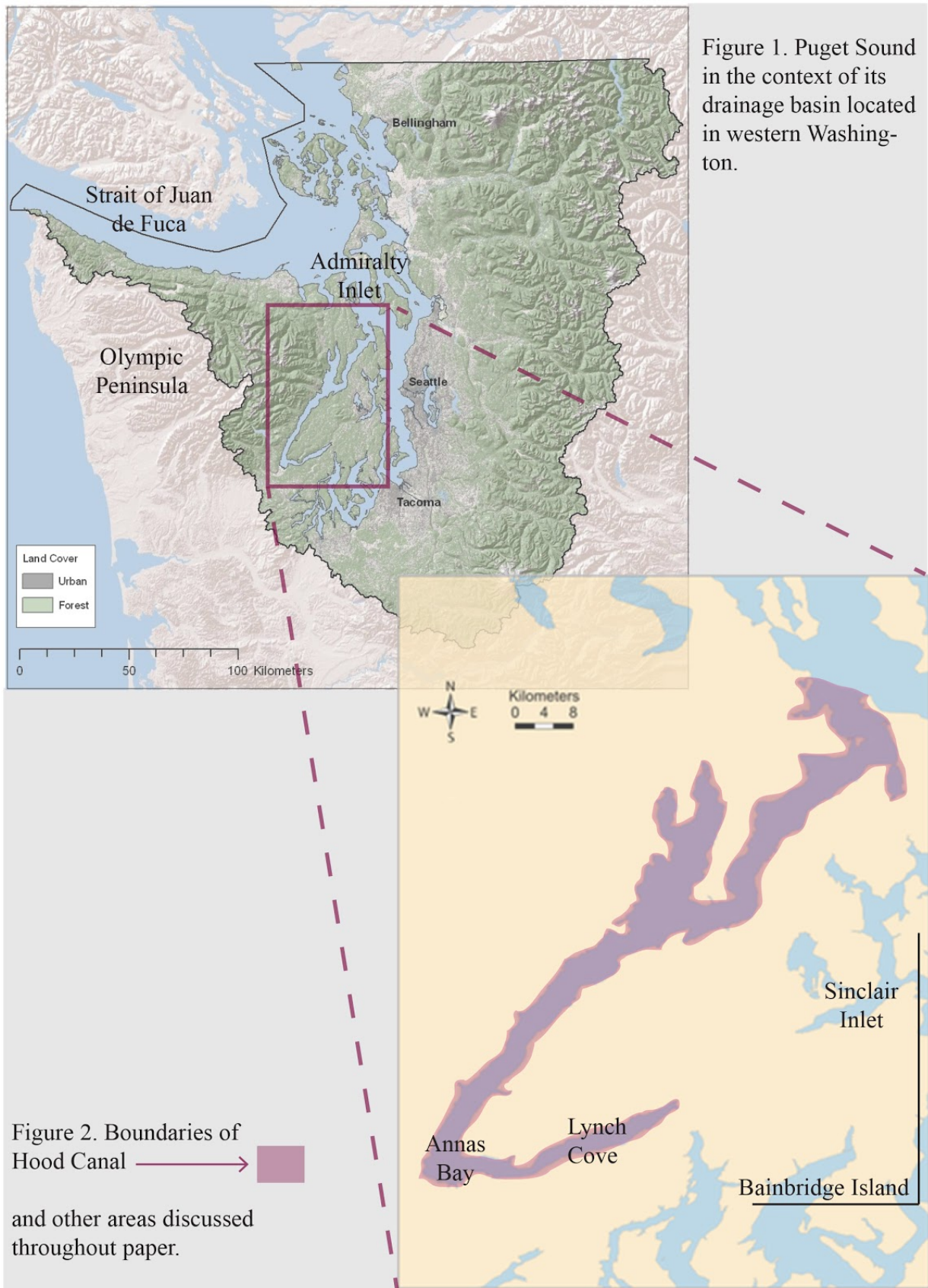# Potential Impacts of Climate Change on Hood Canal Hypoxia

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Figure 1. Puget Sound in the context of its drainage basin located in western Washington.

Bellingham

Strait of Juan de Fuca

Admiralty Inlet

Olympic Peninsula

Seattle

Tacoma

Land Cover
Urban
Forest

0   50   100 Kilometers

N
W — E
S

Kilometers
0   4   8

Sinclair Inlet

Annas Bay

Lynch Cove

Bainbridge Island

Figure 2. Boundaries of Hood Canal ⟶

and other areas discussed throughout paper.

Abstract

Puget Sound can be found nestled in the northwestern corner of the United States. Puget Sound is the only home I have ever known. It is a place of expansive natural heritage with its evergreen forests, mountain ranges, rocky coastlines, rivers, and waterfalls. With this myriad of habitats, Puget Sound sustains thousands of wildlife species. However, the human impact is encroaching on the Sound and the natural processes that occur in the region. Over the past two centuries, human activities such as land clearance and fossil fuel burning have spurred an altered global climatic regime for the 21st century. Model forecasts suggest that global climate change will spur increases in ocean temperature and sea level as well as changes in freshwater flow magnitude and timing. Models also suggest that these changes in physical processes will impact biological processes. In particular, primary production in marine settings is expected to increase (Rabalais et al., 2009). This means that phytoplankton populations will expand, potentially leading to intensified hypoxia occurrences both in frequency and scope.

Hood Canal is one of the multiple estuaries that comprise the Sound. I have chosen to focus exclusively on Hood Canal when available data exists because this region of the Sound experiences the most intense hypoxic conditions relative to the Sound's other estuaries. Estuaries can be characterized as areas where fresh river flows meet ocean waters (Newton, 2003). Some data and information discussed is specific to Puget Sound as a whole rather than exclusively to Hood Canal. I include data and/or analyses specific to the broader context of Puget Sound since this is the existing data most closely related to Hood Canal when Hood Canal-specific data is unavailable and/or nonexistent. Additionally, an information gap exists in terms of the future

outlook of Hood Canal hypoxia. There is a lack of quantitative projections of the frequency and magnitude of Hood Canal hypoxia. Past and current studies have yet to synthesize how the factors that contribute to hypoxia will change in the face of climate change in order to concretely predict the trajectory of hypoxia in Hood Canal.

In this paper, I synthesize some of the most critical factors that contribute to Hood Canal hypoxia, consider how these factors will be altered by climate change, and speculate what this will mean for the future of hypoxia in Hood Canal. The critical factors I examine are snowmelt timing and streamflow, ocean acidification, water temperature, salinity and density, and sea level.

