Climate Change Effects and Adaptation Approaches in Freshwater Aquatic and Riparian Ecosystems in the North Pacific Landscape Conservation Cooperative Region

A Compilation of Scientific Literature

Phase 1 Draft Final Report

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EXECUTIVE SUMMARY

This Phase 1 draft final report provides a first-ever compilation of what is known—and not known—about climate change effects on freshwater aquatic and riparian ecosystems in the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). The U.S. Fish and Wildlife Service funded this report to help inform members of the newly established NPLCC as they assess priorities and begin operations. Production of this report was guided by University of Washington's Climate Impacts Group and information was drawn from more than 250 documents and more than 100 interviews. A final report will be published in 2012 following convening of expert focus groups under Phase II of this project.

Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in southcentral Alaska to Bodega Bay in northwestern California, west of the Cascade Mountain Range and Coast Mountains. The extent of the NPLCC reaches inland up to 150 miles (~240 km) and thus only includes the lower extent of most large watersheds. This area is home to iconic salmon, productive river, lake, and wetland systems, and a wide variety of fish, wildlife, amphibians, and other organisms. Many of these species, habitats, and ecosystems are already experiencing the effects of a changing climate.

Carbon Dioxide Concentrations, Temperature, and Precipitation

Increased atmospheric carbon dioxide (CO_2) contributes to the earth's greenhouse effect, leading to increased air temperature, altered precipitation patterns, and consequent effects for biophysical processes, ecosystems, and species.

- **Atmospheric CO_2 concentrations have increased** to ~392 parts per million (ppm)[1] from the pre-industrial value of 278 ppm,[2] higher than any level in the past 650,000 years.[3] By 2100, CO_2 concentrations are projected to exceed ~600 ppm and may exceed 1000 ppm.[4]
- **Annual average temperatures have increased** ~1-2°F (~0.56-1.1°C) from coastal British Columbia to northwestern California over the 20th century[5] and 3.4°F (~1.9°C) in Alaska from 1949 to 2009.[6] Winter temperatures increased most: 6.2°F (3.4°C) in Alaska[7] and ranging from 1.8 to 3.3°F (1.0-1.83°C) in the remainder of the region.[8] By 2100, the range of projected annual increases varies from 2.7 to 13°F (1.5-7.2°C), with the largest increases projected in Alaska.[9] Seasonally, winter temperatures will continue to warm most in Alaska,[10] while summers are projected to warm most in the remainder of the region (2.7-9.0°F, 1.5-5.0°C).[11] These changes are projected to reduce snowpack[12] and summer streamflow,[13] increase water temperature, [14] and will likely lead to increasing physiological stress on temperature-sensitive species,[15] drying of alpine ponds and wetlands, and reduced habitat quality for dependent reptiles and amphibians.[16]
- **Seasonal precipitation varies but is generally wetter in winter.** Cool season precipitation (Oct-March) increased 2.17 inches (5.51 cm) in Alaska from the periods 1971-2000 to 1981-2010.[17] In Washington and Oregon, winter precipitation (Jan-March) increased 2.47 inches (6.27 cm) from 1920 to 2000.[18] In California, winter precipitation increased between 1925 and 2008,[19] while in British Columbia, both increases and decreases in winter precipitation were observed, depending on the time period studied.[20] Increased cool season precipitation raised winter flood risk in much of the Puget Sound basin and coastal areas of Washington, Oregon, and California.[21] Over the 21st Century, winter and fall precipitation is projected to increase 6 to 11% in BC and 8% in

Washington and Oregon, while summer precipitation is projected to decrease (-8 to -13% in BC and -14% in WA and OR).[22] In southeast Alaska, however, warm season precipitation is projected to increase 5.7%.[23] These changes have implications for future patterns of winter flooding and summer low flows and will affect the water quality and supply that freshwater species rely upon.[24]

Impacts of climate change on freshwater aquatic and riparian systems

Increases in CO_2 and air temperature, combined with changing precipitation patterns, are already altering numerous conditions, processes, and interactions in freshwater aquatic and riparian ecosystems. In most cases, these trends are projected to continue.

- **Reduced snowfall and snowpack, especially at lower and mid elevations:** In Juneau (AK), winter snowfall decreased ~15%, or nearly 1.5 feet (~0.45 m) between 1943 and 2005.[25] In the Cascade Mountains, April 1 snow water equivalent (SWE) has declined 16%[26] to 25%[27] since 1930. And in the lower Klamath Basin (CA), April 1 SWE decreased significantly at most monitoring sites lower than 5,905 feet (1,800 m) but increased slightly at higher elevations.[28] By 2059, April 1 SWE is projected to decline from 28%[29] up to 46%[30] in the NPLCC region. A 73% decline in snow accumulation is projected for California's North Coast under a doubling of atmospheric CO_2 concentrations.[31] For all but the highest elevation basins, loss of winter snowpack is projected to result in reduced summer streamflow, transforming many perennial streams into intermittent streams and reducing available habitat for fish, amphibians, and invertebrates dependent on constant flow and associated wetland conditions.[32]

- **Earlier spring runoff:** In the NPLCC region, the timing of the center of mass of annual streamflow (CT) shifted one to four weeks earlier and snow began to melt approximately 10 to 30 days earlier from 1948 to 2002.[33] From 1995 to 2099, CT is projected to shift 30 to 40 days earlier in Washington, Oregon and Northern California and 10 to 20 days earlier in Alaska and western Canada.[34] Both the spring freshet and spring peak flows are projected to occur earlier for basins currently dominated by glaciers, snow, or a mix of rain and snow.[35] In currently rain-dominant basins, runoff patterns will likely mimic projected precipitation changes.[36] In snowmelt-dominant streams where the seaward migration of Pacific salmon has evolved to match the timing of peak snowmelt flows, reductions in springtime snowmelt may negatively impact the success of smolt migrations.[37]

- **Increased winter streamflow and flooding:** In six glaciated basins in the North Cascades, mean winter streamflow (Nov-March) increased 13.8% from 1963 to 2003.[38] Winter streamflow also increased in non-rain-dominated basins in British Columbia and the Pacific Northwest from 1956 to 2006.[39] In the western U.S. from ~1975 to 2003, flood risk increased in rain-dominant and particularly in warmer mixed rain-snow-dominant basins, and probably remained unchanged in many snowmelt- and cooler mixed-rain-snow-dominant basins in the interior.[40] Under a warmer future climate with increased rainfall and decreased snowfall, winter streamflow and flood risk will increase, particularly for mixed rain-snow basins in the region.[41] At Ross Dam on the Skagit River (WA), the magnitude of 50-year-return flood events is projected to increase 15% by the 2040s (compared to 1916-2006).[42] The egg-to-fry survival rates for pink, chum, sockeye, Chinook, and coho salmon will be negatively impacted as more intense and frequent winter floods wash away the gravel beds salmon use as nesting sites.[43]

- **Decreased summer streamflow:** In the Pacific Northwest, northwestern California, and coastal British Columbia, those watersheds receiving some winter precipitation as snow experienced a decrease in summer streamflow from 3% to more than 40% between 1942 and 2006.[44] By 2100, further declines in the number and magnitude of summer low flow days are projected throughout the region.[45] In Washington's rain- and mixed rain-snow basins, the 7-day low flow magnitude is projected to decline by up to 50% by the 2080s.[46] Projected declines in summer streamflow will reduce the capacity of freshwater to dilute pollutants.[47] Combined with increased summer stream temperature, this will reduce habitat quality and quantity for stream-type Chinook and coho salmon, steelhead, and other freshwater fishes.[48]

- **Reduced glacier size and abundance in most of the region:** Fifty-three glaciers have disappeared in the North Cascades since the 1950s,[49] glaciers in the Oregon Cascades lost 40% to 60% of their area from 1901 to 2001,[50] and the Lemon Glacier near Juneau (AK) retreated more than 2600 feet (792 m) from 1953 to 1998.[51] However, in California, Mt. Shasta's glaciers exhibited terminal advance and little change in ice volume, as increased temperatures were counteracted by increased winter snow accumulation.[52] Limited projections for the 21st century indicate glacial area losses of 30% to 75% in parts of the NPLCC region.[53] The Hotlum glacier on Mt. Shasta is projected to disappear by 2065.[54] Where the contribution of glacial meltwater to streamflow is reduced or eliminated, the frequency and duration of low flow days is projected to increase,[55] raising stream temperature and suspended sediment concentrations and altering water chemistry.[56]

- **Increased water temperature:** Observed increases in lake and river temperatures are generally projected to continue, exceeding the threshold for salmon survival in some areas of the NPLCC region. Annual average water temperature in Lake Washington increased ~1.6°F (0.9°C) from 1964 to 1998.[57] In Johnson Creek (OR) water temperature variability increased over a recent 10-year period, suggesting that stream temperatures frequently exceed the local threshold level of 64.4°F (18°C).[58] In western Washington, simulations of maximum August stream temperatures from 1970 to 1999 showed most stations remained below 68°F (20°C), the upper threshold for salmon survival.[59] However, in the 21st century, a prolonged duration of water temperatures beyond the thermal maximum for salmon is projected for the Fraser River (BC),[60] the Lake Washington/Lake Union ship canal (WA), the Stillaguamish River (WA),[61] and the Tualatin River (OR).[62] In Washington by the 2080s, stream temperatures are projected to increase by 3.6 to 9°F (2-5°C).[63]

- **Changes in water quality:** Documented effects of climate change on water quality were not found, and water quality projections are both limited and widely varying for the NPLCC region. In seasons and areas where increased flows are projected, nutrient contaminants may be diluted (e.g. northwest BC)[64] or alternatively, sediment nutrient loads may be increased (e.g. during winter in the Tualatin Basin, OR).[65] Projected declines in summer flows and water supply may decrease nutrient sediment loads, but projected increases in development or other stressors may counteract the decline.[66] Lakes may experience a longer stratification period in summer[67] which could enhance eutrophication and lead to oxygen depletion in deep zones during summer, eliminating refuges for coldwater-adapted fish species.[68] In coastal areas, saltwater intrusion due to sea level rise was observed in Island County (WA)[69] and is projected to increase in the neighboring Gulf Islands (BC),[70] as well as other areas where coastal water tables are influenced by marine systems.[71]

- **Reduced seasonal ice cover:** The spatial and seasonal extent of ice cover on lakes will be reduced due to climate change.[72] For example, in several British Columbia lakes, the duration of ice cover decreased by up to 48 days over the 1976 to 2005 period.[73] For mid-latitude lakes, each 1.8°F (1°C) increase in mean autumn temperature leads to a 4 to 5 day delay in ice freeze-up, while the same increase in mean spring temperature leads to a 4 to 5 day advance in the onset of ice break-up.[74] Community and invasion processes may be affected as reduced ice cover increases light levels for aquatic plants, reduces the occurrence of low oxygen conditions in winter, and exposes aquatic organisms to longer periods of predation from terrestrial predators.[75] In northern regions where productivity is limited by ice cover and/or temperature, productivity may increase, providing additional food for fish and other species.[76]

Implications for ecosystems, habitats, and species

Climate-induced changes in air temperature, precipitation, and other stressors are already affecting the physical, chemical and biological characteristics of freshwater ecosystems.[77] Many of these trends will be exacerbated in the future. Impacts on habitat (loss and transition) and species (range shifts, invasive species interactions, and phenology) are highlighted here.

Habitat loss and transition

Increasing temperatures and associated hydrologic changes are projected to result in significant habitat impacts. Lake levels and river inputs are likely to decline if increases in evapotranspiration (due to higher temperatures, longer growing seasons, and extended ice-free periods) are not offset by an equal or greater increase in precipitation.[78] However, areas that become wetter could have higher lake levels.[79] Where lake levels are permanently lowered, the productive nearshore zone may be degraded as more shoreline is exposed.[80] Habitat for fish that require wetlands for spawning and nursery habitat would be reduced if lake-fringing wetlands become isolated.[81]

Warmer temperatures, reduced snowpack, and altered runoff timing is projected to cause drying of alpine ponds and other wetland habitats, reducing habitat quality for Cascades frog, northwestern salamander, long-toed salamander, garter snakes, and other dependent species.[82] However, loss of snowpack may allow alpine vegetation establishment, leading to improved habitat conditions for some high elevation wildlife species.[83] In the short term, vegetation establishment will be limited to areas favorable to rapid soil development.[84]

A modeling study suggests two-thirds of Alaska will experience a potential biome shift in climate this century, although the rate of change will vary across the landscape.[85] Much of southeast Alaska may be shifting from the North Pacific Maritime biome (dominated by old-growth forests of Sitka spruce, hemlock, and cedar) to the more southerly Canadian Pacific Maritime biome (dominated by yellow and western red cedar, western and mountain hemlock, amabilis and Douglas-fir, Sitka spruce, and alder).[86]

Range shifts, invasive species, and altered phenology

Climate warming is expected to alter the extent of habitat available for cold-, cool-, and warm-water organisms, resulting in range expansions and contractions.[87] Range-restricted species and habitats, particularly polar and mountaintop species and habitats that require cold thermal regimes,[88] show more severe range contractions than other groups and have been the first groups in which whole species have gone extinct due to recent climate change.[89] Amphibians are among the most affected.[90]

The effects of climate change on aquatic organisms may be particularly pronounced in streams where movements are constrained by thermal or structural barriers.[91] Bull trout distribution is strongly associated with temperature,[92] and in the southern end of their range (WA, OR, northwest CA), this coldwater species is generally found at sites where maximum daily temperatures remain below 60.8°F (16°C).[93] However, summer stream temperatures in many bull trout waters at the southern end of their range are projected to exceed 68°F (20°C) by 2100.[94]

Climate change may enhance environmental conditions such that some species are able to survive in new locations, known invasive species expand into new territories, and species that currently are not considered invasive could become invasive, causing significant impacts.[95] Invasive aquatic species that appear to benefit from climate change include hydrilla, Eurasian watermilfoil, white waterlily,[96] and reed canarygrass.[97] In Washington, Oregon, and Idaho, a habitat suitability model projects 21% of the region could support suitable habitat for the invasive tamarisk by 2099 (a two- to ten-fold increase).[98] Tamarisk currently occupies less than 1% of this area, and the remainder is considered highly vulnerable to invasion.[99]

Numerous ecological studies support a general pattern of species' phenological responses to climate change: on average, leaf unfolding, flowering, insect emergence, and the arrival of migratory birds occur earlier than in the past.[100] A significant mean advancement of spring events by 2.3 days per decade has been observed.[101] Studies of phenology from the NPLCC region have found:

- Lamprey run timing shifted 13 days earlier from 1939 to 2007 as Columbia River discharge decreased and water temperatures increased.[102] Migration occurred earliest in warm, low-discharge years and latest in cold, highflow years.[103]
- Populations of Lake Washington's keystone herbivore, *Daphnia*, show long-term statistically significant declines associated with an increasing temporal mismatch with its food source (the spring diatom bloom).[104] In contrast, although the phytoplankton peak advanced by 21 days, the herbivorous rotifer *Keratella* maintained a corresponding phenological response and experienced no apparent decoupling of the predator-prey relationship.[105]

In the future, populations that are most mistimed are generally expected to decline most in number.[106] For fishes dependent on water temperature for spawning cues, the spawning time may shift earlier if river waters begin to warm sooner in the spring.[107] Changes in plankton populations such as those described for *Daphnia* and *Keratella* in Lake Washington may have severe consequences for resource flow to upper trophic levels.[108]

Adaptation to climate change for freshwater aquatic and riparian systems

Given that CO_2 concentrations will continue to increase and exacerbate climate change effects for the foreseeable future,[109] adaptation is emerging as an appropriate response to the unavoidable impacts of climate change.[110] Adaptive actions reduce a system's vulnerability,[111] increase its capacity to withstand or be resilient to change,[112] and/or transform systems to a new state compatible with likely future conditions.[113] Adaptation actions typically reflect three commonly cited tenets: (1) remove other threats and reduce non-climate stressors that exacerbate climate change effects;[114] (2) establish, increase, or adjust protected areas, habitat buffers, and corridors;[115] and, (3) increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management.[116]

Adaptation actions may occur in legal, regulatory, institutional, or decision-making processes, as well as in on-the-ground conservation activities.[117] For example, actions that maintain or increase instream flow can counteract increased stream temperatures, reductions in snowpack, and changes in runoff regimes such as reduced summer stream flows and altered flow timing.[118] Actions to restore or protect wetlands, floodplains, and riparian areas can help moderate or reduce stream temperatures, alleviate the flooding and scouring effects of extreme rainfall or rapid snowmelt, improve habitat quality, and enable species migrations.[119] Decision-makers may also modify or create laws, regulations, and policies to incorporate climate change impacts into infrastructure planning to protect freshwater ecosystems,[120] promote green infrastructure and low impact development approaches to reduce extreme flows and improve water quality and habitat,[121] and adapt Early Detection and Rapid Response protocols to identify, control, or eradicate new and existing invasive species before they reach severe levels.[122]

Although uncertainty and gaps in knowledge exist, sufficient scientific information is available to plan for and address climate change impacts now.[123] Implementing strategic adaptation actions early may reduce severe impacts and prevent the need for more costly actions in the future.[124] To identify and implement adaptation actions, practitioners highlight four broad steps:

1. Assess current and future climate change effects and conduct a vulnerability assessment.[125]
2. Select conservation targets and a course of action that reduce the vulnerabilities and/or climate change effects identified in Step 1.[126]
3. Measure, evaluate, and communicate progress through the design and implementation of monitoring programs.[127]
4. Create an iterative process to reevaluate and revise the plan, policy, or program, including assumptions. [128]

Adaptive approaches to addressing climate change impacts will vary by sector and management goal, across space and time, and by the goals and preferences of those engaged in the process.[129] In all cases, adaptation is not a one-time activity, but is instead a continuous process, constantly evolving as new information is acquired and interim goals are achieved or reassessed.[130] Ultimately, successful climate change adaptation supports a system's capacity to maintain its past or current state in light of climate impacts or transform to a new state amenable to likely future conditions.[131]

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[3] CIG. (2008)
[4] Meehl et al. (2007, p. 803)
[5] Mote (2003, p. 276); Butz and Safford. (2010, p. 1).
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[7] Alaska Climate Research Center. (2009)
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[9] For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. (2008, Table 3). For OR alone, Mote et al. (2010, p. 21). For CA, CA Natural Resources Agency. (2009, p. 16-17) and Port Reyes Bird Observatory (PRBO). (2011, p. 8)

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[11] B.C. Ministry of Environment. (2006, Table 10, p. 113).
[12] Elsner et al. (2010, Table 5, p. 244); Pike et al. (2010, p. 715); PRBO. (2011, p. 8)
[13] AK Department of Environmental Conservation (DEC). (2010, p. 2-3); Chang and Jones. (2010, p. 94); Mantua, Tohver and Hamlet. (2010, p. 204-205); Pike et al. (2010, p. 719); Stewart. (2009, p. 89)
[14] Mantua et al. (2010)
[15] Mantua et al. (2010)
[16] Halofsky et al. (n.d., p. 143)
[17] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011. The datum for 1971-2000 is an official datum from the National Climatic Data Center (NCDC). The datum for 1981-2010 is a preliminary, unofficial datum acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The NCDC defines a climate normal, in the strictest sense, as the 30-year average of a particular variable (e.g., temperature).
[18] Mote (2003, p. 279)
[19] Killam et al. (2010, p. 4)
[20] Pike et al. (2010, Table 19.1, p. 701)
[21] Hamlet and Lettenmaier. (2007, p. 15)
[22] For BC, BC Ministry of Environment. (2006, Table 10, p. 113); For OR and WA, Mote and Salathé, Jr. (2010, 42-44); Seasonal precipitation projections for California were not available.
[23] Alaska Center for Climate Assessment and Policy. (2009, p. 31)
[24] Allan, Palmer and Poff. (2005, p. 279); Hamlet and Lettenmaier. (2007, p. 16); Martin and Glick. (2008, p. 14); Pike et al. (2010, p. 731); Poff, Brinson and Day. (2002, p. 15)
[25] Kelly et al. (2007, p. 36)
[26] Stoelinga, Albright and Mass. (2010, p. 2473)
[27] Pelto. (2008, p. 73); Snover et al. (2005, p. 17)
[28] Van Kirk and Naman. (2008, p. 1035)
[29] Pike et al. (2010, p. 715)
[30] Elsner et al. (2010, Table 5, p. 244)
[31] PRBO. (2011, p. 8)
[32] Poff, Brinson and Day. (2002)
[33] Stewart, Cayan and Dettinger. (2005); Snover et al. (2005)
[34] Stewart, Cayan and Dettinger. (2004, p. 225)
[35] Chang and Jones. (2010, p. 192); Pike et al. (2010, p. 719); Stewart. (2009, p. 89).
[36] Pike et al. (2010, p. 719)
[37] Mantua, Tohver and Hamlet. (2010, p. 207)
[38] Pelto. (2008, pp. , p. 72-74)
[39] Pelto. (2008, Table 5, p. 72); Pike et al. (2010, pp. , p. 706, 717); Stewart (2009, Table V, p. 89)
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[56] Pike et al. (2010, p. 717)
[57] Arhonditsis et al. (2004, p. 262-263)
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[59] Mantua et al. (2010)
[60] Pike et al. (2010, p. 729)
[61] Mantua, Tohver and Hamlet. (2010, p. 199, 201)
[62] Chang and Jones. (2010, p. 116)
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[64] Pike et al. (2010)
[65] Chang & Jones. (2010)
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[72] Rahel and Olden. (2008, p. 525)
[73] Pike et al. (2010, p. 703)
[74] Nickus et al. (2010, p. 51)
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[76] Austin et al. (2008, p. 189); Pike et al. (2010, p. 729)
[77] Nickus et al. (2010, p. 60)
[78] Allan, Palmer and Poff. (2005, pp. , p. 279)
[79] Poff, Brinson and Day. (2002, p. 15)
[80] Poff, Brinson and Day. (2002, p. 17)
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[104] Winder and Schindler. (2004a, p. 2100)
[105] Winder and Schindler. (2004a, p. 2103)
[106] Both et al. (2006, p. 81)
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[109] ADB. (2005, p. 7)
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[111] Gregg et al. (2011, p. 29)
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[123] Littell et al. (2009)
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[125] Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID. (2009); CIG (2007); ADB (2005); Pew Center (2009)
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[131] Glick et al. (2011a)

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LIST OF KEY ACRONYMS AND ABBREVIATIONS

AOGCM	Atmosphere-Ocean General Circulation Model
AR4	4th Assessment Report (produced by IPCC)
BC	Province of British Columbia, Canada
CA	State of California, United States
CIG	Climate Impacts Group
CO_2	Carbon Dioxide
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency, United States
GCM	Global Circulation Model
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LCC	Landscape Conservation Cooperative
LEK	Local Ecological Knowledge
MoE	Ministry of Environment, British Columbia
NASA	National Aeronautics and Space Administration, United States
NOAA	National Oceanic and Atmospheric Administration, United States
NPLCC	North Pacific Landscape Conservation Cooperative
O_2	Oxygen
OCAR	Oregon Climate Assessment Report (produced by OCCRI)
OCCRI	Oregon Climate Change Research Institute
OR	State of Oregon, United States
PCIC	Pacific Climate Impacts Consortium
PDO	Pacific Decadal Oscillation
PNW	Pacific Northwest
SLR	Sea Level Rise
SRES	Special Report on Emissions Scenarios
SWE	Snow Water Equivalent
TEK	Traditional Ecological Knowledge
WA	State of Washington, United States
WACCIA	Washington Climate Change Impacts Assessment (produced by CIG)

PREFACE

This report is intended as a reference document – a science summary – for the U.S. Fish and Wildlife Service (FWS) Region 1 Science Applications Program. The report compiles findings on climate change impacts and adaptation approaches in freshwater aquatic and riparian ecosystems within the North Pacific Landscape Conservation Cooperative area (NPLCC). The report is intended to make scientific information on climate change impacts within the NPLCC region accessible and useful for natural resources managers and others. It is produced by National Wildlife Federation under a grant from the U.S. FWS (FWS Agreement Number 10170AG200).

This report is a complete "Draft Final" version and represents the fulfillment of Phase One of a two phase project. Under Phase Two, funded through a separate grant, NWF will convene expert focus groups and produce a final report in 2012 that incorporates additional information. A companion "draft final" and final report compiling similar information on marine and coastal ecosystems within the NPLCC area will also be completed under the same timeline.

Production and Methodology

This report draws from peer-reviewed studies, government reports, and publications from non-governmental organizations to summarize climate change and ecological literature on historical baselines, observed trends, future projections, policy and management options, knowledge gaps, and the implications of climate change for species, habitats, and ecosystems in the freshwater environment. Because the report strives to reflect the state of knowledge as represented in the literature, in most cases language is drawn directly from cited sources. By compiling and representing verbatim material from relevant studies rather than attempting to paraphrase or interpret information from these sources, the authors sought to reduce inaccuracies and possible mis-characterizations by presenting data and findings in their original form. The content herein does not, therefore, necessarily reflect the views of National Wildlife Federation or the sponsors of this report. Given the extensive use of verbatim material, in order to improve readability while providing appropriate source attributions, we indicate those passages that reflect verbatim, or near verbatim, material through use of an asterisk (*) as part of the citation footnote. In general, verbatim material is found in the main body of the report, while the Executive Summary, Boxes, and Case Studies generally reflect the report authors' synthesis of multiple sources.

To produce this report, the authors worked with the University of Washington Climate Impacts Group (CIG) and reviewers from federal, state, tribal, non-governmental, and university sectors. CIG provided expert scientific review throughout the production process, as well as assistance in the design and organization of the report. Reviewers provided access to local data and publications, verified the accuracy of content, and helped ensure the report is organized in a way that is relevant and useful for management needs. In addition, we engaged early with stakeholders throughout the NPLCC region for assistance and input in the production of this report. More than 100 people provided input to or review of this document.

Description of Synthesis Documents Utilized

This report draws from primary sources as well as synthesis reports. In synthesis reports, we accepted information as it was presented. Readers are encouraged to refer to the primary sources utilized in those synthesis reports for more information. In most cases, we include the page number for reference. In cases where a primary source is referenced in a secondary source, we have indicated it in the footnote. The global, regional, state, and provincial level synthesis reports drawn from include:

- *Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4): Climate Change 2007.* (2007).
- *Global Climate Change Impacts in the United States.* (2009).
- *Alive and Inseparable: British Columbia's Coastal Environment* (2006).
- *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia.* (2010).
- *Environmental Trends in British Columbia: 2007.*
- *Climatic Change*, Volume 102, Numbers 1-2 (September 2010). This volume published the findings of the Washington Climate Change Impacts Assessment (WACCIA).
- *Washington Climate Change Impacts Assessment (WACCIA)* (2009).
- *Oregon Climate Assessment Report (OCAR)* (2010).
- *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008.*
- *Adapting to Climate Change: A Planning Guide for State Coastal Managers.* (2010).
- *Helping Pacific Salmon Survive the Impact of Climate Change on Freshwater Habitats.* (2007).
- *Preliminary review of adaptation options for climate-sensitive ecosystems and resources.* (2008).
- *Recommendations for a National Wetlands and Climate Change Initiative*. (2009).
- *Strategies for Managing the Effects of Climate Change on Wildlife and Ecosystems.* (2008).
- *The State of Marine and Coastal Adaptation in North America: A Synthesis of Emerging Ideas.* (2011).

How to Use This Document

Being the first reference document of its kind for the North Pacific LCC region, the extensive details on climate change trends and projections are necessary to provide baseline information on the NPLCC. However, we encourage the reader to focus on the general magnitude and direction of projections, their implications, and on the range of options available to address climate change impacts. It is our hope that this document will provide useful information to North Pacific LCC members and stakeholders, and help facilitate effective conservation that accounts for climate change and its impacts in the region.

Acknowledgements

We thank our partner, the U.S. Fish and Wildlife Service, for funding and support throughout the production of this report, with special thanks to the Region 1 Science Applications Program.

We are grateful to our partner, the University of Washington Climate Impacts Group, for their expertise and insight, and for the many improvements that came through their guidance.

