scores and average them.

$$TSI = ((TSI(SD) + TSI(CH) + TSI(TP))/3)$$

My metric represents a **state** in the Puget Sound socio-ecological system, which is trophic lake status. It does that as an index where:

A score of 0 – 40 represents a oligotrophic lake, 40-60 represents a mesotrophic lake, and 60-100 represents a eutrophic lake. It is recommended that the definition of this state be arrived at only after several years of recording measurements (in other words, you need to establish a baseline). In my project, I established a summer's average (Jun-Sep) from 1997 to 2008 for all three TSI attributes for each station. That is my station baseline. I then interpolated TSI values in the lake for areas where stations aren't present. So what I get is a single metric that represents trophic lake status levels over a period of time.

Sub-Step 3B

I will use Carlson's rationale for how he concludes that TSI levels appropriately represent primary productivity in lakes by citing a few passages from *A Trophic State Index for Lakes* (Carlson 1977).

“The ideal trophic state index (TSI) should incorporate the best of both the above approaches, retaining the expression of the diverse aspects of trophic state found in multiparameter indices yet still having the simplicity of a single parameter index.”

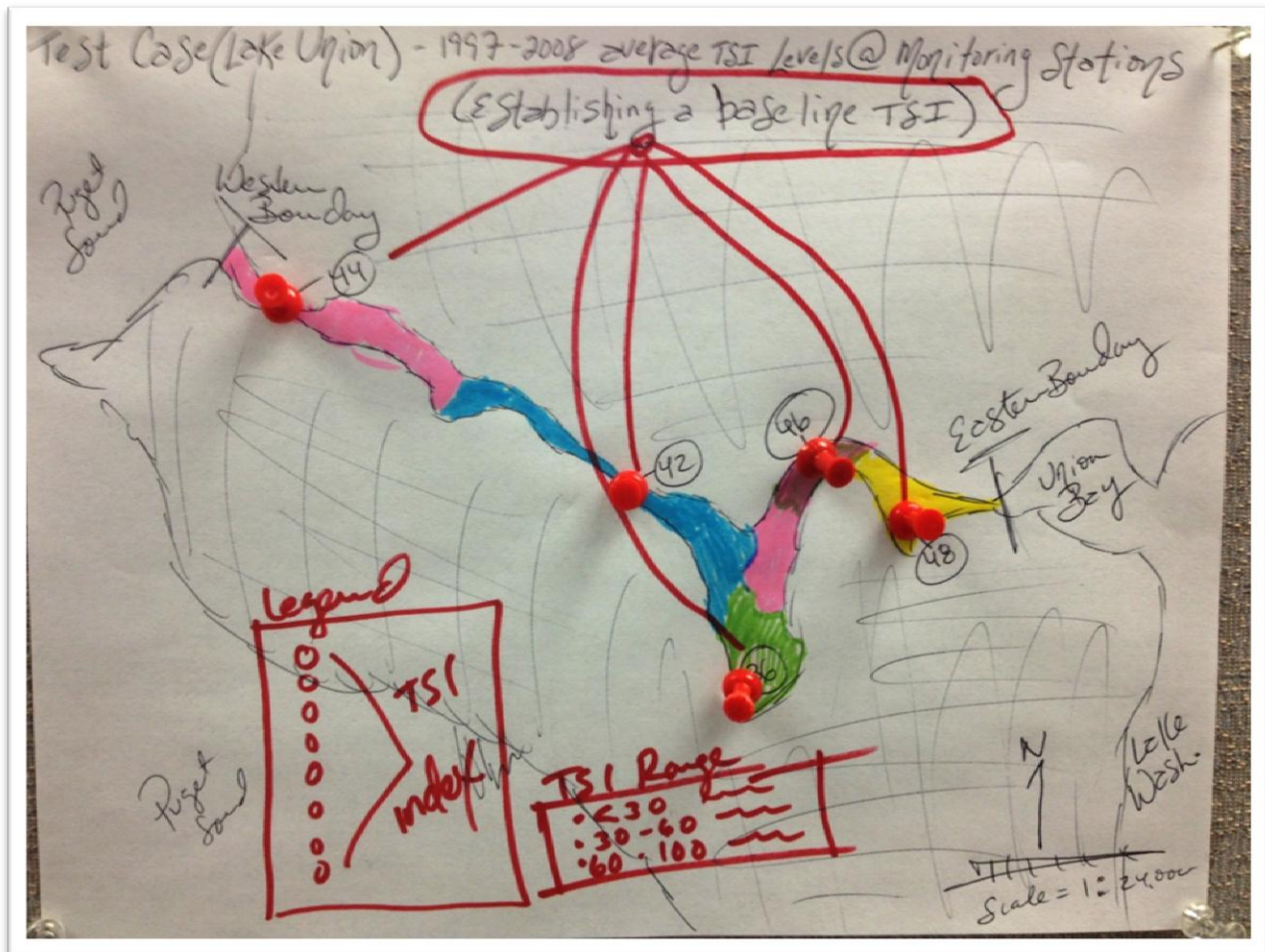
“Calculation of the index for more than one parameter for a given lake also serves as an internal check both on methodology and on assumptions as to relationships between parameters”

“Secchi disk values alone can give a trophic state classification, information that can be collected even by nonscientists in public-participation programs at little expense (Shapiro et al. 1975). If the survey is more extensive, data on chlorophyll and total phosphorus can provide supplementary or alternative index values. The index number gives both the public and the limnologist a reasonably accurate impression of a lake’s water quality.”

I could have maybe went with a water quality index to measure primary productivity, but a water quality index that measures just nitrogen for example may give you thresholds for “good” or “bad” lakes, but again, those are subjective. Also, just measuring TP instead of (TP, CH-A and SD) isn’t as good either because the differing indicators act as a check on each other to make sure one isn’t an outlier – but also because out of the three, there are times of the year where TP isn’t the best indicator (CH-A would be better in the summer for example).

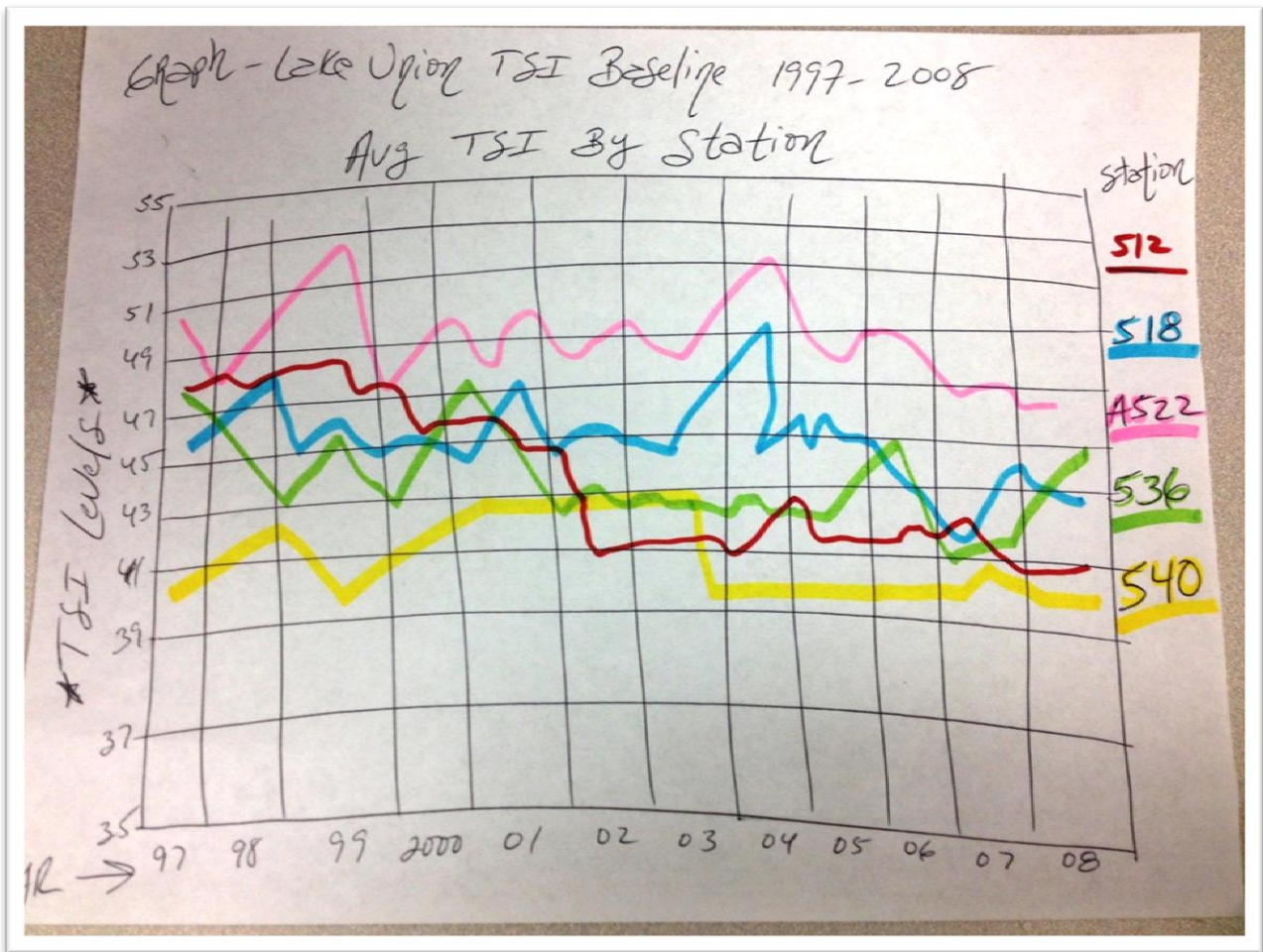
Sub-Step 3C

I have created a sketch of Lake Union as my test case, and this lake represents all lakes in the Puget Sound region. This sketch shows 5 water monitoring stations (red pins), and each of the monitoring stations has averaged TSI scores from 1997-2008 at that particular station. So each station has a single number. Then I interpolated each monitoring station TSI score between the other stations to see what values would look like in other portions of the lake where no monitoring station exists. The goal here was to establish a baseline TSI from which to work from and to measure against in future measurements.



Sub-Step 3D

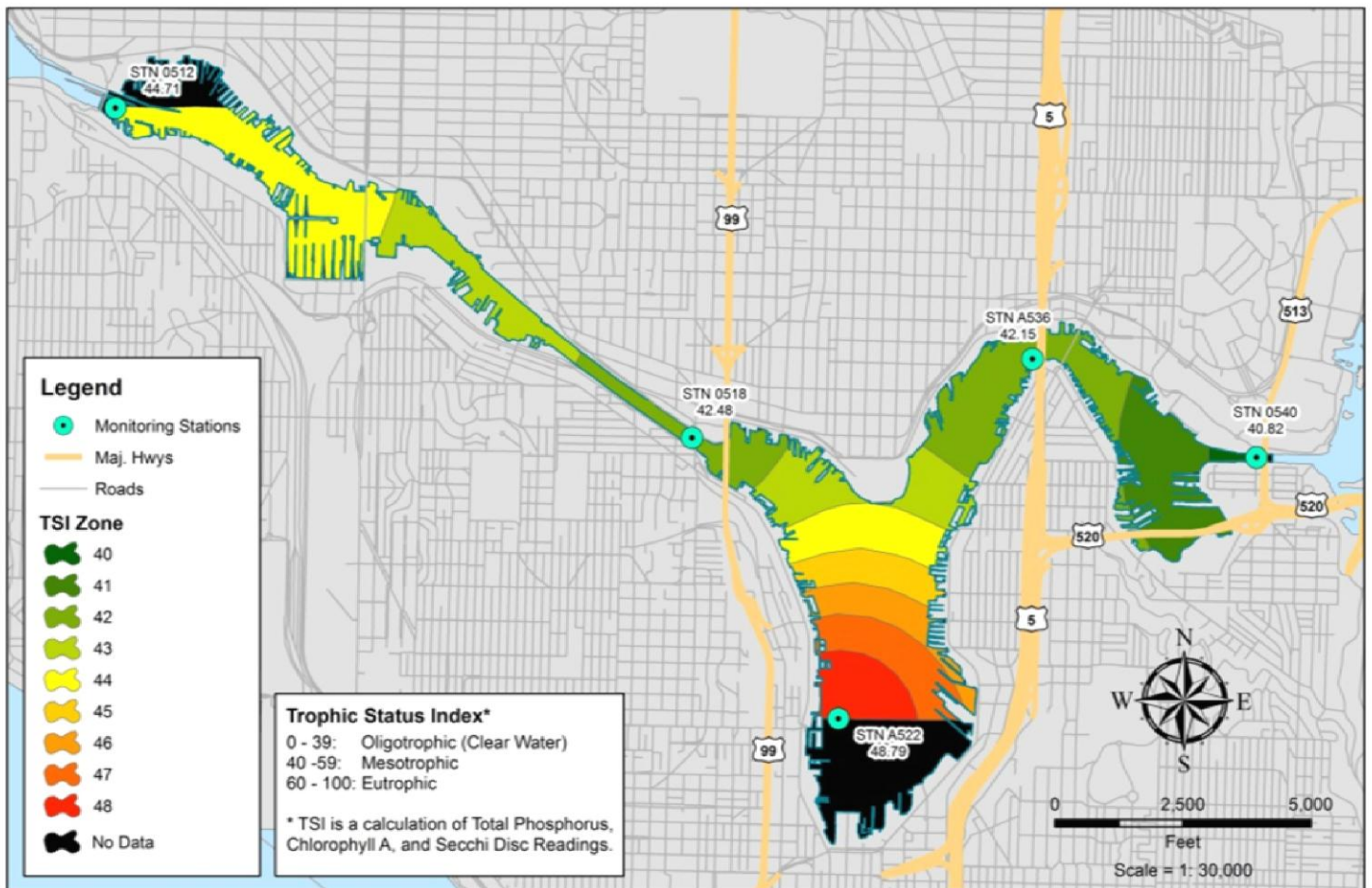
The below graph is basically a visual of yearly TSI recordings at individual stations from 1997-2008. These aren't real – just my idea of what I wanted to do. So on the vertical axis on the left, we have TSI scores. On the right vertical axis, we have the monitoring station ID's. And then on the bottom, I show the years from 1997 – 2008. So if you went back to my map sketch, Station 0536 shows a score of 46. In the graph below, all these years of TSI scores would average out to 46 for Station 0536. (For the sketch portion - map and graph, the numbers are just dummy numbers. I was simply sketching my concepts knowing that real numbers would be plugged into my actual map and graph).



Sub-Step 3E

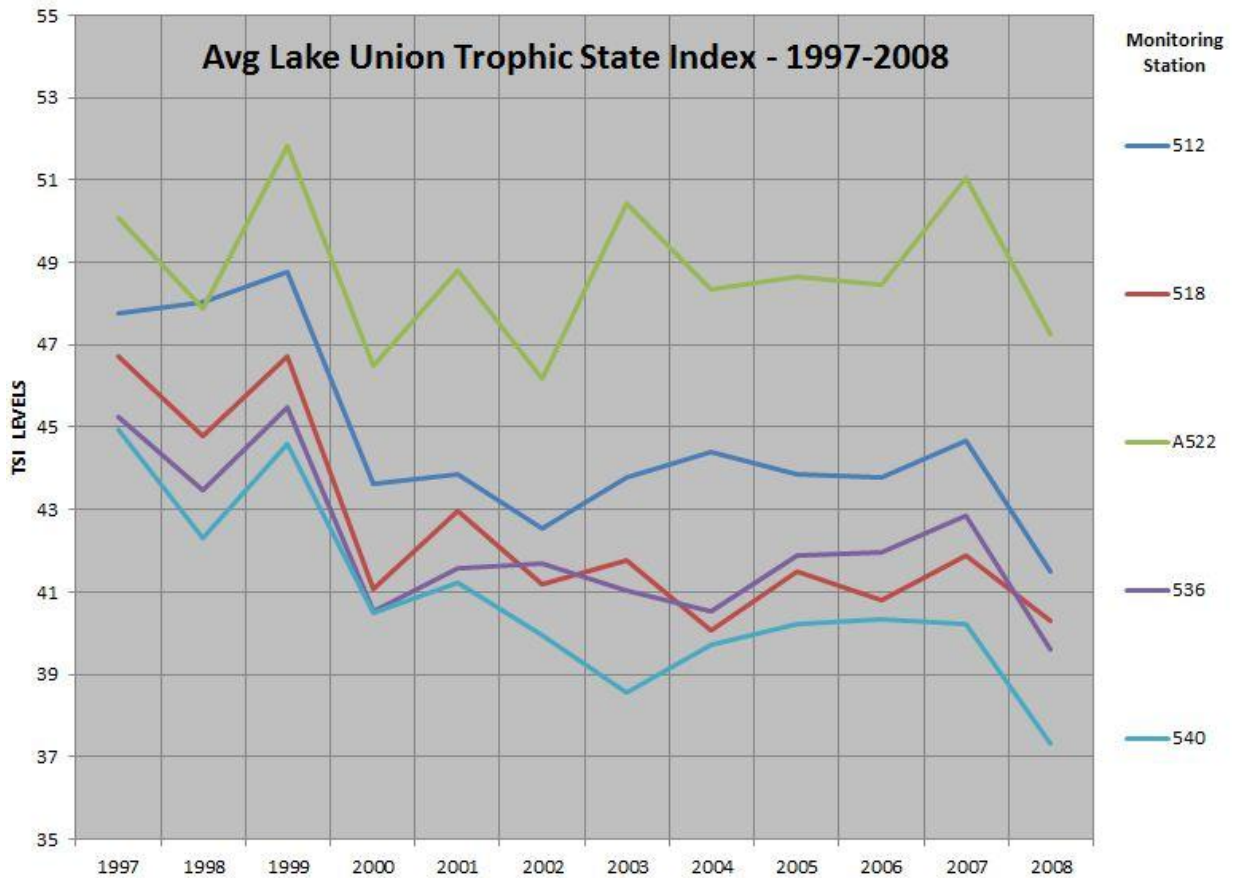
This map is exactly what I had in mind when I did my sketch, except I have actual numbers inputted in the stations below. TSI numbers range from 40 to 48. So I have established a baseline TSI number for each station based on 1997-2008 averaged recordings. I then did a IDW interpolation between the 5 monitoring points to represent lake trophic status where no monitoring points exist. Of course the problem with this is that interpolation won't work if there is no data point to interpolate with, thus we see black areas in at station A522 and station 0512 to represent no data. Each of the color bands represents a TSI score (shown in legend). My IDW didn't work very well when I used Lake Union as the limiter, so I just did the interpolation and did an extract by mask (using lake union as the mask). I then used the INT tool in the math toolset to change the raster to an integer one, so I could convert it to a polygon. The reason I do this, is so I can do a union with the 2009-2012 layer later on. I created a working modelbuilder for this work. Obviously, the northern part of the lake is on the lower part of the TSI rating as compared with the southern portion. The southern monitoring station has a considerably higher TSI score though, so you see the interpolation happening from the south to the north.

AVG. LAKE UNION TROPHIC STATE INDEX LEVELS JUN - SEP. 1997 - 2008



Sub-Step 3F

The graph below shows actual yearly TSI ratings for each monitoring station in Lake Union. I find it interesting that station A522 has spikes from year to year and is consistently more trophic than the other stations. The other stations have mostly trended downwards from 1997 – 2008, which is great. This is why we see in the map that station A522 is much higher than the others, because it hasn't trended downwards like the others.



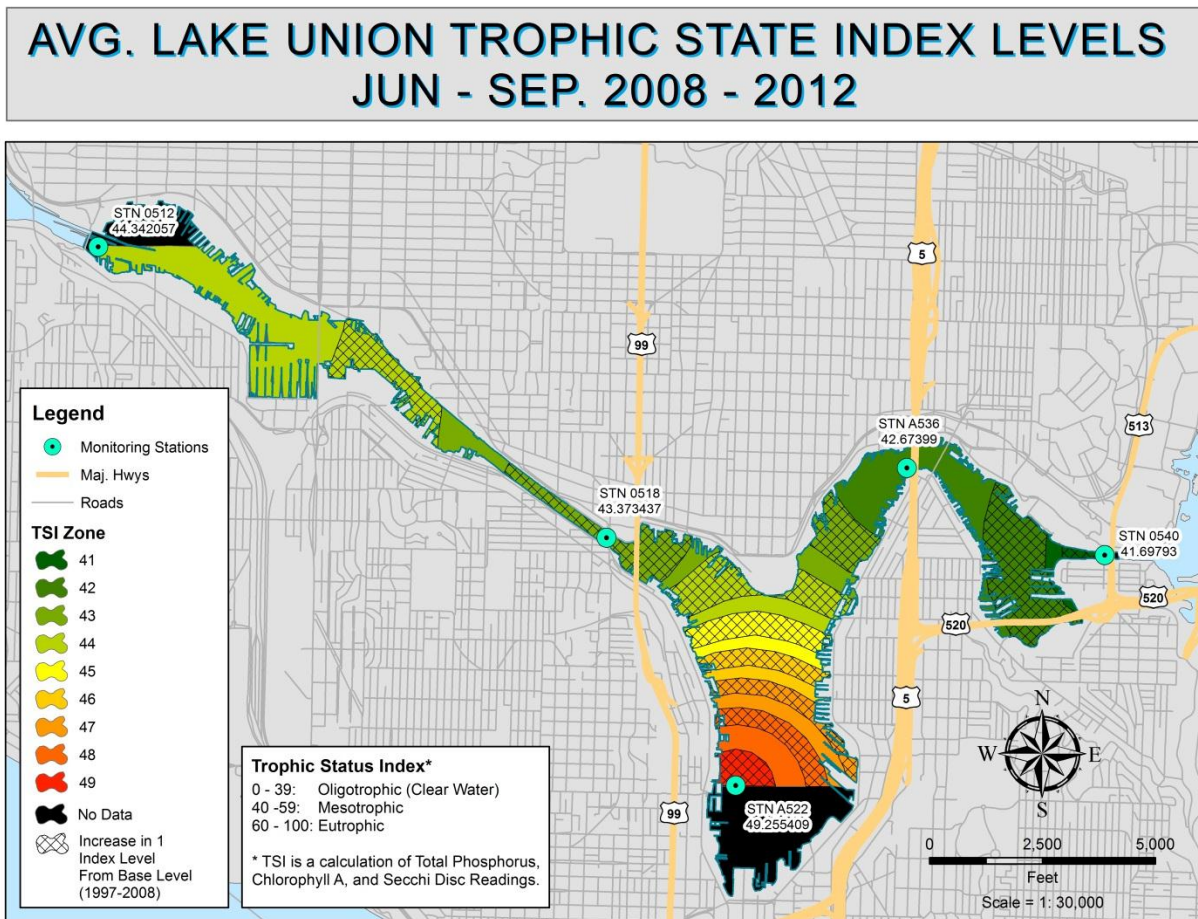
Step 4|5|6

I think my work in step 3 represents trophic lake status reasonably well. My baseline work is a collection of 12 years' worth of Summer TSI averages, which is about what you would want. I mentioned earlier the problems I had with the IDW, which unfortunately resulted in pockets of 'No Data'. This could be remedied by adding more monitoring stations. I struggled with the idea of using interpolation at all. "Is this really useful" I kept asking myself? Well, I think it works better when you add in more stations, but also I think my map would get agency thinking – "If that is the stated interpolated value, maybe we should implement more stations to get the actual values there". King County had several more monitoring stations in its dataset, but recordings were only taken at the 5 I show. My research turned up the fact that recordings would ideally be taken at the deepest part of the lake. This isn't being done at Lake Union – so that is another argument for more monitoring stations. Lastly, I would argue that my interpolation process is most useful later on – when I show areas of change.

I think the graphs paint a pretty good picture – but I did have to plug the raw data into my TSI equation myself and in the interest of time, I plugged in all recordings regardless of depth. It was take additional insight with the data recorders to make sure that was the proper avenue to take – or if some data should have been omitted. That being said – my scores come out in the mesotrophic range, which is what King County and the Dept of Ecology state most of the lakes are in the Puget Sound Region.

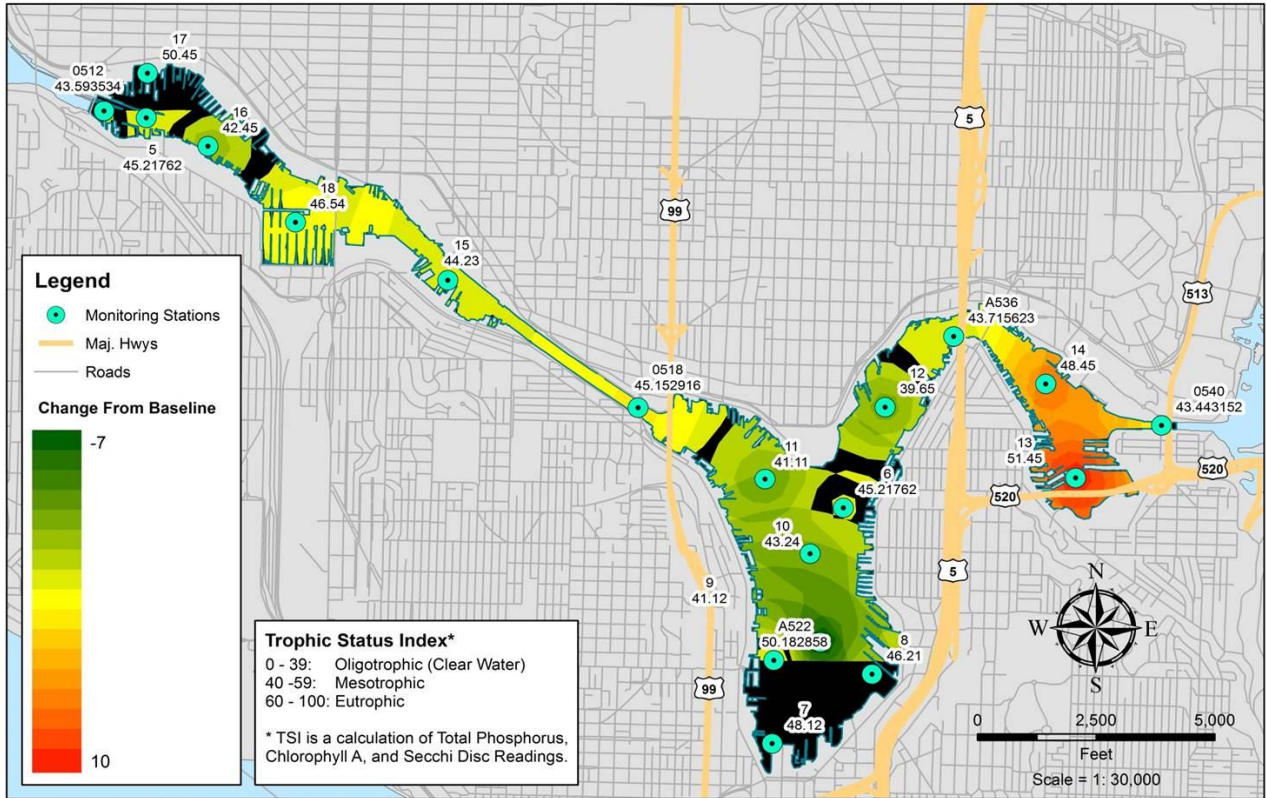
Sub-step 7A

This map is Trophic State Index levels for 4 years after the baseline was recorded. The area where you see hashed marks are the area of increase from the baseline years to this set of years. This is where I see the interpolation as most useful, where it can show you areas of change.



I will also include this map as a 2020 potential situation if more monitoring stations were added. In this map, I have extrapolated out numbers based on historical trends, and then introduced new monitoring stations and simply gave them values based on nothing. My plan was just to show what this interpolation would look like with more monitoring stations. The green areas show areas of improvement from the original baseline map – and areas in red show regression of trophic status.

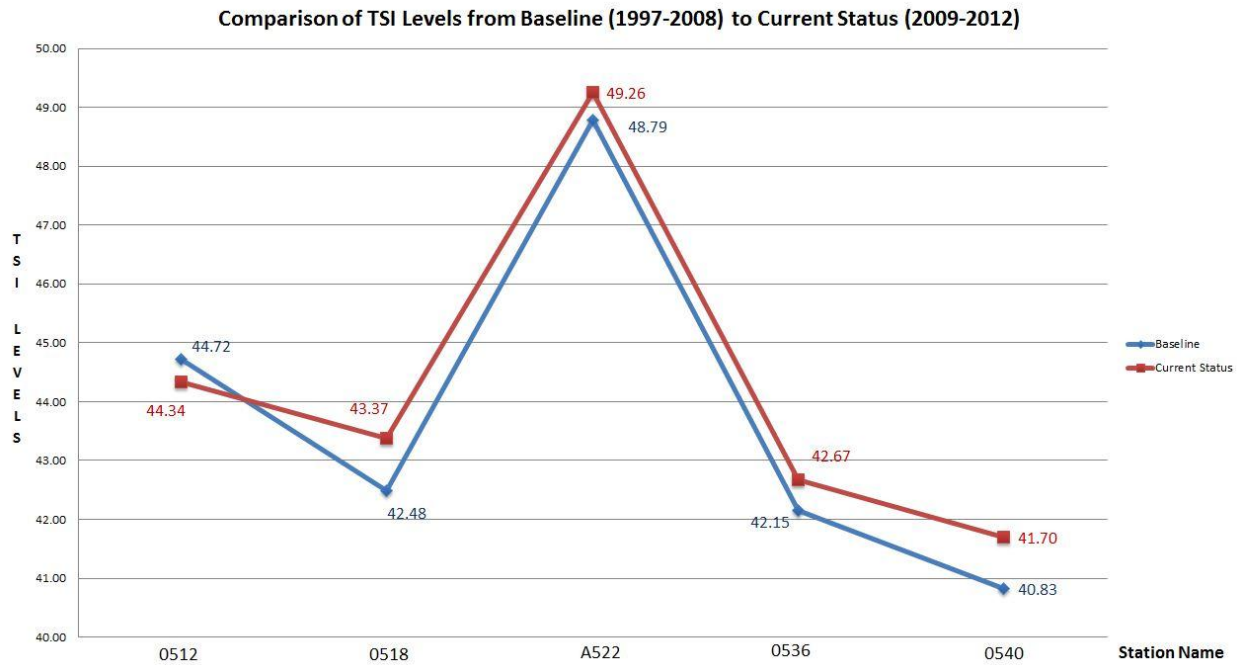
AVG. LAKE UNION TSI CHANGE LEVELS FROM BASELINE TO 2020



Source: King County Major Lakes Monitoring

Sub-step 7B

In this case, I show a graph of change from the baseline to the 2008-2012 block of years. This graph shows worsening scores at 80% of the stations – but big picture, they aren't getting worse by a lot. This could easily be simple natural aging of the lake. But the preferred state is that the scores hadn't jumped wildly and rapidly. Various agencies would be happy with this graph I think because it shows the lake is still a ways away from being classified as eutrophic (score of 60 or greater). The graph below probably wouldn't cause an agency to call for drastic changes at this location – but they can monitor the situation in the context I have laid out in this report.



Sub-step 7C

I believe based on the readings that I would advocate for an optimized change model. I like that this model calls for the decision criteria to be measured in a single metric, which is what my proposed change calls for as well (TSI). This model assumes that my proposed criteria will be able to link with actions that allow Trophic Lake Status to get to a preferred state. I'm pretty comfortable that I have a good plan for that, but also if there is a better plan that has yet to be discovered, if it was also measurable with a single metric – it could compete in this model to see which plan was optimal. Another reason I like this model is that my solution can be implemented in a computer program, which I have already done (efficiently, inside a modelbuilder process). The way it would work is: I would propose a scope of all the lakes within the Puget Sound Region. Some of those lakes would have a history – some wouldn't. That would need to be evaluated up front. From there, we can get in to the processing and representing phase. Data gets processed and inputted into the program for areas where data exist – and the data collection begins in the remaining locations. We introduce requirements, such as number of monitoring stations and number of mandatory testing occurrences. Decisions are made for what constitutes a baseline and what constitutes a trend (how many years would equal enough years to establish a trend?) It is at this time that perhaps my plan gets compared with other change models. Impacts are compared across models and decisions are made as far as which model would be most optimal.

Option B for me might be the anticipatory change model – just because one of the pillars of this model is that it requires the designer to see the whole solution from the get-go. I have a solution that ostensibly does have a complete solution – however this model also typically requires that the designer be experienced in their approach, which I am not. The few actual projects that I have worked on that were completely brand new geodesigns, I also had a complete solution. However, because of inexperience, several changes were made along the way. Because of my inexperience, I see that this could be a possibility with my primary productivity solution. Also, the anticipatory change model is more suited for smaller scale projects that require quick implementation. The changes I am proposing would definitely be in the category of a larger scope. However, I think this plan would might be a good secondary option but definitely not better than my option A.

Appendix 6.

Freshwater quality in lakes as well as streams, and primary organic productivity in freshwater habitats

By Jon Walker

Sub-Step 1A

Currently the streams feeding into the Puget Sound are monitored to assess the overall water quality in relation to certain parameters. These parameters are combined to form a Water Quality Index (WQI) score on a scale of 10 – 100, the higher the better. Currently, scores are averaging in the 70s, with a target of moving into the 80s by 2020.

On page 48 of the “Review for the Puget Sound Partnership” (WSAS), it is recommended to expand on the five conventional pollutants, and include additional components pertinent to freshwater quality such as ammonia, nitrate + nitrite, total nitrogen, total phosphorus, conductivity, suspended solids, fecal coliform bacteria, oxygen, temperature, flow, and pH.

For the conceptual framework of this analysis, I have chosen to put the WSAS recommendation into action, and analyze the levels of ammonia, nitrate + nitrite, total phosphorus, and fecal coliform bacteria at X locations in Water Resource Inventory Area 9. Of particular interest is the contribution of these components at downstream locations from upstream locations. This analysis aims to accomplish two main objectives:

- Strategically identify target areas to apply resources in an effort to have the greatest effect on improving water quality in the watershed
- Identify potential locations where water quality monitoring is needed

This will be accomplished by assessing the component load at a particular monitoring site by multiplying the average parameter rate in 2011 by the average annual flow. Flow data was obtained in cubic feet per second from the Q000D attribute estimated by NHDPlus (NHDPlus V2 User Guide, 131). This load quantity is to be accumulated downstream, and then divided by the downstream flow to obtain a new parameter rate at the downstream location. This new rate gives an indication of how much of the downstream site parameter rate is accumulated from the upstream catchment area. Target rates can then be applied to upstream locations to give an indication of how the downstream parameters will be affected.

In the above description, a few representation choices were made.

- WRIA 9 was chosen as a larger scale focus area, however this analysis is recommended to be applied to the entire Puget Sound watershed.
- Parameter values were averaged for 2011 data. 2011 data was chosen as this is the latest available from the Department of Ecology. Values were averaged to match with average flow data, and to provide a general ‘proof of concept’ model prior to looking at individual dates. It is recommended that this analysis be split up by seasons, and match seasonal parameter rates with seasonal flows.
- Only four parameters were looked at: ammonia, nitrate + nitrite, total phosphorus, and fecal coliform bacteria. These were chosen over parameters such as temperature because they can be applied to flow data in the logical model. Many other variables exist for parameters such as temperature that are outside the scope of this analysis.

Sub-Step 1B

I recommend that biodegradation be incorporated in the model for each of the parameters analyzed. This analysis currently does not take degradation into account, and assumes that any component load that is measured upstream will arrive in full form downstream. In reality, this is likely not the case. With degradation currently not in the model, load quantities downstream are quite possibly overestimated.