What is Hypoxia?

"Hypoxia is the condition in which dissolved oxygen is below the level necessary to sustain most animal life- generally defined by dissolved oxygen levels below 2mg/l [miligrams/liter] (or ppm [parts per million])," (Committee on Environment and Natural Resources, 2000).

Hypoxic zones, commonly referred to as dead zones, are areas in the water column that do not contain sufficient amounts of dissolved oxygen for most marine organisms to survive. Dead zones occur as a response to excess nutrient input to marine systems generally in the form of nitrogen and phosphorus. Nitrogen and phosphorus typically occur in low concentrations in water bodies such as lakes, estuaries, and the upper layers of the ocean. Nitrogen and phosphorus are found in "structural proteins, enzymes, cell membranes, nucleic acids, and molecules that

capture and utilize light and chemical energy to support life," (Cloern et al., 2013). Thus, these nutrients aid phytoplanktonic growth. Phytoplankton are microscopic plants in marine systems that float throughout the water column but are primarily in upper water layers where light can penetrate since they rely on energy from the sun (Hays et al., 2005). Phytoplankton pose as a primary source of oxygen in marine settings since they are engaged in photosynthesis and oxygen is a byproduct of photosynthesis. As these microscopic organisms die and sink to the ocean floor, they become an energy source for bacteria since bacterial respiration absorbs dissolved oxygen.

Human activities have the ability to impact the primary production in marine systems by altering the concentrations of nitrogen and phosphorus in water bodies. Activities can increase the amount of nitrogen and phosphorus that enters water bodies via surficial or sub-surficial transport. Some sources responsible for excess concentrations of nitrogen and phosphorus in marine settings include sewage discharge and agricultural or suburban runoff. Rates of primary production can become unnaturally high due to anthropogenic forcing. Over enrichment of nutrients in marine systems is referred to as eutrophication. Increased primary production elicits responses up the food web by providing additional energy for shellfish and fish which escalates fish yields. However, once production is stimulated beyond a certain threshold and enough dissolved oxygen is depleted, hypoxia can occur. For example, as phytoplankton biomass accumulates during periods of increased primary production, the biomass generates aggregates that stimulate bacterial respiration in bottom water layers which consumes oxygen. If the rate of reoxygenation of water via mixing is less than the rate of bacterial metabolism, the bottom water

layers become hypoxic (Cloern et al., 2013). One of the most notorious dead zones occurs in the Gulf of Mexico as a result of agricultural runoff from the Mississippi Basin.

Seasonal timing and water stratification also play a role in the occurrence of hypoxia. Between late spring and early fall, snowmelt increases freshwater streamflow (water from rivers) which is compounded with warmed surface water in marine systems. In addition, the water column during this time of year is stratified, meaning physical properties such as temperature and salinity vary according to gradients throughout the water column. The freshwater that enters the marine system and the warmed surface water of the marine system have lower densities and form a layer above the cooler, saltier bottom water layers. This stratification of the water isolates the bottom layers from the surface layers which prohibits the bottom layers from receiving a renewed supply of oxygen from the atmosphere. Bacterial absorption of oxygen in bottom water layers coupled with water stratification sets the stage for hypoxic conditions which are exceedingly low concentrations of dissolved oxygen (Gulf Hypoxia, 2014).

History of Hypoxia in Hood Canal

Although hypoxia is most often regarded in the context of anthropogenic causes, hypoxia can occur as a result of the right combination of natural factors. Hood Canal has natural factors that encourage hypoxic conditions. Sediment cores taken from the Canal by the Pacific Northwest National Laboratory suggest that seasonal hypoxic conditions have been occurring for centuries since "low DO levels prevailed in southern Hood Canal in the 1700s, 1800s, and 1900s

with relatively more oxygenated conditions recorded around the middle of each century"
(Brandenberger et al, 2011). Dissolved oxygen in the waters of Hood Canal undergoes seasonal
cycles that are reflective of its physical attributes. For example, Hood Canal has a residence time
of one year, which means the bottom water layers are replaced once per year. Hood Canal has
such a slow flushing rate partly because it is very deep with a maximum depth of two hundred
meters (Newton, 2003). The newly replaced bottom layers are salty and dense, have been
upwelled at the coast, and reach Hood Canal through the Strait of Juan de Fuca which poses as a
water transport route between open ocean water and estuarine water. Once water is transported
through the Strait, water enters Puget Sound through Admiralty Inlet. A relatively shallow sill
sits at the entrance to Hood Canal which hampers water exchange between the Canal and the
Inlet. The bathymetry particularly influences the occurrence of hypoxia since bathymetry
influences how the water moves. The water moves slowly due to the large difference in depth of
the Canal. The entrance to the Canal is relatively shallow at roughly one hundred and fifty feet.
Just south of the inlet, the Canal deepens to roughly five hundred and fifty feet (HCDOP, 2010).
The shallow entrance prohibits water from exchanging quickly. In other words, the shallow
entrance causes the Canal to retain water which results in complete water exchange rates to be in
the magnitude of years (HCDOP, 2010).

The annual water exchange pattern can be represented by the location of the oxygen
minimum zone at the mid-depths of the water column. The oldest, most oxygen-depleted waters
are moved upward as the new bottom waters move in from the Pacific Ocean. As the mid-depth
waters are flushed out and replaced with fresher water from the ocean during winter and spring,
dissolved oxygen concentrations increase. The concentrations decrease throughout the summer

as the demand for oxygen increases with the increase in primary productivity and bacterial activity. Dissolved oxygen is routinely lowest during late summer (Hood Canal Dissolved Oxygen Program, 2012).

Hypoxia in Hood Canal is also related to wind patterns and upwelling along the coast. During winter, winds are southerly, meaning they come from the south and are strong. Conversely, summer winds are northwesterly and weak as "the Aleutian low-pressure systems moves to the northwest and the Pacific High moves northward," (Feely et al., 2010). This seasonal shift in wind direction impacts water circulation on the continental shelf. Water is downwelled in winter and upwelled in summer. Upwelling is a process that transports cold, nutrient rich waters at depth to the ocean surface which provides fuel for primary productivity. Conversely, downwelling is the reverse process which results in the transport of surface waters to deeper depths (NOAA, 2015). Summer upwelling along the coast contributes to saltier and cooler deep-water inflow to Hood Canal . The upwelled inflow is also rich in nutrients which further encourages primary production, particularly in surface water layers (Feely et al., 2010, Hill et al., 1998).