We are indebted to the 100+ individuals who gave generously of their time and knowledge to inform the development of this report. With the expertise of reviewers and interviewees, we were able to acquire and incorporate additional peer-reviewed reports and publications evaluating climate change impacts on relatively small geographic scales. This allowed us to add nuance to the general picture of climate change impacts throughout the NPLCC geography. Further, this report benefitted tremendously from the resources, thoughtfulness, expertise, and suggestions of our 34 reviewers. Thank you for your time and effort throughout the review process. Reviewers and people interviewed are listed in Appendix 6.

We also thank Ashley Quackenbush, Matt Stevenson, and Dan Uthman for GIS support.

Suggested Citation

Tillmann, Patricia. and Dan Siemann. *Climate Change Effects and Adaptation Approaches in Freshwater Aquatic and Riparian Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature*. *Phase 1 Draft Final Report.* National Wildlife Federation – Pacific Region, Seattle, WA. August 2011.

I. INTRODUCTION

This report compiles existing knowledge on known and potential climate change effects on freshwater aquatic and riparian ecosystems within the geographic extent of the North Pacific Landscape Conservation Cooperative (NPLCC). The report also includes a menu of policy and management responses, culled from published science and grey literature, to adapt to climate change in marine and coastal environments. The North Pacific Landscape Conservation Cooperative is one of twenty-one Landscape Conservation Cooperatives (LCCs) planned for the United States, Canada, and Mexico.[1] LCCs are member-directed conservation partnerships among State and Federal agencies, Tribes, nongovernmental organizations, universities, existing partnership efforts, and other conservation entities.[2] Other key partners of the NPLCC will be the three regional Climate Science Centers (CSCs) within the geographic area of the NPLCC – Alaska, Northwest, and Southwest CSCs.[3] The CSCs will deliver basic climate change impact science for their region, prioritizing fundamental science, data and decision-support activities based principally on the needs of the LCCs.[4] LCCs will link the science with conservation delivery.[5] Thus, LCCs are management-science partnerships that inform resource management actions and provide needed tools.[6] More specifically, LCCs generate applied science to inform conservation actions related to climate change, habitat fragmentation, and other landscape-level stressors and resource issues.[7] For further information, please see http://www.fws.gov/science/shc/lcc.html (accessed March 14, 2011).

Description of NPLCC

The NPLCC region comprises approximately 204,000 square miles (530,000 square kilometers, km^2) in seven western U.S. states and Canadian provinces (see Figure 1).[8] The inland extent of the NPLCC is delineated according to the Pacific Flyway, ecoregions, and the crests of several mountain ranges and, from the coast, stretches inland up to 150 miles (~240 km); therefore only the lower extent of many of the larger river watersheds are included within the area. The total amount of coastline is approximately 38,200 miles (~ 61,500 km)[9] and extends from Kenai Peninsula in southcentral Alaska to Bodega Bay in northern California. Public lands make up approximately 78 percent, or 159,000 square miles (412,000

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1 *US Fish and Wildlife Service (US FWS). *Landscape Conservation Cooperatives: Better Conservation through Partnerships in the Pacific Region.* (2010, p. 1)
2 *US FWS. *North Pacific Landscape Conservation Cooperative*. (August 2010, p. 1)
3 US FWS. *North Pacific Landscape Conservation Cooperative (pdf, website).* (December 2010, p. 2). A total of eight CSCs are being established to support the 21 LCCs. They consist mainly of university-based consortiums.
4 *U.S. Department of the Interior. *Interior's plan for a coordinated, science-based response to climate change impacts on our land, water, and wildlife resources (pdf, website).* (n.d., p. 2)
5 *U.S. Department of the Interior. (n.d., p. 5)
6 *US FWS. (August 2010, p. 1)
7 *US FWS. (August 2010, p. 1)
8 US FWS. *North Pacific Landscape Conservation Cooperative High Resolution Map.* (2010). Within the Yukon Territory (YT; 186,272 mi^2, 482,443 km^2), the only land within the NPLCC region is that covered by the Kluane National Park and Preserve (8,487 $miles^2$, 21, 980 km^2; ~4.6% of total area in YT), located in the southwest corner of the Territory. Given the climate impacts in this area are likely to be more similar to adjacent lands in BC and AK than to the Territory as a whole, this report does not specifically address climate data and research from YT. While information on climate change adaptation planning in Kluane National Park and Preserve was limited, information for the Government of Yukon was available. Please see Chapter #, Section # for further information.
9 US FWS. (2010)

km^2) of the NPLCC, with 82,000 square miles (212,000 km^2) of Federal lands in the U.S. portion of the NPLCC and 77,000 square miles (200,000 km^2) of Crown lands in the Canadian portion of the NPLCC.[10]

Numerous small to medium-sized rivers and small, high elevation lakes occur throughout the region.[11] Several large freshwater and saline lakes are also prominent, as is Puget Sound.[12] To the north, glaciated basins increase and are especially common in Alaska.[13] Land types include wetlands, glaciers, forests, beaches, and estuaries. A wide variety of fish, wildlife, and other organisms populate this region. For example, forested habitats in the Pacific Coast range support many resident and migrant birds including the marbled murrelet, spotted owl, and Queen Charlotte goshawk, all species of conservation concern.[14] Recently deglaciated habitats in coastal Alaska are important to breeding Kittlitz's murrelets, also a species of concern.[15]

Organization of Report

Key findings begin in Chapter II, which describes observed trends and future projections, both globally and within the NPLCC geography, for greenhouse gas concentrations, temperature, and precipitation. Chapter III describes the primary effects of changes in greenhouse gas concentrations, temperature, and precipitation on the region's hydrology. The report then describes how the changes presented in Chapter II and the effects on hydrology presented in Chapter III impact freshwater ecosystems (Chapter IV), species, populations, and biological communities (Chapter V), and specific fish, amphibians, and macroinvertebrates in the NPLCC region (Chapter VI). In Chapter VII, the report provides a a menu of policy and management responses to address the impacts of climate change on species and habitats in the freshwater environment described in Chapters IV-VI. These responses are based on general tenets of climate change adaptation for natural systems and are culled from published scientific literature, grey literature, and interviews with experts throughout the NPLCC region. Chapter VIII briefly describes future work in the NPLCC region. Five appendices provide key terms and definitions, an explanation of climate modeling and emissions scenarios, an explanation of long-term climate variability, resources for adaptation principles and responses to climate change, and a list of reviewers and interviewees.

Definitions for Freshwater Aquatic and Riparian Environments

This report covers freshwater ecosystems, their hydrology, and the major physical components of these systems: wetlands, rivers, streams, lakes, ponds, reservoirs, and glaciers.[16] ***Freshwater ecosystems*** are aquatic systems which contain drinkable water or water of almost no salt content.[17] ***Hydrology*** is the science encompassing the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground; the *hydrologic cycle* refers to the existence and movement of water on, in, and above the Earth.[18]

[10] US FWS. (2010)
[11] *Melack et al. *Effects of climate change on inland waters of the Pacific coastal mountains and western Great Basin of North America*. (1997, p. 972)
[12] *Melack et al. (1997, p. 972)
[13] *Melack et al. (1997, p. 972)
[14] US FWS. (December 2010, p. 1)
[15] US FWS. (December 2010, p. 1)
[16] U.S. Environmental Protection Agency (EPA). *Aquatic Biodiversity: Freshwater Ecosystems (website).* (2010)
[17] *U.S. EPA. (2010)
[18] *Brooks et al. *Hydrology and the Management of Watersheds.* (2003)

Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water; wetlands may be permanent or intermittent (e.g. seasonal).[19] The U.S. Fish and Wildlife Service (FWS) defines wetlands as lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.[20] Major freshwater wetland types in the NPLCC region include non-tidal marshes such as wet meadows and vernal pools, forested and shrub swamps, bogs, and fens.[21] Wetlands can be found in lowlands or coastal areas, yet they frequently form the headwater areas for streams or lakes.[22] The patterns of water depth and the duration, frequency, and seasonality of flooding together constitute a wetland's hydroperiod, which determines its vegetation composition, habitat for aquatic organisms, and other ecosystem characteristics.[23]

Streams are defined as the water flowing in a natural channel (as distinct from a canal); ***river is*** the common term for a large stream.[24] The habitats and species that utilize a stream are determined by the stream's shape (i.e., straight, winding, width), the number of branches (zero, one, two or more), the types of rocks and soils that make up the channel and banks, access to and elevation compared to groundwater, and their characteristics over time and space (i.e., continuous, intermittent, seasonal or ephemeral flow; spatial continuity or interruption among stream segments).[25]

Lakes and reservoirs are deepwater habitats with all of the following characteristics: (1) situated in a topographic depression or a dammed river channel; (2) lacking trees, shrubs, persistent emergents, emergent mosses or lichens with greater than thirty percent coverage; (3) total area exceeds twenty acres (eight hectares).[26] A lake may be defined more simply as a very slowly flowing or nonflowing (lentic) open body of water in a depression and not in contact with the ocean (the definition includes saline lakes but excludes estuaries and other mainly marine embayments).[27] Reservoirs are distinguished from lakes: they are constructed by humans, often within river corridors, and levels are generally controlled by an outlet at a dam. Natural lakes that have been dammed may also function as partial reservoirs.

A ***glacier*** is a mass of land ice, formed by the further recrystallization of firn (i.e., old snow that has become granular and compacted), flowing continuously from higher to lower elevations.[28]

[19] *U.S. FWS. *660 FW 2, Wetlands Classification System (website).* (1993)
[20] Cowardin et al. *Classification of Wetlands and Deepwater Habitats of the United States, FWS/OBS-79/31*. (1979, p. 3)
[21] U.S. EPA. *Wetlands – Wetland Types (website). Available at http://water.epa.gov/type/wetlands/types_index.cfm (accessed 8.22.2011).*
[22] Brooks et al. (2003, p. 120)
[23] Poff, Brinson and Day. *Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States*. (2002, p. 18-19)
[24] Brooks et al. (2003); U.S. Geological Survey. *General introduction and hydrologic definitions (website).* (2008)
[25] Brooks et al. (2003); USGS (website).
[26] *Dahl. *Status and trends of wetlands in the conterminous United States 1986 to 1997.* (2000, p. 75). Lakes and reservoirs are part of the lacustrine system, as indicated in Table 1 (p. 15) of the cited report.
[27] Dodds & Whiles. (2010, p. 143)
[28] *American Meteorological Society. *Glossary of Meteorology (website).* (n.d.)

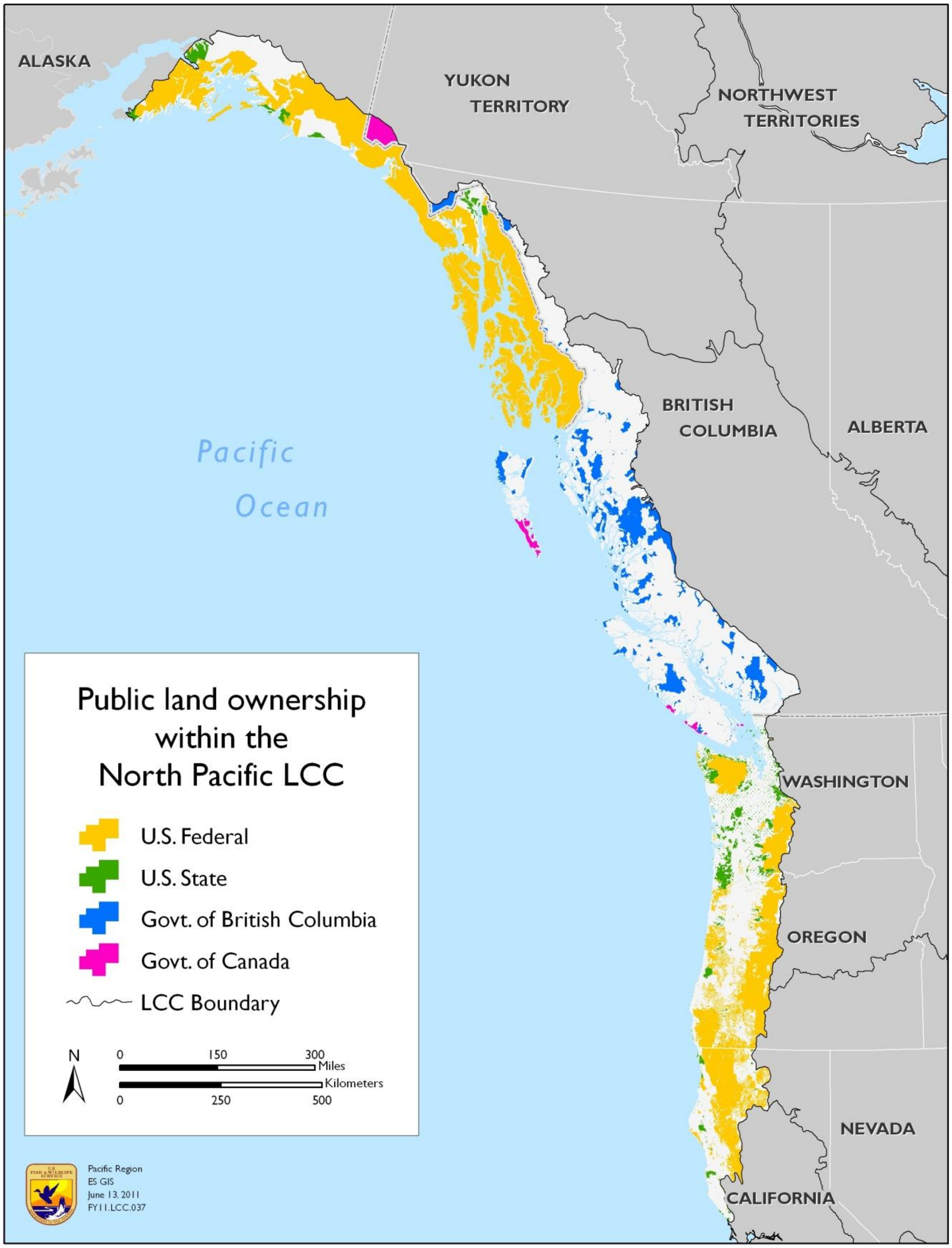

Figure 1. Public land ownership within the North Pacific Landscape Conservation Cooperative (NPLCC). *Source: U.S. Fish and Wildlife Service (2011). This is a preliminary land ownership map, including only federal, state, and provincial lands. At a later date, the map will be updated to include Native Alaskan, First Nations, and Tribal lands. Lands owned by other entities (e.g. NGOs, private property) may be included as well.*

II. CO_2 CONCENTRATIONS, TEMPERATURE, AND PRECIPITATION

Box 1. Summary of observed trends and future projections for greenhouse gas concentrations, temperature, and precipitation.

Observed Trends

- Atmospheric CO_2 concentrations in March 2011 were approximately 392 parts per million (ppm),[29] higher than any level in the past 650,000 years[30] and 41% higher than the pre-industrial value (278 ppm).[31] From 2000-2004, the emissions growth rate (>3%/yr) exceeded that of the highest-emissions IPCC scenario (A1F1), and the actual emissions trajectory was close to that of the A1F1 scenario.[32]
- Annual average temperatures in the NPLCC region increased, in general, 1-2°F (~0.6-1°C) over the 20th century.[33] Alaska is an exception – a 3.4°F (~1.9°C) increase was observed from 1949-2009.[34]
- In the 20th century and early 21st century, the largest increase in seasonal temperature occurred in winter (January-March): +3.3°F (+1.83°C) in western BC, OR, and WA[35] and +1.8-2.0ºF (+1.0-1.1ºC) in northwestern CA.[36] These increases tend to drive the annual trends, particularly in AK (+6.2°F or 3.4°C from 1949-2009 near Juneau).[37]
- In the 20th century and early 21st century, average annual precipitation trends are highly variable, with increases of 2 to approximately 7 inches (~5-18 cm) observed in WA, OR,[38] and northwestern CA,[39] and both small increases and decreases (±1inch or ±2.54 cm) observed in BC's Georgia Basin and coastal areas, depending on the time period studied.[40] Precipitation trends in Alaska were not available. However, precipitation was 32-39 inches (80-100cm) in southcentral Alaska and at least 39 inches (100cm) in southeast Alaska from 1949-1998.[41]
- In the 20th century and early 21st century, seasonal precipitation trends are highly variable, with increases in winter and spring precipitation observed in WA, OR,[42] and northwestern CA,[43] and both increases and decreases observed in BC, depending on location and time period.[44] Specifically, in WA and OR, spring precipitation increased +2.87 inches (7.29cm) and winter precipitation increased 2.47 inches (6.27cm) from 1920 to 2000.[45]

A summary of future projections can be found on the next page.

Note to the reader: In Boxes, we summarize the published and grey literature. The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

[29] National Oceanic and Atmospheric Administration (NOAA). (2011c)
[30] CIG. (2008)
[31] Forster et al. (2007, p. 141)
[32] Raupach et al. (2007)
[33] Mote (2003, p. 276); Butz and Safford (Butz and Safford 2010, 1). Butz and Safford refer the reader to Figures 1 & 2 in the cited report.
[34] Karl, Melillo and Peterson. (2009, p. 139). The authors cite Fitzpatrick et al. (2008) for this information.
[35] Mote. (2003, p. 276)
[36] Butz and Safford (Butz and Safford 2010, 1). The authors refer the reader to Figures 1 & 2 in the cited report.
[37] Alaska Climate Research Center (ACRC). (2009)
[38] Mote. (2003, p. 279)
[39] Killam et al. (2010, p. 2)

Future projections

- Projected atmospheric CO_2 concentrations in 2100 range from a low of about 600 ppm under the A1T, B1, and B2 scenarios to a high of about 1000 ppm in the A1F1 scenario.[46] Recent emissions trajectories are close to that of the A1F1 scenario.[47]
- By 2100, average annual temperatures in the NPLCC region are projected to increase 3.1-6.1°F (1.7-3.4°C) (excluding AK & BC, where temperatures are projected to increase 2.5-2.7°F (1.4-1.5°C) by 2050 and 5-13°F (2.8-7.2°C) after 2050, respectively).[48] The range of projected increases varies from 2.7 to 13°F (1.5-7.2°C); the largest increase is projected in AK.[49] Baselines for projections are: 1960s-1970s in AK, 1961-1990 in BC, 1970-1999 in the Pacific Northwest (PNW), and 1971-2000 in northwest CA.
- By 2100, seasonal temperatures are projected to increase the most in summer (region-wide: 2.7-9.0°F, 1.5-5°C): in BC, 2.7°F to 5.4˚F (1.5-3˚C) along the North Coast and 2.7°F to 9.0˚F (1.5-5˚C) along the South Coast. In WA and OR, 5.4-8.1˚F (3.0-4.5˚C).[50] The exception is AK, where seasonal temperatures are projected to increase the most in winter.[51] The baseline for projections varies by study location: 1960s-1970s in Alaska, 1961-1990 on the BC coast and northern CA, 1970-1999 in the PNW.
- Precipitation may be more intense, but less frequent, and is more likely to fall as rain than snow.[52] Annual precipitation is projected to increase in AK,[53] BC (2050s: +6% along the coast, no range provided),[54] and WA and OR (2070-2099: +4%, range of -10 to +20%),[55] but is projected to decrease in CA (2050: -12 to -35%, further decreases by 2100).[56] Increases in winter and fall precipitation drive the trend (+6 to +11% [-10 to +25% in winter] in BC and +8% [small decrease to +42%] in WA and OR), while decreases in summer precipitation mitigate the upward trend (-8 to -13% in BC [-50 to +5%] and -14% [some models project -20 to -40%] in WA and OR).[57] In southeast AK a 5.7% increase in precipitation during the growing season is projected (no range or baseline provided).[58] Baselines for BC, WA, OR, and CA are the same as those listed in the previous bullet.

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[40] Pike et al. (2010, Table 19.1, p. 701)
[41] Stafford, Wendler and Curtis. (2000, p. 41). Information obtained from Figure 7.
[42] Mote. (2003, p. 279)
[43] Killam et al. (2010, p. 4)
[44] Pike et al. (2010, Table 19.1, p. 701)
[45] Mote. (2003, p. 279)
[46] Meehl et al. (2007, p. 803). This information was extrapolated from Figure 10.26 by the authors of this report.
[47] Raupach et al. *Global and regional drivers of accelerating CO_2 emissions.* (2007)
[48] For BC, Pike et al. (2010, Table 19.3, p. 711). For AK, U.S. Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. *Climate Change (website).* (2008, Table 3) and Mote et al. (2010, p. 21). For CA, California Natural Resources Agency (NRA). (2009, p. 16-17), Port Reyes Bird Observatory (PRBO). (2011, p. 8), and Ackerly et al. (2010, Fig. S2, p. 9).
[49] For AK, Karl, Melillo and Peterson. (2009, p. 139). For WA and OR, CIG. *Climate Change (website).* (2008, Table 3) and Mote et al. (2010, p. 21). For CA, CA NRA.. (2009, p. 16-17) and PRBO. (2011, p. 8).
[50] For BC, BC Ministry of Environment (MoE). (2006, Table 10, p. 113). For OR and WA, Mote and Salathé, Jr. (2010, Fig. 9, p. 42).For CA, PRBO. (2011, p. 8).
[51] Karl, Melillo and Peterson. (2009)
[52] Karl, Melillo and Peterson. (2009)
[53] Karl, Melillo and Peterson. (2009, p. 139)
[54] Pike et al. (2010, Table 19.3, p. 711)
[55] Climate Impacts Group (CIG). *Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts (draft document; pdf).* (2010, p. 2)
[56] California Natural Resources Agency. (2009, p. 16-17)
[57] For BC, BC MoE. (2006, Table 10, p. 113). For OR & WA, Mote & Salathé, Jr. (2010, 42-44).
[58] Alaska Center for Climate Assessment and Policy. (2009, p. 31)

1. CARBON DIOXIDE (CO_2) CONCENTRATIONS – *global observed trends and future projections*

Observed Trends

- Overall change: Atmospheric CO_2 concentrations in March 2011 were approximately 392 parts per million (ppm),[59] higher than any level in the past 650,000 years[60] and 41% higher than the pre-industrial value (278 ppm).[61] Current CO_2 concentrations are about 3.4 percent higher than the 2005 concentration reported by the IPCC's Fourth Assessment Report (AR4: 379 ± 0.65 ppm).[62] From 2000-2004, the actual emissions trajectory was close to that of the high-emissions A1F1 scenario.[63]
- Annual growth rates
  - 1960-2005: CO_2 concentrations grew 1.4 ppm per year, on average.[64]
  - 1995-2005: CO_2 concentrations grew 1.9 ppm per year, on average.[65] This is the most rapid rate of growth since the beginning of continuous direct atmospheric measurements, although there is year-to-year variability in growth rates.[66]
  - 2000-2004: the emissions growth rate (>3%/yr) exceeded that of the highest-emissions IPCC scenario (A1F1).[67]
  - 2010: the annual mean rate of growth of CO_2 concentrations was 2.68 ppm.[68]

[59] NOAA. *Trends in Atmospheric Carbon Dioxde (website).* (2011c)
[60] CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website).* (2008)
[61] Forster et al. (2007, p. 141)
[62] Forster et al. (2007, p. 141)
[63] Raupach et al. *Global and regional drivers of accelerating CO_2 emissions.* (2007)
[64] IPCC. "Summary for Policymakers." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* (2007f, p. 2)
[65] IPCC. (2007f, p. 2)
[66] *IPCC. (2007f, p. 2)
[67] Raupach et al. (2007)
[68] NOAA. (2011c)

Box 2. The Special Report on Emissions Scenarios (SRES).

Changes in greenhouse gas (GHG, e.g. carbon dioxide, CO_2) and sulfate aerosol emissions are based on different assumptions about future population growth, socio-economic development, energy sources, and technological progress. Because we do not have the advantage of perfect foresight, a range of assumptions about each of these factors are made to bracket the range of possible futures, i.e. scenarios. Individual scenarios, collectively referred to as the IPCC Special Report on Emissions Scenarios or SRES scenarios, are grouped into scenario "families" for modeling purposes. Forty individual emissions scenarios are grouped into six families: A1F1, A1B, A1T, A2, B1, and B2. The "A" families are more economic in focus than the "B" families, which are more environmentally focused. The A1 and B1 families are more global in focus compared to the more regional A2 and B2. All scenarios are assumed to be equally valid, with no assigned probabilities of occurrence. While the scenarios cover multiple GHGs and multiple drivers are used to project changes, this report focuses on CO_2 because it is the major driver of climate change impacts and is tightly coupled with many ecological processes.

- The A1 scenarios (A1F1, A1B, and A1T) assume rapid economic growth, a global population that peaks in mid-century, and rapid introduction of new and more efficient technologies. They are differentiated by assumptions about the dominant type of energy source: the fossil-intensive A1F1, non-fossil intensive A1T, and mixed energy source A1B scenarios. Cumulative CO_2 emissions from 1990 to 2100 for the A1T, A1B, and A1F1 scenarios are 1061.3 Gigatons of carbon (GtC), 1492.1 GtC, and 2182.3 GtC, respectively. These correspond to a low-, medium-high, and high-emissions scenario, respectively.
- The B1 scenario assumes the same population as A1, but with more rapid changes toward a service and information economy. This is a low-emissions scenario: cumulative CO_2 emissions from 1990 to 2100 are 975.9 GtC.
- The B2 scenario describes a world with intermediate population and economic growth, emphasizing local solutions to sustainability. Energy systems differ by region, depending on natural resource availability. This is a medium-low emissions scenario: cumulative CO_2 emissions from 1990 to 2100 are 1156.7 GtC.
- The A2 scenario assumes high population growth, slow economic development, and slow technological change. Resource availability primarily determines the fuel mix in different regions. This is a high-emissions scenario: cumulative CO_2 emissions from 1990 to 2100 are 1855.3 GtC.

Scenario	Cumulative CO_2 emissions (GtC), 1990-2100	Population Growth Rate	Economic Development Rate	Fuels used
A1F1	2182.3	Peaks in mid-21st century	Rapid	Fossil fuel intensive
A1B	1492.1	Peaks in mid-21st century	Rapid	Mixed energy sources
A1T	1061.3	Peaks in mid-21st century	Rapid	Non-fossil fuel intensive
A2	1855.3	High	Slow	Determined by resource availability
B2	1156.7	Intermediate	Intermediate	Determined by resource availability
B1	975.9	Peaks in mid-21st century	Rapid – toward service & information economy	Non-fossil fuel intensive

Source: IPCC. *Climate Change 2007: Synthesis Report.* (2007); IPCC. *The SRES Emissions Scenarios (website).* (2010); IPCC. *IPCC Special Report on Emissions Scenarios: Chapters 4.3 & 5.1 (website).* (2010); IPCC. *SRES Final Data (version 1.1) Breakdown (website).* (2000); CIG. *Climate Change (website).* (2008).

Future Projections

- Compared to the concentration in 2005 (~379 ppm), atmospheric CO_2 concentrations are projected to increase over the period 2000-2100 across all six SRES scenarios,[69] from a low of about 600 ppm under the A1T, B1, and B2 scenarios to a high of about 1000 ppm in the A1F1 scenario.[70]
- *Note: Most projections in this chapter are based on climate modeling and a number of emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES, see Box 2 and Appendix 3 for further information).*[71]

Box 3. Why are atmospheric CO_2 concentrations, temperature, and precipitation important for a discussion of climate change effects on freshwater ecosystems?

- Increasing carbon dioxide concentrations in the atmosphere contribute to the greenhouse effect, leading to increases in global average air temperature.
- Changes in air temperature are reflected in water temperature, although there is a lag time due to the temperature-moderating effect of groundwater on surface waters.
- Warmer air holds more water vapor.
- Air temperature affects the timing of key hydrological events (e.g. snowmelt) as well as the amount of precipitation falling as rain and snow: increases in air temperature correspond to more rain, and less snow. Higher temperatures drive higher evapotranspiration and increase drying (even when precipitation is constant).
- Precipitation is important because its type (e.g. rain vs. snow), amount, frequency, duration, and intensity affect other hydrological processes such as the amount of snowpack, timing of snowmelt, amount and timing of streamflow, and frequency and intensity of flooding.
- Together, temperature, precipitation, and CO_2 concentrations affect the land (e.g. erosion), water (e.g. scour, flow), freshwater environment (e.g. nutrient cycling, disturbance regimes), and the habitats and biological communities dependent on each.