Sub-Step 1C

Average parameter 2011 rates for:

- Ammonia
- Nitrate + nitrite
- Total phosphorous
- Fecal coliform bacteria

Average annual flow (cfs)

These attributes can be visualized in the flow map below, which shows both the five monitoring locations, as well as line widths displayed to show average annual flow in cubic feet per second.



Selected monitoring stations (DOE and King County) and average stream flows in cfs (NHDPlusV2)
 WRIA 9, King County Washington

Sub-Step 2A

Freshwater quality

Sub-Step 2B

“The WQI for rivers and streams combines eight measures of water quality. Expectations for four of the component measures (dissolved oxygen, pH, temperature, and fecal coliform bacteria) are tied to the State’s Water Quality Standards for protecting aquatic life and contact recreation. The other four measures (nitrogen, phosphorus, suspended sediment, and turbidity) do not have numeric standards. Toxics are not included in the index.” State of the Sound, 2012

The attributes I have selected take into account the recommendations from WSAS, and directly correspond to the freshwater quality index. It is recommended that these attributes be incorporated in the WQI, and that the model proposed is used as a means to strategically reduce these parameters to 2020 goals.

Shellfish beds are affected by nutrient loads, and can be closed down when water quality levels are low. The shellfish bed indicator utilizes a different set of attributes than freshwater quality, and for this reason, it was seen as possibly benefiting from the model measurements, but not representing the key attributes selected.

Sub-Step 3A

Measures –

Washington Department of Ecology stream monitoring data -
http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html

King County streams water quality monitoring data –
<http://green.kingcounty.gov/wlr/waterres/streamsdata/StreamList.aspx>

Data from the above sources were averaged by station for 2011. These measurements represent a *state* of the freshwater in the Puget Sound, as they are actual measurements at a specific time.

The data were manipulated and changed representation in the following steps:

- Units adjusted from L and mL to ft³
- Parameters multiplied by average annual flow (NHDPlusV2) to obtain average load
- Average load accumulated downstream
- Average load divided by average annual flow to obtain effect downstream from upstream catchment

In the final step above, the original data is transformed to represent the *impact* downstream from upstream catchments.

Pressure changes can be represented by the reduction or increase of site parameter readings, and the estimated impact downstream may be observed.

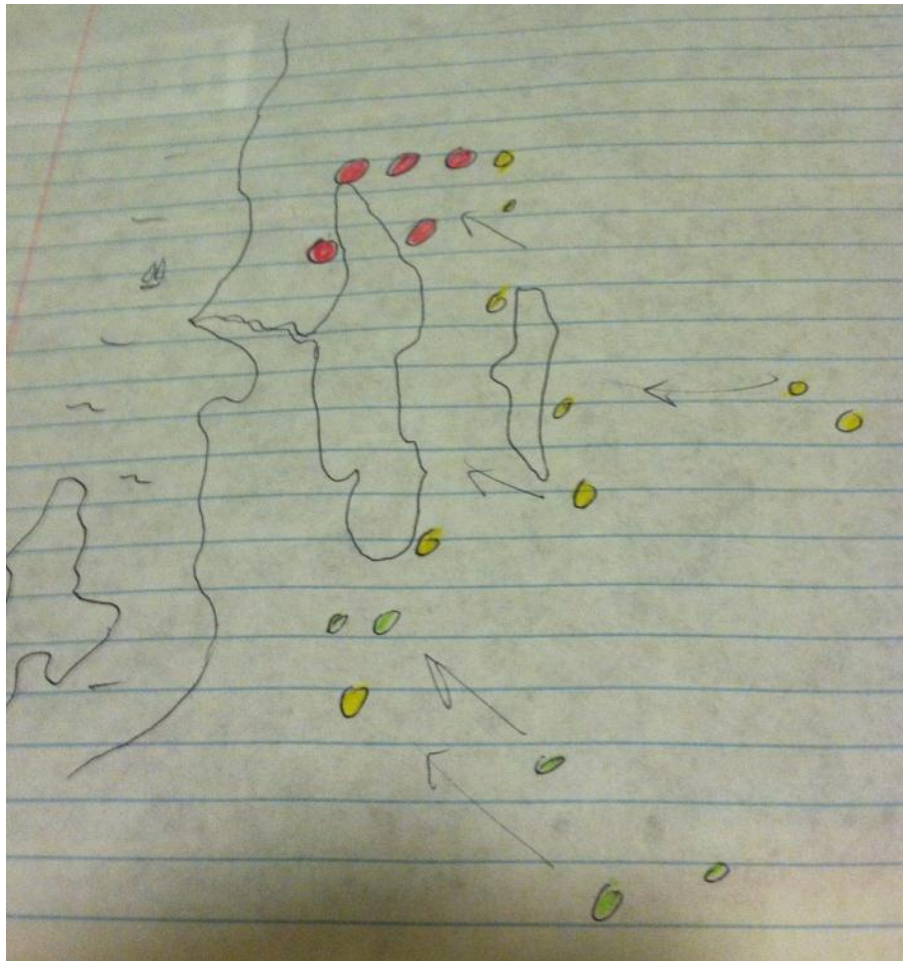
Sub-Step 3B

These are direct measurements of water quality by the DOE and King County, and are recommended by WSAS to be incorporated in the WQI scoring system.

Other measures weren't considered, as this data is clearly the best and most exhaustive data available in regards to water quality in the Puget Sound.

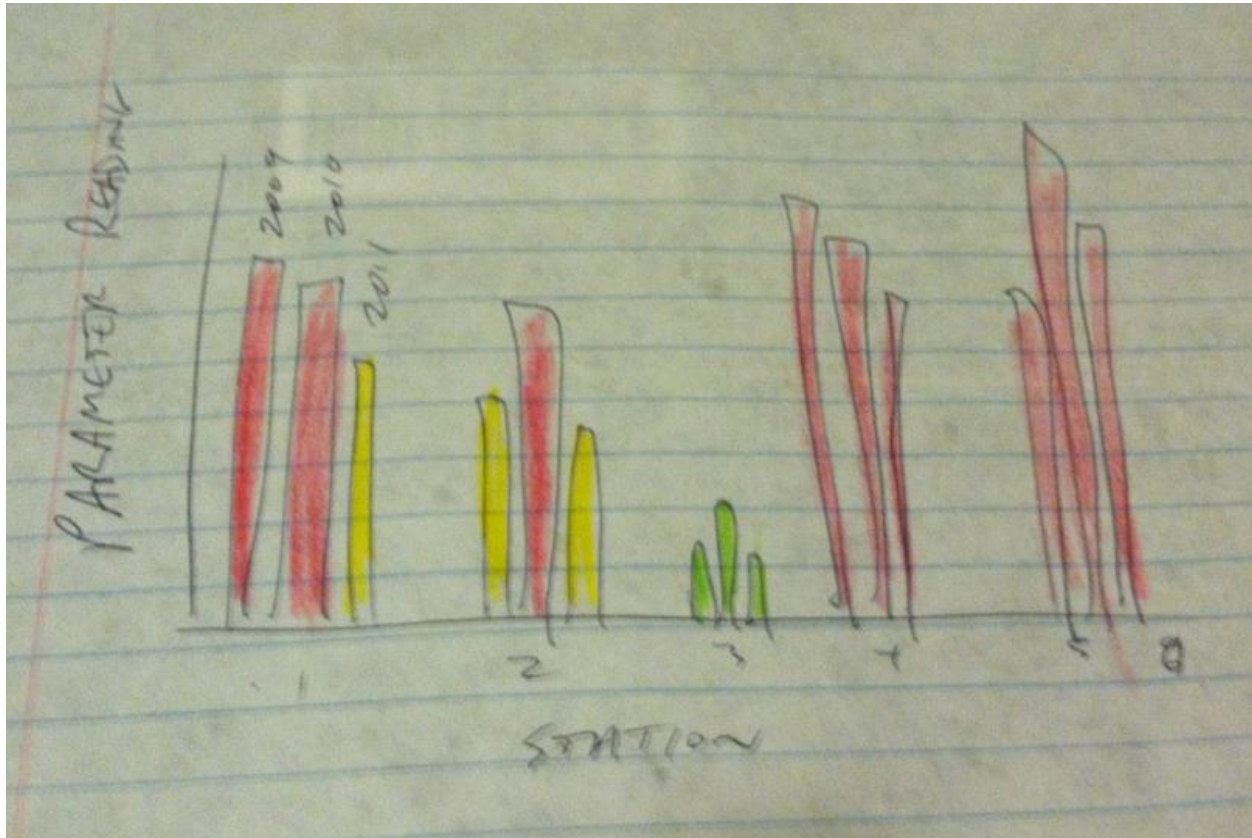
Sub-Step 3C

The map below is a simplistic sketch of water quality monitoring sites throughout King County. Red represents unhealthy readings, yellow of mild concern, and green as healthy. From this image, of interest to me was the geographic spread of the monitoring sites, and the relative impact of pollutant sources upstream on the downstream sites.



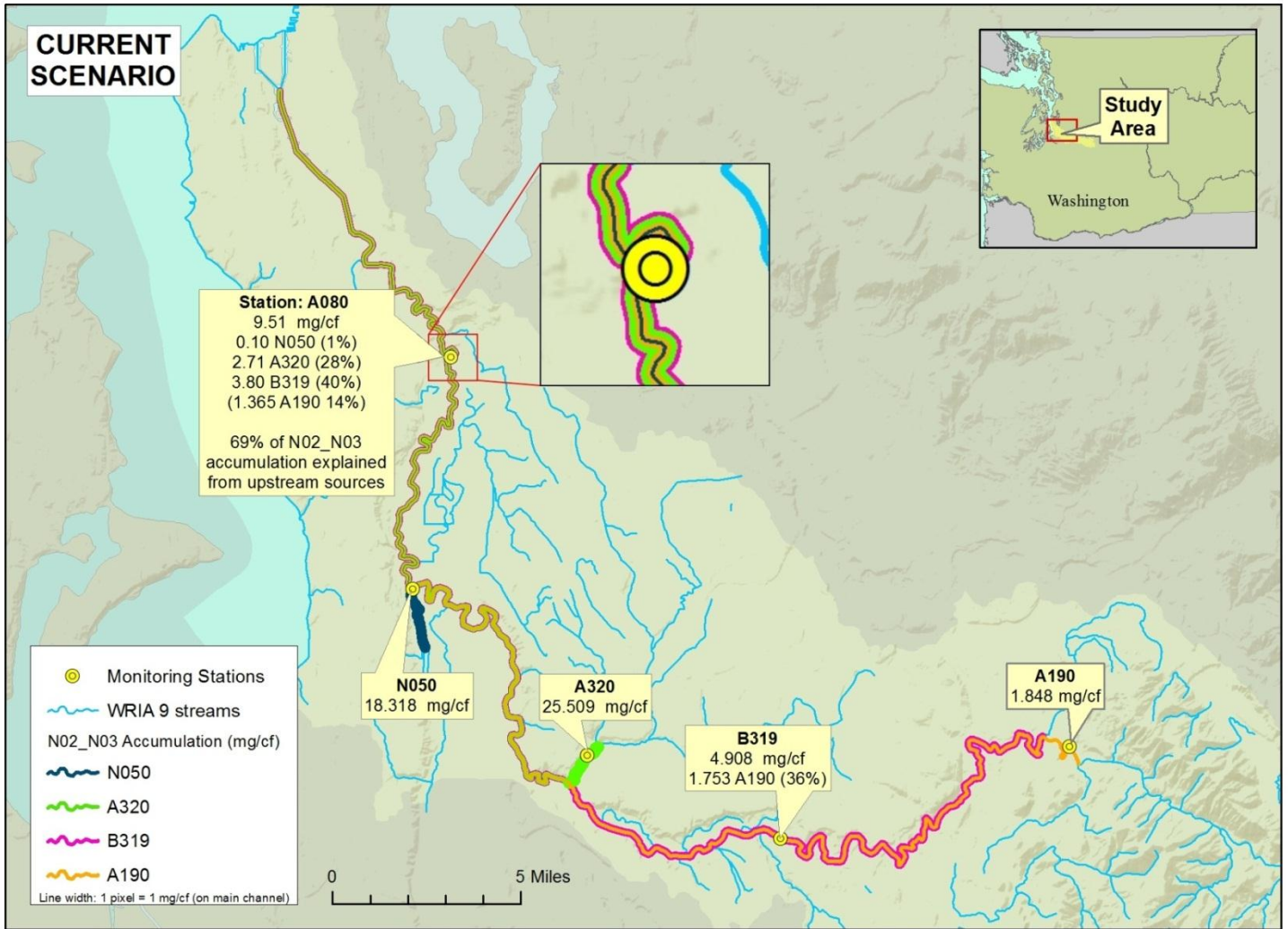
Sub-Step 3D

Below is a simplistic graph of 5 monitoring stations, each with 3 bars to represent 2009, 2010 and 2011. Some stations have healthy readings, while others are of high concern.



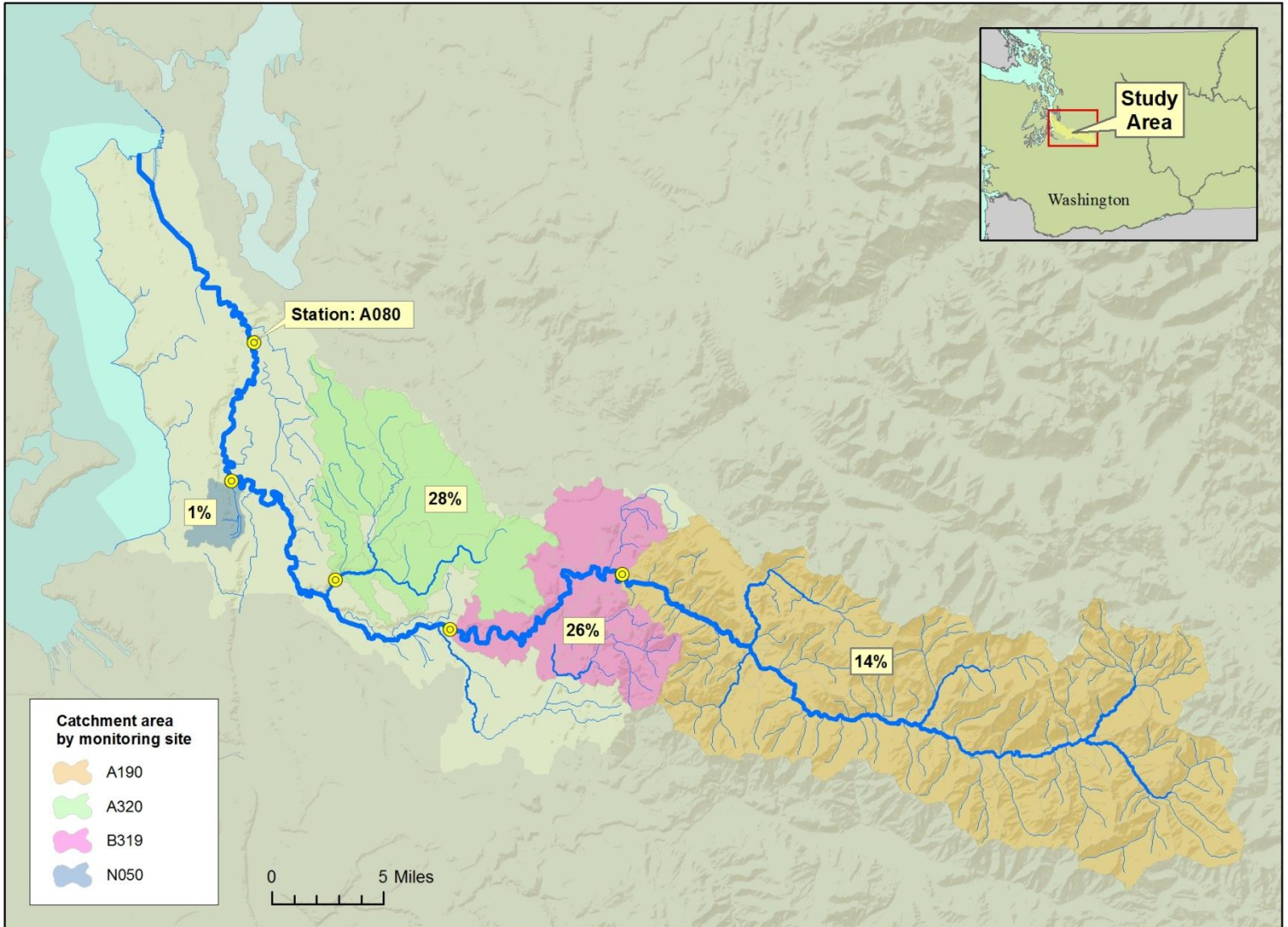
Sub-Step 3E

The map below displays measurements of nitrate + nitrate at five monitoring stations around WRIA 9. The measurements were multiplied by the flow volume at various locations to obtain the per second load average. This load average was accumulated downstream, and then divided by the downstream flow volume to obtain the diluted rate measured at the downstream site.



Map 1. Average 2011 Nitrate + Nitrate (N02_N03) ratings and estimated impacts downstream WRIA 9, King County Washington

The map below displays a representation of the catchment areas and their associated impact level to the pollutant rate measured downstream. Such a visual can be used as a tool to decide which areas to delegate resources in order to experience the greatest benefit on the stream network. This map also makes it clear where other monitoring sites are needed, so that catchment areas responsible for high pollutant generation might be easier to track.



Catchment area effect on monitoring station A080
WRIA 9, King County Washington

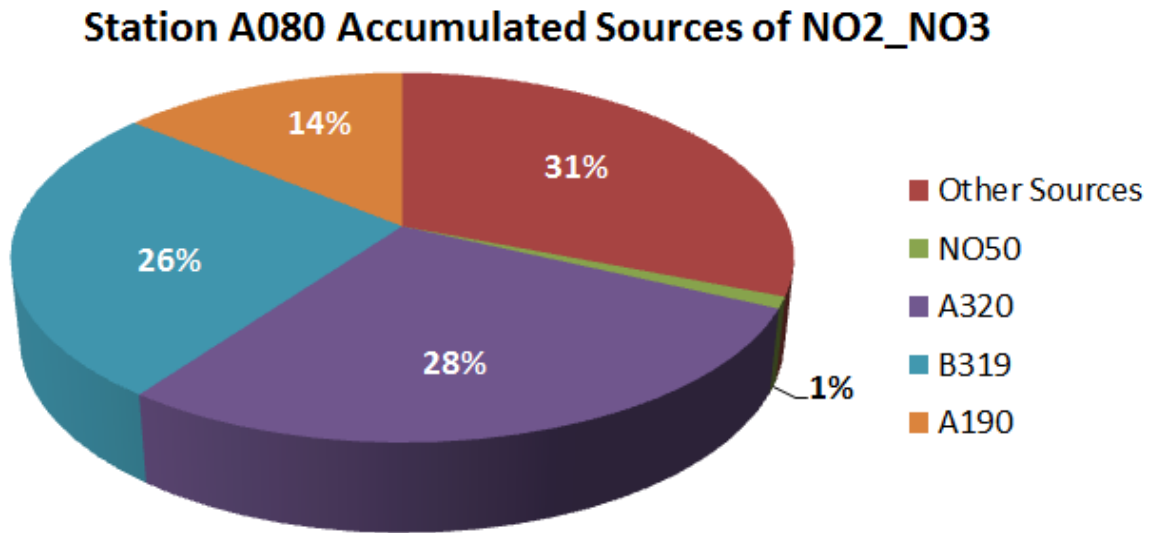
Sub-Step 3F

The table below shows the data input (only 1 year modeled) for the five monitoring stations:

Average 2011 parameters by station (units adjusted to cfs)

STATION	NO2_NO3 (mg)	NH3_N (mg)	OP_DIS (mg)	FC (#)
<i>Washington DOE Monitoring Sites</i>				
09A080	9.514	0.831	0.373	12459.29
09A190	1.848	0.301	0.223	1380.43
09N050	18.318	6.201	1.267	34640.62
<i>King County Monitoring Sites</i>				
B319	4.908	3.988	0.396	2633.44
A320	25.509	0.258	0.693	14630.23

After running the model, the sources of NO₂_NO₃ at station A080 can be explained by the following pie chart:



Step 4|5|6

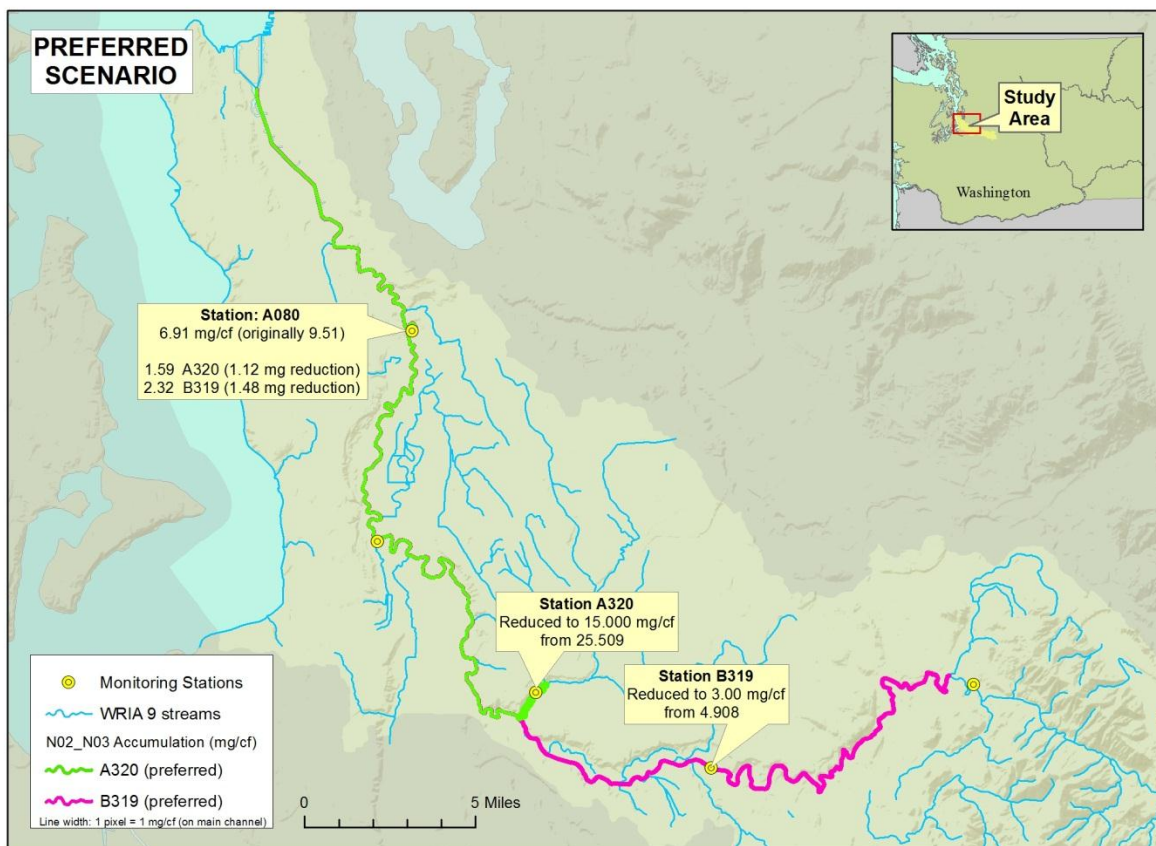
The maps and tables included are a strong representation of the original conceptual framework proposed. The measurements obtained are logical, in that no downstream accumulations from upstream catchments were larger than actual downstream measurements. There is certainly room for improvement in the model (outside of the original conceptual framework) primarily in regards to the following:

- Obtain accurate flow data at the same time as water quality measurements
- Move from an average annual model to a seasonal model, or better yet a storm event model as pollutants enter the stream network at a higher rate during these events
- Incorporate biodegradation for each particular component to more accurately model the effects downstream

Sub-step 7A

Map 2 provides a visual of an imagined future scenario, where water quality improvements have been made at upstream locations. Station A320 has seen a reduction from 25 mg to 15, and station B319 has seen a reduction from 4.9 mg to 3. These improvements have resulted in a reduction downstream at station A080 from 9.5 mg down to 6.9, near the river mouth.

The model can also be used to estimate effects of other parameter load reductions entering the Puget Sound.



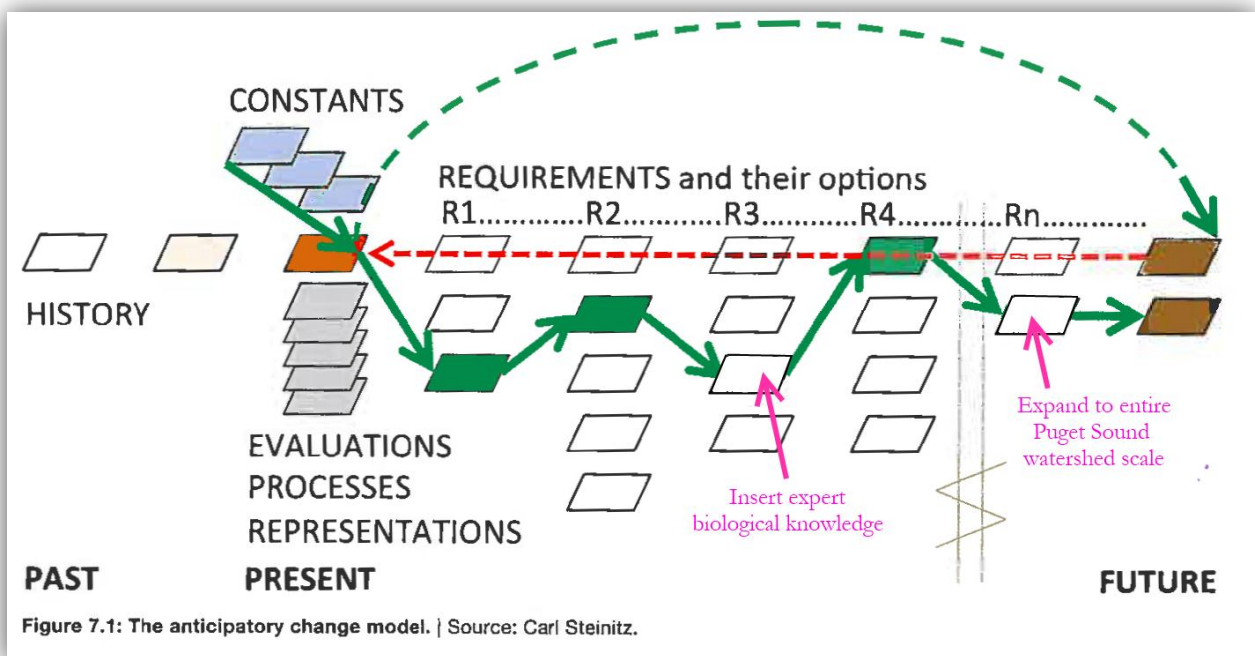
Map 2. Preferred Scenario: Nitrate + Nitrate (N02_N03) reduced upstream rates and estimated improvements downstream WRIA 9, King County Washington

Sub-step 7B

The reduction values can be seen on the previous visual. In order to reduce the reading at station A080 2.5 mg/cfs (28% reduction), the catchment area above Station B319 needs to experience a 39% reduction, and the catchment area of A320 needs to experience a 40% reduction.

Sub-step 7C

I would advocate for the anticipatory change model (option A), as the process has already been outlined. Certainly the model could be made more robust by incorporating biological knowledge of pollutant degradation rates, and expanding the model to include all monitoring sites and chemicals for the entire Puget Sound region. The visual below depicts what the process might look like.



With the process for this model already setup, none of the other Steinitz models seem to appropriately match the process. I would only advocate for the Anticipatory Change Model at this time.

Appendix 7.

Four broad attributes of human well-being

By Chris Gardner and Ian Price

Sub-Step 1A

We are using a conceptual framework similar to that developed by Levin et al. (2011) to identify the major structural elements and processes of the state of the Puget Sound social-ecological system.

The key attributes of the framework that we are utilizing for our development of indicators of human well-being will primarily include three of the broad attributes of human well-being proposed by the WSAS in its review of the development of social indicators by the Puget Sound Partnership: *Ecological Indicators, Market Activities, and Accessibility and Recreation*. (WSAS 2012, p. 70) There are other key attributes identified in the framework designed by Levin that we may draw upon in the course of our study, including *Physical/Chemical Parameters in Sediments and the Water Column* and *Trace Inorganic & Organic Chemicals in Sediments and the Water Column* that also reflect the quality of human well-being in the Puget Sound region as it pertains to consumption of aquatic resources and recreational opportunity. (Levin et al. 2011)

The primary reason we selected this framework is that the key attributes contained in it were developed to encompass the same range of key attributes that are identified by the Environmental Protection Agency (EPA), the Heinz Center, and the Puget Sound Partnership (PSP). The key attributes contained in the framework proposed by Levin et al. (2011) were selected from a larger, more comprehensive set of attributes in an effort to create a simplified list of broad key attributes. This allows for the framework to be flexible in that each broad attribute may potentially be informed by multiple types of indicators, which can be very helpful when indicator data availability is limited. Additionally, the hierarchical nature of this framework provides a mechanism for selecting indicators so that all the relevant ecosystem components are included when the number of potential indicators is restricted. Lastly, the WSAS considers this a valid reference framework and recommends that the PSP adopt a similar framework when it revises its set of environmental indicators, so it represents a somewhat vetted approach to modeling indicator development.

Sub-Step 1B

In the course of our literature review we investigated several other conceptual frameworks. Schneidler and Plummer (2009) discuss three conceptual frameworks – taxonomic, causal chain, and criteria frameworks. The taxonomic framework organized indicators into groups that share common attribute values. This approach is useful for matching specific policy interest to specific indicators or subsets of indicators that share attributes pertaining to such policies.

Causal chain frameworks operate by modeling the chains connecting ecological and human systems. The *Driver-Pressure-State-Impact-Response (DPSIR)* conceptual models are an example of a causal chain model that describes connections within a system with consideration of human impacts. One of the merits of the causal chain approach is that it accounts for how changes in policy lead to changes in the system, allowing for the creation and identification of indicators that can monitor the effects of these policies. (Schneidler and Plummer 2009, p. 9-10)

Stakeholder selection frameworks allow both communities and stakeholders to participate in the process of choosing a set of indicators to evaluate a policy effort. This approach has value in the sense that the indicator selection process accounts for policy and value choices implicitly and it engages and empowers the public, resulting in the selection of indicators that are more likely to meet the needs of the public and stakeholders alike. However, to meet the objectives of the WSAS critique of the PSPs efforts in indicator development, a sound, scientifically-vetted approach is necessary and the bias that this framework appears to impart toward public involvement and policy mandates in the indicator selection process may undermine its scientific credibility.

O'Neill, Bravo, and Collier (2008) also describe a DPSIR framework in terms of the causal links between drivers (human activities that are detrimental to an ecosystem), and pressures (stresses that these drivers apply to an ecosystem) that negatively impact the state of ecosystem components. As a consequence of these impacts, stakeholders and the citizenry can react and put forth a response to these drivers, pressures, and impacts in the form of policies, laws, and other measures that constrain human activities or mitigate their effects. This framework does an excellent job of conceptually linking human activities with their impacts but it's not designed to provide provisional key attributes to select from like the Levin et al. framework does.

Sub-Step 1C

To reiterate what was stated in Sub-Step 1A, the key attributes of the framework that we are utilizing for our development of indicators of human well-being will primarily include three of the broad attributes of human well-being proposed by the WSAS in its review of the development of social indicators by the Puget Sound Partnership: *Ecological Indicators, Market Activities, and Accessibility and Recreation*. (WSAS 2012, p. 70) There are other key attributes identified in the framework designed by Levin that we may draw upon in the course of our study, including *Physical/Chemical Parameters in Sediments and the Water Column* and *Trace Inorganic & Organic Chemicals in Sediments and the Water Column* that also reflect the quality of human well-being in the Puget Sound region as it pertains to consumption of aquatic resources and recreational opportunity. (Levin et al. 2011)

In an attempt to create a well-rounded, robust set of market activity indicators, we have also branched out and included some measures based off of social and economic data to use in tandem with the measurement of Puget Sound's natural resources. While not explicitly measured from resource measurements, we found a lack of reliable, ecologically-driven data to address this indicator category. Using changes in median family income (over the last ten years) per census tract provides a strong indicator of human welfare due to market activity. Ideally we would wish to create a measure of changes to median family income as it relates to median property value but we found very little reliable real estate data available.

Addressing the recreation and accessibility indicator set, we have dissolved multiple data layers of public land together. Public seashores, national parks, state parks, county parks, city parks, national forests and wilderness areas are all included in this data. The final indicator will be a measure of "proximity to public lands" per census tract in our study region.

As a hybrid-indicator attribute, the production level of crops and agricultural goods within the region indicates strong market activity, the ecological health of the region, and perceptions of the region. The Washington State Department of Agriculture makes yield data available for many of the agricultural products of our region (from fruit and vegetable crops to shellfish). Since agricultural areas are not

evenly dispersed throughout the region, we suggest the increases and decreases of agricultural production and revenue be tabulated on a per-county basis to build this hybrid measurement.

Sub-Step 2A

To represent the broad key attribute *Ecological Indicators*, we are developing the indicator called *Landuse/Landcover* to reflect changes in landuse and the trend of decreasing forest cover in the Puget Sound Region, both within and outside of the urban growth areas (UGAs), over time.

We decided to take a multi-step approach to representing *Market Activity Indicators* due to the diverse economy of the Puget Sound Region. Taking data from the last two decennial United States' censuses, we measured the increase and decrease in median family income in between 2000 and 2010 per Census tract. While we wished to brace this against cost of living for each area, there was a lack of comprehensive data relating to the cost of goods or of real estate trends.

We have included combined crop yields as an indicator of *Market Activity*, *Ecological Indicators*, and of *Perceptions of the Puget Sound Region*.

To address the broad attribute category of *Recreation and Accessibility*, we have created an index that measures proximity of different areas to a variety of public lands. These lands include public seashores (with varying degrees of accessibility, forest lands, wilderness lands, and public park lands. This proximity analysis works on the assumption that there are rural areas that may have little access to public lands, while there are urbanized areas which may have a wide variety of easily accessible public lands available. As such, the accessibility of and amount of public lands within a defined radius of Census tract centroids defines an overall index for the category.

Sub-Step 2B

In its executive summary of the review of the development of indicators by the PSP, the WSAS mentions that “The Land Use/Land Cover indicator is important in recognizing tradeoffs inherent in different types of land use. We recommend that it be modified so that the metrics are independent of policy and goal statements, and that further development of this indicator be accomplished expeditiously”. (WSAS 2011, p. 5) Clearly this statement echoes the need for a simplified yet relevant approach to using Land Use/Land Cover as an indicator. The tradeoffs in different types of land use referred to by the WSAS may include situations where new developments force the elimination of natural areas, resulting in an overall increase in the percentage of impervious surfaces, the elimination of terrestrial and/or aquatic habitats, and consumption of natural resources. With so many ecological impacts associated with Land Use/Land Cover, it serves as a valid Ecological Indicator.

Eelgrass is another ecological indicator of human well-being. Eelgrass is used primarily as an indicator of estuarine health because it responds quickly to human factors that affect water and sediment quality. Changes in its abundance and distribution are a reflection of the health of the estuarine environments throughout the Puget Sound. However, eelgrass exists in an underwater realm that is less tangible to the average person living in Puget Sound than the terrestrial realm of forested areas. Despite its importance to the health of species that humans rely upon as food resources, such as juvenile salmonoids, its importance is less obvious to many Puget Sound residents when compared to the importance of forested areas. Both eelgrass and land use/land cover are important and valid ecological attributes of human well-being. However, in the interest of time, we must focus our efforts on the development of a single indicator from this broader category and in choosing between the two, land use/land cover appears to be an indicator that will be more accessible and comprehensible to a wider audience.

