CLIMATE CHANGE AND CLEANUP: A VULNERABILITY ASSESSMENT AND ADAPTATION STRATEGY FOR WASHINGTON STATE'S CONTAMINATED SITES

CHANCE ASHER Chance.asher@ecy.wa.gov

(Washington Department of Ecology) Olympia, WA, USA.

ABSTRACT: Climate change impacts pose risks to the integrity of remedies employed to clean up contaminated sites, including sediment, soil, groundwater, landfills, and mining sites. Washington State has extensive marine and freshwater shorelines including Puget Sound, one of the largest estuaries in the United States and where a majority of contaminated sites are located. A vulnerability assessment was conducted on the state's 11,000 cleanup sites to 1) identify the climate change impacts that posed the highest risk to cleanup sites and 2) assess the sensitivity, exposure, and adaptive capacity of cleanup sites. Results revealed 1) that sea level rise, more severe flooding, storm events, and wildfire, and increased incidence of landslide posed the highest risks and 2) the types of sites, locations, and aspects of remedies with the highest vulnerability. These results informed development of an adaptation strategy to increase the resilience and sustainability of cleanup remedies.

INTRODUCTION

Adapting to climate change impacts is a critical challenge for Washington State. The state is projected to experience impacts from climate change that will affect the security of our economy, the health and safety of our people, and the health of our environment and abundant natural resources. Some of these impacts include:

- Rising sea levels and increasing inundation of low-lying coastal areas.
- More frequent extreme precipitation events and earlier spring melting of the snowpack, resulting in increasing flood hazards, erosion, and landslides.
- More severe drought in the summer months.
- Increasing risk of wildfires.
- Acidification of the marine waters in Puget Sound and along the Pacific coast.

The Department of Ecology's Toxics Cleanup Program (Ecology) manages the cleanup of contaminated sites to protect human health and the environment — now and in the future. Our ability to prepare for the impacts of climate change is critical. By improving the resilience of our cleanup remedies to regionally-specific climate change impacts, we can help ensure that our efforts are effective in the long-term. Implementing adaptation measures during early stages of the cleanup process may increase the feasible cleanup options, maximize their integrity, and reduce costs in some situations.

To start, Ecology researched current climate science specific to the Pacific Northwest to understand environmental trends and climate projections. This science was used to conduct a vulnerability assessment for the state's cleanup sites to assess the sensitivity, exposure, and adaptive capacity of cleanup sites which informed the development of an adaptation strategy to increase the resilience of the state's cleanup sites.

Observed Climate Trends in the Pacific Northwest. Following is a summary of observed environmental trends in Washington State's climate that are related to temperature, precipitation, and hydrology and may specifically impact cleanup sites.

When Puget Sound is referenced, it refers to Puget Sound, the Strait of Juan de Fuca, and all of the land that drains into them.

Relative sea level has risen 8.6 inches at the Seattle gauge from 1900 to 2008, consistent with global trends (Figure 1). The rate of sea level rise varies due to factors such as land subsidence or uplift, weather patterns, and ocean currents (CIG 2015, IPCC 2014, NOAA 2016 & 2017a).

Increased flooding due to tidal influences. Sea level rise in Seattle has resulted in tidal flood increases, also called nuisance floods, with the greatest number occurring in 2010 to 2011 (NOAA, 2016 & 2017a; Figure 2).

