INTRODUCTION – Salmon and Climate Change

Salmon are central to the lifeways of the Tulalip people. Since time immemorial, the ancestors of the Tulalip Tribes celebrated the return of salmon to the rivers in spring. The salmon have always been a major source of food for the people, and are central to tribal culture. The salmon brought life to the people and the river, and the people revered and thanked the salmon for its sacrifice and promised to always protect it.

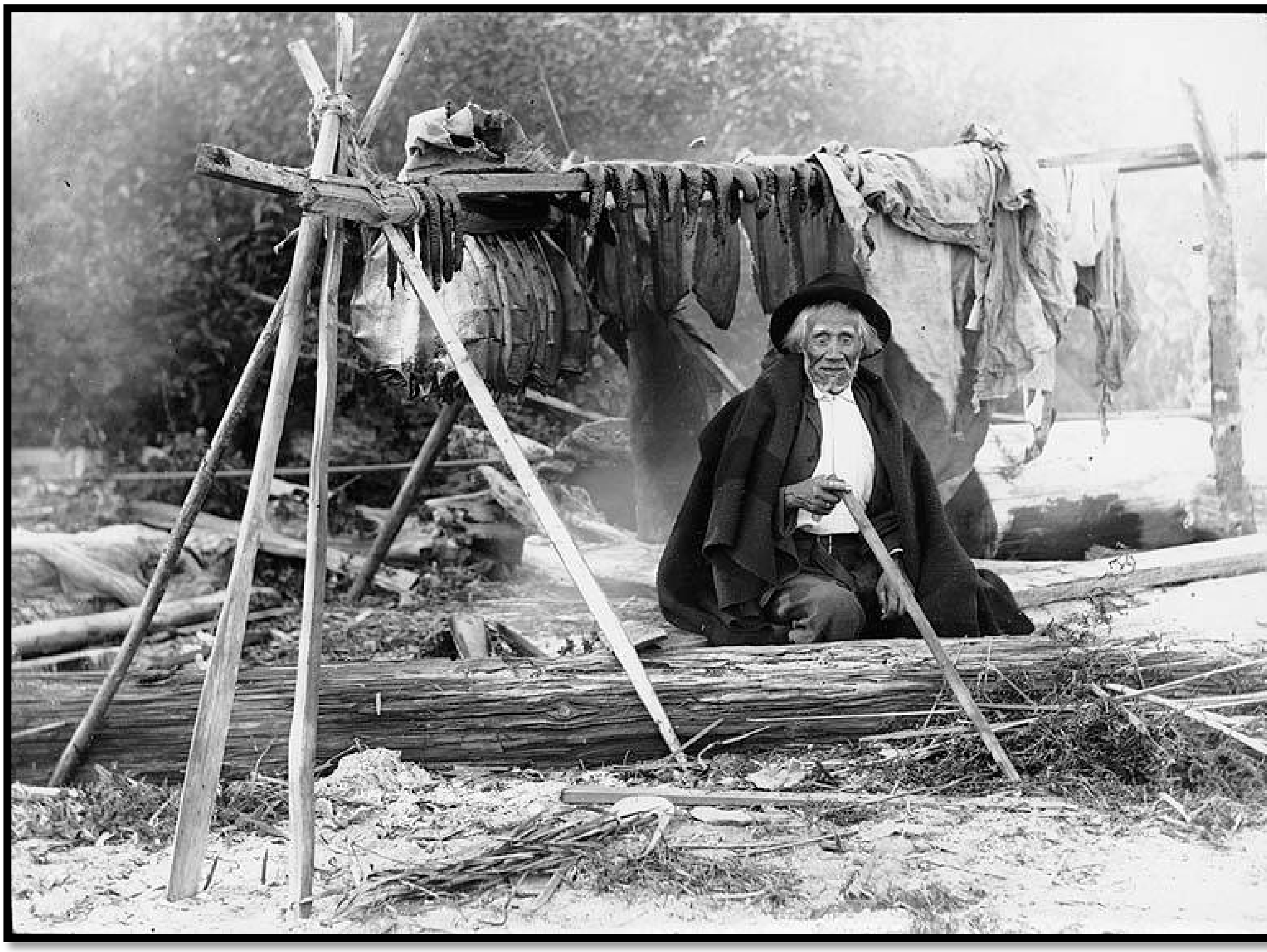

Photo: Salish man named William Weahlup smoking salmon. Tulalip Indian Reservation, 1906. University of Washington Libraries, Special Collections, #NA709

Today, the salmon are threatened by a landscape transformed by resource extraction and development. Millions of people now live on Tulalip's historic lands adjacent to the Salish Sea. The fresh water ecosystems salmon depend on are simplified and degraded, pollutants are ubiquitous, and natural hydrology is interrupted by the impact of humans. The western societies that settled in the lands of Tulalip's ancestors did not revere and respect the salmon, and the fight to protect the salmon from extinction is entering a new era of urgency.

Human activity has also transformed the atmosphere of the planet. Climate change is now exacerbating degradation and threatening habitat at every stage of the salmon life cycle, from the spawning streams with not enough water, to the vast Pacific Ocean with fewer returning adult fish. Changes due to climate change have been observable for more than 20 years, and we anticipate more extreme changes to emerge in the future. It is important to identify how the climate is changing and project its future impacts on salmon if we are to build successful strategies to help salmon recover, and even avoid extinction. Identifying all climate impacts is a monumental task, especially considering how widely salmon are dispersed across the landscape, from highland streams, lowland streams, rivers, estuaries, the Puget Sound, beaches, the coast and the massive Pacific Ocean. Each of these vital salmon habitats contributes to the salmon life cycle in a different way, and climate change affects each differently.

Table 1. Climate Impacts on Salmon

Hydrology	• **Lower summer flows – access to spawning reaches, decreased quantity of available spawning habitat, risk of drying redds, higher susceptibility to increased temperature, decreased dilution of pollutants in Puget Sound.** • **Higher winter flows – Risks from flooding – directly interfering with spawning, burying and scouring redds pre emergence, harming and/or flushing juveniles downstream, encouraging habitat destroying flood protection activities (revetments, levees, and tree removal), and flashier hydrographs.**
Temperature	• **Increased summer temperatures – stress on migrating/spawning adults, yearling parr, and late rearing estuarine juveniles, increases in recreation activities and associated habitat degradation (including wood removing hazard reduction).**

	• **Increased winter temperatures – Shorter egg development and early emergence timing, increased flows.**
Stormwater	• **Flashier hydrographs – unnatural high flows, spiking quickly, flushing out wood and leaf litter** • **Increased contaminant delivery – quantity and intensity, especially harmful to coho, overwhelmed outdated systems requiring expensive retrofits.**
Sedimentation	• **Increased sediment loads – Buried and scoured redds, unhealthy suspended sediment, encouraging dredging and other harmful protection activities**
Sea Level Rise	• **Increased armoring and protective measures – degradation of nearshore habitat.** • **Coastal Squeeze – Beaches squeezed between rising water and beach armoring – decreasing and degrading habitat, estuaries will move inland, potentially limiting the benefit of current lower elevation restoration.** • **Increased pollution – especially from septic systems.**
Ocean acidification	• **Disrupted ecosystems – Marine ecosystems that support salmon will change. Food webs will change with them – altering the abundance and composition of food available for salmon (e.g. crab larvae and herring) during marine life stages.**

Freshwater

Salmon begin and end their lives in fresh water. After spending most of their lives in the ocean, adult salmon return to rivers to spawn mostly in the spring, summer, and fall. Chum and some populations of Coho are adapted to spawn during winter months. There are two types of Steelhead. Winter steelhead enter rivers in winter and spawn relatively quickly in the late winter and spring. Summer steelhead enter rivers in summer then reside in streams through the fall and winter where they sexually mature and spawn in the late winter and spring. The timing of river entry, spawning, juvenile emergence, and juvenile rearing are associated with seasonal patterns in water flows and food availability affected by climate change. Environmental conditions during these critical life stages are vitally important to the survival of salmon.

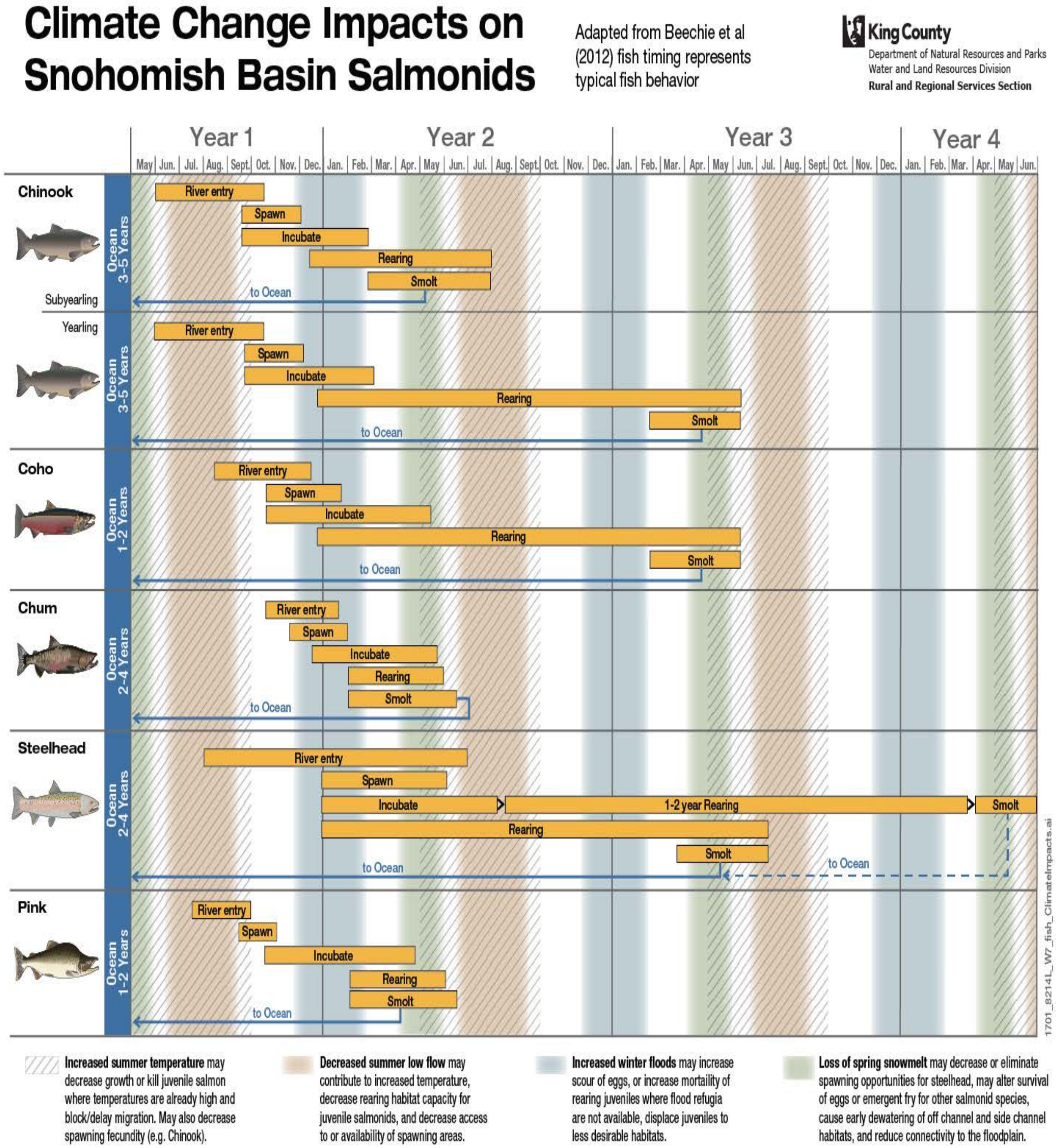

Figure 1. Salmon adult and juvenile freshwater life stages and associated climate impacts (King Co. 2017; adapted from Beechie et al. 2012).

Seasonal patterns in the source and delivery of water determine river hydrology. Topography (elevation and shape of the landscape) interacts with local climates and weather in different seasons to determine rain and snow patterns (figure 2), as well as delivery of meltwater. Higher elevation watersheds are dominated by snowmelt (Sauk River – figure 2), while low elevation watersheds are dominated by rain (Samish River – figure 2). Many large watersheds in the Pacific Northwest drain both mountains and lowland valleys and have seasonal hydrology that is a mix of rain and snow (Snohomish River- figure 2).

Specific climate change impacts are highly dependent on the seasonal hydrologic patterns of a particular watershed.

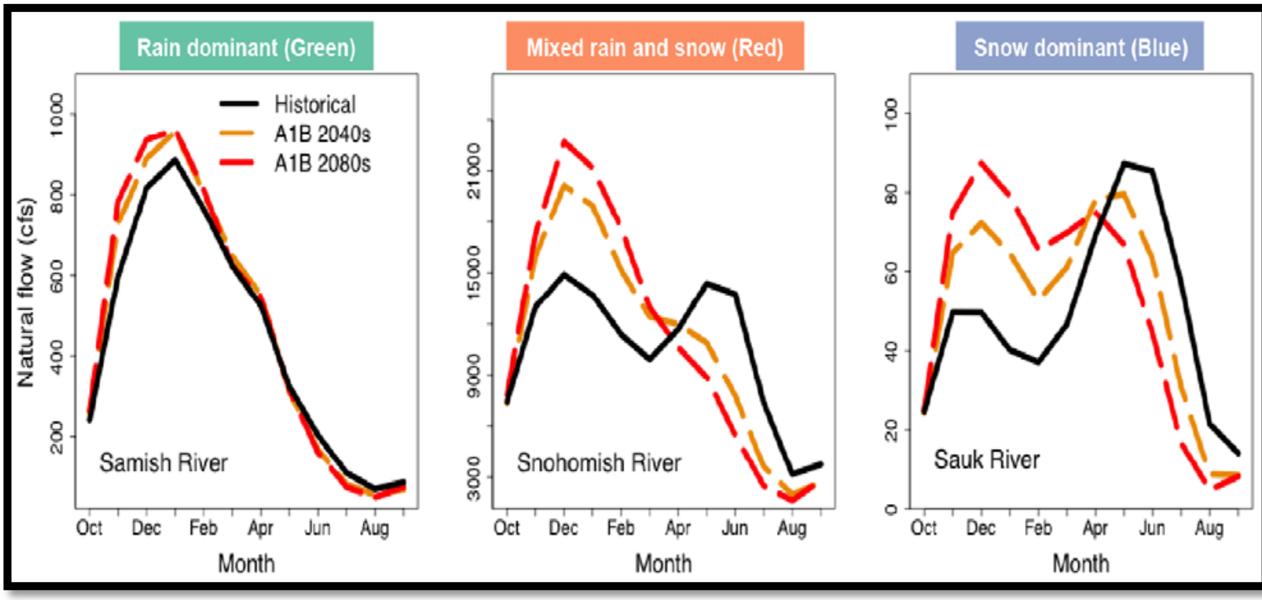

Figure 2. Streamflow is projected to increase in winter and decrease in late spring and summer for all basin types for the A1B (moderate) greenhouse gas emission scenario. Shifts will be more severe if emissions continue to increase. (Mauger et al., 2015).

As the climate warms, freezing levels rise, causing more precipitation to fall as rain and less as snow (figure 3). Regional precipitation is also expected to increase in intensity in winter and decrease in summer (Figure 4, Mauger et al. 2015). More winter precipitation with higher freezing levels results in less snow accumulation at high elevations to melt in the summer and more water flowing through river systems in the winter.