While not a perfect measurement of the health of market activity, measuring changes in median family income does give a general idea of economic trends across the region. Lack of cost-of-living data has kept us from expounding upon this measure, but we can generally assume that, even if housing and service costs are higher in one area than another, that areas with the highest incomes indicate the presence of successful businesses and agencies in the area.

The agricultural yields that we are measuring directly impact the strength of our regional economy while relying on the healthy energy and material flows of a functioning ecological system. Climatic events, mineral amounts, and the availability of agricultural products may all influence changes in crop yields. One aspect of the agricultural economy that we'd like to investigate further is how diversification of the crops grown may indicate well-being, as it represents that farmers have the ability to take risks, helps to safeguard the local economy from consequences of market prices sharply declining for individual crops, and allows the citizens of the region to have access to a greater variety of goods.

In order to measure recreation and accessibility, we have attempted to create a coverage of all types of natural recreational lands that Puget Sound citizens may rely on. Public shorelines, national parks, state parks, local parks, national forests, and wilderness areas may all be used for recreational purposes. While we believe it would be more accurate to measure accessibility to these areas by travel time instead of proximity (as the crow flies) we did not find a reliable method through which to calculate these times. Distances to different recreational areas have been calculated from the centroid of each Census tract in the Puget Sound region while areas of different types have been weighted by accessibility. The underlying assumption of this weighting system is that remote, hard-to-reach lands will provide recreation for less people than those which have high levels of accessibility, even if both types of areas were the same distance from a group of people.

Sub-Step 3A

We are using percent forest cover (inclusive of deciduous, evergreen, and mixed forest types) by watershed sub-basin over time as our relevant measure for the *Landuse/Landcover* indicator described in Sub-Step 2A. In selecting Percent Forest Cover as a relevant measure, we are using a metric that is indirectly related to many forms of land use. For example, as development expands within and outside of urban growth areas (UGAs), forest cover is reduced, resulting in impacts to aquatic and terrestrial habitats as well as natural areas that are utilized for recreation. Additionally, as forested areas outside of the UGAs are cleared for new developments, impervious surfaces increase, also changing the distribution of land cover types in the region. Hence, percent forest cover is a metric that could be used as a relevant measure for at least two broad attributes of human well-being: *Ecological Indicators* and *Accessibility & Recreation*.

Percent forest cover by subbasin through time represents an *impact* within the DSPIR framework because it is reflecting changes in the “state” variable *forest cover* within the Puget Sound social-ecological system over discrete temporal intervals. An overall trend of decline in the amount of forest cover within the Puget Sound region can be tracked over time by comparing surveyed snapshots of the amount of forest cover present within subbasins at temporal intervals. The percent change in forest cover by subbasin allows us to visualize which subbasins are declining the most rapidly so that stakeholders and policy shapers can prioritize efforts their efforts and develop “responses” to this impact.

As for changes to median family income as a driving force behind market activities, the more income that residents see means the more disposable income and domestic security they have. This disposable income is often spent in area businesses, providing further market activity. When median family incomes decrease (whether or not the cost-of-living changes in the corresponding area) it generally means there is a lack of market activity or market stagnation. As such, we propose that this simple, readily available measurement be the key attribute that drives market activity.

Using county-level agricultural yields provides a glimpse into the ecological health of our region as well as an indicator of market activity of a bedrock, primary industry. Furthermore, the agricultural market of our region widely impacts perceptions of the region. The agricultural economy cannot flourish in poor ecological conditions or with a decrease in arable land. Furthermore, agricultural products are part of a primary industry that Washington relies on; only limited mining happens in our region and the forestry industry has been in decline over the past couple decades. For a strong regional economy we need primary quadrant industries that we can rely on as technology and trades wax and wane.

Proximity to (and accessibility of nearby) public lands is a measurement that takes the amount of public land within a 25 mile radius of the centroid of each census tract and measures the amount of public land within, weighted by accessibility level on a scale of 1 (restricted access) to 4 (full public access). Interestingly enough, rural areas do not necessarily have a higher level of access to public lands than urban areas in the region. We believe this measure is indicative of the ability for local citizens to actually make use of their public lands.

Sub-Step 3B

In its Land Cover Change Analysis report covering WRIA 8 (2011), King County attempts to answer two broad questions:

1. Is forest cover being retained in priority WRIA 8 subbasins?
2. Are riparian buffers being protected along priority streams inside WRIA 8?

Percent change in forest cover over time by watershed subbasin was calculated over several time intervals spanning the years 1991 through 2006 to help answer the two questions above. Forest cover is a type of land cover that tends to get replaced by impervious surfaces and other ecologically unattractive forms of development. By measuring its loss, other types of land use and land cover can be inferred as well. For instance, in areas such as the Sammamish plateau that have experienced extensive large-scale residential development over the past two decades, loss of forest cover correlates with an increase in residential land use. Landsat imagery and high-resolution aerial photography helped the researchers perform this study with a high degree of accuracy at spatial scales that were small enough to identify specific regions of pronounced decline in forest cover. These subbasin-level observations can also be aggregated to comprise a smaller-scale, more regional picture of the general trend of declining forest cover in WRIA 8 over time.

A number of other candidate relative measures were considered and discarded. For example, measurements of trace organic and inorganic minerals could provide ecological information regarding the state of energy and material flows but the available data was inconsistent at best. We attempted to create a ratio measurement of median family income versus cost-of-living, but cost-of-living data was not widely available (whether relating to median housing costs or the costs of raw goods in a given area). We considered trying to create a measure of “population condition” that would measure whether or not the population of an area was balanced (age-wise and economically) but decided against it as even if an area has a high proportion of older residents who may not be in the workforce, their presence

may create area jobs while they still contribute to the economy. The extent and total area of eelgrass beds throughout the Puget Sound region over time were also considered as relevant measures and a fair amount of effort was devoted to trying to locate workable datasets for these parameters. However, the data that were available from the Washington State Department of Natural Resources' (DNR) Submerged Vegetation Monitoring Program (SVMP) for these metrics were not consistently collected at the same geographic locations over time so the ability to compare measurements from the same locations over time was not possible. Because of the large number of potential monitoring sites (up to 2,465), the DNR applies a statistical approach to selecting representative sites to survey for eelgrass each year that can represent trends over broader geographic areas so it's understandable that the data are collected and reported in this manner. (DNR 2011)

Of all the broad indicator groups proposed by WSAS, the most difficult for us to quantify has been *Perceptions of the Puget Sound Region*. While attempts to measure the influx of tourism are sometimes done by the Washington State Office of Financial Management, it appears to be on a statewide level. Furthermore, tourism dollars spent is not a reliable measure of the positivity/negativity of perceptions of our region due to people usually only traveling when their domestic economic situation allows.

Sub-Step 3C

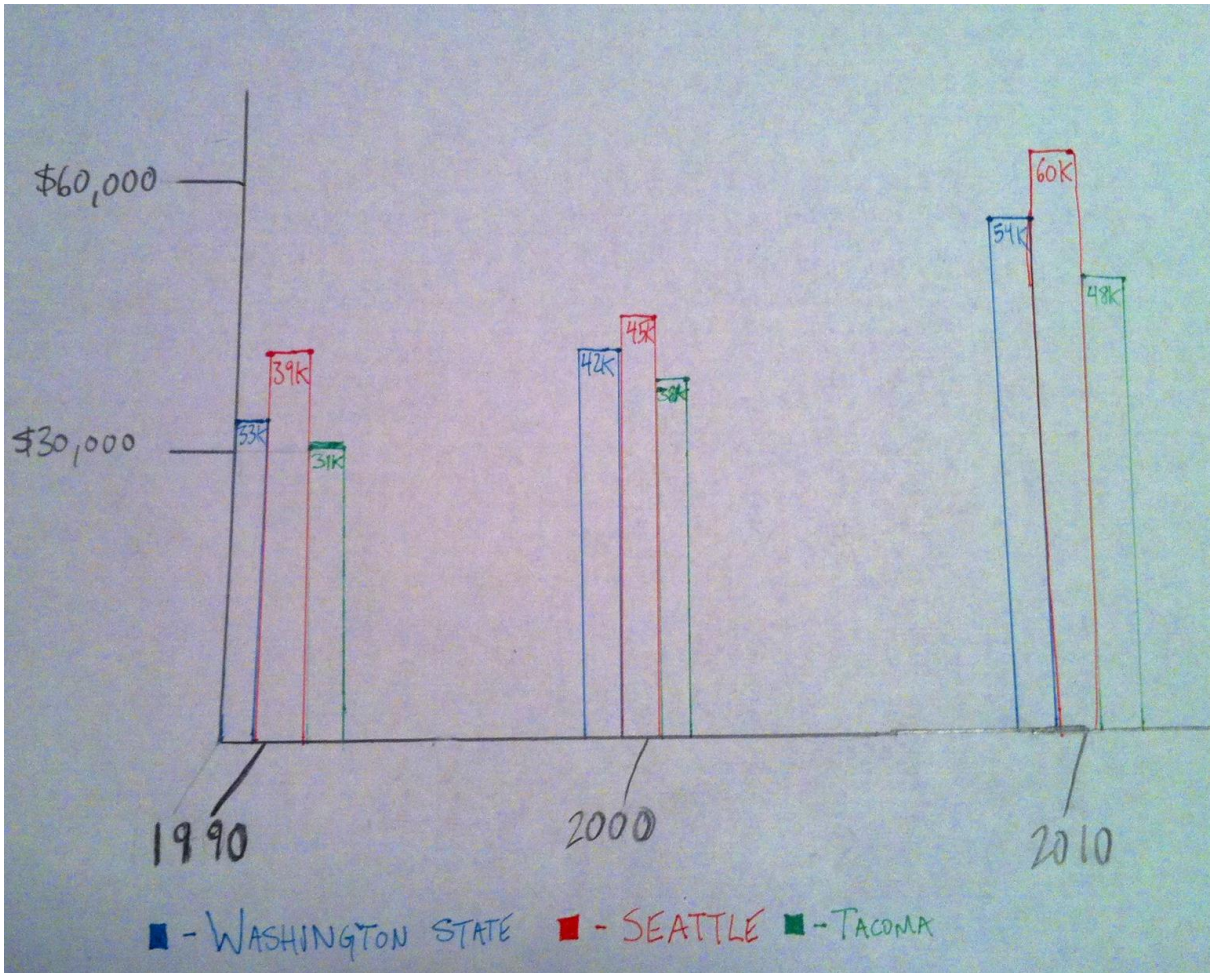
Due to the multi-indicator approach we must take to measuring human well-being across Puget Sound, we will focus on a single indicator out of those we selected for this part of the final. Additionally, we presented a preliminary sketch showing percent forest cover by subbasin in WRIA 8 in 1991 during our status report presentation and feel it may be redundant to include it again.

The map sketch below shows the areas of higher-than-average (green) and lower-than-average (red) median family incomes across the Puget Sound region as of 2010. One can see that, in relation to the rest of the state, the Seattle-Tacoma metropolitan area possesses a large portion of the higher-than-average MFIs in the Puget Sound Region, especially in King County's eastern urban areas.



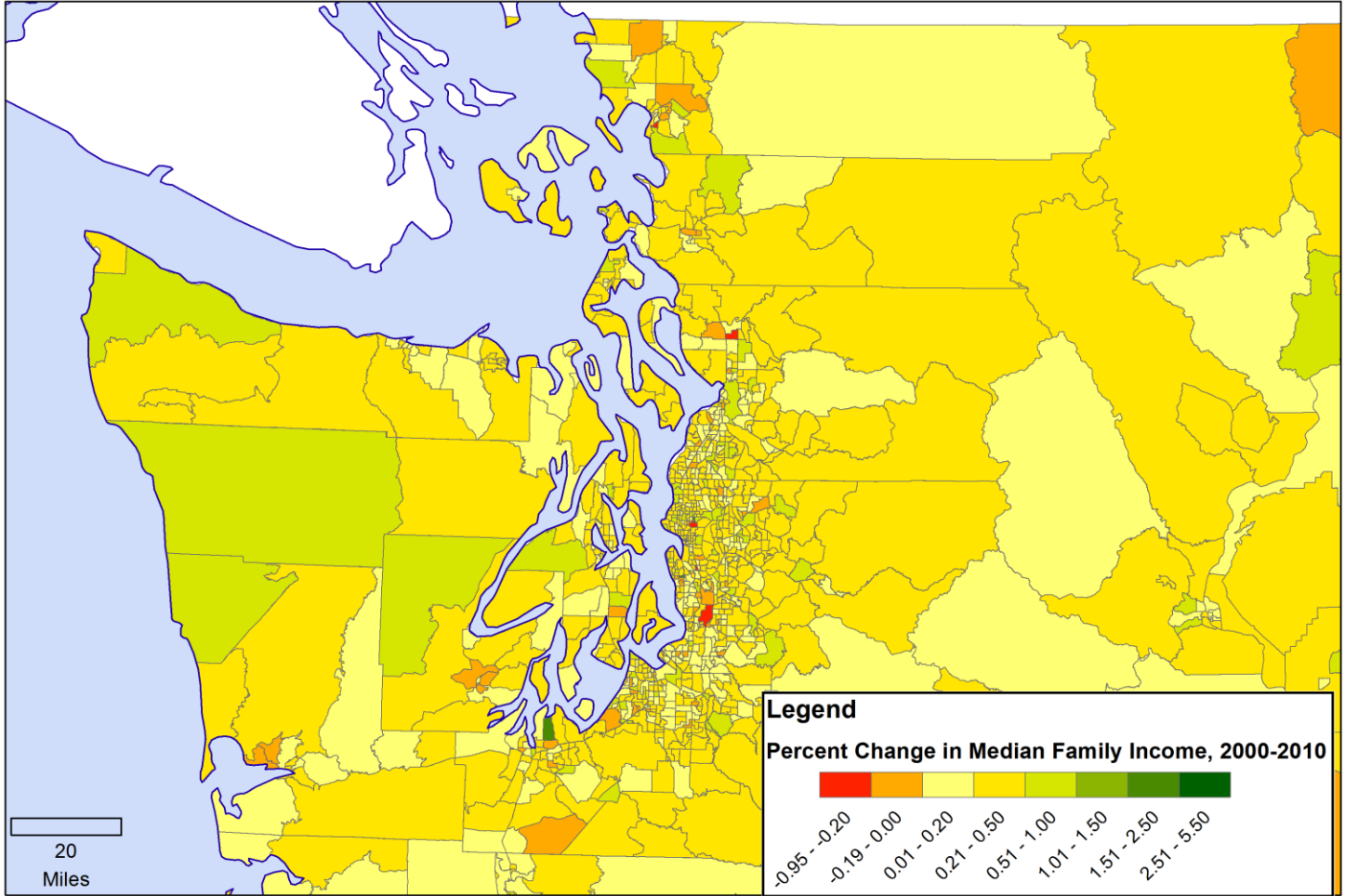
This graph shows median family income for Washington State, Seattle, and Tacoma in 1990, 2000, and 2010. Each time, Seattle's MFI has been above the state's average while Tacoma has been below it. The 20-year temporal span of this graph encompasses a fairly broad timeframe and the consistent pattern observed in relative MFIs among Seattle, Tacoma, and the State over this span suggests the pattern will persist into the near-future unless changes are made at the system level to affect real economic change. With this in mind, we proceeded with our design knowing that this did not mean that there was necessarily a higher amount of well-being in Seattle than Tacoma and that further calculations would be necessary before reaching a conclusive indicator.

Sub-Step 3D



Sub-Step 3E

Change in Median Family Income in Washington State, 2000-2010



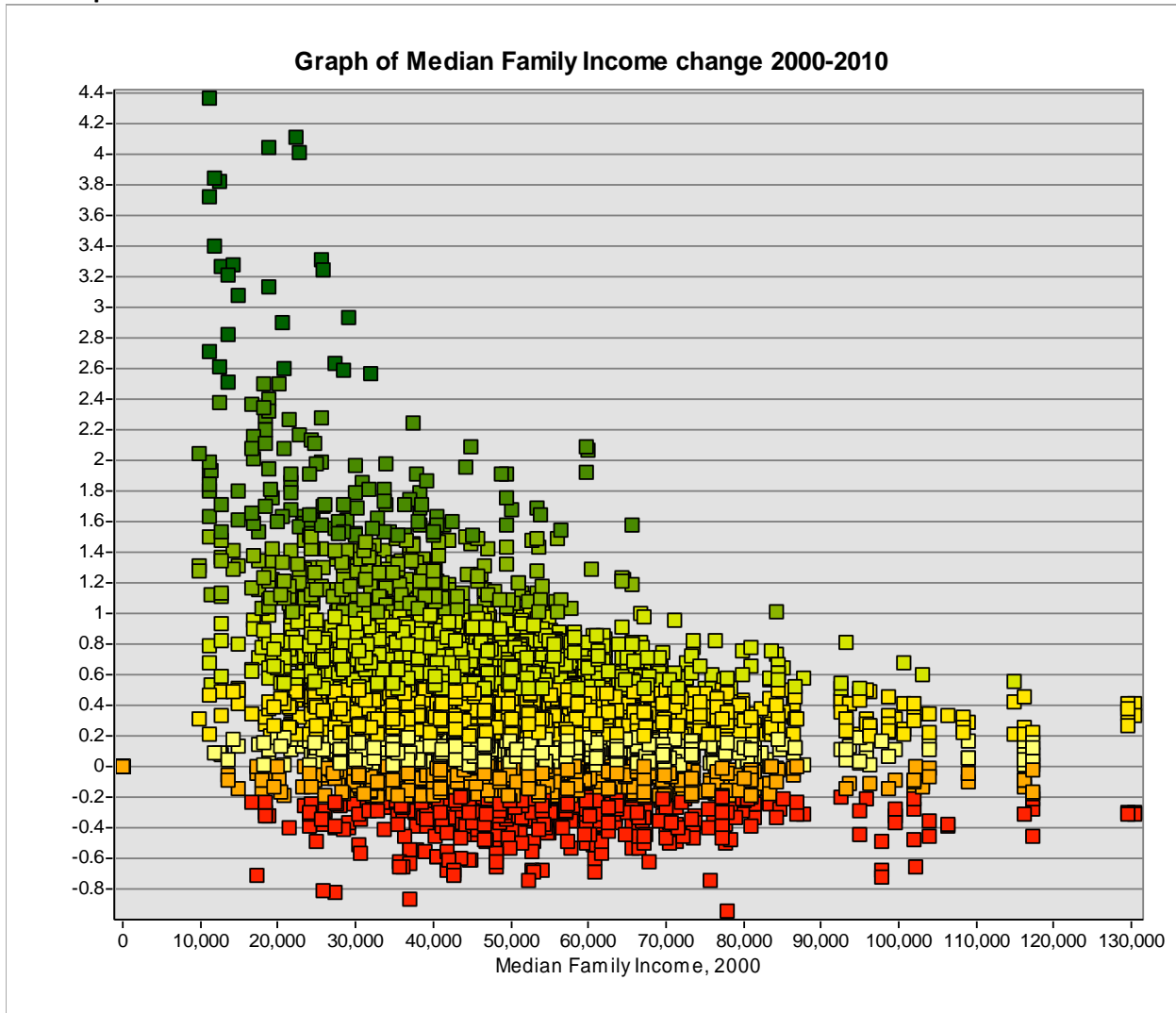
Ian Price, 2012

All statistical data obtained through the United States Census Bureau, November 2012

Since census tract geography changes per decennial census, all 2000 and 2010 tracts were dissolved together using a union overlay operation, with 'artifact areas' (areas smaller than 800 sq. ft., smaller than any tract in the 2010 census) removed. A percentage difference between the 2000 and 2010 MFIs was calculated for each new area.

Spatially, there are a few trends we noticed. Industrial towns such as Shelton, Aberdeen, and Marysville experienced the brunt of decreases in MFI, while most other areas experienced a modest increase in MFI. Many tribal areas saw quite large (greater than 50%) increases in MFI, and the highest percent increases all had low (less than \$35000) annual MFIs in the 2000 census (as seen in the following pages).

Sub-Step 3F



This scatterplot shows the median family income per census tract in 2000 plotted against the percent change in MFI from 2000-2010. One very noticeable trend is that the areas which experienced the highest change in MFI were overwhelmingly lower-income areas, with none of the fifteen highest increases occurring in areas with a 2000 MFI of above 35,000. To us, this is a very important trend; the areas which experienced income increases were areas that, it could be argued, were not areas where citizens had disposable income. As such, using percent increase in MFI appears to be a much more meaningful measure than purely measuring average income per tract.

Step 4|5|6

We believe MFI is a strong indicator of market activity, but would caution agencies from using it without weighing it against up-to-date cost-of-living data. If the cost-of-living expenses outpace the observed percentage increases in MFI over the 10-year interval shown in the graph in step 3F, it follows that percent change in MFI is not an effective relative measure. However, this is but one key attribute going into our set of indicators to be used to give a final measure of human well-being, and we believe that

our full set of indicators provides a wide range of important data, but needs further work before being considered a comprehensive set.

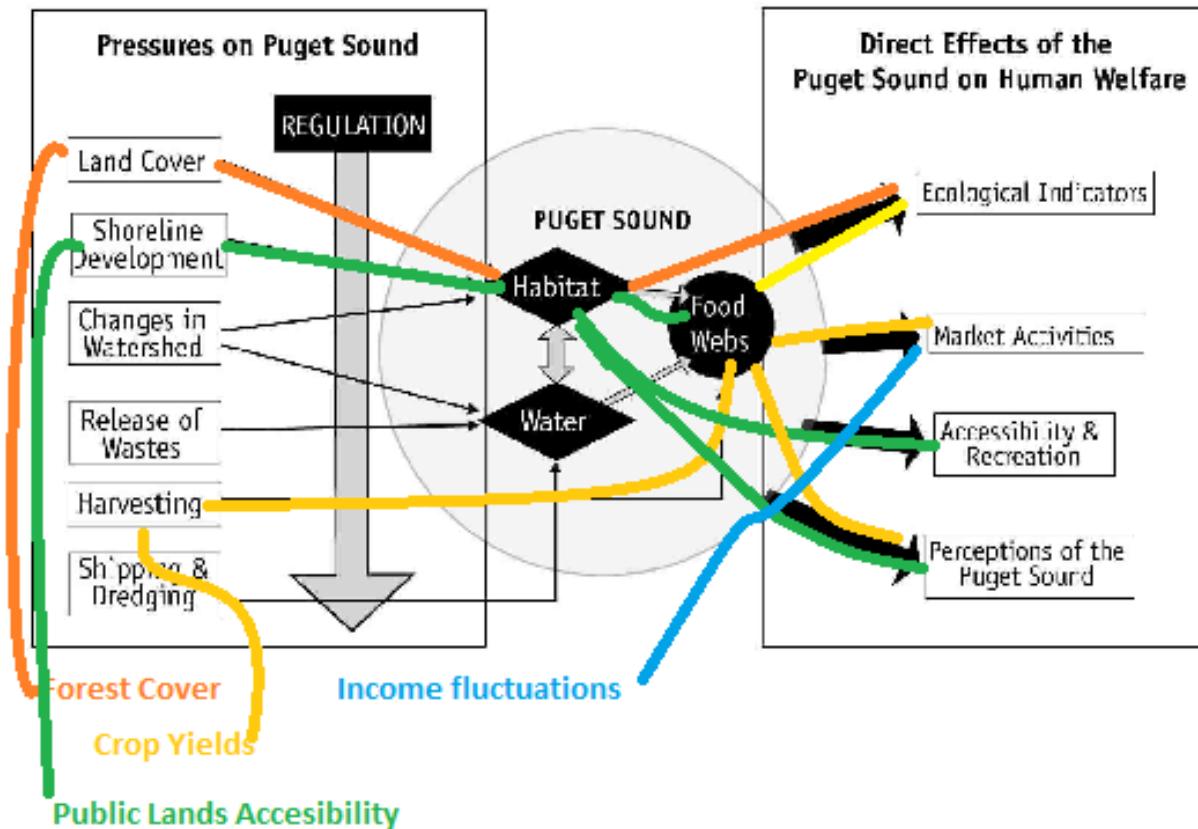
We believe that our full indicator set provides strong indicators of market activity (percent income change and county-aggregated agricultural yields, in dollars), ecological indicators (percent forest cover and county-aggregated agricultural yields, in production amounts), and recreation and accessibility (amount of public land, rated by accessibility, within a 25 mile radius of each census tract's centroid), but have failed to find a suitable metric which indicates perceptions of the Puget Sound region. However, this does not necessarily impact the well-being of the citizens of our region.

Sub-step 7A

A map representation of what we would prefer to see economically in our area is unnecessary for the following reason: We would like to see incomes rise for all areas of our state, most particularly in the areas with lower incomes (and, as a result, in the highest need). While a certain amount of economic polarity is to be expected, it seems that our region shows a wide disparity between incomes. Our map of an "ideal situation" would show steady increases across the board! However, it is unrealistic to expect this achievement to occur, so it is worth envisioning the largest increases to low income areas.

A map representation of a preferred state of forest cover could be made to show an idealized condition in which the current percent of forest cover within the subbasins of WRIA 8 remains unchanged or increases marginally over time. However, the Puget Sound region is still experiencing steady growth, both within and outside of the urban growth areas, and the continued clearing of forested areas to make way for new developments is inevitable in the long run, making such an idealized future state of forest cover highly unlikely. A more tempered, realistic rendering of the future state of forest cover in WRIA 8 would show a modest decline in overall forest cover, but would show the bulk of the reductions occurring outside of riparian corridors and other sensitive habitat areas. A more sustainable approach to managed growth in our region should provide for sustained levels of forest cover within sensitive habitat areas and try to constrain new development that requires clearing of forest to areas that can better absorb such losses.

To tie this back in to our system as a whole, the changes in forest cover, accessibility to public lands, and agricultural production all add to the overarching measure of human well-being as well. The simple graphic below shows our indicator set in relation to the WSAS' proposed framework.



Sub-step 7B

Once again, for this particular measure we would wish to see increases to MFI across all areas, but expecting there to be a limited amount of 'available growth' in any given time period, we would wish to see the largest increases happen in the areas with lowest MFI. The processes which must occur for this to happen vary from area to area, but may include the following policies:

1. Investment in industrial, logging, and mining-centered economies which have seen stagnation in many areas of the state.
2. Business Enterprise Centers, focused on increasing the numbers of small businesses through startup funds, low-interest business loans, and worker training, in low-income areas.
3. Continued support of and incentives for businesses and agencies to grow in or re-locate to Washington.
4. Cultivating sustainable primary and secondary industrial growth to supplement and/or replace failing industries.

Sub-step 7C

We would suggest the combinatorial change model as the best approach to improving *this particular* facet of human well-being (market activity). There are a myriad of ways in which a regional economy can grow and any solution which improves on the current situation in a poverty-stricken area would be welcomed. The most appropriate choices to be made to increase market activity will vary greatly over time as well as from area to area. Multiple approaches to this problem may be executed at the same time while requiring many constants to be considered (there is limited amount of space available for industrial use, a limited amount of natural resources, a workforce with a given basic skill set, and only a workforce of a particular size at any given time). The combinatorial change model allows for multiple scenarios to work towards the same desired result, and approaching such a complex problem as economic growth requires that the designers working to alleviate the issue be flexible and open to new solutions over time.

As a secondary option, we would suggest the constraining model, which is suited for situations where the importance of requirements for the final design solution are not completely known. Successive iterations of the framework narrow the options at hand and rank them by importance, allowing a city or regional agency to re-evaluate the economic goals based off of the current economic climate and growth trends. The performance of given indicators and relative measures can be assessed and fed back into the model, refining the results with each iteration to hone-in on those indicators and measures that perform best. This feedback process would be invaluable to a team working with economic conditions.

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Appendix 8.

Marine Water Quality

By Jeff Dong

Sub-Step 1A

The primary conceptual framework to be used for this project, will be the one also used by the Puget Sound Partnership's Science Panel: Drivers, Pressures, State, Impact, Response (DPSIR). This framework will be used to identify the processes of the state of the Puget Sound's social-ecological system.

The framework used to identify the major structural elements and identify key attributes will be Table 4 as described in the Washington State Academy of Science's Report (WSAS, 2012). This framework outlines the "Goals", "Key Attributes", and "Dashboard Indicators".

The reasons for selecting these frameworks over Steinitz were to ensure continuity of the terminology used by the PSP, Washington State Academy of Sciences (WSAS), and that the legislature had already been briefed on; capitalize on the familiarity of the existing framework; and to build on the existing foundation that the PSP had created (as recommended by the WSAS).

Sub-Step 1B

Other conceptual frameworks that were considered were: the US Environmental Protection Agency Science Advisory Board's; the National Research Council's; and the Heitz Center's frameworks. It is important to note that the SAB's framework "explicitly lists the dynamic attributes of hydrology and geomorphology, which are critical for understanding ecosystems like Puget Sound" (Washington State Academy of Sciences, p. 15).

Another important factor is that the SAB and NRC's frameworks are nationally recognized. Therefore, data is more likely to exist for their respective attributes/indicators and it may be more familiar when working with outside agencies.

Reference: Washington State Academy of Sciences, *Sound Indicators: A Review for the Puget Sound Partnership*. August 2012

Sub-Step 1C

The key attributes I chose to focus on was the Physical / Chemical Parameters surrounding Marine Water Quality.

Sub-Step 2A

The indicator dissolved oxygen was selected to represent the key attribute "Physical / Chemical Parameters".

Sub-Step 2B

Throughout the water column, all organisms depend on Dissolved Oxygen (DO) to sustain life (Narragansett Bay, 2012). A low DO count can result in hypoxia, which can result in negative physiological effects. According to Geoscience Australia (2012), even short-term changes in DO levels (outside the norm) can cause large scale "kills" of aquatic organisms and the immune systems of fish could be suppressed, thus causing them to become susceptible to disease for several years.

Furthermore, “the toxicity of many [toxicants \(lead, zinc, copper, cyanide, ammonia, hydrogen sulfide and pentachlorophenol\)](#) can double when DO is reduced from 10 to 5 mg L⁻¹” (Australian Government, 2012).

In terms of the key attribute (Marine Water Quality), the ability for water to sustain life is a powerful indicator of its quality. The quality of life of communities that surround healthy aquatic ecosystems is generally greater than those that are collocated with dead / dying ones.

Hazardous chemicals introduced into marine waters are likely caused by human involvement, whereas low levels of DO can occur naturally in nature. While there are other indicators that could represent Marine Water Quality (nitrates, phosphates, etc.), the level of DO, as an indicator can still be used in remote areas with limited or no human interaction.

This DO is such an important indicator in determining water quality that monitoring its levels recommended for simple ecosystems such as man-made ponds. Also, data collection is so easy to use that some agencies rely on volunteers, with very basic training, to obtain samples.

Also, unlike other indicators, DO levels are more likely to decrease exponentially, as the dying/dead organisms increase the consumption rate of oxygen.

The fact that without oxygen marine organisms could not live and that low levels of DO can naturally occur in nature are the basis for Dissolved Oxygen being selected as an indicator of Marine Water Quality. For what better indicator is there in determining the quality of water than the basic element required to sustain life itself. What is the point in monitoring toxic levels if the basics for life are not present to sustain organic life that naturally cleans the water?

Reference:

Australian Government. *Dissolved Oxygen*. Webpage. Retrieved 28 Nov 2012.
http://www.ozcoasts.gov.au/indicators/dissolved_oxygen.jsp

Narragansett Bay Watershed Counts. *Marine Water Quality*. Webpage. Retrieved 28 Nov 2012.
http://watershedcounts.org/marine_water_quality.html

Sub-Step 3A

When collecting data involving Dissolved Oxygen (DO), it is important to have a sound model for measurements. DO is measured as a percentage of milligrams per liter (mg/L⁻¹) and typically ranges from 6 to 14 mg/L⁻¹ (Australian Government, 2012). DO is a measure of the state of marine water quality.

There are several factors that can affect these levels. The depth the measurement/sample was taken from should be recorded as the percentage of DO typically decreases with increases in depth. Depth is commonly recorded in meters when discussing marine water quality.

Temperature also affects the levels of DO where an increase in temperature lowers the percentage of DO. This is because at cold water can hold more oxygen than warmer water (USGS, 2012). It is important for the water temperature to be taken at the sample point, as this information can help determine whether or not the readings are within normal seasonal ranges. Recordings are traditionally documented in degrees centigrade.

Time is another key factor to record during data collection. DO levels can dramatically change from day to night because it is during these low light hours where maximum respiration occurs. During the day, photosynthesis takes place whereas at night this contribution of oxygen is not possible. As mentioned above, DO levels can vary with the seasons due to changes in sunlight exposure, temperatures and tides. Tides help disrupt stratification and help balance distribution of DO levels throughout the marine area.

Therefore, it is also important to record the date the sample/reading was taken, which is typically documented according to the Gregorian calendar. Time should be recorded according to a 24-hour clock.

Salinity of the marine water can affect the DO levels. A higher salt content results in a lower DO reading (Murphy, 2012), hence, fresh waters commonly have higher DO levels than salt waters.

Humans contribute the most to low DO levels by introducing organic waste into marine waters. Organic waste typically enters the waters from sewage plants, storm water runoff (carrying traces of fertilizers, animal waste, dead grass/leaves, etc.). This causes a spike in marine organisms that are necessary to decompose these organic wastes. This spike can cause algae blooms resulting in the consumption of more oxygen within the ecosystem and therefore lowering the DO levels. (Murphy, 2012)

Stratification is naturally occurring in marine waters, due to differences in water quality (temperature, salinity, concentration of organics, etc.), and can prevent the mixing of oxygenated waters with those more depleted. This is why it is recommended that DO samples be taken at different depths throughout the water column - to prevent one sample representing the entire water column.

The drivers of human activity on the DO levels are the introduction of unfiltered storm water, sewage and other organic wastes into marine waters. The pressures that this has on the ecosystem are that it causes a spike in microorganisms thus changing its state by increasing the consumption rate of oxygen. This impacts the fragile ecosystem by pushing marine life away from these areas or killing those that cannot flee. Algae blooms can negatively affect humans by the closing of recreational areas, thus driving away tourism dollars, or by creating illness from the consumption seafood containing toxic algae. Society can limit their impact on DO levels by reducing the amount of material introduced into marine waters.

Reference:

Australian Government. *Dissolved Oxygen*. Webpage. Retrieved 28 Nov 2012.
http://www.ozcoasts.gov.au/indicators/dissolved_oxygen.jsp

Murphy, Sheila. City of Boulder/USGS Water Quality Monitoring. *General Information on Dissolved Oxygen*. Retrieved: 2 Dec 2012. <http://bcn.boulder.co.us/basin/data/NEW/info/DO.html>

US Geological Society. The USGS Water Science School. *Water Properties: Dissolved Oxygen*. Retrieved 1 Dec 2012. <http://ga.water.usgs.gov/edu/dissolvedoxygen.html>

Washington State department of Ecology. How to Measure Dissolved Oxygen. Retrieved: 1 Dec 2012.
<http://www.ecy.wa.gov/programs/wq/plants/management/joysmanual/4oxygen.html>

Sub-Step 3B

The selection of the above measurements were chosen based on the US Environmental Protection Agency, WA Department of Ecology, and the US Geological Society's use of these common measurements to document DO levels. Other measures considered were: nitrates, vegetation, and marine organisms. Although they can greatly affect DO levels, they were not selected due to time / cost constraints surrounding their collection.