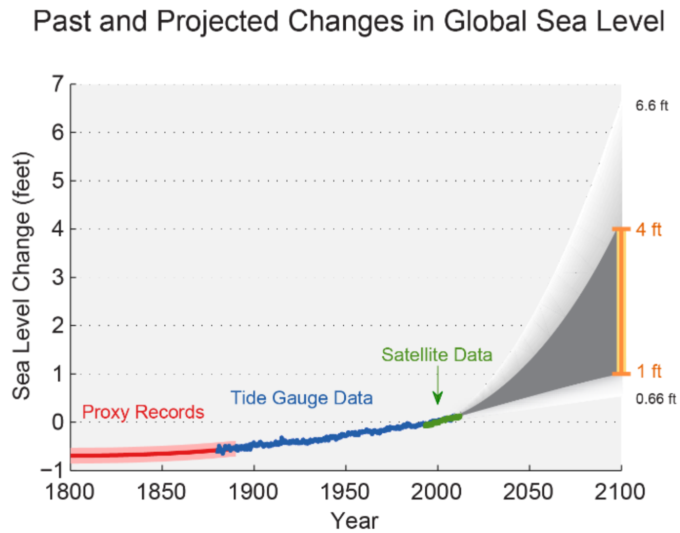

Figure 1: Estimated, observed, and projected global sea level rise from 1800 to 2100.

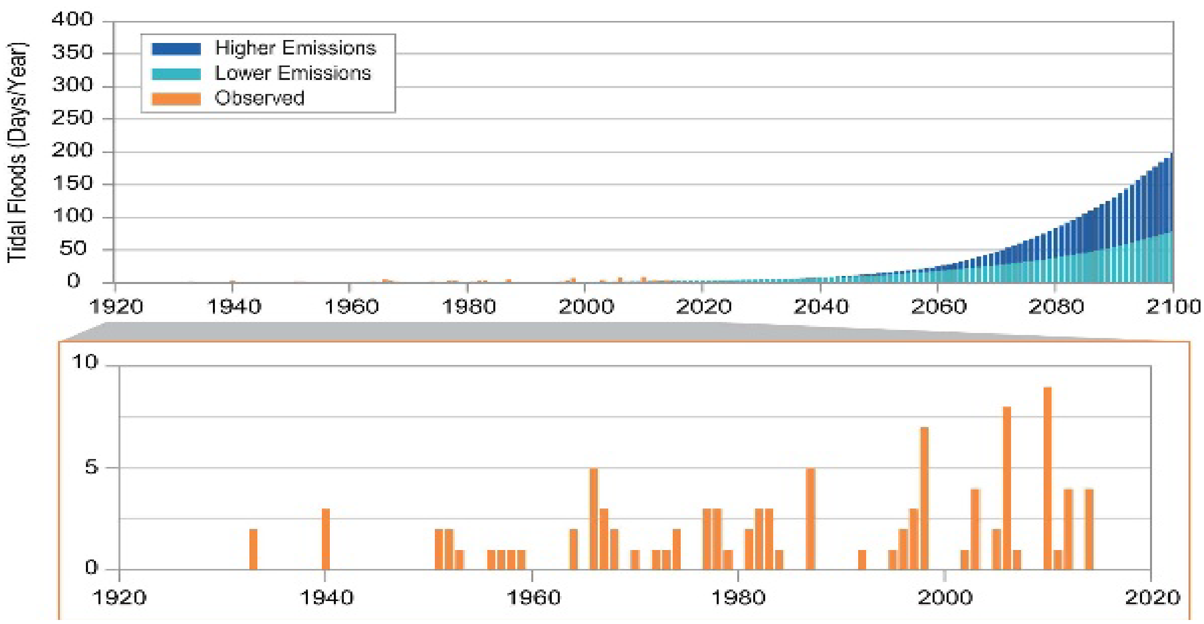

Figure 2: Observed and projected annual number of tidal floods for Seattle, WA.

Precipitation. Annual and seasonal precipitation have remained relatively constant between 1895 and 2014. However, extreme precipitation (the heaviest 1% of all 24-hour events, from 1901 – 2012) has increased in frequency and intensity in Western Washington (NOAA 2016, 2017a; Figure. 3).

Coastal flooding. In Seattle, incidence of coastal flooding has increased from 0.90 average number of flood days per year in the 1950s to 3.33 days in the 2010s (NOAA 2016; Figure 4).