Hypoxia in the Canal occurs seasonally, starting in the summer as hypoxic conditions develop at depth. As the season progresses, hypoxic conditions expand to be closer to the surface. The extent of hypoxic conditions in the Canal varies annually, but hypoxia generally occurs from midsummer to fall (Newton et al., 2002).

Episodic fish kill events are evidence of oxygen stress associated with hypoxic conditions. During these events, large amounts of dead fish and other marine life are found on shores. Fish kill events have been observed in Hood Canal throughout the early 2000s during

summer and fall months. The events have been linked to the annual flushing cycle which gradually moves the oxygen minimum zone to shallower depths which brings waters with low concentrations of dissolved oxygen closer to the surface (Newton et al., 2002).

Streamflow and Snowmelt Timing

Local environmental factors play a significant role in the oceanographic characteristics of Puget Sound. Streamflow and snowmelt timing are examples of local environmental factors that influence the physical and biological qualities of the Sound. For example, reductions in stream flows in the past have resulted in heightened salinity concentrations in shallow waters. Seasonal variety of streamflows and timing such as high flow events in spring play a part in water temperature, salinity, and flushing characteristics (Newton et al., 2003). Streamflow plays a relatively significant role in determining other physical qualities of Puget Sound according to a model study of the Sound's circulation which specifically considered variability in residence times and salinity. The study determined streamflow to play a large part in stratification and exchange flows (Sutherland et al., 2011).

Puget Sound is supplied freshwater through rivers that drain into the region. Relative to other subbasins within Puget Sound, Hood Canal maintains fresh surface layers throughout the year. Five main rivers that supply Hood Canal with freshwater are the Skokomish, Hamma Hamma, Dosewallips, Duckabush, and Big Quilcene. These rivers originate in the Olympic mountains and flow east. Due to the steep gradients of these rivers, they are able to transport high concentrations of dissolved oxygen. Once these oxygen-rich waters reach the Hood Canal,

they remain near the surface. The oxygen rich inflows can amplify stratification which is favorable for hypoxia development. The Skokomish is the largest source of freshwater even though it only experiences peak flow once per year during winter (Moore et al., 2008, Banas et al., 2014). Supplemental rivers have spring peak flows as a response to snowmelt which may contribute to the year round fresh surface layer. Each spring, freshwater flows are maximized as winter snowpack begins to melt in the surrounding mountain ranges like the Olympics and the Cascades and makes its way into surface or subsurface flows that ultimately reach Hood Canal (Moore et al., 2015, Cole, 2007).
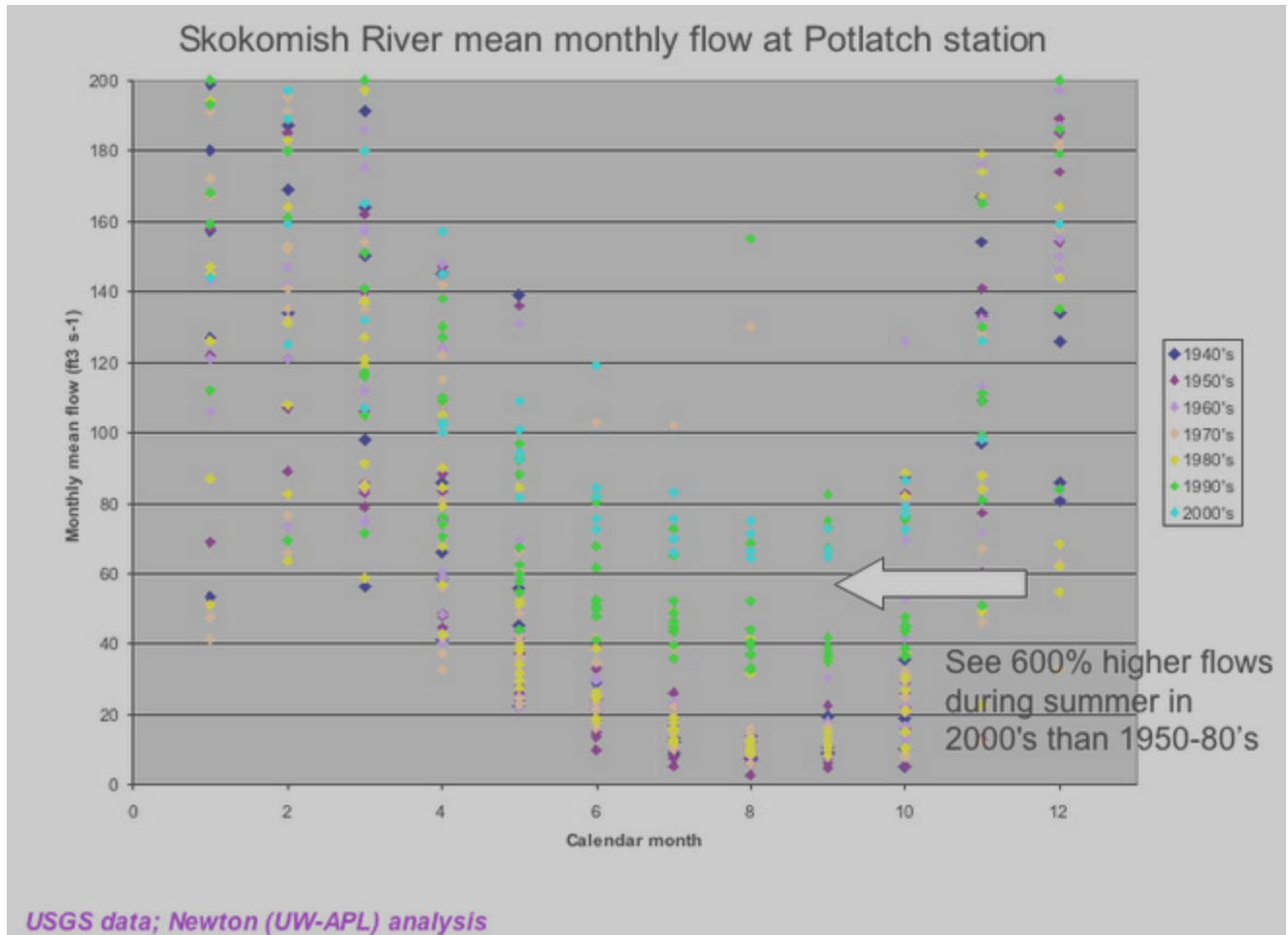
Figure 3. Monthly mean flow of the Skokomish is compared across a sixty year interval. Two trends are strongly apparent. First, average monthly flow is lowest during summer months. Second, average monthly flows have been increasing from the 1940s to present (Newton, 2003).