Reference:

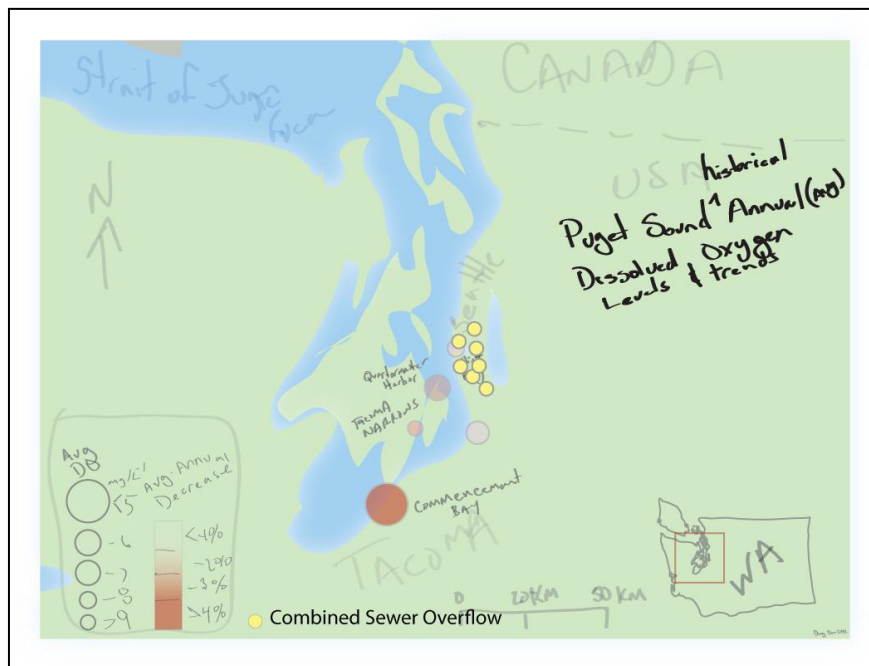
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Sub-Step 3C

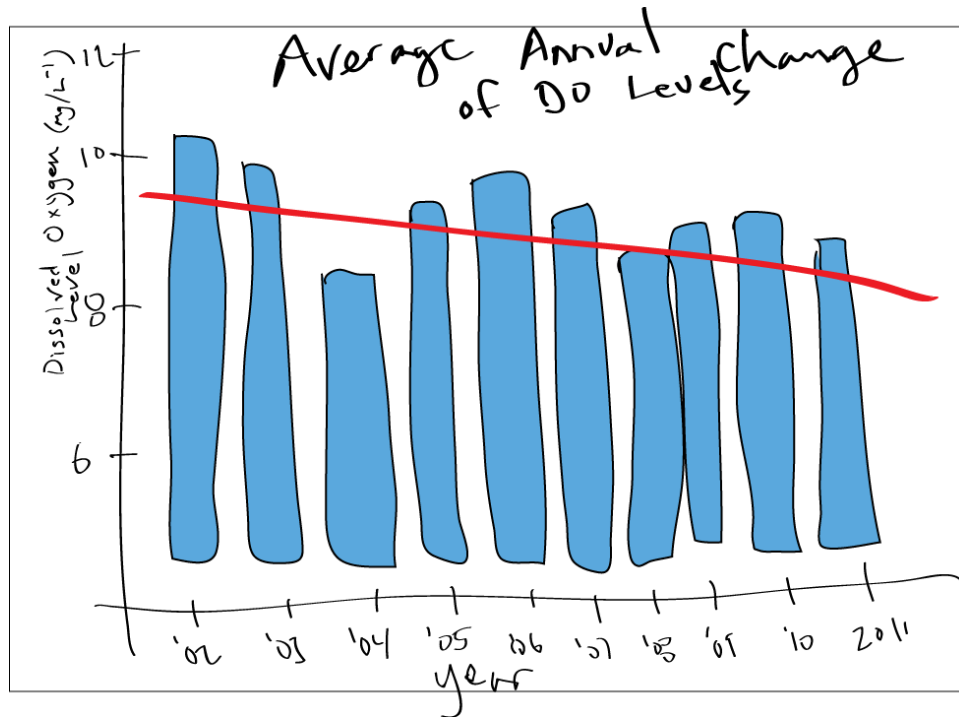
Documented below, in Sketch 1, are marine water monitoring stations (represented by the circles) within the Puget Sound region. The size of the circle represents the average annual percentage of Dissolved Oxygen for the respective Marine Water Monitoring station – the larger the size, the greater the danger of oxygen deprivation (lower DO levels). The color red represents a negative change in average DO levels – the more saturated the color (red), the greater the annual decrease. The yellow circles represent combined sewer overflow. Data represented is as recent as 2011. A scale size of 1:300,000 was chosen to best display the chosen water monitoring sites as well as provide enough detail of the shoreline to help orientate the viewer to the region.



Sketch 1

Sub-Step 3D

Sketch 2 below, represents the average annual change in Dissolved Oxygen levels for a specific Water Monitoring Station. The Y-axis represents the average DO level for that station, while the X-axis represents the year the readings were taken. The red line represents the trend of all the yearly averages (since the trend is negative, the color chosen was red a color commonly associated with negative values).



Sketch 2

Sub-Step 3E

Map 1 below represents the computational solution that represents the past state of Dissolved Oxygen levels for the Puget Sound.

First, vector base map shapefiles were imported to the ArcMap geodatabase. One shapefile represented the counties that make up Washington State and the other represented the water. A neutral grey was chosen to represent the state's landmass to create more contrast between figure and ground, while a more standard blue was selected to represent the water.

During data analysis, outliers were identified and removed from the data set. Also removed were those water-sampling stations with too few of readings. Selected stations had data ranging from 1989 to 2011.

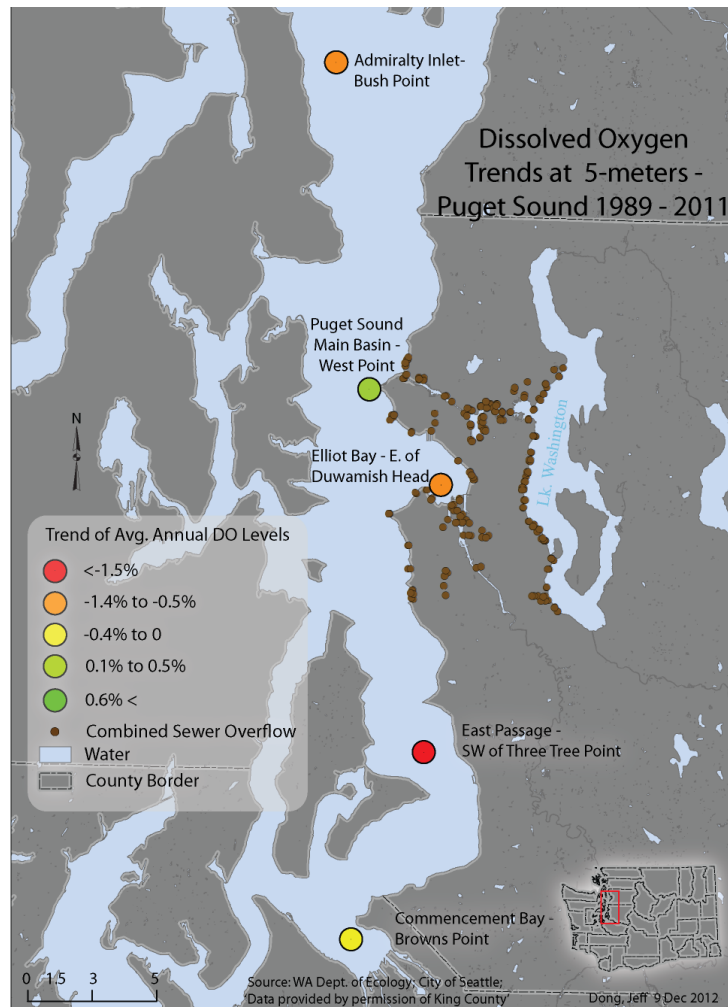
Annual Dissolved Oxygen (DO) averages for the respective water sampling stations were calculated (via Tableau 7.0) for samples collected at 5-meters (to normalize data) and then year-to-year changes of those averages were generated (via Tableau 7.0). From those year-to-year changes, a trend line was calculated for the entire sample period and exported to an Arcmap geodatabase via Arc Catalog. A shapefile was created from the sampling stations' respective coordinates (via the Display XY data tool).

The coordinate reference system was transformed from a geographic reference system (GCS_North_American_1983_HARNS) to match that of the basemap – a projected coordinate system (NAD 1983 HARN StatePlane Washington North FIPS 4501 (Feet)). The symbology was changed to represent the trend line data via a red, yellow, and green gradient color bar. With red representing a stronger negative trend, orange a milder negative trend and green a positive trend.

Next, Combined Sewer Overflow vector pointfiles were imported into the geodatabase after failing to locate any water treatment data for the same time period.

If data were available on sewer overflows, the annual averages would have been calculated and a trend line operation performed on those averages to determine whether or not there was any correlation between the drop in DO levels.

With the data available, it appears as if there is a lower rate of decrease in DO levels in the more populated Seattle region versus the less dense area around the East Passage water sampling station, which has the highest rate of decrease. However, without Combined Sewer Overflow data for that region, it is difficult to determine the cause of the decrease in annual DO levels.

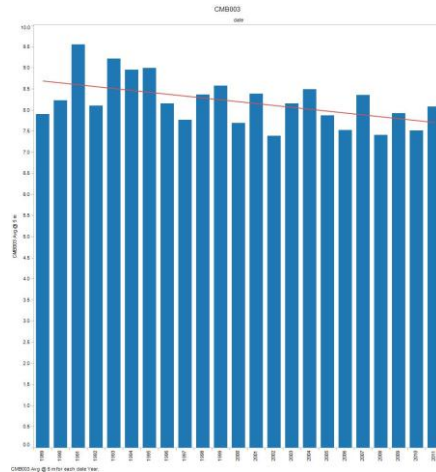


Map 1

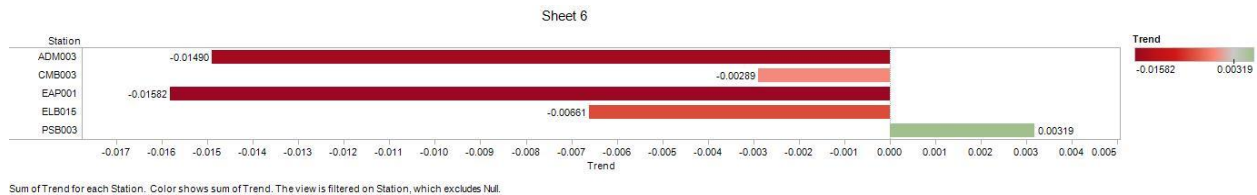
Sub-Step 3F

Graph 1 below shows the year-over-year change in average annual DO levels for a single water monitoring station (East Passage – SW of Three Trees Point), from 1989 to 2011. Notice the red trend line that represents the negative trending.

Graph 1b displays all five selected water-monitoring stations and their respective trends of year-over-year DO levels. This graph allows viewers to more easily identify the stations with higher rates of decline from those that are improving.



Graph 1

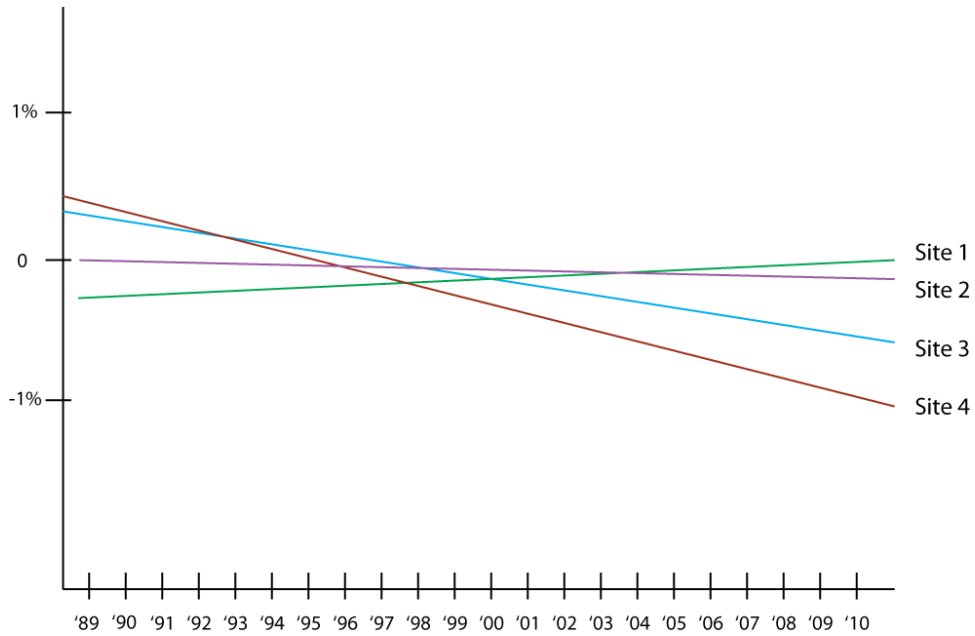


Graph 1b

Step 4|5|6

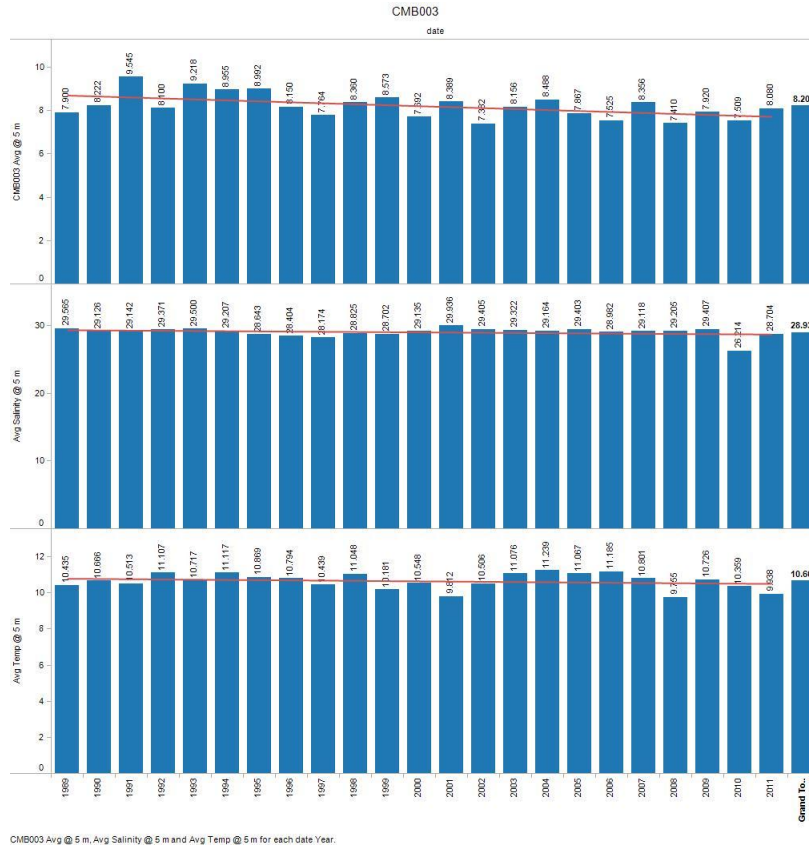
The maps and graphs displayed in steps 3 do represent the past state of Dissolved Oxygen.

The above graph displays the average DO levels year-over-year accompanied w/ the trend line. However it is somewhat limited in it's comparison with other stations. A graph that displays all the trend lines, with color identifying the respective stations, would convey more information and be more visually appealing (see sketch 3).



Sketch 3

Also comparative graph of DO averages and other indicators combine sewer overflow would be more exciting in determining if overflow could be used as a predictor for DO levels. Since the data were not available, an example in graph 1c below illustrates DO Trends in comparison with the trends in salinity and trends in temperature. It is obvious that all three show a negative trend. Typically, a rise in salinity or temperature would cause a drop in DO readings.

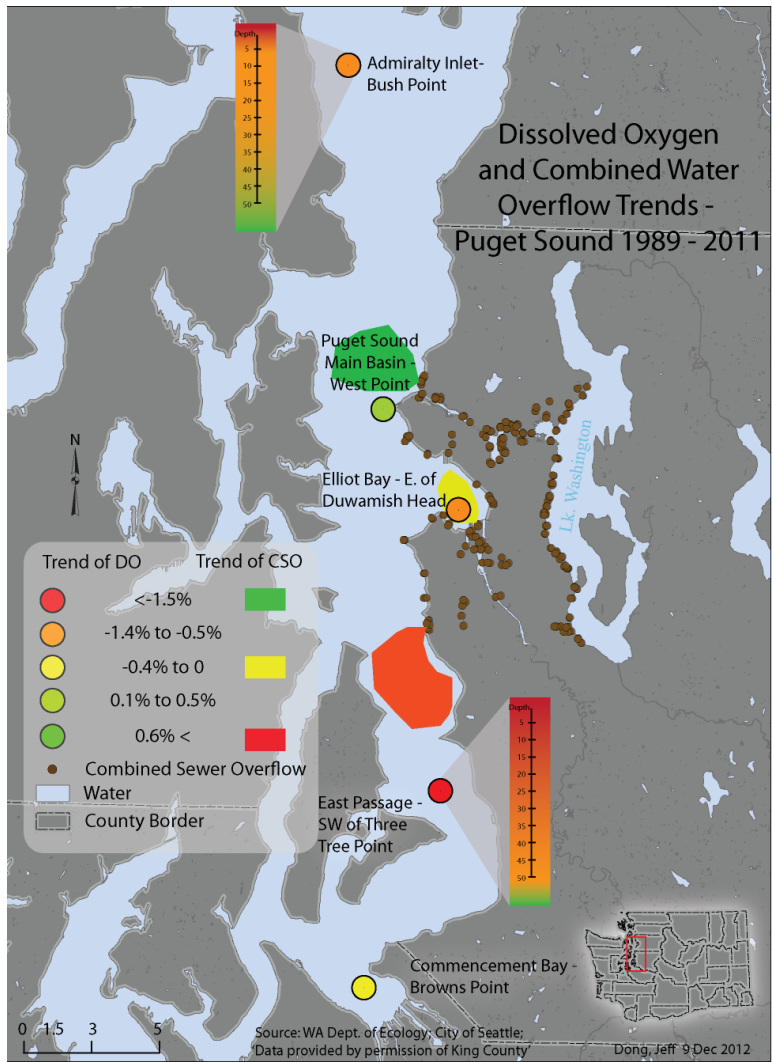


Graph 1c

The lack of available data forced a change in direction from the original concept sketch. Still the data represented in the map 1 above fails to truly convey the intent of the model originally designed – one that documents the human drivers (combined sewer overflow entering the Puget Sound) that create pressures on the DO levels. If data were available, conceptually, the map would appear as shown in map 1b below.

It is recommended that a public agency NOT use these maps as they are incomplete and do not support the known evidence that low DO levels can be predicted by the amount of organic waste introduced into the water column.

Further investigation is warranted into the actual amounts of organic waste introduced into the Puget Sound.

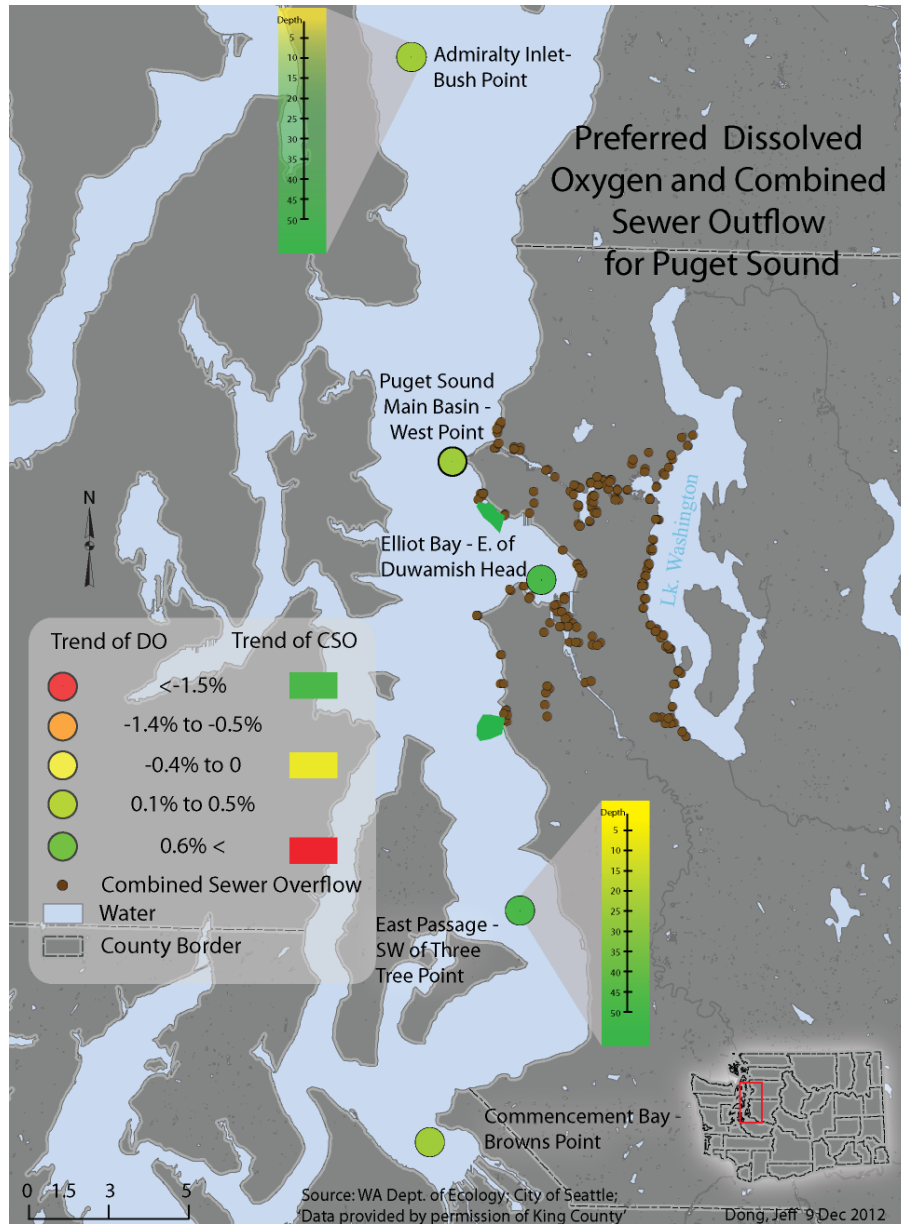


Map 1b

Sub-step 7A

According to the King County Auditor's Office report titled, "Performance Audit of Combined Sewer Overflow Program" (Anderson, et. al. 2012), the Washington State goal is to have less than 1 untreated discharge per year, by the year 2030. Now that the goal has been established, models can be created to help determine how to attain it.

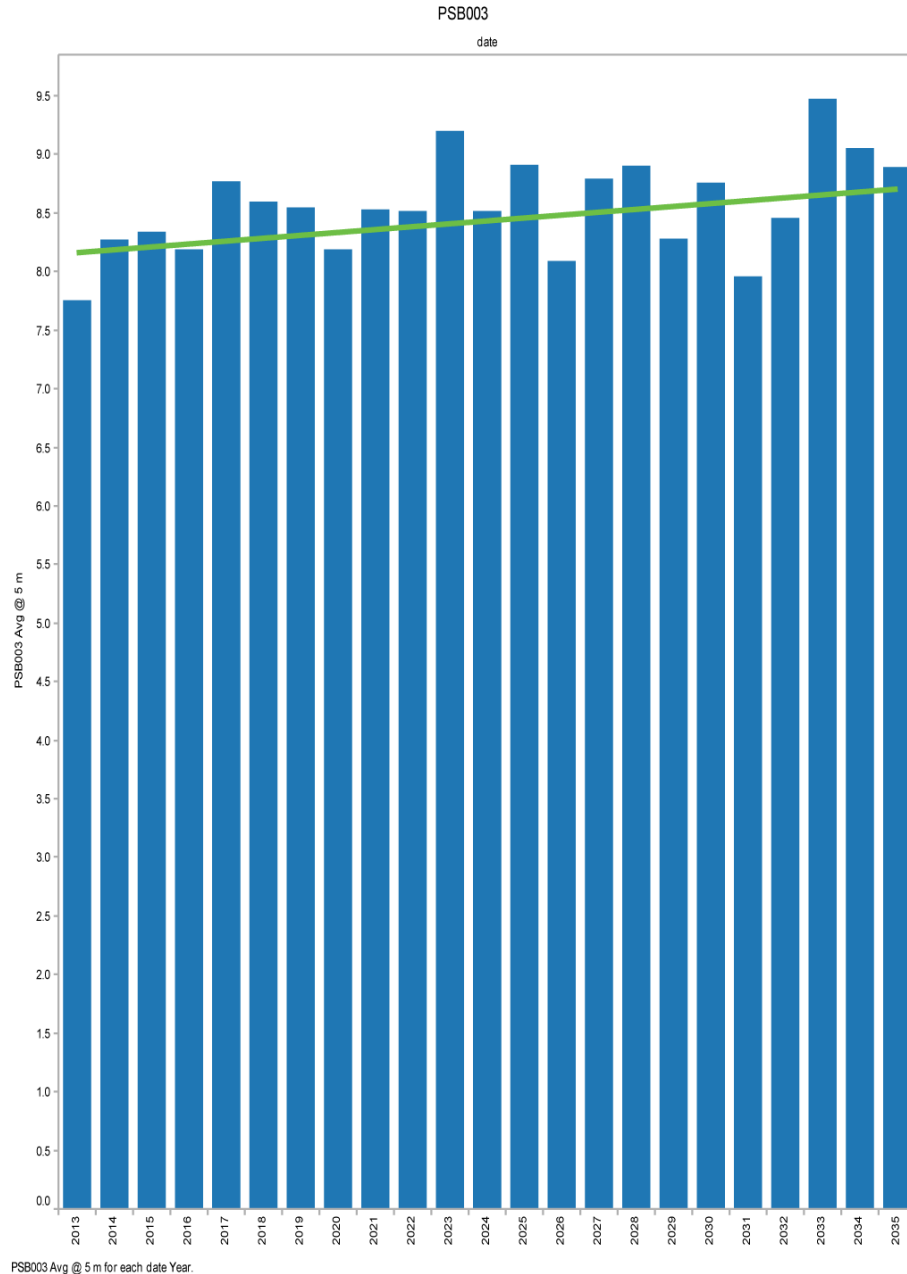
Map 2 (see below) illustrates the preferred outcome for Dissolved Oxygen levels and Combined Sewer Overflow discharges. Notice that the colors have changed to a more greenish-yellow hue. This represents a slowing of decline or increase in DO levels. It also represents fewer CSO discharges.



Map 2

Sub-step 7B

The drivers that were changed to reduce the pressures on the Puget Sound were the reduction in organic waste released marine waters. Notionally, attempts to meet WA state's goals of less than one untreated discharge per year resulted in increased capacity and better management of storm water by water treatment facilities. Increases in storm water overflow catchments were constructed, thus diverting the runoff to waste water treatment plants. Also, utilization of predictive models allowed for better management of any necessary discharges of untreated wastewater to ensure that they minimally impacted the marine ecosystem.



Graph 2

Sub-step 7C

Since the problem of Combined Sewer Overflow is a regional issue, there are many stakeholders who must participate in the process. Fortunately, the state of Washington has identified the goal for other municipalities and counties to strive for. However, with so many stakeholders with a variety of budget sizes, the change model is likely to be unique for each agency. I would recommend that a participatory change model be adopted. This allows for other designers to feel as if their opinions and unique circumstances are being heard and/or being addressed.

However, a secondary option would be the combinatorial change model. With the politics surrounding public policy/budgets and the indecisiveness of decision makers; this approach may be more familiar to those involved since it allows for key requirements to be resolved before moving on to less critical ones. This may prove beneficial when dealing with all levels of government (Federal, State, County, and municipal).

Appendix 9.

Marine Primary Productivity

By Kory Kramer

Sub-Step 1A

I have decided to use the EPA Science Advisory Board's conceptual ecological framework from 2002 to identify the major structural elements and processes of the Puget Sound social-ecological system and identify its key attributes (U.S. Environmental Protection Agency. (2002). *A framework for assessing and reporting on ecological condition: An SAB report*. U.S. Environmental Protection Agency Science Advisory Board, Washington, D. C. (Eds.) Young, T. F., & Sanzone, S. EPA-SAB-EPEC-02-009).

This conceptual framework uses six overarching categories to describe ecosystem structure and functioning: Landscape condition, Biotic condition, Ecological process, Chemical and physical characteristics, hydrology and geomorphology, and natural disturbance regimes. Of course the glaring omission of this framework, when set in the context of a *social*-ecological system, is the human element. I'll address this below.

Strengths of this conceptual framework are that it does a complete job of capturing the major ecosystem components as well as processes. In less complete conceptual frameworks that I reviewed, it would be easy to miss major ecosystem attributes simply because the framework was far too generalized. I felt that the SAB framework provided enough subcategories nested within each major component, to begin to understand relationships and interactions within the system. In very general frameworks, such as that of the Heinz Center (2008), I felt that there was so little contextual information that it would be difficult to conceptualize ecological interactions.

While not a salient feature, and not highlighted by the WSAS committee as a major difference between the three frameworks that it cites, the SAB framework addresses temporal and cyclical phenomena, looking at "Community *dynamics*," "Population *dynamics*," "Organic Carbon *Cycling*," "Other nutrient *cycling*," "Spatial and *Temporal* Salinity Patterns," "Hydro *dynamics*," "Sediment supply/*movement*," and *frequency* and *duration* as part of Natural Disturbance Regimes (emphasis mine). The other frameworks and models that I reviewed didn't as clearly address temporal and cyclical phenomena as the SAB framework. While one could argue that Simenstad's framework explicitly addresses cycling with its complex system of different types of arrows, I frankly found it difficult to understand and not as informative as the SAB framework.

Now to address the major omission of the human element: the WSAS committee states that while these generic conceptual frameworks are useful, they "can and should be supplemented by ecosystem-specific models." (WSAS, 2012). This is the level at which I feel the SAB framework could be supplemented with region-specific human interactions as related to the Puget Sound.

So while the more specific conceptual models (and I am purposely differentiating between the larger *framework*, and a region-specific *model*) provide greater detail in terms of interactions, process and functioning of the system (like Simenstad's Puget Sound Nearshore Partnership model), I found this type of conceptualization to be too focused on the process, not providing enough information about the major ecosystem components to be able to determine the key attributes that would be necessary to create indicators.

I feel compelled to add that reviewing the conceptual frameworks and models based solely on their graphical representations is superficial, and that upon reviewing the source material, most of these frameworks in fact do substantially account for what I thought was lacking from the graphics. Two key examples are the PSNERP framework and the Puget Sound Ambient Monitoring Program's (PSAMP) framework. These two provide a great juxtaposition. While the PSNERP graphic focuses on the relationships and interactions between ecological components of a system, and I had critiqued it as being too focused on the interactions and not providing enough detail about what the components were, reading through the source material (Technical Report 2006-03, Conceptual Model for Assessing Restoration of Puget Sound Nearshore Ecosystems) provides a very well-thought out, structured explanation of the reasoning behind the model. Interestingly, the PSNERP "conceptual model" proclaims that it can in fact be used as a "'framework' from which additional, more explicit 'submodels' can be consistently developed and applied to specific nearshore stressors, landscape segments, functions, or restoration designs." I was highly impressed with the explanations provided in PSNERP's technical report, and in fact this document explains how the Conceptual Model covers multiple spatial and temporal scales, ecosystem processes, explanation and prediction of change and, notably, *feasibility of translation into a computational model*. With all of that, however, I still feel that breaking down ecosystem components only into air, water, sediment and atmosphere doesn't provide enough context for me to be able to determine key attributes. Also, having to refer to a 41 page technical document in order to get the overall concept isn't as accessible as many of the other conceptual frameworks or models.

In terms of conceptualizing the social side of interactions in the Puget Sound region, I think that the PSAMP conceptual model does a fantastic job. This model is very heavily focused on the social aspects, including only one, non-detailed box referencing "Ecosystem Components." The source document does allude to the fact that there is a more detailed form, directly stating, "In its more detailed forms, the conceptual model helps identify ecosystem components and environmental stresses that are important to monitor." Nonetheless, I was unable to find the more detailed form.

To summarize, for my purposes in understanding ecological interactions in the Puget Sound, I would choose to use the SAB framework, realizing that it is missing the social component. To serve as a more complete framework for the Puget Sound social-ecological system, I would propose linking the PSAMP and SAB model/framework into an understandable framework as seen below in Figure 1. I find this to be understandable and provide a sufficient level of detail about structural components and interactions to begin to choose key attributes for which to develop indicators.

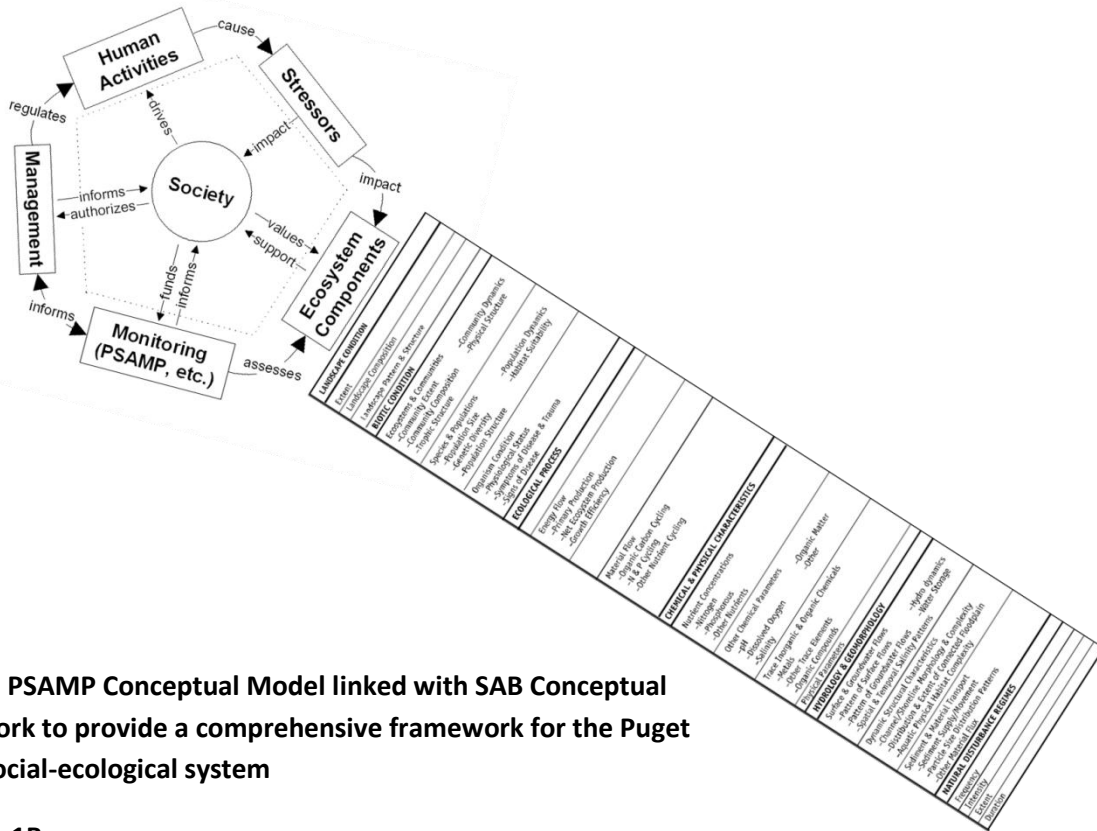


Figure 1. PSAMP Conceptual Model linked with SAB Conceptual Framework to provide a comprehensive framework for the Puget Sound social-ecological system

Sub-Step 1B

In addition to the SAB framework and the PSNERP and PSAMP conceptual models discussed above, I also reviewed the NRC and the Heinz Center frameworks that were provided in the WSAS document as well as a conceptual framework provided in Sound Science (Sound Science: Synthesizing ecological and socioeconomic information about the Puget Sound ecosystem. 2007. Mary H. Ruckelshaus and Michelle M. McClure, coordinators; prepared in cooperation with the Sound Science collaborative team. U.S. Dept. of Commerce, National Oceanic & Atmospheric Administration (NMFS), Northwest Fisheries Science Center. Seattle, Washington. 93 p.) I found the framework used in Sound Science to be overly focused on the human element, with only approximately one-fourth of the framework devoted to ecosystem structure and function, similar to the PSAMP example. This category included geology, climate, physical processes, habitat, species, and terrestrial/marine linkages, but didn't offer any kind of temporal or cyclical component. There was also nothing in this framework about energy and material flow, and considering that Primary Productivity is one of four missing indicators that the WSAS committee recommends be added, I felt that the framework should contain an energy and material flow component as a fundamental attribute of ecosystem functioning.