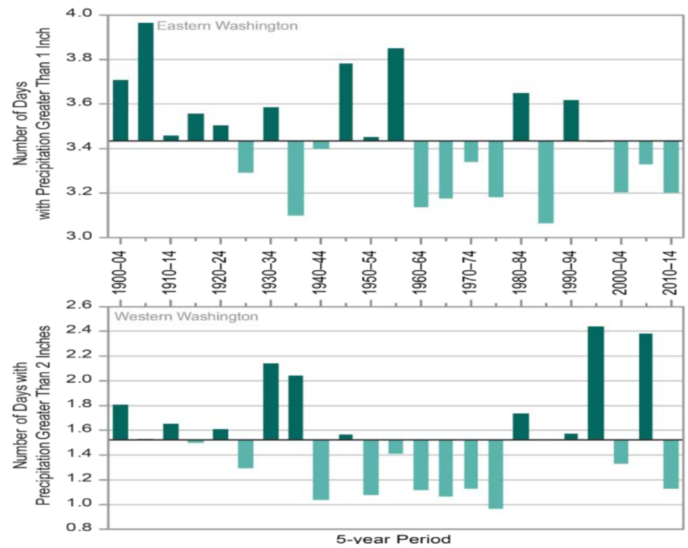

Figure 3: Observed extreme one-day precipitation events in East and West Washington.

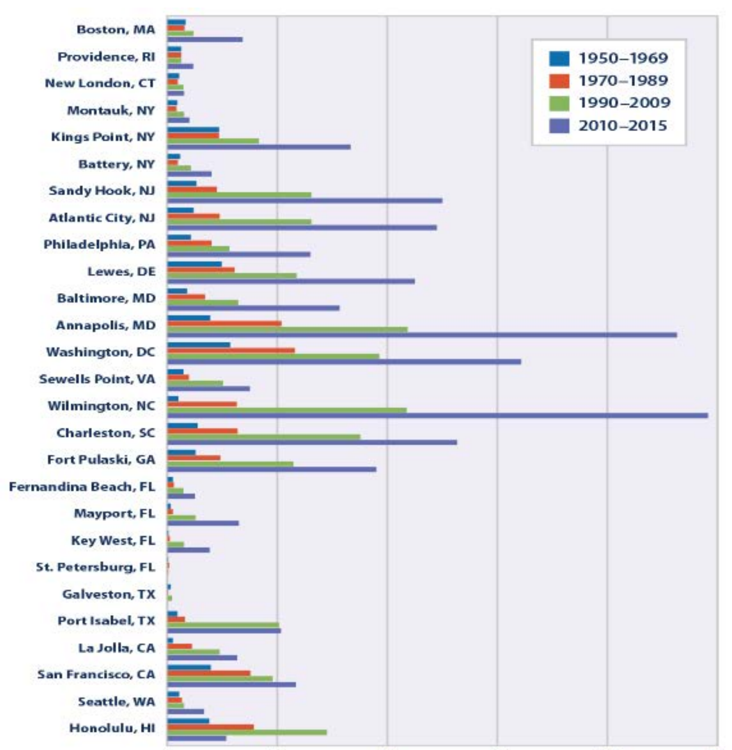

Figure 4: Average number of coastal flooding events per year in the U.S. from 1950 to 2015.

Snowpack in the Cascades declined by about 25% from the mid-20th century to 2006, with substantial natural year-to-year variability (CIG 2015).

Peak spring stream flow has occurred earlier in the season by 0 to 20 days in many snowmelt-influenced rivers between 1948 and 2002 (CIG 2015).

Glaciers at Mount Rainier, Olympic Mountains, and North Cascades have been shrinking. Mount Rainer's glaciers decreased 14% by volume from 1970 to 2008; Olympic Mountains glaciers decreased by 7% in area and 31% in number from 1980 to 2009; and glaciers in the North Cascades have lost 56% in area from 1900 to 2009 (CIG 2015).

Average annual air temperature increased by ~1.3°F between 1895 and 2014 in the Puget Sound region with warming occurring in winter, fall, and summer. As of 2017, the past three decades have been warmer than any other recorded period for the globe, with 2015 the hottest on record at ~3.9°F above the long-term average (CIG 2015, EPA 2016, NOAA 2017a; Figure 5).