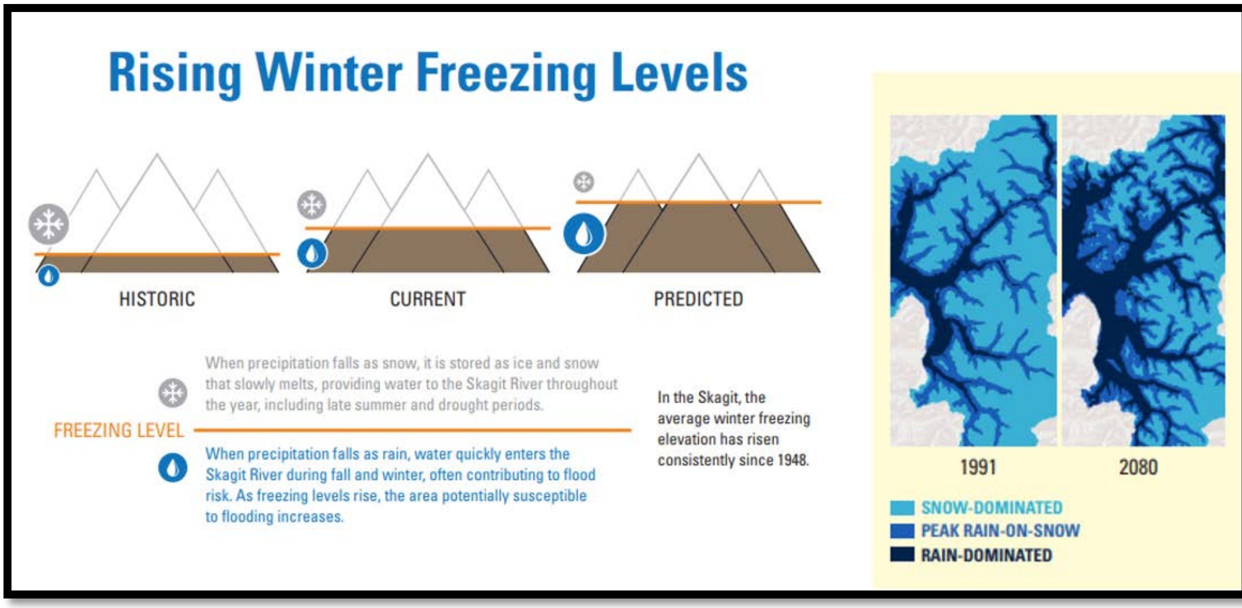

Figure 3. Effects of rising temperatures and freezing levels on mountain snowpacks in the Skagit river watershed. source: Skagit Climate Consortium (http://www.skagitclimatescience.org/wp-content/uploads/2016/07/FINAL_CaseStudy_Glaciers-Snowpack_2.pdf)

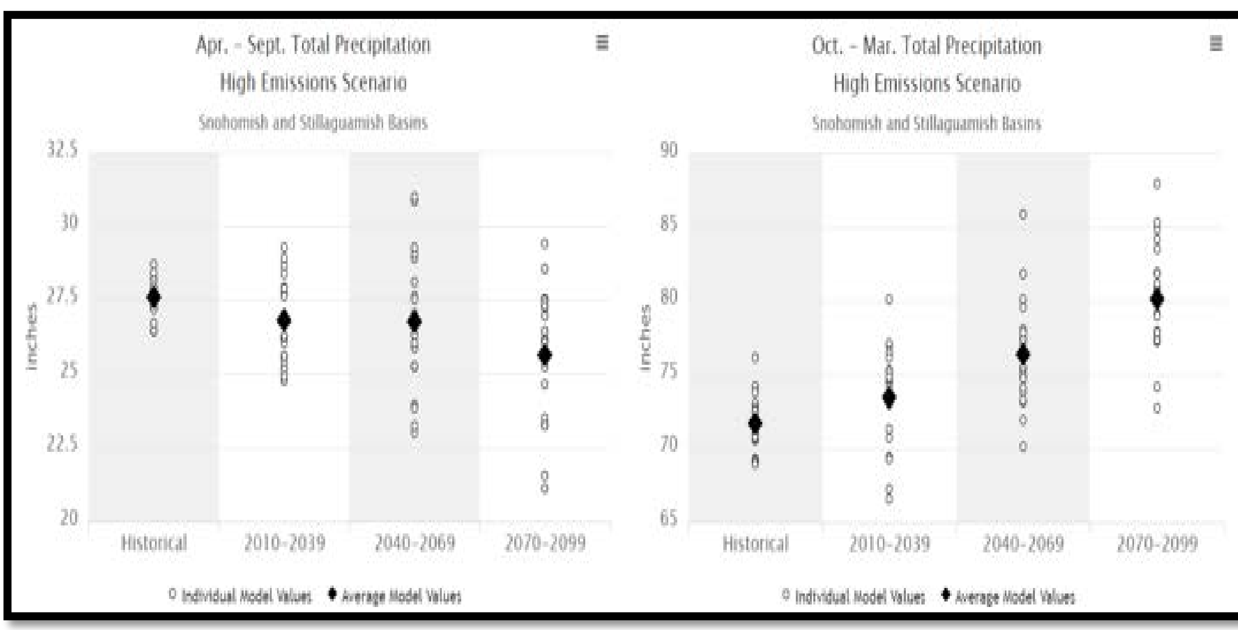

Figure 4. Projected changes in summer (Apr – Sept) and winter (Oct – March) precipitation in the Snohomish and Stillaguamish basins. (CIG Tribal Climate Tool, 2018)

Hydrology is the fundamental river process that underlies all other processes in freshwater systems, it is also directly tied to climate and seasonal cycles. As climate change alters the nature of seasonal weather patterns, seasonal hydrology will change with them. Hydrology affects flows and floods, temperatures, sediment delivery and deposition, habitat development, stormwater systems, and even marine conditions in the Salish Sea. Hydrologic processes are the central determinant of climate change impacts to salmon during their freshwater life stages, and are necessarily a central focus of climate change adaptation in these complex terrestrial ecosystems.

Summer Hydrology

Mountain snow packs are a natural reservoir of water that accumulates during the freezing winter and melts through spring into the summer. Snowmelt provides cool water to aquifers, streams, and rivers, often when precipitation is limited. As the climate warms, freezing levels will rise, changing seasonal hydrologic patterns (Figure 2 and 3). Rising freezing levels cause less snow to accumulate in the mountains, where it remains until the weather warms with the season. The Puget Sound region is projected to have 77% less snowback between 2070 and 2100, (Figure 4, Mauger et al. 2015). Weather conditions in the winter of 2015 resulted in unusually low snow packs similar to conditions we expect in the future (Figure 5). In 2015 the amount of precipitation was normal (black line), but the snow pack (blue line) was well below the normal accumulation (red line). This means precipitation fell as rain instead of snow. Water usually stored as ice until it melts in the spring snowmelt left the system in winter, which means less water is available to melt into the summer months. This also has important implications for winter hydrology.

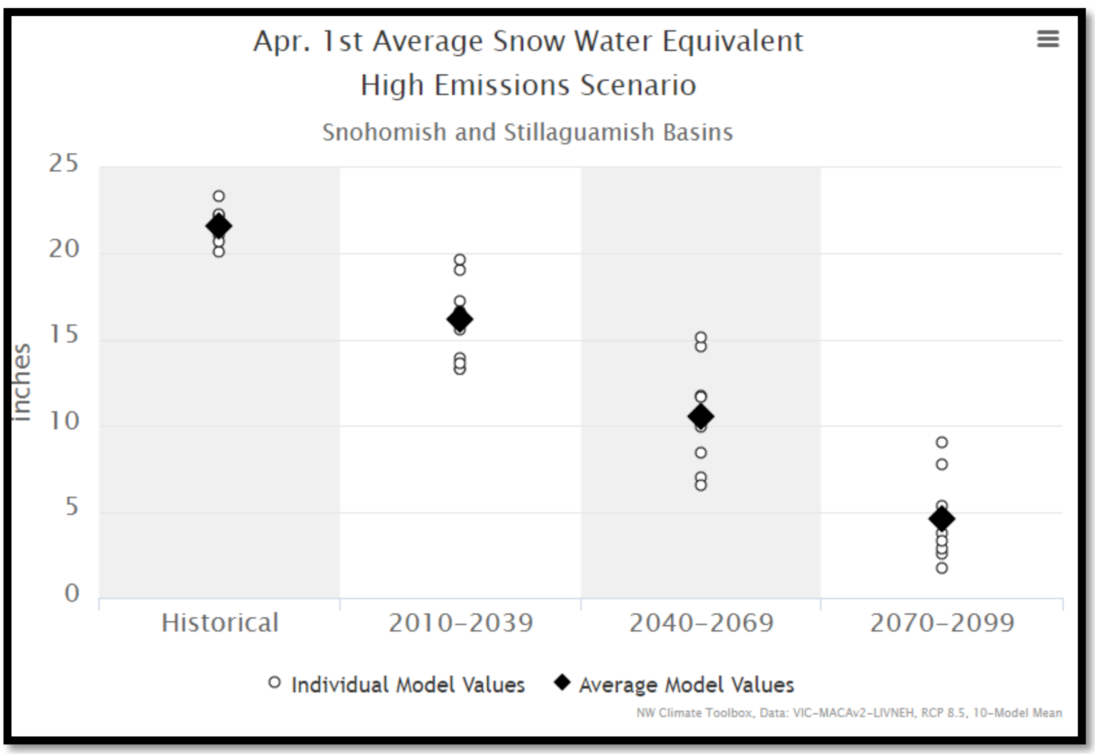

Figure 4. Decreases in snow fall will result in less snowpack. Snow pack is measured in snow water equivalents,

which is how much water a certain amount of snow contains. Under a high emissions scenario, the April 1st Snow water equivalent is expected to decrease by ~77% between 2070 and 2099. (CIG Tribal Climate Tool, 2018)

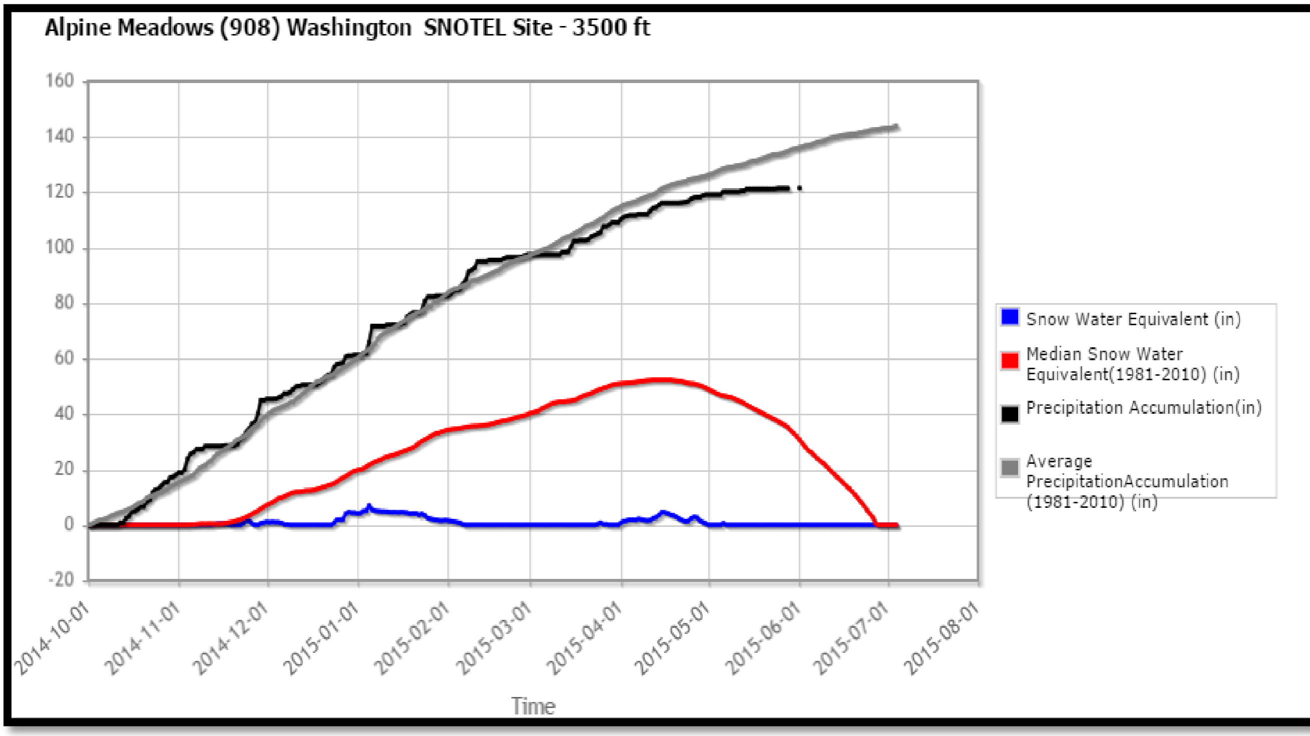

Figure 5. SNOTEL data from Alpine Meadows, north of the North Fork Tolt River. The graph shows normal precipitation volumes, but snow volumes consistently near zero (NRCS 2017).

Low snow packs negatively impact freshwater conditions. This is particularly evident during the summer. There are significant declining trends in snow pack over the last 70 years (figure 6). Snowmelt feeds streams and rivers and fills groundwater aquifers that supply stream flow throughout the summer. Climate modeling predicts less precipitation during the summer, 22% less by 2050, which makes snowmelt even more important for summer hydrology as droughts become more common (Mauger et al 2015).

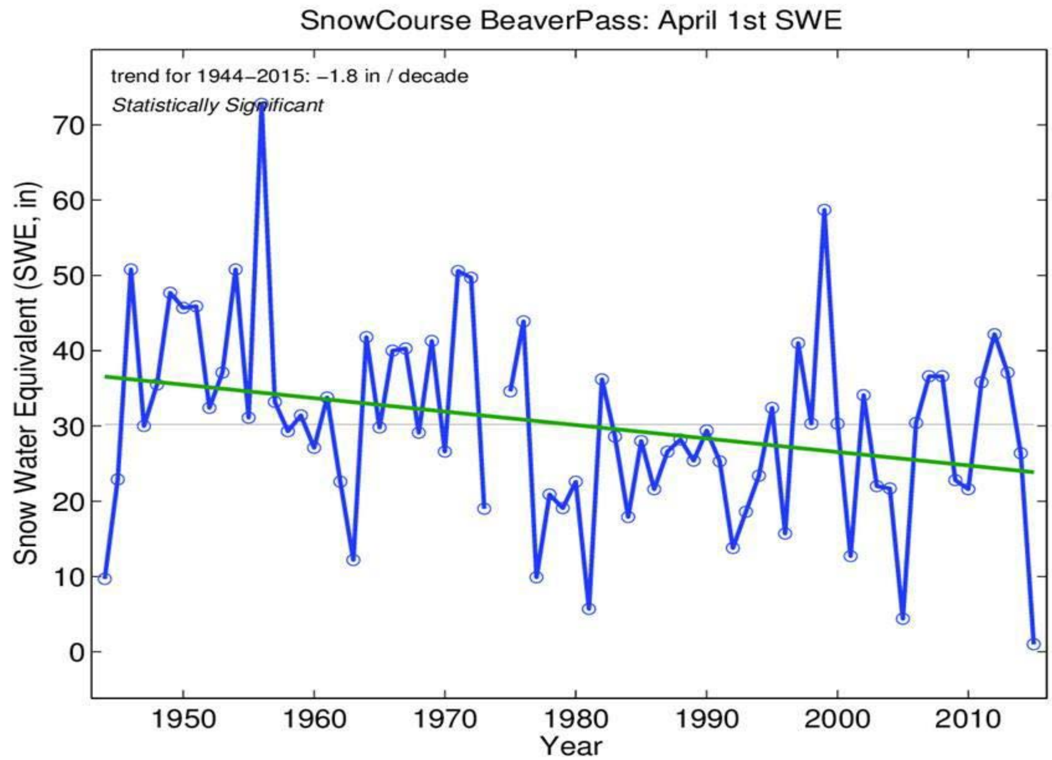

Figure 6. Snow pack for Beaver Pass in the North Cascades 1944-2015 showing a statistically significant downward trend, with a decline of -1.8in per decade. (https://cig.uw.edu/resources/analysis-tools/seattle-city-light-trends/)

Low snow packs result in low stream flows and decreased aquifer supply. Low flows can reduce spawning habitat by drying gravel beds, and kill eggs if the water table drops below salmon redds. Low flows can result in fish passage barriers limiting spawning migration and access to spawning habitat.