Sources: Allan, Palmer, and Poff (2005); Hamlet et al. (2007); Pew Center on Global Climate Change (2011); Rieman & Isaak (2010); Trenberth et al. (2007).

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[69] Meehl et al. *Climate Change 2007: The Physical Science Basis: Global Climate Projections.* (2007, p. 803). This information has been extrapolated from Figure 10.26 by the authors of this report.
[70] Meehl et al. (2007, p. 803). This information has been extrapolated from Figure 10.26 by the authors of this report.
[71] IPCC. *Climate Change 2007: Synthesis Report.* (2007c, p. 44)

2. TEMPERATURE – *global and regional observed trends and future projections*

Observed Trends

Globally

- In 2010, the combined land and ocean global surface temperature was 58.12°F (14.52°C; NCDC dataset).[72] This is tied with 2005 as the warmest year on record, at 1.12°F (0.62°C) above the 20th century average of 57.0°F (13.9°C; NCDC dataset).[73] The range associated with this value is plus or minus 0.13°F (0.07°C; NCDC dataset).[74]
    - From 1850 through 2006, 11 of the 12 warmest years on record occurred from 1995 to 2006.[75]
    - In 2010, Northern Hemisphere combined land and ocean surface temperature was the warmest on record: 1.31°F (0.73°C) above the 20th century average (NCDC dataset).[76]
- From 1906 to 2005, global average surface temperature increased ~1.34°F ± 0.33°F (0.74°C ± 0.18°C).[77]
    - From the 1910s to 1940s, an increase of 0.63°F (0.35°C) was observed.[78] Then, about a 0.2°F (0.1°C) decrease was observed over the 1950s and 1960s, followed by a 0.99°F (0.55°C) increase between the 1970s and the end of 2006 (Figure 2).[79]
- The 2001-2010 decadal land and ocean average temperature trend was the warmest decade on record for the globe: 1.01°F (0.56°C) above the 20th century average (NCDC dataset).[80]
    - From 1906-2005, the decadal trend increased ~0.13°F ± 0.04°F (0.07°C ± 0.02°C) per decade.[81] From 1955-2005, the decadal trend increased ~0.24°F ± 0.05°F (0.13°C ± 0.03°C) per decade.[82]
- Warming has been slightly greater in the winter months from 1906 to 2005 (December to March in the northern hemisphere; June through August in the southern hemisphere).[83] Analysis of long-term changes in daily temperature extremes show that, especially since the 1950s, the number of very cold days and nights has decreased and the number of extremely hot days and warm nights has increased.[84]

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[72] NOAA. *State of the Climate Global Analysis 2010 (website).* (2011b)
[73] NOAA. (2011b)
[74] NOAA. (2011b)
[75] *IPCC. *Climate Change 2007: Synthesis Report: Summary for Policymakers.* (2007g, p. 2)
[76] NOAA. *State of the Climate Global Analysis 2010 (website).* (2011b)
[77] *Trenberth et al. *Climate Change 2007: The Physical Science Basis: Observations: Surface and Atmospheric Climate Change.* (2007, p. 252)
[78] Trenberth et al. (2007, p. 252)
[79] Trenberth et al. (2007, p. 252)
[80] NOAA. (2011b)
[81] Trenberth et al. (2007, p. 237)
[82] Trenberth et al. (2007, p. 237)
[83] *Trenberth et al. (2007, p. 252)
[84] *Trenberth et al. (2007, p. 252)

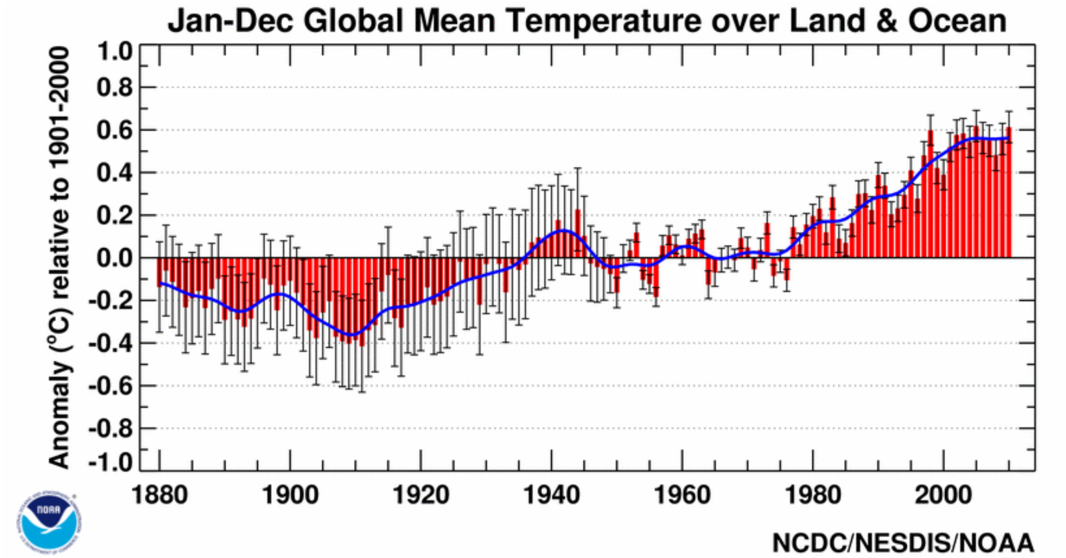


Figure 2. Jan-Dec Global Mean Temperature over Land & Ocean. *Source: NCDC/NESDIS/NOAA. Downloaded from http://www.ncdc.noaa.gov/sotc/service/global/global-land-ocean-mntp-anom/201001-201012.gif (7.27.2011).*

Southcentral and Southeast Alaska

- Annual average temperature has increased 3.4°F (~1.9°C) over the last fifty years, while winters have warmed even more, by 6.3°F (3.5°C).[85] The time period over which trends are computed is not provided. However, compared to a 1960s-1970s baseline, the average temperature from 1993 to 2007 was more than 2°F (1.1°C) higher.[86]
  - Annual average temperature increased 3.2°F (1.8°C) in Juneau over 1949-2009.[87] From 1971 to 2000, temperatures in Anchorage increased by 2.26°F (1.27°C).[88]
- From 1949 to 2009, winter temperatures increased the most, followed by sprng, summer, and autumn temperatures.[89] For example, in Juneau, winter temperatures increased by 6.2°F (3.4°C), spring temperatures increased by 2.9°F (1.6°C), summer temperatures increased by 2.2°F (1.2°C), and autumn temperatures increased 1.4°F (0.8°C).[90]

[85] *Karl, Melillo and Peterson. *Global Climate Change Impacts in the United States.* (2009, p. 139). The report does not provide a year range for this information. The authors cite Fitzpatrick et al. (2008) for this information.
[86] Karl, Melillo and Peterson. (2009, p. 139). See the figure entitled *Observed and Projected Temperature Rise*.
[87] Alaska Climate Research Center. *Temperature Change in Alaska (website).* (2009)
[88] Alaska Center for Climate Assessment and Policy. *Climate Change Impacts on Water Availability in Alaska (presentation).* (2009, p. 4)
[89] Alaska Climate Research Center. (2009)
[90] Alaska Climate Research Center. (2009)

- A comparison of official data from the National Climatic Data Center (NCDC) for 1971-2000 and unofficial National Weather Service (NWS) data for 1981-2010 for Juneau, Alaska indicates average annual, warm season (April – September), and cold season (October – March) temperatures have increased from 1971-2000 to 1981-2010 (Table 1):[91]
  - Annual: +0.6°F (+0.33°C), from 41.5°F (5.28°C) to 42.1°F (5.61°C).[92]
  - April-September: +0.2°F (+0.1°C), from 50.9°F (10.5°C) to 51.1°F (10.6°C).[93]
  - October-March: +0.8°F (+0.444°C), from 32.1°F (0.0556°C) to 32.9°F (0.500°C).[94]

Table 1. Annual and seasonal temperature trends for Juneau, AK over two thirty-year time periods.

		1971-2000* °F (°C)	1981-2010* °F (°C)	Absolute Change °F (°C)	Percent Change†
Annual	Average	41.5 (5.28)	42.1 (5.61)	+0.6 (+0.33)	+1.45
	Average maximum	47.6 (8.67)	48.1 (8.94)	+0.5 (+0.27)	+1.05
	Average minimum	35.3 (1.83)	36.1 (2.28)	+0.8 (+0.45)	+2.27
Warm season (April – Sept)	Average	50.9 (10.5)	51.1 (10.6)	+0.2 (+0.1)	+0.393
	Average maximum	58.2 (14.6)	58.3 (14.6)	+0.1 (0.06)	+0.172
	Average minimum	43.5 (6.39)	44.0 (6.67)	+0.5 (+0.28)	+1.15
Cold season (Oct – March)	Average	32.1 (0.0556)	32.9 (0.500)	+0.8 (+0.444)	+2.49
	Average maximum	37.0 (2.78)	37.7 (3.17)	+0.7 (+0.39)	+1.89
	Average minimum	27.2 (-2.67)	28.1 (-2.17)	+0.9 (+0.50)	+3.31

*Data for 1971-2000 are official data from the National Climatic Data Center (NCDC). Data for 1981-2010 are preliminary, unofficial data acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The official data for 1981-2010 are scheduled for release by NCDC in July 2011. The table was created by the authors of this report and approved by Tom Ainsworth and Rick Fritsch on June 10, 2011.
†Percent change reflects the relative increase or decrease from 1971-2000 to 1981-2010.

Western British Columbia

- Observed trends in the annually averaged daily minimum, mean, and maximum temperatures from 1950 to 2006 are available for four stations along the BC coast (Table 2).[95]

[91] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[92] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[93] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[94] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[95] BC Ministry of Environment (MoE). *Environmental Trends in British Columbia: 2007: Climate Change.* (2007, p. 7)

Table 2. Trends in the average daily minimum, mean, and maximum temperatures per decade in °F (°C) in southern coastal British Columbia, 1950-2006.

	Temperature	Annual	Winter	Spring	Summer	Autumn
Abbotsford Airport, near Vancouver	Minimum	0.72 (0.40)	1.58 (0.88)	0.86 (0.48)	0.58 (0.32)	0.23 (0.13)
	Average	0.59 (0.33)*	0.52 (0.29)*	0.68 (0.38)*	0.74 (0.41)*	0.27 (0.15)*
	Maximum	0.20 (0.11)	1.13 (0.63)	-0.41 (-0.23)	1.21 (0.67)	-0.76 (-0.42)
Comox Airport, east Vancouver Island	Minimum	0.58 (0.32)*	0.40 (0.22)*	0.79 (0.44)*	0.65 (0.36)*	0.38 (0.21)*
	Average	0.41 (0.23)*	0.40 (0.22)*	0.50 (0.28)*	0.45 (0.25)*	0.22 (0.12)*
	Maximum	0.23 (0.13)*	0.31 (0.17)*	0.23 (0.13)	0.27 (0.15)	0.11 (0.06)
Port Hardy Airport, NE Vancouver Island	Minimum	0.38 (0.21)*	0.43 (0.24)*	0.50 (0.28)*	0.45 (0.25)*	0.04 (0.02)
	Average	0.34 (0.19)*	0.49 (0.27)*	0.36 (0.20)	0.31 (0.17)	0.07 (0.04)
	Maximum	0.27 (0.15)*	0.52 (0.29)*	0.41 (0.23)*	0.14 (0.08)	0.05 (0.03)
Victoria Airport, near Victoria	Minimum	0.40 (0.22)*	0.36 (0.20)*	0.63 (0.35)*	0.45 (0.25)*	0.20 (0.11)*
	Average	0.45 (0.25)*	0.40 (0.22)*	0.58(0.32)*	0.52 (0.29)*	0.22 (0.12)*
	Maximum	0.43 (0.24)*	0.52 (0.29)*	0.43 (0.24)*	0.49 (0.27)*	0.18 (0.10)

Note: Asterisks indicate a statistically significant difference, meaning there is at least a 95% probability that the trend is not due to chance.
Source: Adapted from B.C. MoE. (2007, Table 1, p. 7-8) by authors of this report.

Pacific Northwest (Figure 3)

- Average 20th century warming was 1.64°F (0.91°C; the linear trend over the 1920-2000 period, expressed in degrees per century).[96]
- Warming over the 20th century varied seasonally, with average warming in winter being the largest (+3.3°F, +1.83°C), followed by summer (+1.93°F, +1.07°C), spring (+1.03°F, +0.57°C), and autumn (+0.32°F, +0.18°C).[97] Data reflect the linear trend over the 1920-2000 period, expressed in degrees per century; data for summer are significant at the 0.05 level.[98]
- Increases in maximum and minimum temperatures in the cool (October-March) and warm (April-September) seasons from 1916 to 2003 and from 1947 to 2003 have been observed (Table 3).[99]
- When comparing the 1981-2010 climate normals (i.e., the 30-year average) to the 1971-2000 climate normals, both maximum and minimum temperatures are about 0.5°F (~0.3°C) warmer on average in the new normals across the United States.[100] The averaged annual statewide increases in maximum and minimum temperatures observed over this period are:
    - **Maximum:** +0.3 to +0.5°F (~+0.2-0.3°C) in Washington and Oregon.[101]

[96] Mote. *Trends in temperature and precipitation in the Pacific Northwest during the Twentieth Century.* (2003, Fig. 6, p. 276)
[97] Mote (2003, Fig. 6, p. 276)
[98] Mote (2003, Fig. 6, p. 276)
[99] Hamlet et al. *Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States.* (2007, Table 1, p. 1475).
[100] *NOAA. *NOAA Satellite and Information Service: NOAA's 1981-2010 Climate Normals (website).* (2011a)
[101] *NOAA. (2011a, Fig. 1)

- **Minimum:** +0.3 to +0.5°F (~+0.2-0.3°C) in Washington and +0.1 to +0.3°F (~+0.06-0.3°C) in Oregon.[102]

Northwestern California

- PRISM data (a climate-mapping system) suggest that most of the Six Rivers National Forest area, located in northwestern California, experienced increases in mean annual temperature of about 1.8ºF (1ºC) between the 1930s and 2000s, although some coastal areas have seen a slight decrease in temperature.[103] Average temperatures at the Orleans station increased approximately 2ºF (1.1ºC) in the period from 1931 to 2009 (1931 baseline: ~56.2ºF, or ~13 ºC).[104] The trend is driven by a highly significant increase in mean minimum (i.e., nighttime) temperature, which rose by almost 4ºF (2.2ºC) between 1931 and 2009 (1931 baseline: ~42ºF, or ~5.5ºC).[105] *Note: For a figure showing mean annual temperature and annual temperature seasonality from 1971 to 2000, please see Figure S1 in the link included in the footnote.*[106]

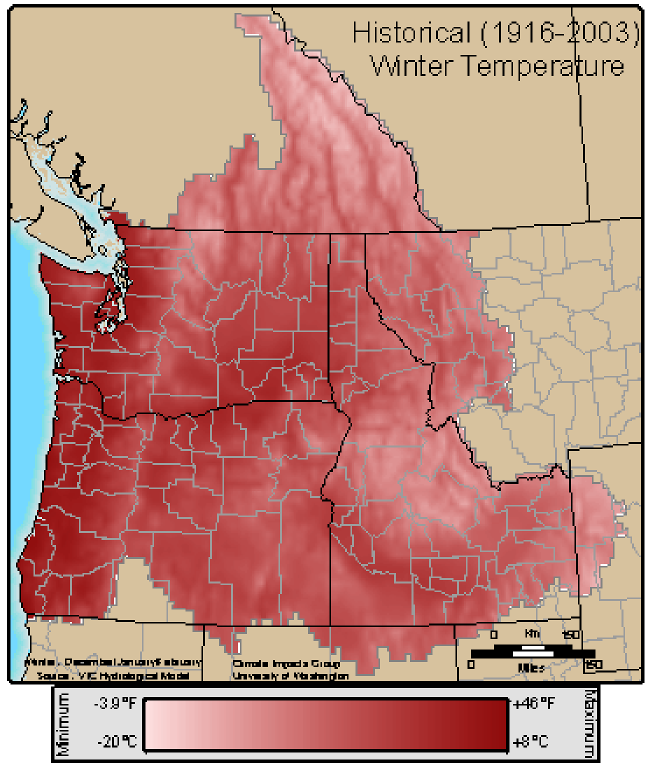


Figure 3. Historical average (1916-2003) winter temperature in the Pacific Northwest.
Source: Downloaded with permission from Center for Science in the Earth System August 13, 2011. (http://cses.washington.edu/cig/maps/index.shtml).

[102] *NOAA. (2011a, Fig. 2)
[103] *Butz and Safford. *A summary of current trends and probable future trends in climate and climate-driven processes for the Six Rivers National Forest and surrounding lands (pdf).* (2010, p. 1). Butz and Safford refer the reader to Figure 1 in the cited report.
[104] *Butz and Safford. (2010, p. 1). Butz and Safford refer the reader to Figure 1 in the cited report. For the 1931 baseline, please see Figure 2 in the cited report.
[105] *Butz and Safford. (2010, p. 1). Butz and Safford refer the reader to Figure 2 in the cited report.
[106] Ackerly et al. *The geography of climate change: implications for conservation biogeography (Supplemental Information)*. (2010). http://onlinelibrary.wiley.com/store/10.1111/j.1472-4642.2010.00654.x/asset/supinfo/DDI_654_sm_Data_S1andFig_S1-S8.pdf?v=1&s=93f8310b31bb81d495bae87579a8d7f4d710ca3e (accessed 6.8.2011).

- When comparing the 1981-2010 climate normals (i.e., the 30-year average) to the 1971-2000 climate normals, both maximum and minimum temperatures are about 0.5°F (~0.3°C) warmer on average in the new normals across the United States.[107] The averaged annual increase in maximum and minimum temperatures in California observed over this period are:
    - **Maximum:** +0.3 to +0.5°F (~+0.2-0.3°C).[108]
    - **Minimum:** +0.3 to +0.5°F (~+0.2-0.3°C).[109]

Table 3. Regional-scale maximum and minimum temperature trends during 1916-2003 and 1947-2003 for the cool season (October-March) and warm season (April-September) in the Pacific Northwest.
(°F per century with °C per century in parentheses; trends extrapolated from 1916-2003 and 1947-2003 data records)
Source: Modified from Hamlet et al. (2007, Table 1, p. 1475) by authors of this report.

Maximum temperature	October-March	1916-2003 1947-2003	1.82 (1.01) 3.47 (1.93)
	April-September	1916-2003 1947-2003	0.40 (0.22) 2.68 (1.49)
Minimum temperature	October-March	1916-2003 1947-2003	3.01 (1.67) 4.09 (2.27)
	April-September	1916-2003 1947-2003	2.43 (1.35) 3.47 (1.93)

Future Projections

Note: The studies presented here differ in the baseline used for projections. Baselines include 1980-1999 (IPCC), 1961-1990 (BC, CA), 1970-1999 (WA, OR), 1971-2000 (CA) and 1960-1970s (AK).

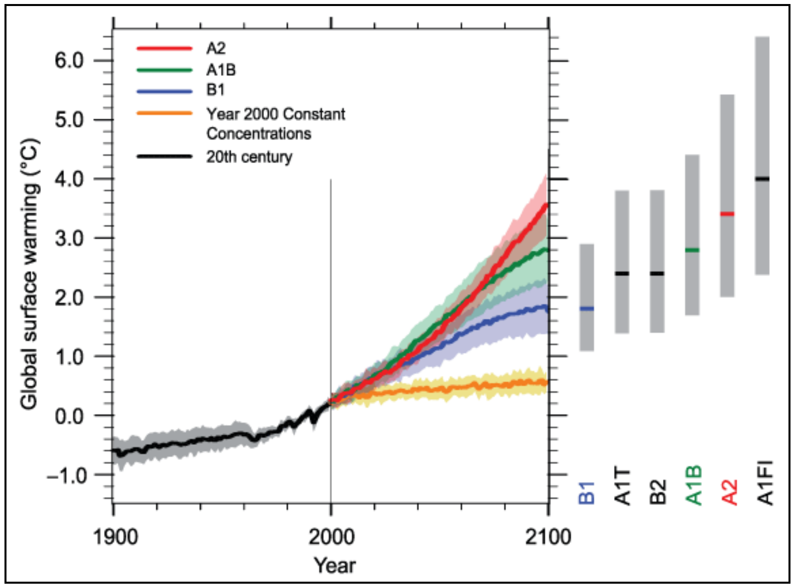
<u>Globally (1980-1999 baseline)</u>

- Even if greenhouse gas (GHG) concentrations were stabilized at year 2000 levels (not currently the case), an increase in global average temperature would still occur: 0.67°F (0.37°C) by 2011-2030, 0.85°F (0.47°C) by 2046-2065, 1.01°F (0.56°C) by 2080-2099, and 1.1°F (0.6°C) by 2090-2099 (all compared to a 1980-1999 baseline).[110,111]
- Global average temperatures are projected to increase at least 3.2°F (1.8°C) under the B1 scenario and up to 7.2°F (4.0°C) under the A1F1 scenario by 2090-2099 compared to a 1980-1999 baseline.[112] The range of projected temperature increases is 2.0°F (1.1°C) to 11.5°F (6.4°C) by 2090-2099, compared to a 1980-1999 baseline (Figure 4).[113]

[107] *NOAA. (2011a)
[108] *NOAA. (2011a, Fig. 1)
[109] *NOAA. (2011a, Fig. 2)
[110] *IPCC. (2007g, p. 8). See Figure SPM.1 for the information for 2090-2099.
[111] Meehl et al. (2007). Data for 2011-2030, 2046-2065, 2080-2099, and 2180-2199 were reproduced from Table 10.5 on p. 763. Data for 2090-2099 were obtained from p. 749.
[112] IPCC. (2007g, p. 8). See Figure SPM.1.
[113] IPCC. (2007, Table SPM.3, p. 13). AOGCMs are Atmosphere Ocean General Circulation Models.

- A study by Arora et al. (2011) suggests that limiting warming to roughly 3.6°F (2.0°C) by 2100 is unlikely since it requires an immediate ramp down of emissions followed by ongoing carbon sequestration after 2050.[114]

Figure 4. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the **likely** range assessed for the six SRES marker scenarios. The assessment of the best estimate and **likely** ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and10.29} *Source: Reproduced from IPCC.* (2007, Fig. SPM.5, p. 14) *by authors of this report.*



Southcentral and Southeast Alaska (1960s-1970s baseline)

- By 2020, compared to a 1960-1970s baseline, average annual temperatures in Alaska are projected to rise 2.0°F to 4.0°F (1.1-2.2°C) under both the low-emissions B1 scenarios and higher-emissions A2 scenario.[115]
- By 2050, average annual temperatures in Alaska are projected to rise 3.5°F to 6°F (1.9-3.3°C) under the B1 scenario, and 4°F to 7°F (2.2-3.9°C) under the A2 scenario (1960-1970s baseline).[116] Later in the century, increases of 5°F to 8°F (2.8-4.4°C) are projected under the B1 scenario, and increases of 8°F to 13°F (4.4-7.2°C) are projected under the A2 scenario (1960-1970s baseline).[117]
- On a seasonal basis, Alaska is projected to experience far more warming in winter than summer, whereas most of the United States is projected to experience greater warming in summer than in winter.[118]
- No data were found for mean temperatures associated with the ranges reported here.

[114] *Arora et al. *Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases.* (2011)
[115] Karl, Melillo and Peterson. (2009, p. 139). See the figure titled *Observed and Projected Temperature Rise* (section on Regional Impacts: Alaska)
[116] Karl, Melillo and Peterson. (2009, p. 139)
[117] Karl, Melillo and Peterson. (2009, p. 139)
[118] *Karl, Melillo and Peterson. (2009)

Western British Columbia (1961-1990 baseline)

- Along the North Coast by the 2050s, annual air temperature is projected to increase 2.5˚F (1.4˚C) compared to a 1961-1990 baseline (multi-model average; scenarios not provided).[119] Along the South Coast, annual air temperature is projected to increase 2.7˚F (1.5˚C) compared to a 1961-1990 baseline (multi-model average; scenarios not provided).[120] The North Coast extends from the border with Alaska to just north of Vancouver Island; the South Coast extends to the Washington border.[121]
- Along the North Coast by 2050, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
    - In winter, temperatures are projected to increase 0°F to 6.3˚F (0-3.5ºC), and
    - In summer, temperatures are projected to increase 2.7°F to 5.4˚F (1.5-3˚C).[122]
- Along the South Coast by 2050, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
    - In winter, temperatures are projected to increase 0°F to 5.4˚F (0-3˚C), and
    - In summer, temperatures are projected to increase 2.7°F to 9.0˚F (1.5-5˚C).[123]

Pacific Northwest (1970-1999 baseline)

- Average annual temperature could increase beyond the range of year-to-year variability observed during the 20th century as early as the 2020s.[124] Annual temperatures, averaged across all climate models under the A1B and B1 scenarios, are projected to increase as follows (1970-1999 baseline):
    - By the 2020s: 2.0˚F (1.1°C), with a range of 1.1˚F to 3.4˚F (0.61-1.9°C),
    - By the 2040s: 3.2˚F (1.8°C), with a range of 1.6˚F to 5.2˚F (0.89-2.89°C), and
    - By the 2080s: 5.3˚F (~3.0°C), with a range of 2.8˚F to 9.7˚F (1.56-5.4°C).[125]
- Seasonal temperatures, averaged across all models under the B1 and A1B scenarios, are projected to increase as described in Table 4 (compared to a 1970-1999 baseline).
- In another look at the Pacific Northwest by the 2080s, temperatures are projected to increase 2.7 to 10.4 °F (1.5-5.8 °C), with a multi-model average increase of 4.5˚F (2.5°C) under the B1 scenario and 6.1˚F (3.4°C) under the A1B scenario (1970-1999 baseline).[126]

[119] Pike et al. *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia.* (2010, Table 19.3, p. 711).
[120] Pike et al. (2010, Table 19.3, p. 711)
[121] Please see the map available at http://pacificclimate.org/resources/publications/mapview (accessed 3.16.2011).
[122] B.C. Ministry of Environment. *Alive and Inseparable: British Columbia's Coastal Environment: 2006*. (2006, Table 10, p. 113). The authors make the following note: From data in the Canadian Institute for Climate Studies, University of Victoria (*www.cics.uvic.ca*) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).
[123] B.C. Ministry of Environment. (2006, Table 10, p. 113). The authors make the following note: From data in the Canadian Institute for Climate Studies, University of Victoria (*www.cics.uvic.ca*) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000).
[124] *CIG. *Climate Change Scenarios: Future Northwest Climate (website).* (2008)
[125] CIG. *Climate Change: Future Climate Change in the Pacific Northwest (website).* (2008, Table 3)
[126] Mote, Gavin and Huyer. *Climate change in Oregon's land and marine environment.* (2010, p. 21)

Table 4. Projected multi-model average temperature increases, relative to the 1970-1999 mean. (°F with °C in parentheses) *Source: Modified from Mote and Salathé, Jr. (2010, Fig. 9, p. 42) by authors of this report. Please see Figure 9 in the cited report for the range of each average shown below.*						
	2020s		2040s		2080s	
	B1	A1B	B1	A1B	B1	A1B
Winter (Dec-Feb)	2.0 (1.1)	2.2 (1.2)	2.9 (1.6)	3.4 (1.9)	4.9 (2.7)	5.9 (3.3)
Spring (March-May)	1.8 (1.0)	1.8 (1.0)	2.5 (1.4)	3.1 (1.7)	3.8 (2.1)	5.0 (2.8)
Summer (June-Aug)	2.3 (1.3)	3.1 (1.7)	3.4 (1.9)	4.9 (2.7)	5.4 (3.0)	8.1 (4.5)
Fall (Sept-Nov)	1.8 (1.0)	2.0 (1.1)	2.7 (1.5)	3.6 (2.0)	4.3 (2.4)	6.1 (3.4)

Northwestern California (1961-1990 and 1971-2000 baselines)

- Compared to a 1961-1990 baseline under the B1 and A2 scenarios, California-wide annual average temperatures are projected to increase as follows:
  - By 2050: 1.8 to 5.4 ˚F (1-3 °C), and
  - By 2100: 3.6 to 9 ˚F (2-5 °C).[127]
- In northwestern California, regional climate models project mean annual temperature increases of 3.1 to 3.4°F (1.7-1.9°C) by 2070 (no baseline provided).[128] In contrast, Ackerly et al. (2010) project a mean annual temperature increase of more than 3.6˚F (2°C) but less than 5.4˚F (3°C) by 2070-2099 (Figure 5; 1971-2000 baseline).[129]
  - By 2070, mean diurnal (i.e., daily) temperature range is projected to increase by 0.18 to 0.36˚F (0.1-0.2°C) based on two regional climate models.[130] No baseline was provided.
- In northern California, Cayan et al. (2008) project average annual temperature increases of 2.7°F (1.5°C) or 4.9°F (2.7°C) under the B1 scenario (PCM and GFDL models, respectively) and 4.7°F (2.6°C) or 8.1°F (4.5°C) (PCM and GFDL models, respectively) under the A2 scenario by 2070-2099 (1961-1990 baseline).[131]
- Seasonally, the projected impacts of climate change on thermal conditions in northwestern California will be warmer winter temperatures, earlier warming in the spring, and increased summer temperatures.[132] Average seasonal temperature projections in northern California are as follows (1961-1990 baseline):[133]
  - Winter projections:
    - 2005-2034: at least ~0.18°F (0.1°C; A2, PCM model) and up to 2.5°F (1.4°C; A2, GFDL model).