The Puget Sound *Alexandrium* Harmful Algal Bloom Team of NOAA has utilized a mechanistic modeling approach involving hydrologic and climatic simulations congruent with climate change in order to predict changes in "timing, duration, and extent of [Alexandrium] blooms," (Moore et al., 2015). The modeling approach resulted in projections that suggest streamflow minimum, a summer event, may occur twenty days earlier than events observed recently due to changes in shallow water salinity and earlier snowmelt. An earlier peak runoff

means lower streamflows later in summer and increased salinity concentration in Puget Sound.

Heightened salinity lessens the Sound's ability to hold dissolved oxygen and thus the risk of

hypoxia development increases. This shift toward earlier stratification may be able to modify the

seasonal patterns of primary productivity in the whole of Puget Sound, however, impacts on

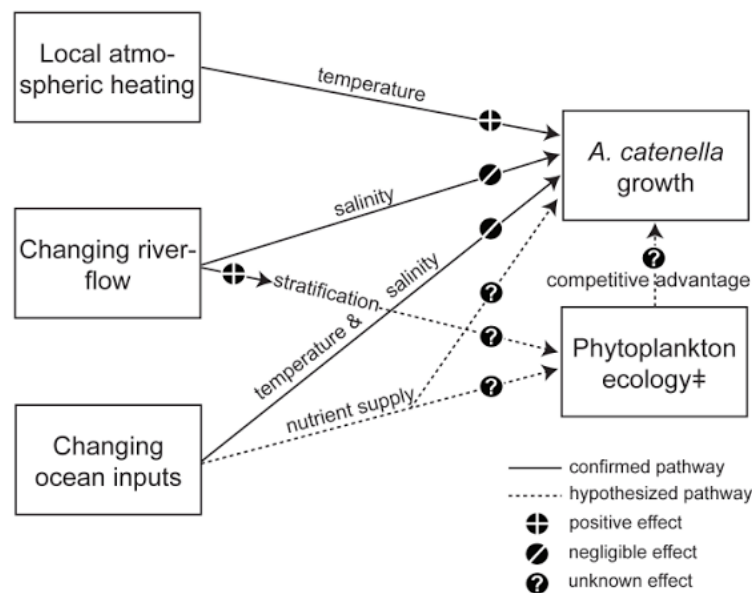specific species under these potential conditions are still unknown (Moore et al., 2015).

Figure 4. "Climate pathways identified by this study to influence Alexandrium catenella growth in Puget Sound. ‡ Indicates a hypothesized pathway based on general principles of phytoplankton ecology," (Moore et al., 2015).
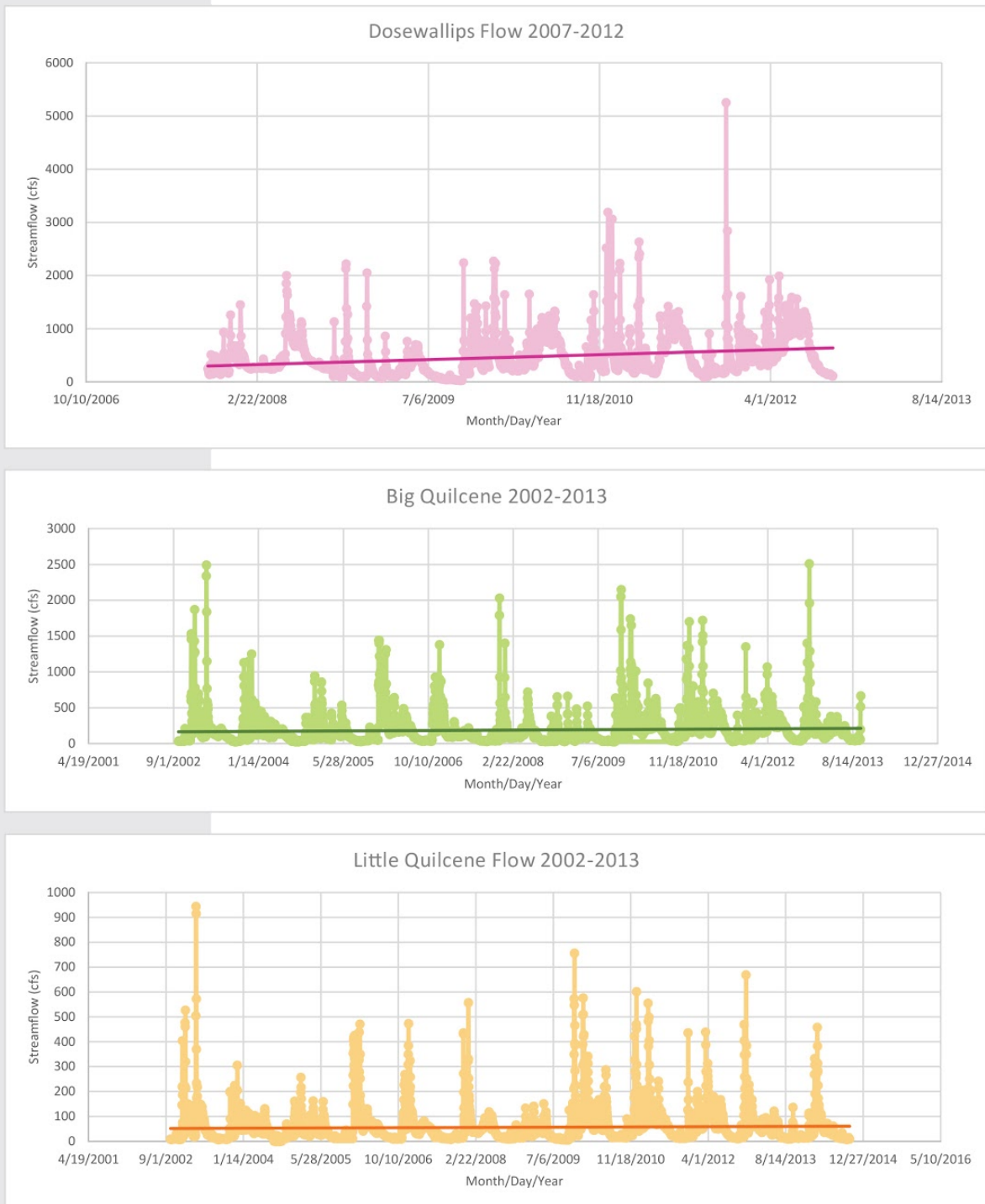
Figure 5. Data gathered from Washington State Department of Ecology. All available data which consisted of daily streamflow averages for Little Quilcene, Big Quilcene, and Dosewallips Rivers is represented (data for additional important rivers relative to Hood Canal was unavailable). All three graphs demonstrate a slight trend of increasing magnitudes in streamflow over the past decade. Dosewallips experienced the greatest increase in average daily streamflow.