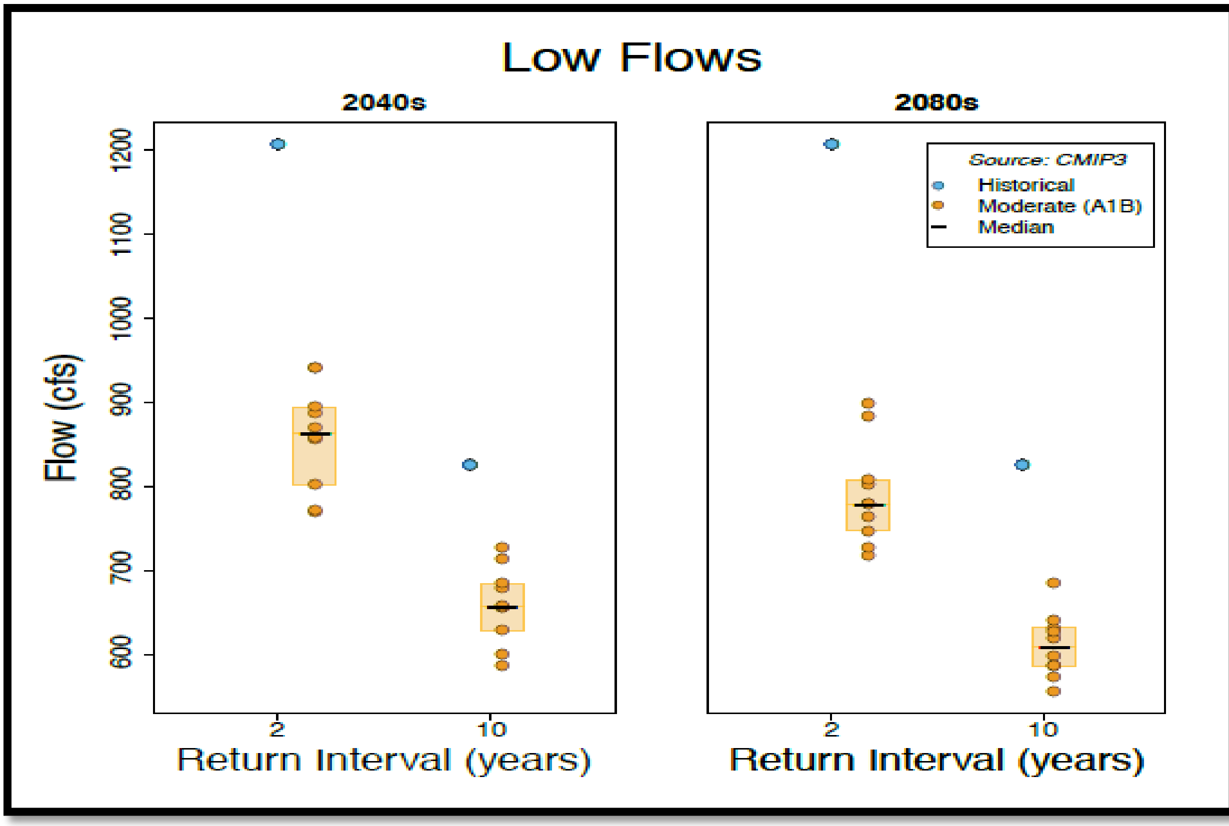

Figure 7. Changes in low flow in the Snohomish River for historical (blue) vs. Projected (orange) flows that occur statistically every 2 and 10 years (return interval; Mauger et al. 2015).

Decreased snow pack and snow melt decrease the volume of water that flushes into the Salish Sea, especially in later months. This decreased volume concentrates pollutants like nutrients from point and non-point sources like wastewater treatment plants, residential areas, and farms. Flows are also shifting earlier in the melt season (Figure 8). River flows (especially those from the Fraiser River in British Columbia which accounts for 2/3rds of all river inflow to the Salish Sea) are responsible for driving salt water exchange between Puget Sound and the ocean (PSEMP Marine Waters Workgroup. 2015). Decreased flows resulting in decreased exchange has the consequence of concentrating human derived nutrients in the Puget Sound. The more slowly moving waters warms. These conditions are hypothesized to result in a shift in food web dynamics within the Puget Sound, resulting in unhealthy phyto and zooplankton communities harmful to salmon and the food web that supports them (figure 9; Krembs). This phenomenon exemplifies the complexity of the relationship between climate and salmon, and shows that even actions like decreasing nutrient pollution are actually strategies to address climate impacts.

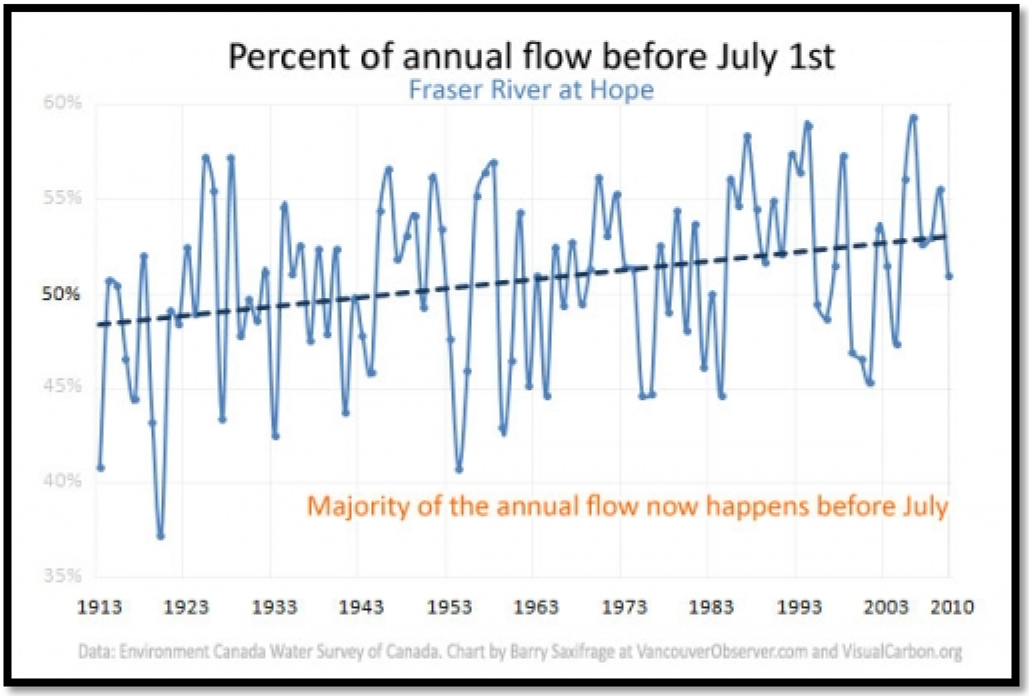

Figure 8: An increasing proportion of the Frasier River snowmelt is melting earlier in the year. (https://www.vancouverobserver.com/blogs/climatesnapshot/fraser-river-salmon-dying-climate-change-heats-waters)

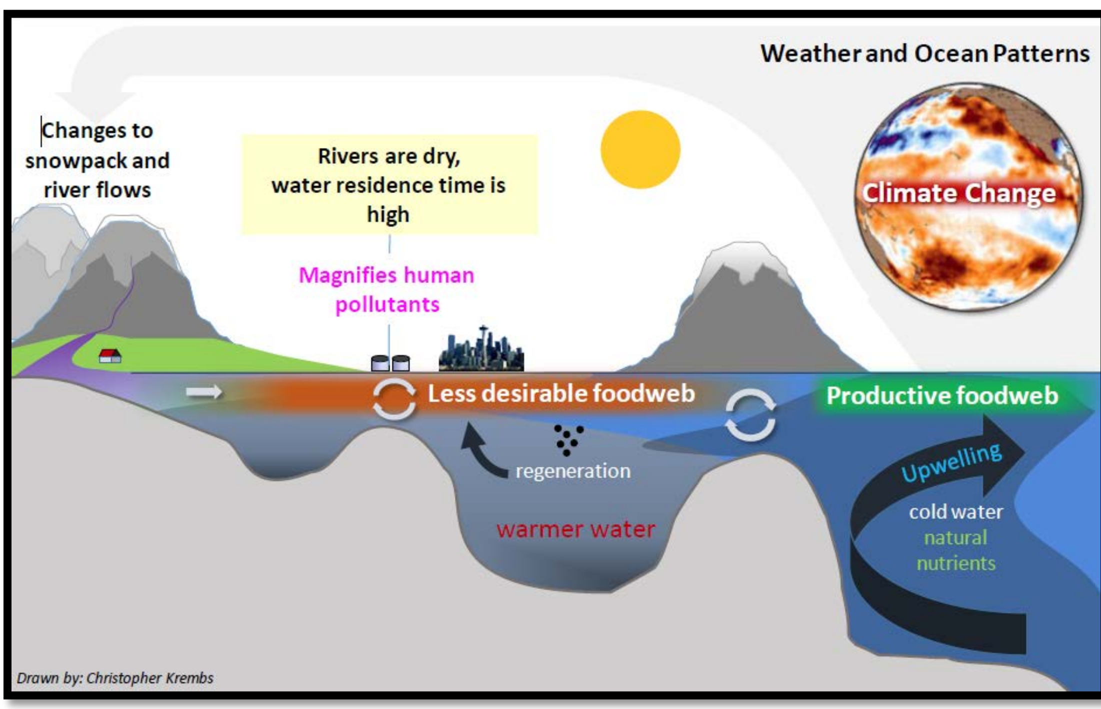

Figure 9: Effect of climate change on summer hydrology – food web shifts due to concentration of pollutants and decreases in upwelling exchange. (Source:

Christopher Krembs, Washington State
Dept of Ecology)

Winter Hydrology –

Flooding in the Snoqualmie valley extends from valley wall to valley wall even at moderate flood stages.

Snowmelt happens in the spring and summer, but the snow that melts accumulates during the winter. Climate models predict increased precipitation in the winter, which might lead one to expect a corresponding increase in snow pack. However, despite more precipitation, warmer winter temperatures will cause a larger proportion of that precipitation to fall as rain and less as snow. As precipitation shifts toward more rain, less water is stored as snow and more will flow into rivers. This increases winter flows and flooding. Climate models suggest that the historical 50 year flood will become a 10 year flood. That is to say that major floods that only happen roughly every 50 years will be much more frequent, happening every 10 years. Likewise, today's 100 year flood will be tomorrow's 50 year flood (Figure 10; Mauger et al. 2015). In this way, increased winter flooding is directly related to decreased summer flow, both of which are harmful to salmon.

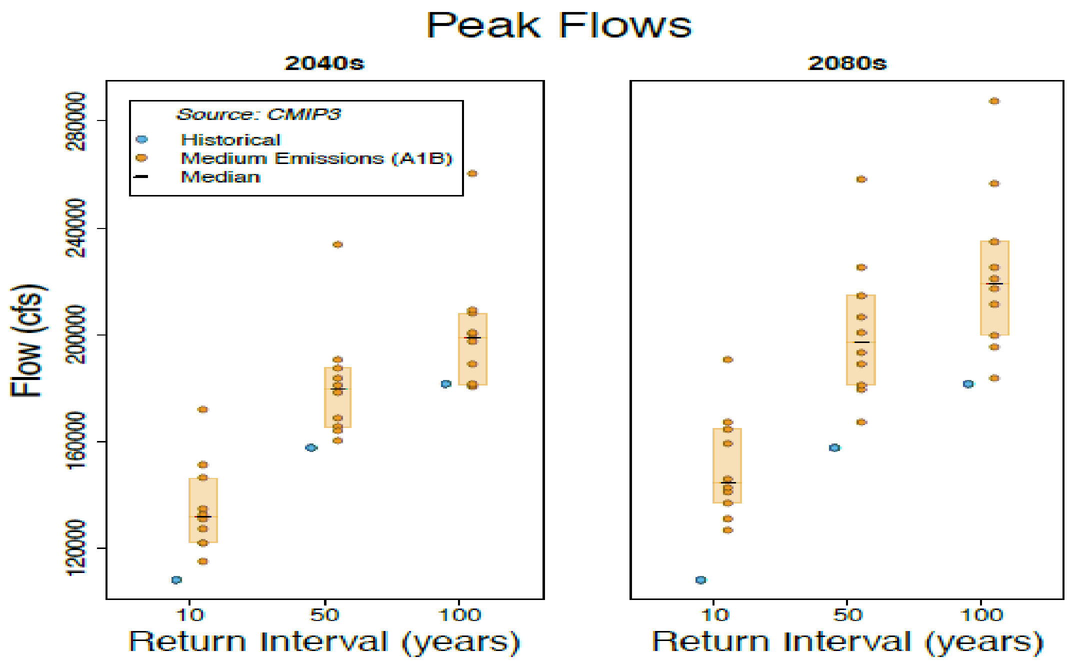

Figure 10. Changes in peak flow in the Snohomish River for historical (blue) vs. Projected (orange) flows that statistically occur every 10, 50, and 100 years (return interval). Mauger et al. 2015.

Flooding is a natural risk to salmon in the winter. It can disrupt spawning in the late fall and early winter and bury or scour salmon eggs in redds. Flooding also strands juvenile fish on the floodplain out of river channels, and in unhealthy drainage ditches, and flushes juveniles downstream before they are physiologically prepared for estuarine or saltwater life stages.

Juvenile chinook stranded in a field following the retreat of flood waters. King County, 2017.

Flooding is also a major risk to humans, who protect communities from floods in ways that degrade salmon habitat, like building levees, removing wood, and dredging channels. Levees cut off rivers from the floodplain, amplifying the negative effects of flooding by constraining flows in fast, deep, simplistic channels. Levees also limit or eliminate the natural processes that provide flood benefits like wood recruitment and channel formation.