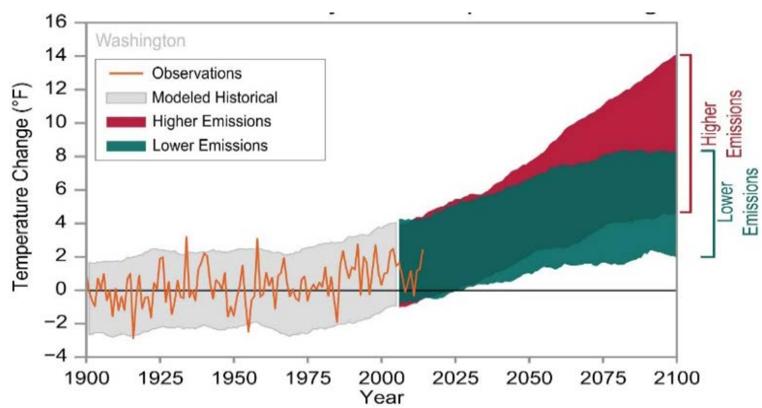

Figure 5: Observed and projected temperature changes for Washington State.

Nighttime heat waves increased in frequency west of the Cascades from 1901 to 2009. Since 1990, the nighttime average of warm nights (above 60°F in Eastern Washington and 65°F in Western Washington) has been above the long-term average (CIG 2015; EPA 2016). These are defined as three or more consecutive days above the 99th percentile for the maximum temperature anomalies (for daytime heat waves) or minimum (for nighttime heat waves).

Frost-free season has lengthened. The frost-free season (growing season) increased by more than 30 days in the Puget Sound region from 1920 to 2014 (CIG 2015, EPA 2016).

Wildfire. Although wildfires are a natural part of most Pacific Northwest forest ecosystems, warmer and drier conditions have helped increase the number and extent of wildfires in western U.S. forests since the 1970s (Mote et al. 2014). While trends in observed wildfire are complicated by a history of fire suppression east of the Cascades and infrequent fires west of the Cascades, the 2015 wildfire season was the most destructive in Washington's history. Over one million acres burned, which is more than six times Washington's average (NOAA 2017a).

Ocean acidification. Increasing concentrations of carbon dioxide in the atmosphere raise the equilibrium level of dissolved carbon dioxide in the ocean. This increases the level of oceanic carbonic acid and reduces the pH (NOAA 2012). As a result of carbon dioxide in the atmosphere, Puget Sound is experiencing a reduction in pH, and the pH of the Northeast Pacific Ocean surface waters has decreased by -0.27 from 1991–2006 (CIG 2015).

Future Environmental Conditions in the Pacific Northwest. Below is a summary of climate projections that may impact the state's cleanup sites. Where ranges are shown, they correspond to a low-to-high greenhouse gas emissions scenario, where high equates to continued increases in greenhouse gas emissions. Where data exists, projections are included for the mid-century (i.e., the 2050s, which are defined as years 2040 to 2069) and end of the century (2100). The following future climate scenarios for the Pacific Northwest were used to conduct the vulnerability assessment

Sea level rise. Absolute sea level for Puget Sound is projected to change and coastal areas will experience varying sea level rise due to different area-specific vertical land movement. There are previous sea level rise projections for the Pacific Northwest, but they are not based on a probabilistic framework (Mote, et al. 2008; 2013, NRC 2012, Reeder, et al. 2014, and CIG 2015). Under the low greenhouse gas emissions scenario, thermal expansion of the oceans and melting of small mountain glaciers is projected to result in a ~1 foot of absolute sea level rise by 2100 on a global scale. Even with a drastic reduction in greenhouse gas emissions, sea level rise will continue through the end of the century because the oceans take a long time to respond to temperature conditions at the earth's surface. Combining thermal expansion with glacial and ice sheet melting makes 4-feet of sea level rise plausible on a global scale by 2100 under a high greenhouse gas emissions scenario (NOAA 2016).