Ocean Acidification

Marine waters can be analyzed with the pH scale which is a scale that measures acidity and alkalinity. The scale ranges from zero to fourteen, zero being the most acidic and fourteen being the most basic. A pH measurement of seven describes a neutral substance. The pH of a substance relates to the concentration of hydrogen ions within that substance. Acidity increases as the concentration of hydrogen ions increases (Morgan and Siemann, 2011).

Global climate change impacts the pH of ocean waters. As more atmospheric carbon dioxide is absorbed by the ocean, ocean pH declines (Guinotte and Fabry, 2008). Oceanic pH declines as a result of the products formed by reactions between carbon dioxide and oceanic water. One of these products is carbonic acid "which breaks apart into hydrogen, bicarbonate, and carbonate ions," (Morgan and Siemann, 2011). This increases the concentration of hydrogen ions which results in a reduced oceanic pH. Projections suggest that within this century, oceanic pH may decrease between 0.15 and 0.31 (Doney et al., 2008).

A study conducted by the University of Washington sought to analyze the relationship between carbon dioxide concentrations and ocean acidification in Puget Sound. By measuring inorganic carbon in Puget Sound, the study found that pH measurements throughout the water column were much lower than what could be singularly attributable to carbon dioxide absorption heightened by anthropogenic activity. This study suggests that pH has declined by 0.11 since the pre-industrial era. Between one quarter and one half of this 0.11 can be traced to ocean acidification. However, ocean acidification may have an increasing relative impact on pH

measurements in Puget Sound, "accounting for 49-82% of the pH decrease in subsurface waters for a doubling of atmospheric carbon dioxide," (Feely et al., 2010).

Decreasing pH measurements and increasing carbon dioxide concentrations could have a positive or negative impact on phytoplanktonic productivity. One experiment discussed in *Ecology Letters* used an integrative model to analyze growth rates of phytoplankton by taking into account air-water exchange, carbon chemistry, and atmospheric carbon dioxide. The model produced predictions regarding rates of phytoplankton productivity under future atmospheric carbon dioxide scenarios. The results concluded that changes in atmospheric carbon dioxide are proportional to changes in phytoplankton productivity. If carbon dioxide concentrations double in the next century, phytoplankton productivity can be expected to double as well. With increased primary productivity, hypoxic conditions will likely intensify (Riebesell, 2004, Schippers et al., 2004).

The Puget Sound may develop particularly intensified hypoxic conditions due to its status as an estuary. The natural cycles of nutrient enrichment coupled with anthropogenic nutrient enrichment in estuaries promote primary production and "subsequent remineralization of organic matter leading to hypoxia and low pH waters," (Feely et al., 2010). The upwelled inflow also has low pH values and the combination of these factors ultimately leads to conditions of exceedingly low pH. Exceedingly low pH coupled with the Pacific Northwest coast's predisposition to naturally low carbonate concentrations makes Puget Sound particularly susceptible to developing intensified hypoxic conditions as climate shifts occur (Feely et al., 2010). It is impossible to predict with positive certainty the degree to which hypoxic conditions will intensify, but in order

to keep generating probable projections, additional monitoring of the Sound's biogeochemistry is needed as concentrations of atmospheric carbon dioxide continues to increase.

Water Temperature

Global air temperatures are expected to rise as a result of global climate change. Congruently, temperatures of ocean waters are expected to rise since these waters pose as the primary sink for excess heat energy (Brunello, 2008). Atmospheric carbon dioxide concentrations are currently the highest they have been in 800,000 years and are expected to keep rising which will significantly impact atmospheric and oceanic temperatures (Luthi et al., 2008). Since the mid-twentieth century, ocean waters have been absorbing over eighty percent of the heat energy that has been added to the climate system (USAID, 2009). Ocean models of coastal circulation near Washington State, Puget Sound in particular, predict water temperatures will increase by 2.2 degrees Fahrenheit throughout the twenty first century (Mote and Salathe, 2009). Temperature has an inverse relationship with ocean water's dissolved oxygen content. Water's ability to retain dissolved oxygen decreases as water temperature increases. In other words, colder water holds more dissolved oxygen. Temperature and salinity determine the amount of dissolved oxygen water can hold. Salt water cannot retain as much dissolved oxygen as freshwater and warm water cannot retain as much dissolved oxygen as cold water. This means that as temperature and salinity increase, dissolved oxygen decreases. The saturation value is the largest concentration of dissolved oxygen water can hold (USEPA, 2001).
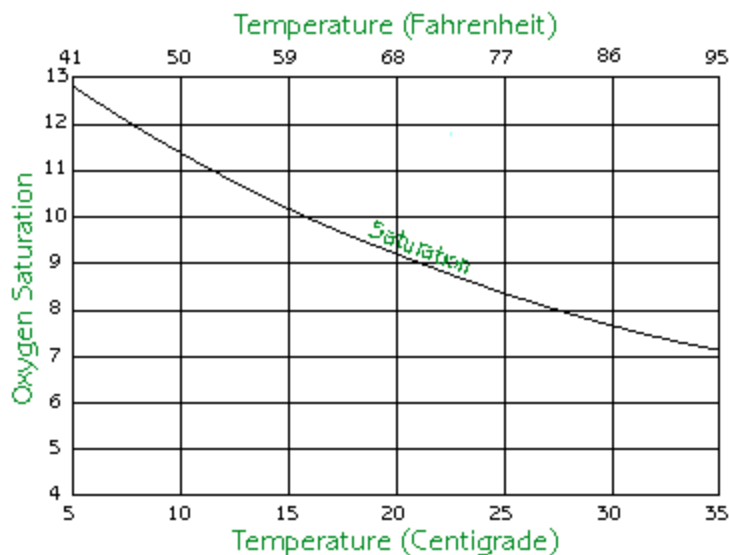
Figure 3. Graph of the inverse relationship between temperature and dissolved oxygen (Morgan and Siemann, 2010).