[127] California Natural Resources Agency. *2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008*. (2009, p. 16-17). Figure 5 (p. 17) indicates projections are compared to a 1961-1990 baseline.
[128] *Port Reyes Bird Observatory. *Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0 (pdf).* (2011, p. 8)
[129] Ackerly et al. (2010, Fig. S2, p. 9). Ackerly et al. use bias-corrected and spatially downscaled future climate projections from the CMIP-3 multi-model dataset. Data are downscaled to 1/8th degree spatial resolution (see p. 2).
[130] *Port Reyes Bird Observatory. (2011, p. 8). This data was based on two regional climate models presented in Stralberg et al. (2009).
[131] Cayan et al. *Climate change scenarios for the California region*. (2008, Table 1, p. S25)
[132] *Port Reyes Bird Observatory. (2011, p. 8)
[133] Cayan et al. (2008, Table 1, p. S25)

    - 2035-2064: at least 1.6°F (0.9°C; A2, PCM model) and up to 4.3°F (2.4°C; B1, PCM model).
    - 2070-2099: at least 3.1°F (1.7°C; B1, PCM model) and up to 6.1°F (3.4°C; A2, GFDL model).
  - Summer projections:
    - 2005-2034: at least ~1°F (0.6°C; B1, PCM model) and up to 3.8°F (2.1°C; A2, GFDL model).
    - 2035-2064: at least ~2.0°F (1.1°C; B1, PCM model) and up to 6.1°F (3.4°C; A2, GFDL model).
    - 2070-2099: at least 2.9°F (1.6°C; B1, PCM model) and up to ~12°F (6.4°C; A1, GFDL model).
- Coastal regions are likely to experience less pronounced warming than inland regions.[134]

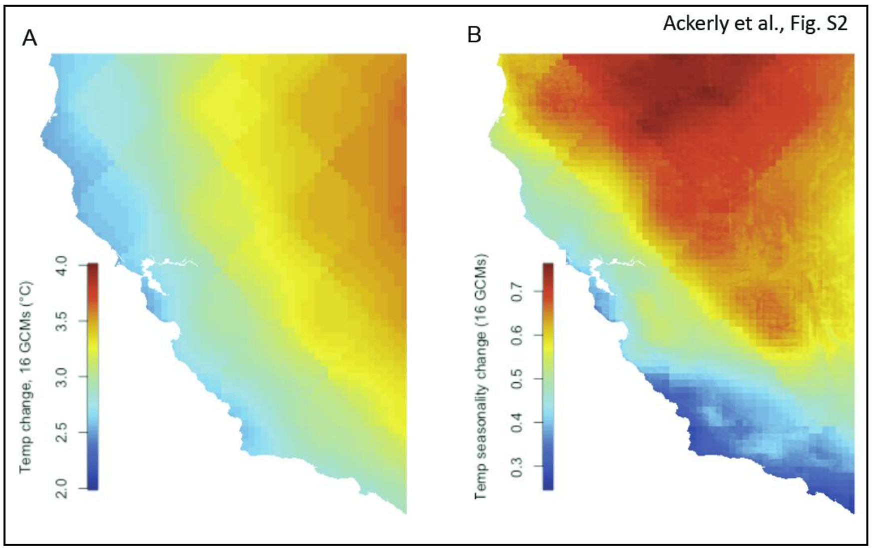


Figure 5. Changes in (A) mean annual temperature and (B) temperature seasonality, averaged over 16 GCMs, A1B scenario, for 2070-2099 (1971-2000 baseline).
Source: Reproduced from Ackerly et al. (2010, Fig. S2, p. 9) by authors of this report.
Note: Temperature seasonality is the standard deviation of monthly means. Lower values indicate temperature varies less throughout the year, i.e. temperature is more constant throughout the year in blue areas than in yellow and red areas.

[134] *California Natural Resources Agency. (2009, p. 17)

3. PRECIPITATION – *global and regional observed trends and future projections*

Observed Trends

Note: Please see Box 4 for information on extreme precipitation in the NPLCC region.

Global (see also: projections below)

- Atmospheric moisture amounts are generally observed to be increasing after about 1973 (prior to which reliable atmospheric moisture measurements, i.e. moisture soundings, are mostly not available).[135]
- Most of the increase is related to temperature and hence to atmospheric water-holding capacity,[136] i.e. warmer air holds more moisture.

Southcentral and Southeast Alaska

- In southeast Alaska from 1949 to 1998, mean total annual precipitation was at least 39 inches (1000 mm).[137] The maximum annual precipitation over this period was 219 inches (5577 mm) at the Little Port Walter station on the southeast side of Baranof Island about 110 miles (177 km) south of Juneau.[138]
- In southcentral Alaska from 1949 to 1998, mean total annual precipitation was at least 32 inches (800 mm) and up to 39 inches (1000 mm).[139]
- A comparison of official data from the National Climatic Data Center (NCDC) for 1971-2000 and unofficial National Weather Service (NWS) data for 1981-2010 for Juneau, Alaska indicates annual, warm season, and cold season precipitation increased.[140] The official NCDC record indicates average snowfall increased from 1971-2000 to 1981-2010, but the local NWS database indicates average snowfall decreased over the same time periods (Table 5, see notes).[141] In addition:
    - The date of first freeze occurred, on average, one day earlier over 1981 to 2010 than over 1971 to 2000, on October 3 instead of October 4.[142]
    - The date of last freeze occurred two days earlier, on average, over 1981 to 2010 than over 1971 to 2000, on May 6 instead of May 8.[143]

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[135] *Trenberth et al. *The changing character of precipitation.* (2003, p. 1211). The authors cite Ross and Elliott (2001) for this information.
[136] *Trenberth et al. (2003, p. 1211).
[137] Stafford, Wendler and Curtis. *Temperature and precipitation of Alaska: 50 year trend analysis.* (2000, Fig. 7, p. 41).
[138] Stafford, Wendler and Curtis. (2000, Fig. 7, p. 41)
[139] Stafford, Wendler and Curtis. (2000, Fig. 7, p. 41)
[140] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[141] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[142] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.
[143] This information was obtained from and approved by Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on June 10, 2011.

Table 5. Annual and seasonal precipitation and date of freeze trends for Juneau, AK over two thirty-year time periods.

		1971-2000* inches (cm)	1981-2010* inches (cm)	Absolute Change inches (cm)	Percent Change†
Annual and date of freeze trends	Total annual precipitation (including melted snow)	58.33 (148.2)	62.17 (157.9)	+3.84 (+9.75)	+6.58
	Average snowfall (Jan-Dec, NWS/Juneau)	93.0# (236)	86.8 (220)	-6.2 (-16)	-6.7
	Average snowfall (Jan-Dec, NCDC/Asheville)	84.1# (214)	N/A*	N/A	N/A
	Date of first freeze, on average	October 4	October 3	One day earlier	N/A
	Date of last freeze, on average	May 8	May 6	Two days earlier	N/A
Warm season (April – Sept)	Average seasonal precipitation (mostly rain)	26.85 (68.20)	28.52 (72.44)	+1.67 (+4.24)	+6.22
	Average snowfall (NWS/Juneau)	1.0 (2.5)	1.1 (2.8)	+0.1 (+0.3)	+10
	Average snowfall (NCDC/Asheville)	1.0 (2.5)	N/A*	N/A	N/A
Cold season (Oct – March)	Average seasonal precipitation	31.48 (79.96)	33.65 (85.47)	+2.17 (+5.51)	+6.89
	Average snowfall (NWS/Juneau)	92.0# (234)	85.7 (218)	-6.3 (-16)	-6.8
	Average snowfall (NCDC/Asheville)	83.1# (211)	N/A*	N/A	N/A

*Data for 1971-2000 are official data from the National Climatic Data Center (NCDC). Data for 1981-2010 are preliminary, unofficial data acquired from Tom Ainsworth and Rick Fritsch (Meteorologists, NOAA/National Weather Service, Juneau) on May 12, 2011. The official data for 1981-2010 are scheduled for release by NCDC in July 2011. The table was created by the authors of this report and approved by Tom Ainsworth and Rick Fritsch on June 10, 2011.
†Percent change reflects the relative increase or decrease from 1971-2000 to 1981-2010.
#Two values for average snowfall for 1971-2000 are reported due to differences between the locally held National Weather Service (NWS) database in Juneau and the official NWS database in Asheville, North Carolina. Differences represent the quality assurance processing and filtering that occurs at the National Climatic Data Center (NCDC) in Asheville (the source of official U.S. climate data) as well as missing data in the NCDC record. The Juneau office of the NWS is investigating the discrepancy.

<u>Western British Columbia</u>

- Annual and seasonal precipitation trends over thirty, fifty, and 100-year time periods in the Georgia Basin and remaining coastal regions of B.C. within the NPLCC region are summarized in Table 6.[144] The Georgia Basin includes eastern Vancouver Island and a small portion of the mainland east of Vancouver Island; the coastal region includes all remaining areas in B.C. within the NPLCC region.[145]

[144] Pike et al. *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia.* (2010, Table 19.1, p. 701)
[145] Pike et al. *Compendium of forest hydrology and geomorphology in British Columbia: Climate Change Effects on Watershed Processes in British Columbia.* (2010, Fig. 19.1, p. 702)

Table 6. Historical trends precipitation in 30-, 50-, and 100-year periods, calculated from mean daily values as seasonal and annual averages.
(inches per month per decade, with millimeters per month per decade in parentheses)
Source: Modified from Pike et al. (2010, Table 19.1, p. 701) by authors of this report.

	Time period	*Coastal B.C.*	*Georgia Basin*
Annual	30-year: 1971-2004	0.064 (1.63)	-0.017 (-0.42)
	50-year: 1951-2004	0.040 (1.01)	-0.017 (-0.43)
	100-year: 1901-2004	0.089 (2.25)	0.047 (1.20)
Winter (Dec-Feb)	30-year: 1971-2004	-0.24 (-6.08)	-0.32 (-8.06)
	50-year: 1951-2004	-0.12 (-3.06)	-0.21 (-5.35)
	100-year: 1901-2004	0.13 (3.39)	0.070 (1.78)
Summer (June-Aug)	30-year: 1971-2004	0.14 (3.50)	-0.071 (-1.80)
	50-year: 1951-2004	0.083 (2.11)	-0.011 (-0.27)
	100-year: 1901-2004	0.036 (0.91)	0.034 (0.93)

Pacific Northwest

- Annual precipitation increased 12.9% (6.99”; 17.76cm) from 1920 to 2000.[146]
- Observed relative increases were largest in the spring (+37%; +2.87”; 7.29cm), followed by winter (+12.4%; 2.47”; 6.27cm), summer (+8.9%; +0.39”; 0.99cm), and autumn (+5.8%; +1.27”; 3.22cm) from 1920 to 2000.[147] The spring trend (April-June) is significant at the $p < 0.05$ level.[148]
- From about 1973 to 2003, clear increases in the variability of cool season precipitation over the western U.S. were observed.[149]
- *Note: For the reader interested in trends in mean temperature, maximum temperature, minimum temperature, and precipitation annually, seasonally, and monthly, an online mapping tool produced by the Office of the Washington State Climatologist is available at http://www.climate.washington.edu/trendanalysis/ (accessed 6.8.2011).*

146 Mote. *Trends in temperature and precipitation in the Pacific Northwest during the Twentieth Century*. (2003, p. 279)
147 Mote. (2003, p. 279)
148 Mote. (2003, p. 279)
149 Hamlet and Lettenmaier. *Effects of 20th century warming and climate variability on flood risk in the western U.S*. (2007, p. 15)

Northwestern California

- A preliminary study found annual precipitation increased 2 to 6 inches (~5-15cm) from 1925 to 2008.[156] There also appears to be a shift in seasonality of precipitation: an increase in winter and early spring precipitation and a decrease in fall precipitation from 1925 to 2008.[157]
- From 1925 to 2008, the daily rainfall totals show a shift from light rains to more moderate and heavy rains that is especially evident in northern regions.[158] The increase in precipitation intensity over this time period is similar to results from other regions of the United States.[159]

Future Projections

Note: The studies presented here differ in the baseline used for projections. Baselines include 1961-1990 (BC, CA) and 1970-1999 (WA, OR).

Note: Please see Box 4 for information on extreme precipitation in the NPLCC region.

Global

- Global precipitation patterns are projected to follow observed recent trends, increasing in high latitudes and decreasing in most subtropical land regions.[160] Overall, precipitation may be more intense, but less frequent, and is more likely to fall as rain than snow.[161]
- *Note: There is greater confidence overall in projected temperature changes than projected changes in precipitation given the difficulties in modeling*

Box 4. Trends and projections for extreme precipitation in the NPLCC region.

Trends. In the Pacific Northwest, trends in extreme precipitation are ambiguous.[150] Groisman et al. (2004) find no statistical significance in any season in the Pacific Northwest (1908-2000).[151] Madsen and Figdor (2007) find a statistically significant increase of 18% (13-23%) in the Pacific states (WA, OR, CA), a statistically significant increase of 30% (19-41%) in Washington, and a statistically significant decrease of 14% (-4 to – 24%) in Oregon (1948-2006).[152] In southern British Columbia and along the North Coast, Vincent and Mekis (2006) report some stations showed significant increases in very wet days (the number of days with precipitation greater than the 95th percentile) and heavy precipitation days (≥0.39", 1.0cm).[153] A limited number of stations also showed significant decreases.

Projections. Precipitation patterns in the Northwest are expected to become more variable, resulting in increased risk of extreme precipitation events, including droughts.[154] In northern California, daily extreme precipitation occurrences (99.9 percentile) are projected to increase from 12 occurrences (1961-1990) to 25 (+108%) or 30 (+150%) occurrences by 2070-2099 under A2 simulations in the PCM and GFDL models, respectively.[155]

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150 Mote, Gavin and Huyer. (2010, p. 17)
151 Groisman et al. *Contemporary changes in the hydrological cycle over the contiguous United States: Trends dervied from in situ observations.* (2004, Fig. 8, p. 71)
152 Madsen and Figdor. *When it rains, it pours: Global warming and the rising frequency of extreme participation in the United States (pdf).* (2007, App. A & B, p. 35-37)
153 Vincent and Mekis. *Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century*. (2006, Fig. 5, p. 186)
154 Capalbo et al. *Toward assessing the economic impacts of climate change on Oregon.* (2010, p. 374)
155 Cayan et al. (2008, Table 4, p. S30). For the 99 percentile, the occurrence of extreme precipitation is projected to increase from 111 (1961-1990) to 161 (45%) or 127 (~14%) occurrences by 2070-2099 under A2 simulations in the PCM and GFDL models, respectively.
156 Killam et al. *California rainfall is becoming greater, with heavier storms*. (2010, p. 2)
157 *Killam et al. (2010, p. 4)
158 *Killam et al. (2010, p. 3)
159 *Killam et al. (2010, p. 3)
160 *IPCC. (2007g, p. 8)
161 *Karl, Melillo and Peterson. (2009)

precipitation[162] *and the relatively large variability in precipitation (both historically and between climate model scenarios) compared with temperature.*

Southcentral and Southeast Alaska (1961-1990 and 2000 baseline)

- Climate models project increases in precipitation over Alaska.[163] Simultaneous increases in evaporation due to higher air temperatures, however, are expected to lead to drier conditions overall, with reduced soil moisture.[164]
    - Using a composite of five Global Circulation Models (GCMs) under the A1B scenario,[165] one study projects an average increase of 0.59 inches (15 mm) by 2090-2099 (1961-1990 baseline), from a mean of 3.1 inches (78 mm) in the 1961-1990 period to a mean of 3.7 inches (93 mm) in the 2090-2099 period, an approximately 19% increase from the 1961-1990 mean at the rate of approximately 0.059 inches per decade (+1.5 mm/decade).[166]
- In the coastal rainforests of southcentral and southeast Alaska, precipitation during the growing season (time period between last spring freeze and first fall frost) is projected to increase approximately four inches (~100 mm, or 5.7%) from 2000 to 2099, from approximately 69 inches (~1750 mm) in 2000 to approximately 73 inches (1850 mm) in 2099 using a GCM composite (scenario not provided).[167]
- The University of Alaska – Fairbanks Scenarios Network for Alaska Planning (SNAP) has web-based mapping tools for viewing current and future precipitation under the B1, A1B, and A2 scenarios for the 2000-2009, 2030-2039, 2060-2069, and 2090-2099 decades (baseline not provided). Tools are available at http://www.snap.uaf.edu/web-based-maps (accessed 3.16.2011).[168]

Western British Columbia (1961-1990 baseline)

- By the 2050s, annual precipitation is projected to increase 6% (range not provided) along the B.C. coast compared to a 1961-1990 baseline (multi-model average; scenarios not provided).[169]
- Along the North Coast by the 2050s, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
    - In winter, precipitation is projected to increase 6%[170] (0 to +25%),[171]
    - In spring, precipitation is projected to increase 7% (range not provided),
    - In summer, precipitation is projected to decrease 8%[172] (-25 to +5%),[173] and
    - In fall, precipitation is projected to increase 11% (range not provided).[174]

162 CIG. (2008) The authors cite the IPCC AR4, Chapter 8 of the Working Group I report, for this information.
163 Karl, Melillo and Peterson. (2009, p. 139)
164 *Karl, Melillo and Peterson. (2009, p. 139). The authors cite Meehl et al. (2007) for this information.
165 Alaska Center for Climate Assessment and Policy. (2009, p. 10-11)
166 Alaska Center for Climate Assessment and Policy. (2009, p. 13)
167 Alaska Center for Climate Assessment and Policy. (2009, p. 31)
168 Maps are also available for current and future mean annual temperature, date of thaw, date of freeze up, and length of growing season. The scenario and decadal options are the same as those described for precipitation.
169 Pike et al. (2010, Table 19.3, p. 711)
170 Pike et al. (2010, Table 19.3, p. 711)
171 B.C. Ministry of Environment. (2006, Table 10, p. 113). B.C. Ministry of Environment makes the following note: "From data in the Canadian Institute for Climate Studies, University of Victoria (*www.cics.uvic.ca*) study of model results from eight global climate modelling centres. A total of 25 model runs using the eight models were used to determine the range of values under different IPCC emission scenarios (Nakicenovic and Swart 2000)."
172 Pike et al. (2010, Table 19.3, p. 711)
173 B.C. Ministry of Environment. (2006, Table 10, p. 113)

- Along the South Coast by the 2050s, seasonal projections are as follows compared to a 1961-1990 baseline (multi-model average; scenarios not provided):
    - In winter, precipitation is projected to increase 6%[175] (-10 to +25%),[176]
    - In spring, precipitation is projected to increase 7% (range not provided),[177]
    - In summer, precipitation is projected to decrease 13%[178] (-50 to 0%),[179] and
    - In fall, precipitation is projected to increase 9% (range not provided).[180]

Pacific Northwest (1970-1999 baseline)

- Annual average precipitation is projected to increase as follows (1970-1999 baseline):
    - By 2010-2039, precipitation is projected to increase 1% (-9 to +12%),
    - By 2030-2059, precipitation is projected to increase increase 2% (-11 to +12%), and
    - By 2070-2099, precipitation is projected to increase 4% (-10 to +20%).[181]
- Winter projections are as follows (1970-1999 baseline):
    - In 2010-2039 and 2030-2059, 58 to 90% of models project increases in precipitation.[182]
    - In 2070-2099, an 8% increase in precipitation is projected (small decrease to +42%; 1.2 inches; ~3cm).[183]
- Summer precipitation is projected to decrease 14% by the 2080s, although some models project decreases of 20 to 40% (1.2-2.4 inches; 3-6cm) compared to a 1970-1999 baseline.[184]
- These regionally averaged precipitation projections reflect all B1 and A1B simulations, along with the weighted reliability ensemble average (REA, an average that gives more weight to models that perform well in simulating 20th century climate).[185]

Northwestern California (1961-1990 baseline)

- Annual average precipitation is projected to decrease 12 to 35% by mid-century, with further decreases expected by 2070-2099 compared to a 1961-1990 baseline. [186] Over 2005-2034, small to moderate decreases are projected compared to a 1961-1990 baseline.[187] These projections are based on six climate models using the A2 and B1 emissions scenarios.[188]

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[174] Pike et al. (2010, Table 19.3, p. 711)
[175] Pike et al. (2010, Table 19.3, p. 711)
[176] B.C. Ministry of Environment. (2006, Table 10, p. 113)
[177] Pike et al. (2010, Table 19.3, p. 711)
[178] Pike et al. (2010, Table 19.3, p. 711)
[179] B.C. Ministry of Environment. (2006, Table 10, p. 113)
[180] Pike et al. (2010, Table 19.3, p. 711)
[181] The range of precipitation reported here was obtained from the Climate Impacts Group. It can be found in a document titled *Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts.* A draft version is available online at http://www.ecy.wa.gov/climatechange/2010TAGdocs/20100521_projecteddrivers.pdf (last accessed 1.5.2011).
[182] Mote and Salathé Jr. *Future climate in the Pacific Northwest.* (2010, p. 43-44)
[183] Mote and Salathé Jr. (2010, p. 43-44)
[184] Mote and Salathé Jr. (2010, p. 42)
[185] Mote and Salathé Jr. (2010, p. 39)
[186] *California Natural Resources Agency. (2009, p. 17-18)
[187] *California Natural Resources Agency. (2009, p. 17-18)
[188] California Natural Resources Agency. (2009, p. 17-18)

Information Gaps

- Information on seasonal temperature projections in California is needed.
- One reviewer suggested updated regional runs could be made for Oregon and Washington. Another reviewer stated precipitation extremes are generally not well captured due to the spatial scale of the GCMs. Regional scale models are providing some guidance (e.g., Salathe et al., 2010), but additional research is needed.
- Peterson and Schwing (2008) identify four categories of information needs for the California Current region (south of Vancouver, B.C.) – climate data, monitoring, models, and climate products and forecasts:
    - Climate data are needed to provide the climate forcing and environmental context for climate impacts on the CCE, for developing science-based operational indicators, and to provide continuity of satellite data and products.[189]
    - Monitoring needs include large-scale monitoring to provide information on gyre-scale circulation, monitoring in the coastal region, and maintaining NDBC monitoring and data archives.[190]
    - Modeling of climate and atmospheric and oceanic physics needs to be linked with similar work being carried out by NOAA and its partners.[191]
    - Climate product and forecasting needs include indicators and indices of climate variability, seasonal and longer-term forecasts and projections, and additional research to understand the mechanisms linking equatorial ENSO processes and teleconnections with California Current conditions and their populations.[192]

[189] *Peterson and Schwing. *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs: California Current Ecosystem.* (2008, p. 49)
[190] *Peterson and Schwing. (2008, p. 49)
[191] *Peterson and Schwing. (2008, p. 49)
[192] *Peterson and Schwing. (2008, p. 50)

III. MAJOR CLIMATE IMPACTS ON HYDROLOGY IN THE NPLCC REGION

The hydrologic cycle – the pathway of water movement on Earth and in the atmosphere – is strongly coupled to the climate system.[193] The distribution of water on the Earth's surface plays a central role in governing temperature and precipitation patterns.[194] It is also controlled by those patterns.[195] As a result, hydrologic changes, particularly the changes in snowpacks and runoff patterns described herein, are among the most prominent and important consequences of climate change.[196]

Regional patterns of warming-induced changes in surface hydroclimate are complex and less certain than those in temperature, with both regional increases and decreases expected in precipitation and runoff.[197] Continued warming and changing precipitation patterns will have a large effect on the hydrology of western North America, with significant implications for water resources, the economy, instrastructure, and ecosystems.[198] Based on a search of the scientific and grey literature, including global and regional synthesis reports (see Preface), the following major climate change effects on hydrology in the NPLCC region have been identified (Figure 6):

1. Changes in snowpack, runoff, and streamflow regimes
2. Reduced glacier size and abundance
3. Increased flooding and extreme flow
4. Increased water temperature
5. Changes in water quality
6. Altered groundwater levels, recharge, and salinity

The following structure will be used to present information on climate change effects on hydrology in the NPLCC region:

- **Section summary box** – summary of the section's key points
- **Dynamic interactions influencing impact –** definition and description of physical, chemical, and/or biological dynamics and processes contributing to each impact
- **Observed trends** –observed changes, compared to the historical baseline, for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. Section 1 also includes information on changes observed across the NPLCC region.
- **Future projections** – projected direction and/or magnitude of future change for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. Sections 1 and 4 also include information on future projections across the NPLCC region.
- **Information gaps** – information and research needs identified by reviewers and literature searches.

[193] *Furniss et al. *Water, climate change, and forests: watershed stewardship for a changing climate*. (2010, p. 19)
[194] *Furniss et al. (2010, p. 19)
[195] *Furniss et al. (2010, p. 19)
[196] *Furniss et al. (2010, p. 19)
[197] *Milly, Dunne and Vecchia. *Global pattern of trends in streamflow and water availability in a changing climate.* (2005, p. 347)
[198] *Schnorbus et al. *Hydrologic impacts of climate change in the Peace, Campbell and Columbia watersheds, British Columbia, Canada.* (2011, p. 1)

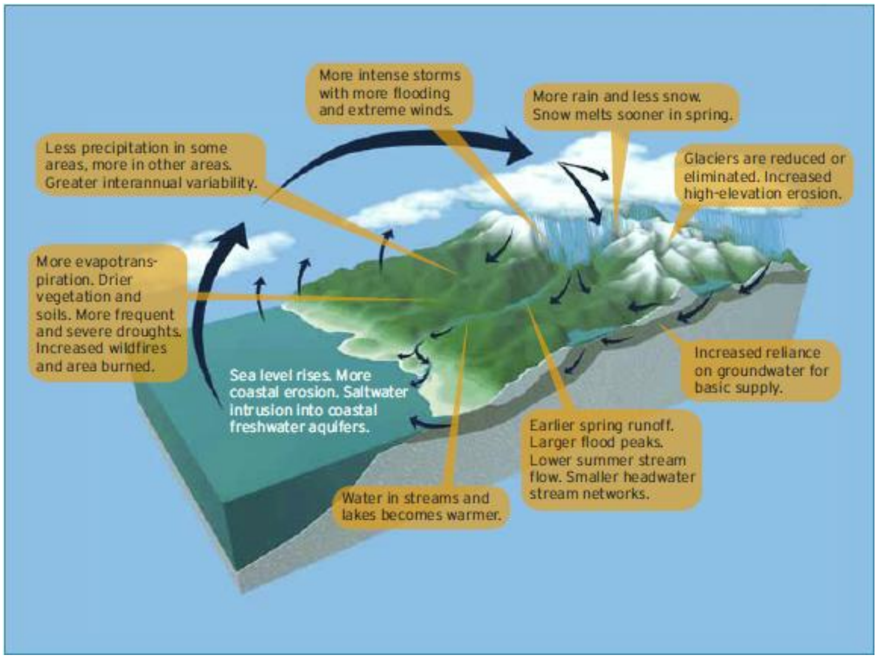

Figure 6. Examples of potential direct and indirect effects of climate change on the hydrologic cycle. Most components are intensified by climate warming. Base image from the COMET program, used by permission by Furniss et al. (2010). *Figure reproduced from Furniss et al. (2010, Fig. 16, p. 23) by authors of this report.*

1. CHANGES IN SNOWPACK, RUNOFF, AND STREAMFLOW REGIMES

Box 5. Summary of observed trends and future projections for changes in snowpack, runoff, and streamflow regimes.

