Appendix D:

WRIA 9 Climate Change Impacts on Salmon

ROGER TABOR

WRIA 9 Climate Change Impacts on Salmon

Technical briefing for the update to the WRIA 9 Salmon Habitat Plan. Authored by Jessica Engel, Kollin Higgins and Elissa Ostergaard with input by the WRIA 9 Implementation Technical Committee. July 2017

Introduction

In the twelve years since the adoption of the 2005 Green/Duwamish and Central Puget Sound Watershed Salmon Habitat Plan (Plan), there have been many successes and challenges for the salmon recovery effort in our local watershed, and the greater Puget Sound. With each recovery project planned and implemented, we understand more about the complexity of this undertaking. One of the most pressing environmental concerns affecting the long-term success of salmon recovery in the Green/Duwamish Watershed is the impacts of climate change. Climate change science was not incorporated into the 2005 Plan, because future climate scenarios were unclear. However, climate change has been the focus of intense research, both global and regional, over the last decades. The research from the Puget Sound region, especially from the University of Washington's Climate Impact Group (CIG), has been informative. The clear message from this research is that we must prepare for the current and future impacts of climate change and incorporate what we know about climate change into salmon recovery actions.

Climate change will directly impact salmon recovery work done in the Green/Duwamish and Central Puget Sound watershed. CIG and others predict that Pacific Northwest precipitation patterns will change, bringing warmer, wetter falls, winters, and springs. Floods will be more intense and more frequent. As winters become warmer and wetter, snow will melt from the mountains earlier and more quickly. The decrease in amount and earlier disappearance of the snow pack will exacerbate drought-like summer low flow conditions in currently snow-dominated areas of the watershed. Hotter air temperatures will increase water temperature in both rivers and the ocean. Nearshore and estuary areas will be impacted by sea level rise, food web alteration and ocean acidification. A changing climate will exacerbate typical climate variability causing environmental conditions that will negatively impact our salmonids and their habitat. This was observed in summer of 2015 when a warm, wet winter with extreme low snow pack levels, coupled with a dry, hot summer, created dire conditions for salmon (DeGasperi 2017). The Muckleshoot Indian Tribe reported adult Chinook salmon dying in the stream just below the Soos Creek hatchery (H. Coccoli, pers. comm.), and Washington Department of Fish and Wildlife data indicated higher than typical numbers of female Chinook with high egg retention (pre-spawn mortality) (Draft WDFW data 2017) . The true impact of 2015 will not be understood for several years. We do know that impacts from climate change are occurring, will continue and get worse, and will affect all life stages of Pacific salmon (Mauger et al. 2015).

While we know the climate is changing, the magnitude and precise timing of those changes are less certain. This issue briefing is for planners, citizens, policy makers and restoration practitioners involved in salmon recovery to understand the expected impacts and help prioritize restoration and protection actions that will help mitigate the effects of climate change. For this paper, we rely on the science in the CIG State of Knowledge report, which predicts climate change impacts into mid-century. This document is intended to highlight the best available

science about climate change and the ways salmon and their habitat will be impacted in the Green/Duwamish and Central Puget Sound watershed. The key actions from this report are recommendations for restoration priorities that build resilience for salmon as well as the larger ecosystem, rather than a list of specific prioritized habitat restoration projects. References to the relevant literature are included; readers may refer to those for more information on topics of interest.

Climate variability, expected changes, and impacts to salmon

The Puget Sound's diverse landscape and climate have driven adaptation and biodiversity in our local flora and fauna. The Pacific Northwest climate naturally varies seasonally as well as year to year between cool and hot, wet and dry. We are familiar with the natural variability in our atmospheric weather and oceanic patterns, but ocean conditions also vary on inter-annual and decadal scales. Year to year variability is generally associated with the familiar El Niño Southern Oscillation (ENSO) which affects ocean temperatures as well as global precipitation and temperature. Longer term decadal patterns are often described by the Pacific Decadal Oscillation (PDO; see section 6 for more information), a pattern defined by variations in sea surface temperatures in the North Pacific (NWFSC, NOAA https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/ca-pdo.cfm).

The Puget Sound region is already experiencing some of the ways climate change will exacerbate and prolong naturally occurring stressful environmental conditions. The rate of current greenhouse gas emissions will make these extreme conditions more common in coming decades. We have already seen higher than normal air temperatures; by mid-century, annual average air temperatures are projected to rise between 2.3 and 3.3 degrees Celsius (C) (4.2 – 5.9 degrees Fahrenheit), exacerbating surface water warming. Models used to inform the Climate Impact Group's State of the Knowledge Report show a decline in summer precipitation and increases in precipitation during fall, winter and spring. The region's snowpack is expected to decrease with warmer, wetter winters. The decline in snow pack has been observed through the National Resource Conservation Service (NRCS) snow telemetry monitoring (SNOTEL). In 2015, the water derived from snow melt was recorded well below the 30 year median from December to July. However, the data from NRCS show that overall precipitation in the Green/Duwamish watershed was average in 2015, indicating that in this year precipitation shifted from snow to rain (www.wcc.nrcs.usda.gov/snow/) (Figure 1). The data from NRCS and other sources show that typical snow-dominated elevations are shifting to more rain and less snow, and that headwater areas typically dominated by rain-on-snow events will become rain-dominated. This suggests that our region will experience more precipitation as rain, less snow, more frequent and severe rain-driven flooding events, and more very low summer flows (Mauger et al. 2015).

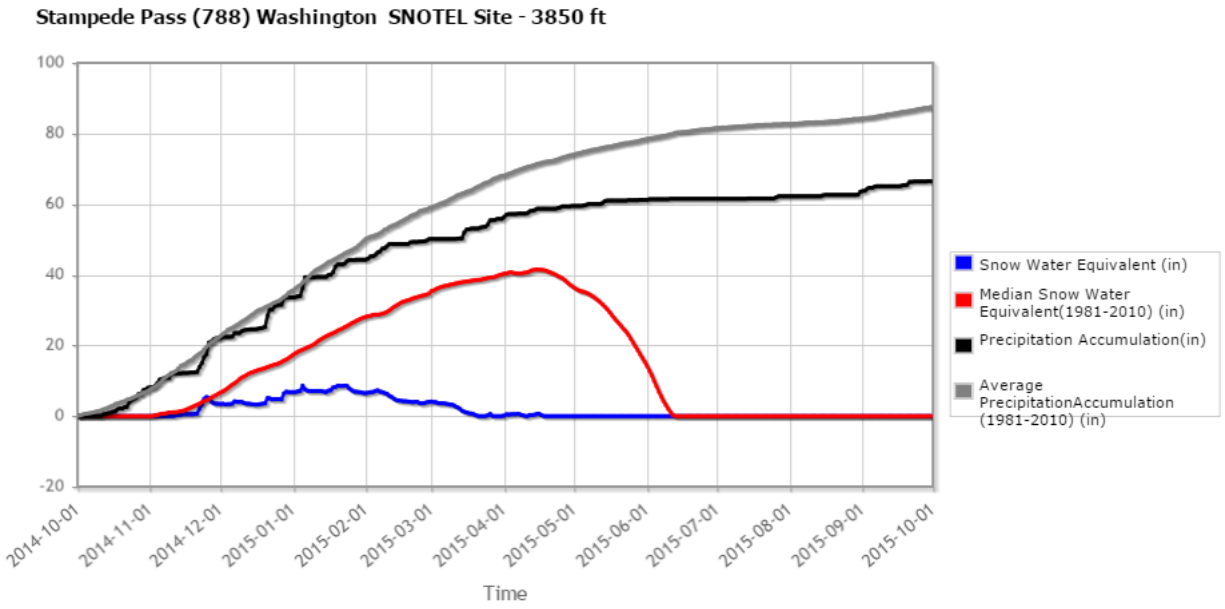

Figure 1. Plot of cumulative snow water equivalent and precipitation for 2015 water year at the Stamped Pass SNOTEL site compared to historic data (from King County 2017

Climate change will challenge the survival of salmon in our watershed. Pacific Northwest salmon populations have declined dramatically over the last several decades, and climate change impacts are expected to further degrade salmon numbers in the years ahead, affecting salmon life histories, feeding, migration, growth, and health. Thus it is urgent that we implement projects and policies that restore and protect areas to improve our basin's hydrologic patterns and habitat functions that support salmon in their various life stages. Salmon recovery advocates in the basin must implement restoration and protection actions that remain successful under a changing climate. Climate effects should influence the way WRIA 9 partners approach recovery now and in the future.

Projected climate changes and their impacts to salmon are summarized in Figure 2, which shows the anticipated timing of climate impacts seasonally and their effects on the associated salmonid life stages in fresh water and estuarine areas. Table 1 shows each climate impact's effects on salmon - as well as the primary areas of the basin where each effect will be felt. Together, the table and figure can be used to understand, in brief, how and where projected climate impacts will affect salmon in the Green/Duwamish and Central Puget Sound watershed.

Climate Change Impacts on WRIA 9 Salmonids

Adapted from Beechie et al. (2012). Fish timing represents typical fish behavior.