I will say that the Sound Science document recommends that “in building an ecosystem management framework from the conceptual model for Puget Sound (Figure 2-1), it is important to consider the context of an integrated, dynamic system in which humans play the part of both drivers and beneficiaries of ecosystem services (NRC 2004).” To directly address Sub-step 1B, it is this human component that needs to be better incorporated into the SAB framework that I have chosen. For the purpose of developing an indicator that measures energy flow as primary productivity in the ecosystem, I feel that the SAB framework provides a sufficient basis; however, to completely address the Puget Sound social-ecological system with one conceptual framework, we should go ahead and add something like the “Goods and Services” category from the Heinz Center framework, which finds concurrence in the Sound Science document as “Ecosystem Goods and Services” that lead to “Human Well-being and Values”. Ultimately, we end up with a graphical representation of this concept in Figure 1 above.

Sub-Step 1C

I have chosen to focus specifically on **Energy Flow** as a key attribute, which in the SAB framework is part of the major component Ecological Processes.

Sub-Step 2A

Given that I am interested in using Energy Flow as a way of telling us something about the major functioning of the Puget Sound social-ecological system, I have selected marine **Primary Productivity** as the indicator to represent this key attribute.

Sub-Step 2B

The WSAS committee writes that “ ‘energy and material flow’ is inadequately represented by the proposed marine water quality index. Although the index provides valuable information, a better indicator for this attribute would be primary productivity. Primary productivity appears as a key attribute in all of the ecological schemes in Table 1, and is also a key component of ecosystem processes that benefit humans.” (WSAS, pg. 43) In making this assertion, the committee cites three valid sources (SAB, NRC, and the Heinz Center) that, respectively, include “primary production,” “Productivity, including Net Primary Production” (a measure that I’ve learned may be more often associated with terrestrial systems, but the concept applies to marine primary productivity), and “ecological productivity.” The EPA’s Science Advisory Board provides the rationale for using Primary Productivity to represent Energy Flow in an ecosystem, stating, “The most basic ecosystem attribute, fundamental to life on earth, is ecosystem productivity, or the ability to capture sunlight and convert it to high energy organic matter (biomass), which then supports the non-photosynthetic trophic levels, including grazers, predators, and decomposers. The balance among production, consumption, and decomposition defines the efficiency of an ecosystem and its ability to provide the goods and services upon which society depends.” (US EPA. A Framework For Assessing and Reporting on Ecological Condition: An SAB Report. June, 2002. EPA-SAB-EPEC-02-009)

The committee roadmap states that an indicator should explicitly describe “the rationale for determining that the indicator accurately represents the attribute by using a conceptual model or an empirical association with predictive power.” From the research that I’ve done into marine primary productivity, there is a demonstrated empirical association between system energy, in the form of sunlight, heat and nutrients, and the productivity of primary producers, namely phytoplankton. Phytoplankton abundance responds directly to increased amounts of sunlight and nutrients, and their abundance, in turn, can be measured directly. I felt that this was a more direct relationship to productivity than using growth efficiency which is a statistic derived from other direct measurements or changes in O₂ or CO₂. For example, it is now well established that as phytoplankton grow, they consume CO₂ and release O₂, and as they die and decompose, they consume O₂ (this is closely linked to the dissolved oxygen problem in Hood Canal). So we could use fluctuations in O₂ and CO₂ as a proxy for primary productivity in this system, but it wouldn’t make sense since we can get good, direct measurements of phytoplankton growth and abundance, and probably provide a truer, more certain representation of how the ecosystem is responding to inputs.

Sub-Step 3A

The relevant measure that I will use for Primary Productivity is mg/m^2 of chlorophyll-a found in the water column. Using chlorophyll-a as a proxy for marine (and freshwater) primary productivity is well-established both in research literature as well as in practice. The Washington Department of Ecology states that “chlorophyll is a proxy for phytoplankton biomass in the ocean. We use depth integrated (0-50 m) concentrations and subtract a time- averaged seasonal cycle (13 yrs.) from the dataset that is specific to each station. From monthly de-seasonalized data we calculated yearly averages for each region.” http://www.ecy.wa.gov/programs/eap/mar_wat/trends.html

In a 2011 evaluation of Puget Sound indicators by Kershner, et al., chlorophyll-a is shown to be diagnostic (responding to few as opposed to many key attributes) and good as an early warning sign of imbalances in the ecosystem as phytoplankton growth responds quickly to changes in system input. Responding to few key attributes as opposed to many means that there is less scope for confounding relationships. In other words, we can be more confident that changes in levels of chlorophyll-a really are directly related to changes in primary productivity (phytoplankton production).

Interestingly, there is a lack of conformity in the units used to measure chlorophyll-a. The Washington State Department of Ecology (DOE) uses mg/m^2 , King County uses ug/L , while NASA (the SeaWiFS [Sea-viewing Wide Field-of-view Sensor] mission), uses mg/m^3 . The differences in units are less important than the actual collection technique which seems to be where the greatest room for uncertainty, and hence debate, lies. MacFadyen (1998) conducted a comparison of chlorophyll-a measurements taken from the SeaWiFS satellite sensor to those taken *in situ* from cruise data in Monterey Bay off the coast of California. Her results showed SeaWiFS to overestimate chlorophyll in all seasons, and that the problem tends to be most acute within 100 km of the coast; i.e. the SeaWiFS data is the least comparable to *in situ* measurements closest to the coast, so that to use this data to monitor Puget Sound might not be the best decision. This problem stems from the fact that many of the processing algorithms were calibrated from a marine optical buoy moored off the coast of Hawai'i. While the frequency and coverage of the satellite data is impressive, acquiring approximately 15 pole-to-pole orbital swaths of data per day, scanning approximately 90% of the ocean surface every two days, this is precisely the reason that the satellite data shouldn't be used for Puget Sound. This mission was designed to collect information about global patterns and is not well suited for a large-scale (smaller area) study such as that of Puget Sound and its subregions.

The next obvious problem with relying on satellite data to monitor Puget Sound indicators is that we don't have control of the collection. The SeaWiFS mission has now ended, so that if this were our method of data collection, we now wouldn't have any present or future data. The final issue that I have with using remotely sensed data for chlorophyll-a is that it is only taking near-surface readings. *In situ* measurement methods such as those discussed below, despite the fact that they often average readings from throughout the water column, are capable of taking measurements at varying depths. This would allow for much more complex analysis and understanding of the ecological and physical properties of the Sound that affect primary productivity.

This brings us to examine the data collection methods and measurement units employed by DOE and King County. It seems that both use stationary, moored buoys and fluorometers to measure chlorophyll-a. A key characteristic of chlorophyll is that it fluoresces. When irradiated with light of a particular wavelength, it emits light of a higher wavelength (lower energy). The ability of chlorophyll to fluoresce is the basis for measuring it *in situ*. As with remotely sensed data, an algorithm is employed to

convert a sample's fluorescence to $\mu\text{g/L}$ or mg/m^2 . That California Water Board's Surface Water Ambient Monitoring Program provides example conversion calculations to convert from $\mu\text{g/L}$ to mg/m^2 , implying that these two units of measure are fungible with the difference really being one of scale represented by the sample collection size.

With the indicator and unit of measure established, we are able to measure the State of one aspect of the Puget Sound social-ecological system related to energy flow. Drivers that would be related to this state would be agriculture and population growth insofar as they are major contributors of excessive nutrients into Puget Sound in the form of nitrogen and phosphorous (Pressures). The ecological Impact of these pressures can be measured as the difference between a baseline State and a subsequent State, and causes for that change can be correlated to Pressures. Finally, there may be a Response to the Impact, in the form of macroeconomic policy measures (similar to the Growth Management Act) that influence the Drivers, or environmental policies that target Pressures. An example of the latter might be mandating a 300 ft. buffer that should remain forested along riparian corridors; or if not forested, using a mix of regulations and incentives to increase forest cover along riparian corridors. Whether the Responses are effective, and how effective, should be computable in subsequent measures of the system's State, in this case, the amount of chlorophyll-a at a monitoring station (controlled by season).

Kershner J, Samhouri JF, James CA, Levin PS (2011) Selecting Indicator Portfolios for Marine Species and Food Webs: A Puget Sound Case Study. PLoS ONE 6(10): e25248. doi:10.1371/journal.pone.0025248

MacFadyen, A. (1998) Modeling Primary Productivity From Satellite-Derived Chlorophyll in the Monterey Bay Region. University of Victoria.

Sub-Step 3B

Sources are cited in the discussion above as well as other measures considered and reasons that those were not appropriate.

Sub-Step 3C

Using a base map outline of Puget Sound, I sketched out the concept of representing chlorophyll-a levels around the Sound. The Sound contains a number of moored monitoring stations that measure chlorophyll-a and report levels in mg/m^2 . As discussed throughout the responses above, chlorophyll-a is a proxy for primary productivity in the Puget Sound social-ecological system. Primary productivity is a good thing and is absolutely necessary to support higher trophic levels. I believe that there is a common misconception when thinking about marine primary productivity, especially because we're looking at phytoplankton abundance, to think of it on a scale that places high levels as bad, and assumes that lower levels then are good. However, there must be a normal or "optimal" phytoplankton production level and deviations that vary too far above or too far below that optimum, should be seen as indicators of something wrong with the system.

There are many factors that contribute to and affect primary productivity in a marine environment including current, nutrient levels (which can come from ocean upwelling or input from terrestrial systems such as dairy farms, agricultural fertilizers, and leaking septic tanks), oxygen availability, salinity (determined by freshwater input from rivers and water temperatures that affect density and at what depth stratification occurs) and light (closely correlated to season, with late spring and summer bringing high levels of sunlight to the Sound).

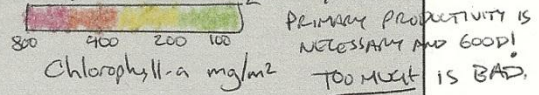
This representation is showing chlorophyll-a levels at *one point in time*, interpolated into a raster representation from the original point data. There are some important decisions to be made regarding this representation.

1. At this scale, I think that it is reasonable to represent chlorophyll-a levels in this way since it is a snapshot of a very large area. Any movement of phytoplankton caused by current, or presence caused by upwelling of nutrients will be indicated as higher levels of chlorophyll-a in those areas. It is only when we want to trace back what the causes might be of overly high levels, that we will need to analyze flow direction and determine if levels may be affected by human pressures.
2. In a static map, it will be *difficult to capture the seasonality* of phytoplankton blooms. Perhaps any visual representation of this should include at a minimum the high (summer) levels and low (winter) levels. Seasonality is then nested within year-to-year trends, as *really it is the year-to-year trends that we will ultimately be interested in*. I think this is what the DOE's methodology aims at through its methodology: "We reduce the volume of information by using regional reporting, and we restrict information to higher order indices (MWCI and the Eutrophication Index). This reduces noise in the annual index scores and reduces the number of reporting units. By calculating trends from 1999 to 2008, we additionally reduce inter-annual variability to focus attention on trends with a high degree of certainty. As a result, we arrive at a clearer picture: the largest overall changes in the MWCI and Eutrophication Index are predominantly occurring in the reporting region of Admiralty Reach, Central Basin and South Sound."
3. While symbolizing the actual values of chlorophyll-a at each station, or interpolating values to cover regions of the Sound is important, because each representation would be an instantaneous one at one point in time, I think that it would be good to represent the *change of the indicator* from one point in time to another. After all, this is really the core of what we're interested in – is primary productivity steadily increasing as time passes? Because if it is, it will undoubtedly reach a point when there are too many blooms, too often, occurring over greater amounts of the year, and causing grave imbalances in the Puget Sound ecosystem. These are the long-term trends that we need to address.

Given the considerations above, I might imagine that if we examine levels of chlorophyll-a across the Sound that we will see high levels around areas where major rivers enter. These rivers travel through agricultural areas and because of rivers' historical power to draw human settlement to their mouths, there are major cities located at these points. Seattle, Tacoma, Everett, and Olympia are key areas to study in this sense. Without having analyzed any data, I would think that terrestrial patterns would have an impact on primary productivity around these major cities and drainage points and this would be an interesting spatial pattern to explore further.

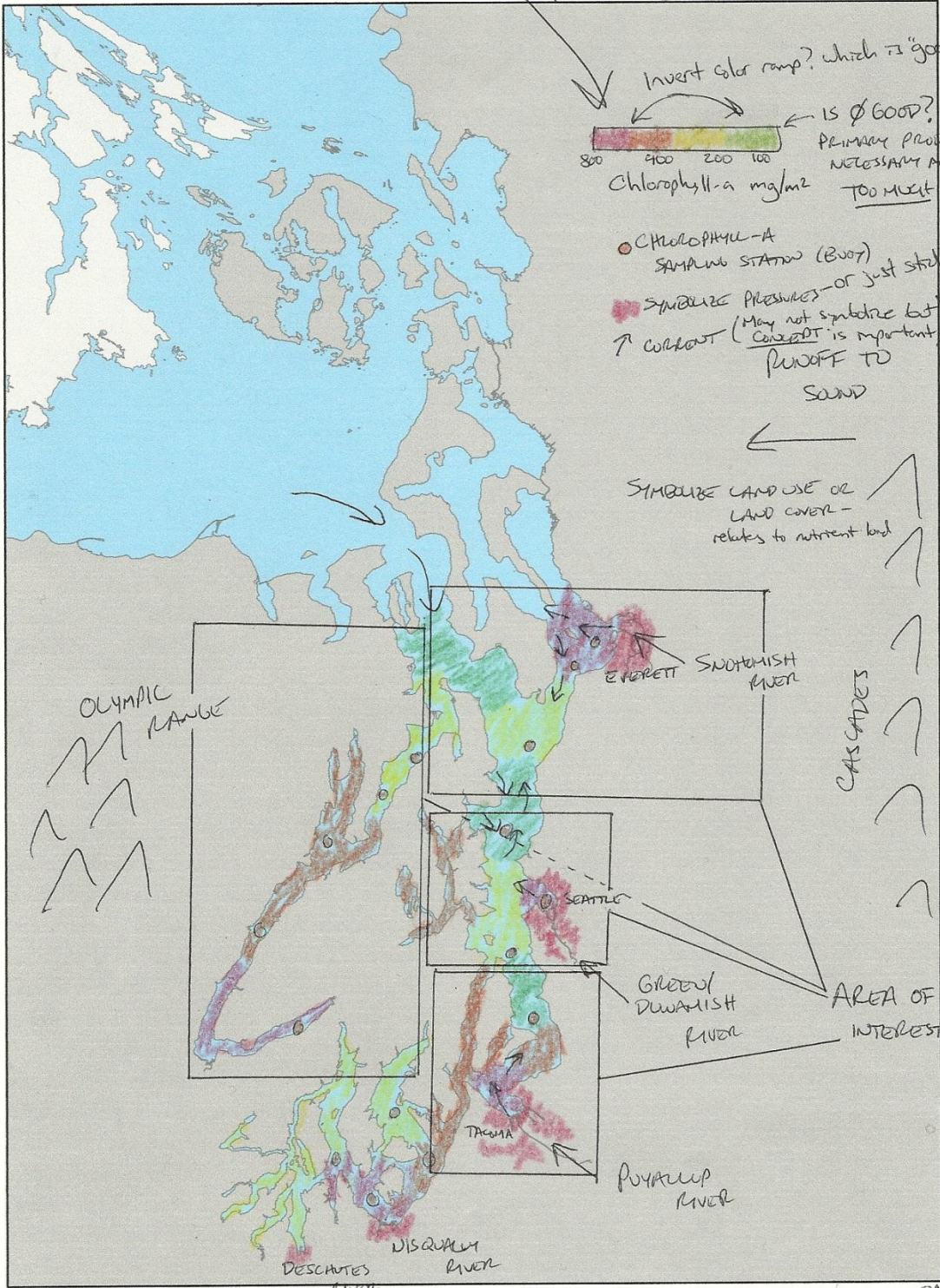
Shouldn't be good → bode is more complex w/ optimal range AND TOO HIGH (threshold) + TOO LOW (threshold)

Invert color ramp? which is 'good'?



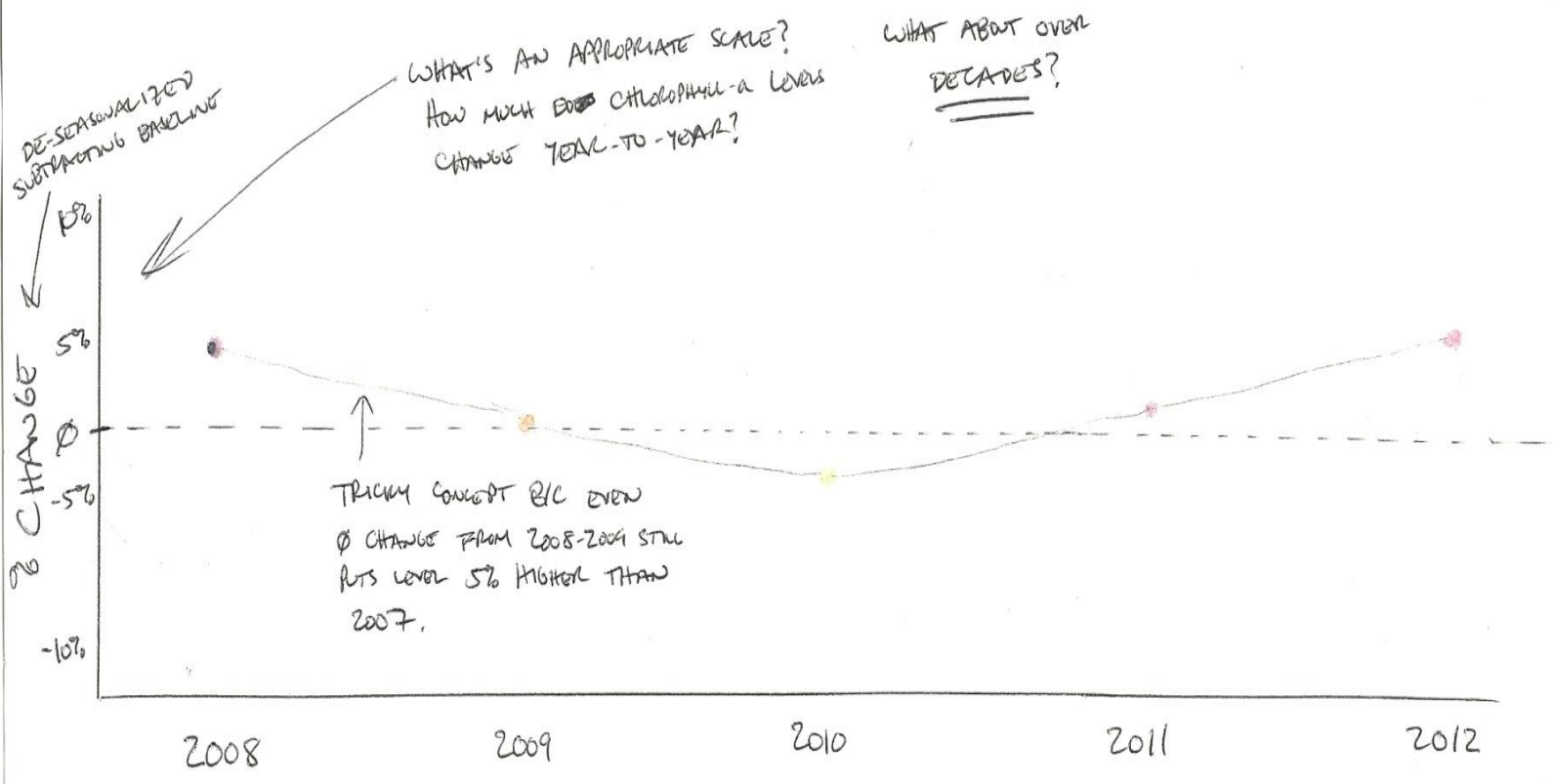
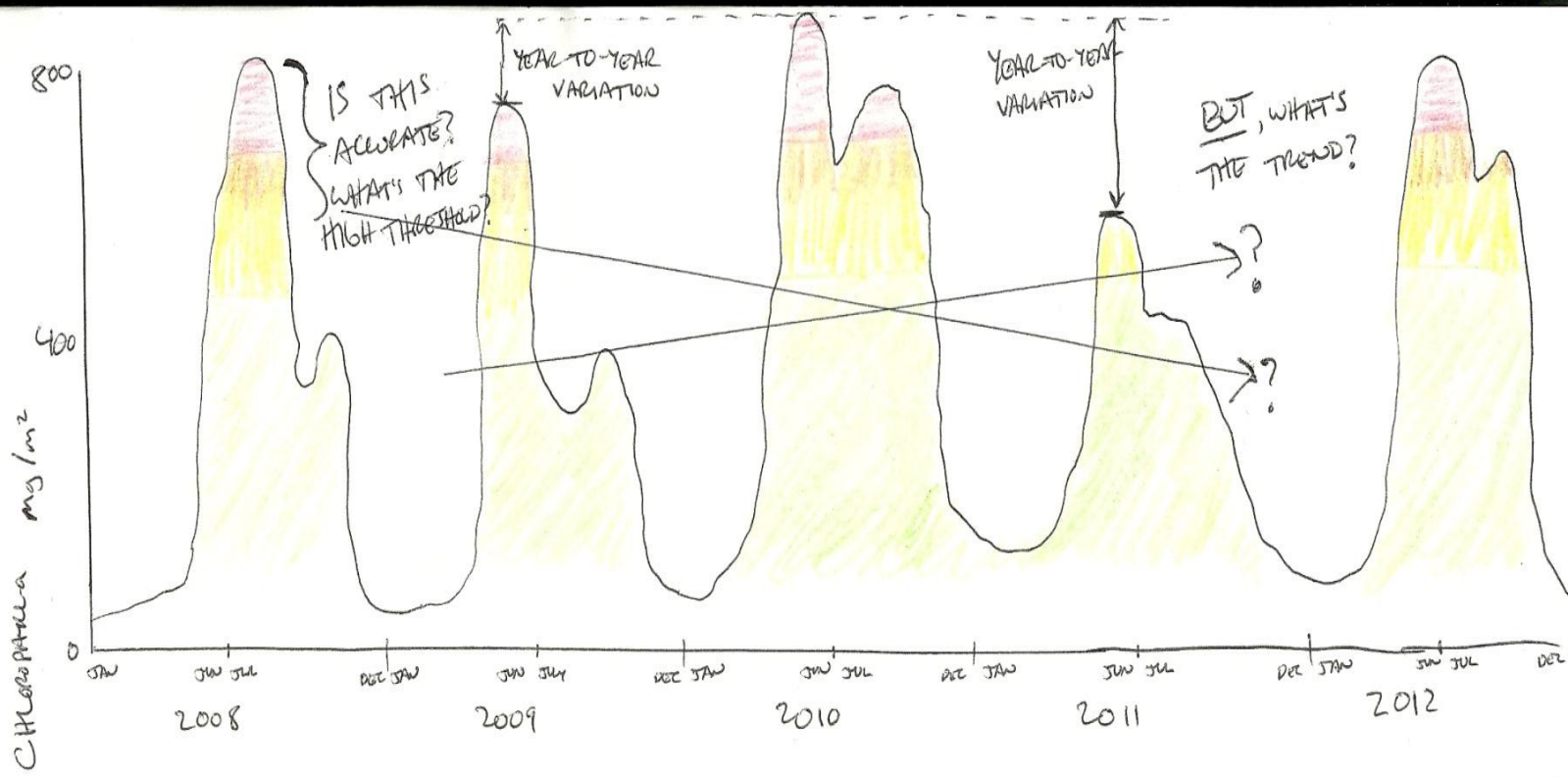
- CHLOROPHYLL-A SAMPLE STATION (BOAT)
- SYMBOLIZE PRESSURES — or just stick to analyze chlorophyll a?
- ↑ WORKOUT (May not symbolize but CONCEPT is important) RUNOFF TO SAND

SYMBOLIZE LAND USE OR LAND COVER — relates to nutrient load



- RIVERS TIE HUMAN PRESSURES TO SOUND IN FORM OF NUTRIENTS. FROM WHAT? NITROGEN - DAIRY, PHOSPHORUS - AG
- AT THIS SCALE MAYBE WE CAN INTERPOLATE POINT DATA TO PASTER TO SHOW GENERAL TREND ACROSS SOUND. BUT FORCED IN NEED TO BE MORE AWARE OF LOCAL CURRENT EFFECTS - SEPTICS (POPULATION)

Sub-Step 3D



As partially discussed for the map sketch, primary productivity, as evidenced by measuring chlorophyll-a, is highly correlated to season. In lakes, temperature can be more of an influential factor, while in the Puget Sound, with water temperature moderated by much larger ocean systems, nutrients and light are more influential. We should see the natural seasonal blooms of phytoplankton usually in May or June, remaining pretty high through the summer, sometimes with a secondary bloom in late summer and finally a sharp decline in productivity during the winter months. This is the typical pattern, yet as with most natural cycles, there is natural variation. It may be that one year there is a higher amount of productivity than in the next year, or there may even be natural cycles on a multi-year scale. So we need to be careful about placing too much emphasis on one very high year, or one very low year, and focus on trends over 5-10 year cycles. What are chlorophyll-a levels in 2012 compared to 2002? Compared to 1992? What about 1962?

In Lake Washington, studies have shown that temperature changes over the last 50 years are causing the entire productivity period to be extended by about 25 days. So we would see the large spike in this graph about 16 days earlier every year and last about 9 days later. I suppose that a temporal pattern such as this could occur without necessarily changing the magnitude of the bloom. However, temporal disturbance to an ecological system can be as devastating as spatial or attribute disturbance because not all species are able to adapt quickly enough. This can cause a ripple effect up and down the food chain that can be detrimental to both the environment and the economy.

Is such a temporal shift occurring in Puget Sound primary productivity? Would we be able to see it if we were only concerned with a 5 or 10 year change measurement? This is a critical question, but it has more to do with the representation and analysis of the data than the acquisition. With the data that we have decided to collect, and at a daily collection frequency, averaged to the month, all of the raw material is there to construct change analyses for the spatial, temporal and attribute components of our indicator. If the blooms are starting to occur regularly in March and last through October (*temporal*), we could see that with the data we are collecting. If the blooms are causing higher spikes in chlorophyll-a levels (*attribute*), we could see that with the data we are collecting. And if the blooms are occurring in different parts of the Sound (*spatial*), we could see that with the data we are collecting. This will all be important to consider when we think about our preferred state as we get into designing a solution to this complex social-ecological phenomenon.

Although this background data must exist, I was unable to find it readily available to the public. There is access to a limited amount of chlorophyll-a data through DOE's Environmental Information Management (EIM) system database; however, that data is less consistent in terms of the time range monitored at any given point in the Sound. For example, some stations have data from 2006-2009, while others have data for some years before 2000, while others still have more recent data at certain stations up to about 2011. This stems from the fact that the chlorophyll-a EIM database contains records from a number of independent studies, rather than a comprehensive, long-term monitoring effort. So while the data is still important to have, and can show seasonal patterns at each station (see Figure 2), it does not enable us to determine long-term trends in levels of chlorophyll-a (primary productivity) across the Sound.

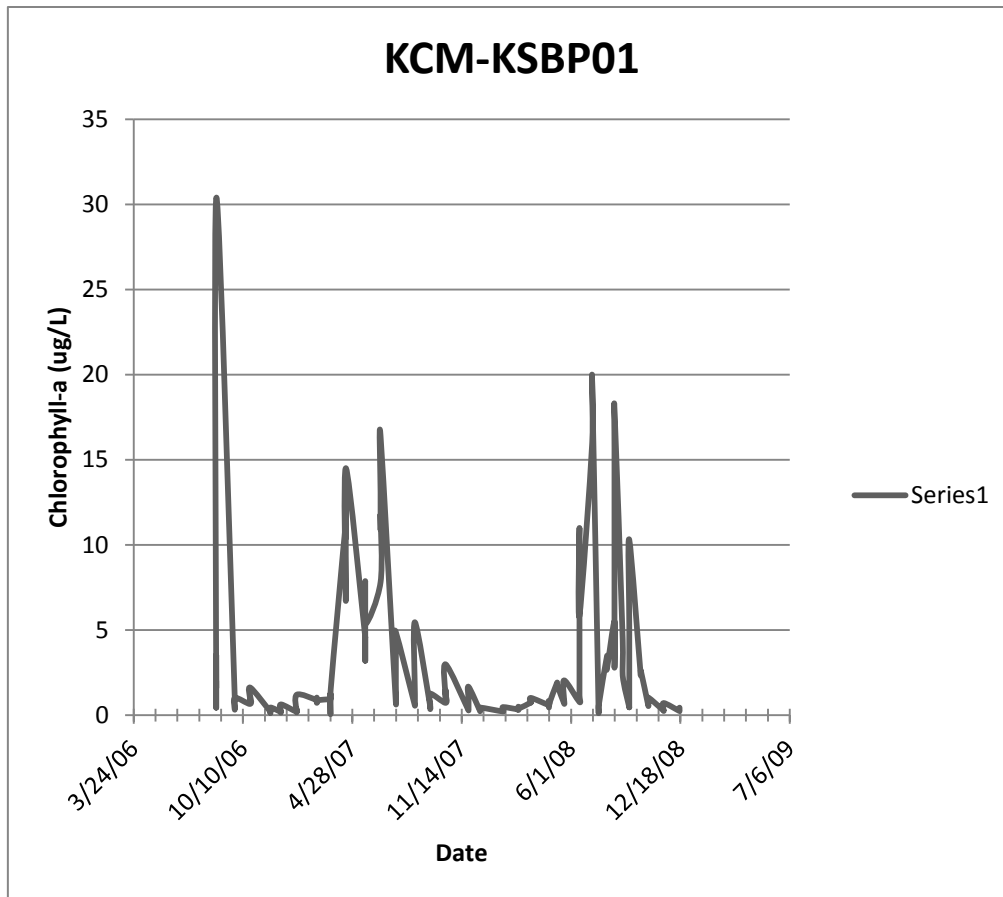


Figure 2. Chlorophyll-a levels from a moored monitoring buoy in Puget Sound from 2006 to 2008. Seasonal variation is apparent. Data extracted from DOE’s EIM database.

As I became familiar with the chlorophyll-a data, and started to understand the large seasonal variability, but also the fact that these variations are nested within a larger Pacific Decadal Oscillation (PDO) [whispers of Braudel] which is a “pattern of Pacific climate variability that shifts phases on an inter-decadal time scale and affects Washington’s marine waters” (Mantua et al., 1997), it became apparent that it is not necessarily meaningful to compare one year to another outside the context of what could simply be normal variation. That is, we’re not just interested in looking at increases or decreases. We’re interested in looking at increases or decreases in chlorophyll-a levels that are significantly different (or anomalous) from what we would see due to natural fluctuations alone. And this is what finally led me to more fully understand the 127 page DOE report explaining the reasoning and methodology behind the Marine Water Condition Index. (WA Department of Ecology. Marine Water Condition Index. May 2012. Publication No. 12-03-013)

The DOE methodology de-seasonalizes their data so that we can look at a number that accurately represents a certain year, but then they also compare that to a long-term baseline (at this point averaged over about 13 years) in order to account for natural fluctuations. So is this good enough for our purpose of measuring our indicator in order to determine what is happening with marine primary productivity and possibly elicit a corrective management intervention? I think so. The DOE data does allow us to determine how the data is trending over long time periods. With an indicator that is so quick

to respond to changes in system input (remember Kershner, et. al.), it is important to not base decisions on one chlorophyll-a level reading during one season, during one year. This approach would lead to a lot of reversals in management interventions!

The MWCI report provides a great graphic explanation of how this level of information detail is related to temporal and spatial scale in Figure 3 below. This gets to the core of the dilemma that I have had with this data. That is, it is appropriate and necessary to be collecting monthly data so that we can see and analyze seasonal patterns, because there will likely be changes at this level of resolution. However, for landscape-level decision making, we will need to look at long-term trends caused by much broader, more pervasive issues than one particularly high nitrogen load during one season.