Observed Trends

The dominant trends across the NPLCC region over the 20th century are reduced snowpack, earlier spring runoff, and decreased summer flows:[199]

- British Columbia's coastal watersheds are shifting towards increased winter rainfall and flow, declining snow accumulation, decreased summer flow, and an earlier spring freshet.[200]
- In the Pacific Northwest, significant reductions in snowpack over the 20th century have been observed, runoff timing has shifted earlier in the spring, and strong and significant declines in annual runoff have been observed in many locations.[201]
- In the Klamath Basin (OR and CA), April 1 snowpack decreased significantly at most snow courses lower than 5,905 feet (1,800 m) and increased slightly at higher elevations (comparing 1977-2005 to 1942-1976).[202]

Future Projections

- Overall, the dominant future trend is one of transition: glacier-augmented regimes shift to snow-dominant regimes, snow-dominant regimes shift toward mixed rain-snow regimes, and mixed rain-snow regimes shift toward rain-dominant regimes.[203]
- From 1995 to 2009 under a Business as Usual scenario, the date of the center of mass of annual flow is projected to shift 10 to 40 days earlier across western North America: 30 to 40 days earlier in the contiguous U.S. and 10 to 20 days earlier in Alaska and western Canada.[204]
- Near Juneau (AK), runoff is projected to increase and snowpack is projected to decrease.[205]
- Throughout the rest of the NPLCC region, the largest changes are projected for mixed rain-snow regimes: reduced April 1 snowpack, increased winter runoff, and decreased summer runoff.[206]
- Projected loss of interannual snowpack and ongoing glacial recession would reduce late summer soil moisture and streamflow and increase water temperature.[207]

Note to the reader: In Boxes, we summarize the published and grey literature. The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

[199] Pike et al. (2010); Luce & Holden. (2009); Pelto. (2006); Snover et al. (2005)
[200] Pike et al. (2010)
[201] Luce & Holden. (2009); Pelto. (2006); Snover et al. (2005)
[202] Van Kirk & Naman. (2008)
[203] Pike et al. (2010); Mantua, Tohver and Hamlet. (2010); Chang and Jones. (2010)
[204] Stewart, Cayan and Dettinger. (2004, p. 225)
[205] Kelly et al. (2007)
[206] Chang and Jones. (2010); Elsner et al. (2010); Hamlet and Lettenmaier. (2007); Mantua et al. (2010); Pike et al. (2010); Stewart. (2009)
[207] Pike et al. (2010); Chang and Jones. (2010); Hamlet et al. (2007)

Relationship between temperature, precipitation, snowpack, runoff, and streamflow

The role of snow in the climate system includes strong positive feedbacks related to albedo (i.e., reflectivity; higher values are more reflective) and other, weaker feedbacks related to moisture storage, latent heat and insulation of the underlying surface, which vary with latitude and season.[208] In the temperature-albedo positive feedback loop, rising temperatures increase melting of snow and sea ice, reducing surface reflectance, thereby increasing solar absorption, which raises temperatures, and so on.[209] The feedback loop can also work in reverse.[210] Feedbacks between temperature, cloud cover and radiation are also potentially important agents of climate change.[211] It is thought that if climate warms, evaporation will also increase, in turn increasing cloud cover.[212] Because clouds have high albedo, more cloud cover will increase the earth's albedo and reduce the amount of solar radiation absorbed at the surface.[213] Clouds should therefore inhibit further rises in temperature.[214] However, cloud cover also acts as a blanket to inhibit loss of longwave radiation from the earth's atmosphere.[215] By this process, an increase in temperature leading to an increase in cloud cover could lead to a further increase in temperature – a positive feedback.[216] Knowing which process dominates is a complex issue.[217] As reported in the IPCC AR4, the radiative forcing due to the cloud albedo effect, in the context of liquid water clouds, is estimated to be –0.7 (range: –1.1 to +0.4) W/m^2, with a *low* level of scientific understanding (emphasis in original).[218]

Box 6. Why are changes in snowpack, runoff, and streamflow regimes projected?

Warmer air holds more water vapor and air temperature affects the timing of key hydrologic events. Projected increases in cold season temperatures will reduce snow accumulation, because a greater fraction of precipitation will fall as rain, while warmer spring temperatures would hasten snowmelt, thereby shifting runoff timing earlier in the season and reducing the amount of summer and fall streamflows.

Sources: Hamlet et al. (2007); Trenberth et al. (2007); Stewart (2009).

The timing, volume, and extent of mountain snowpack, and the associated snowmelt runoff, are intrinsically linked to seasonal climate variability and change (see Box 8).[219] Trends in April 1 snow-water equivalent (SWE, the liquid water content of the snowpack[220]) appear to be driven primarily by temperature, which, along the Pacific Coast, is a function of elevation and latitude,[221] and secondarily

208 *Lemke et al. *Climate Change 2007: The Physical Science Basis: Observations: Changes in Snow, Ice and Frozen Ground.* (2007, p. 342). The authors cite M. P. Clark et al. (1999) for information on latent heat and insulation of the underlying surface.
209 *National Snow and Ice Data Center (NSIDC). *Arctic Climatology and Meteorology: Feedback Loops: Interactions that Influence Arctic Climate (website).* (2011)
210 *National Snow and Ice Data Center (NSIDC). (2011)
211 *National Snow and Ice Data Center (NSIDC). (2011)
212 *National Snow and Ice Data Center (NSIDC). (2011)
213 *National Snow and Ice Data Center (NSIDC). (2011)
214 *National Snow and Ice Data Center (NSIDC). (2011)
215 *National Snow and Ice Data Center (NSIDC). (2011)
216 *National Snow and Ice Data Center (NSIDC). (2011)
217 *National Snow and Ice Data Center (NSIDC). (2011)
218 *Forster et al. *Climate Change 2007: The Physical Science Basis: Changes in Atmospheric Constituents and in Radiative Forcing.* (2007, p. 132)
219 *Stewart. *Changes in snowpack and snowmelt runoff for key mountain regions.* (2009, p. 78)
220 *Elsner et al. *Implications of 21st century climate change for the hydrology of Washington State.* (2010, p. 228)
221 *Van Kirk and Naman. *Relative effects of climate and water use on base-flow trends in the lower Klamath Basin.* (2008, p. 1036). The authors cite Knowles and Cayan (2004) and Mote (2006) for this information.

by precipitation.[222] Warmer cold season temperatures reduce snow accumulation, because a greater fraction of the precipitation is rain (lower snow to total precipitation ratio), while warmer spring temperatures hasten snowmelt, thereby shifting the timing of runoff to earlier in the season and reducing the amount of summer and fall flows.[223]

Variations in precipitation quantity determine the total runoff volume, while the seasonality of precipitation affects the fraction stored as snow and therefore the volume of the spring snowmelt.[224]

Streamflow regimes are controlled primarily by seasonal patterns of temperature and precipitation, as well as watershed characteristics such as glacier cover, lake cover, and geology.[225] Streamflow analyses can be strongly affected by the date metrics used to identify trends.[226] For example, analyses of changes in the date of the center of volume (i.e. the date by which half of the volume of annual total streamflow has occurred) gave varying results when computed for the calendar year and water year (generally, October 1 to September 30 in the Northern Hemisphere).[227] More recent studies have found the continuation of streamflow timing trends through 2009; however, in spite of the recent very warm decade, an acceleration of streamflow timing changes is not clearly indicated.[228]

The hydrologic effects of climate change will have an important influence on all types of watersheds, not just those with cold-season precipitation storage as snowpack (see Box 7).[229] For example, if glaciers are initially in equilibrium with current climatic conditions (i.e., if snow accumulation balances ablation of snow and ice), then the onset of climatic warming will produce an initial increase in glacial melt and runoff contributions to streamflow.[230] Eventually, however, the loss of glacier area will reduce total meltwater generation, resulting in a decrease in glacier runoff contributions to streamflow.[231] Glaciers are key sources of alpine summer streamflow.[232] Four types of runoff regimes are found in the NPLCC region: glacier-dominant, snow-melt dominant, mixed-rain-and-snow/hybrid/transient, and rain-dominant (see Box 7). For consistency, this report uses “transient rain-snow” to refer to the transient/mixed/hybrid regimes.

[222] *Van Kirk and Naman. (2008, p. 1036). The authors cite Hamlet et al. (2005), Mote et al. (2005) and Stewart et al. (2005) for this information.
[223] *Stewart. (2009, p. 78-79). The authors cite Mote et al. (2005) and Stewart et al. (2005) as examples.
[224] *Stewart. (2009, p. 79)
[225] *Pike et al. (2010, p. 718)
[226] *Pike et al. (2010, p. 705)
[227] *Pike et al. (2010, p. 705). The authors cite Déry et al. (2009) for this information.
[228] *Fritze, Stewart and Pebesma. *Shifts in western North American snowmelt runoff regimes for the recent warm decades.* (2011)
[229] *Pike et al. (2010, p. 719)
[230] *Pike et al. (2010, p. 717). The authors cite Hock et al. (2005) and Moore et al. (2009) for this information.
[231] *Pike et al. (2010, p. 717)
[232] *Pelto. *Impact of climate change on North Cascades alpine glaciers, and alpine runoff.* (2008, p. 72). The authors cite Bach (2002) for this information.

Box 7. Characteristics of the four runoff regimes found in the NPLCC region.

Glacier-dominant: In British Columbia, drainage basins with more than two to five percent of the area covered by glaciers have regimes similar to snow-dominant regimes, except that the period of high flows extends from about May to August or September, and low-flow conditions occur only when precipitation is accumulating in the snowpack, usually from December to March (e.g. Lillooet River Basin).[233] The extended melt freshet is partly associated with the higher elevations typical of glacierized drainage basins that hold snow later into the summer, but is primarily associated with the presence of glaciers which, during the melt season, act as reservoirs of water.[234]

Snow-melt dominant: In snowmelt-dominant watersheds (e.g. Columbia River Basin), much of the winter precipitation is stored in the snowpack, which melts in the spring and early summer resulting in low streamflow in the cool season and peak streamflow in late spring or early summer (May-July).[235] Low flows may also occur during the late summer and fall as a result of low precipitation inputs and the exhaustion of the water supply from snowmelt.[236]

Mixed/hybrid/transient: These watersheds exhibit characteristics of both rain- and melt-dominated streamflow regimes (e.g. Willamette River Basin),[237] and are termed mixed rain-snow, hybrid, or transient rain-snow regimes depending on the cited source. For consistency, this report uses "mixed rain-snow" to refer to these watersheds. They are characterized as mixed rain-snow due to their mid-range elevation and where winter temperatures fluctuate around freezing.[238] Mixed rain-snow watersheds receive some snowfall, some of which melts in the cool season and some of which is stored over winter and melts as seasonal temperatures increase.[239] The relative importance of the rainfall influence decreases inland from the coast or northwards up the coast; in both cases, the mean temperature tends to decrease, promoting the occurrence of snow rather than rain during the winter.[240] Rivers draining these watersheds typically experience two streamflow peaks: one in winter coinciding with seasonal maximum precipitation, and another in late spring or early summer when water stored in snowpack melts.[241]

Rain dominant: Rain-dominant watersheds are typically lower in elevation, receive little snowfall, and occur mostly on the west side of the mountain ranges such as the Cascade Mountains (e.g. Chehalis River Basin).[242] Streamflow peaks in the cool season, roughly in phase with peak precipitation (usually November through January).[243]

233 *Eaton and Moore. *Compendium of forest hydrology and geomorphology in British Columbia: Chapter 4: Regional Hydrology (pdf).* (2010, p. 86)
234 *Eaton and Moore. (2010, p. 86)
235 *Elsner et al. (2010, p. 226)
236 *Eaton and Moore. (2010, p. 86)
237 *Eaton and Moore. (2010, p. 86)
238 *Elsner et al. (2010, p. 226)
239 *Elsner et al. (2010, p. 226)
240 *Eaton and Moore. (2010, p. 86)
241 *Elsner et al. (2010, p. 226-227)
242 Elsner et al. (2010, p. 226)
243 *Elsner et al. (2010, p. 226)

Observed Trends

Regional

Widespread and regionally coherent trends toward earlier onsets of springtime snowmelt and streamflow have taken place across most of western North America, affecting an area that is much larger than previously recognized (encompasses half a continent, see Table 7).[244] In general (66% of all gauges), a consistent one to four week earlier shift in streamflow in recent decades compared with the 1950s to 1970s was observed throughout the West (Figure 7).[245] These trends were found to be strongest in the interior Pacific Northwest, western Canada and coastal Alaska for mid-elevation gauges.[246] By contrast, for non-snowmelt-dominated streams from 1948 to 2000, the date of center of mass of annual flow at most gauges are trending in the opposite direction, toward later snowmelt timing, with shifts five to twenty-five days later.[247]

There is also evidence, that a set of vulnerable basins throughout western North America experienced runoff regime changes, such that basins that were snowmelt dominated at the beginning of the observational period shifted to mostly rain dominated in later years.[248] The most vulnerable regions for regime shifts are in the California Sierra Nevada, eastern Washington, Idaho, and north-eastern Mexico (i.e., outside NPLCC region).[249]

Table 7. Summary of observed changes in snow cover and snowmelt-derived streamflow for the western North American mountain ranges **Note: This table is reproduced from Stewart (2009, Table V, p. 89) by authors of this report. The references listed are those from the cited publication.*

Findings	Study Period	References
General decline of SWE and snowpack, especially in spring, except for cold high elevations or where precipitation increased	1916-2002; 1950-2000	Mote, 2003b; Mote et al., 2005; Regonda et al., 2005; Earman and Dettinger, 2006; Kalra et al., 2006
Reduced and earlier peak snowpack; greatest SWE changes in coastal areas where winter temperatures remain close to freezing (Oregon, California); more winter runoff, earlier spring peak flows by up to 45 days; no consistent precipitation trends	1916-2003	Hamlet et al. (2007)
Reduction in the snow to precipitation ratio connected to temperature increases, largest for sites that remain close to freezing in winter; less groundwater recharge	1949-2004	Earman and Dettinger (2006); Knowles et al. (2006)
Earlier start of the snowmelt runoff (i.e. spring pulse onset); earlier timing of the center of mass by one to four weeks; increasing March flow; decreasing April-June flows	1948-2002	Cayan et al, 2001; McCabe and Clark, 2005; Regonda et al., 2005; Stewart et al., 2005; Kalra et al., 2006; Hamlet et al., 2007

[244] Stewart, Cayan and Dettinger. *Changes toward earlier streamflow timing across western North America.* (2005, p. 1136)
[245] *Udall and Bates. *Climatic and hydrologic trends in the western U.S.: A review of recent peer-reviewed research (pdf).* (2007, p. 4)
[246] *Udall and Bates. (2007, p. 4)
[247] *Stewart, Cayan and Dettinger. (2005, p. 1142)
[248] *Fritze, Stewart and Pebesma. *Shifts in western North American snowmelt runoff regimes for the recent warm decades*. (2011, p. 1)
[249] *Fritze, Stewart and Pebesma. (2011, p. 1)

Southcentral and Southeast Alaska

In southcentral and southeast Alaska over 1948 to 2002, the timing of the center of mass of annual flow has shifted at least ten days earlier, while the timing of the spring pulse onset has shifted five to fifteen days earlier in some locations and up to five days later in others (see Figure 7).[250] Information on snowfall and snow cover trends for the City and Borough of Juneau are summarized in a report to the Mayor produced by a Scientific Panel on Climate Change:

- Snowfall has been consistently below average since the mid-1970s with the exception of a period in the early 1990s.[251] Average winter snowfall at the airport decreased by almost 1.5 feet (~0.45 m), from 109 inches to 93 inches (~277 cm to ~236 cm) between 1943 and 2005.[252]
- The trends in climate appear to affect late winter and early spring snowfalls in Juneau most strongly.[253] Since 1975, average snowfall in March and April in Juneau has decreased significantly; however, there has not been a significant change in average snowfall in other months in which snow typically falls at sea level.[254]
- The decrease in snowfall at sea level appears to be driven by climate warming rather than a decrease in winter precipitation.[255]
- The negative mass balance for most local glaciers suggests that snowfall at higher elevations is also decreasing.[256] It is possible, however, that a warmer, wetter climate will result in an increase in snowfall at the highest elevations within the City and Borough of Juneau (such as the upper reaches of the Juneau Icefield) where winter temperatures are consistently well below the freezing point of water.[257]

[250] Stewart, Cayan and Dettinger. (2005, Fig. 2, p. 1141)
[251] *Kelly et al. *Climate Change: Predicted impacts on Juneau. Report to: Mayor Bruce Botelho and the City and Borough of Juneau Assembly (pdf).* (2007, p. 37)
[252] *Kelly et al. (2007, p. 36)
[253] *Kelly et al. (2007, p. 39-40)
[254] *Kelly et al. (2007, p. 40)
[255] *Kelly et al. (2007, p. 36)
[256] *Kelly et al. (2007, p. 40)
[257] *Kelly et al. (2007, p. 40)

Box 8. The role of the Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) in regional climate.

ENSO and PDO are major sources of climate variability in the NPLCC region. The PDO is often described as a long-lived, El Niño-like pattern of climate variability in the Pacific. Two main characteristics distinguish the Pacific Decadal Oscillations (PDO) from El Niño/Southern Oscillation (ENSO): first, 20th century PDO "events" persisted for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months; second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. For example, on B.C.'s South Coast, some streams that are normally rainfall-dominated have snowmelt runoff in the spring during cool La Niña years. This can result in years with two streamflow peaks in watersheds where normally only one would occur (e.g., Chemainus River). In areas that typically flood in January or February in the simulations (i.e., coastal areas), when precipitation signals are most pronounced, changes in floods associated with ENSO and PDO may be unusually large. This can be seen in the effects of ENSO on flood risks in basins in western Washington and Oregon. The potential for precipitation and temperature extremes is higher when ENSO and PDO are in the same phase.

- **A warm ENSO (i.e. El Niño) is** characterized by December-January-February sea-surface temperatures >0.5 standard deviations above the mean and has been associated with:
  - Warmer than average sea-surface temperatures in the central and eastern equatorial Pacific Ocean
  - Reduced strength of easterly trade winds in the Tropical Pacific
  - Flood risks generally lower in PNW and northern CA.
- **A neutral ENSO is** neither warm nor cool. There are no statistically significant deviations from average conditions at the equator.
- **A cool ENSO (i.e., La Niña) is** characterized by December-January-February mean sea-surface temperatures <-0.5 standard deviations and has been associated with:
  - Cooler than average sea-surface temperatures in the central and eastern equatorial Pacific Ocean
  - Stronger than normal easterly trade winds in the Tropical Pacific
  - Flood risks generally higher in PNW and northern CA.
  - Some rainfall-dominated streams in B.C. have snowmelt runoff in the spring.
- **A warm PDO is** characterized by sea-surface temperatures >0.5 standard deviations above the mean for the October-November-December-January-February-March mean and has been associated with:
  - Negative upwelling in winter-spring
  - Warm and fresh continental shelf water
  - Advance spring or summer freshet, lower peak flows, cause drier summer periods in B.C.
  - Flood risks generally lower in PNW and northern CA.
- **A neutral PDO is** neither warm nor cool.
- **A cool PDO is** characterized by sea-surface temperatures <-0.5 standard deviations for the October-November-December-January-February-March mean and has been associated with:
  - Positive upwelling in winter-spring
  - Cold and salty continental shelf water
  - Flood risks generally higher in PNW and northern CA.

Sources: CIG. http://cses.washington.edu/cig/pnwc/ci.shtml#anchor2 (accessed 8.14.2011); Hamlet & Lettenmaier. (2007, Table 1, p. 6); Independent Scientific Advisory Board. (2007, Table 4, p. 61); Mantua. (2000). http://www.jisao.washington.edu/pdo/ (accessed 8.14.2011); Pike et al. (2010, p. 708). *Pike cites Fleming et al. (2007) and Zhange et al. (2000).*

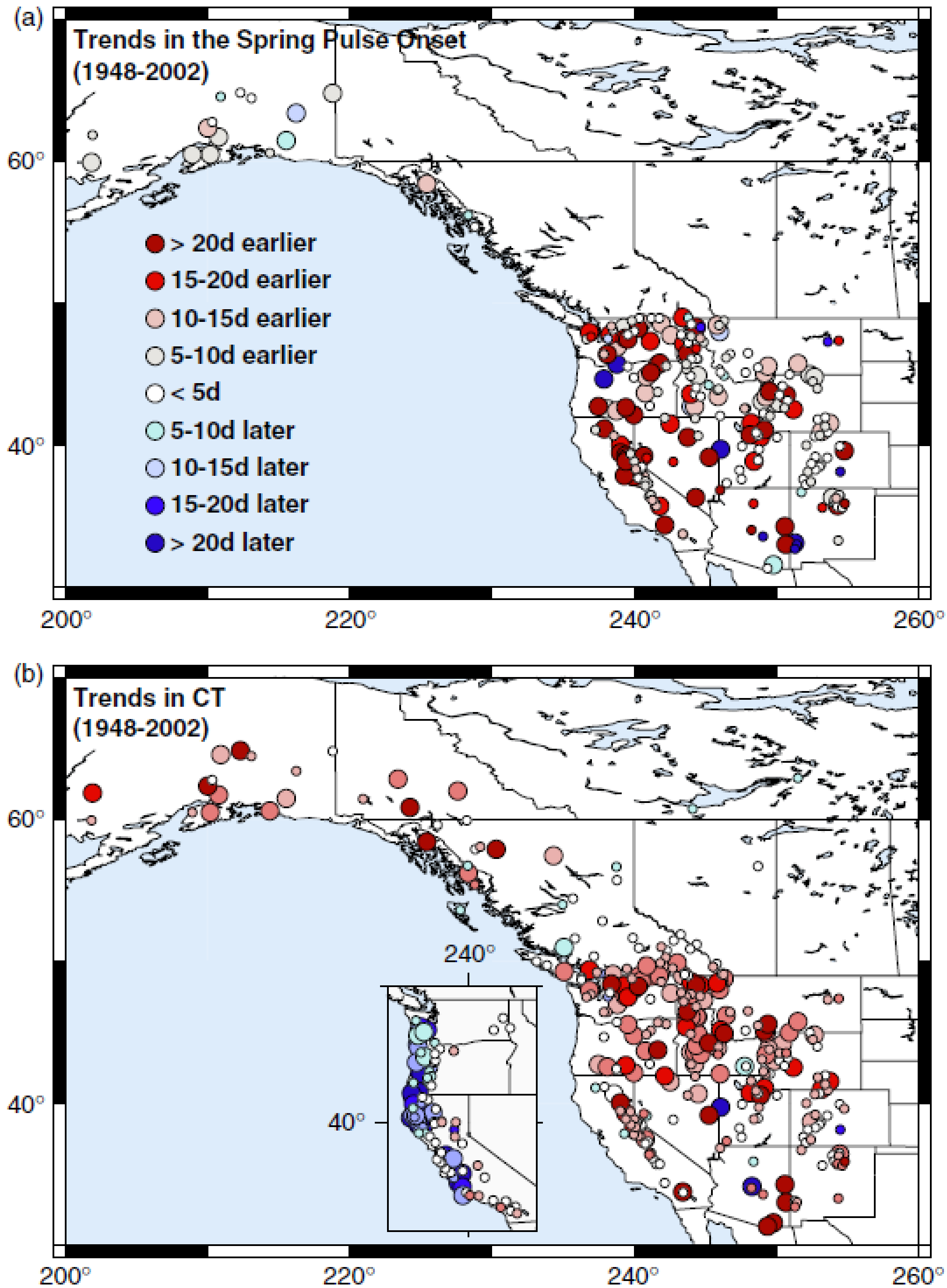

Figure 7. Trends in (a) spring pulse onset and (b) date of center of mass of annual flow (CT) for snowmelt- and (inset) non-snowmelt-dominated gauges across western North America. Shading indicates magnitude of the trend expressed as the change (days) in timing over the 1948-2000 period. Larger symbols indicate statistically significant trends at the 90% confidence interval. Note that spring pulse onset dates could not be calculated for Canadian gauges. *Source: Reproduced from Stewart, Cayan and Dettinger. (2005, Fig. 2, p. 1141) by authors of this report.*

British Columbia

The Ministry of Environment reported overall decreasing trends in April 1st SWE from 1956 to 2005 based on data from 73 long-term snow courses (63 decreased, 10 increased).[258] The largest decreases occurred in the mid-Fraser Basin, whereas the Peace (northeast B.C.), Skeena (west-central B.C.), and Nechako (south-central B.C.) Basins had no notable change over the 50-year study period, and the provincial average SWE decreased eighteen percent.[259]

The dominant trend of glacier retreat has influenced streamflow volumes:[260] negative trends have been documented for summer streamflow in glacier-fed catchments in British Columbia, with the exception of the northwest, where streamflow has been increasing in glacier-fed catchments.[261] Thus, it appears that the initial phase of streamflow increases associated with accelerated glacier melt has already passed for most of the province, whereas the northwest is still experiencing augmented streamflow.[262] In B.C.'s coastal watersheds, regimes are shifting towards increased winter rainfall, and declining snow accumulation, with subsequent changes in the timing and amount of runoff (i.e., weakened snowmelt component).[263] This, coupled with decreased summer precipitation, is shifting the streamflow pattern in coastal watersheds:[264]

- Over the last fifteen years (specific date range not provided), the Fraser River (snow-glacial system near Vancouver) shows increased peak flows and lower recessional flows, illustrating changes in the associated watersheds, perhaps away from a glacier-dominated regime towards a snow-dominated regime with an earlier freshet and faster recessional period.[265]
- The Chemainus River showed predominantly increased flow in winter and decreased flow during May, although the response varied over the record (1956-2006).[266] This is a snow-supported but rainfall dominant system located on south Vancouver Island.[267]
- The Swift River showed increased winter and spring flows and decreased summer flow (1956-2006).[268] This is a snow-dominant system located in northwest B.C.[269]
- On the Chemainus and Swift Rivers, increased streamflow from November to April and decreased streamflow from June to September was observed (1973-2006).[270]

[258] *Pike et al. (2010, p. 703)
[259] *Pike et al. (2010, p. 703). The authors cite B.C. Ministry of Environment (2007) for this information.
[260] *Pike et al. (2010, p. 703). The authors cite Moore et al. (2009) for this information.
[261] *Pike et al. (2010, p. 717)
[262] *Pike et al. (2010, p. 717)
[263] *Pike et al. (2010, p. 706)
[264] *Pike et al. (2010, p. 706)
[265] *Pike et al. (2010, p. 706)
[266] *Pike et al. (2010, p. 706). The Chemainus River's basin size is 355 km^2.
[267] *Pike et al. (2010, p. 706)
[268] *Pike et al. (2010, p. 717)
[269] *Pike et al. (2010, p. 706)
[270] *Pike et al. (2010, p. 706). Note that results for the Chemainus and Swift Rivers are a trend analysis of sequential 5-day average runoff values.