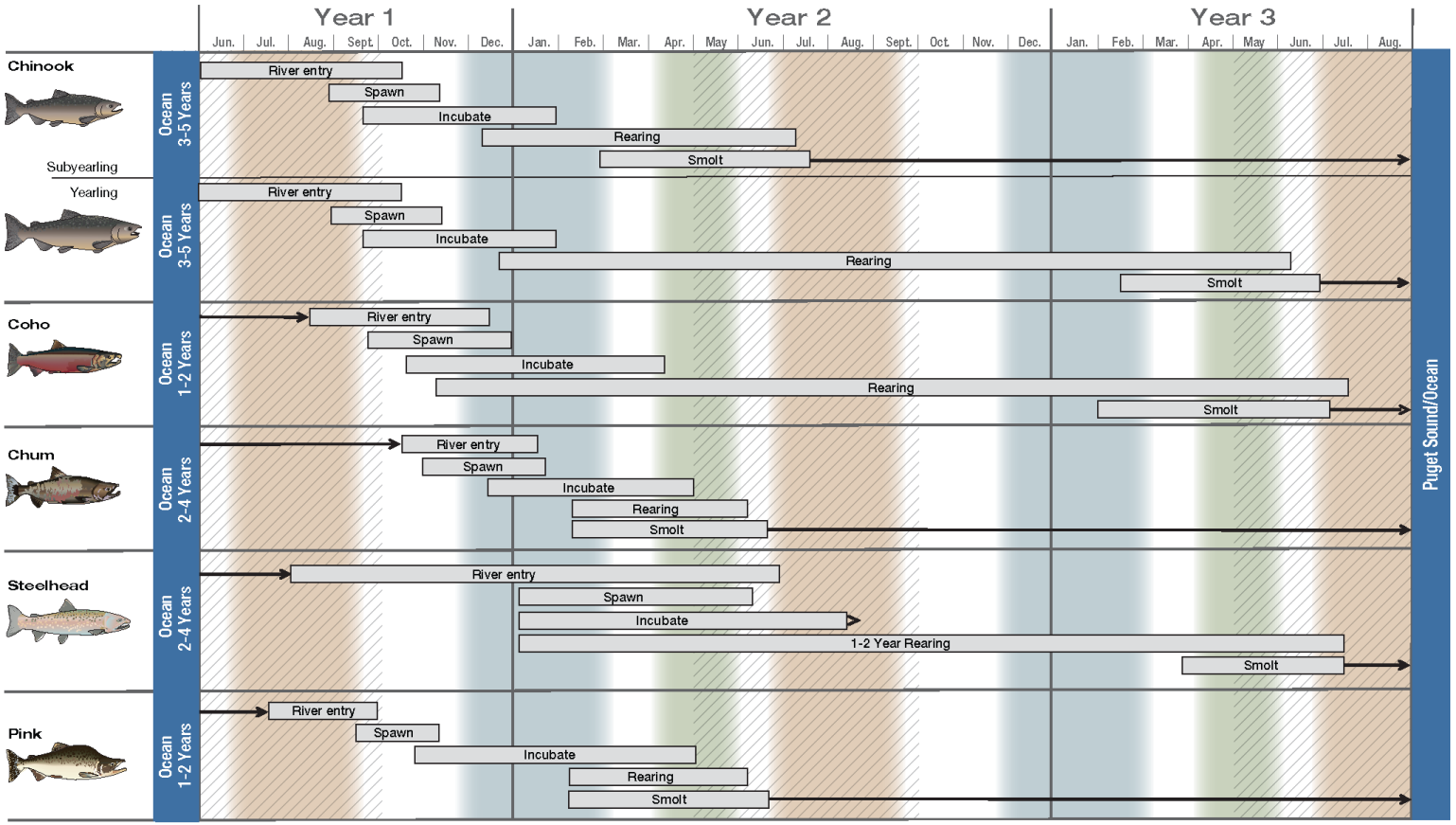

Figure 2. Salmonid life stages and impacts of climate change (adapted from Beechie et al., 2012.)

Table 1. Anticipated climate effects, impacts to salmon and critical geographic areas of occurrence.

Climate impact	Salmon impact	Primary geographic area
Hydrology	Shifting timing of life cycle transitions; scouring/smothering redds; stranding redds and juveniles; loss of thermal and flood refugia; less complex habitat; migration barriers due to extreme low and/or high flows	Upper Green, tributaries and nearshore drainages, especially where it is currently snow-dominated in winter will have the greatest impacts – Soos, Newaukum, Mill, Mullen creeks (and other lower elevation tributaries) will be impacted primarily by increased winter rain intensities and lower flows as they are not directly affected by mainstem flow management or snow. Impacts to the Middle and upper Lower Green spawning reaches may be somewhat mitigated by water management at the HHD.
Temperature	Can be lethal above 22 degrees C; sub-lethal effects above 17 C include developmental abnormalities, altered growth rates, non-fertilization of eggs; altered food web; altered migration timing; altered predator/prey relationship; reduced disease resistance	Temperature will be a concern for the whole watershed. However, the mainstem is generally warmer than the tributaries and will likely to remain so into the future.
Stormwater runoff	Increased peak flows and reduced summer base flows causing channel scour and incision, channel and habitat degradation for fish as well as benthic invertebrates, resulting in an altered food web, and compounding other hydrologic effects. Increased erosion could cause an increase in mobilized fine sediments, which in addition to degrading habitat for salmon by filling in gravels and smothering redds, may carry toxic contaminants. Increased water pollution may cause chemical contamination of juvenile salmon and their prey, food web alteration and pre-spawn mortality.	Existing developed areas generally do not meet today's stormwater control standards; runoff generally is directed quickly via pipes to streams and Puget Sound without treatment. Hydrologic effects are primarily to tributary streams and direct drainages to Puget Sound. Infiltration reduces pollutant concentrations and slows the flows into streams, reducing potentially harmful peak flows. Frequent, intense peak flows could result from a combination of increased urban density and more intense winter storms. Some toxic pollutants may increase due to increased storm runoff in combination with increases in population, particularly those that are detected year-round.
Sedimentation	Lethal conditions, smothering of interstitial spaces in redds and choking of gills; interference with migration cues; decreased resistance to disease; altered /decreased habitat	Upper Green, Middle Green
Sea level rise	Shifting habitat range; loss of estuarine habitat; altered food web; could create passive gains in habitat depending on	The Puget Sound nearshore and the Duwamish River. Lower lying areas and armored shorelines in the Central Puget Sound watershed nearshore

	nearby infrastructure constraints, elevation, and vegetation gradients	(West Point to Federal Way and Vashon-Maury Island) and Duwamish estuary are most at risk to habitat shifts/loss
Ocean acidification and increased temperature	Altered food webs; decreased food availability; decreased ocean survival; diminished dissolved oxygen affecting metabolism; altered migration pattern	Puget Sound, Salish Sea, and Pacific Ocean

Hydrology

Climate Impacts on Winter Hydrology

Stream flows in winter will be affected in the following ways:

- More winter precipitation will fall as rain and less as snow.
- Upper areas of the watershed will have less snowpack, which will change the runoff pattern dramatically. Instead of having moderate runoff events in winter and again in spring, there will be much more runoff in winter and much less in spring (Figure 4 and 4). This will affect water temperatures as well, especially in spring and early summer.
- More intense rainstorms in winter will cause higher winter peak flows.
- Winter peak flows are expected to increase by 28%-34% by the 2080s (Mauger et al. 2015).
- Average annual rainfall is projected to increase slightly (but the increase will be small relative to natural variability) (Mauger et al. 2015).

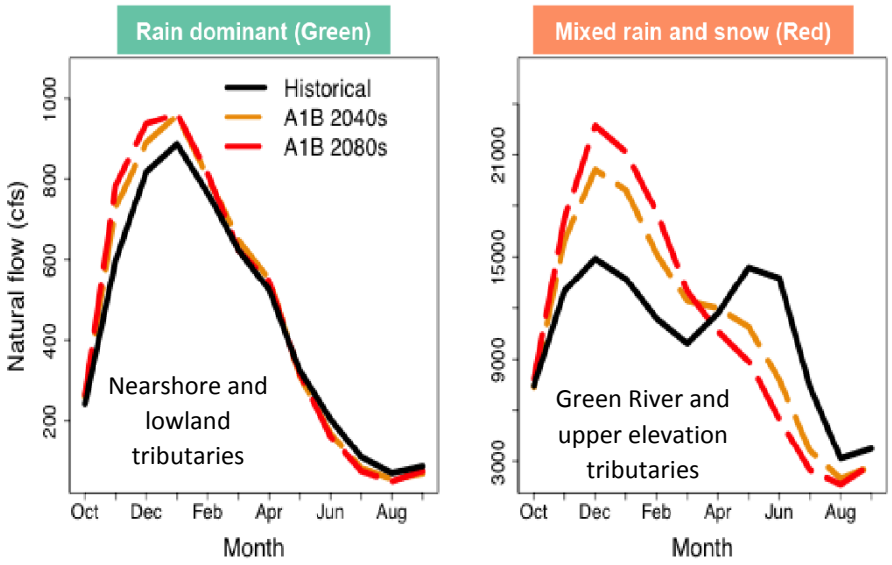

Figure 3. Streamflow is projected to increase in winter and decrease in spring and summer in all WRIA 9 drainages, with the biggest changes occurring in "mixed rain and snow" basins. Results are shown for a typical warm, lowland basin (left), and a typical upper elevation basin with substantial area near the current snow line. Adapted from Hamlet et al. (2013)