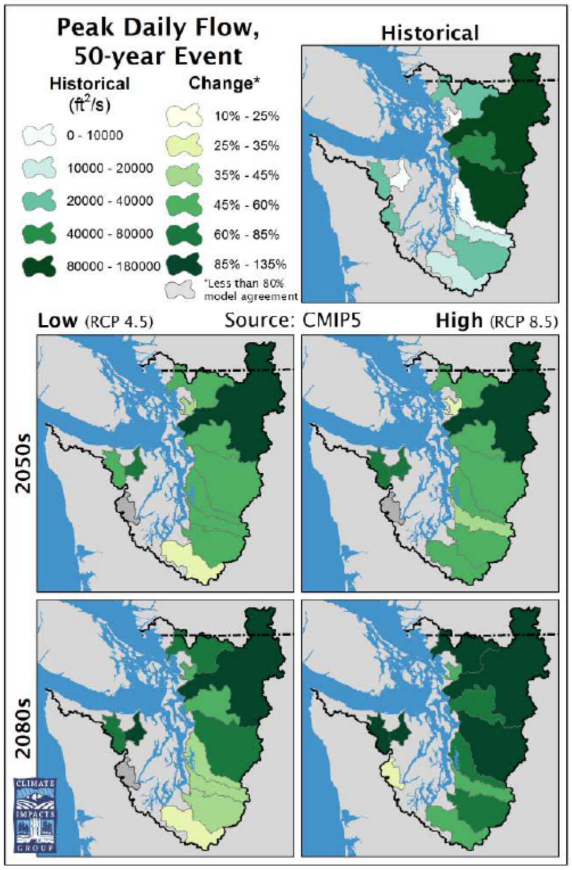

Figure 18b. Peak daily streamflow, 50-year event, newer projections. As in Figure 18a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

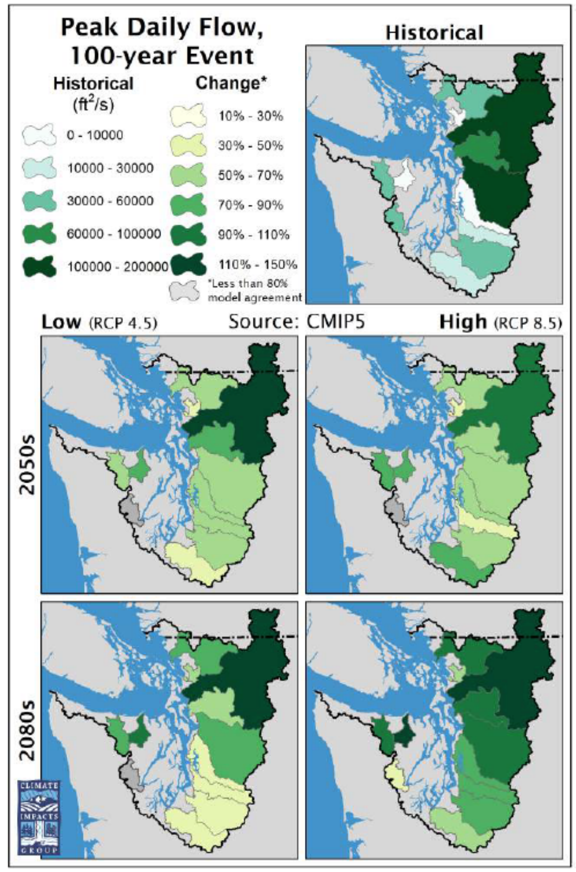

Figure 19b. Peak daily streamflow, 100-year event, newer projections. As in Figure 19a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

Figure 11. Changes in projected return frequencies and volumes for 50 and 100 year floods in the Puget Sound.

As floods get worse, and outdated flood protection infrastructure becomes insufficient, there will be pressures to build new bigger levees, to dredge river channels, and remove wood. These pressures are already occurring in areas like the lower Tolt River near the City of Carnation where old levees were built without adequate understanding of geomorphic processes. Flood protection actions are complex, expensive, and fraught with political influence. When protections from floods are simplistic and shortsighted, like dredging or building levees taller around constrained channels, protections also pose major threats to salmon. The channelization of rivers (levees and dredging) and armoring of banks are harmful to salmon populations (The Plan, 2005). Furthermore, dredging or just building a levee taller are temporary fixes, which might be cheaper in the short term, but defer solutions and greater expenses to future generations. Fortunately, actions like levee setbacks offer significant opportunities for salmon restoration by improving habitat while simultaneously offering substantially more flood protection far into the future, especially as a changing climate increases flood risks. Levee setbacks are one of the best tools we have to improve both salmon habitat and flood protection for communities. However, these kinds of multi-benefit projects often require the acquisition of private land that can be expensive, politically sensitive, and limited by the cooperation of landowners.

Juvenile salmon
using restored habi

While flooding is harmful to salmon when they are in the river, it is also a natural habitat forming process that erodes banks, recruits trees and large wood into rivers to form log jams, moves sediment, and forms new channels and spawning and juvenile rearing habitat. Salmon are well adapted to bounce back from major floods when they are infrequent and given the opportunity to create habitat. More frequent and larger floods, particularly those constrained in leveed reaches, and the tendency for humans to respond to flooding by degrading habitat, will increase risks to salmon populations.

Increased winter precipitation will increase stormwater runoff in both duration and volume. Increased stormwater runoff is likely to amplify stormwater impacts from toxic contaminants and flashy amplified hydrographs in urbanizing catchments. These impacts will intensify as population growth, development, and traffic increase independent of climate change. Stormwater systems will be challenged by increased flows. Insufficient culverts can cause erosion and road failure and limit access for salmonids. Heavier winter rain will increase erosion, soil saturation, and landslide potential, which will increased sediment loads in rivers and streams. High sediment loads can bury salmon eggs or erode redds and harm juvenile and adult fish by smothering gills, and limiting foraging opportunity.

Salmon eggs among gravel on a stream bottom. (WDFW: https://wdfw.wa.gov/wildwatch/salmon/hatchery.html)

A salmon attempts to swim over the roadbed of 399th Street outside Gold Bar in October, 2009, after waters from the Wallace River flowed over the road during flooding. (Mark Mulligan/Herald file photo; https://www.heraldnet.com/opinion/editorial-no-avoiding-duty-to-restore-salmon-habitat/)

Strategies - Hydrology –

As the fundamental process that underlies the river system, hydrologic processes are responsible for forming and maintaining the habitats salmon depend on and actions that improve climate resiliency for salmon are typically associated with restoring and protecting hydrology. While climate change will manifest itself differently in different seasons, summer and winter hydrology are two sides of the same coin, so effective strategies for protecting and restoring natural hydrologic process benefit hydrology and address climate impacts all year long.

- **Target actions that naturalize hydrologic processes, increasing summer flows and decreasing winter flows.**
- Remove and/or set back levees.
- Remove bank armoring and revetments.
- Reconnect and restore floodplains and floodplain vegetation.
- Avoid simple responses to flood hazards – understand processes responsible for causing hazards and use process based approaches to address them (e.g. use engineered log jams to direct flow

away from sensitive banks, use levee setbacks to decrease sediment aggradation and bank erosion).

- Protect and restore wetlands.
- Restore beaver populations.
- Update culverts and other conveyances to allow increases in flow and improve salmon access.
- Update stormwater systems to decrease surface water conveyance to streams, store water, and recharge aquifers.
- Support complex habitat formation and groundwater exchange by supporting recruitment of large wood or engineering log jams.
- Avoid hydrologic impacts of timber harvest by avoiding hydrologically important areas, and increasing the length of harvest rotation (older forests; Perry and Jones 2016)).
- **Protect and restore natural hydrology in the 4 components of hydrology as directed in the Snohomish Basin Protection Plan – delivery, storage, recharge, discharge.**
  - Delivery – (how precipitation enters the river system) Improve by protecting and restoring forest cover, especially in snow and rain-on-snow dominant areas, increasing size of protected areas around streams and wetlands.
  - Storage – (accumulation of surface runoff) Protect and restore wetlands, encourage beaver activity, reconnect and restore floodplains and floodplain vegetation, reduce artificial channelization (e.g. ditches, and incised main channels), using better designed drainage systems, increasing size of protected areas around streams and wetlands
  - Recharge – (process where surface water infiltrates the aquifer to become groundwater) Reduce groundwater withdrawls, capture runoff to allow for greater infiltration, limit development and logging in areas with permeable soils, reduce artificial channelization (e.g. ditches), increase the size of protected areas around streams and wetlands, reconnect and restore floodplains and floodplain vegetation.
  - Discharge – (process where ground water becomes surface water) Reduce artificial channelization (e.g. ditches), reduce groundwater withdrawls, protect wetlands (especially upslope wetlands) reconnect and restore floodplains and floodplain vegetation.

Temperature

Diseased and dead pre-spawn Sockeye in the Columbia River basin in 2015. (Steve Ringman/Seattle Times)

As the climate changes, summers will be warmer and drier, with more intense and longer heat waves, and longer periods without rain, decreasing summer low flows. Winters will also be warmer, with fewer freezing days, and more precipitation deposited as rain instead of snow, leading to higher winter flows and smaller snow packs. Warmer air can also hold more moisture, which is the primary reason winter storms are expect to increase in severity. Increased air temperatures (2.2 to 3.3 degrees C by 2050; Mauger et al., 2015; figure 6) will cause diminished snow packs to melt quicker and increase stream water temperatures (Figures 12, 13).

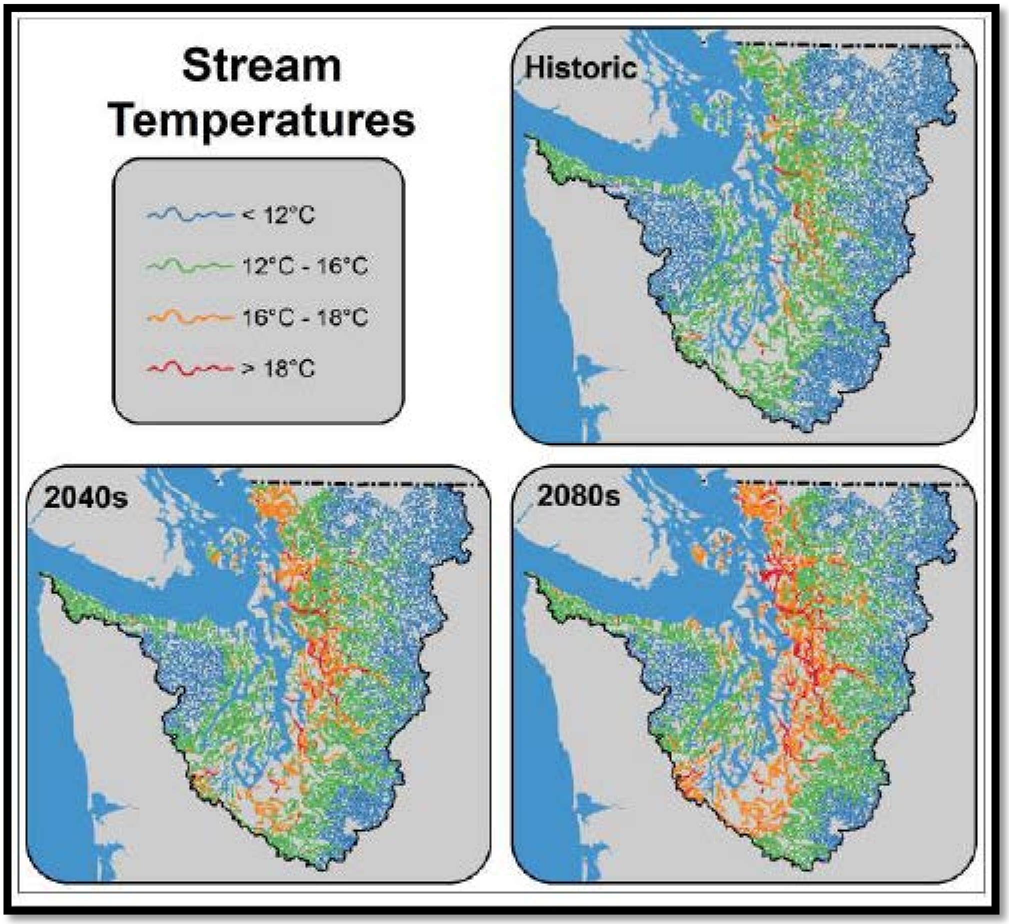

Figure 12. Projected increases in average August stream temperatures in the Puget Sound Basin for the 2040s and 2080, compared to historic conditions (1970-1999). Projections are an average of ten global climate models based on a moderate greenhouse gas scenario (A1B). If emissions continue at the current rate, projections will be significantly higher (Mauger et al. 2015). ***Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used the IPCC 2007 report. Data source: Isaak et al. 2011.***

These conditions increase the likelihood that stream temperatures will exceed the healthy tolerances of salmon more often and for longer periods (Figure 12). Generally, increased temperatures negatively affect metabolic rates, feeding requirements, prey composition and availability, disease/infection resistance, and oxygen concentration, resulting in reduced productivity, fitness, disease, and mortality – similar to effects observed in the summer of 2015 (Figure 13).

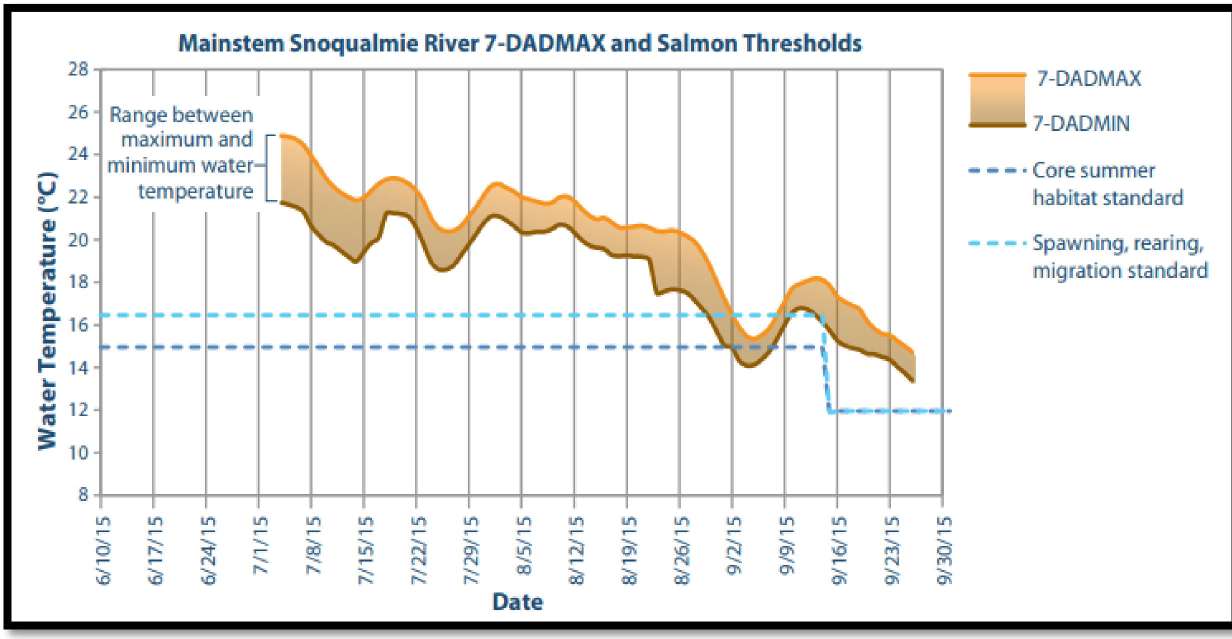

Figure 13. Temperature (7 day average daily maximum [7-DADMAX] and minimum) in the mainstem Snoqualmie River during the summer of 2015. Department of Ecology temperature standards for the period are shown as dashed lines. (King County 2016)