Only a limited number of studies have evaluated changes in storm surge and waves for Washington State. Current research suggests that these will not change in the future. These events may have a greater impact due to a higher base sea level, but the amount of storm surge or the height of ocean waves is not projected to change (CIG 2015). Rising sea levels combined with high tide, storm surges, and subsidence contribute to:

- An increase in the elevation, depth, or extent of inundation along the marine and coastal shorelines.
- An amplification of the inland reach of high tides, resulting in increased flooding further inland of the coastline, especially when compounded by severe storm events.
- Movement of the saltwater wedge further upstream in tidally influenced rivers.
- Saltwater intrusion into groundwater.
- Increased landslide risk or rates of erosion along coastal bluffs.
- Sources: CIG 2015, EPA 2016, IPCC 2014, NOAA 2016 & 2017a

Precipitation. The total annual amount of precipitation in the Pacific Northwest is projected to remain the same, but amplification of seasonal precipitation patterns may occur by the 2050s (compared to the 1950 to 1999 timeframe). On average, models project the following changes (CIG 2015):

- An increase in precipitation between 2 to 11% in the fall, winter, and spring.
- A decrease of 22% in the summer.

By the 2080s, extreme precipitation events (24-hour rain events) are projected to increase in intensity by 22% on average, as well as frequency (compared to the 1980s). This would be an increase to about 8 days per year, on average, as opposed to just 2 days per year in the past. The increasing frequency and intensity of atmospheric rivers—those moist airflows that extend from the tropical Pacific to the west coast of North America during winter—are expected to carry more moisture in the future, causing our big rain events to become more intense (CIG 2015, OCCRI 2013).

Snow to rain transition and declining snowpack. More winter precipitation will fall as rain instead of snow, and snowmelt is expected to begin earlier in the spring. These warming-driven changes are expected to result in a shorter snow season on average and earlier peak streamflow in rivers with a significant snowmelt component. These changing precipitation patterns contribute to:

- Flow changes in major snowmelt-influenced rivers, with higher flows in winter and lower flows in summer.
- More frequent and severe river flooding.
- Increased landslide risk due to saturation of soil.

- Increased erosion and riverine sediment transport in fall, winter, and spring.
- Sources: NOAA 2017b, CIG 2015

Air Temperature. The average annual air temperatures in the Puget Sound region are projected to increase by 4.2 °F to 5.5 °F on average by the 2050s. This means that the average temperatures by the 2050s will be higher than the warmest temperatures in the previous 100 years. Much higher warming is projected after mid-century. These changing temperature patterns contribute to:

- Warmer water temperatures in Puget Sound, estuaries, and freshwater bodies.
- More severe drought and potentially lower groundwater tables.
- More frequent and intense heat waves in summer.
- Less frequent and intense cold events in winter.
- Reduced amount of snowpack and earlier snowmelt, which is expected to reduce an important source of water during the drier summer months, and increase the frequency and intensity of summer wildfires.
- Sources: CIG 2015, EPA 2016, IPCC 2014, NOAA 2016 & 2017b

MATERIALS AND METHODS

The vulnerability assessment involved the following steps:

1. *Identifying climate change impacts* that posed the highest risk to cleanup sites [i.e., sediment, soil, groundwater, landfill, mining sites, and underground storage tanks (e.g., gas stations)] and determining their sensitivity, exposure, and adaptive capacity. This involved:
   a. Researching and applying the latest science from the University of Washington Climate Impacts Group, Intergovernmental Panel on Climate Change, Environmental Protection Agency, and the National Oceanic Atmospheric Administration to understand past environmental trends and climate change projections globally, nationwide, and for the Pacific Northwest.
   b. Working with the Environmental Protection Agency to learn their approach used to conduct a vulnerability assessment for the nation's Superfund sites.
2. *Conducting GIS analysis* by collecting data on the climate change impacts identified as posing highest risk to cleanup sites, developing a GIS application, and analyzing sensitivity and exposure of the state's cleanup sites.
3. *Interpreting results,* by identifying types of sites, specific locations, and specific remedies that are most vulnerable.