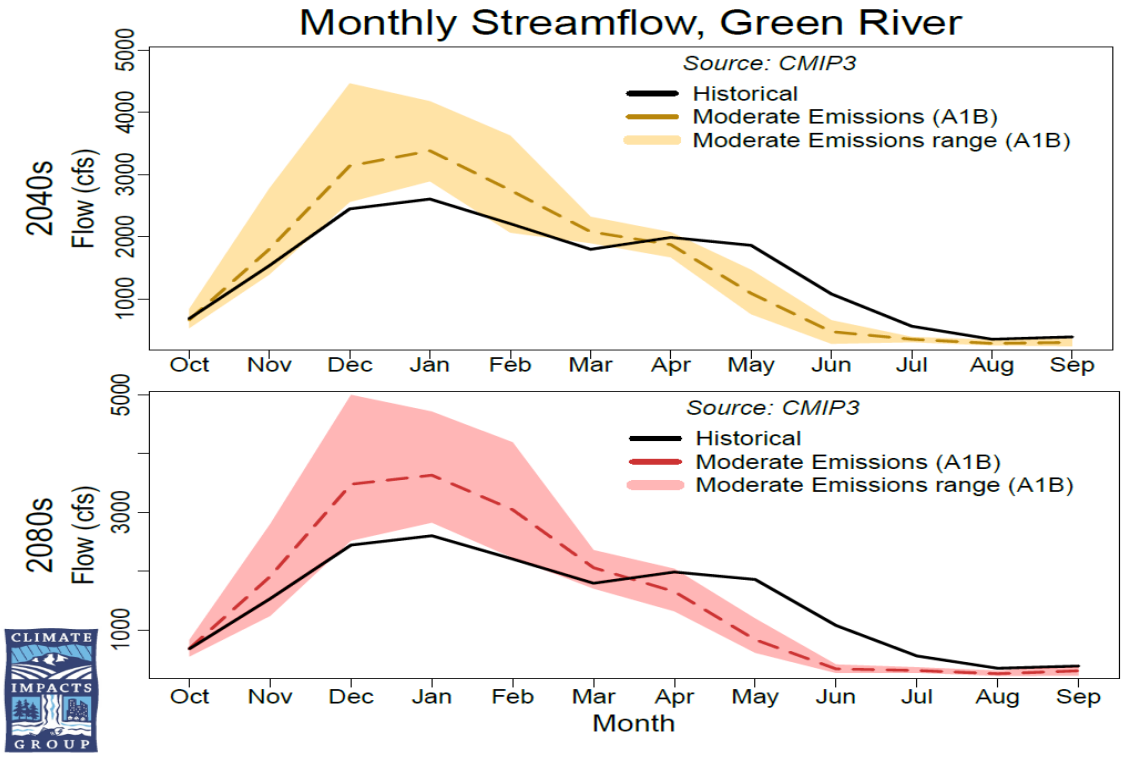

Figure 4. Less snow and more rain in winter is projected to cause higher peak stream flows in winter and less stream flow in spring. This pattern becomes more pronounced over time. Source: University of Washington Climate Impacts Group, PS State of Knowledge Report (Mauger et al. 2015)..

Climate Impacts on Summer Hydrology

Summer stream flows are expected to change in the future as follows:

- Diminishing snowpack will lead to lower river flows earlier in the year and extending through summer.
- Decline in summer rain (22% less summer rain likely by 2050's (Mauger et al. 2015)).
- Less summer rain will extend the duration of low flow impacts such as warmer stream temperatures, streams disconnected from floodplains and lakes, changes from year-round to seasonal flow over more area, and less available habitat.
- Lower water during summer will result in less complex habitat for fish because the channel edge will no longer be next to edge vegetation, which fish use as cover.

Salmon Impacts

- The change in hydrologic patterns from climate change will likely have both episodic and catastrophic impacts to the survival rate of salmonid populations.
- Hydrologic disruption will alter the timing and magnitude of high and low stream flows and the corresponding temperatures.

Winter Impacts on Salmon

- More frequent winter floods will increase the risk of redd scouring and flushing early hatched fry down into lower river and salt water habitats, reducing incubating egg and fry survival rates respectively. This impact will occur throughout spawning reaches, but especially in spawning reaches with levees that focus flood energy and limit floodplain connectivity. These risks can be reduced or increased on the mainstem by flow management choices made at the Howard Hanson Dam. Risks can be reduced by capturing flood waters above the dam. Risks can be increased, especially when flows are kept artificially high (above scour velocities) for longer periods than natural to reduce water levels in the reservoir to make room for incoming storms. CIG is undertaking further analysis of climate change impacts on the Green River that takes into account the effects of the Howard Hanson Dam. This section should be revisited after that analysis is completed.
- In tributaries, increased winter flows can bring increased sediment loads that smother redds, and reduce a juvenile salmon's ability breath, reducing survival. In the mainstem Green River below Howard Hanson Dam, sedimentation rates are expected to be low because a large amount of the coarse sediment is captured above the dam in the reservoir.
- High winter flows will decrease slower water habitat available for juvenile fish in some areas. In others, it will increase juvenile salmon access to off-channel, floodplain habitats for rearing. High flows may also cause benefits by causing channel migration, which could create new slow water habitats. In such cases, stranding of juveniles could occur.
- Lack of slower water habitat increases the risk of flushing juveniles rearing in the freshwater out to estuary or ocean too soon.
- Higher peak flows are expected to increase bank erosion, creating wider bank full widths for local area streams, especially in snow dominated areas. This will exacerbate existing undersized culverts (Wilhere et al. 2016).

Summer Impacts on Salmon

- Reduced water levels early and higher water temperatures could disrupt or modify juvenile chinook migration, and salmon and steelhead adult migration and spawning.
- Less water will limit the amount of spawning habitat available.
- Declining snowpack will reduce duration and volume of spring snow melt.
- Decreased spring and summer flows and warmer water will be the result of dry summers and high air temperatures, as we saw in summer 2015 (Figure 5) (DeGasperi 2017).
- Earlier low flows can disconnect stream habitats and strand juvenile fish and prevent access to spawning areas.
- The concentration of fish in a few areas due to low flows, can increase the spread of disease, food competition and predation.

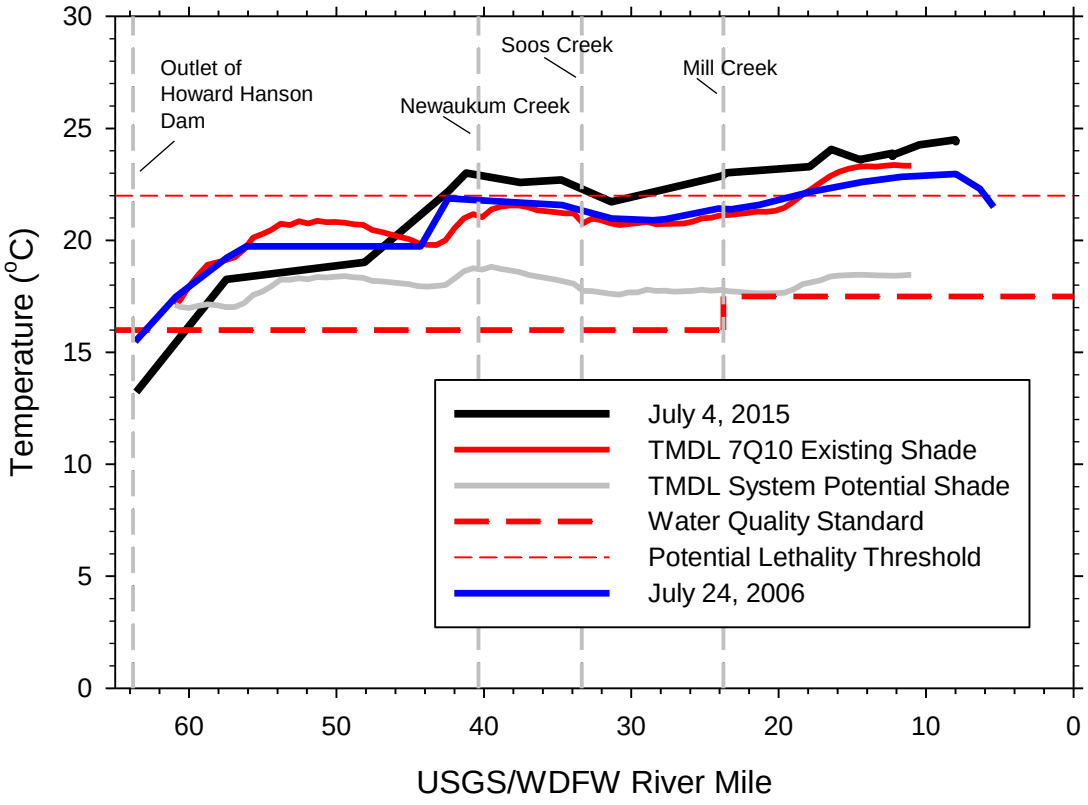

Figure 5. Stream temperatures measured along the length of the Green River from above the Howard Hanson Dam reservoir to Tukwila at River Mile 7.9 on July 4, 2015. Temperatures are well above state temperature standards for the 7-day average daily maximum, and reached lethal levels in all subwatersheds. From (DeGasperi 2017).