Anthropogenic activity has resulted in heightened concentrations of carbon dioxide and other greenhouse gases within the atmosphere. In response to this, surface temperatures on earth are rising quickly. The IPCC suggests that earth's average surface temperature may increase as much as 11.5 degrees Fahrenheit before the twenty first century is over with continued fossil fuel use. Warmer water temperatures in mid-depth and deep water layers may increase rates of bacterial respiration since temperature is a moderator of metabolic processes. Thus, dissolved oxygen will be consumed and depleted faster (IPCC, 2007, Snover et al., 2005, Iriberri et al., 1985). The Metabolic Theory of Ecology predicts that respiration rates will increase faster than photosynthetic rates because "activation energies for autotrophic processes are half of those for heterotrophic processes," (Harris et al., 2006, Brown et al., 2004). One study quantitatively predicts a four degree Celsius increase in water temperature in a northern hemisphere estuary

during summer months would increase primary production by 20% and respiration by 43%. (Harris et al., 2006).

A particular planktonic genus, *Alexandrium*, will be impacted by warmer surface water temperatures. Warmer temperatures will increase the maximum growth rates achievable by *Alexandrium* species in addition to increasing the temporal extent of hypoxic events. It is predicted that by 2050, as many as thirty more days could experience hypoxic conditions. This conclusion was drawn from a simulation model which compared observed climate regimes of the late twentieth century to predicted climate regimes for the mid-twenty first century. Three climatic factors were considered for the simulation: changes in atmospheric temperatures, changes in streamflow timing and magnitude, and changes in inflow due to upwelling. Based on the simulation, changes in water temperature will have a greater influence on *Alexandrium* growth rates than changes in salinity or coastal upwelling (PS-AHAB, 2015). Heightened water temperatures in Puget Sound have the potential to boost inputs of nutrient runoff which would further boost conditions that are favorable for hypoxia (Glick et at., 2007). More days with hypoxic conditions would enable algal blooms to become established significantly earlier in the year than they do presently. Additionally, earlier and longer lasting hypoxic conditions may cause algal blooms to occur in greater magnitudes (Moore et al., 2015).

Salinity and Density

As previously stated, an inverse relationship exists between salinity, the concentration of dissolved salt, and dissolved oxygen content in water. Also, salt water is denser than freshwater.

This difference in density causes two primary layers to form in the water column, light, freshwater near the surface and dense, salty water near the bottom. Water density is determined by temperature (heat content) and salinity. More dissolved salts (increased salinity) creates higher mass and thus higher density. Stratification of the water column does not allow for much vertical mixing to occur by creating layers of water with different densities. Warm, freshwater floats on top of cold, salty water. This limits the amount of oxygenated water that is able to reach lower depths. Therefore, lower depths are more prone to becoming oxygen depleted than shallower depths. Primary factors that influence salinity in Puget Sound are the salinity concentrations present in inflows from the Pacific Ocean as well as the magnitude and timing of streamflow inputs. Salinity has not been historically monitored in the region, so long term salinity measurements and patterns are unavailable. However, measurements beginning in the late twentieth century suggest that times of streamflows with smaller magnitudes are linked to increased salinity at shallow depths whereas high streamflows are linked to decreased salinity (Snover et al., 2005, Newton et al., 2002, Newton, 2003).
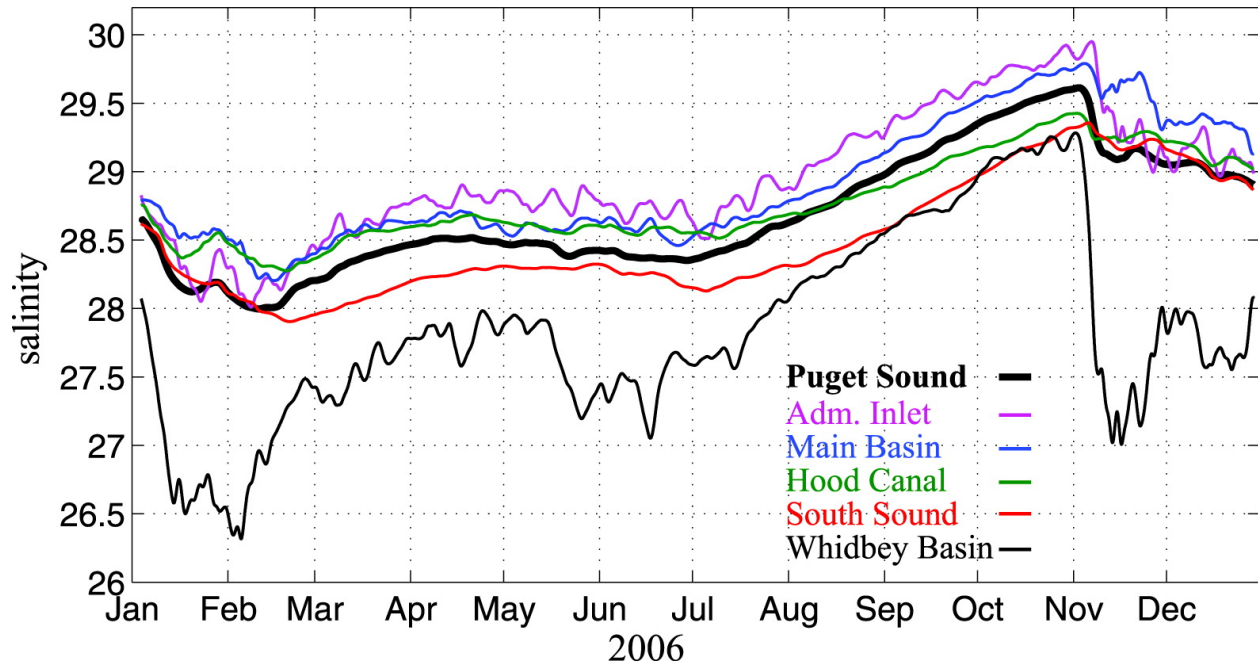
Figure 3: Mean salinities by month in Puget Sound and its constitutive basins over one calendar year (Sutherland et al., 2011).