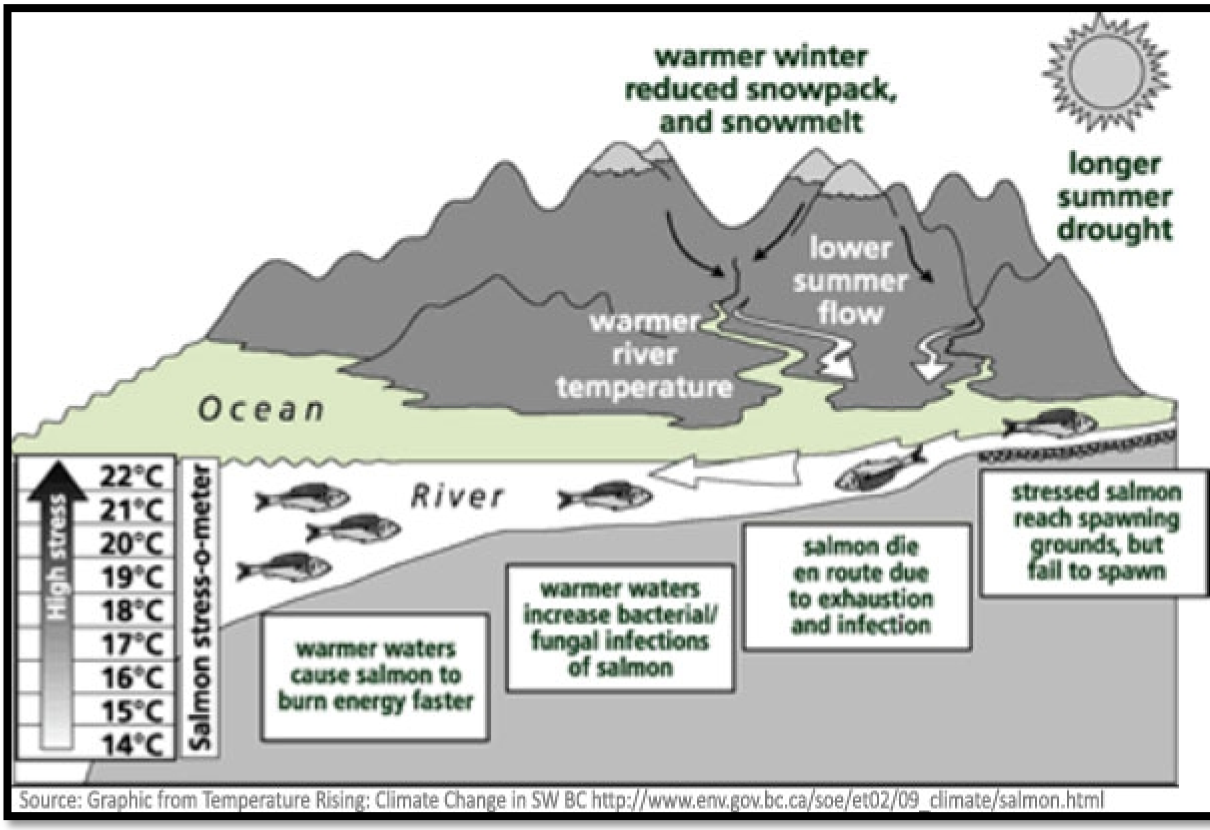

Figure 14: As a changing climate results in less water and warmer air temperatures, water temperatures increase risks to salmon. https://www.vancouverobserver.com/blogs/climatesnapshot/fraser-river-salmon-dying-climate-change-heats-

Thermal refugia are places where cold water is maintained in a river systems. They can be deep pools, places of groundwater discharge in a stream channel or cold tributaries. Thermal refugia will become increasingly important as the climate changes. Identifying and protecting these cold water refugia will be increasingly important as the climate changes. One important thermal refugia is the South Fork of the Skykomish River above Sunset Falls. Sunset falls is a natural barrier to migration, but a trap and haul program operated by the Department of Fish and Wildlife provides for passage above the falls. In low return years, such as 2015, the habitat above the falls is a vital thermal refuge for spawning salmon (Figure 15). The program must be maintained and operations improved to maintain and improve access. Other thermal refugia include the Sultan River in the lower Skykomish, and the Tolt River in the Snoqualmie River. Both of these systems are controlled by dams, which release cold water from thermally stratified reservoirs. In 2015 unusually high numbers of Skykomish Chinook entered and spawned in the Sultan River.

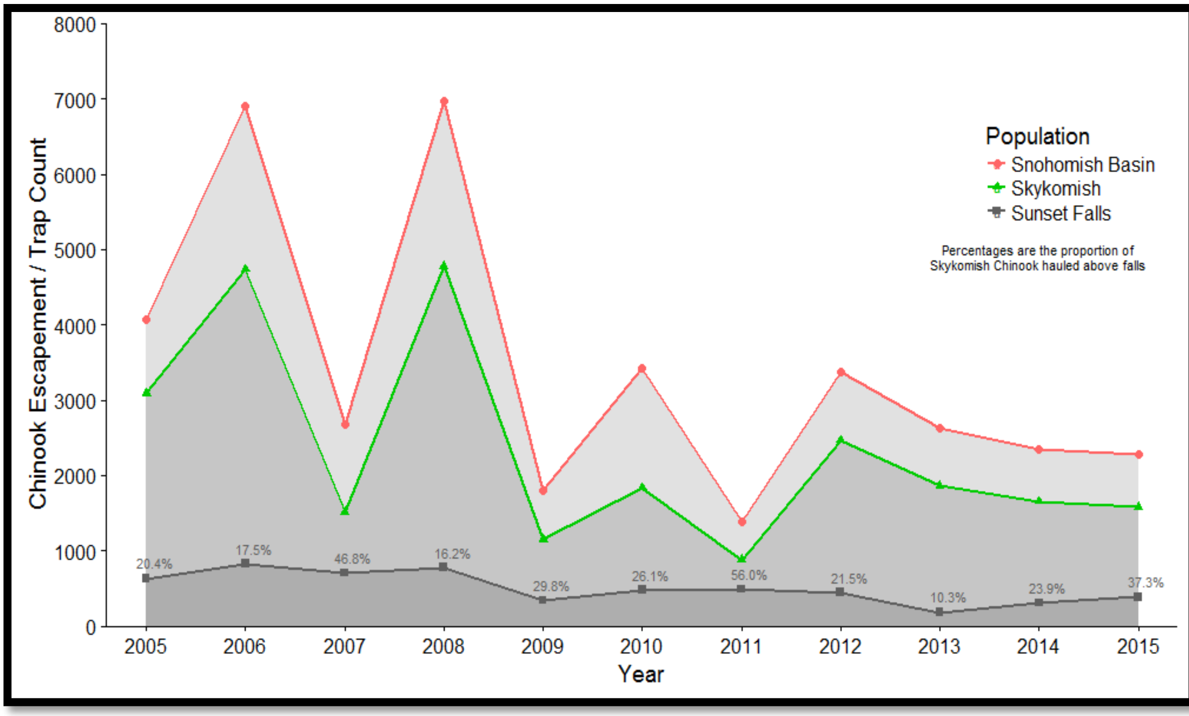

Figure 15. Sunset Falls trap and haul counts (grey), relative to total population in the Skykomish and greater Snohomish Basin. In low return years, the South Fork Skykomish supports a significant portion of Snohomish Chinook.

Sunset Falls on the South Fork of the Skykomish River. Fish cannot swim up the falls, and WDFW operates a trap and haul operation to pass fish above the falls to access the large amount of high quality habitat upstream. The river system above the falls is an important thermal refugia that supports a significant the Skykomish Chinook population in low return years like 2015.

Strategies – Temperature –

Stream temperatures are one in a series of stresses that will challenge salmon populations as the climate changes. As with most recovery actions, focusing on restoring the natural processes that support salmon habitats, particularly hydrology, is the most effective way to restore habitat and build resilience for climate change.

- Restoration and protection of hydrologic processes – see hydrologic strategies above.
- Identify and protect cold-water sources and the habitats and hydrologic processes that produce them.
- Restoration and protection of riverine habitat heterogeneity – deep pools, riffles, large wood, riparian forests.
- Reconnection of floodplains, removal of shoreline armoring and levees, and restoration of edge habitat.
- Protect and Restore riparian forests.
- Protect and restore processes and habitats in tributaries, which are cooler.
- Increase large wood recruitment, installation of large wood where appropriate.
- Protect and Restore wetlands and beaver habitat.
- Remove barriers to fish passage in tributaries (culverts, dams, ect.) to expand spawning habitat in cool reaches.

- Maintain Sunset Falls trap and haul operation. The South Fork Skykomish above the falls is a large thermal refugia in drought years.

Stormwater –

Projected increases in precipitation, particularly heavy winter rainfall events, will increase the volume of stormwater runoff and stress the capacity of stormwater systems, especially older systems. Increased stormwater runoff will increase the delivery of pollutants to streams and rivers and the Puget Sound. Increased stormwater runoff will increase the potential for delivery of pollutants, including nutrients, fine sediments, fecal coliforms, pesticides, heavy metals, oils, hydrocarbons, and hydrocarbon combustion waste products. These pollutants generally degrade the freshwater and marine ecosystems salmon depend on, they also directly impact fish in the water column by increasing toxic stresses and unhealthy conditions. Coho salmon are particularly susceptible to stormwater runoff from urban areas. Coho in the Puget Sound region have been dying prematurely in urban streams at high rates (60-90% of total runs), due to undefined toxins in urban runoff. Scientists are currently studying mortalities to identify the contaminants responsible (Figure 16; Feist et al 2017). While coho are particularly sensitive to runoff, stormwater certainly has effects on other salmonid species, and changes in climate are expected to increase those impacts.

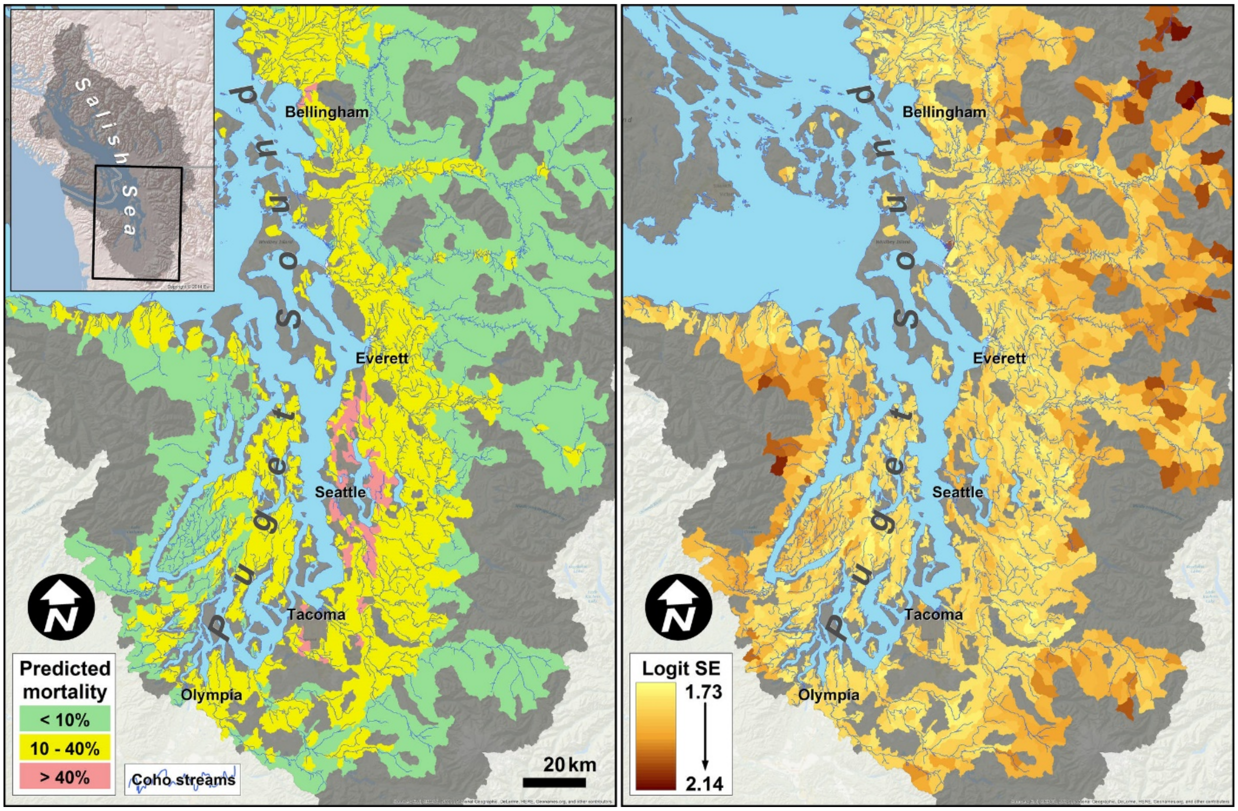

Figure 16. NOAA researchers are estimating coho morality across the Puget sound region (left) based on urban density and stormwater. The right side estimates the certainty of estimates (darker = less certain). http://www.knkx.org/post/simple-infrastructure-fixes-could-keep-stormwater-killing-puget-sound-coho

Artificial drainage systems such as stormwater systems can also degrade stream and river ecosystems by altering flows. When rainwater is not allowed to infiltrate into soils naturally, but is collected on impervious surfaces and transported directly and quickly to streams, these streams experience acute and flashy high flows that they usually would not experience. These flows increase erosion, sediment loads, bank incision, and simplify and channelize streams, and remove habitat elements like wood and leaf litter.

The landscape is like a sponge. It fills with water and stores it during and after rain events. Stormwater systems, by quickly transferring surface water to streams and rivers, reduce the capacity for the landscape to soak up water and slowly deliver it throughout the year. In watersheds with significant impervious surfaces and stormwater systems, less groundwater can decrease or eliminate summer flows, amplifying the negative effects of climate change on summer hydrology. Furthermore, stormwater systems are expanding with the human population. As the population grows and the landscape is increasingly developed, stormwater systems must be expanded to accommodate additional stormwater. This human impact will amplify the climate impacts from stormwater.