Local context

The majority of the basin will feel the effects of higher winter flows due to either reductions in snow fall or increases in rain intensity. Increases in the length of time of summer low flows will likely affect portions of the upper Green subwatershed most, as well as the mainstem Green River below the dam. The effects on the mainstem below the dam may be mitigated to a limited extent by water management of the reservoir.

Reaches that are leveed, even partially, and disconnected from their floodplains will exhibit the largest impacts in frequency and intensity of winter flows. The Lower Green has a high proportion of leveed banks, and the Middle Green River has discontinuous levees. In the Lower Green the floodplain has been largely disconnected, with only about 20% of its historic floodplain area still accessible during a 100-year flood event (Figure 6). Even the less frequently leveed spawning reaches in the Middle Green River will be less hospitable to salmon with these hydrologic changes.

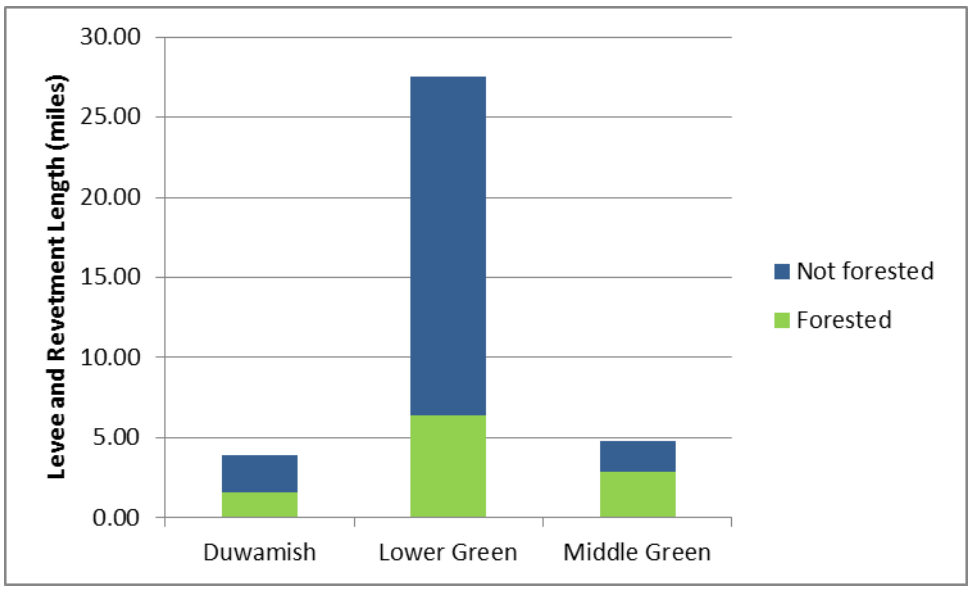

Figure 6. Length of banks with levees and revetments managed by King County Flood Control District in each subwatershed area along the main stem Green and Duwamish Rivers, and the amount forested and unforested. Data from King County GIS (does not include all flood facilities).

Lower summer flows will affect most streams and rivers. These conditions will reduce the amount of habitat area available, allow for quicker increases in water temperature, and the loss of the late spring/early summer increase in flows from snow melt may cause younger fish to leave the system earlier due to warm water and less habitat area, resulting in lower overall productivity. Small tributaries in the Green River valley, Duwamish tributaries, and nearshore drainages will likely go dry or become disconnected from the mainstem or Puget Sound more frequently.

Technical Recommendations

- To address low summer flows, groundwater, and low volume storm events, implement low impact development practices and green stormwater infrastructure, including runoff dispersion and infiltration, where soil conditions allow and where it will not increase risks of landslides or flooding downslope. Increasing infiltration can replenish groundwater and maintain stream flows during warm, dry weather.
- Install and/or retrofit stormwater management infrastructure to address the increased runoff volume from current and future development and projected climate change.
- Research and implement innovative restoration practices (e.g., beaver introduction, wetland restoration, stormwater management programs, policies and technologies) where appropriate to dampen the effects of shifting hydrology. Work toward resilience by encouraging natural processes that may moderate expected shifts.
- Identify how habitat boundaries, such as floodplains, are changing. Protect shorelines at risk of being armored as climate change advances. Protect habitat outside current habitat boundaries. Secure land that will be inundated by increased flooding and sea level rise.

- Headwaters are critical to providing cool, plentiful water. Monitor land use closely to minimize impacts to hydrology. In particular, where headwater streams are disconnected from their floodplains, work on reconnection to restore processes of water storage.
- Restore floodplain areas that provide flood storage and slow water during frequent, "ordinary" flood events (e.g., those that occur every one to five years) by reconnecting the floodplain (e.g., removing/setting back levees). This will be important above and adjacent to spawning grounds to counter the increased risk of higher flows scouring spawning areas.
- Remove and fix barriers like culverts and floodgates to ensure access to tributaries.
- Culverts have a life span of 50 to 100 years. Design new and replaced culverts to accommodate expected flows in 50 to 100 years so new fish passage barriers are not created.
- Work with water supply and dam operators like the U.S. Army Corps of Engineers and Tacoma Public Utilities to use reservoirs to ameliorate hydrologic impacts, especially during low flow periods.
- Undertake an evaluation of water rights in the basin. Consider creating a follow up program to acquire water rights to rededicate back to the river, and support efforts to retain sufficient flows for fish.
- Support expanding outreach programs that reduce water usage in order to have more water available for streams and rivers (e.g. basic education, incentives for residences to upgrade to low flow devices, improve efficiency of irrigation systems).
- Consider placing more importance on increasing amount of a large wood in rivers in streams to improve hyporheic exchange that could moderate maximum temperatures.
- Studies have shown that young tree stands (<100 years) can decrease summer base flows by almost half. Work with forestry managers and researchers to investigate longer stand rotations and selective logging to improve basin hydrology (Perry and Jones 2016).

Temperature

Climate Impacts

- Water temperatures will be affected by the air temperature anticipated increase by 4 to 5 degrees F by 2080 (Figure 7) (Mauger et al. 2015, Mauger 2016),
- Increased air temperatures keep streams from cooling down as they used to over evenings or seasons. Over the last century, the frost-free season has lengthened by 30 days, with nighttime temperatures increasing by 1.1 degrees C (Mauger et al. 2015).
- Globally, fifteen of the last sixteen years have been the warmest years on record (NOAA 2016) (Mauger et al. 2015)
- Warmer temperatures will accelerate snow melt in the summers and decrease snow accumulation in the winters. Streams will not have a source of cool water in spring in the upper portions of the watershed.
- During low flow periods, groundwater will likely have a greater influence on streams as a water source and temperature regulator (King County, 2016, unpublished raw data).