The GIS application was used to conduct an initial screening to understand the potential vulnerability of cleanup sites to the following climate change impacts:

- *Sea level rise.* We used base flood elevation and mean higher high water to identify 1) areas projected to be inundated due to sea level rise at high tide (on a daily basis), and 2) areas projected to be inundated during severe storms (on an infrequent basis).
- *Flooding.* We used FEMA floodway and floodplain data to identify 1) areas within current 100- and 500-year flood plains, and 2) snow melt influenced rivers that have a projected increased risk of flooding (FEMA 2005, 2017a, 2017b).
- *Landslide and erosion*. We used mapped landslides to identify areas that have experienced landslide (DNR 2017a, 2017b).
- *Wildfire*. We used modeling data to identify areas projected to have an increase in area burned (Little 2010; NRC 2011).

We then interviewed fifteen cleanup experts with experience in different media and types of sites (groundwater, soil, landfills, mining, and sediment). We posed questions based on the vulnerabilities assessment: 1) What are the current vulnerabilities you have observed based on past environmental events, and 2) Based on the GIS analysis, what do you anticipate will be the highest risk vulnerabilities for different types of sites, specific locations, and specific remedies?

For example, damage from waves and currents on a sediment or upland waterfront site can be exacerbated by sea level rise, which can increase the severity of coastal storms and high tides. The events can compromise shoreline stabilization structures and alter sediment transport processes. Similar to landfills, confined disposal facilities may be impacted by rising groundwater tables, erosion, or inundation. These effects may change bathymetry, sediment transport, and deposition/erosion, which may impact natural recovery and recontamination processes.

Sea level rise coupled with a severe storm event can also affect a sediment cap's integrity and performance. Scouring and erosion, for instance, can damage armored caps, isolation caps, thin-layer caps, habitat layers, and *in-situ* treatment caps, especially those located in shallow water or intertidal zones.

Shoreline areas are particularly vulnerable to damage from intermittent high river stage, high tides, and extreme precipitation events. Damage to riverbanks or shoreline stabilization structures may occur at upland cleanup sites along the waterfront, along with potential loss of integrity and release of contaminants to sediment. Intertidal or capped areas may be impacted by various materials carried by high river stage, such as large woody debris or vessels breaking away from moorings (Figure 6).

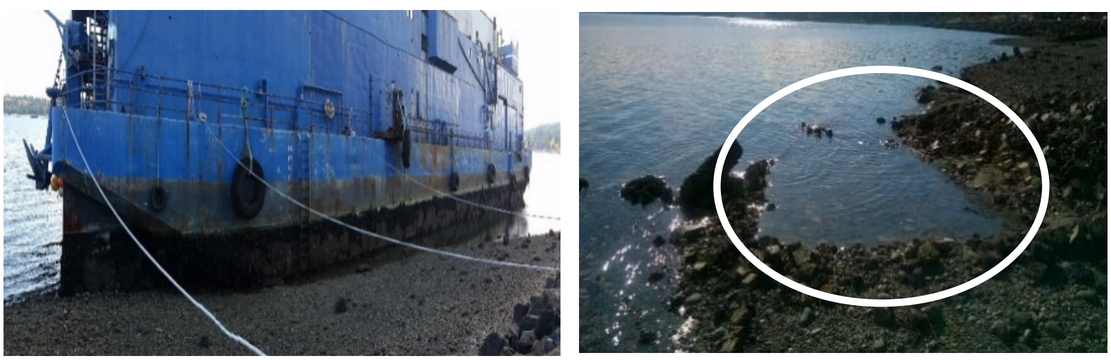

Figure 6: Vessel that broke loose from its mooring during an severe storm event in Puget Sound (left) and resulting damage to a sediment cap (right, circled in white). WA Department of Ecology.

RESULTS AND CONCLUSIONS

We identified climate change impacts with the greatest potential to adversely affect contaminated sites and cleanup remedies, which include:

- Rise in sea level and coastal inundation
- More severe riverine flooding
- Increased landslide and erosion risk
- More severe and frequent wildfire
- More severe drought.