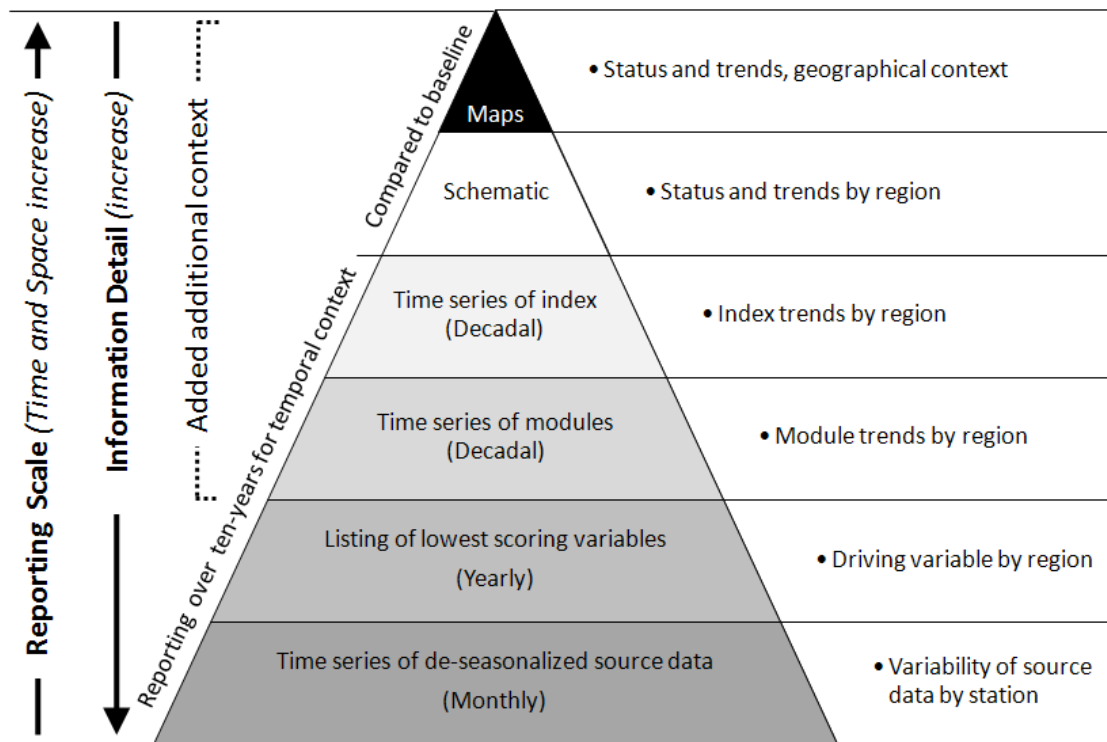


Figure 3. Hierarchy of scale and information for reported layers

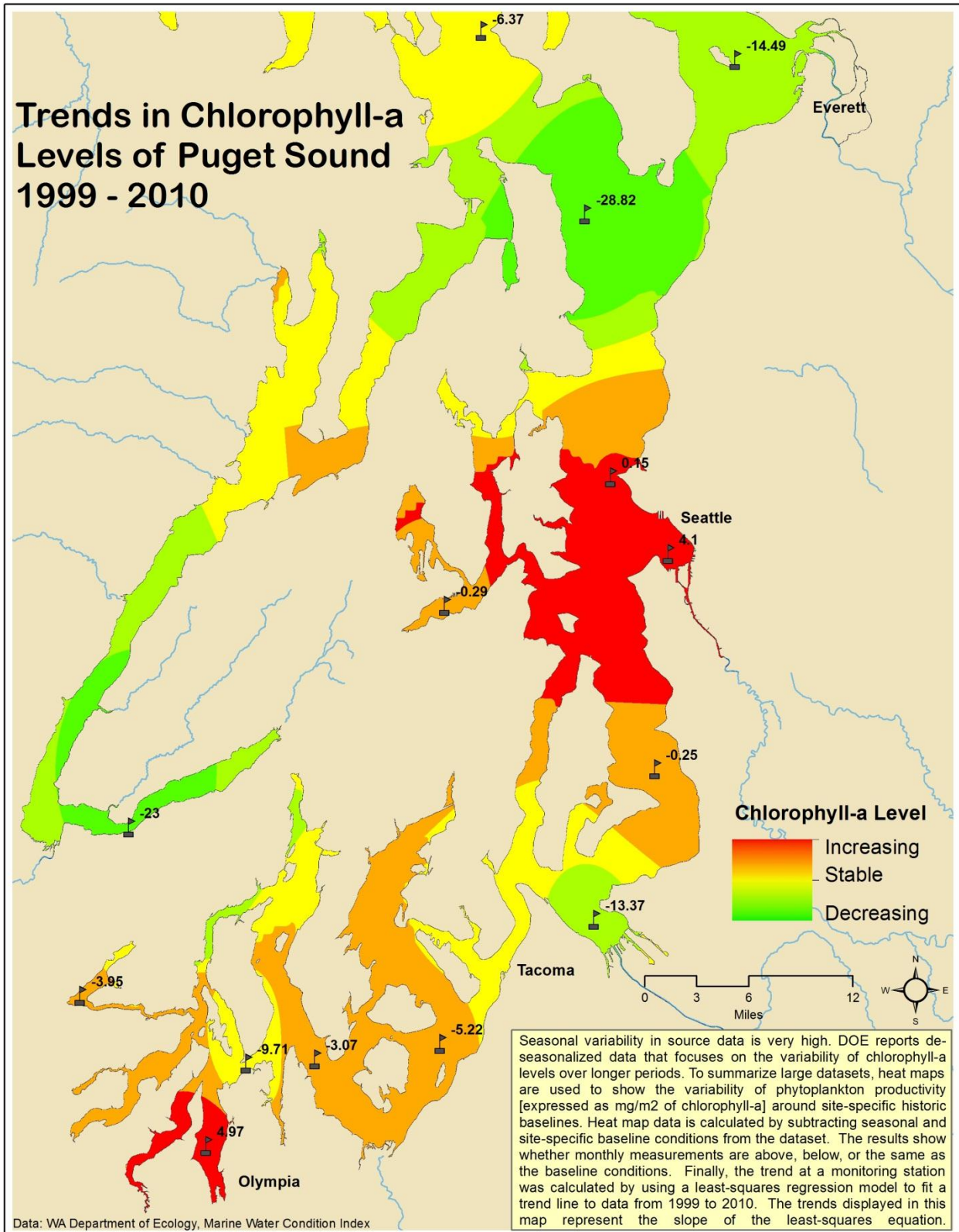
The MWCI report authors are very aware of these spatial-temporal considerations, and the reasons that we might have to focus on the tip of the pyramid versus the reasons for focusing on the base of the pyramid. The report states “The significant MWCI trends for Puget Sound’s Central Basin and Admiralty Reach indicate that Puget Sound continues to increase in nutrients on a large temporal and spatial scale. River loads of nitrogen on the other hand have declined (Hallock 2009). One possible explanation for the increase in nutrient conditions above ocean conditions is the increase in population density over the last 10 years, consistent with other U.S. estuaries (Paerl et al., 2006). This localized increase in population affects nutrient discharges for many sewage treatment plants limited to two mechanical and biological treatment stages and could increase non-point inputs (e.g., stormwater, failing septic tanks). Nutrient inputs from sewage treatment plants are sizable (Roberts et al., 2008).”

At the same time they acknowledge that a drawback of the MWCI is that it is not “designed to detect change in extremes in environmental conditions when median conditions remain unchanged. Other

monitoring approaches to address this issue are needed. These approaches include using continuously deployed sensors and reporting tools focusing on the amplitude, frequency, and duration of events.” Amplitude, frequency and duration of events would look more like Figure 2 above; that is, focused on a smaller spatial extent, and shorter temporal period.

So if, as the report states, one possible explanation for the increase in nutrient conditions is the increase in population density over the last 10 years, might we expect to see upward trending (that is, increases in chlorophyll-a levels) around high population areas of Puget Sound? Let’s take a look at the map below.

Sub-Step 3E



In order to produce the computational representation of chlorophyll-a trends, I started with the Department of Ecology (DOE) data from 1999-2010. This data does not provide the raw measurements at each station, rather it gives chlorophyll-a numbers by month after subtracting a historical baseline. I have briefly explained the reasoning behind that methodology above. While at this stage we are still working in mg/m², we need to understand that the data has already been processed in a number of ways. Firstly, at each station, samples are taken from a number of depths, with an average measurement calculated. DOE calls this a “depth-integrated” measurement. Then, daily or more frequent measurements are averaged into one number for each month. The most interesting result of this preprocessing step is that it actually produces negative numbers, even though it is representing a measure of chl-a presence at a point in time. This is because if the historical baseline is greater than the measurement, when the baseline is subtracted, a negative number is produced. DOE codes these negatives with the color green, indicating that a reduced chl-a level is desirable. Numbers higher than the baseline are red while numbers hovering around the baseline (little to no change) are black. This methodology already incorporates a level of change, comparing a measurement in time (present) to an averaged baseline. However, it still isn’t generalized enough to show us a trend.

In order to calculate a long-term trend, I needed to be able to compare an average chl-a level from one year to the next, and ultimately compare from 1999 to 2010. I averaged the DOE’s monthly chl-a levels to produce one average number to represent the year. Yearly numbers were placed in a heat-map similar to DOE’s (Table 1), and I determined a trend by graphing the yearly levels and fitting a trend line to the data (see Graph 1 in the next step).

ST_ID	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	TREND
ADM001	65.26	83.44	24.73	-53.62	76.62	-11.54	13.94	-32.20	23.44	-25.17	-28.96	15.67	-6.37
ADM002	191.71	30.93	-11.00	-18.63	47.53	17.19	28.60	-20.36	15.61	-13.94	4.91	-0.90	-8.37
ADM003	613.74	139.79	81.22	23.79	105.21	-10.44	7.08	-15.28	62.50	-26.10	23.46	41.51	-28.82
BLL009	-10.30	-21.69	43.38	6.61	70.04	-9.32	11.04	-1.84	-12.34	20.67	7.98	6.30	0.00
BUD005	-98.29	-3.25	72.35	-39.47	54.30	-61.50	87.62	-1.34	33.77	-26.55	40.79	26.28	4.97
CMB003	307.41	72.97	23.03	-19.56	39.13	22.10	56.10	-7.29	54.67	-25.27	-7.39	32.10	-13.37
DNA001	133.45	47.60	93.62	-27.37	12.46	14.37	47.83	29.00	39.07	-16.09	-45.17	-11.06	-9.71
EAP001	-100.61	67.71	70.11	-11.73	51.99	61.25	61.01	-35.17	84.81	-70.92	-5.56	22.49	-0.25
ELB015	-15.69	19.57	28.28	-17.78	66.12	-3.76	12.22	-21.05	84.27	13.93	29.52	67.79	4.10
GOR001	11.15	20.02	84.59	-23.37	89.21	89.54	53.42	19.15	30.31	-30.43	-27.83	-14.34	-5.22
GRG002	14.57	24.68	56.81	-6.45	66.56	5.16	90.54	-21.96	58.33	-19.13	20.58	81.17	1.08
GYS004	-1.41	0.04	0.45	-3.65	3.35	-3.02	31.97	2.25	26.18	-3.69	3.82	-13.20	0.20
GYS008	-1.41	0.04	1.15	-1.71	-0.86	1.72	5.27	-2.94	1.32	-1.20	11.28	5.95	0.62
GYS016	39.14	-6.11	-4.92	32.01	-3.62	-1.73	19.59	7.14	7.90	14.88	8.13	1.62	-0.74
HCB004	-35.43	631.24	57.96	98.76	178.60	-13.55	-10.95	8.44	13.19	-25.11	13.05	10.21	-23.00
NSQ002	-70.99	39.27	72.23	-45.83	-14.66	71.27	37.74	1.76	34.53	-44.13	-55.39	-37.40	-3.07
QAK004	54.17	20.54	0.66	-10.60	-1.69	7.19	23.29	-2.91	-3.66	-36.37	-15.68	0.42	-3.95
PSB003	11.78	51.45	29.52	-29.36	66.31	73.54	53.97	-19.90	28.93	-2.39	23.57	57.67	0.15
PSS019	205.22	101.91	57.87	38.43	51.41	21.51	19.55	-19.42	19.97	-24.06	-3.84	-4.95	-14.49
SAR003	30.81	80.82	11.44	-9.60	164.11	12.35	45.56	-38.89	-1.30	19.76	-10.26	-36.18	-7.11
SIN001	33.95	18.80	1.35	-11.72	41.48	-20.08	10.32	9.16	10.01	-8.59	21.78	26.49	-0.29
WPA001	7.38	8.20	-2.50	5.70	0.76	-11.26	8.37	-16.54	5.87	6.29	-10.07	-1.05	-0.79
WPA003	7.38	8.20	-0.89	7.26	4.43	-2.22	8.95	0.25	1.08	-1.74	18.45	1.58	-0.03
WPA004	50.47	16.99	-2.46	-0.11	-2.49	-5.71	14.29	11.77	0.12	10.52	6.47	-4.42	-1.90
WPA006	24.12	5.98	-8.78	-6.37	-5.85	-16.06	17.34	23.78	9.18	-3.52	24.61	-8.56	0.16
WPA007	4.46	1.14	0.43	-3.03	-1.69	-5.77	3.70	3.62	9.21	-8.61			-0.19
WPA008	15.48	-1.26	-5.45	-2.53	1.02	-3.91	2.04	4.11	8.77	-6.66			-0.44

Table 1. Yearly chlorophyll-a levels in mg/m². Trends were calculated by fitting a trend line to data from 1999 to 2010. The trends represent the slope of the regression equation.

That covers the data and how it was transformed to be able to represent the underlying phenomenon of interest which is the trend in chl-a levels in Puget Sound over time.

Monitoring stations were included as a tab in the DOE MWCI data using NAD83 latitude and longitude. A side note is that the DOE data places the stations in China, having left out the negative sign for longitude! I did make the assumption that longitude should have been on the order of -122 degrees, changed the data, and checked that the stations do in fact show up in Puget Sound.

With the monitoring points established, Table 1 above was joined to the spatial point layer through a simple join based on the ST_ID field. At this point, I was able to symbolize each discrete point based on its trend, so that upward trending chl-a levels were represented with red, downward trending levels with green and less dramatic changes with yellows and orange.

Simply displaying a change at one point in the Sound doesn't help us "see" the changes over the entire Sound from 1999 to 2010. In order to depict the potential patterns across the entire Sound, I chose to use the Inverse Distance Weighting (IDW) tool from the Spatial Analyst toolbox. I set the processing extent to ensure that the entire Sound would be covered in the result, and based the interpolation on the closest three points with the Power setting at 3. The default setting in ArcMap for number of points is 12 and the power is set to 2. What this means is that at each station, the software will consider the values at the next closest 12 stations and interpolate intermediate raster cell values based on those values with the influence of each of the 12 points diminishing by the square of its distance from the point of calculation. Because there are only 27 stations, and because of the irregular shape of the Sound, which in turn causes a lot of local variation in current patterns, I felt that the interpolation between points should be restricted more locally. Even then, I changed the inverse distance weighting factor because the response of chl-a to local conditions is quite rapid meaning that a very high measurement at one point can be the result of a highly local Pressure like insufficiently treated wastewater entering the Sound, or input from a river. These Pressures will affect chl-a levels in that vicinity, but the extent of the impact will depend more on currents and light than on distance.

One operations issue that I ran into was with the points considered for each calculation. The map above shows that the Hood Canal results are being affected by values from monitoring stations across the Kitsap Peninsula, when obviously this shouldn't be the case. I did convert the Washington state polygon data into polyline data in order to set up a barrier for the IDW calculation, but that did not solve the issue. Ultimately, I would devote more time to solving this problem if this analysis were to be used to make a real-world decision, because there are some recognized misrepresentations in the map.

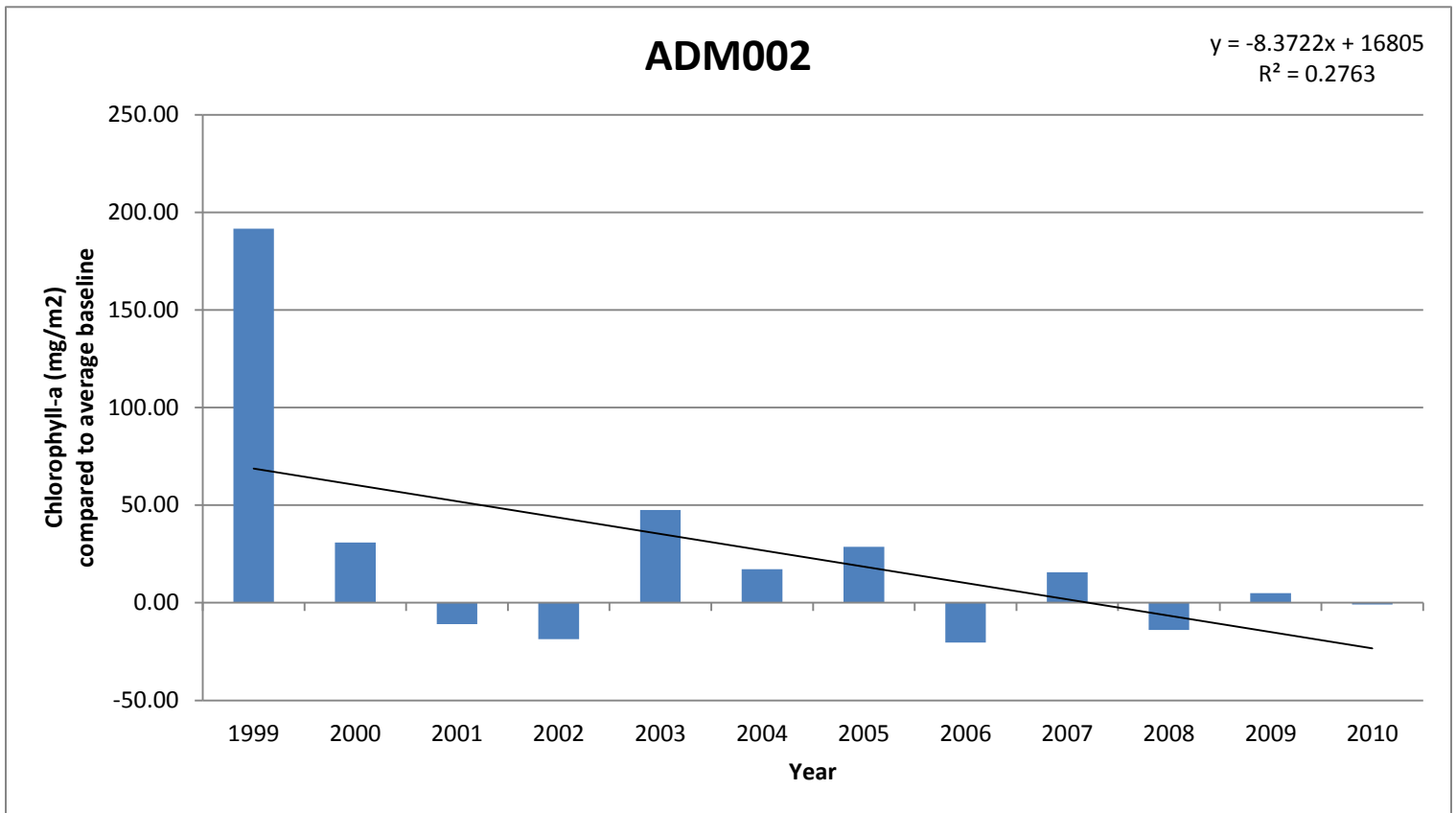
With the raster representation created, I decided to symbolize the trends in an intuitive manner with red showing areas of increased chl-a levels and green showing areas of decreasing chl-a levels. This is certainly an oversimplified view of representing chl-a trends and what is "good" vs. what is "bad", primarily because a decreasing trend may be good while levels are above what is considered a healthy norm for the Sound; however, if primary productivity levels were lower than normal, and we were still seeing a decrease over time, we would have cause for concern. With atmospheric CO₂ levels increasing and causing acidification of marine environments, it could be that primary productivity levels decline below what is needed to support food webs. Is it possible that we'll reach a balance by continuing to load the Sound with human-produced nutrients?

While the stretched symbology of the raster representation looks better, I wanted to be able to clearly classify numbers above 0 as red and then ramp colors appropriately below 0. Because of this, I classified

the data into 5 categories and split at 0. If there had been a wider range of values above 0, I could have used varying degrees of red to represent that as well.

With the data processed, transformed from vector to raster, and symbolized, we are able to see areas of the Sound that are experiencing changes in primary productivity over time. The most interesting spatial pattern for me is to see that Tacoma and Everett have experienced a general decreasing trend of chl-a levels while Seattle and Olympia have seen increasing trends. We need to examine what differences in policy, infrastructure, population, and other factors might be leading to these different trends. These clues will ultimately help in designing a solution to guide us to our preferred future state.

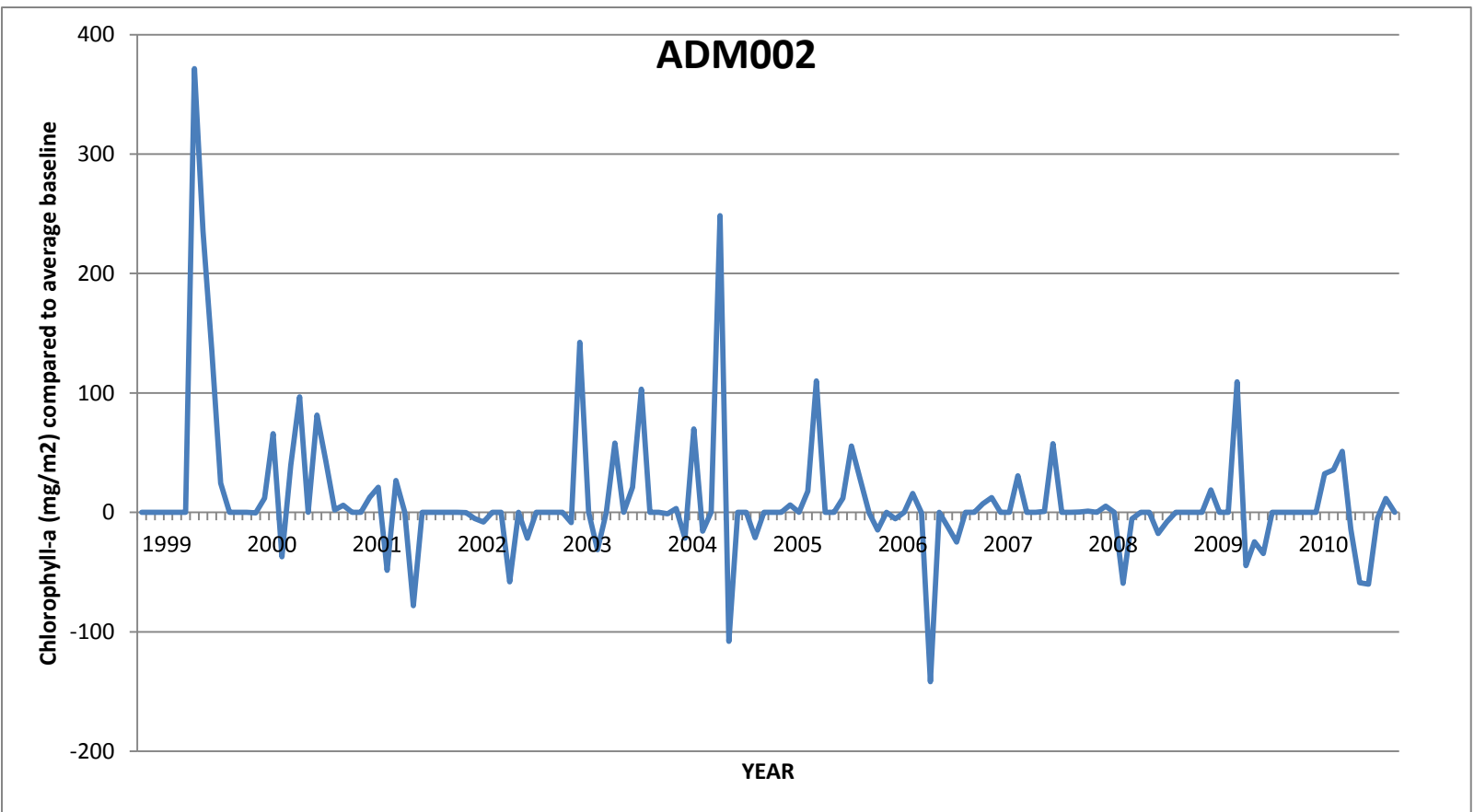
Sub-Step 3F



The above graph shows chlorophyll-a levels in mg/m² compared to an average baseline based on DOE's methodology. This shows what is generally happening with energy flow in terms of primary productivity at one monitoring point. There are 27 monitoring points spread around Puget Sound, Gray's Harbor and Willapa Bay that are collecting this type of data. Some of these monitoring points demonstrate declining trends in chl-a levels over 11 years, some demonstrate increasing trends and others show steady trends. This is an interesting temporal pattern that gives us a clear picture of what is happening over time.

Just as interesting to me, but at a greater level of detail, is the graph below that breaks out each of the above bars into their seasonal patterns. The year 2002 is interesting because of its conformity to the overall baseline. Remember that this doesn't mean that production was 0, it means that production was "normal" as compared to a 13-year average. The spike in 2004 also draws my attention. It would be

worthwhile to investigate what was happening in 2004 at this monitoring station that caused such an anomaly. This could help provide clues as to what directly affects productivity and could inform decisions about how to keep primary productivity within its healthy range.



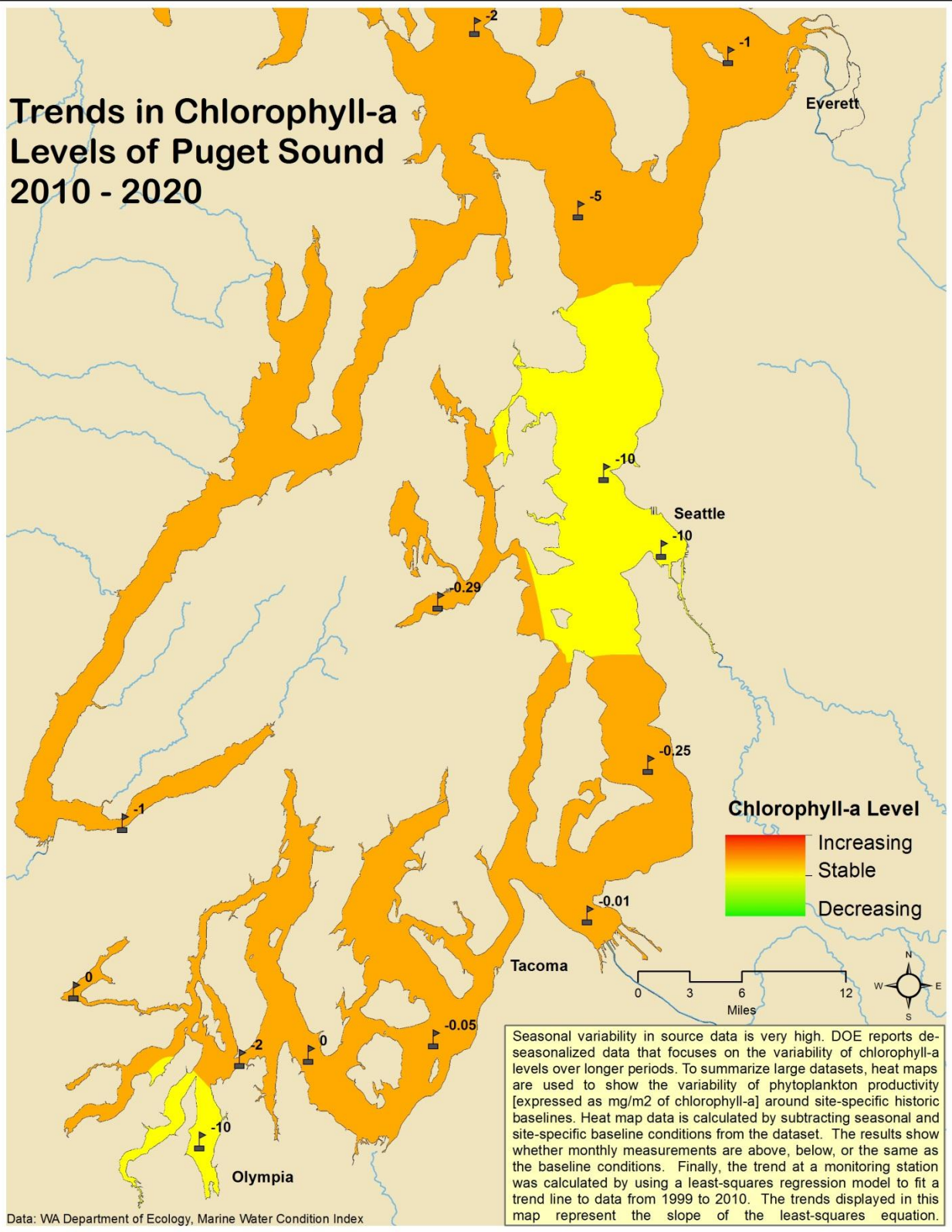
Step 4|5|6

I believe that the maps and graphs that I've designed do a good job representing primary productivity and are capable of displaying data at varying levels of spatial and temporal resolution for appropriate analyses at differing scales.

In the WSAS committee's Missing Attributes section, it is apparent that they are looking for indicators that will provide more insight into overall ecosystem health and functioning. They write that "In Puget Sound itself, and in major freshwater lakes in its watershed, the conversion rate of inorganic to new organic matter by photosynthesis is a basic determinant of entire ecosystem functioning. Changes in productivity usually affect the ability of an ecosystem to provide goods and services, but the relationships between productivity and different ecosystem services are neither simple nor easy to evaluate. Decreases in primary productivity are often of concern, but increases may result in eutrophication of freshwaters and create marine dead zones. Moreover, alterations of ecosystem productivity to increase a particular ecosystem service (wood production, food) often reduce the ability of an ecosystem to provide other services (biodiversity preservation, recreation). In its discussion of the Dashboard indicators, the PSP recognizes the importance of primary productivity but proposes no indicator for it."

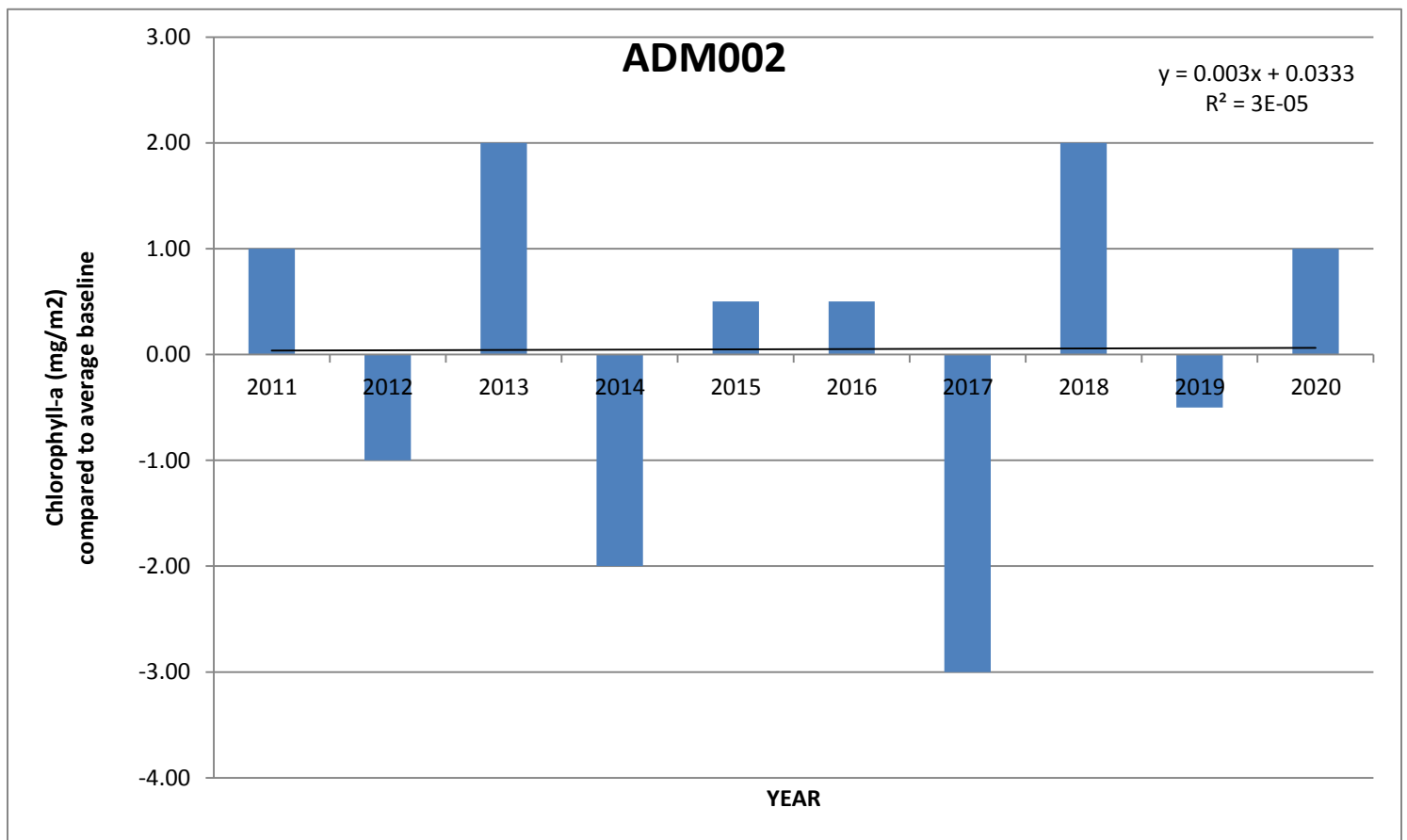
What I found most enlightening about this process of investigation is that the Department of Ecology has all of the necessary data in order to provide a robust and actionable response to the WSAS committee. DOE has many reasons for compiling and reporting their data the way that they do, discussed extensively in the MWCI report and summarized in Figure 3 above. However, with the recent WSAS recommendations calling for an indicator to be developed for primary productivity, it seems that DOE would be able to extract their chl-a data from the Eutrophication Module and monitor it alone using a methodology similar to that illustrated above. This would provide a clearer understanding of how the Puget Sound ecosystem is functioning, thus successfully addressing the committee's recommendation.

Sub-step 7A



This second map showing a preferred future state was created by hypothesizing preferred trends from 2010 to 2020. Areas that showed increasing trends from 1999-2010 are now decreasing, while areas that were showing major decreases are now stabilizing. While we expect some fluctuation above and below a stable level, it is desirable for 10-year trends to remain fairly steady. If looking at this over 50 to 100 years, the trends should be strongly correlated to natural cycles such as the Pacific Decadal Oscillation mentioned above. Apart from that, the preferred state is that primary productivity is not being affected by human Drivers or Pressures.

Sub-step 7B



Whether we're observing increasing or decreasing trends at monitoring stations, the ultimate preferred state is stability, that is, a dynamic equilibrium. In order for Graph 1 to look more like Graph 2, there needs to be a more equal distribution around the baseline from year to year. As mentioned many times throughout this study, we expect natural variation of chl-a levels from one year to the next, and even one decade to the next. What we don't expect is that chl-a levels (meaning primary productivity of an ecosystem) can indefinitely increase nor indefinitely decrease. Such persistent trends would be devastating and are the reason for developing this indicator. That is the mathematical process that needs to occur to get to Graph 2. How does that translate into policy change and on-the-ground projects? Let's move on to exploring a potential geodesign solution to this issue.

Sub-step 7C

In selecting an appropriate change model to get from our existing situation to a preferred situation, I have pulled three key considerations from Steinitz. It is important to consider our *certainty* of the phenomenon and our understanding of its causes, the *scale* at which the phenomenon occurs, as well as a *strategy* that is commensurate with the certainty and scale.

I think that our understanding of how human inputs into a system affect chl-a levels is adequate. We are confident enough in understanding the relationships between nutrients, light, human activity and chl-a that we can say with certainty that increased population, without appropriately designing ways to mitigate harmful inputs into the Sound, corresponds to an increase in chl-a. There is empirical evidence that documents this relationship. So at a scale where human population is most dense, the cities along the fringe of Puget Sound, our certainty of relationships between social and ecological components is high.

However, as we broaden our scope beyond one city's limits, and start to think about how processes at the county and watershed levels are affecting primary productivity in the Sound, our certainty decreases. There are many more confounding variables, and nature begins to muddle up our understanding of processes. When we are at a city-scale, most things are built by humans – we have drawings, plans, dimensions, measurements, connections, data and maps that give us high confidence in what is happening in that environment, and enable us to assert a higher level of manipulation, even control, over processes.

And this leads to what design strategy might be appropriate. With high certainty and a smaller area to work with, it is more likely that we can go with an offensive strategy. I equate this to project-based design. As the area of interest increases and our certainty decreases, it is likely that we should find a solution in a defensive strategy. Because we're still within the realm of human influence, I will associate this strategy with policy-based design.

So what is an appropriate change model to take us from Map 1 to Map 2? If considering the whole Puget Sound social-ecological system, or even if dividing it into its component watersheds and addressing a design at that scale, I think that the combinatorial approach would be appropriate. Steinitz recommends this change model when we're "not sure of the appropriate choices in the sequence of decisions to create the design" and goes on to say that the combinatorial approach is "commonly applied to investigate alternative scenarios for the future." We are able to enumerate the human-caused contributors to altered chl-a levels in Puget Sound such as nutrient input into rivers from dairy farming and agricultural fertilizers, an overall pattern of decreased forest buffer in riparian zones, leaking septic tanks and inadequate wastewater treatment. These causes occur at different scales yet are all of similar importance in addressing this issue. Again from Steinitz, "a combination of the key requirements must be resolved before continuing with less important ones."