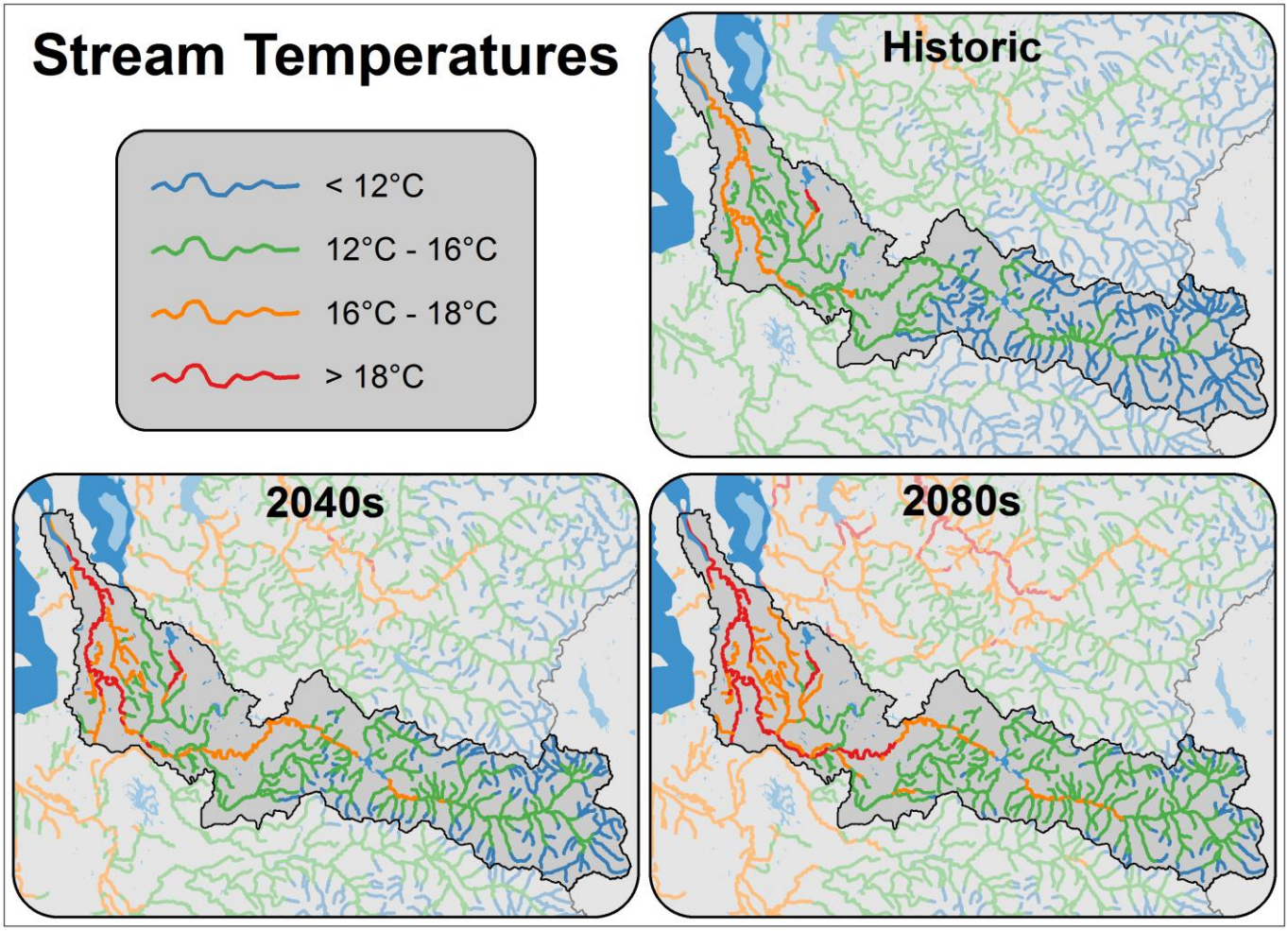

Figure 7. Projections of how changes in air temperature produced by climate models will affect stream temperatures in the Green River Basin (Mauger 2016, based on NoRWeST data).

Salmon Impacts

- Warm water temperatures in fresh, estuarine, and marine waters can cause lethality and many sub-lethal effects that can reduce productivity for many life history stages of salmon
- Water temperatures above 23 degrees Celsius can kill salmonids within a few seconds to hours (Ecology, 2000).
- Warm water impacts on adult salmon:
    - Adult salmon avoid swimming through water warmer than 16 degrees Celsius, which can disrupt their migration for spawning.
    - Water at 21-22 degrees Celsius can block migration, resulting in pre-spawn mortality.
    - When salmonids hold and migrate in higher temperature water, there is an increase in sub-lethal effects such as egg abnormalities (e.g., odd number of eyes) or outright mortality (Richter and Kolmes 2005).

- Sub-lethal effects of warmer stream temperatures can lead to lower growth, reduced fitness and survival of juvenile salmonids as follows:
    - Warm water decreases the supply of oxygen available to fish, disrupts metabolism, and increases susceptibility to toxins (Crozier 2015).
    - Dissolved oxygen decreases in warm water, creating "dead zones." Even if fish can leave these zones, some important food sources cannot move and will die, decreasing salmon food supply. If the fish cannot escape the "dead zones," they too can die.
    - Warmer temperatures can reduce preferred insects and their availability, causing weight loss.
    - Slight increases in water temperatures increase juvenile metabolism rates, sometimes causing them to stop feeding even if food is available.
    - Warmer temperatures increase susceptibility to sediment toxicity (Servizi and Martens 1991).
    - Warmer temperatures early in the year can disrupt the smoltification process and change how and when juveniles outmigrate from the system.
- By 2080 it is expected that in the Green River the number of river miles exceeding salmonid thermal tolerances (>18°C) will increase by 70 miles (Figure 7).

Local Context

Increased water temperatures are already a problem in many areas of the watershed, and are expected to worsen.

- In extreme low-flow, hot summers, tributaries including Crisp Creek (RM 39.6), Icy Creek (RM 48.3), Palmer Springs (RM 56.3), Resort Springs (RM 51.3), Black Diamond Springs (RM 49.5), Lones Levee Channel (RM 37.5), Coho Channel (RM 36.9), and the Duwamish tributary at RM 6.4appear to maintain cooler temperatures, but some can still exceed state 7 day average temperature standards (DeGasperi 2017).
- Many major tributaries to the Green River, while cooler than the Green River, regularly exceed state water temperature standards, including Soos, Newaukum and Mill Creeks, largely due to lack of riparian buffers (DeGasperi 2017).
- Cold water refugia not associated with tributaries or side channels include the Green River Gorge due to topographic shading, groundwater and hyporheic exchange zones from RM 55-32 in the Middle Green, and areas around alluvial deposits between Soos Creek (RM 33.4 and Mill Creek (RM 23.8).
- Above Howard Hanson Dam, cold water refugia may include the North Fork Green, Charley Creek, Gale Creek, Smay Creek and Sunday Creek (DeGasperi 2017).
- The reservoir above Howard Hanson Dam becomes thermally stratified during the summer, with cooler, dense water at the bottom and warmer water near the surface. Water is released from approximately 40 feet above the bottom of the reservoir, and therefore, the Green River immediately downstream of the spillway is cooler during the summer and warmer in late summer and fall than it was at the same point prior to dam construction (DeGasperi 2017).

Technical Recommendations

- Identify, protect and enhance processes and habitats that provide cool water. Protect cool headwater streams and other cold water refugia (at least 2 degrees Celsius colder than the daily maximum temperature of adjacent waters). Locate groundwater sources and seeps and protect natural processes

that create critical habitats like wetlands, tidal flats, marshes and estuaries; this will help ensure that water can be stored, recharged, and delivered at a moderated pace and temperature.

- Protect and restore the Green/Duwamish tributaries that are cooler than the mainstem river and can provide salmon with cold water refugia. Emphasize opening access to floodplain tributaries, including small stream systems. Continue work to moderate mainstem temperatures by setting back levees and softening bank revetments, and planting trees.
- Remove and fix barriers like culverts and floodgates to ensure access to tributaries, connect oxbows, and protect pools to restore cold water refugia.
- Monitor land use changes, particularly tree removal and new development, to quantify and mitigate for impacts to temperature.
- Undertake an evaluation of water rights in the basin. Consider creating a follow up program to acquire water rights to rededicate rights back to the river.
- Look at creating/expanding outreach programs that reduce residential/commercial/industrial potable water usage in Tacoma in order to have more water available for streams and rivers (e.g. basic education, incentives for residences to upgrade to low flow devices, improve efficiency of irrigation systems)
- Evaluate the impacts of water withdrawals for irrigation and cooling, and determine if other sources can be used, including reclaimed water.
- Investigate the relative contribution of runoff from paved surfaces on water temperatures, and where appropriate,
- Increase the use of low impact development practices in both developed and developing areas, including reducing impervious area, infiltrating or dispersing runoff, and planting trees to minimize the impact of urban areas on stream temperatures (Herb et al. 2008, Jones et al. 2012, Van Buren et al. 2000).
- Promote and fund the WRIA 9 Riparian Revegetation Strategy (Ostergaard et al. 2016) to increase the rate of planting and protecting riparian buffers to help stabilize in-stream temperatures and reduce sediment and toxin load.
- Work with the ACOE to further explore work done by WEST (2011) regarding how water is passed from the reservoir to downstream habitats to determine whether the outlet could be redesigned to release cooler water.

Ocean Conditions

Climate Impacts

Salmon spend much of their lives in the North Pacific feeding from the ocean's food web. Natural variations in climate cycles strongly influence ocean conditions. One of these cycles is the Pacific Decadal Oscillation (PDO). PDO is a climate index based on multi-decadal patterns in sea surface temperatures (NWFSC 2015). As an indicator, PDO has warm and cool phases. Over the past century, these phases oscillated irregularly over a period of 10-40 years with more recent short-term (3-5 year) events (NWFSC 2016). These phases are correlated with Northwest climate and ecology and variations in northeast Pacific marine ecosystems. Specifically, PDO is correlated with patterns in atmospheric pressure, prevailing winds, currents, coastal upwelling impacts, winter land-surface temperature and precipitation and stream flow, as well as historic salmon landings from Alaska to California (Mantua et al. 1997).

These warm and cool phases are linked to composition, abundance, and distribution of plankton communities, the basis of the ocean food web. PDO is hypothesized to alter the source of ocean water off the West Coast. In cooler

phases, northerly winter winds bring cold water and boreal zooplankton communities from the Gulf of Alaska south into the California Current. Northerly winds cause coastal upwelling which generally brings cold, salty, nutrient-rich water to the surface. These conditions increase phytoplankton production that support zooplankton communities dominated by cold-water, lipid-rich copepods. These conditions are correlated with good salmon survival. When the PDO shifts to a warm phase, warm southwesterly winds result in more water from the warmer, fresher, North Pacific Current and its associated tropical and sub-tropical warm water lipid-depleted copepods. These conditions are correlated with poor salmon survival for populations in the lower 48 states.