Pacific Northwest

April 1 snowpack, a key, temperature-sensitive indicator of natural water storage available for the warm season, has already declined substantially throughout the region:[271]

- Snover et al. (2005) report that April 1 snowpack (measured as SWE) has declined markedly almost everywhere in the Cascade Mountains (OR and WA) since 1950 (no end date provided).[272] These declines exceeded twenty-five percent at most study locations, and tended to be largest at lower elevations.[273]
- Stoelinga et al. (2010) examined snowpack data in the Cascade Mountains over a longer time period (1930-2007) and concluded that snowpack loss occurred at a relatively steady rate of two percent per decade (after Pacific variability is removed), yielding a sixteen percent loss.[274]
- Pelto (2008) find the increase in winter temperature has led to a twenty-five percent decline in April 1 SWE at eight USDA snow course sites since 1946 (no end date provided).[275] This decline occurred despite an increase in winter precipitation (e.g., Nov-March precipitation increased 3% at Concrete and Diablo Dam from 1946-2005[276]).[277] The declining ratio between winter precipitation (Nov-March) and April 1 SWE demonstrates that reduced April 1 SWE is not due to precipitation decline, but to reduced accumulation of snowpack and winter ablation of existing snowpack.[278] This reflects warmer conditions, yielding more rainfall events, leading to more winter melt and less snowpack accumulation.[279] Specific observed trends in April 1 SWE (1946-2005) include:
    - -1.2 feet (-0.37 m) at Lyman Lake (mean: 5.31 ft., or 1.62 m)
    - -0.95 feet (-0.29 m) at Rainy Pass (mean: 3.31 ft., or 1.01 m)
    - -2.5 feet (-.075 m) at Stevens Pass (mean: 3.94 ft., or 1.20 m)
    - -1.3 feet (-0.40 m) at Fish Lake (mean: 2.9 ft., or 0.89 m)
    - -0.95 feet (-0.29 m) at Miners Ridge (mean: 4.33 ft., or 1.32 m)

Changes in the timing, amount, and frequency of runoff and streamflow have also been found, though results vary by study (Table 8). While factors such as land use practices and natural cycles of ocean-atmospheric change (e.g., PDO) may play a role in observed changes, the changes are consistent with climate change.[280] For example, in a study investigating the detection and attribution of streamflow timing changes to climate change, Hidalgo et al. (2009) concluded the observed trends (1950-1999) toward earlier center timing of snowmelt-driven streamflows in the western United States are detectably different from natural variability.[281] With very high confidence, recent

[271] *Karl, Melillo and Peterson. (2009, p. 135).
[272] *Snover et al. *Uncertain Future: Climate Change and its Effects on Puget Sound*. (2005, p. 16-17)
[273] *Snover et al. (2005, p. 17)
[274] Stoelinga, Albright and Mass. *A new look at snowpack trends in the Cascade Mountains.* (2010, p. 2473). This loss is very nearly statistically significant and includes the possible impacts of anthropogenic global warming. It is also calculated with Pacific climate variability removed.
[275] *Pelto. (2008, p. 73)
[276] *Pelto. (2008, p. 71)
[277] *Pelto. (2008, p. 73)
[278] *Pelto. (2008, p. 72)
[279] *Pelto. (2008, p. 73)
[280] Snover et al. (2005, p. 17). The authors note “a portion of the observed trends is probably due to reservoir management and changing land use, which were not corrected for in this analysis.”
[281] *Hidalgo et al. *Detection and attribution of streamflow timing changes to climate change in the western United States*. (2009, p. 3838). They are significant at the $p < 0.05$ level.

trends toward earlier streamflows in the Columbia River basin are in part due to anthropogenic climate change.[282] Similarly, Barnett et al. (2008) find that up to sixty percent of the climate-related trends of river flow (center timing: 0.3 to 1.7 days per decade earlier[283]), winter air temperature (Jan-March: +0.50-0.77 °F/decade, -+0.28-0.43 °C/decade), and snowpack (SWE to precipitation rato: -2.4 to -7.9%) between 1950 and 1999 are human-induced.[284]

Northwestern California

Climate has been proposed as the primary cause of base-flow decline in the Scott River, an important coho salmon rearing tributary in the Klamath Basin.[285] Based on comparison with a neighboring stream that drains wilderness, Van Kirk and Naman (2008) estimate that thirty-nine percent of the observed 10 million cubic meters (Mm^3) decline in July 1-October 22 discharge over 1977-2005 (as compared to 1942-1976) in the Scott River is explained by regional-scale climatic factors.[286] The remainder of the decline is attributable to local factors, which include an increase in irrigation withdrawal from 48 to 103 Mm^3 per year since the 1950s.[287] Van Kirk and Naman also found that:

- Of eighteen snow courses studied in the lower Klamath Basin, April 1 SWE decreased significantly at most snow courses lower than 5,905 feet (1,800 m) and increased slightly at higher elevations.[288] Mean April 1 SWE was lower in the 1977-2005 period at all seven snow courses below 1,800 meters, and these differences were significant at four of these courses and marginally significant at a fifth.[289] Mean April 1 SWE was higher in the 1977-2005 period at five of the nine courses with elevations above 1,800 meters, but none of these differences were significant.[290]
- Base flow decreased significantly in the two streams with the lowest latitude-adjusted elevation and increased slightly in two higher-elevation streams:[291] base-flow decline in the Scott River was larger than that in all other streams and larger than predicted by elevation.[292] Five streams were studied.[293]
- Van Kirk and Naman note: our estimate that thirty-nine percent of the decrease in Scott River base-flow is due to climatic factors is contrary to that of Drake et al. (2000), who concluded that seventy-eight percent of the decrease is due to decline in April 1 SWE.[294] The disparity in these conclusions is easily explained by analysis methods.[295]

[282] *Hidalgo et al. (2009, p. 3838). The authors cite Solomon et al. (2007a; box TS.1.1) for the term "very high confidence."
[283] *Barnett et al. *Human-induced changes in the hydrology of the western United States.* (2008, p. 1080-1081)
[284] *Barnett et al. (2008, p. 1080)
[285] *Van Kirk and Naman. (2008, p. 1035)
[286] *Van Kirk and Naman. (2008, p. 1035)
[287] *Van Kirk and Naman. (2008, p. 1035)
[288] *Van Kirk and Naman. (2008, p. 1035)
[289] *Van Kirk and Naman. (2008, p. 1042). The authors cite Table 2 in the cited publication.
[290] *Van Kirk and Naman. (2008, p. 1042)
[291] *Van Kirk and Naman. (2008, p. 1035)
[292] *Van Kirk and Naman. (2008, p. 1035)
[293] *Van Kirk and Naman. (2008, p. 1035). The five basins studied are listed in Table 1 (pp.1039) as the Scott River, Indian Creek, Salmon River, South Fork Trinity River, and Trinity River.
[294] *Van Kirk and Naman. (2008, p. 1047)
[295] *Van Kirk and Naman. (2008, p. 1047). The authors explain the discrepancy on p. 1047.

Table 8. Observed trends in the timing, amount, and frequency of runoff and streamflow, NPLCC region.
Note: Table created by authors of this report. Table continues on next page.

Observed Trends	Location	Study Period	Citation
TIMING			
• The peak of spring runoff shifted from a few days to as many as thirty days earlier.[296]	NPLCC region	1950-2000	Karl et al. (2009)
• The dates of maximum snowpack and 90% melt-out have shifted five days earlier.[297]	Cascade Mountains	1930-2007	Stoelinga et al (2010)
• *Summer* melt events in Thunder Creek accounted for 17 of the 26 (65%) highest peak flows from 1950-1975, but from 1984 to 2004, 8 of 13 (62%) yearly peak flow events resulted from *winter* rain on snow melt events, the other five (38%) occurring in summer.[298] • The earlier release of meltwater has become more pronounced since 1990.[299]	North Cascade Mountains, WA	1950-2004	Pelto (2008)
• A twelve day shift toward earlier onset of snowmelt	Puget Sound WA	1948-2003	Snover et al. (2005)
AMOUNT			
• Trends in the lower part of the distribution of annual streamflow show strong and significant declines at a large majority (72%) of gauging stations.[300] • In addition, the driest 25% of years are becoming substantially drier.[301]	Pacific Northwest	1948-2006	Luce and Holden (2009)
• An 18% decline in the fraction of annual river flow entering Puget Sound between June and September.[302] • A 13% decline in total inflow due to changes in precipitation in Puget Sound.[303]	Puget Sound WA	1948-2003	Snover et al. (2005)
• Increased mean winter (Nov-March) streamflow: +17% in Newhalem Creek, +20% in Thunder Creek, +13.8% in all six basins studied,[304] and +0.344%/year (range: 0.01%/yr to 0.55%/yr) across all six basins studied.[305] • Declining mean summer streamflow: -28% in Newhalem Creek, -3% in Thunder Creek,[306] and	North Cascade Mountains, WA	1963-2003	Pelto (2008)

[296] *Karl, Melillo and Peterson. (2009, p. 135). The authors cite Stewart, Cayan and Dettinger (2004) for this information.
[297] *Stoelinga, Albright and Mass. (2010, p. 2473). Both shifts are statistically insignificant.
[298] Pelto. (2008, p. 73)
[299] *Pelto. (2008, p. 73)
[300] *Luce and Holden. *Declining annual streamflow distributions in the Pacific Northwest United States, 1948-2006.* (2009, p. 5)
[301] *Luce and Holden. (2009, p. 5)
[302] *Snover et al. (2005, p. 17)
[303] *Snover et al. (2005, p. 17)
[304] Pelto. (2008, p. 73)
[305] Pelto. (2008, Table 5, p. 72)
[306] Pelto. (2008, p. 73)

-0.48%/yr (range: -0.04%/yr to -1.11%/yr) in all six basins studied.[307] • Mean spring streamflow was nearly unchanged: +0.0233%/yr (range: -0.01%/yr to +0.31%/yr)[308]			
• Depending on the basin, glacial contribution to summer streamflow was 1-12% above normal.[309]	North Cascades, WA	1993-2009	Riedel & Larrabee (2011)
• In the Cascade Range of western Oregon, relative streamflow in August decreased significantly in two snow-dominated basins, but not in two rain-dominated basins.[310]	Cascade Mountains, western OR	20th century	Chang and Jones (2010) citing Jefferson et al. (2006)
• Runoff ratios and baseflow have declined significantly during spring, but they have not changed during summer or winter.[311]	H.J. Andrews Experimental Forest, OR	1952-2006	Chang and Jones (2010)
FREQUENCY			
• An increase in the likelihood of both low and unusually high daily flow events.	Puget Sound WA	1948-2003	Snover et al. (2005)

[307] Pelto. (2008, Table 5, p. 72)
[308] Pelto. (2008, Table 5, p. 72)
[309] *Riedel & Larrabee. *North Cascades National Park Complex glacier mass balance monitoring annual report, Water year 2009: North Coast and Cascades Network*. (2011, p. 9)
[310] *Chang and Jones. *Climate change and freshwater resources in Oregon*. (2010, p. 80). The authors cite Jefferson et al. (2006) for this information.
[311] *Chang and Jones. (2010, p. 80). The authors cite Moore (2010), Figure 3.10, for this information.

Box 9. Trends and projections for evapotranspiration in the western United States, southcentral British Columbia, and Alaska.

Definition of evapotranspiration: Evapotranspiration refers to water evaporation from soils, plant surfaces, and water bodies and water losses through plant leaves.[312]

Role of evapotranspiration in the watershed: Evapotranspiration affects water yield, largely determines what proportion of precipitation input to a watershed becomes streamflow, and is influenced by forest, range, and agricultural management practices that alter vegetation.[313] Surface waters will decline even if precipitation increases, if evapotranspiration increases by a greater amount.[314]

Observed trends: Hamlet et al. (2007) found that throughout the western United States and southcentral British Columbia from 1916 to 2003, trends in simulated warm season evapotranspiration as a whole have followed trends in precipitation; however, in areas with substantial snow accumulation in spring, some systematic changes associated with temperature are also apparent:

- In early spring, water availability from snowmelt has generally increased due to earlier snowmelt, and evapotranspiration during April–June has followed these upward trends.
- In late summer, simulated increases in temperature result in decreasing trends in water availability from snowmelt, which has tended to reduce evapotranspiration during July–September.
- Changes in the seasonal timing of evapotranspiration in summer in coastal areas of the Pacific Northwest and California are much more clearly related to temperature changes, because there is relatively little precipitation in summer to offset losses of water availability due to earlier snowmelt.[315]

Future projections: In Alaska, increases in evaporation due to higher air temperatures are expected to lead to drier conditions overall, with reduced soil moisture.[316]

Sources: Allan, Palmer & Poff. (2005); Brooks et al. (2003); Hamlet et al. (2007); Karl, Melillo & Peterson. (2009).

Future Projections

<u>Regional</u>

Across western North America, Stewart et al. (2004) project earlier streamflow timing by thirty to forty days from 1995 to 2099 using a statistical model and assuming that observed trends of streamflow timing continue.[317] Most strongly impacted by this projected shift in the date of the center of mass of annual flow (CT) are the Pacific Northwest, the Sierra Nevada, and the Rocky Mountains.[318] Somewhat less impacted are the Alaskan, and western Canadian rivers, where shifts of ten to twenty days are predicted by the end of the century, despite the fact that temperatures, and local temperature indices (TI), trends increase poleward in the climate projection (using a Parallel Climate Model Business as Usual scenario).[319] The weakening of the CT_{TI} trends in Canada and Alaska reflects the historical tendency for the CT of northern rivers to be less sensitive to temperature fluctuations, at least in part because the basins are so cold that 'normal' temperature fluctuations have less influence on snowmelt

312 *Brooks et al. *Hydrological Processes and Land Use.* (2003)
313 Brooks et al. (2003)
314 Allan, Palmer and Poff. *Climate change and freshwater ecosystems.* (2005)
315 Hamlet et al. (2007)
316 Karl, Melillo and Peterson. (2009). The authors cite Meehl et al. (2007) for this information.
317 Stewart. (2009, Table V, p. 89). Stewart is summarizing the results of Stewart et al. (2004).
318 *Stewart, Cayan and Dettinger. *Changes in snowmelt runoff timing in western North America under a 'Business as Usual' climate change scenario.* (2004, p. 225)
319 *Stewart, Cayan and Dettinger. (2004, p. 225)

timing that in basins nearer the freezing point (emphasis in original).[320] Data analyzed by Milly (see Figure 8) projects:

- a twenty to forty percent increase in runoff in Alaska (more than 90% of models in agreement)
- a ten to twenty percent decrease in runoff in California (more than 90% of models in agreement), and
- in Washington and Oregon, the range of projected runoff changes is -2 to +2 percent (more than 66% of models in agreement).

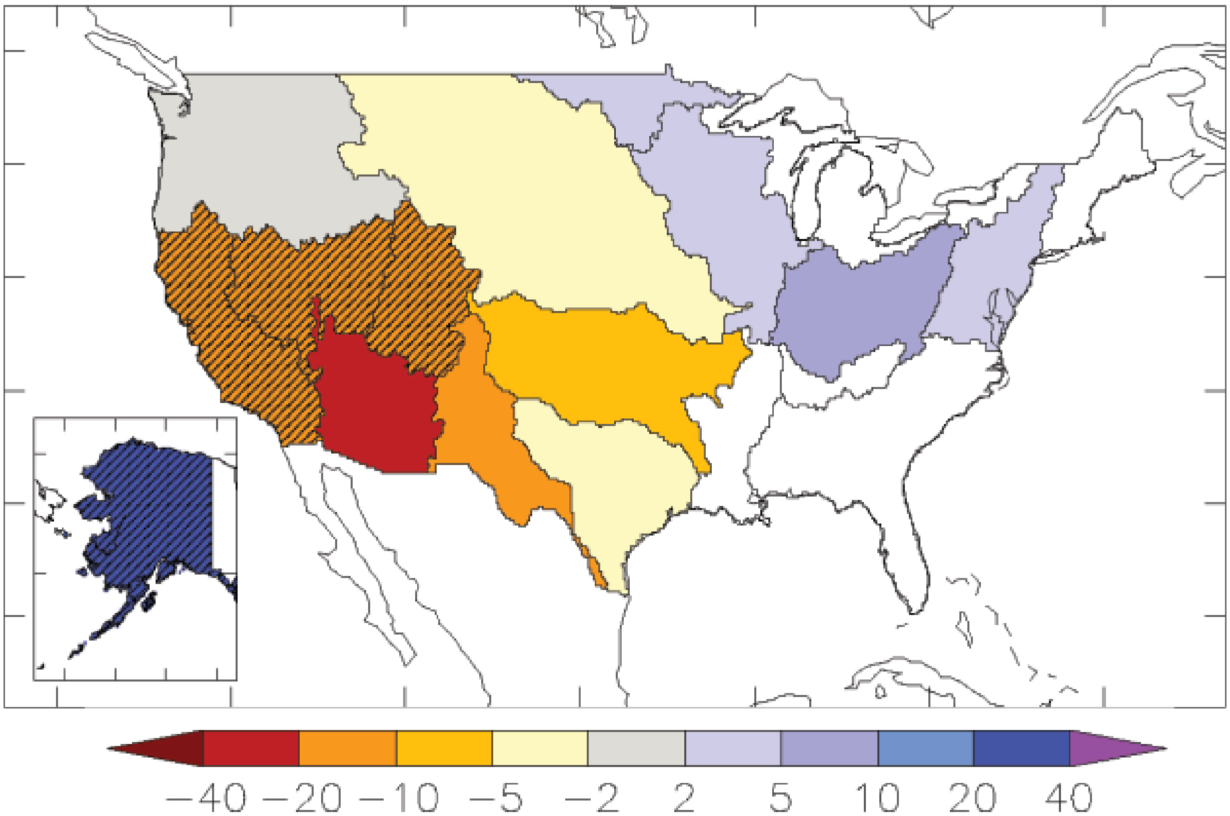

Figure 8. Median, over 12 climate models, of the percent changes in runoff from United States water resources regions for 2041-2060 relative to 1901-1970. More than 66% of models agree on the sign of change for areas shown in color; diagonal hatching indicates greater than 90% agreement. Recomputed from data of Milly, Dunne, and Vecchia (2005) by Dr. P.C.D. Milly, USGS. *Source: Reproduced from Palmer et al. (2008, Fig. 6.14, p. 25) by authors of this report.*

Southcentral and Southeast Alaska

Increases in winter precipitation could lead to increased snowpack, however, winter melting events and a shortening of the period of snow accumulation could have the opposite effect.[321] If the latter conditions dominate and overall snowpack decreases, Alaska could expect a shorter spring melting period with lower runoff intensity and generally lower summer baseflows.[322] As precipitation in southeastern Alaska shifts toward increased rain

[320] *Stewart, Cayan and Dettinger. (2004, p. 225)
[321] *AK Department of Environmental Conservation (DEC). *Final Report Submitted by the Adaptation Advisory Group to the Alaska Climate Change Sub-Cabinet (pdf)*. (2010, p. 2-2 to 2-3). The authors cite Serreze et al. (2000) for information on precipitation and snowpack.
[322] *AK-DEC. (2010, p. 2-3)

and less snow, more water will run off the landscape rather than being stored.[323] While effects will vary regionally, impacts to Alaska's freshwater ecosystems are generally expected to include reduced summer and fall stream flows.[324]

British Columbia

By the 2050s (2041–2070) increased air temperatures will lead to a continued decrease in snow accumulation, earlier melt, and less water storage for either spring freshet or groundwater storage.[325] Projected declines in snow are most notable on the central and north coast of British Columbia and at high-elevation sites along the south coast.[326] Watersheds that may be the most sensitive to change are those occupying the boundary between rainfall and snow deposition in the winter (transient rain-snow regimes).[327] Overall, the following changes to B.C.'s hydrologic regimes are projected:

- **The response of rain-dominated regimes will likely follow predicted changes in precipitation**.[328] For example, increased magnitude and more numerous storm events will result in increasingly frequent and larger stormdriven streamflow (including peaks) in the winter.[329] Projected warmer and drier summers also raise concerns about a possible increase in the number and magnitude of low flow days.[330]
- **Snow-melt dominated watersheds might exhibit characteristics of transient regimes.**[331] With projected elevated temperatures, the snow accumulation season will shorten and an earlier start to the spring freshet will likely occur, which may lengthen the period of late-summer and early-autumn low flows, especially in southern British Columbia.[332] Where snow is the primary source of a watershed's summer streamflow, loss of winter snowpack may reduce the late-summer drainage network, transforming once perennial streams into intermittent streams.[333]
- **Transient rain-snow regimes might transition to rain-dominated regimes** through the weakening or elimination of the snowmelt component.[334] In the Coast's transient regimes, snowpacks are normally deep enough to absorb and store a significant amount of rain, thus dampening the response of watersheds to large midwinter rain events.[335] If these snowpacks no longer form or are very shallow, and increases in temperature and wind speeds occur, large midwinter snowfall events will become large rain or melt events, and thereby increase the frequency of high flows occurring throughout the winter in these watersheds.[336] Subsequently, spring peak flow volumes will decrease and occur earlier because less

[323] *Kelly et al. (2007, p. 53)
[324] *AK-DEC. (2010, p. 5-2)
[325] *Pike et al. (2010, p. 713). The authors cite Rodenhuis et al. (2007) and Casola et al. (2009) for information on snow accumulation; Mote et al. (2003) for information on earlier melt; Stewart et al. (2004) for information on the spring freshet.
[326] *Pike et al. (2010, p. 714). The authors cite Rodenhuis et al. (2007) for this information.
[327] *Pike et al. (2010, p. 714)
[328] *Pike et al. (2010, p. 719). The authors cite Loukas et al. (2002) for this information.
[329] *Pike et al. (2010, p. 719)
[330] *Pike et al. (2010, p. 719)
[331] *Pike et al. (2010, p. 719)
[332] *Pike et al. (2010, p. 719). The authors cite Loukas et al. (2002) and Merritt et al. (2006) for this information. The authors also refer the reader to Figure 19.8 (pp. 715) of the cited report, where southern B.C. is explicitly mentioned.
[333] *Pike et al. (2010, p. 719). The authors cite Thompson (2007) for this information.
[334] *Pike et al. (2010, p. 719). The authors cite Whitfield et al. (2002) for this information.
[335] *Pike et al. (2010, p. 719)
[336] *Pike et al. (2010, p. 719)

precipitation is stored as snow during the winter, and winter flows will increase because more precipitation will fall as rain instead of snow.[337]

- **Glacier-augmented systems might shift to a more snowmelt-dominated pattern** in the timing and magnitude of annual peak flows and low flows.[338] Peak flows would decrease and occur earlier in the year.[339] In the long term, the reduction or elimination of the glacial meltwater component in summer to early fall would increase the frequency and duration of low flow days in these systems.[340]

Specific changes to snowpack and streamflows are also projected, as described in Table 9.

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[337] *Pike et al. (2010, p. 719)
[338] *Pike et al. (2010, p. 719)
[339] *Pike et al. (2010, p. 719)
[340] *Pike et al. (2010, p. 719)

Table 9. Projected changes in SWE, snowpack, and streamflow in coastal B.C.
Table created by authors of this report.

Projected Changes	*Location*	*Study Period (Baseline)*	*Citation*
SNOWWATER EQUIVALENT & SNOWPACK			
• Some variation is evident in the spatial distribution of change but, on average, models project a 28% decline in SWE.[341] • Snowpack is projected to increase at high elevations in the Coast Mountain ranges.[342]	Fraser River Basin	2050s (1961-1990) *Six different GCM emissions scenarios were used.	Pike et al. (2010)
STREAMFLOWS			
• Peak flows are projected to occur eleven days earlier by 2010-2039, eighteen days earlier by 2040-2069, and twenty-four days earlier by 2070-2099.[343] • Mean flows are projected to increase 1.8 to 5.1% over the 21st century, while mean minimum flows are projected to increase 14 to 44% over the 21st century.[344] • Mean peak flows are projected to decrease 4.7% by 2010-2039, 11% by 2040-2069, and 18% by 2070-2099.[345]	Fraser River near Hope (east of Vancouver)	2010-2039, 2040-2069, 2070-2099 (1961-1990) *Two downscaled GCMs were used, HadCM2 and CGCM1	Morrison et al. (2002)
• Future glacier retreat produced continuing declines in summer flows, particularly for July to September.[346]	Bridge River	Not provided	Pike et al. (2010), citing Stahl et al. (2008)
• Where groundwater is the primary source of a watershed's summer streamflow, flows will still continue but with volume reductions in response to changes in the seasonal snowpack accumulation that recharges groundwater.[347]	None stated	Not provided	Pike et al. (2010), citing Thompson (2007)

[341] Pike et al. (2010, p. 715)
[342] Pike et al. (2010, p. 715). The authors refer to Figure 19.7, pp. 714.
[343] Morrison, Quick and Foreman. *Climate change in the Fraser River watershed: flow and temperature projections.* (2002, p. 237). See Table 2.
[344] Morrison, Quick and Foreman. (2002, p. 237). See Table 2.
[345] Morrison, Quick and Foreman. (2002, p. 237). See Table 2.
[346] Pike et al. (2010, p. 706). The authors are summarizing the work of Stahl et al. (2008).
[347] Pike et al. (2010, p. 719). The authors cite Thompson (2007) for this information.

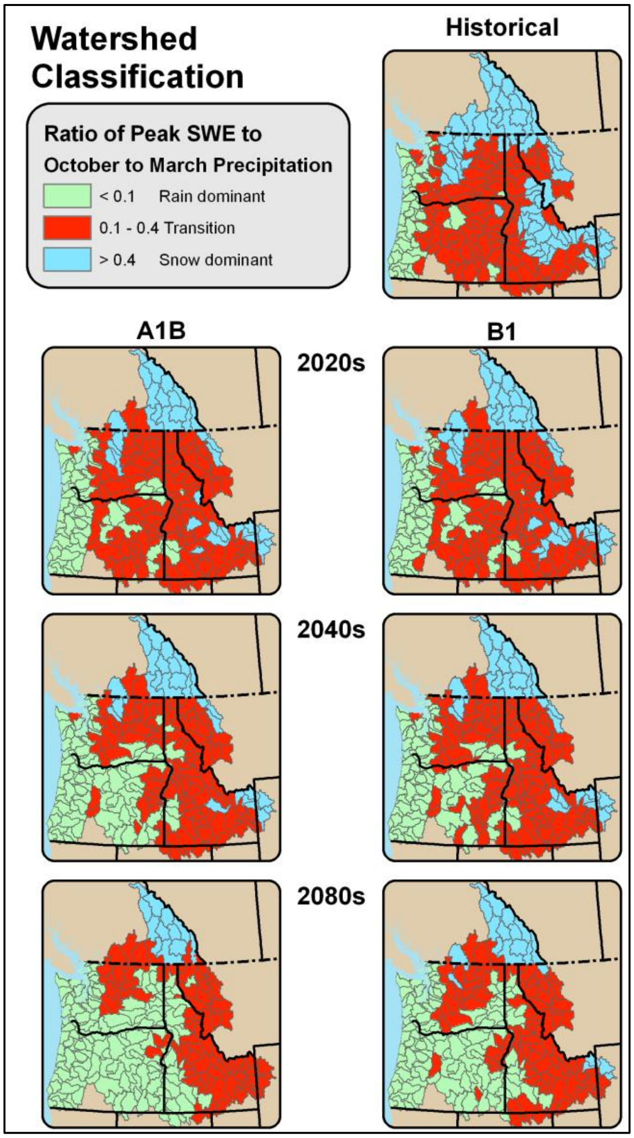

Figure 9. Watershed classification based on the ratio of April 1 SWE to total March-October precipitation for the historical period (1916-2006), for the A1B scenario (left panels), and for the B1 scenario (right panels) at three future time periods (2020s, 2040s, 2080s).
Source: Reproduced from Tohver and Hamlet. (2010, Fig. 2, p. 6) by authors of this report.