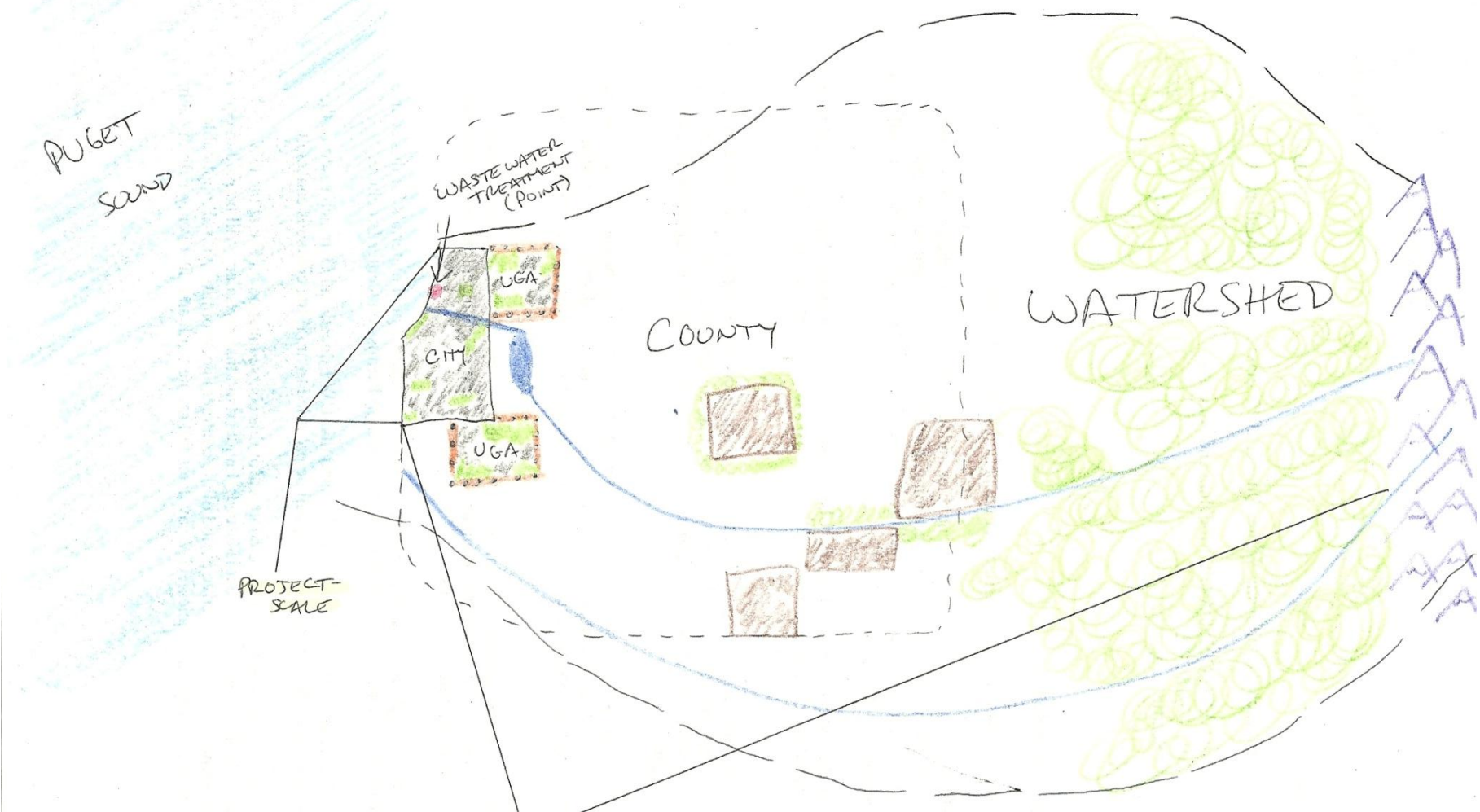
Steinitz advises to always consider defensive strategies first in design. I can relate to this philosophy after having worked on a tropical forest restoration project. Seeing the amount of time, labor and money required to attempt to restore an area of degraded forest, knowing that it is still unlikely that the forest will return to provide the same level of ecosystem services as before, it is apparent that it makes more sense both ecologically and economically to use our money and time to conserve existing forest rather than restoring what once was. This philosophy has led to policies such as the Growth Management Act – an attempt at controlling the extent of human influence on the landscape. There are

also forest policies about the amount of riparian buffer that must remain along streams and rivers when harvesting timber. Perhaps we're already experiencing the benefits of these policies as it seems that landscape-level contributions to the primary productivity problem, while an important consideration, are not the main concern: "The significant MWCI trends for Puget Sound's Central Basin and Admiralty Reach indicate that Puget Sound continues to increase in nutrients on a large temporal and spatial scale. River loads of nitrogen on the other hand have declined (Hallock 2009). One possible explanation for the increase in nutrient conditions above ocean conditions is the increase in population density over the last 10 years, consistent with other U.S. estuaries (Paerl et al., 2006). This localized increase in population affects nutrient discharges for many sewage treatment plants limited to two mechanical and biological treatment stages and could increase non-point inputs (e.g., stormwater, failing septic tanks). Nutrient inputs from sewage treatment plants are sizable (Roberts et al., 2008)."

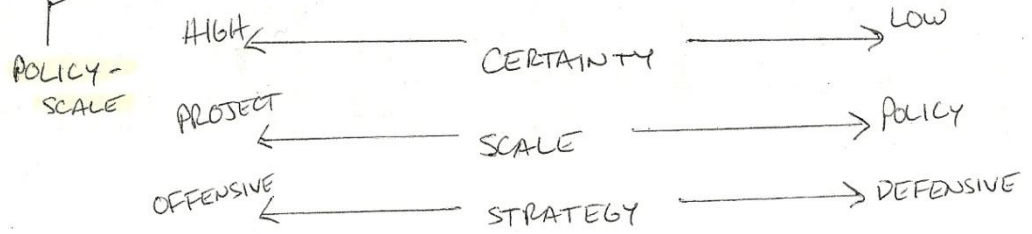
Does this mean that while the UGA policy is working to increase density in cities, we haven't come up with an adequate solution to mitigate human Pressures on the environment? This leads me to propose a second option for a change model. If we are confident that it is the increased population density and its accompanying infrastructure (impermeable surfaces, leaking septic tanks, channeled and inadequately treated sewage, and a short-sighted combined sewer overflow system) then we could implement a change model that is appropriate at the project scale. There are certain projects that could use the Anticipatory change model because they have already been tested and proven successful in other cities.

I have in mind the problem of combined sewer overflows in Seattle. In the city of Seattle, storm water is combined with sewage water in the same pipes that flow to the treatment plant. However, in order to handle large storm events, there are overflows that allow for the release of untreated sewage into lakes and the Sound. In contrast, in the 1950s, the city of Tacoma began a long-term project to separate their surface water pipes from their sewage pipes. Now, there is no way for sewage to be introduced to the Sound without first being treated. Could this be leading to the difference in trends seen in Map 1? This design is a good candidate for the anticipatory change model. We have a clear picture of the solution and there are engineers with experience in creating this solution – it's been done in a city right down the road! This is a case where I'm sure everybody can agree on the future vision, but the cost of implementation is a large obstacle.

BONUS SKETCH



GEOG 562
COASTAL GIS
DECEMBER 7, 2012
K. KRAMER



Appendix 10.

Terrestrial Primary Productivity

By Elizabeth Johnstonbaugh

Sub-Step 1A

The Puget Sound Partnership's dashboard of indicators includes deforestation, or as they call it, "Lowland Habitat Loss." According to their 2007 State of the Sound report, "streams and rivers flowing into Puget Sound...depend on forests to provide shade, to keep the water cool, filter rain runoff, and provide nutrients and food sources for salmon and other aquatic species," (p. 60). Within their conceptual framework, habitat preservation appears to be a primary goal.

Photosynthesis, however, one of the greatest ecological services provided by a forest, is not mentioned. The whole food web relies on sunlight trapped by chlorophyll, including orcas, salmon, and any other flagship species chosen as indicators. According to the Washington State Academy of Sciences, "Primary productivity appears as a key attribute in all of the ecological schemes...and is also a key component of ecosystem processes that benefit humans" (p. 43). The Puget Sound Partnership mention "Energy and Materials Transport" as an area of interest, but did not include a relevant indicator. The Washington State Academy of Sciences proposes primary productivity as a relevant indicator. Although the data will be similar to the deforestation data, the primary productivity indicator would be organized under the target of "Food Web," rather than under habitat, correcting a bias toward over-representing high trophic levels.

If the ecological services that forests provide determine their place in the conceptual framework, then we could also look at the results of photosynthesis. Many of the existing published sources use carbon density as a metric for forests' productivity. As trees photosynthesize, they sequester carbon from the environment into biomass. Biomass is not a perfect proxy for the amount of photosynthesis, but they are closely related.

Monitoring biomass would also give us a window into the physical carbon cycle. Currently, our conceptual frameworks of the Puget Sound do not address broader concerns, such as global warming. Inevitably, these issues will intrude on any local solution, whether through rising sea level or changing weather patterns. I chose to begin geodesigning part of a local solution for carbon sequestration, believing that a functional indicator of primary productivity in Puget Sound forests would emerge from the process.

Sub-Step 1B

Placing monetary value on the ecological services provided by a forest seems to be a temptingly valid framework. Humans do harvest benefits from these services—the salmon fishing industry is a clear example. Pricing these services also lays the foundation for economic incentives to change policy.

I chose not to monetize the model because the scientific foundation is not fully developed yet. We can't predict the true costs of habitat destruction or global warming, but we can very accurately price lumber and suburban land. So I suspect the economic value of the long-term services would be under-valued in comparison with short-term services.

However, economic incentives have been used in developing countries. As carbon sequestration looms bigger in international negotiations, it may become more useful to calculate an approximate price tag on our forests.

Sub-Step 1C

The key attribute here is the productivity of our forests.

Sub-Step 2A

The indicator of productivity will be high areal density of carbon biomass.

Sub-Step 2B

I considered two different indicators of primary productivity—chlorophyll and biomass. The main difference between the two lies in the temporal aspects, and their placement in the DPSIR framework. Perhaps the differences between these two indicators exemplify the reasons why both the PSP and the WSAS prefer ‘state’ indicators.

Measuring chlorophyll shows photosynthesis happening at the time of measurement. This temporally fine-grained measurement is responsive to seasonal cycles and other short-term fluctuations. Photosynthesis is a ‘driver’ of the system, an ongoing process, so measuring it requires intensive data collection.

Biomass, on the other hand, is a ‘state’ indicator. An annual measurement of biomass will integrate the net result of an entire year’s gains and losses. Photosynthesis becomes visible as growth. Deforestation and land conversion decrease biomass proportionally to the decrease in photosynthesis. Temporary fluctuations are unlikely to cause significant noise, so true trends will be more readily apparent.

My decision may have been swayed by a desire to make use of existing research, and an interest in carbon sequestration. However, I also believe biomass is both the more practical and the more interpretable indicator.

Sub-Step 3A

(See step 2B for discussion of DPSIR framework)

The most commonly used metric for biomass is mass of carbon per unit area. A promising way to measure this attribute seems to be a LiDAR method developed for tropical rainforests. This method could be highly automated, other than the annual acquisition of LiDAR data, and an initial regional calibration (a field survey of the relationship between the height and diameter of our trees).

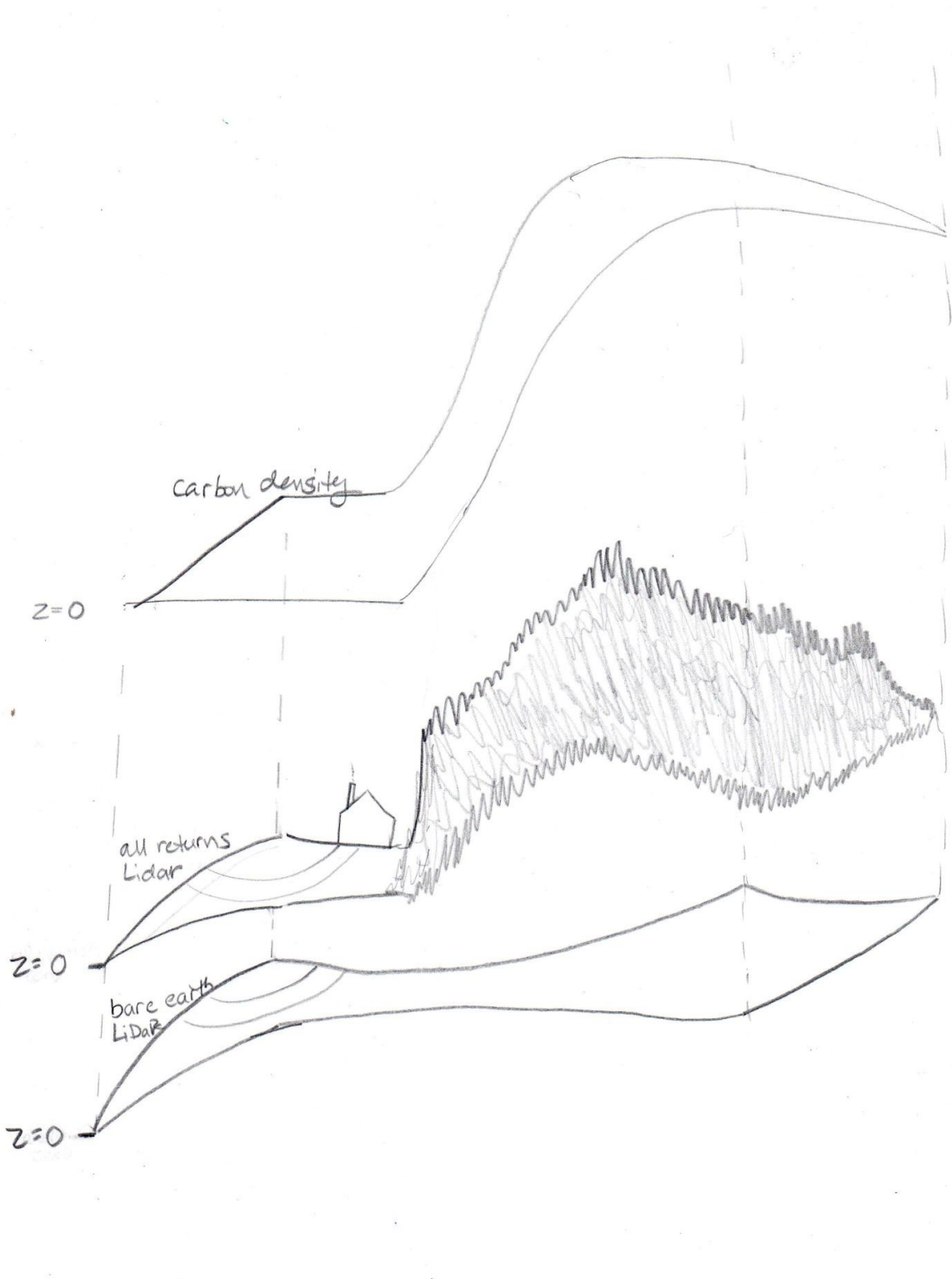
Sub-Step 3B

I did not consider any other metric besides areal carbon density because such a large body of published research already supports its use. A different option would be to use traditional field surveys, or allometric techniques, to estimate carbon density, rather than remote sensing. However, the new method is much less labor intensive, and supposedly equally accurate when properly calibrated.¹

Sub-Step 3C

This conceptual sketch stacks 3-D representations of the LiDAR surfaces used in the calculation, along with a surface representing carbon density. The places with the largest difference between the bare earth LiDAR and the all returns LiDAR will have the highest carbon density (although obviously buildings and other ‘returns’ will need to be excluded when calculating canopy height). Although a color ramp on

a two-dimensional map may end up being a more practical representation, using ArcScene seems like an interesting way to demonstrate the scientific basis of the metric.



Sub-Step 3D

This graph represents the conceptual relationships between canopy height, basal area of the trees, and carbon density. These underlying concepts are most visible in one of the first mathematical models I came across in my research: a survey of techniques for remote sensing biomass in tropical forests, by Asner et al.

Asner's research showed a linear relationship between basal area, wood density (which I did not include in the graph), and canopy height. In my pictogram, the height of the trees and the size of their trunks are proportional. It is somewhat misleading, because canopy height is directly proportional to basal area, and therefore exponentially related to trunk diameter.

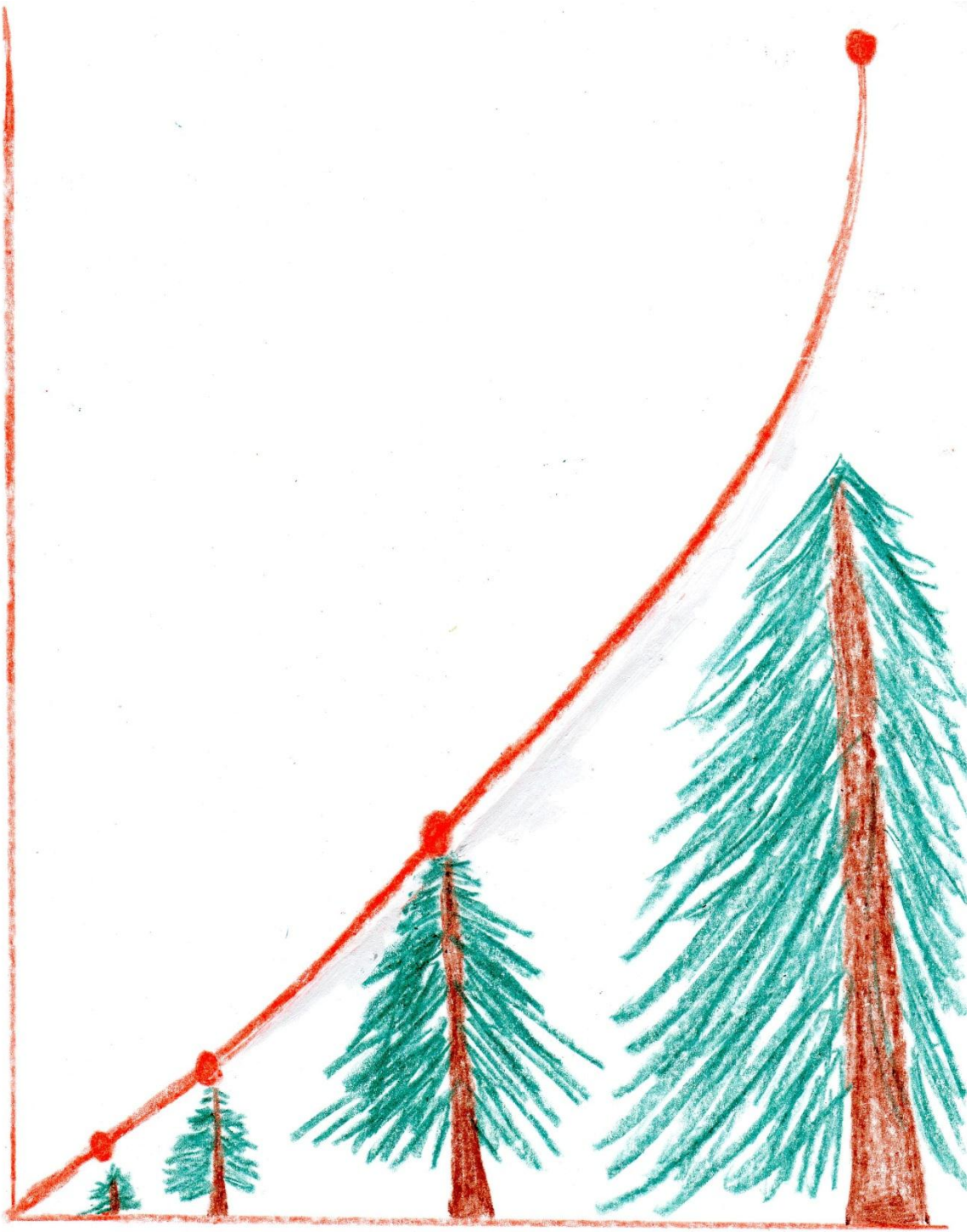
The pictogram is not actually related to the line on the graph. The orange line roughly represents a parabolic curve relating the size of the trees to the carbon density, based on Asner's general equation:

$$\text{Carbon Density} = 2.04(\text{Mean Canopy Height})^{0.436}(\text{Basal Area})^{0.946}(\text{Wood Density})^{0.912}.$$

Calibrating the equation for the Puget Sound region would involve identifying regional averages for Basal Area and Wood Density. Without doing those values, it isn't possible to include real numbers, but carbon density will increase rapidly and nonlinearly as canopy height and basal area both increase.

Because I am still developing the metrics for this indicator, I can't really identify any temporal trends yet. However, the magnitude of contribution from the regional averages of Basal Area and Wood Density suggest that miscalibration would cause serious problems. It would be best to plan on periodic recalibrations.

→ Carbon density



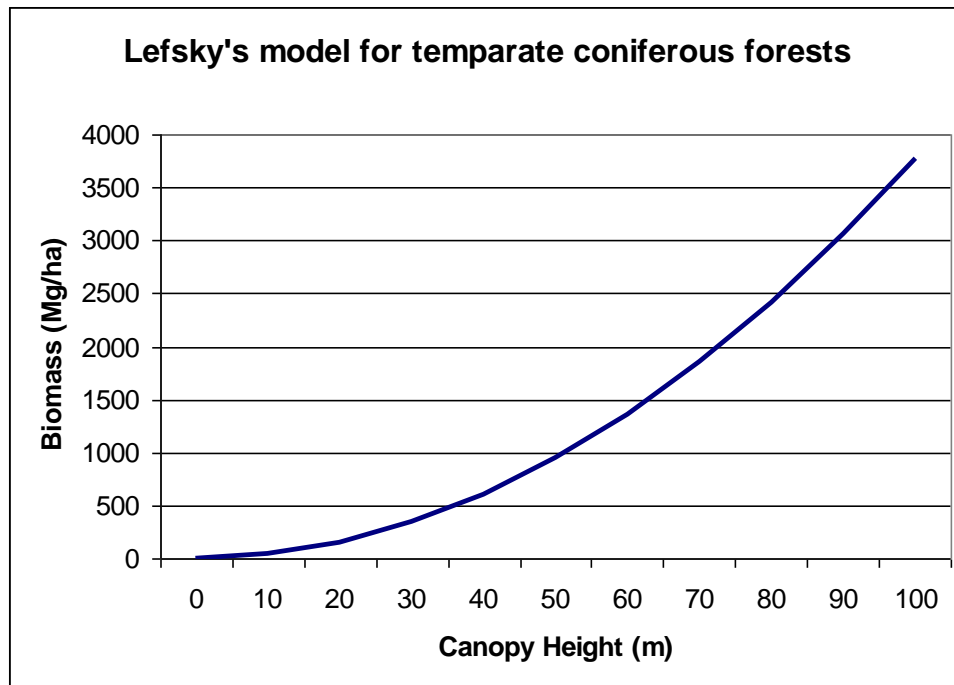
bigger taller trees →

Sub-Step 3F

A computational solution to this problem requires specifying the exact equation of the mathematical model. My first strategy was to attempt adapting Asner's general equation by including regionally specific estimates of wood density and basal area. I did find a forest service study on the relationship between tree height and wood density, focusing on Douglas fir and western hemlock in Gifford Pinchot national forest². Unfortunately, this geographically applicable study used a normalized measurement of tree height, rather than canopy height. Models are also being developed to estimate basal area from LiDAR, in coniferous forests of Montana and Idaho, but the results are not definitive yet.

Fortunately, at that point I stumbled across a model developed by Lefsky et al, which predicts temperate coniferous forests. The calibration was carried out on the western side of the Cascade mountain range, although it was in Oregon rather than Washington. Since this model seemed most applicable to our region, as well as delightfully simple, I decided to use it in my computational model:

$$\text{Biomass} = 0.378 (\text{Mean Canopy Height})^2$$



Sub-Step 3E

The Puget Sound LiDAR consortium has collected significant amounts of LiDAR data, and more may be available from other sources, but coverage is still patchy. I chose to focus on a small area on the Nooksack river as "proof of concept".

Since I have never used LiDAR data before, every step of this creating this map was a learning process. Of the several data formats available, I found TIF files the easiest to use. After downloading both the bare earth and the all-returns data, I georeferenced the alignment of the tiles and mosaicked them into two raster datasets. Where two tiles overlapped, I opted to keep the maximum of the values, in order eliminate zeroes which were actually "no data".

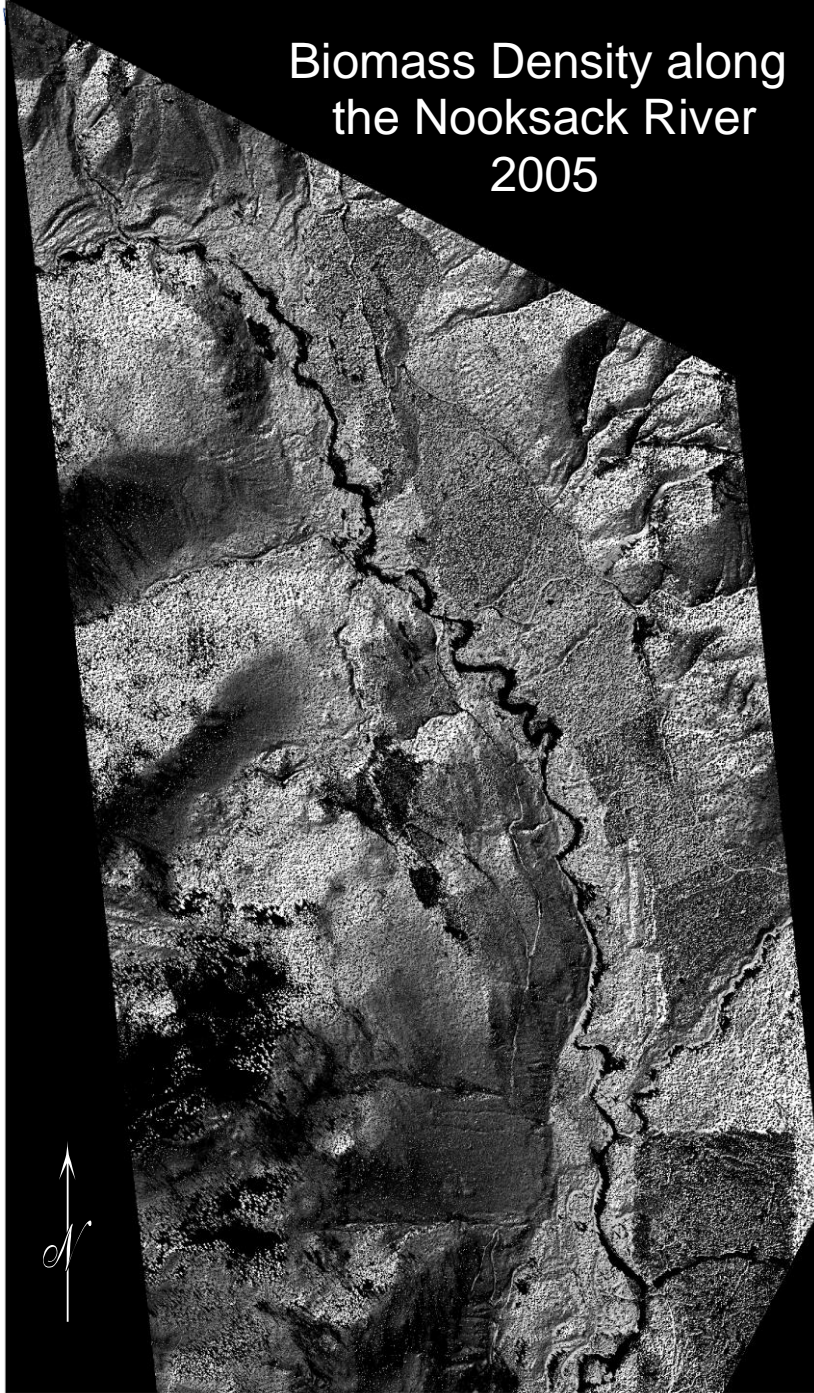
I then used the raster calculator to find canopy height from the distance between the layers and implement Lefsky's mathematical model for predicting biomass. I also included terms to convert the units between feet (used in the original dataset) and meters (used in the mathematical model). My expression was:

$$0.378 * (((\text{"AllReturnsTIF"} - \text{"BareEarthTIFS"}) * 0.3048) * ((\text{"AllReturnsTIF"} - \text{"BareEarthTIFS"}) * 0.3048))$$

There must be data cleaning steps which I am unaware of, because subtracting either raster from the other resulted in negative values. I am confident I did not mislabel my files, because the surfaces look distinctively different. Since the canopy height values are squared anyway, the final results are all positive.

Because I am more confident in the relative values than I am in the exact numbers used in the calculations, I chose to leave my map without units. If I wanted the map to communicate anything more than a general impression, I would make note of the data range from 24,387 to 0 Mg/ha.

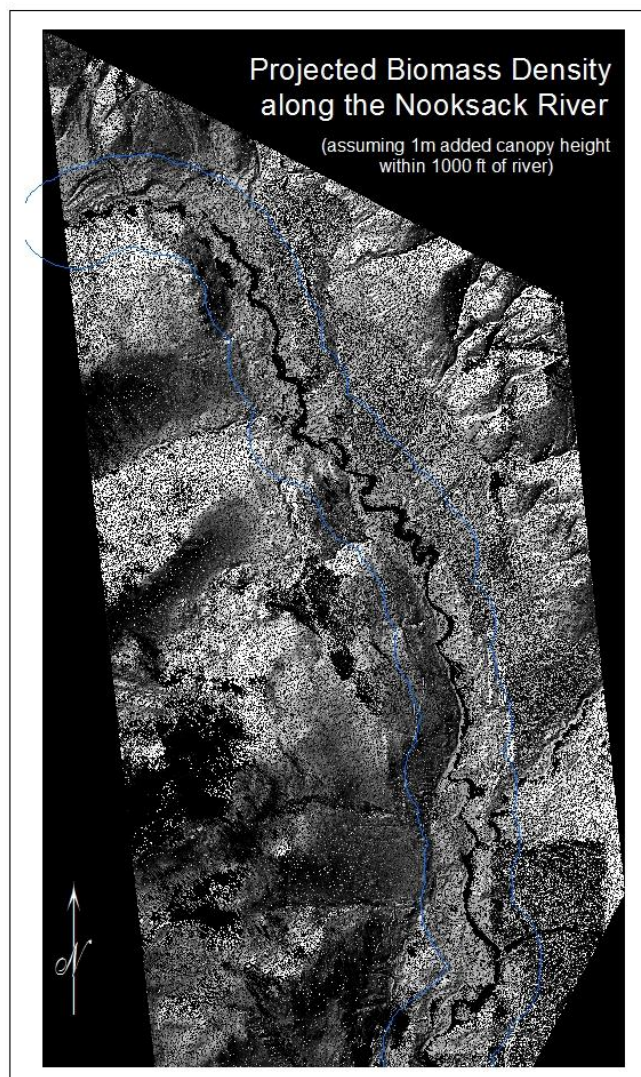
Biomass Density along
the Nooksack River
2005



Step 4|5|6

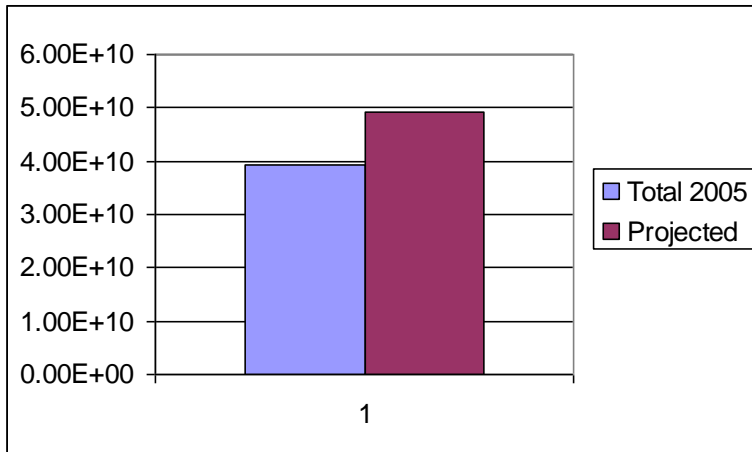
My narrow focus on forests falls short of the systematic ecosystem-wide approach recommended by the WSAS. Plankton, algae, sea grasses, and other terrestrial plants all drive the carbon cycle and the food web in their respective habitats. I excluded other questions just to limit the scope of my topic. I do believe my work could be used to model similar solutions in other areas, particularly in conjunction with other groups' ongoing research into habitat extents and plankton productivity. It would be most useful, though, for shaping policies specific to forests.

Sub-step 7A The current dashboard indicator of forest extent focuses on the importance of riparian habitat for spawning salmon. Despite my choices to veer away from this indicator, there is a significant body of research and policy supporting the regrowth of the riparian zone. My projection investigates the results of a small improvement near the river. To create this map, I digitized a polygon from the river visible in the bare earth LiDAR, and buffered 1000 feet around it. Masking that zone, I recalculated the carbon density assuming an added meter of canopy height beyond what the 2005 LiDAR shows. Where trees cannot grow (such as the middle of the river), a very small false value will appear (0.378) but those cells will still appear very dark on the map.



Sub-step 7B

Although this is obviously not an extension of my earlier graphs, because they did not have a temporal component, this graph shows the gain in carbon sequestration just from the change projected in map 2. I ran zonal statistics on the entire area, and found significant gains created by the targeted growth in the riparian zone. The first column shows the 2005 status of the area, the second column adds the projected gains from one meter of added canopy height in the area within one thousand feet of the river. Again, to keep the emphasis on the relative picture, rather than the potentially erroneous numbers, units (Mg/ha) have been intentionally omitted.



Sub-step 7C

This project has really shown me how many different reasons there may be even for preserving forests, without even look at issues that may divide stakeholders or even scientific experts. Because the issues are so complex that no one person could possibly be an expert from all points of view, I believe a participatory change model will be necessary for any effective solution.

My second choice would be an optimized solution which places monetary value on ecological services, because that strategy has already been utilized effectively in other places. As the costs of lost ecological services become more apparent and the demand becomes greater, the estimation of their monetary value will continue to rise.

¹ Asner, G. P., Muller-Landau, H. C., Muller-Landau, H. C., Hall, J. S., Hall, J. S., Hall, J. S., Hall, J. S., ... Breugel, M. (January 01, 2012). A universal airborne LiDAR approach for tropical forest carbon mapping. *Oecologia*, 168, 4, 1147-1160.

² http://www.fs.fed.us/pnw/pubs/pnw_rp347.pdf

³ <http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1183&context=usdafsfacpub>

⁴ Lefsky, M. A., Cohen, W. B., Harding, D. J., Parker, G. G., Acker, S. A., & Gower, S. T. (September 01, 2002). Lidar remote sensing of above-ground biomass in three biomes. *Global Ecology & Biogeography*, 11, 5, 393-399.