While regional climate in the Pacific Northwest is driven by these natural variations in climate and ocean conditions in the Pacific, we don't know how climate change will affect these variations. Climate change is expected to increase ocean temperatures in the northeast Pacific by 1.8C by 2040 (Mauger et al. 2015), which experts hypothesize will result in a 1-4% increase in marine mortality for salmon from Puget Sound to California. Weather patterns in 2014 and 2015 caused +2-4C temperature anomalies over a large area of the northeast Pacific Ocean labeled "The Blob," which may be a precursor of extreme climatic variations that will become more common in the future. Salmon returns in 2015 were some of the worst on record, and fish that did return to freshwater experienced high mortality from blob-related drought and subsequent warm and low stream flows in freshwater habitat (Peterson et al. 2015).

Salmon Impacts

- While it is clear that PDO cycles affect salmon survival, the impacts of climate change on the natural variations in PDO cycles that determine ocean conditions are not known, and the effect of ocean conditions on salmon is not well understood.
- The ways in which salmon are impacted will depend on the life stage 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 might be already doing so.

Local Context and Technical Recommendations

Effects of ocean conditions will be felt most strongly in Pacific Ocean, but may also be seen in the Puget Sound nearshore within WRIA 9.

Stormwater Runoff

Climate Impacts

- Increases in predicted rainfall events will increase flow volumes from areas not retrofitted to new stormwater standards accounting for climate change impacts. In some cases, this could also increase pollutant discharges from stormwater runoff or groundwater leaching through contaminated areas into rivers and streams, particularly for those pollutants that are detected in stormwater year-round, such as PAHs, phthalates and pesticides (Hobbs et al. 2015). Some of these issues may be addressed by new stormwater standards being implemented with new and redevelopment.
- Stormwater can also increase the peak flows during storm events, scouring stream beds and banks, adding to sediment loads due to channel and bank erosion, and flushing out habitat forming debris.

Salmon Impacts

- Stormwater impacts to salmon are varied and can cause both lethal and sub-lethal conditions.

- Toxics from stormwater can cause mutations in salmonid eggs and rearing juvenile salmonids, harm brain and heart development, and cause direct mortality (McIntyre et al. 2015).
- Stormwater washes in excess sediment and nutrients that can cause dissolved oxygen to decrease, creating hypoxic conditions for both fish and macroinvertebrates, disrupting the food chain (McIntyre et al. 2015).
- A direct, observable impact of untreated stormwater is pre-spawn mortality, when adult coho die before they are able to spawn (Spromberg et al. 2016).

Local Context

Stormwater affects urban and suburban areas that drain to small streams and tributaries, such as Miller and Walker creeks, Longfellow Creek, Soos Creek, Newaukum Creek, and Mill Creek, as well as urbanized areas along the Lower Green like Kent, Auburn, Renton and Tukwila. As detailed in a recent stormwater retrofit analysis of WRIA 9, most developed areas in the watershed did not initially have any stormwater controls, and the early stormwater control methods and requirements have generally been deemed inadequate by today's standards in terms of improving water quality and impacts to stream hydrology. These areas are not yet retrofitted to minimize stormwater runoff (King County 2014). Cities and businesses are already implementing municipal and individual stormwater management permits (known as NPDES, or National Pollutant Discharge Elimination System) to manage stormwater on new and redeveloping areas, control pollution sources at businesses, and track and eliminate illicit discharges into the storm system. In addition, treating and retaining stormwater on developed areas before it runs off into streams and rivers will reduce fish exposure to chemicals and stressful hydrologic and water quality conditions (Spromberg et al. 2016).

Technical Recommendations

- Study and prioritize areas that need stormwater retrofits and accelerate those actions (See King County (2014) for one possible approach).
- Conduct small-scale subwatershed stormwater infiltration feasibility studies and prioritize potential retrofit projects, looking for cost savings where capital projects are already planned (e.g., Miller-Walker Stormwater Retrofit Implementation Plan (HDR Engineering 2015)).
- Incentivize public-private partnerships to increase the rate of stormwater retrofits on private properties and road right-of-ways.
- Infiltrate road and parking lot runoff wherever possible, prioritizing the areas with the highest use. Partner with Washington State Department of Transportation to develop and implement a plan to retrofit state highways throughout the basin. Use the Miller-Walker Basin as a case study to determine the amount of retrofit needed to improve hydrologic and water quality conditions.

Sedimentation

Climate Impacts

- Heavier rains will increase landslide potential across the basin, including marine bluffs.
- Heavier rains will also increase stream flows, which can increase erosion and move more sediment downstream.
- Increased sediment loads can affect sedimentation rates in estuary and delta areas.
- Increased fine sediments may temporarily cause spawning gravels to fill in, smothering incubating eggs.

- Increased flows on the mainstem may be dampened by HHD operations, depending on flow rate decisions. Sediment is already decreased in the mainstem basin due to the amount of sediment trapped behind the dam; gravel supplementation is continuing in order to maintain spawning habitat in the Middle Green River.

Salmon Impacts

- High levels of suspended solids can kill salmonids by burying redds after spawning and potentially harm juvenile fish by decreasing dissolved oxygen or smothering their gills.
- Suspended sediments also cause chronic sub-lethal and behavioral effects including; reduced foraging capabilities, stunted growth, stress, lowered disease resistance and interference with migration cues (Bash 2001).

Local Context

More frequent rain events will likely bring sedimentation impacts from landslides on the hillslopes throughout the watershed. There existing issues with increased sediment inputs above HHD due to historic logging practices (e.g. dense road network on steep slopes). The high rains will likely increase the rate of landslides and sedimentation in this area. While anadromous salmon don't have access at this time, creating access to the upper watershed is a high priority action in the Plan. Sedimentation in the upper basin will not impact the Middle and Lower Green River areas in the near term because the reservoir acts like a large sediment retention pond. However, there will likely be some increased sedimentation issues in the Middle and Lower Green caused by bank erosion and inputs from local streams. The off channel habitat *creation* projects in the Lower Green are at a higher risk than other project types if sedimentation increases. At this time, it is not clear if the increased sediment load will be substantial enough to degrade the resilience of restoration projects. The increased rain events will also likely increase the rate of landsliding and beach feeding along the marine shorelines of WRIA 9. Most drift cells within WRIA 9 have experienced shoreline armoring that has cut off significant amounts of beach feeding bluffs over the last 100 years (WRIA 9 Implementation Technical Committee 2012). While the exact effects are not known at this time and it will likely be drift cell specific, increased sedimentation/beach feeding rates may actually improve beach conditions by offsetting historic armoring that starved beaches.

Technical Recommendations

- Restore riparian buffers more quickly to help reduce sediment load.
- Protect intact buffers to reduce sediment load and minimize erosion.
- Study and understand sedimentation changes in mainstem and nearshore areas.

Coastal

Effects to the ocean environment are harder to predict and quantify than freshwater effects, but there will be impacts to salmon survival. The most notable changes expected in Puget Sound's coastal and marine ecosystems are sea level rise and ocean acidification.

Sea Level Rise

Climate impacts

- Sea level in Puget Sound rose 20 centimeters from 1900-2008 and sea level rise (SLR) will continue, though it is hard to predict exactly how much.
- The State of the Knowledge report projects sea level will rise 0.6 meters by 2100 (The Nature Conservancy and Climate Impacts Group 2016).
- Beach habitats and infrastructure along Puget Sound shorelines are already being impacted by SLR.

Nearshore

- Increases in SLR means that extreme high water levels will increase and in response flood events will become more frequent. This means that damaging storms will occur more frequently because storms will occur at higher water levels (Mauger et al. 2015).
- A 1ft increase in water surface elevation means an order of magnitude increase in high water events—so a 100 year event turns into a 2 year event (Mauger et al. 2015)
- Sea level rise will have a myriad of effects on the marine nearshore, including increased bank/bluff erosion, landslides and "coastal squeeze." A study in the San Juan islands estimated that toe of bank erosion caused by SLR would likely double existing bluff erosion rates.
- Combined with toe of bluff erosion, the predicted 22% more rain in the winter will increase the risk of destabilizing nearshore slopes and increase landslides that are triggered from upslope mechanisms.
- While sediment supply is critical to a productive and healthy nearshore environment and increased beach feeding through landslides may benefit beach habitats, increased landslides could heighten the demand for new bulkheads and enlarging existing bulkheads, further degrading this important process.
- Coastal squeeze is a phenomenon that occurs in response to SLR. Marine shorelines that are unarmored have beaches and beach habitats that migrate inland in response to SLR. Armored shorelines not only restrict the natural migration of beaches, the beach habitats slowly get squeezed out of existence (Figure 8).