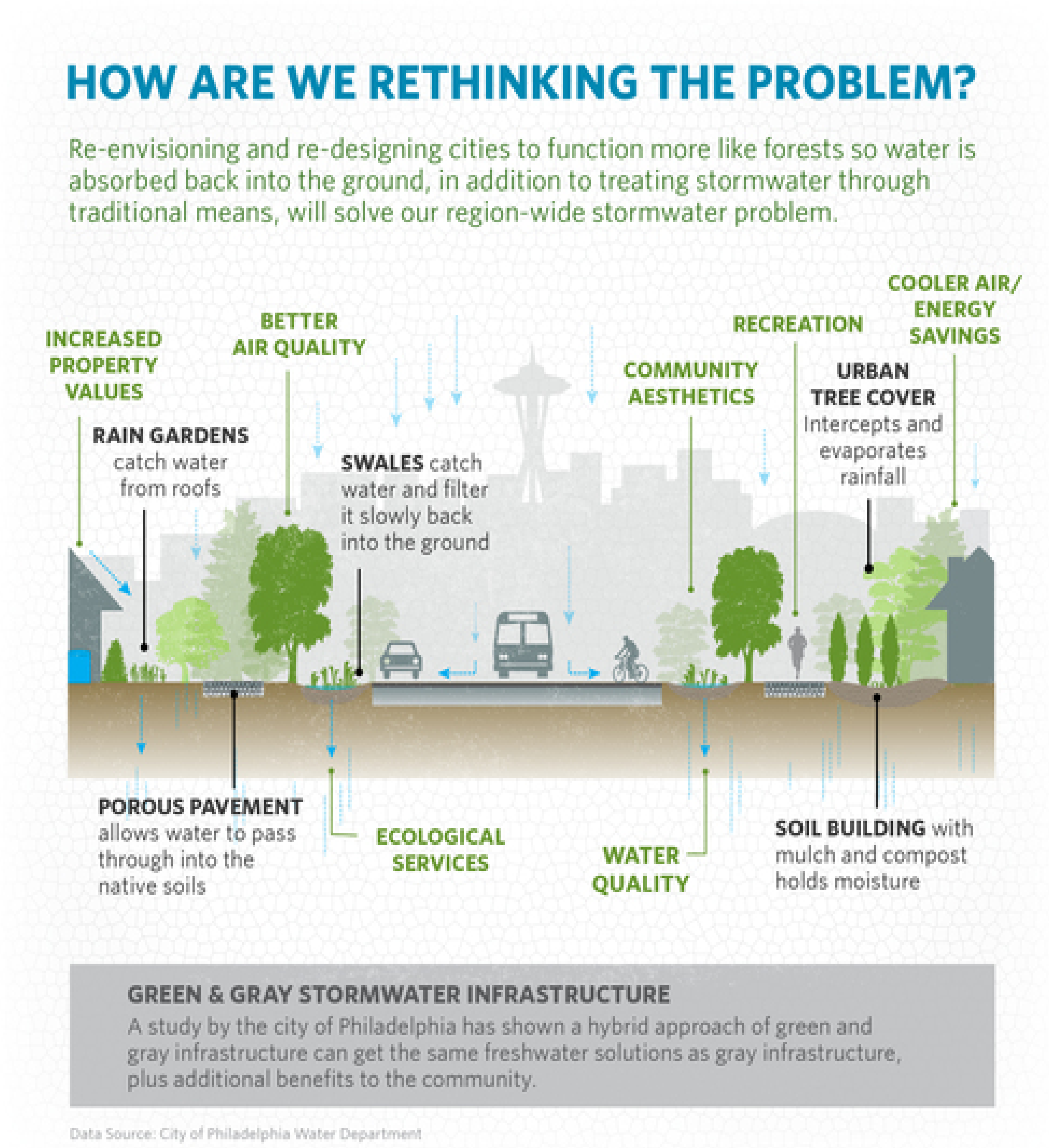

Figure 17. Green stormwater systems that mimic the natural hydrology of the landscape provide benefits to hydrologic systems, but also offer additional community benefits.

Strategies – Stormwater

Stormwater systems are often highly engineered to accommodate the needs of the local environment. Historically these systems were designed simply to deliver water to waterways like streams. As scientists have observed the ecological impacts of stormwater, control measures have developed to increasingly rely on water retention systems like vaults and stormwater ponds. These engineered systemic elements can significantly ameliorate the impacts of stormwater. They can decrease delivery volume and allow water to infiltrate through designed wetland-like systems, which allows biological communities and plants to clean the water, store sediment, decrease high flows, and increase infiltration to groundwater, improving hydrologic impacts.

Other stormwater control measures:

- Concentrate development of new land as much as possible to decrease footprint of impervious surfaces and stormwater systems.
- Prioritize development on land that has already been developed and retrofit green infrastructure.
- Decrease impervious surfaces and use permeable materials as much as possible (e.g. permeable pavement, green roofs).
- Engineer stormwater systems (e.g. rain gardens) to behave as more natural systems, storing water, increasing infiltration into ground water, and reducing direct flows to streams and rivers.
- Capture stormwater runoff to prevent the transport of pollutants and toxic contaminants to streams and rivers.
- Identify the source of coho mortality and stop it, either through system design or regulation of toxic substances.

Sedimentation –

Changes in winter precipitation and hydrology is expected to increase sedimentation of river systems as the climate changes. These changes will increase soil saturation and landslide potential, as well as erosion, flooding and associated sediment transport. Increased sediment loads will increase sediment deposition in low gradient reaches of streams and rivers. Suspended fine sediment in the water column is detrimental to juvenile and adult salmon. It can clog and erode gills and interfere with hunting, particularly for juveniles. Sediment transport can also bury salmon reds and eggs, suffocating them.

Image: Oso landslide

Strategies – Sedimentation

Sedimentation risks are associated with hydrology, particularly winter hydrology, as well as bank conditions, riparian vegetation, and hillslope vegetation. Strategies to reduce sedimentation risks including decreasing impacts from winter hydrology and restoring natural floodplain processes along banks with native riparian vegetation, and restoring upland forests along hillslopes, particularly those with high landslide risks. Restoring upland forests is also a strategy for ameliorating hydrologic impacts generally.

- Restore and protect natural winter hydrology.
- Restore and protect floodplain processes and bank vegetation.
- Restore and protect upland forests to improve general hydrologic patterns, especially on hillslopes prone to landslides.

RISKS - Saltwater

Salmon spend most of their lives in salt water. From the moment they move downstream to the estuary and Puget Sound as juveniles, they are exposed to the marine environment. Many salmon rear in estuaries to grow quickly as they feed on the abundant food webs in these productive ecosystems. Once salmon leave the river system they move through the marine environment, often near the shore. Beaches and nearshore habitats provide refuge from predators and a dynamic productive environment with abundant food to continue growth. Some salmon may remain residents within the Puget Sound and Salish Sea, but most will continue westward to the Pacific Ocean.

Once salmon enter the Pacific Ocean, they can distribute widely across an enormous range, depending on age and species. The Pacific Ocean is a vast and dynamic environment that both is affected by global climate change, and affects regional climate in the Pacific Northwest**.** This ecosystem supports Chinook to grow to massive sizes, sometimes historically over 100 pounds – very large fish for their age. These size fish were common in historic fish runs but are exceedingly rare today. Their prolific growth in just a few years is fueled by the productive ocean ecosystem and allows salmon, particularly Chinook salmon to carry many thousands of eggs and produce many offspring when they spawn. Chinook today are smaller, due to selective fishing that targets large fish, and more recently potentially due to shifts in saltwater and ocean conditions do not allow them to grow as large.

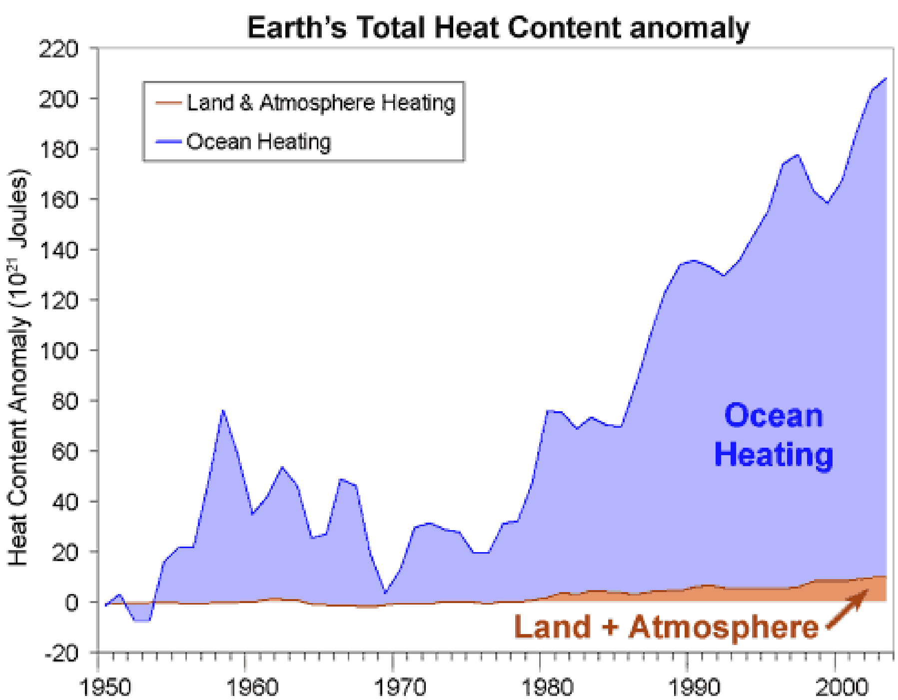

Figure 18. Most of the Energy of the biosphere is absorbed by the atmosphere. This graph shows the relative heat anomalies (from historic average) in the ocean and land + atmosphere. Increased heat in the ocean affects weather and climate, as well as sea level rise (via thermal expansion), and ocean ecosystems (phytoplankton, zooplankton, and food chains including salmon). Murphy et al. 2009

The ocean and marine ecosystem play an important role in climate change. The ocean is affected by a changing atmosphere, but it also affects climate patterns at global scales, from carbon storage, to sea level rise, to ocean currents, pressure systems, and the jet stream. It is difficult to predict exactly how the ocean ecosystem will change but we can predict how likely changes will affect salmon.

Sea Level Rise

Sea levels around the Puget sound have risen by about 8 inches since 1900 (NRC, 2012; figure 19). As the climate changes sea level rise is expected to accelerate. Predicting future sea level rise is a complicated, probabilistic science. Due to uncertainty in the rate that the Greenland and Antarctic ice will melt, predictions of sea level rise are highly variable.

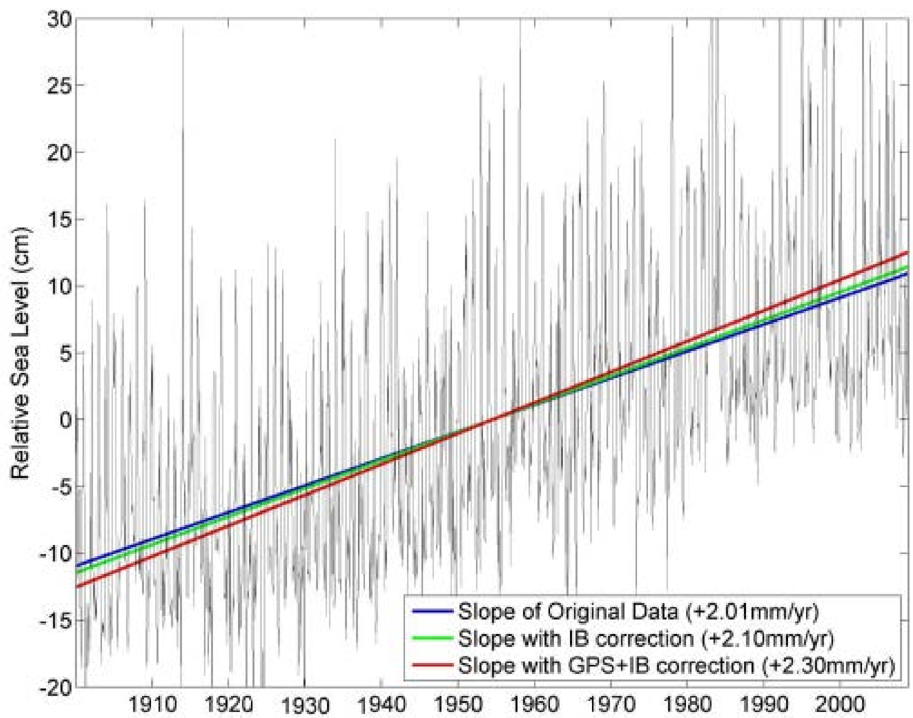

Figure 19. Historic (1900-2008) monthly sea level rise for Seattle, Wa. We have observed roughly 8 inches (20 cm) of se level rise since 1900. The "relative sea level" is relative to the average sea level (zero) of the period in question.

We discuss Sea level rise projections in terms of the probability of exceeding a certain elevation. The most recent projections for Washington State suggest, at the current rate of greenhouse gas emissions (high), there is a 50% chance of exceeding 2ft of sea level rise by 2100 (Miller et al. 2018). There is an 83% chance of exceeding 1.4 ft and a 10% chance of exceeding 3.1ft (Table 1). Recent research has led to an increase in high-end projections, and it is possible future research will do the same (Kopp et al. 2014).

Table 2. Absolute sea level rise projections, in feet, for Washington State. Projections are expressed in terms of the "probability of exceedance" for three different time periods (2050, 2100, 2150) and two different greenhouse gas Scenarios (RCP 4.5 [low], and RCP 8.5 [high]). Projected changes are assessed relative to contemporary sea level, defined as the average sea level over the 19-year period from 1991-2009. Projections

for 2050 and 2100 under the high greenhouse gas scenario (RCP 8.5 – highlighted below) are also shown in Figure 20 below (Miller et al. 2018).

PROJECTED ABSOLUTE SEA LEVEL CHANGE
(feet, averaged over each 19-year time period)

Time Period	Greenhouse Gas Scenario	Central Estimate (50%)	Likely[5] Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
				10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
2050 (2040-2059)	Low	0.6	0.4 - 0.8	0.9	1.2	1.8
	High	0.7	0.5 - 0.9	1.0	1.3	2.0
2100 (2090-2109)	Low	1.6	1.0 – 2.2	2.5	4.1	7.2
	High	2.0	1.4 - 2.8	3.1	4.8	8.3
2150 (2140-2159)	Low	2.5	1.5 - 3.8	4.4	8.5	16.2
	High	3.4	2.3 - 4.9	5.6	10.0	18.3

The higher the elevation in question, the lower the likelihood. For instance, there is a 1% probability of exceeding 4.8 ft by 2100. These are estimates for *absolute* sea level rise (Figure 20). This is the height of the ocean relative to a fixed reference point. However, the earth's crust is not a fixed reference point. Complex geologic processes cause the land to rise and fall over time relative to the ocean. Even within Washington State these processes result in significant variability in sea level rise between different locations. In most of Puget Sound, the land is subsiding, which *increases* sea level rise. On much of the peninsula, the land is uplifting, decreasing the effect of sea level rise. For the Snohomish River delta, elevations with equivalent probabilities are about 0.2ft higher than the absolute sea level. Here, near the Tulalip Reservation, there is a 50% chance of exceeding 2.2ft by 2100 (Miller et al. 2018**,** Figure 21).