A uniform seasonal trend in salinity can be observed throughout Puget Sound as seen in Figure 3. Salinity increases rapidly during the summer months and peaks in the beginning of November around 29.5 psu (practical salinity unit) in Hood Canal. In winter, the Sound freshens to a relatively stable state until the cycle begins again in summer. The Strait of Juan de Fuca is a primary driver of the seasonal salinity flux within Puget Sound (Sutherland et al., 2011).

Salinity in Hood Canal has a strong relationship to streamflow inputs. Due to the high ratio of streamflow to the water volume within Hood Canal, Hood Canal experiences high-salinity stratification. Salinity stratification is particularly noticeable at shallow depths during the months of high streamflow, February and March (Yang and Khangaonkar, 2010).

Sea Level

Global warming directly and indirectly fuels global sea level rise. Rising atmospheric temperatures spur the melting of polar ice sheets and glaciers which causes global sea levels to rise due to the increasing amount of liquid water. This change in volume of the world's oceans and the consequent rise in sea level is a phenomenon referred to as eustatic change (Snover et al., 2005). Over the past century, the global average sea level has risen by 6.7 inches, "which is about 10-times faster than the rate of sea-level rise over the last 3,000 years," (IPCC, 2007). Locally observed sea level rise is dependent on additional factors such as geologic land movements of uplift and subsidence. Instances of geologic land movements in local contexts can shift projected sea level rise away from projected global averages. Hood Canal is located in a geologically active region in terms of subsidence and uplift. Tectonically, Hood Canal is situated on the North American Plate. However, the Juan de Fuca plate is subducting beneath the North American Plate. What results is a vertical movement upward, or uplift, of northwestern Washington. In particular, the Olympic Peninsula has been observed to be uplifting by two mm/yr whereas the southern reaches of Puget Sound have been vertically moving downward, or subsiding, at a similar rate. Assuming these patterns will continue, south Puget Sound will experience the largest sea level rise and the northwestern region of the Olympic Peninsula will experience the smallest sea level rise (Mote et al., 2008, Morgan and Siemann, 2010). Heightened sea levels may lead to inundation of terrestrial areas or inundation of wetlands by the waters of Puget Sound. Inundation may lead to the destruction of natural water filters such as wetland plants. This is one of the fundamental ways in which sea level rise may impact the

habitats of Puget Sound. Inundation via salt water adds to the salinity concentrations of the terrestrial surface and subsurface flows. Both plant and animal species maintain particular salinity tolerances and sustained inundation may not be favorable for certain species. A loss in natural filtration enables more nutrients to reach Puget Sound, thus contributing to conditions suitable for hypoxia development (Glick et al., 2007).

One study of sea level rise in the Puget Sound conducted by the National Wildlife Federation utilized the Sea Level Affecting Marshes Model in order to discern the critical factors that lead to wetland inundation. The model incorporated projections of global sea level rise with local tidal data, wetland data from the Fish and Wildlife Service National Wetlands Inventory, LiDAR data, and topographic data with the goal of projecting the impacts of sea level rise on wetland habitat. Also, the model used IPCC projections for sea level rise that suggest a 3 inch rise globally by 2025 and a 27.3 inch rise by 2100. However, new inquiries predict a more rapid rate of sea level rise and project a total rise of 78.7 inches by 2100. The study analyzed eleven zones, taking into account each zone's properties such as topography, sediment deposition, habitat or land cover, and geologic activity. Certain processes such as uplift and sedimentation can counteract sea level rise whereas other processes such as subsidence can add to the effect of sea level rise. Inundation and resultant loss of certain habitat types will be more detrimental than the loss of other habitat types in terms of the future status of hypoxia. For example, coastal marsh habitat functions as an important regulatory mechanism for filtering excess nutrients out of surface and subsurface flows and runoff (Glick et al., 2007).
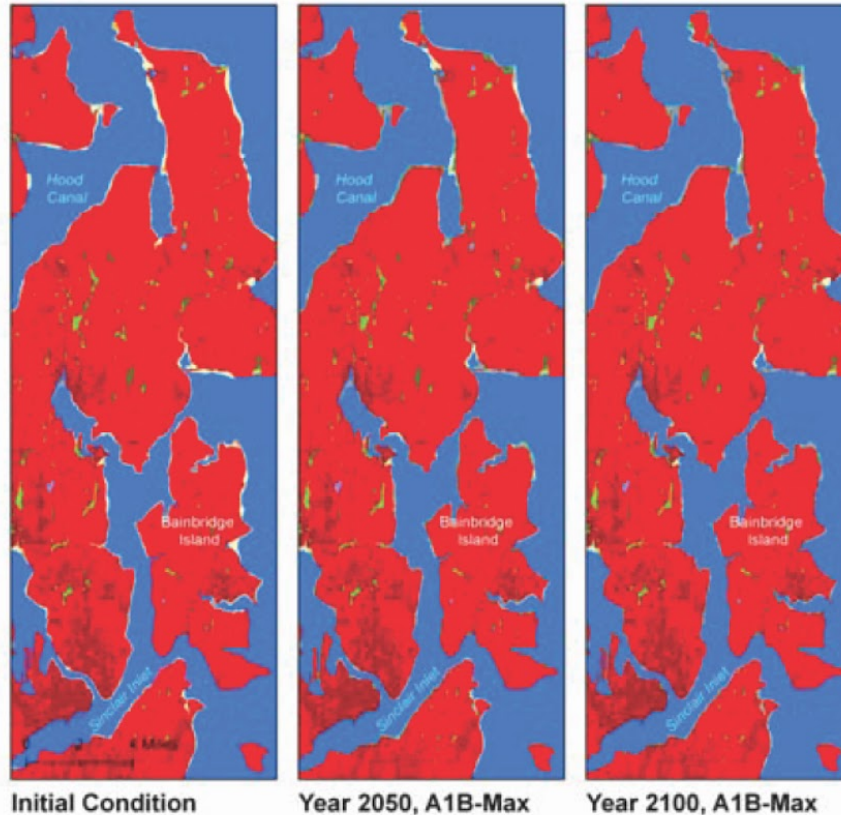
Two of the chosen study sites concern Hood Canal, Sites six and eight. Site six encompasses the entrance to Hood Canal as well as the Canal's eastern terrestrial boundary. Site

eight is composed of the southern bend of Hood Canal known as Annas Bay in addition to the

southeastern arm of the Canal known as Lynch Cove. Based on the model simulations, both sites

six and eight will experience sea level rises above the predicted global averages. This is likely

attributable to the current subsidence rates of the southern regions of Puget Sound.