Of these, we found that sea level rise had the highest potential risk to sediment and upland cleanup sites in or near marine and tidally influenced waterbodies. The next highest potential risks in descending order were flooding, wildfire, landslide/erosion, and drought for upland cleanup sites located further inland. Landfill and mining sites have high vulnerability to drought because rainfall is a limiting factor for growth and maintenance of vegetative covers and to heavy precipitation events and flooding. Groundwater sites have high vulnerability to flooding and wildfire because the treatment systems can be impaired, wellheads compromised, and the hydrodynamic assumptions made for the remedy may be altered. All types of sites are vulnerable to landslide if they are located in landslide prone areas or recently burned areas.

Based on the results from the vulnerabilities assessment and science related to environmental projections for the Pacific Northwest, we developed adaptation strategy guidance — *Adaptation Strategies for Resilient Cleanup Remedies* Publication no. 17-09-05 — aimed at helping cleanup project managers increase the resilience of cleanup remedies to the specific climate change impacts identified that pose highest risk to the integrity of remedies. The guidance which includes recommendations on:

1. How to assess the vulnerability of individual cleanup sites and remedies to climate change impacts. This includes a web-based interactive GIS application to locate vulnerable cleanup sites and understand the potential risks to help identify adaptation actions.
2. How to implement adaption actions to increase the resilience of cleanup remedies, with recommendations that cleanup project managers can apply during each phase of the cleanup process: site investigations; remedy selection, design, and implementation; and operation and maintenance.
3. How to develop a risk management approach based on no, low, moderate, high, and very high risk scenarios that can be applied at each phase of cleanup: investigation, selection of a remedy, engineering design, and post-cleanup monitoring.

ACKNOWLEDGEMENTS

The Department of Ecology would like to thank the following authors of this guidance Chance Asher, Ecology; Teresa Michelsen, Farallon Consulting, L.L.C; Scott O'Dowd, Ecology; Hugo Froyland, Ecology

And, the following for their significant expert review and/or technical contributions to this report:

- Ecology: Pete Adolphson, Russ McMillan, Jeff Johnston, Elaine Heim (Technical Editor), Bobbak Talebi, Jerry Franklin, Mark Adams, Liliana Bastian, John Evered, Arianne Fernandez, Brian Sato, Jason Cocke, Ching-Pi Wang, Jason Landskron, Annette Ademasu, Kris Grinnell, Hugh Shipman
- Hart Crowser: Mike Ehlebracht, Mark Dagel, Chris Poulsen
- Farallon Consulting, L.L.C: Emerald Erickson-Mulanax, Clyde Moore, Dave Johnson
- Environmental Protection Agency: Mike Cox, Beth Sheldrake, Carlos Pachon
- Ian Miller, Washington Sea Grant
- Kelly Klima, RAND Corporation
- Barry Kellems, Integral Consulting

Ecology would like to acknowledge the critical contribution of the Climate Impacts Group at the University of Washington. Their body of work in climate science and climate change adaptation has been instrumental in laying the groundwork for practitioners to develop and implement climate change adaptation plans, such as this guidance. In addition, we would like to thank Amy Snover, Guillaume Mauger, Harriett Morgan, and Robert Norheim for their scientific expertise and peer review of this guidance.

REFERENCES

CIG. (2015). Mauger, G.S., J.H. Casola, H.A. Morgan, R.L. Strauch, B. Jones, B. Curry, T. M. Busch Isaksen, L. Whitely Binder, M.B. Krosby, and A.K. Snover. "State of knowledge report: Climate change in Puget Sound.," Prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration by Climate Impacts Group at the University of Washington, Seattle, WA, doi:10.7915/CIG93777D. Retrieved from: https://cig.uw.edu/resources/special-reports/ps-sok/.