Pacific Northwest

The Columbia basin shifts towards more rain dominant behavior as the region's temperatures warm, which creates changes in both flood and low flow statistics that vary with mid-winter temperatures and other factors.[348]
These changes are related primarily to changes in snowpack and associated effective basin area during extreme precipitation events.[349] Figure 9 shows the maps of the shifting characterizations of these basins, measured as the ratio of April 1 snowpack to October-March total precipitation, as time progresses through the 21st century under the A1B and B1 scenarios.[350] The topmost map illustrates the spatial distribution of basin types for the historical period (1970-1999).[351]

In projections for the 21st century, future warming results in a progressive shift from snow dominant to transient basins and from transient basins to rain dominant basins (lower panels of Figure 9).[352] Furthermore, this shift in basin characterization occurs at a faster rate for the A1B than for the B1 scenarios, because the rate of warming is faster.[353] By the 2080s for the A1B scenario, there is a complete loss of snowmelt dominant basins in the Cascades and the Rockies in the U.S., and only a few transient basins remain at higher elevations.[354] This shift in basin type has implications for the timing of peak flows since the mechanism driving the flows is changing under warmer conditions.[355]

A study by Stoelinga et al. (2010) projects nine percent loss of Cascade Mountain spring snowpack due to anthropogenic climate change between 1985 and 2025.[356] Another study by Elsner et al. (2010) finds April 1 SWE is projected to decrease by 28% to 30% across Washington State by the 2020s, 38% to 46% by the 2040s, and 56% to 70% by the 2080s, based on composite scenarios for the B1

[348] *Tohver and Hamlet. *Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America.* (2010, p. 5)
[349] *Tohver and Hamlet. (2010, p. 5). The authors cite Hamlet and Lettenmaier (2007) for this information.
[350] *Tohver and Hamlet. (2010, p. 5)
[351] *Tohver and Hamlet. (2010, p. 5)
[352] *Tohver and Hamlet. (2010, p. 5)
[353] *Tohver and Hamlet. (2010, p. 5)
[354] *Tohver and Hamlet. (2010, p. 5-6)
[355] *Tohver and Hamlet. (2010, p. 6)
[356] *Stoelinga, Albright and Mass. *A new look at snowpack trends in the Cascade Mountains.* (2010, p. 2473)

and A1B scenarios, respectively (baseline: water years 1917-2006).[357] Climate change effects on SWE are projected to vary by elevation:

- **The lowest elevations** (below 3,280 feet; 1,000 meters) will experience the largest relative decreases in snowpack, with reductions of 38% to 40% by the 2020s to 68% to 80% by the 2080s.[358]
- **Mid-level elevations** (3,280-6,558 feet; 1,000-2,000 meters) will experience relative decreases in snowpack of 25% to 27% by the 2020s and 53% to 67% by the 2080s.[359]
- **The highest elevations** (above 6,558 feet; 2,000 meters) will experience the smallest relative decreases in snowpack of 15% to 17% by the 2020s and 39% to 55% by the 2080s.[360]

Reductions in the magnitude of summer low flows are predicted to be widespread for Washington State's rain-dominant and transient runoff river basins in southwest Washington, the Olympic Peninsula, and Puget Sound.[361] For these locations, future estimates of the annual average low flow magnitude (7Q2, which is the seven-day average low flow magnitude with a two year return interval) and more extreme (7Q10) low flow periods are projected as follows:

- **7Q2**: Projected decline by up to fifty percent by the 2080s under both the A1B and B1 emissions scenarios.[362]
- **7Q10**: Projected decline in rain-dominant and transient runoff basins ranges from five to forty percent (no average provided).[363]

In all watershed types, the duration of the summer low flow period is projected to expand significantly.[364] For example, the loss of glacier area in the North Cascades will lead to further declines in summer runoff in glacier-fed rivers as the glacier area available for melting in the summer declines.[365]

Oregon

In the Western Cascades of Oregon, SWE is predicted to decline and peak runoff is predicted to occur earlier by the 2080s.[366] In the Willamette River basin in particular, the ratio of April 1st SWE to Precipitation (SWE/P) declined substantially from the reference period of 1970-1999 under two GHG emission scenarios with a greater reduction in the 2080s.[367] The decline in the ratio is most pronounced under the A1B scenario.[368] This is a combined result of increase in precipitation falling as rainfall in winter and earlier snowmelt caused by rising temperature.[369]

[357] *Elsner et al. (2010, p. 244)
[358] Elsner et al. (2010, Table 5, p. 244)
[359] Elsner et al. (2010, Table 5, p. 244)
[360] Elsner et al. (2010, Table 5, p. 244)
[361] *Mantua, Tohver and Hamlet. *Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State*. (2010, p. 204)
[362] *Mantua, Tohver and Hamlet. (2010, p. 204-205)
[363] *Mantua, Tohver and Hamlet. (2010, p. 205)
[364] *Mantua, Tohver and Hamlet. (2010, p. 206). The authors cite Elsner et al. (2010) for this information.
[365] *Pelto. (2008, p. 74)
[366] *Chang and Jones. (2010, p. 192)
[367] *Chang and Jones. (2010, p. 90)
[368] *Chang and Jones. (2010, p. 90)
[369] *Chang and Jones. (2010, p. 90)

Changes in streamflow across runoff regimes are also projected:

- In snowmelt-dominated sites such as the Columbia River at the Dalles, flows are projected to increase in the winter months and decrease in the summer months through the 21st century.[370] Peak flow shifts earlier into the spring at both sites in this scenario.[371]
- At sites where the peak flows occur in the wetter winter months (Willamette and Calapooia), flows are projected to increase in the winter and decrease slightly in the summer.[372]
- The High Cascade basins that are primarily fed by deep groundwater systems are expected to sustain low flow during summer months despite declining snowpacks, although the absolute amount of summer flow will decline.[373]
- Models suggest that spring and summer streamflow in transient rain-snow basins, such as those in the Western Cascade basins, will be sensitive to changes in precipitation and temperature.[374]

Northwestern California

Studies by Miller et al. (2003) and Dettinger et al. (2004) project further declines in winter snowpack, earlier streamflow timing, and declines in summer low flows from 1900 to 2099 and from 2011 to 2100, respectively.[375] With a doubling of atmospheric CO_2 concentrations, Snyder et al. (2004) project snow accumulation will decrease by seventy-three percent in the North Coast region of California.[376] Projected reductions in monthly median snow heights from January to April ranged from 1.8 to 4.37 inches (46-111 mm).[377] Cayan et al. (2008b) projected overall snowpack losses for San Joaquin, Sacramento, and parts of the Trinity drainages will range from about thirty-two to seventy-nine percent loss by the end of the century.[378] Most of these changes are projected to occur because warming temperatures cause more precipitation to fall as rain, rather than snow.[379] There do not appear to be any model projections of future streamflow patterns for Northwestern California.[380] The reduction in snowpack in this region would suggest that snow-fed flows will decrease in duration and magnitude. [381]

Information Gaps

While substantial information on observed trends and future projections is available for the NPLCC region, additional precipitation information, such as extreme precipitation projections, is needed for the region. In addition, projections for smaller geographic areas are also needed.

[370] *Chang and Jones. (2010, p. 94). The authors note these results are obtained using VIC outputs (hybrid delta, ensemble mean of 10 GCMs, A1B scenario) and credit Hamlet et al. (2010) of the Climate Impacts Group.
[371] *Chang and Jones. (2010, p. 94)
[372] *Chang and Jones. (2010, p. 94)
[373] *Chang and Jones. (2010, p. 132)
[374] *Chang and Jones. (2010, p. 131)
[375] *Stewart. (2009, p. 89). Stewart is summarizing studies by Miller et al. (2003) and Dettinger et al. (2004).
[376] *PRBO. *Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0 (pdf).* (2011, p. 8)
[377] *PRBO. (2011, p. 8)
[378] *PRBO. (2011, p. 8)
[379] *PRBO. (2011, p. 8-9)
[380] *PRBO. (2011, p. 9)
[381] *PRBO. (2011, p. 9)

2. REDUCED GLACIER SIZE AND ABUNDANCE

Box 10. Summary of observed trends and future projections for reduced glacier size and abundance.

Observed Trends

Over the 20th century, widespread volume losses and glacial retreat have been observed throughout the NPLCC region.[382] In many areas, the rate of loss and/or retreat has increased in recent years:

- From the mid-1950s to the mid-1990s, volume losses from 67 of Alaska's glaciers were more than double the estimated annual losses from the entire Greenland Ice Sheet over the same time period.[383]
- In the North Cascades (WA), 53 glaciers have disappeared since the 1950s.[384] The remaining glaciers are in disequilibrium with the climate, with increasingly negative cumulative mass balance.[385]
- Between 1900 and 2004, the glaciers in Oregon have lost about 40% of their area, while some have lost as much as 60%.[386]

Mount Shasta's glaciers (CA) are an exception to the trend. Despite the strong warming trend over the past 20–30 years, ice volumes have changed little and the termini have continued to advance due to a concurrent increase in winter snow accumulation.[387]

Future Projections

- Alaska's tidewater glaciers will grow more unstable, with increased calving and subsequent melting.[388]
- Under the A2 and B1 scenarios, the Bridge Glacier (BC) is projected to continue its retreat, with a projected loss of over 30% of its current area by 2100.[389]
- By about 2057, the estimated area of the Coe Glacier (OR) will be about 61% of its present-day area.[390]
- Whitney Glacier (CA) would shrink by 65 to 75% percent by 2080, retreating to a terminus elevation of 11, 155 feet (3,400 m).[391]
- The Hotlum Glacier would disappear entirely by 2065.[392]

Note to the reader: In Boxes, we summarize the published and grey literature. The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

[382] Arendt et al. *Rapid wastage of Alaska glaciers and their contribution to rising sea level.* (2002); Chang & Jones (2010); Pelto (2006); WA-ECY. *Facts about Washington's retreating glaciers and declining snow pack (pdf).* (2007)
[383] Arendt et al. (2002)
[384] WA-ECY. (2007)
[385] Pelto. (2006)
[386] Chang & Jones. (2010)
[387] Howat et al. *A precipitation-dominated, mid-latitude glacier system: Mount Shasta, California*. (2007, p. 96)
[388] Motyka et al. *Post Little Ice Age Glacial Rebound in Glacier Bay National Park and Surrounding Areas.* (2007)
[389] Pike et al. (2010), citing Stahl et al. (2008)
[390] Chang & Jones. (2010)
[391] Howat et al. (2007, p. 96)
[392] Howat et al. (2007, p. 96)

Hydrologic dynamics of glaciers and climate change

A glacier can be divided into two regions (Figure 10).[393] At the high end of the glacier, more snow (mass) accumulates than is lost every year.[394] This region is called the *accumulation zone*.[395] The ice flows downhill into the lower region where more snow (mass) is annually lost than is gained through snowfall.[396] The lower region is called the *ablation zone* (ablation means mass loss in all its forms, including melting, sublimation, and calving).[397] The dividing line between the accumulation and ablation zones is the *equilibrium line*, for which the altitude changes on an annual basis because it is dependent on the amount of snowfall received during winter and the amount of snowmelt on the glacier during summer.[398] During *glacial retreat*, the rate of ablation exceeds the rate of accumulation for an extended period of time (the mass balance of the glacier is negative), and the position of the glacier terminus retreats toward the origin of the glacier.[399] Note that the ice continues to flow downhill and that the glacier becomes thinner.[400] *Glacial advance* occurs when the rate of accumulation exceeds the rate of ablation (ice also flows downhill).[401]

Glaciers support a unique runoff regime and have been studied as sensitive indicators of climate for more than a century.[402] Glaciers respond to climate by advancing with climate cooling (because of increased snowfall and decreased summer melting) and snowfall increase and retreating with climate warming.[403] Tidewater glaciers that terminate in the ocean can be an exception to this rule because their advance and retreat is often controlled more by the morphology of the glacier terminus and receiving fjord than by climate forcings.[404] The long-term trends that in particular affect glaciers are changes in mean ablation-season temperature (i.e., the warm summer season, typically May-September) and winter-season snowfall.[405]

Box 11. Surface mass balance and thinning: key indicators in the analysis of glaciers and climate change.

- Measurements of surface mass balance (i.e., the difference between winter water accumulation and summer loss of water by ablation) are the most sensitive indicator of short-term glacier response to climate change because mass balance is a direct measure of annual climate conditions. It indicates whether the glacier is gaining or losing volume. Terminus behavior, on the other hand, is determined by cumulative, multi-year impacts of climate and other glaciologic factors.
- Thinning in the accumulation zone indicates a glacier no longer has a substantial consistent accumulation zone. Thinning occurs when the rate of ice melt exceeds the rate of replacement through ice flow downward from the upper glacier. To maintain equilibrium in an average year, ~65% of a glacier's area needs to be in the accumulation zone at the end of the summer melt season.
- The key indicator that a glacier is in disequilibrium is substantial thinning along the entire length of a glacier.

Sources: Pelto (2006); Pelto (2008); Expert commentary (June 2011).

[393] *Granshaw and Fountain. *Glaicer Change in the Upper Skagit River Basin: Questions about Glaciers, Climate and Streamflow (website).* (2003)
[394] *Granshaw and Fountain. (2003)
[395] *Granshaw and Fountain. (2003)
[396] *Granshaw and Fountain. (2003)
[397] *Granshaw and Fountain. (2003)
[398] Comment from reviewer. (June 2011)
[399] *W. W. Norton and Company. *Chapter 18: Amazing Ice: Glaciers and Ice Ages (website).* (2011)
[400] *W. W. Norton and Company. (2011)
[401] *W. W. Norton and Company. (2011)
[402] *Pelto. (2008, p. 65)
[403] *Pelto. (2006, p. 769)
[404] Comment from reviewer (June 2011); Personal communication with reviewers. (April, May, June 2011)
[405] *Pelto. (2006, p. 771)

Given future climate scenarios, glaciers will ultimately retreat under sustained conditions of negative net mass balance, although a lag is often associated with glacier dynamics (see Box 11).[406] Glacier retreat will continue until the glacier loses enough of its lower-elevation ablation zone that total ablation matches total accumulation.[407] In some cases, climate warming can result in ablation exceeding accumulation over all elevations on a glacier, in which case the glacier would ultimately disappear.[408]

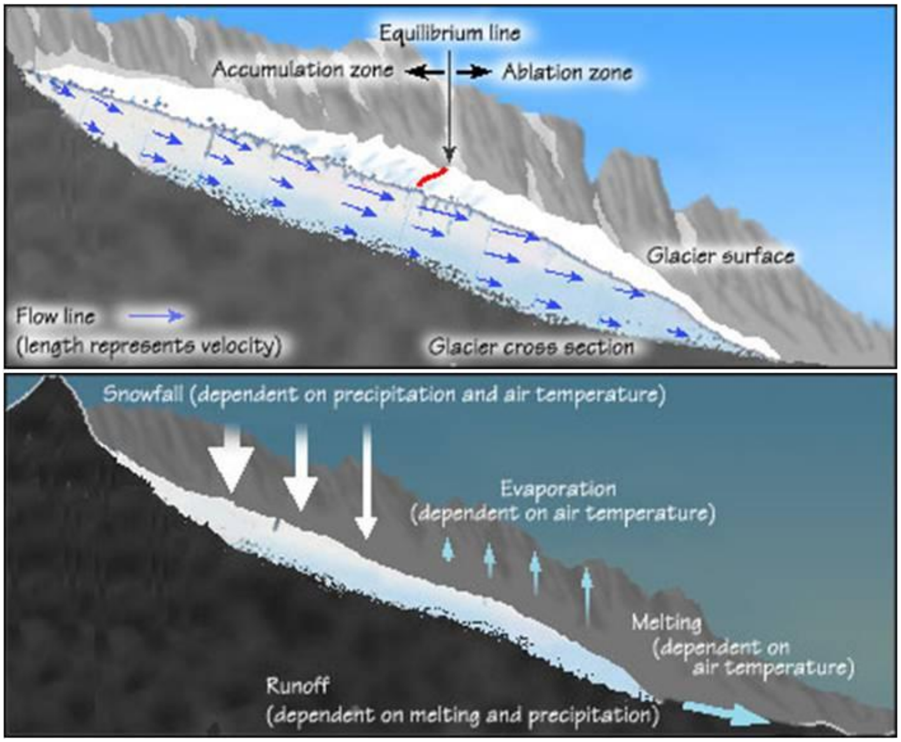

Figure 10. (TOP) Cross section of a typical alpine glacier showing the two major zones of a glacier and ice flow within the glacier. The blue arrows show the direction and speed of the moving ice. The longer the arrow, the faster that ice is moving. (BOTTOM) A simplified diagram of a glacier mass budget, showing major mass input (snowfall) and outputs (melting, and runoff). *Source: Reproduced from Granshaw and Fountain. (website). (2003, Fig. 2, Fig. 6) by authors of this report.*

Future glacier retreat will influence a range of aquatic habitat characteristics, including stream temperature, suspended sediment concentrations, and stream water chemistry.[409] Physical considerations and empirical evidence consistently indicate that summer stream temperatures should increase as a result of glacier retreat; however, the magnitude of this change is difficult to predict.[410]

406 *Pike et al. (2010, p. 716). The authors cite Arendt et al. (2002) as an example for this information.
407 *Pike et al. (2010, p. 716)
408 *Pike et al. (2010, p. 716)
409 *Pike et al. (2010, p. 717)
410 *Pike et al. (2010, p. 717)

Observed Trends

Southcentral and Southeast Alaska

Currently, the majority of glaciers in southeastern Alaska are thinning and retreating.[411] Rates of glacier thinning now exceed ten feet (~3 meters) per year at lower elevations (Figure 11).[412] Moreover, rates of glacial ice loss appear to be increasing in recent decades.[413] Arendt et al. (2002) studied sixty-seven glaciers and found that recent volume losses are nearly double the estimated annual losses from the entire Greenland Ice Sheet during the same time period (mid-1950s to mid-1990s).[414] Rapid glacier wastage in southeastern Alaska is reflected in extreme rates of glacio-isostatic rebound, a rising of the earth where it formerly was depressed by the mass of ice.[415] Recent losses of glacier ice appear to be associated with climate warming rather than changes in precipitation regimes.[416] Observed changes in specific glaciers include:

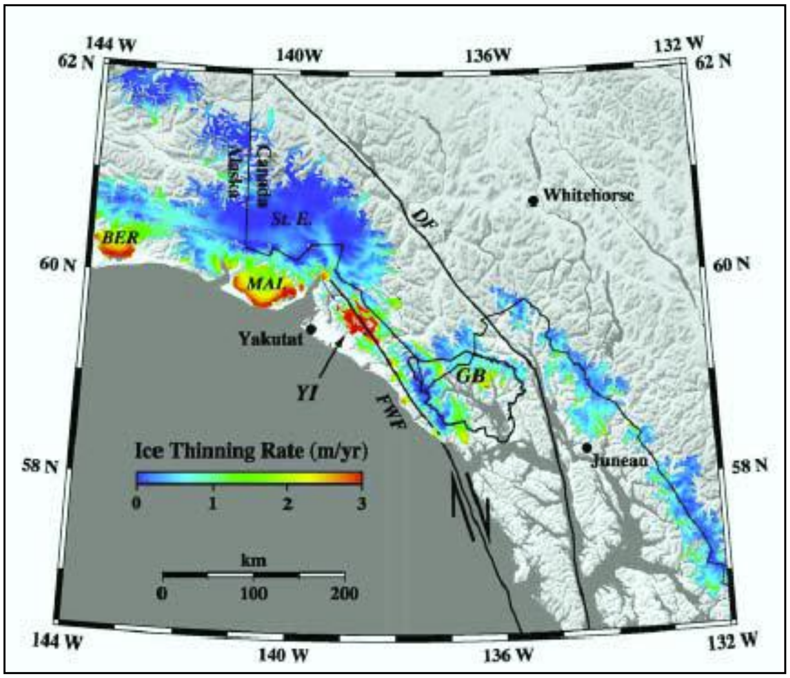

Figure 11. Current rates of glacier ice thinning in southeastern Alaska as measured by laser altimetry. Ice in lower elevations and around the Yakutat Icefield (YI) is thinning most rapidly. The Glacier Bay Little Ice Age Icefield (GB) is outlined. FWF depicts the location of the Fairweather Fault. Figure from Larsen et al., 2005.
Source: Reproduced from Kelly et al. (2007, Fig. 21, p. 35-36) by authors of this report.

- The most dramatic loss of glacial ice in Alaska since the end of the Little Ice Age occurred in Glacier Bay, near Juneau.[417] Within the west arm of the bay, glaciers have retreated more than sixty miles and lost nearly one mile in thickness.[418] As a result, less than thirty percent of Glacier Bay National Park is now covered by glaciers.[419]
- The mass balance record for the Lemon Glacier near Juneau is one of the longest in North America, and it indicates a dramatic loss of volume in recent decades.[420] During the period 1953-1998, the Lemon Glacier thinned nearly eighty-one feet (~25m) and retreated more than 2600 ft (~0.5 miles, 792m).[421]

[411] *Kelly et al. (2007, p. 34)
[412] *Kelly et al. (2007, p. 34). The authors cite Larsen et al. (2005) and Larsen et al. (2007) for this information.
[413] *Kelly et al. (2007, p. 34). The authors cite Arendt et al. (2002)
[414] *Arendt et al. (2002, p. 382)
[415] *Kelly, et al. (2007, p. 36)
[416] *Kelly, et al. (2007, p. 34). The authors cite Arendt et al. (2002) and Motyka et al. (2002) for this information.
[417] *Kelly, et al. (2007, p. 33)
[418] *Kelly, et al. (2007, p. 33)
[419] *Kelly, et al. (2007, p. 33)
[420] *Kelly, et al. (2007, p. 33)
[421] *Kelly, et al. (2007, p. 33). The authors cite Miller and Pelto (1999) for this information.

- Some southeastern Alaska glaciers, including the Carroll, Johns Hopkins, Lamplugh, Reid, Margerie, Brady, and Grand Pacific glaciers in Glacier Bay and the Taku glacier have shown periods of advance during the latter half of the 20th century.[422]
- From the mid-1950s to the mid-1990s, the average rate of thickness change of sixty-seven glaciers was 1.7 feet per year (ft/yr; -0.52 m/yr).[423] Repeat measurements of twenty-eight glaciers from the mid-1990s to 2000-2001 suggest an increased average rate of thinning, equaling 5.9 ft/yr (-1.8 m/yr).[424]

The effects of climate change on southeastern Alaska glaciers may be very different for tidewater glaciers in contrast to glaciers with grounded termini.[425] Glaciers that terminate at tidewater typically follow their own cycles of advance and retreat – they are often independent of short-term changes in regional climate.[426] For example, Hunter and Powell (1993) found that terminus dynamics at the Grand Pacific and Muir Glaciers in Glacier Bay are controlled by morainal bank (an accumulation of boulders, stones, and other debris deposited by a glacier) sediment dynamics and concluded that these tidewater glaciers are insensitive to climate forcing.[427]

British Columbia

Glaciers in British Columbia are out of equilibrium with the current climate and are adjusting to changes in seasonal precipitation and elevated temperatures, with widespread glacial volume loss and retreat in most regions.[428] In general, glaciers have been retreating since the end of the Little Ice Age (mid-19th century), although some glaciers have exhibited periods of stability at the terminus and even advances.[429] Specific changes to B.C. glaciers include:

- The Illecillewaet Glacier in Glacier National Park has receded over 0.62 miles (1 km) since measurements began in the 1880s.[430] Moore et al. (2009) reported that the terminus of Illecillewaet Glacier remained stationary from 1960 until 1972, and then advanced until 1990.[431] It has subsequently resumed its retreat.[432] This behavior is consistent with the decadal time scale of glacier terminus response to climate variability.[433]
- A compilation of glacier area changes in the period 1985–2005 indicates glacier retreat in all regions of the province, with an eleven percent loss in total glacier area over this period.[434] On Vancouver Island, the central Coast Mountains, and the northern Interior ranges, ice-covered areas have declined by more than twenty percent over this period (1985-2005).[435]

[422] *Kelly, et al. (2007, p. 35). The authors cite Pelto and Miller (1990) and Miller et al. (2003) for information on the Taku glacier. The authors cite Hall et al. (1995) for information on the remaining glaciers.
[423] *Arendt et al. (2002, p. 382)
[424] *Arendt et al. (2002, p. 382)
[425] *Kelly, et al. (2007, p. 35)
[426] *Kelly, et al. (2007, p. 35)
[427] *Kelly, et al. (2007, p. 35)
[428] *Pike, et al. (2010, p. 703)
[429] *Pike, et al. (2010, p. 703). The authors cite Moore et al. (2009) for this information.
[430] *Pike, et al. (2010, p. 703). The authors cite Parks Canada (2005) for this information.
[431] *Pike, et al. (2010, p. 703)
[432] *Pike, et al. (2010, p. 703)
[433] *Pike, et al. (2010, p. 703). The authors cite Oerlemans (2001) for this information.
[434] *Pike, et al. (2010, p. 703). The authors cite Bolch et al. (2010) for this information.
[435] *Pike, et al. (2010, p. 703). The authors cite Bolch et al. (2010) for this information.

- Schiefer et al. (2007) reported that the recent rate of glacier loss in the Coast Mountains is approximately double that observed for the previous two decades.[436]

Washington

Monitoring has occurred on several glaciers in Washington, including the South Cascade Glacier (located in the North Cascades), Mount Rainier glaciers, and the Blue Glacier in the Olympic Mountains.[437] Glaciers in the North Cascades exhibit consistent responses to climate from year to year.[438] The response time is comparatively short: five to twenty years for the initial response to a climate change, and thirty to one hundred years for a response that begins to approach equilibrium.[439]

Specific changes to the surface mass balance, thickness, and advance/retreat of North Cascades glaciers are summarized in Table 10. Overall, fifty-three glaciers in the North Cascade Mountains have disappeared since the 1950s.[440] Seventy-five percent of the North Cascade glaciers observed are thinning appreciably in the accumulation zone and are in disequilibrium with current climate.[441]

A progressive temperature rise from the 1880s to the 1940s led to a ubiquitous rapid retreat of North Cascade alpine glaciers from 1880 to 1944.[442] From 1944 to 1975, all eleven Mt. Baker glaciers advanced (when conditions became cooler and precipitation increased[443]).[444] By 1984, all Mt. Baker glaciers were again retreating.[445] The glacier margin retreat has been as significant at the head of many glaciers as at the terminus.[446] This indicates thinning in the upper reaches of the glacier.[447] If a glacier is thinning not just at its terminus, but also at its head then there is no point to which the glacier can retreat to achieve equilibrium.[448]

In conclusion, the current climate change favors glacier retreat.[449] Cumulative mass balance for the North Cascade glaciers is becoming increasingly negative, indicating that, instead of approaching equilibrium as the glaciers retreat, they are experiencing increasing disequilibrium with current climate.[450] The recent loss of several glaciers in the North Cascades raises the question as to whether glaciers can reach a new point of equilibrium with the current climate.[451]

[436] *Pike, et al. (2010, p. 703)
[437] Pelto. (2006)
[438] *Pelto. (2008, p. 68)
[439] *Pelto. (2006, p. 770). The authors cite Schwitter and Raymond (1993) and Pelto and Hedlund (2001) for this information.
[440] *WA Department of Ecology. (2007, p. 2)
[441] *Pelto. (2008, p. 71)
[442] *Pelto. (2008, p. 70). The authors cite Rusk (1924), Burbank (1981), Long (1955), and Hubley (1956) for information on glacial retreat.
[443] *Pelto. (2008, p. 70). The authors cite Hubley (1956) and Tangborn (1980) for this information.
[444] *Pelto. (2008, p. 70). The authors cite Pelto (1993) and Harper (1993) for this information.
[445] *Pelto. (2008, p. 70). The authors cite Pelto (1993) for this information.
[446] *Pelto. (2008, p. 70)
[447] *Pelto. (2008, p. 70)
[448] *Pelto. (2008, p. 70). The authors cite Pelto (2006) for this information.
[449] *Pelto. (2006, p. 770)
[450] *Pelto. (2006, p. 774). The authors refer the reader to Figure 4 in the cited report.
[451] *Pelto. (2006, p. 770). The authors cite Pelto and Hedlund (2001) for information on the recent loss of several glaciers.