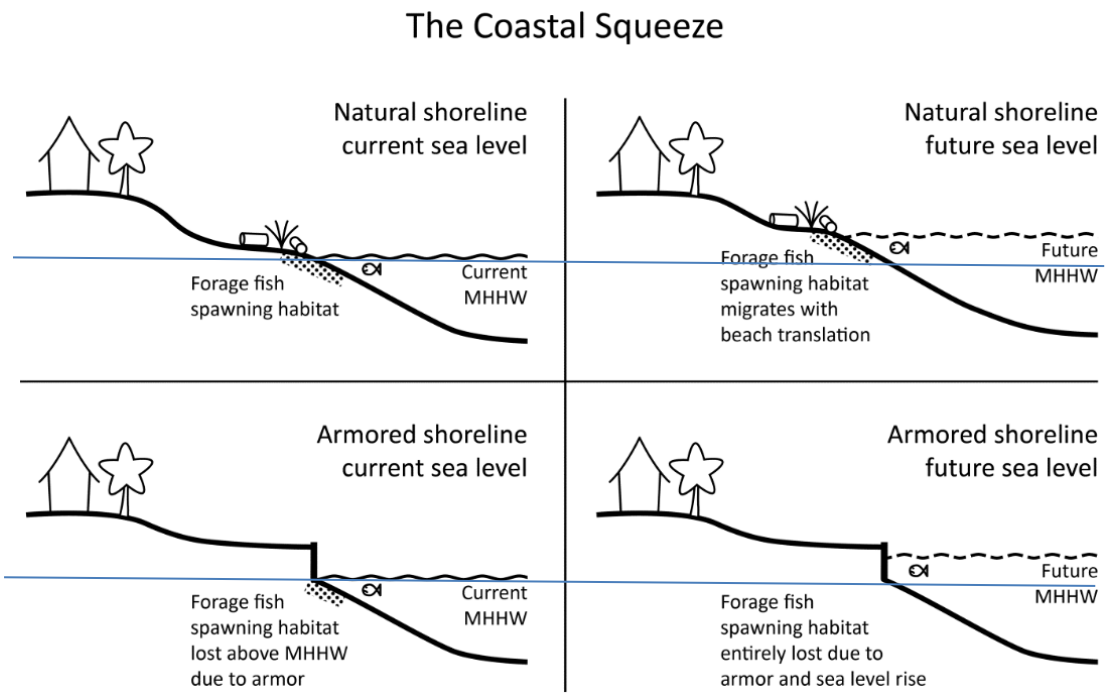

Figure 8. Coastal squeeze in nearshore graphic along the Puget Sound Nearshore refers to the shallow areas where forage fish spawn being squeezed out of existence by shoreline armoring and sea level rise (from Coastal Geologic Services).

Estuary

- SLR may convert existing estuarine habitats into predominately salt water habitats and convert some fresh water habitats (e.g. wetlands) into estuarine habitats.
- In the tidally influenced areas of the Duwamish River (up to approximately River Mile 11), SLR may convert shallow water mudflats to deep water, tidal habitats and marsh areas to mudflats. Marsh areas may be flooded, and as they move upslope on steep banks, become increasingly narrow edge habitats over time.
- Sea level rise may move salt wedge further upstream into areas that are currently freshwater.
- SLR will likely begin to flood low lying upland areas, creating a need to decide if the areas should be 'defended' against SLR with levees and other infrastructure or if the areas should be converted to wetland/estuarine habitats.

Salmon impacts

- According to the CIG State of the Knowledge report, sea level rise will increase the area of salt marsh and transition marsh, shifting the ranges of habitat used by salmon. However, given that the Duwamish estuary and Central Puget Sound nearshore are highly developed with docks, bulkheads, tide gates and culverts, it will likely lose marsh and mudflat area and types from coastal squeeze.
- Increased erosion from sea level rise and landslides is already bringing requests for more and bigger bulkheads along the nearshore to protect existing development; additional sea level rise will likely increase these requests (Kollin Higgins, pers. comm.).
- Additional bulkheads will cut off the sediment supply needed by forage fish, a key salmonid prey.

- The amount of shallow water habitats heavily used by juvenile salmon in late spring early summer in the nearshore will decrease due to coastal squeeze within the largely armored shorelines of WRIA 9

Local Context

Impacts of SLR and coastal squeeze will be focused in the Duwamish estuary and along the Central Puget Sound nearshore.

Technical Recommendations

- Identify areas most at risk of losing estuarine habitat, such as mudflat and marsh, by mapping elevations and monitoring the habitat over time.
- Include a diversity of elevations in estuary projects to allow for shifting boundaries of intertidal and subtidal habitats into the future.
- Undertake an evaluation of upland areas within the Duwamish most at risk of inundation through SLR, in conjunction with the communities, businesses, and other stakeholders, to look for opportunities to transition low-lying upland habitats to aquatic habitats in ways that provide economic, social justice, and environmental equity benefits (Figure 9).
- Protect marine and freshwater shorelines at risk of being armored as climate change continues.
- Protect habitat outside current habitat boundaries that will become future estuarine habitat.
- Improve regulatory protection in all unarmored marine areas.
- Encourage bulkhead removal or retrofit where possible, but especially at historic feeder bluffs.
- Buy land that will be directly impacted by sea level rise, remove existing infrastructure if necessary, to allow marine shoreline migration, bluff erosion and/or estuarine marsh migration.
- Work with partners to understand vulnerability of estuary infrastructure under SLR, including levee maintenance and drainage needs, transportation corridors and wastewater facilities.

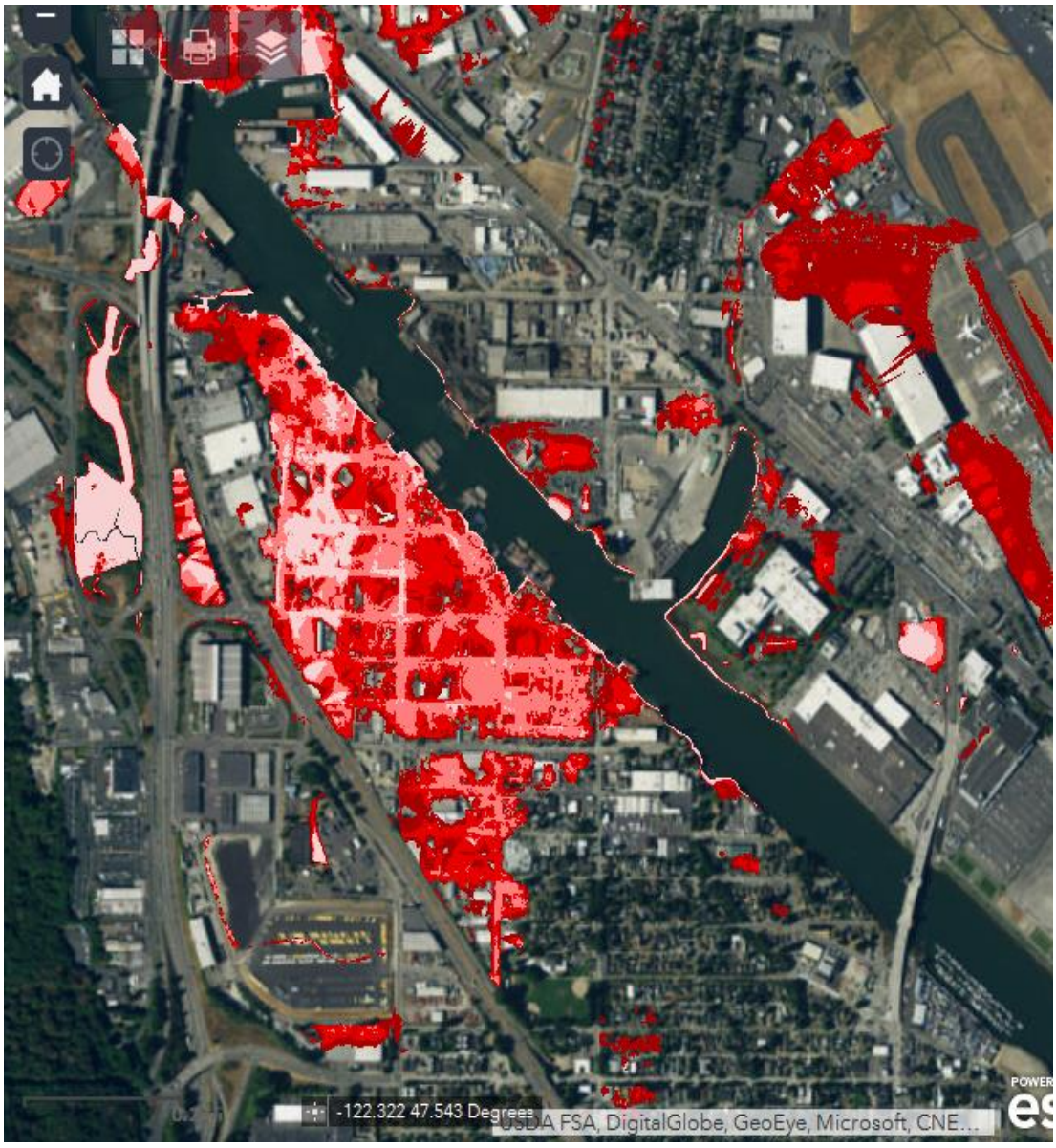

Figure 9. Map showing projected areas of inundation due to sea level rise in the Duwamish subwatershed, between the 1st Ave S. and South Park bridges (City of Seattle 2012).