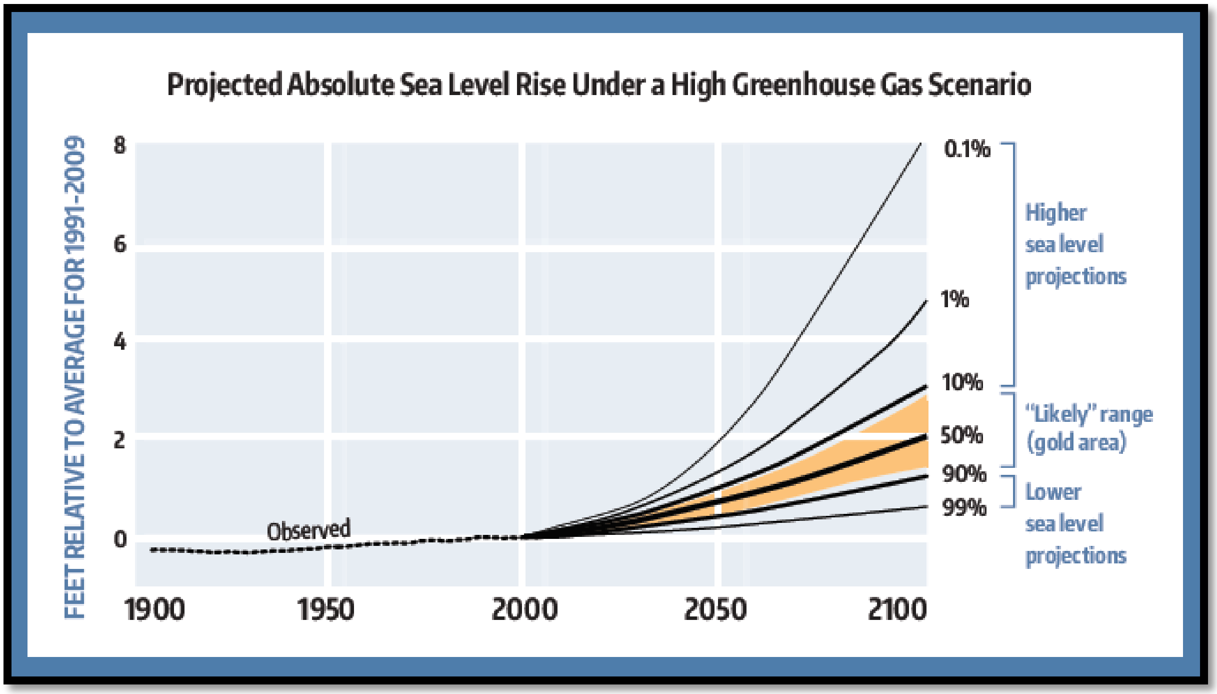

Figure 20. Probabilistic sea level rise predictions. (Miller et al. 2018)

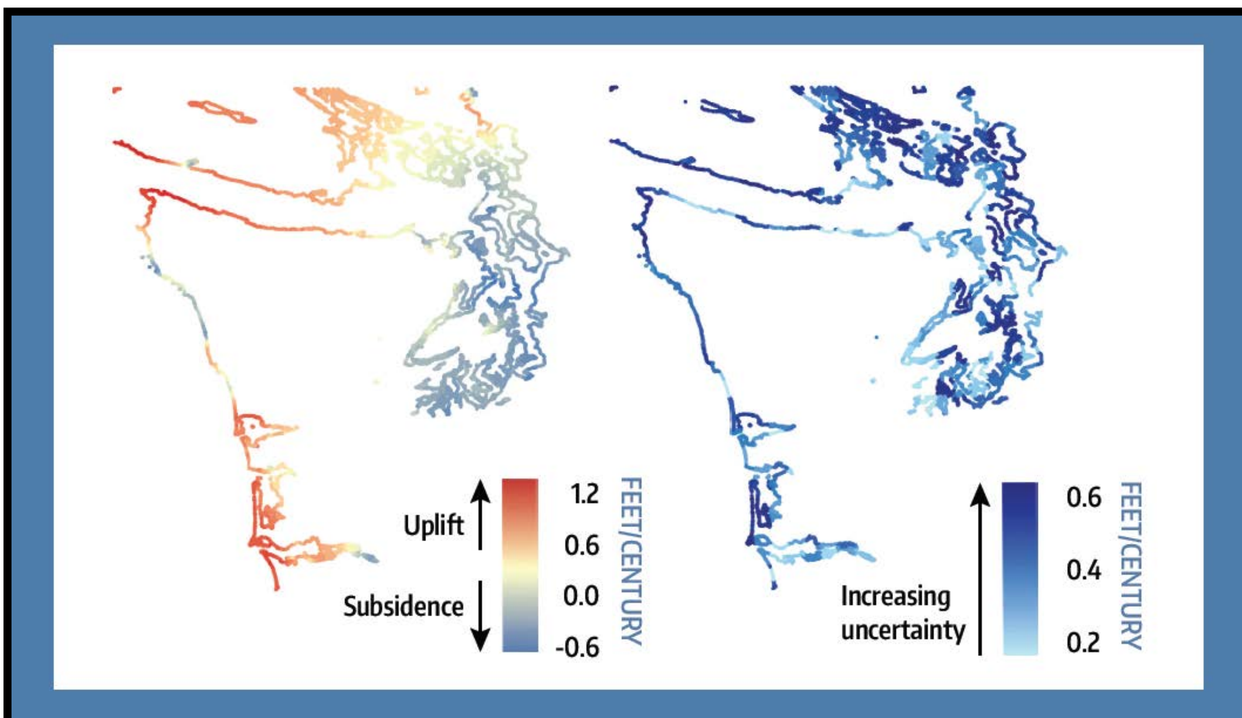

Figure 21. Vertical land movement best estimate rates (left) expressed in feet per century and their uncertainties (1 standard deviation, right) as estimated for Washington's coastline (Miller et al. 2018).

Sea level rise has major implications for the human population, which has built cities along the shores of the Puget Sound. Effects on salmon are less direct, but they are significant and many are associated with human responses to sea level rise. Like flooding, the usual human responses to sea level rise are bad for salmon. The typical response is to armor beaches and waterfronts with sea walls to prevent erosion and direct wave energy away from the shore and the toes of bluffs. These approaches squeeze nearshore habitat for salmon and other prey species they depend on the beach between rising seas and armored shorelines (Figure 22).

Directing energy back toward the water with sea walls decreases bluff erosion and starves beaches of the sediments needed to maintain healthy beach substrates. Armored beaches also create a high-energy environment that can erode the beach face harm juvenile fish and diminish a vital refuge juvenile fish depend on during their growth and migration to deeper marine waters.

Beaches are also important ecosystems that support the marine food web. Small forage fish that young salmon feed on also require the proper substrates and beach conditions to reproduce. One aspect of salmon recovery involves the nourishment of beaches and the removal of armoring to naturalize beach habitats so they can support juvenile salmon and the forage fish they depend on later in life. Sea level rise will increase the need to restore beach processes. This will be an important conflict in the coming century if we are to recover salmon and the ecosystems of the Salish Sea in general.

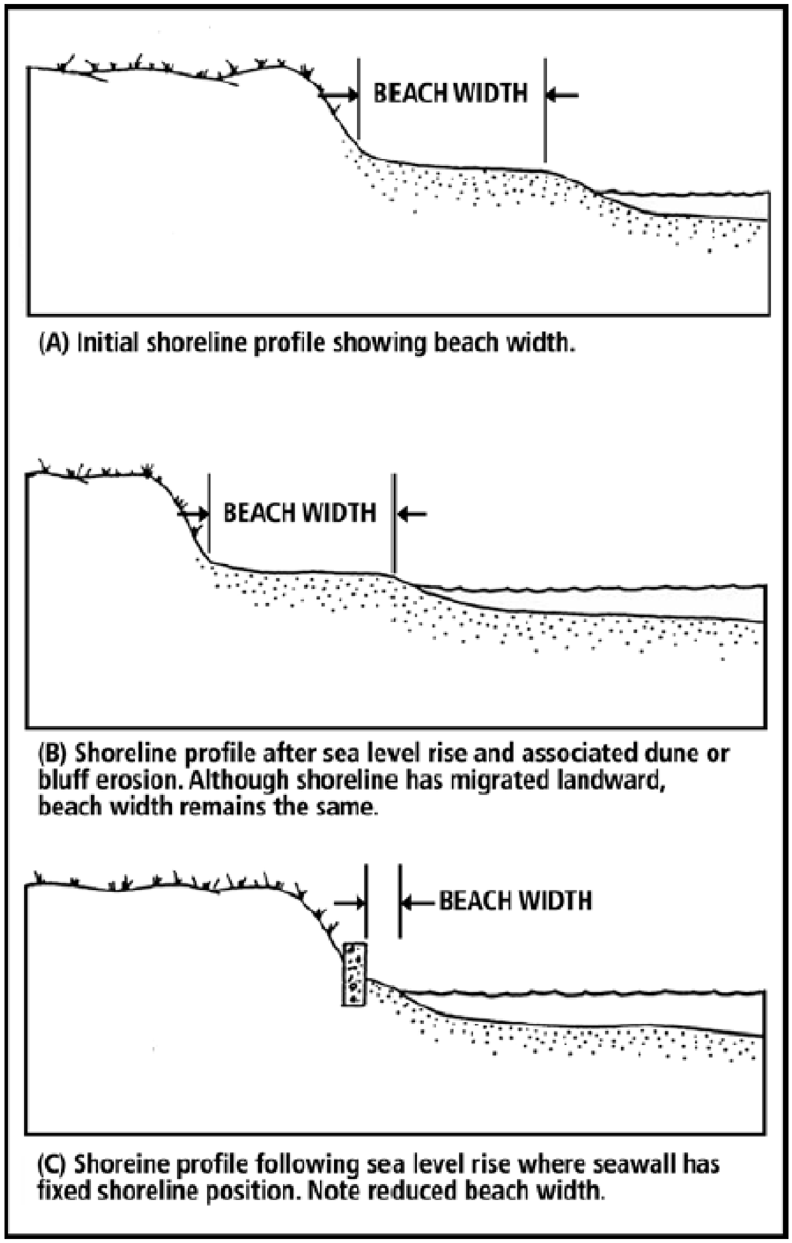

Figure 22. Examples of passive erosion including natural beach migration (B) and Beach squeeze (C).

Similar to beaches, as the sea level rises, if estuaries do not have room to move to higher elevations in river systems, they will be squeezed between rising seas and the levees that protect land upstream. Estuary habitats are vital for salmon survival and estuarine habitat is already 70-90% smaller than it was historically (Figure 23). Restoring estuaries, removing levees, and expanding estuarine habitat in the higher estuaries will be important to accommodate sea level rise and adapt to climate change. Furthermore, many of these lower estuarine habitats were converted to farmland. As the sea level rises, and groundwater in low elevation farmlands in historic estuaries rise with it, farmland will become far less productive, and should be targeted for restoration.

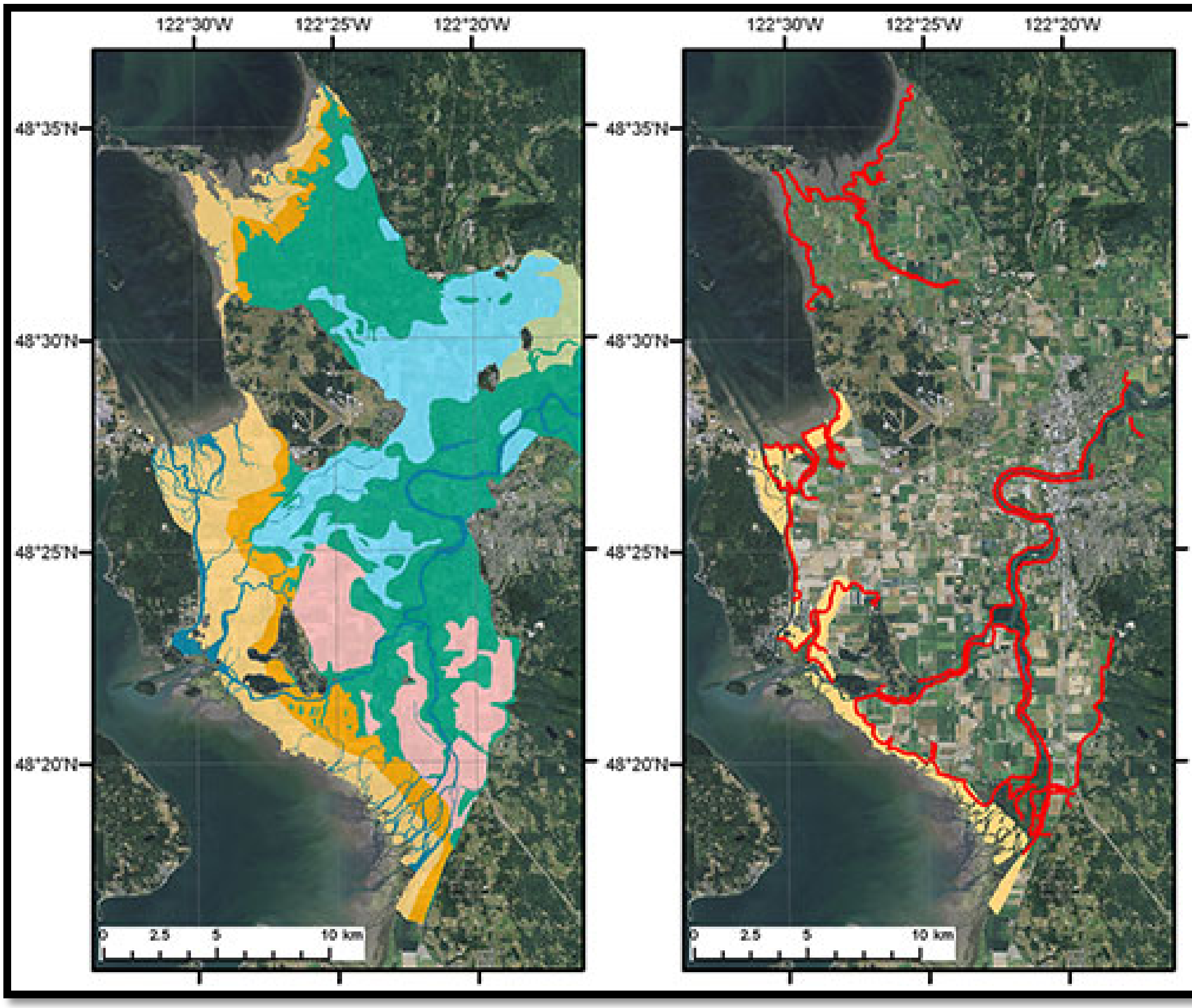

Figure 23. Aerial photograph of the Skagit River delta, in the Puget Sound area of Washington, illustrating changes between 1850 (left) and 2010 (right). In 1850 the delta included extensive wetlands providing important habitat for salmon spawning (orange). By 2010 most of the delta had been "reclaimed" for development by a system of dikes and levees (red), greatly reducing the habitat available to salmon. Left: courtesy of Brian Collins, University of Washington. Right: Eric Grossman, USGS. (https://walrus.wr.usgs.gov/climate-change/lowNRG.html)

Strategies – Sea level rise

Sea level rise primarily affects salmon by threatening to reduce habitat in estuaries, and adjacent to beaches and nearshore habitats. Because the Puget Sound is extensively developed by humans, especially along the shoreline, as sea levels rise, the already limited existing habitats in these areas will be squeezed between rising seas and human desires to maintain property. In an undeveloped landscape, the habitats would shift upslope with sea level rise. Strategies usually involve getting people off land and upslope away from the lands that will be affected by sea level rise to make space for habitats to shift

- Restore estuaries, especially mid to high elevation estuaries to allow for estuary gradients to shift upland.

- Reduce shoreline armoring and move lowland infrastructure away from beaches and bluff faces where possible. In some cases complete removal may be necessary.
- Disincentivize building sea wall and armoring to protect habitat.
- Restore beaches and reconnect the near shore to bluffs to restore and protect natural sediment sources and beach maintenance.

Ocean Conditions

There are a few large scale climate cycles that naturally influence ocean conditions in the North Pacific, including the Pacific Decadal Oscillation (PDO), the North Pacific Gyre Oscillation (NPGO), and the El Nino Southern Oscillation (ENSO). These interacting and overlapping oscillations in water temperature and pressure systems influence ocean currents, air and water temperatures, plankton assemblages and distributions, upwelling patterns, and marine survival rates of salmon. PDO, referred to as having warm and cold years, is correlated with salmon survival (Mantua et al. 1997; Figure 24).