DNR. (2017a). "Shallow landslide hazard forecast map," Olympia, WA: Washington Department of Natural Resources, Division of Geology and Earth Resources, Geologic Hazards Section. Retrieved March 2017 from: http://www.dnr.wa.gov/slhfm

DNR. (2017b). "Natural hazards [website]," Olympia, WA: Washington State Department of Natural Resources, Geology & Earth Resources Division / Washington's Geological Survey. Retrieved June 2017 from: https://fortress.wa.gov/dnr/protectiongis/geology/?Theme=natural_hazards

EPA. (2016). "Climate change indicators in the United States, 4th ed.," (EPA 430-R-16-004), Washington, D.C.: U.S. Environmental Protection Agency, Public domain, retrieved on November 4, 2016 from: www.epa.gov/climate-indicators, "Climate indicators report," Washington, D.C.: U.S. Environmental Protection Agency. Retrieved March 2017 from: https://www.epa.gov/climate-indicators/downloads-indicators-report

FEMA. (2005). "FEMA wave runup and overtop: FEMA coastal flood hazard analysis and mapping guidelines focused study report," Washington, D.C.: Federal Emergency Management Agency.

FEMA. (2017a). "Federal Emergency Management Agency flood insurance program," Washington, D.C.: Federal Emergency Management Agency. Retrieved from: https://www.fema.gov/base-flood-elevation

FEMA. (2017b). "National flood hazard GIS layers from FEMA national flood insurance program," *Washington*, D.C.: Federal Emergency Management Agency. Retrieved from: https://www.fema.gov/national-flood-hazard-layer-nfhl

IPCC. (2014). "Climate change 2014: Synthesis report*," Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland: The Intergovernmental Panel on Climate Change, Public domain access.

Littell, J.S., Oneil, E.E., McKenzie, D., Hicke, J.A., Lutz, R.A., Norheim, M.M. Elsner. (2010). "Forest ecosystems, disturbance, and climatic change in Washington state, USA," *Climate Change*. doi 10.1007/s10584-010-9858-x.

Mote, P.W., A. Petersen, S. Reeder, H, Shipman, and L. Whitely Binder. (2008). "Sea level rise in the coastal waters of Washington State," University of Washington Climate Impacts Group and the Washington Department of Ecology.

Mote, P.W., Snover, A.K., Capalbo, S.M., Eigenbrode, S., Glick, P., Littell, J.S., Raymondi, R., Reeder, S. (2014). "Northwest. Chapter 21 in Climate Change Impacts in the United States," *The Third U.S. National Climate Assessment*, J. Melillo, Teresa (T.C.) Richmond, and G.W. Yohe, Eds., U.S. Global Change Research Program, 16-1-nn.

NOAA. (2012). "Scientific summary of ocean acidification in Washington State marine waters," Washington, D.C.: National Oceanic and Atmospheric Administration.

NOAA. (2016). "Sea level rise and nuisance flood frequency changes around the United States," *Technical report NOS CO-OPS 073*, Washington, D.C.: National Oceanic and Atmospheric Administration. Public domain access.

NOAA. (2017a). "Global and regional sea level rise scenarios for the United States*,"* Silver Spring, MD: National Oceanic and Atmospheric Administration, National Ocean Service *Technical Report NOS CO-OPS 083*, Public domain access.

NOAA. (2017b). “State climate summaries,” Washington, D.C.: National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Retrieved March 2017 from: https://statesummaries.ncics.org/. Public domain access.

NRC. (2012). “Sea level rise for the coasts of California, Oregon, and Washington: Past, present, and future,” National Research Council, Committee on sea level rise in California, Oregon, Washington. Board on Earth Sciences Resources Ocean Studies Board Division on Earth Life Studies, *The National Academies Press*, https://doi.org/10.17226/13389

OCCRI. (2013). “Climate change in the Northwest: Implications for our landscapes, waters, and communities,” M. Dalton, P. Mote, A. Snover (Eds.). Corvallis, OR: Oregon State University, Oregon Climate Change Research Institute and University of Washington, Climate Impacts Group.

Reeder, W.S., P. Ruggiero, S.L. Shafer, A.K. Snover, L.L. Houston, P. Glick, J.A. Newton, S.M. Capalbo. (2013). “Coasts: Complex changes affecting the Northwest’s diverse shoreline,” Chapter 4, pp. 67-109, In M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate change in the Northwest: Implications for our landscapes, waters, and communities,* Washington D.C.: Island Press.