Ocean Acidification – Climate Impacts

- Ocean acidification is projected to increase 150-200% by 2100 based on current CO_2 emission scenarios (The Nature Conservancy and the Climate Impacts Group 2016).
- Warmer air temperatures will likely cause sea surface temperatures to increase as well (Mauger et al. 2015).
- Together these factors can have a wide range of impacts on marine and coastal ecosystems.

Salmon Impacts

- Ocean acidification is expected to change food availability for salmon during the smolt and ocean life cycle phases.
- The role affected species play in supporting Puget Sound salmon raises concerns about how acidification could affect the entire Puget Sound and ocean food web (Washington Department of Ecology 2012)

Technical Recommendations

- Protect and restore areas of carbon uptake – including forests, eelgrass and tidal marshes.

Discussion

Tremendous change is expected in the Puget Sound region over the next 20-30 years with respect to increased human population growth and climate change. The Puget Sound coastal shoreline counties account for 68% of Washington state's population: 4,779,172 out of 7,061, 530 people (Alberti and Russo 2016). Nearly half of these people live in King County. By 2030, the Puget Sound population is estimated to exceed 5.7 million – an 18.2% increase from 2014 estimates as compared to a 12.7% national growth rate predicted in the same time frame (Alberti and Russo 2016). This rapid and extensive growth has direct implications to the Green/Duwamish and Central Puget Sound Watershed.

With the growing demand for homes, clean drinking water, transportation systems, agricultural products, and strong economies, addressing the impacts of climate change for threatened salmonids is increasingly complex. Where and how people live in Puget Sound, including the patterns of development and transportation systems, and economic development all contribute to salmon survival, and hopefully, recovery in the Puget Sound. Climate change gives urgency to actions that can help mitigate known future effects, in particular, planting riparian trees for shade. It also gives more urgency to fish passage through Howard Hanson Dam, to open up this extremely large and higher elevation area for spawning and rearing.

To address these competing forces, planning and implementing salmon recovery actions needs to become more complex, interdisciplinary, and integrated. We need solutions that benefit many interests and sectors. Salmon recovery and climate change information needs to be incorporated into local jurisdiction comprehensive plans, shoreline master programs, critical areas ordinances. We also need additional enforcement of existing land use regulations, particularly with riparian buffers and nearshore bulkheads.

Efforts to address the impacts of climate change are already underway in many of the WRIA 9 jurisdictions. This work will need to continue and accelerate to keep ahead of the pace of population growth and climate change.

Conclusions

Different salmon species and their life history types are varied. Over the centuries, species have evolved with slight differences across the species and within salmonid types to better withstand and adapt to habitat, climate and ocean conditions. The Plan has identified recovery actions that address viable salmonid population (VSP) criteria, such as life stage diversity, abundance, productivity, and spatial structure. By addressing these criteria, we hope to give salmon the best chance for recovery. Climate impacts will directly affect these VSP criteria. For instance, water temperatures across the basin will likely increase, making some areas inhospitable to salmon, and

causing dire conditions for unique life history types such as yearling Chinook. Climate impacts could potentially decrease suitable summer habitat, impacting the spatial diversity in the system, or increased winter scouring could affect population abundance and ultimately productivity.

The summer of 2015 shed light on what could be expected in years to come. Along with large-scale strategies at a global, national and state level to dampen these impacts, work must be done at a basin level. For salmon recovery, restoration and protection actions must amplify the species' natural ability to adapt. To give salmonids the best chance of survival, we must continue implementing the Plan strategy of restoring and protecting river processes that can adapt and create resilient habitat.

The proposed actions above and summarized in Table 2 and 3 are not new. For the most part they are described in other Green/Duwamish planning documents. What has changed is the urgency and need to change the rate of implementing these actions. We must think beyond direct habitat needs (which are still important), to decrease the intensity of climate impacts likely in 10, 20, and 50 years.

Table 2. Summary of technical recommendations that could be taken for each climate impact

Climate impact	Technical Recommendations
Hydrology	● Implement low impact development practices and green stormwater infrastructure in urban areas. ● Work with water supply and dam operators to use reservoirs to ameliorate hydrologic impacts, especially during low flow periods. ● Evaluate water rights in the basin, and support efforts to retain sufficient flows for fish. ● Support expanding outreach and incentive programs that reduce water usage. ● Consider increasing amount of a large wood in rivers in streams to improve hyporheic exchange that could moderate maximum temperatures. ● Work with forestry managers and researchers to investigate longer stand rotations and selective logging to improve basin hydrology. ● Encourage natural processes that may moderate expected shifts. ● Protect habitat uphill of current floodplains and beaches so habitats can shift and adapt. ● Monitor land use in headwater areas to minimize impacts to hydrology. ● Reconnect disconnected floodplains in mainstems and headwaters. ● Remove and properly size barriers like culverts and floodgates to ensure access to tributaries, connect oxbows, and protect pools.

Climate impact	Technical Recommendations
Temperature	● Identify, protect and enhance processes and habitats that provide cool water. ● Protect and restore tributaries and other areas that are cooler than the Green River and can provide salmon with cold water refugia. ● Remove and fix barriers like culverts and floodgates to ensure access to tributaries, connect oxbows, and protect pools to restore cold water refugia. ● Monitor land use changes, particularly tree removal and new development, to quantify and mitigate impacts to temperature. ● Restore riparian buffers more quickly to help stabilize in-stream temperatures and reduce sediment and toxin load by promoting and funding the WRIA 9 Riparian Revegetation Strategy. ● Reduce summer water use by encouraging more potable water conservation in Tacoma and reclaimed water for irrigation and cooling where water is being withdrawn from the Green River. ● Increase the use of low impact development practices and GSI. ● Work with ACOE to determine whether colder water could be released from HHD.
Stormwater	● Study and prioritize areas that need stormwater retrofits and accelerate those actions. ● Incentivize public-private partnerships to increase the rate of stormwater retrofits on private properties and road right-of-ways. ● Infiltrate road and parking lot runoff wherever possible, developing partnerships and prioritizing areas of highest use.
Sedimentation	● Restore riparian buffers more quickly to help reduce sediment load. ● Protect intact riparian buffers. ● Study and understand sedimentation changes in mainstem areas.
Sea level rise	● Identify how habitat boundaries, such as nearshore and estuaries, are changing. ● Protect marine and freshwater shorelines at risk of being armored as climate change continues. ● Protect habitat at higher elevations than current habitat boundaries. ● Improve regulatory protection in all unarmored marine areas. ● Encourage bulkhead removal or retrofit where possible, but especially at historic feeder bluffs. ● Buy land that will be directly impacted by sea level rise, remove existing infrastructure if necessary to allow marine and estuary shoreline migration and bluff erosion. ● Evaluate upland areas in the Duwamish subwatershed at risk of inundation, and work with community partners transition to aquatic habitat while providing other benefits.
Ocean acidification and increased temperature	● Protect and restore areas of carbon uptake, including forests, eelgrass and tidal marshes.

Table 3. Summary of strategies and actions and what climate impact they address

Strategies and Actions	Climate Impact
Encourage natural processes that may moderate expected shifts.	Hydrology, Temperature
Encourage natural processes and novel restoration practices such as beaver reintroduction in appropriate areas to help moderate flows and temperature.	Hydrology, Temperature
Protect habitat at higher elevations than current habitat boundaries so habitats can shift and adapt.	Hydrology, Seal level rise
Monitor land use in headwater areas closely to minimize impacts to hydrology.	Hydrology, Temperature
Reconnect disconnected floodplains in mainstems and headwaters.	Hydrology, Temperature
Remove and resize barriers like culverts and floodgates to ensure access to tributaries, connect side channels, and protect pools.	Hydrology, Temperature
Reduce summer water use by encouraging more potable water conservation in Tacoma and reclaimed water for irrigation and cooling where water is being withdrawn from the Green River watershed.	Hydrology, Temperature
Identify, protect and enhance processes and habitats that provide cool water (e.g., replant riparian forests, remove levees).	Temperature, Sedimentation
Protect and restore Green River tributaries that are cooler than the mainstem river and can provide salmon with cold water refugia.	Temperature
Remove and fix barriers like culverts and floodgates to ensure access to tributaries, connect oxbows, and protect pools to restore cold water refugia.	Hydrology, Temperature, Sedimentation
Increase the rate of implementation of riparian buffer restoration to help stabilize in-stream temperatures and reduce sediment and toxin load.	Temperature, Sedimentation, Stormwater Runoff
Study and prioritize areas that need stormwater retrofits and accelerate those action	Stormwater Runoff
Protect marine and freshwater shorelines at risk of being armored due to climate change.	Sea level rise
Improve regulatory protection on in all unarmored marine areas.	Sea level rise
Encourage bulkhead removal or retrofit where possible, but especially at historic feeder bluffs	Sea level rise
Buy land that will be directly impacted by sea level rise, remove existing infrastructure if necessary in order to allow marine and estuary shoreline migration and bluff erosion.	Sea level rise

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