	2050 11.2 inch rise	2100 27.3 inch rise
Site 6: Dyes Inlet, Sinclair Inlet, Bainbridge Island	14 inches	31.3 inches
Site 8: Annas Bay and Skokomish Estuary	13.3 inches	30.5 inches

Table 1. Comparison of the IPCC projections of global average increases in sea level rise
to model projections of sea level rise in Hood Canal. The predicted global average rise in
sea level by 2050 is 11.2 inches and the predicted global average rise in sea level by 2100
is 27.3 inches (Glick et al., 2007).
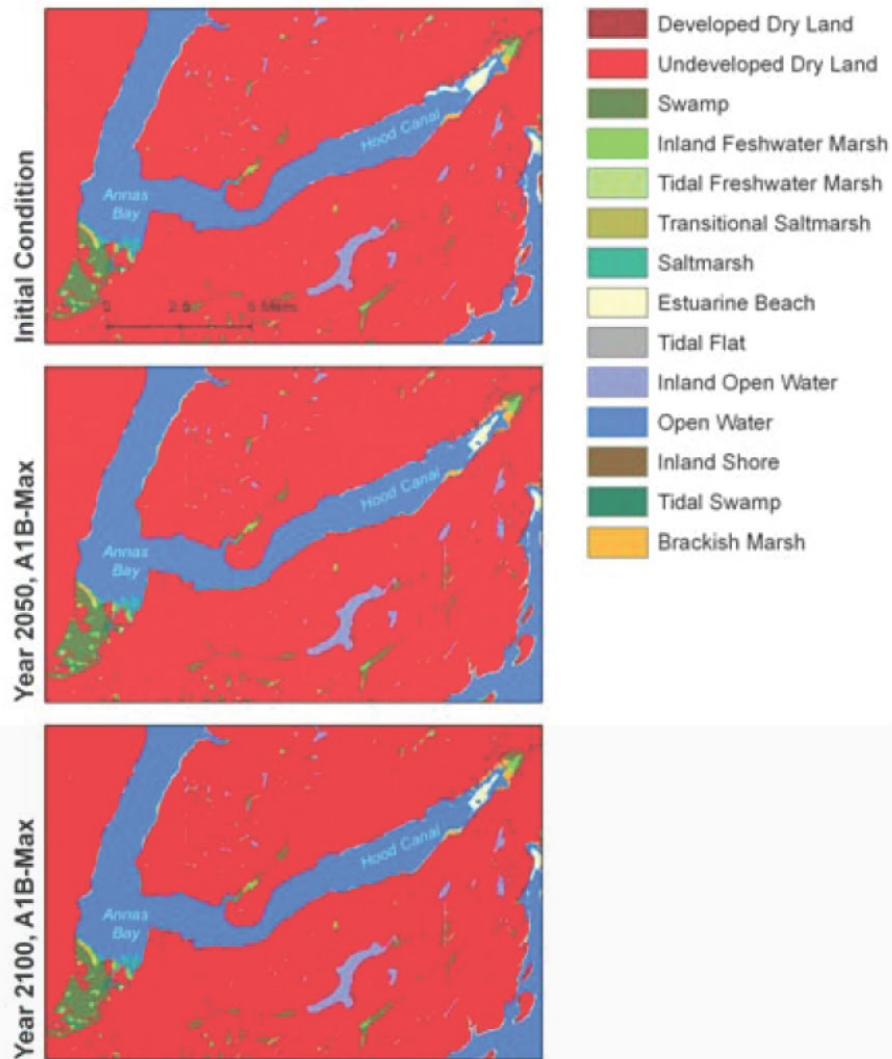
Site 6: Dyes Inlet, Sinclair Inlet, & Bainbridge Island

- Developed Dry Land
- Undeveloped Dry Land
- Swamp
- Inland Freshwater Marsh
- Tidal Freshwater Marsh
- Transitional Saltmarsh
- Saltmarsh
- Estuarine Beach
- Tidal Flat
- Brackish Marsh
- Rocky Intertidal
- Inland Open Water
- Open Water
- Inland Shore
- Tidal Swamp

Initial Condition   **Year 2050, A1B-Max**   **Year 2100, A1B-Max**

Temporal progression of land masses on the eastern border of Hood Canal (Glick et al., 2007).

The eastern boundary of Hood Canal is mostly dry land and has a high enough elevation to not be at risk of inundation with projected sea level rises. However, over half of the extent of beach habitat is projected to be lost to inundation and will likely be transformed into tidal flats by 2050. However, saltmarsh and transitional marsh areas are expectd to increase which is positive in terms of hypoxia control since the marshes will pose as more sufficient nutrient filters than dry land.

Site 8: Annas Bay & Skokomish Estuary

Legend:
- Developed Dry Land
- Undeveloped Dry Land
- Swamp
- Inland Feshwater Marsh
- Tidal Freshwater Marsh
- Transitional Saltmarsh
- Saltmarsh
- Estuarine Beach
- Tidal Flat
- Inland Open Water
- Open Water
- Inland Shore
- Tidal Swamp
- Brackish Marsh

Temporal progression of southern Hood Canal land coverage (Glick et at., 2007).

Based on model predictions, this region of Hood Canal will be relatively less impacted by sea level rise than other study sites. This is likely a consequence of the high land elevation. Also, this area is primarily composed of dry land with some minimal swamp and estuarine beach habitat. About one third of the estuarine beach zones will be inundated

Conclusions

A cumulative impact on Hood Canal hypoxia due to climate change is difficult to predict because we have yet to fully understand how all the factors that contribute to hypoxia within the Canal interrelate. Some factors may have higher relative influences on contributing to hypoxic conditions or events than other factors. Some factors could have both positive and negative impacts on hypoxia. For example, increases in streamflow delivery to Hood Canal could increase nutrient and oxygen supply but instead spurs additional stratification of the water column which ultimately decreases dissolved oxygen.

Climate change projections inherently come with some degree uncertainty. In other words, we can never be certain about how or when climate change will affect a natural system, especially if that system is composed of smaller natural systems. The case of Hood Canal hypoxia is particularly tricky because both natural factors and anthropogenic factors will play a role in how it reacts to climate change. Ultimately, we can always benefit from continued research and monitoring of complex systems and their temporal variability.

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