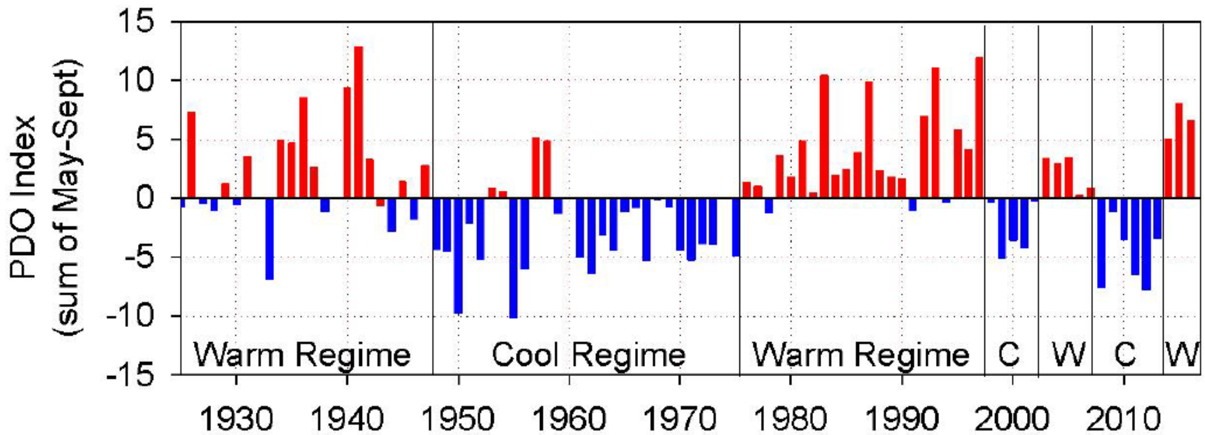

Figure 24. Pacific Decadal Oscillation (PDO), 1925-present. Blue bars represent cold years, red bars represent warm years.

Understanding ocean conditions is exceedingly complicated due to the vast numbers of interacting climatic and ecological cycles, and our lack of data describing such a vast ecosystem. We know that ocean conditions have profound impacts on marine survival, or the number of fish that survive the ocean to return to rivers. In some years, marine survival is much better than others, and salmon runs are better. We are not very good at prediction when marine survival is poor, but we are getting better, and are using more conservative estimates to ensure populations are not overharvested . Generally, as the atmosphere warms, the ocean will warm with it. A warmer north Pacific, like what was observed in 2015 during “The Blob,” will result in a significant increase in marine mortality. Along with other factors associated with warm water conditions, such as upwelling and plankton communities, these changes will challenge the survival of salmon populations (Figure 25).

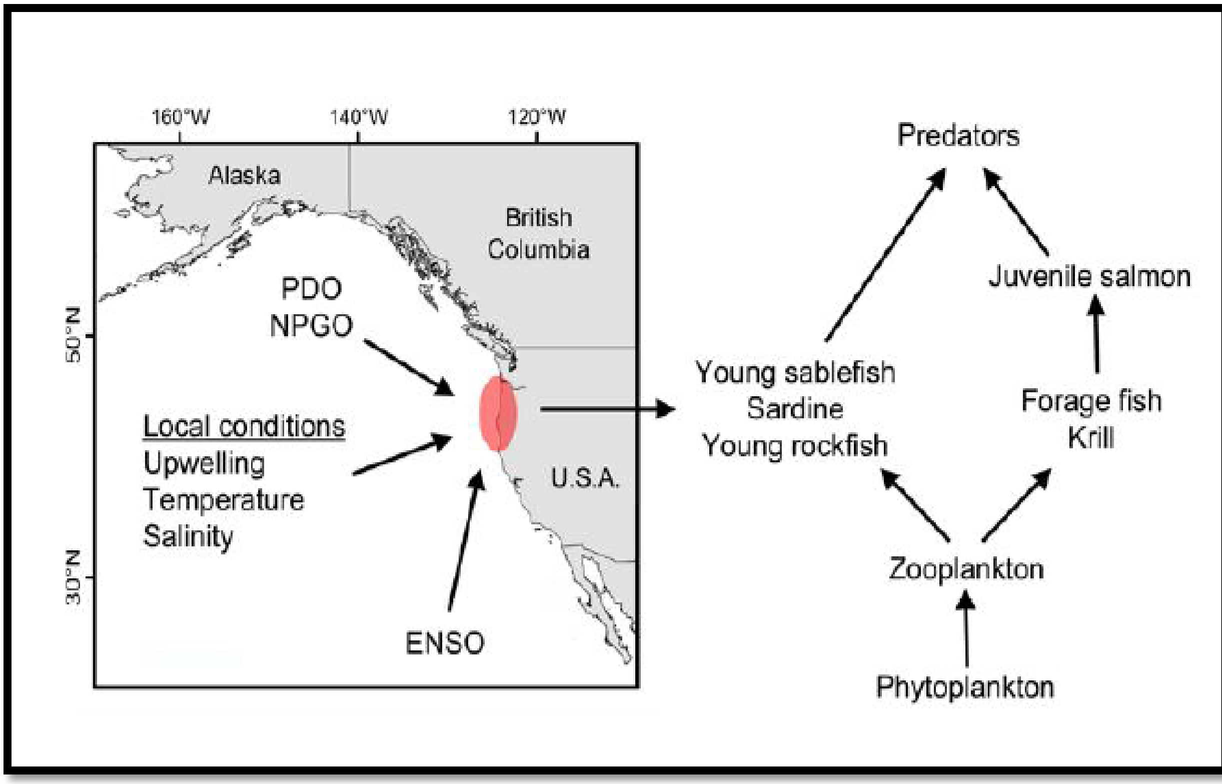

Figure 25. Illustration of how basin-scale and local-scale physical forces influence the northern California Current and resultant food web structure. PDO = Pacific Decadal Oscillation. NPGO = North Pacific Gyre Oscillation. ENSO = El Nino-Southern Oscillation (Peterson et al., 2015)

Strategies – ocean conditions

It is clear that PDO cycles affect salmon survival. However, the impacts of climate change on the natural variations that determine ocean conditions are not known, and the effect of ocean conditions on salmon is not well understood. While there are informative correlations between survival and ecosystem indicators, changes in any indicator can confound relationships between others. The ways in which salmon are impacted will depend on their life stage while in the ocean ecosystem, how long they spend in the ocean, and other ocean variables like plankton communities. Further study is important to understand how climate change will affect salmon, and is likely already doing so. There are few direct actions we can take to influence ocean conditions, but continuing to better measure and understand what is happening in the ocean and how that affects salmon survival is extremely important. Our effects on the atmosphere are likely to have profound impacts on the ocean food web, so anticipating those changes and responding to them now instead of once they are observed is important. As with all threats from climate change, the most effective solution is to stop it from happening.

- Increase study of ocean conditions to better understand patterns and their impact.
- Stop carbon emissions and climate change.
- Increase global carbon storage and carbon sinks.
- Restore estuaries, important carbon sinks associated with salmon survival.

Ocean Acidification

Gases in the atmosphere exchange between the air and the water in the ocean. They are at an equilibrium state where gas enters water and off gases to the atmosphere. However, as the atmospheric concentration of carbon dioxide (CO_2), increases more carbon dioxide absorbs into the ocean. Due to this process, the CO_2 concentration in ocean and marine waters projected to increase 150-200% by 2100 based on current CO_2 emission scenarios (TNC, 2016).

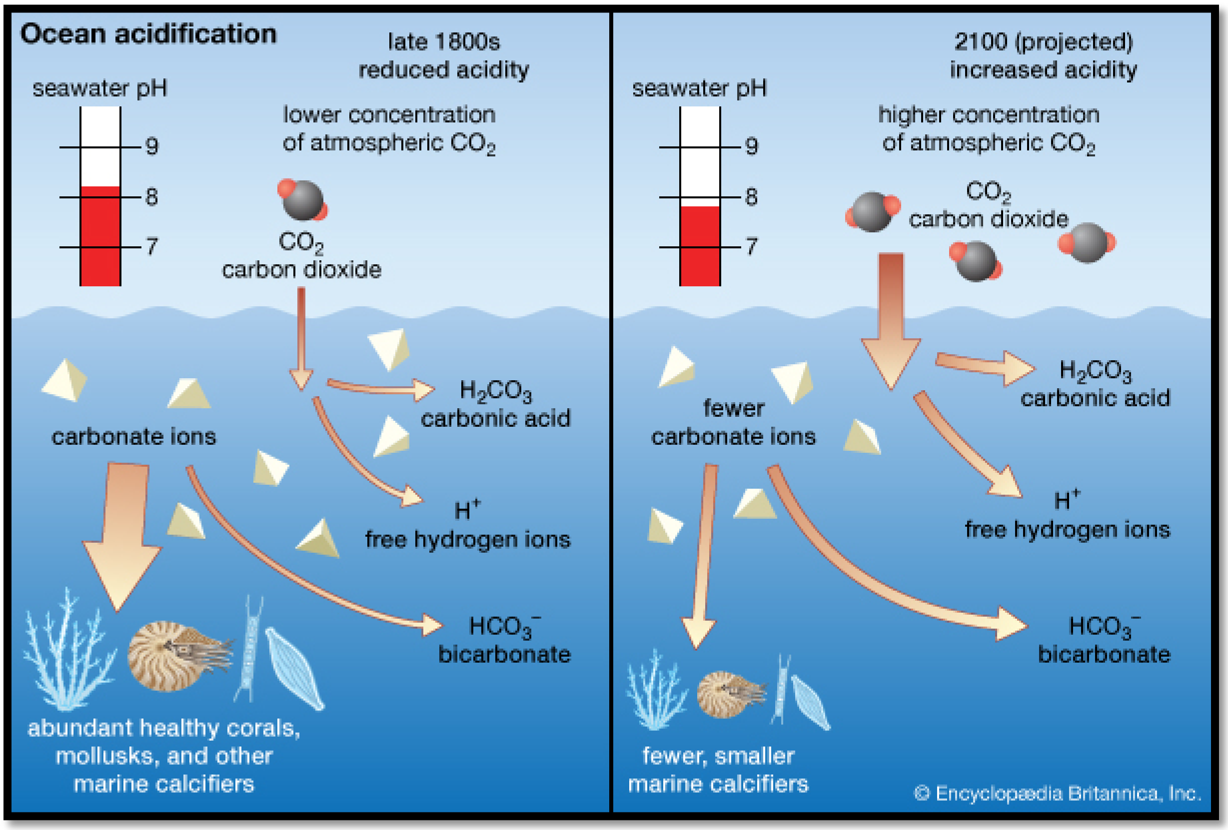

Figure 26. Conceptual diagram comparing the state of carbonate ions in the ocean under the lower-acid conditions of the late 1800s and the higher acid conditions expected in 2100 (https://www.britannica.com/story/ocean-acidification-how-carbon-dioxide-is-hurting-the-seas)

As the ocean acidifies, marine species that form calcium-based shells (like shellfish) are directly impacted because more acidic conditions inhibit the formation of shell and actually can dissolve it. These species are not just clams and oysters, which are vital to the marine food web, but also species in the water column, such as plankton and juvenile crab, which are important food sources for juvenile salmon, as well as forage fish adults depend on. As the ocean acidifies and populations of these important elements of the ocean food web are challenged, it will change food availability for salmon during their smolt and ocean life cycle phases. For instance, acidification will reduce the availability of crab larvae, an important food source for juvenile salmonids and the forage fish adult salmonids depend on. The role affected species play in supporting Puget Sound salmon, and the entire food web in general raises significant concerns about how acidification could affect the entire Puget Sound and ocean food web as the climate changes (Ecology, 2012).

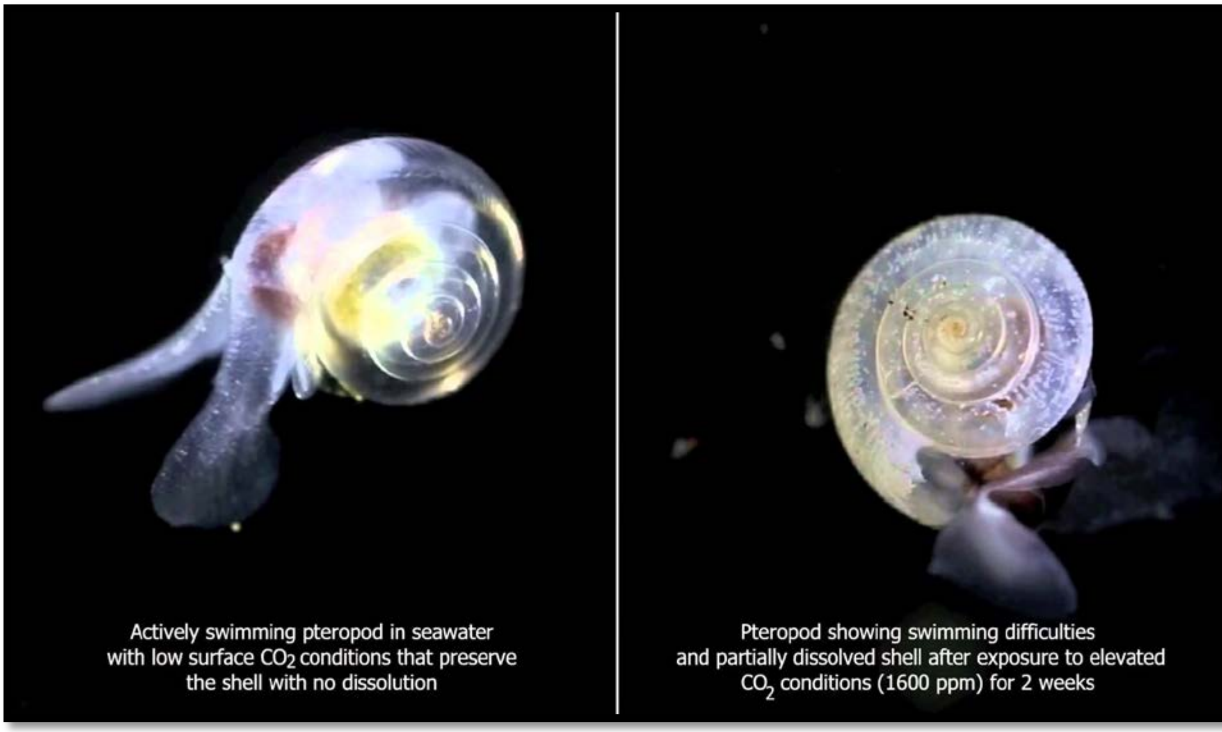

Image: This video shows the difference in swimming behavior and shell dissolution between a pteropod in seawater with low surface CO2 conditions and that of a pteropod exposed to elevated CO2 conditions (https://www.pmel.noaa.gov/co2/story/Ocean+Acidification).

Strategies – Ocean Acidification

Ocean acidification will result in major shifts in marine and ocean food webs. The exact nature of these changes in such a complex system is not known, and effects on salmon are difficult to quantify, but major perturbations in food webs invariably challenge populations of predators at the top of the food chain. Because ocean acidification is a passive effect of increased carbon dioxide in the atmosphere, the only effective way to stop it is to decrease atmospheric carbon dioxide concentrations by lowering emissions and increasing carbon uptake into biotic carbon sinks.

- Increase study of ocean conditions to better understand patterns and their impact.
- Stop carbon emissions and climate change.
- Increase global carbon storage and carbon sinks.
- Restore estuaries, important carbon sinks associated with salmon survival.

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