Appendix 11

Water Quantity

By David Schmitz

Sub-Step 1A

I used a combination of conceptual frameworks that were shown in the Washington State Academy of Sciences 2012 review of Sound indicators, along with one other addition. Mentioned in the WSAS 2012 report were the frameworks of the Heinz Center, the Science Advisory Board of the Environmental Protection Agency, and the framework put forth by Levin, et al (2011). The SAB framework had some subsets within which I thought attributes pertaining to water quantity, whereas the Heinz Center framework had categories broad enough for some of the attributes of water quantity to apply. The Levin framework, possibly due to having previously been used in past Puget Sound Partnership work, appeared to be the most focused of the frameworks in context of water quantity. Additionally, a stripped-down framework is seen in a 2009 PSP technical memorandum (entitled *Identification of Ecosystem Components and Their Indicators and Targets*). Water quantity is broken down only into stream flow and hydrologic regime. I found the simpleness to be optimal for a framework, and it somewhat resembles the final framework I adopted.

Sub-Step 1B

The framework in the 2008 PSP Action Agenda was very extensive, which for a framework probably is not the most optimal thing. Also, it has mention of human support or human interaction in many parts of the framework. It does mention finfish harvest, under which salmon could be categorized. The framework also mentions snow pack, glacier mass balance, annual maximum daily flow, annual mean flow, flow flashiness, annual 7-day low flow, and instream flow violations. Again, these are factors to take into account, but human interaction can only change so many of the factors.

The PSP's 2009 paper entitled *Ecosystem Status & Trends*, did not generate a visual framework beyond the table of contents, but it did list water quantity as one of six "systems" which garnered elaboration within the document. It listed the indicator of water quantity as "stream flow in major rivers." It also listed "hydrologic alteration related to urbanization" as a possible future indicator, which I found very interesting, but unfortunately outside the scope and time allowance of this particular project.

The PSP's 2011 *Puget Sound Science Update* has a framework pertaining to water quantity on page 38 (Figure 7). While the goal of "water quantity" has basically itself as the focal component, the focal component is then broken down into key attributes called Surface Water Hydrologic Regime, Groundwater Level Flows, and Consumptive Water Use and Supply. The three key attributes are further broken down into a total of eight indicators. While I do like the detail of the eight indicators in this context, I find that simple discharge measurements signify sort of an amalgamation of a lot of variables. In other words, if the discharge is too low, at that point one can go back and check into the reasons why the discharge is low. If the discharge is sufficient, then the salmon have sufficient flow with which to spawn and enrich the Sound ecosystem accordingly.

Sub-Step 1C

Specifically, the key attribute I am focusing on is streamflow, specifically volume through a given point per time.

Sub-Step 2A

The key attribute of streamflow is selected to represent the indicator of percentage of stream flows below critical levels. In turn, a level of streamflow is necessary for salmon to spawn. Salmon serve as somewhat of an indicator species for the overall biology of Puget Sound (WSAS 2012, p. 54).

Sub-Step 2B

Perhaps measuring the number of salmon or salmon eggs themselves might seem like a more direct way to determine the state of the salmon, and indirectly the Sound. However, such measurements would seem a lot more discrete (definitely non-continuous) in nature, at least in comparison to continuous monitoring of stream level and discharge by permanent gages stationed at several points on a river or stream. Streams and rivers are coherent and continuous from the source to the mouth, dams notwithstanding. Salmon eggs and salmon themselves would be far from continuous and therefore a lot more difficult to measure.

Note that much in the same way the PSP 2011 *Puget Sound Science Update* had water quantity listed in a framework as the focal component to the goal which was also water quantity, it seems streamflow below critical levels is best represented by measuring streamflow, then seeing if it approaches critical levels.

Sub-Step 3A

The relevant measure or metric for streamflow is a moving volume per time, in this case cubic feet per second. There are dozens of stream gages along various in western Washington which measure stream stage (depth or height), and given further measurements, these stage readings are able to give us the discharge of the stream at that gage (<http://ga.water.usgs.gov/edu/streamflow3.html>).

The measurement of streamflow in cubic feet per second represents a state within the Puget Sound social-ecological system. Needs for irrigation water (possibly economic) could be pressure humans to divert water from the streams. In this case, the diversion of water for irrigation purposes would be the driver, as it is the human activity that alters the state of the river. If the river is in a state that requires critical flows to be put into effect, human recreation activities may be affected.

Sub-Step 3B

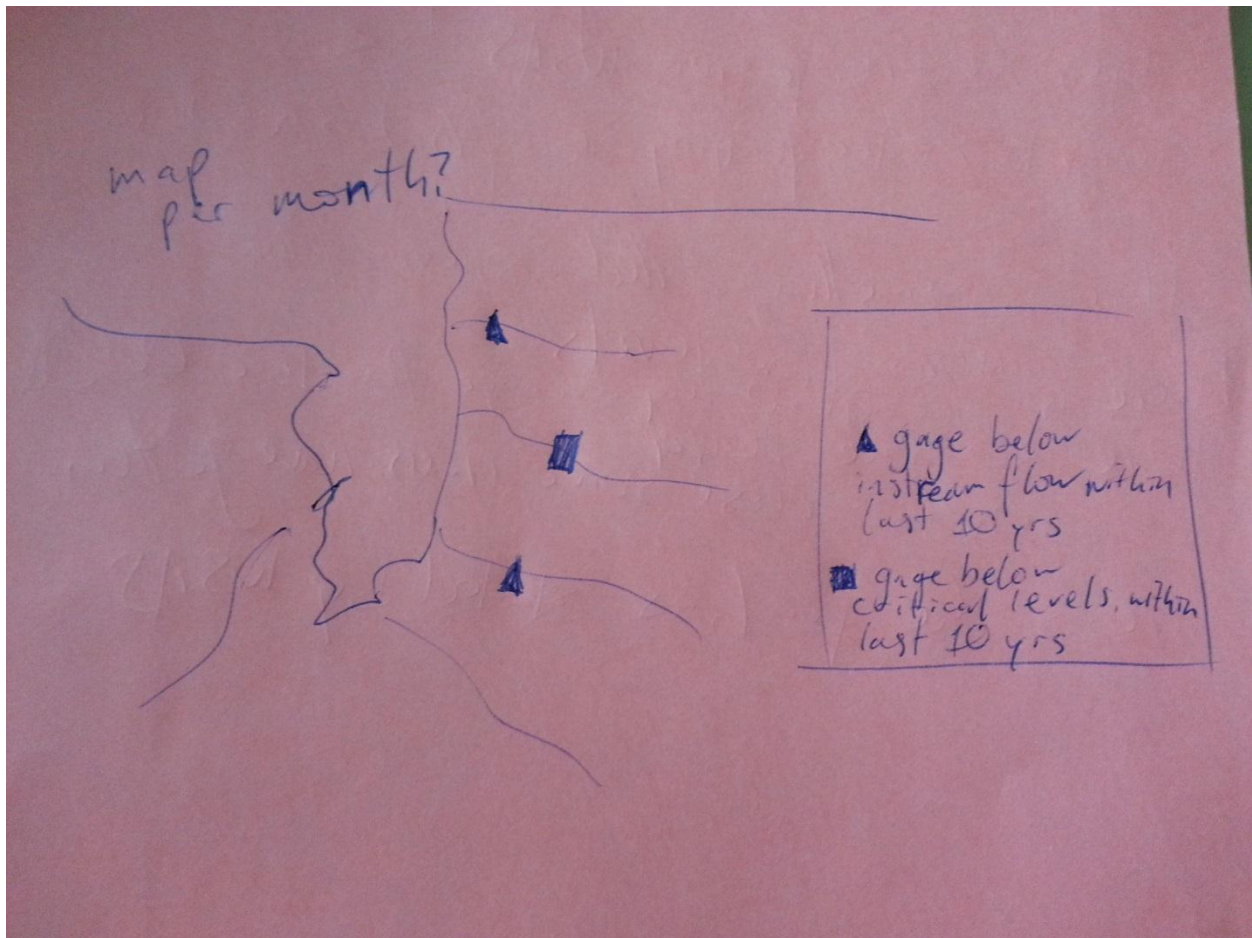
The Washington State Academy of Sciences cites “lowest 30-day average flow June-October” as a salmon-friendly metric. In a paper entitled *Protection of low flow periods critical for fish production*, Brad Caldwell of the Washington Department of Ecology cited multiple studies all coming to more or less the same conclusion: a higher low-flow level in the summer resulted in more abundant adult salmon returning to the streams to spawn in the following years. Further in the same document, Caldwell says the Department of Ecology found a number of streams where a loss of 1% in streamflow resulted in roughly a 1% loss of salmon habitat.

The only other serious consideration for a relevant measure would have been stream height or depth, irrelative of the dynamic nature of the stream. It is true that stream stage or height is one of the things continuously measured by the stream gages. The measurement by itself, however, seems to almost imply something static. A doorknob might be three feet off the floor and a basketball hoop may be ten feet off the ground, but most likely they will stay there. Stream height can rise and fall, sure, but to focus merely on rising and falling as the only vectors involved ignores an entire direction as well as the

dynamic nature of a stream. A stream stage of 19.5 feet, for example, does not necessarily tell us if the stream is nearly placid or if the stream is a raging torrent that could quickly sweep away a wayward swimmer. Additionally, the very fact that streams originate in the mountains, then gradually flow downhill (in other words, lose elevation) toward the Sound practically begs for a type of measurement more complicated than stream stage. As such, a measurement in cubic feet per second implies a volume moving past a given point in a fixed amount of time.

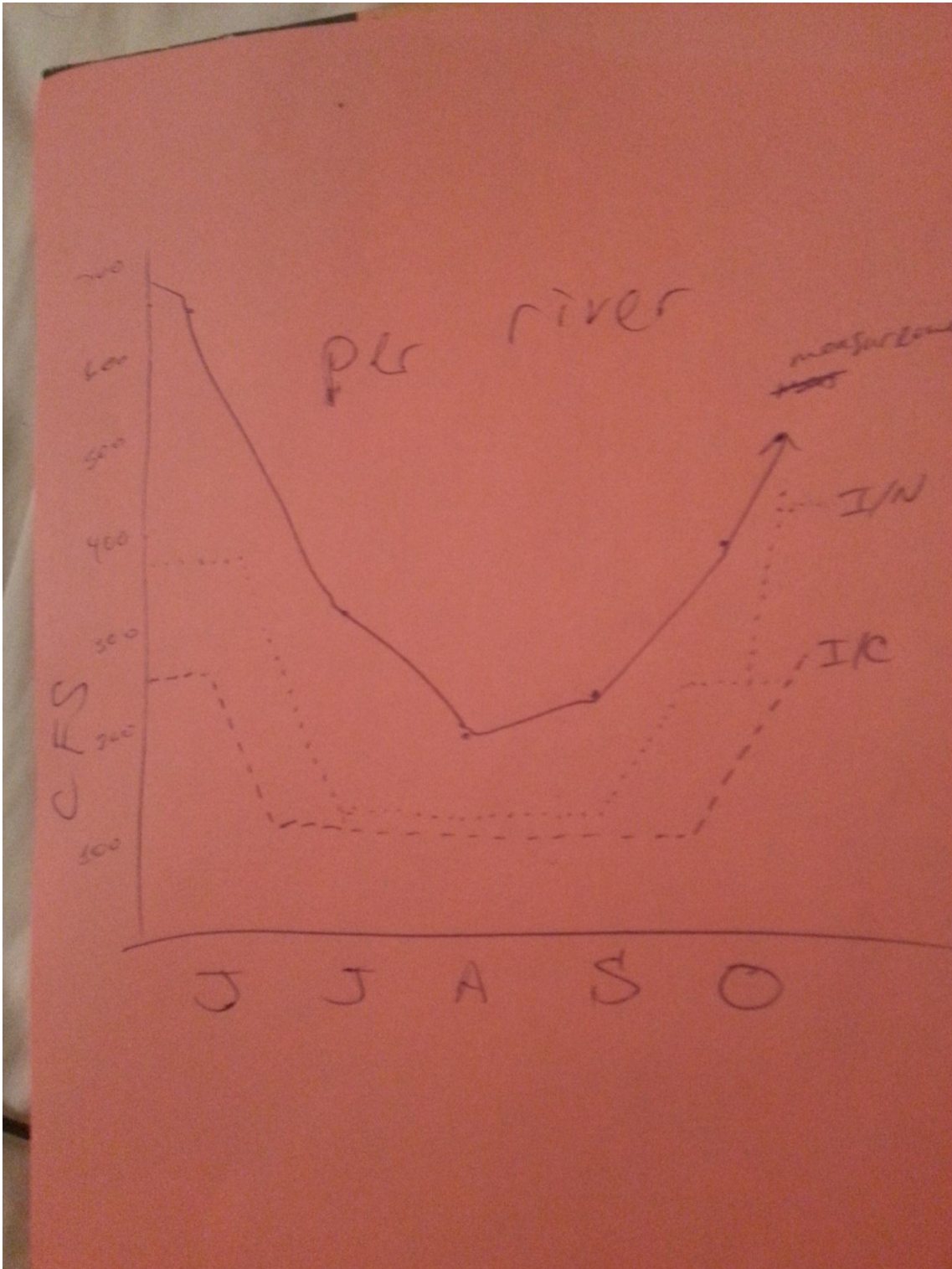
Sub-Step 3C

This hand-drawn map displays the original design of what the map eventually came to be. In this design, I was going to display different polygons to represent gages along the Washington State Academy of Sciences' named streams (Nooksack, Samish, Skagit, Stillaguamish, Snohomish, Cedar, Green, Duwamish, Puyallup, Nisqually, Deschutes, Skokomish, Dosewallips, Dungeness, Elwha) that showed monthly readings that were either below instream flow levels or below critical levels within the last 10 years. The scale at which I showed the map would encompass the Puget Sound area.



Sub-Step 3D

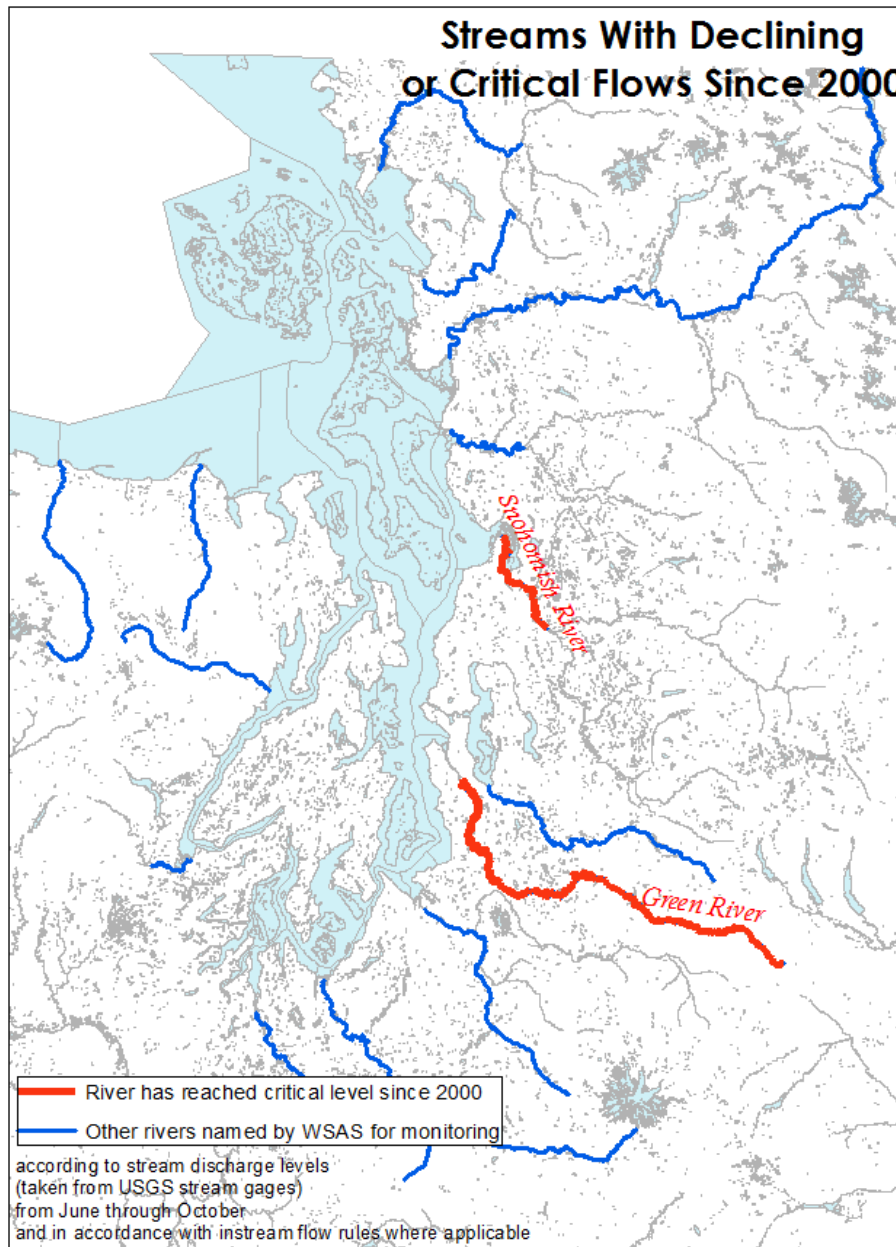
The following is a hand-drawn graph of all-time mean per-month discharges (via US Geological Survey) from June to October on the Cedar River near Renton. The dotted and dashed lines plotted upon on the same graph indicate instream flow levels in a normal year (dotted line, higher values) and instream flows in a critical year (dashed line, lower values). Though my map in the previous step can show all of the needed streams, the graphs are a different story. This is mainly due to the fact that every river has different flow rates, flow regimes, etc. Additionally, not every river has instream flow rules, nor does every river have critical flow levels. Note that this exact design did not hold up for the final design.



Sub-Step 3E

The map represents what the “present state” is intended to look like, assuming all relevant links to the data, from tab delimited data from the gages all the way to importing into ArcGIS, etc. The data was perused, though ultimately not linked all the way into the final .mxd file. The map reflects the intention in which rivers in question were going to be shown as having approached critical levels. The Snohomish and the Green rivers were the rivers reaching critical flow since 2000. Instream flow levels are available here:

<https://fortress.wa.gov/ecy/publications/UIPages/PublicationList.aspx?IndexTypeName=Program&NameValue=Water%20Resources&DocumentTypeName=WAC>



Sub-Step 3F

The following are the graphs pertaining to the two rivers which are flagged on the map in Step 3E as being below critical level at some point since 2000. The bases for these graphs are data from USGS stream gages from the respective streams, as shown below.

First, the discharge data since 2000 of the Snohomish River at the confluence with the Tolt River:

00060, Discharge, cubic feet per second,					
YEAR	Monthly mean in cfs				
	Jun	Jul	Aug	Sep	Oct
2000	633.3	232.9	152.6	268.4	326.8
2001	410.5	246.8	200.0	157.5	504.5
2002	791.5	340.5	170.9	147.9	145.3
2003	224.8	141.3	112.3	148.6	620.8
2004	360.0	178.0	272.7	496.9	441.3
2005	408.4	281.5	154.1	192.3	315.2
2006	447.1	180.5	126.1	172.5	228.8
2007	314.3	179.2	132.5	114.6	471.2
2008	1,066	433.7	283.4	208.6	295.3
2009	471.0	216.0	156.3	218.7	567.6
2010	812.2	249.5	166.4	362.7	426.3
2011	764.0	413.1	205.6	155.5	
mean, all-time	553	293	181	242	435

mean,
2000-pres. 559 258 178 220 395

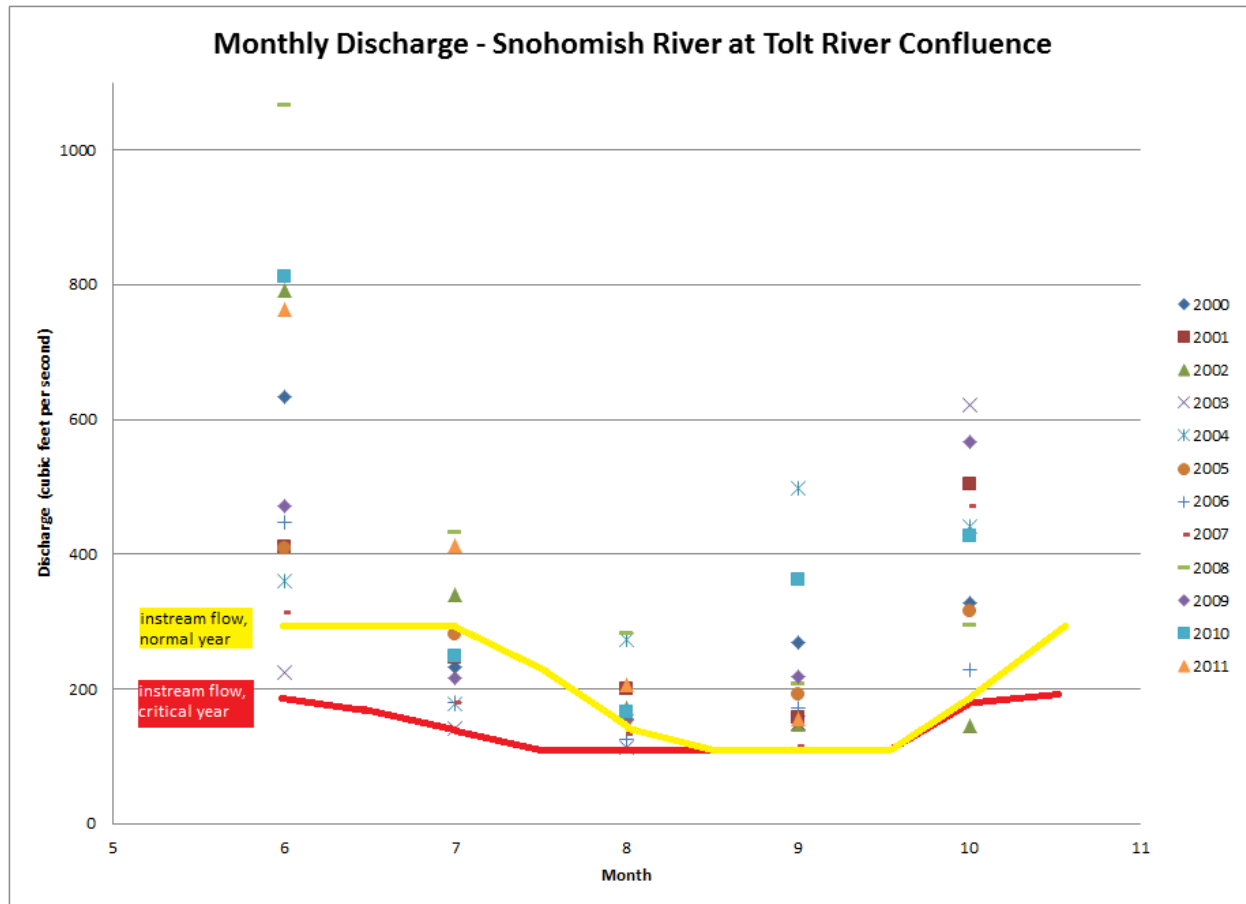
Secondly, the discharge data since 2000 of the Green River near Palmer:

00060, Discharge, cubic feet per second,					
YEAR	Monthly mean in cfs				
	Jun	Jul	Aug	Sep	Oct
2000	916.5	282.3	119.0	205.8	615.0
2001	680.5	243.3	125.4	190.1	722.9
2002	1,246	665.0	127.6	170.2	196.6
2003	368.6	134.2	140.9	147.7	534.9
2004	765.3	217.6	175.8	678.2	568.4
2005	442.7	213.0	172.9	311.1	656.3
2006	657.0	189.8	135.4	165.0	193.2
2007	496.8	201.7	156.2	298.1	732.9
2008	1,722	583.6	175.1	238.5	412.5
2009	968.6	242.7	142.4	194.8	512.0
2010	1,346	331.2	149.5	477.0	730.8
2011	1,445	600.9	187.8	284.7	
mean, all-time	744	320	161	244	479

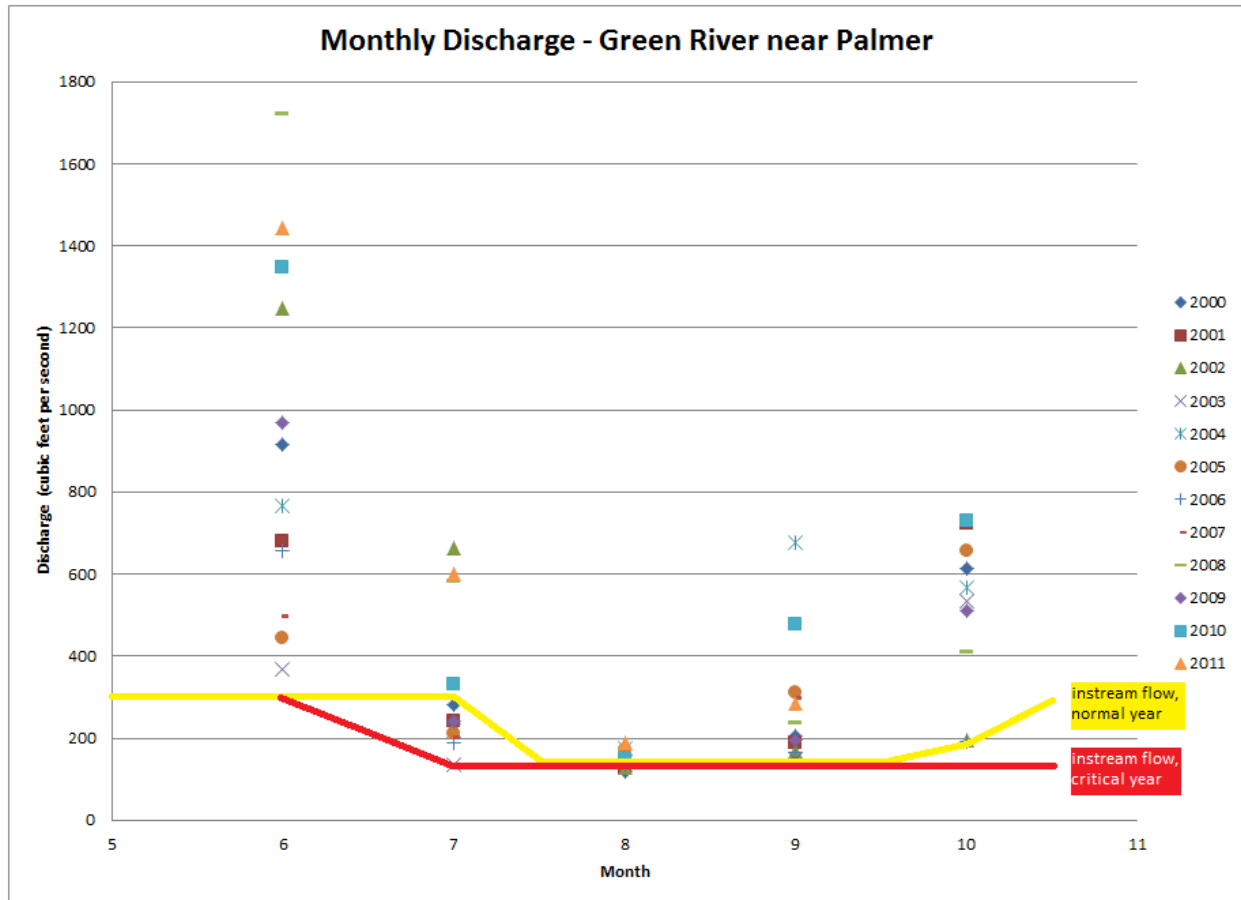
mean,
2000-pres. 921 325 151 280 534

Based on the USGS data (<http://waterdata.usgs.gov/WA/nwis/current/?type=flow>), I generated the following graphs using Excel. Discharge is on the y-axis, and the calendar month is represented on the x-axis. For purposes of this graph, x = 7 would be synonymous with July 1st. Some instream flow rules make mention of the 15th in certain months. Additionally, in case it is not clear, the red line signifies critical flow levels per the instream flow rules of that particular river basin. The yellow line signifies instream flow levels in normal years.

First, the Snohomish River:



Next, the Green River:



Step 4|5|6

As the maps and the graphs stand right now, this information alone would not be something upon which I would recommend policy intervention. For one, the Green River is already regulated by the Howard Hanson Dam. This project probably would not be revealing anything new to anyone tracking the Green River. Additionally, it is difficult to make comparisons between rivers due to each river being dealt with on a case-by-case basis. Not all rivers have instream flow rules, for instance, and even fewer rivers have critical flow levels. When trying to determine how many of these streams are below critical level, it is made somewhat difficult when "critical" is not defined for many of the rivers.

All the work in this project was based on a few controlling factors. The WSAS' terminology of "lowest 30-day average flow June-October" was the metric that needed to have a measurement that signified a flow sufficient for salmon to spawn. Upon inspection of the data, I found that using the monthly streamflow data was the easiest way to fulfill the caveat of "30-day average" as stated in the metric. Furthermore, the "June-October" stipulation enabled me to pare down some of the data and narrow the focus of the maps, graphs, etc.

Another controlling factor, once I found out about it, was instream flow (detailed in Washington Department of Ecology document 98-1813-WR). An instream flow functions as a water right for the stream. Water rights owned before implementation of the instream flow rules supersede the instream flow rules (grandfathered), whereas water rights attained after the implementation will be subject to

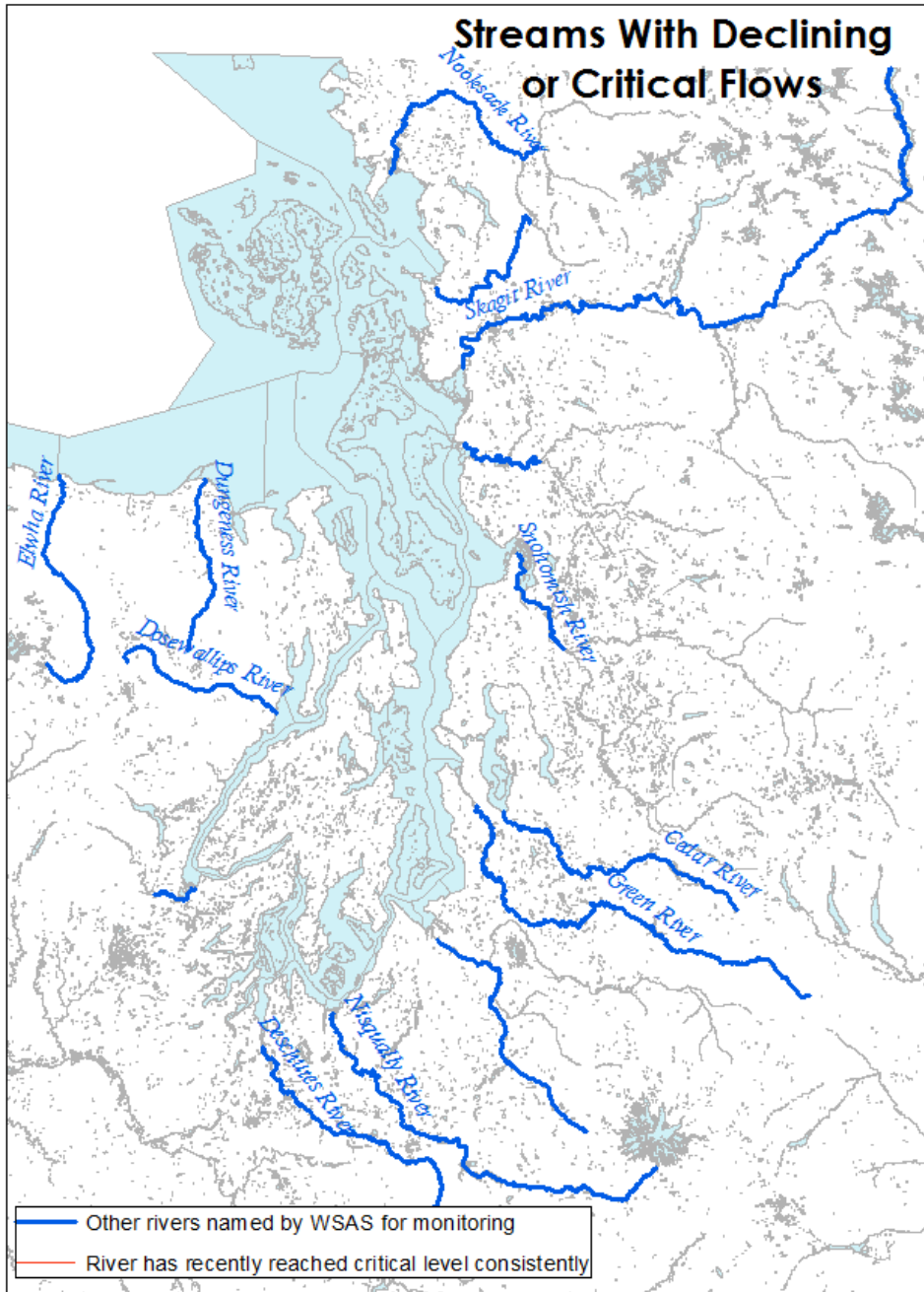
the instream flow rules. This is important because the instream flow rules are a sort of limit below which those whose water rights are junior to the instream flow rules are required to stop consuming water from the river. From a purely numerical standpoint, if an instream flow level was approached, the reduction of consumption from those with water rights would then result in a net gain in flow for the stream itself.

Though I displayed two graphs that both had instream flow rules for normal and critical years, most of the streams named by WSAS for monitoring do not have instream flow levels for critical years. In fact, the Skagit, Samish, Stillaguamish, Dosewallips, Skokomish, Elwha, and Dungeness rivers are all currently without fully established instream flow rules. The remaining rivers have instream flow rules, but the rules do not set any critical levels.

Sub-step 7A

Given the map in 3E, the preferred situation is fairly obvious. The preferred situation would be one in which none of the rivers named by the WSAS would be seeing their streamflow decline or approach critical flow levels. In this map, references to time had to be changed to account for record books permanently marking the Snohomish and Green rivers as having been critical at some point since 2000. Additionally, we would hope that none of the other rivers would be showing downward trends.

Streams With Declining or Critical Flows



Sub-step 7C

It became fairly apparent early on in this project that the one Steinitz change model that was the best fit in the situation was the rule-based change model. The levels below which stream flows should not reach are finite numbers. Instream flow rules are in effect on various rivers, so some guidelines are established. Ultimately for rivers that have dipped to critical flow levels, the flow needs to increase in order to transform into the preferred situation. Similarly, an increase in flow would also be needed in any river that was approaching instream flow levels (non-critical). Additionally, streams facing a steady year-to-year decline in streamflow would also need their flows to be increased. The short equation I imagined to encompass this entire scenario follows:

$$W_f \geq W_0 + R_1 + R_2 + R_3 + \dots + R_n$$

W_f = resultant flow

W_0 = initial flow

$R > 0$ snowmelt, precip,
stream closures

$R < 0$ irrigation, diversions, dams

How would this increase in streamflow be attained? Seemingly the simplest ways would be either to close more streams to consumption during the late summer months, adjust the timing or quantity of dam releases during the times in question, or raise the instream flow levels. All of these remedies would probably be rife with legal ramifications, especially the last one.

Perhaps the second choice I could envision for use of a change model would be the anticipatory approach. The existence of rules would play a role in this. Steinitz cites the ability to make a “great leap forward” (p. 56), but the fact that the rules have laid out concrete numbers and thresholds adds clarity to the situation. In the most basic terms, the end result of any policy that would come out of this would be for an increase in streamflow. Ultimately we have to account for everything that would give a river its flow and everything that would subtract flow from a river. Then a determination would have to be made as to what factors could be controlled and what could not be controlled. Unfortunately humans cannot control snowpack or rainfall, which are very large factors in the equation above.