Oregon

Glaciers in Oregon, like much of the west have been receding since the start of the last century when observations first began.[452] The glaciers rapidly retreated since about 1910, slowed and advanced during the 1960s to middle 1970s before retreating again in the early 1980s.[453] Since the late 1990s glacier retreat has accelerated. Between 1900 and 2004, the glaciers in Oregon have lost about forty percent of their area.[454] Some glaciers have lost as much as sixty percent.[455] No glaciers are advancing in Oregon,[456] although the Ladd Glacier advanced ten meters from 1989 to 2000 and the summer terminus of the Eliot Glacier advanced eighteen meters downvalley from its summer 2000 terminus (which was at its farthest upvalley position in the past century).[457] Lillquist and Walker (2006) document that the termini of Coe, Eliot, Ladd, Newton Clark, and White River glaciers, all on Mount Hood, have receded between 1901 and 2001; however, magnitude, timing, and rate of glacier terminus change varied considerably among these glaciers:[458]

- **Ladd Glacier:** Despite a recent advance, the net 1901-2000 change in terminus was -3615 feet (-1102 m), a sixty-one percent loss in length.[459] These values are the highest of any of the five glaciers analyzed by Lillquist and Walker.[460]
- **Eliot Glacier:** A net 1901-2001 change of -2542 feet (-775 m), representing a twenty-two percent loss in total length, was observed.[461]
- **White River Glacier:** Despite the alternating nature of advances and retreats over at least the past sixty years, a net 1901-2000 change in terminus was -2024 feet (-617 m), a thirty percent decline in length.[462]
- **Coe Glacier:** A net 1901-2001 change in the terminus of -1339 (-408 m), a twelve percent loss in glacier length, was recorded.[463]
- **Newton Clark Glacier:** The net 1901-2000 change in the terminus was only -203 feet (-62 m), a five percent decline in length.[464] This represents the least terminus retreat of any of the glaciers analyzed.[465]

Lillquist and Walker conclude the similar pattern of Mount Hood's northern glacier terminus fluctuations, combined with qualitative analysis of glacier terminus fluctuation and climate data, suggests that temperature and precipitation played a significant role in Mount Hood's glacier terminus fluctuations during the past century.[466] Other factors affecting glacier terminus fluctuations include the physical characteristics of each glacier; it is also

[452] *Chang and Jones. (2010, p. 84). The authors cite Nylen (2004) and Hoffman et al. (2007) as examples of publications discussing glaciers in the west. The authors cite Lillquist and Walker (2006) and Jackson and Founatin (2007) for information on glaciers in Oregon.
[453] *Chang and Jones. (2010, p. 84)
[454] *Chang and Jones. (2010, p. 84)
[455] *Chang and Jones. (2010, p. 84)
[456] *Chang and Jones. (2010, p. 84)
[457] *Lillquist and Walker. *Historical Glacier and Climate Fluctuations at Mount Hood, Oregon.* (2006, p. 403)
[458] *Lillquist and Walker. (2006, p. 401)
[459] *Lillquist and Walker. (2006, p. 403)
[460] *Lillquist and Walker. (2006, p. 403)
[461] *Lillquist and Walker. (2006, p. 403)
[462] *Lillquist and Walker. (2006, p. 405)
[463] *Lillquist and Walker. (2006, p. 407-408)
[464] *Lillquist and Walker. (2006, p. 405)
[465] *Lillquist and Walker. (2006, p. 405)
[466] *Lillquist and Walker. (2006, p. 409)

likely that volcanic and geothermal activity, subglacial topography, and debris cover have played an important local role in Mount Hood's historical glacier termini fluctuations.[467]

Northwestern California

Howat et al. (2007) document observed trends in Mount Shasta's Whitney and Hotlum Glaciers. Throughout the historical record, fluctuations in the size of Mount Shasta's glaciers have been closely correlated with sustained periods of either high or low precipitation under increasing winter and summer temperatures.[468] Total winter precipitation appears to be the dominant control on glacier volume at Mount Shasta on both inter-decadal and inter-annual scales.[469] The period of most rapid wastage of the glaciers occurred during the drought conditions of the 1920s and early 1930s, concurrent with the lowest recorded monthly mean temperatures on record.[470] Subsequent glacier growth corresponded with an increase in both precipitation and temperatures.[471]

Despite the strong warming trend over the past 20–30 years, ice volumes have changed little and the termini have continued to advance due to a concurrent increase in winter snow accumulation.[472] A series of anomalously high precipitation years from the late 1960s until the early 1980s resulted in a highly positive transient balance state, resulting in no terminus retreat during the 1985–1991 drought period.[473] These alternating periods of high and low total precipitation, and glacier expansion and retreat, are concurrent with shifts in the ocean-atmosphere state of the northern Pacific, as indexed by the PDO.[474] Specific changes for the Hotlum and Whitney Glaciers include:

- **Hotlum Glacier:** After a terminus retreat of over 2132 feet (650 m) and an increase in elevation of over 656 feet (200m) between 1920 and 1944, the glacier stabilized between 1944 and 1955 and then advanced rapidly, forming a new end moraine.[475] This new moraine advanced 560 m to a minimum elevation of 10,203 feet (3,110 m) between 1944 and 2003, with the greatest advance (820 feet; 250m) occurring between 1965 and 1975.[476] Following a stall between 1985 and 1995, the terminus continued its advance in the most recent decade, and, in 2003, was less than 164 feet (50 m) above the 1920 position.[477]
- **Whitney Glacier:** Compared to a 1925 aerial photography and 1894 topographic map, in 1944 the terminus of the glacier was approximately 1640 feet (500 m) higher in elevation than in 1925 (8,530 feet above sea level, f.a.s.l.; 2,600 meters above sea level, m.a.s.l.), suggesting that this glacier underwent a similar wastage to that of the Hotlum Glacier.[478] From 1944 to 1975, Whitney Glacier advanced 2198 feet (670 m) down a elevation of 492 feet (150 m).[479] Following this period, the glacier terminus split into two adjoining lobes of debris-covered ice.[480] Advance of this eastern lobe stalled in the early 1970s, only

[467] *Lillquist and Walker. (2006, p. 409)
[468] *Howat et al. (2007, p. 96)
[469] *Howat et al. (2007, p. 96)
[470] *Howat et al. (2007, p. 96)
[471] *Howat et al. (2007, p. 96)
[472] *Howat et al. (2007, p. 96)
[473] *Howat et al. (2007, p. 96)
[474] *Howat et al. (2007, p. 96)
[475] *Howat et al. (2007, p. 88)
[476] *Howat et al. (2007, p. 88-89)
[477] *Howat et al. (2007, p. 89)
[478] *Howat et al. (2007, p. 89)
[479] *Howat et al. (2007, p. 89)
[480] *Howat et al. (2007, p. 89)

advancing 40m between 1975 and 2003.[481] Over this period, the western lobe advanced another 935 feet (285 m), down 328 feet (100 m) in elevation to 9,121 f.a.s.l (2,780 m.a.s.l).[482]

Future Projections

Southcentral and Southeast Alaska

In southeast Alaska, glacial melt is already occurring, and is likely to continue.[483]

British Columbia

Projections based on future climate scenarios indicate that a negative net balance will continue over at least the next few decades.[484] Stahl et al. (2008) used three scenarios to model the response of the Bridge Glacier in the southern Coast Mountains: one was a continuation of current climatic conditions until 2150, and two others were based on the A2 and B1 emissions scenarios developed by the IPCC and simulated by the CGCM3.[485] Even with no further climate warming, the Bridge Glacier is sufficiently out of equilibrium with current climatic conditions that it is projected to lose approximately twenty percent of its current area, reaching a new equilibrium by about 2100.[486] Under the two warming scenarios investigated, glacier net balance remained negative and the glacier continued to retreat over the next century, with a projected loss of over thirty percent of its current area by the end of this century.[487]

Washington

Seventy-five percent of the North Cascades glaciers observed by Pelto (2008) are in disequilibrium and will melt away during the 21st century with the current climate.[488]

Oregon

By about 2057, Chang and Jones (2010) estimate the Coe Glacier's area will be about sixty-one percent of its present-day area.[489]

Northwestern California

A modeling study of Mount Shasta's Whitney and Hotlum Glaciers by Howat et al. (2007) finds that the RegCM2.5 regional climate model estimates a large increase in summer temperatures relative to winter precipitation under greenhouse-driven warming that would result in the loss of most of Mount Shasta's glacier volume over the next fifty years with near total loss by the end of the century:[490]

- Whitney Glacier would shrink by sixty-five to seventy-five percent by 2080, retreating to a terminus elevation of 11, 155 feet (3,400 m).[491]

481 *Howat et al. (2007, p. 89)
482 *Howat et al. (2007, p. 89)
483 *AK-DEC. (2010, p. 2-3)
484 *Pike et al. (2010, p. 716)
485 *Pike et al. (2010, p. 716). The authors are summarizing Stahel et al.'s (2008) work.
486 *Pike et al. (2010, p. 716)
487 *Pike et al. (2010, p. 716)
488 *Pelto. (2008, p. 74)
489 *Chang and Jones. (2010, p. 84)
490 *Howat et al. (2007, p. 97)
491 *Howat et al. (2007, p. 96)

- The Hotlum Glacier would disappear entirely by 2065.[492]
- The 4.7°F (2.6°C) increase in temperature forecasted by RegCM2.5 for 2050 would require a concurrent fifty-two percent increase in precipitation to maintain steady-state compared to the predicted seventeen percent increase.[493]

In contrast, under a historical trend scenario for the future, Whitney Glacier would likely remain within ±20% of its present volume until 2040 when it would begin to grow, reaching up to 140% of its present volume by 2100.[494] For this volume increase the glacier would expand to the outermost terminal moraines at 8530 feet above sea level (2,600 meters above sea level).[495] The Hotlum Glacier would likely lose volume until 2040, at which time growth would begin.[496] These variations correspond to a shift in the oscillatory components to greater precipitation and lower temperatures, resulting in rapid volume growth that is sustained through a second climate oscillation shift.[497]

Information Gaps

Information is needed on future projections of glacier size and abundance in all jurisdictions except British Columbia and California.

Note to the reader regarding sea ice and permafrost thawing: While loss of sea ice and permafrost thaw are critical issues facing Alaska and British Columbia, they are not major issues within the areas of southcentral and southeast Alaska and coastal B.C. included in our study region. For this reason, we do not discuss these impacts in this report. A large map of the extent of permafrost in the Northern Hemisphere is available at http://www.climate4you.com/images/PermafrostDistributionIPA%20LARGE.gif (accessed 3.12.2011). It shows isolated patches of permafrost in the North Cascades (WA) and coastal B.C., and sporadic patches in southcentral and southeast Alaska. A map of the extent of sea ice in March and September 2009 is available at http://www.arctic.noaa.gov/report09/seaice.html (accessed 3.12.2011). March is typically the month of maximum extent of sea ice, September the minimum.

492 *Howat et al. (2007, p. 96)
493 *Howat et al. (2007, p. 96)
494 *Howat et al. (2007, p. 96)
495 *Howat et al. (2007, p. 96)
496 *Howat et al. (2007, p. 96)
497 *Howat et al. (2007, p. 96)

Table 10. Trends in glacial surface mass balance, loss, retreat, thinning, and ice thickness, North Cascades, WA, 1880-2007. *Table created by authors of this report. Tables continues on next page.*

REDUCED SURFACE MASS BALANCE			
Glacier(s) studied	*Years*	*Findings*	*Citation*
10 glaciers	1984-2006	Mean loss of -12.4 meters of water equivalent (m w.e.), compared to the mean annual balance of -1.8 ft/year (-0.54 m/yr).[498]	Pelto (2008)
Columba Glacier	1984-2002	Cumulative change of -6.09 m w.e.[499]	Pelto (2006)
Lower Curtis Glacier	1984-2002	Cumulative change of -6.26 m w.e.[500]	Pelto (2006)
North Klawatti, Silver, Noisy, Sandalee	1993-2009	Cumulative balance ranges from -16.67 m w.e. (North Klawatti) to -9.49 m w.e. (Silver)[501]	Riedel & Larrabee (2011)
LOSS AND RETREAT			
Glacier(s) studied	*Years*	*Findings*	*Citation*
47 glaciers[502]	1979-1984	35 of 47 glaciers observed annually had begun retreating	Pelto (2006)
	By 1992	All 47 glacier termini were retreating	
	By 2004	Four glaciers disappeared	
North Klawatti, Silver, Noisy, Sandalee	1996-2009	Modest volume increases from 1996-2003 (negative long-term trend resumed afterward)	Riedel & Larrabee (2011)
	2000-2009	Average negative vertical change of 11.67 m w.e. Total volume loss of 32 Mm^3 of w.e.	
Mt. Baker glaciers	1880-1950	Average terminus retreat of 4724 feet (1440 m) from Little Ice Age moraines[503]	Pelto (2008)
38 North Cascades glaciers	1880-1950	Retreat of 3986 feet (1215 m)[504]	Pelto (2008)
Mt. Baker glaciers[505]	1984-2007	Average retreat of 1115 feet (340 m), ranging from 951 to 1509 feet (290-460 m). *Note: all eleven Mt. Baker glaciers advanced from 1944-1975.*	Pelto (2008)
Ice Worm Glacier	1984-2005	Retreated 541 feet (165 m) at its head and 472 feet (144 m) at its terminus.[506] This corresponds to ~25 feet per year (ft/yr; 7.9 m/yr) and ~22 ft/yr (6.9 m/yr), respectively.	Pelto (2008)
Columbia Glacier	1984-2005	Retreated 236 feet (72 m) at its head and 390 feet (119 m) at its terminus.[507] This corresponds to ~11 ft/yr (3.4 m/yr) and 18.6 ft/yr (5.7 m/yr), respectively.	Pelto (2008)

498 Pelto. (2008, p. 68)
499 Pelto. (2006, p. 776)
500 Pelto. (2006, p. 776)
501 Riedel & Larrabee (2011, p. 8)
502 Pelto. (2006, p. 775)
503 Pelto. (2008, p. 70).
504 Pelto. (2008, p. 70). The authors cite Pelto and Hedlund (2001) for this information.
505 Pelto. (2008, p. 70). The authors cite Pelto (1993) and Harper (1993) for information on 1944-1975 trends.
506 Pelto. (2008, p. 70)

THINNING AND REDUCED ICE THICKNESS			
Glacier(s) studied	*Years*	*Findings*	*Citation*
10 glaciers	1984-2006	Minimum loss of 45.9 feet (14.0 m) in glacier thickness (20-40% loss of total volume)[508]	Pelto (2008)
9 glaciers	1984-2004	Minimum loss of ice thickness of 31 feet (9.5 m), representing 18 to 32% of total volume[509]	Pelto (2006)
12 glaciers	1984-2002	Loss of 18.7 to 20.7 feet (-5.7 to -6.3 m) in thickness[510]	Pelto (2006)
South Cascade glacier & 10 North Cascade glaciers	1984-2006	75% percent of the North Cascade glaciers observed are thinning appreciably in the accumulation zone and are in disequilibrium with current climate.[511]	Pelto (2008)
Easton Glacier[512]	Since 1916	Lost 151 feet (46 m) of ice thickness	Pelto (2006)
	1984-2002	Lost 43 feet (13 m) of ice thickness, a rate of 2.4 ft/yr (0.72 m/yr).	
	1984-2002	Greatest thinning at terminus May be capable of retreating to a new stable position	
Lower Curtis Glacier[513]	1908-1984	Lost 148 feet (45 m) of ice thicknesss, a rate of 1.9 ft/yr (0.59 m/yr)	Pelto (2006)
	1984-2002	Lost an additional 20 feet (6 m) of ice thickness, a rate of 1.1 ft/yr (0.33 m/yr).	
	1984-2002	Greatest thinning in accumulation zone, averaging 33 feet (10 m), versus 20 feet (6 m) for the entire glacier	
Columbia Glacier[514]	1911-1984	Lost about 187 feet (57 m) of ice thickness, a rate of 2.6 ft/yr (0.78 m/yr)	Pelto (2006)
	1965-2002	Lost 36 feet (11 m) of ice thickness, a rate of 0.97 ft/yr (0.30 m/yr)	
	1984-2002	Lost 26 feet (8 m) of ice thickness, a rate of 1.4 ft/yr (0.44 m/yr)	
	1984-2002	Greatest thinning in accumulation zone, averaging 43-52 feet (13-16 m), versus a glacier-wide average thinning of 26 feet (8 m)	

507 Pelto. (2008, p. 70)
508 Pelto. (2008, p. 65)
509 Pelto. (2006, p. 773-774)
510 Pelto. (2006, p. 769)
511 Pelto. (2008, p. 71)
512 Pelto. (2006, p. 776)
513 Pelto. (2006, p. 776). The authors cite Pelto and Hartzell (2004) for information on maximum thinning being located in the accumulation zone.
514 Pelto. (2006, p. 776). The authors cite Pelto and Hartzell (2004) for information on maximum thinning being located in the accumulation zone.

3. INCREASED FLOODING AND EXTREME FLOW

Box 12. Summary of observed trends and future projections for increased flooding and extreme flow.

Observed Trends

Warming from 1916 to 2003 across the western U.S. has:

- increased or decreased simulated flood risk in transient basins (most basins in WA, OR, & CA on the west slopes of the Cascades and Sierras showed increasing flood risks), decreased flood risk in many cold snowmelt-dominant watersheds, and left flood risks in rain dominant basins essentially unchanged.[515] From ~1975 to 2003, increases in cold season precipitation variability increased simulated flood risks in most areas (e.g., much of Puget Sound basin, coastal areas in WA, OR, & CA).[516]

Late 20th century climate (~1975-2003) in the western U.S., which is associated with increased precipitation variability and systematic warming, has:

- increased flood risks in rain-dominant basins (due to precipitation changes), e.g., in much of the Puget Sound basin and coastal areas in WA, OR, and CA;
- strongly increased flood risks in many near-coastal areas in WA, OR, and CA with transient rain-snow basins (warming and precipitation changes tend to increase flood risks); and,
- has probably left flood risks in many snowmelt-dominant basins and cooler transient rain-snow basins in the interior largely unchanged (effects of warming and precipitation changes are comparable in magnitude and in opposite directions).[517] The largest increases in flood risk were associated with years the PDO and ENSO were "in-phase."[518]

Future Projections

- In Washington and the Pacific Northwest, the largest increases in flood return frequency are predicted for transient rain-snow basins.[519] Rain-dominant watersheds are predicted to experience small changes in flood frequency due to increasing winter precipitation.[520] Spring floods are projected to decrease in basins currently fed by snowmelt.[521]
- At Ross Dam on the Skagit River (WA) by the 2040s, magnitudes of the 20-, 50-, and 100-year-return flood events are projected to increase 5, 15, and 22%, respectively, under the B1 scenario (compared to a 1916-2006 baseline).[522]
- A gradual increase in annual maximum-week runoff is projected for much of the lower Klamath Basin (OR & CA).[523] 25-year storm frequency is projected to increase near Portland, OR.[524]

Note to the reader: Boxes are summaries of published and grey literature . The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

515 Hamlet and Lettenmaier. (2007)
516 Hamlet and Lettenmaier. (2007)
517 Hamlet and Lettenmaier. (2007, p. 15-16)
518 Hamlet and Lettenmaier. (2007)
519 Tohver and Hamlet. (2010)
520 Tohver and Hamlet. (2010)
521 Mantua, Tohver and Hamlet. (2010)
522 Seattle City Light (2010). The authors cite CIG (2010) for this information.
523 Reclamation. *SECURE Water Act Section 9503(c) - Reclamation Climate Change and Water, Report to Congress.* (2011)
524 Chang and Jones. (2010)

Hydrologic dynamics of increased flooding, extreme flow, and climate change

In basins dominated currently by a mix of rain and snow, if the snowpacks no longer form or are very shallow, and increases in temperature and wind speeds occur, large midwinter snowfall events will become large rain or melt events, and thereby increase the frequency of high flows occurring throughout the winter in these watersheds.[525] Subsequently, spring peak flow volumes will decrease and occur earlier because less precipitation is stored as snow during the winter, and winter flows will increase because precipitation will fall as rain instead of snow.[526] On the other hand, flood risks tend to decline in snowmelt-dominant basins because of systematic reductions in spring snowpack.[527]

Observed Trends

Southcentral and Southeast Alaska

Information needed.

British Columbia

No information on flooding in coastal B.C. was found. However, information on peak flows was found:

- For low-relief coastal basins where the seasonal streamflow regime is dominated by rainfall inputs, the annual peak flows typically occur in the fall and winter: generally no later than the end of February and as early as mid- to late-September on the central coast and mid-October on the south coast.[528]
- In high-relief coastal basins, stations with significant snowmelt contributions to their seasonal streamflow regimes may be subject to annual peak flows over many months in response to various peak flow generating mechanisms: in the fall as a result of rain events, in May, June, or July in response to seasonal snowmelt, in October or early November as a result of early snowfall, followed by a warm frontal system producing rain-on-snow events.[529]
- In drainage basins that have significant glacier cover, intense melting of glacier ice in the summer drives a distinct population of floods, which are superimposed on the rain, rain-on-snow, or snowmelt-generated peak flow regimes that are otherwise typical of the region.[530]

Pacific Northwest and northwestern California

Taken together, the increased precipitation variability and systematic warming associated with the late 20th century (~1975-2003) climate has

- increased flood risks in rain-dominant basins (precipitation changes),
- strongly increased flood risks in many near-coastal areas in WA, OR, and CA with transient snow (warming and precipitation changes tend to increase flood risks), and
- has probably left flood risks in many snowmelt-dominant basins and cooler transient basins in the interior largely unchanged (effects of warming and precipitation changes are comparable in magnitude and in opposite directions) (Figure 12).[531]

[525] *Pike et al. (2010, p. 719)
[526] *Pike et al. (2010, p. 719)
[527] *Hamlet and Lettenmaier. (2007, p. 11)
[528] *Eaton and Moore. (2010, p. 104)
[529] *Eaton and Moore. (2010, p. 106)
[530] *Eaton and Moore. (2010, p. 106)

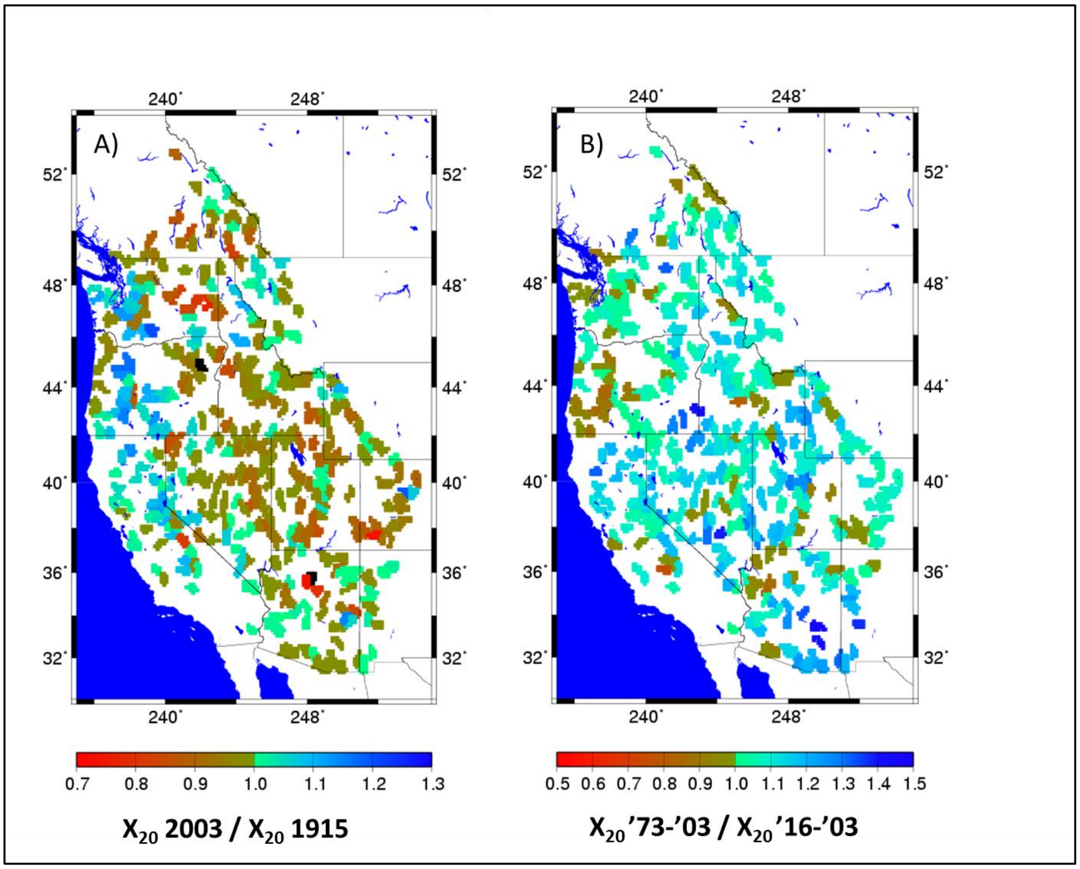

Figure 12. Changes in the simulated 20-Year flood associated with A) 20th Century warming trends, and B) increases in cool season precipitation variability since 1973. Ratios larger than 1.0 (aqua to blue) show increases in flood risk, ratios less than 1.0 (brown to red) show decreases in flood risk. *Source: Hamlet, A.F.* (Note that many, but not all, locations along the coast show increases in flood risk from both factors.)

In general, the largest changes in simulated flood risks are associated with years when PDO and ENSO are ‘‘in phase.’’[532] Changes in the variability of cool season precipitation after about 1973, the causes of which are uncertain, are shown to result in increased flood risk over much of the western U.S. in the simulations.[533] The simulated effects of century-scale warming, climatic variations associated with the PDO and ENSO, and late 20th century changes in precipitation variability on flood risks across the region provide evidence that flood risks are not constant in each year and are slowly evolving as the region warms.[534]

Neiman et al. (submitted for publication) found that flooding over the 1980 to 2009 water years in western Washington’s Queets, Satsop, Sauk River, and Green River basins occurred during the landfall of atmospheric rivers (e.g. Pineapple Express) within the warm sectors of extratropical cyclones (usually occurring between 30° and 60° latitude) that were accompanied by warm advection, temperatures in the lower troposphere 7.2 to 10.8°F (4-6°C) above normal, strong low-level water vapor fluxes from over the Pacific, and low-level moist-neutral

[531] *Hamlet and Lettenmaier. (2007, p. 15-16)
[532] *Hamlet and Lettenmaier. (2007, p. 1)
[533] *Hamlet and Lettenmaier. (2007, p. 1)
[534] *Hamlet and Lettenmaier. (2007, p. 16)

stability.[535] On average, rain rather than snow fell within almost the entirety of these basins, leading to enhanced runoff. [536]

Future Projections

Southcentral and Southeast Alaska

While effects will vary regionally, impacts to Alaska's freshwater ecosystems are generally expected to include increased winter flooding.[537]

British Columbia

In basins dominated currently by a mix of rain and snow, if the snowpacks no longer form or are very shallow, and increases in temperature and wind speeds occur, large midwinter snowfall events will become large rain or melt events, and thereby increase the frequency of high flows occurring throughout the winter in these watersheds.[538] Subsequently, spring peak flow volumes will decrease and occur earlier because less precipitation is stored as snow during the winter, and winter flows will increase because precipitation will fall as rain instead of snow.[539]

For all streamflow regimes, a complex relationship will likely develop between rain-on-snow events and changes in regional air temperature and precipitation patterns.[540] This is because the magnitude of rain-on-snow floods fluctuates depending on the duration and magnitude of precipitation, the extent and water equivalent of the antecedent snowpack, and the variations in freezing levels.[541] Climatic changes will influence all of these factors.[542] For example, McCabe et al.'s (2007) modeling study showed that as temperatures increase, rain-on-snow events decrease in frequency primarily at low-elevation sites.[543] Higher elevations are likely less sensitive to changes in temperature as these sites remain at or below freezing levels in spite of any temperature increase that would affect snow accumulation.[544]

Pacific Northwest

Specific projections for flood magnitude and frequency include:

- Basins identified as transient, characterized by a mixed runoff of rain and snow, are projected to be the most sensitive to warming temperatures.[545] These basins are found at higher elevations in coastal mountains (western Cascades, Olympic and Coast Ranges).[546] Under a warmer future climate, the greater proportion of winter precipitation falling as rain, rather than snow, will intensify winter flood risk for warmer transient basins.[547] This trend is depicted spatially in the 20 and 100-year flood ratio maps (Figure

535 Neiman et al. *Flooding in Western Washington: The Connection to Atmospheric Rivers.* (2010, p. 22)
536 *Neiman et al. (2010, p. 22)
537 *AK-DEC. (2010, p. 5-2)
538 *Pike et al. (2010, p. 719)
539 *Pike et al. (2010, p. 719)
540 *Pike et al. (2010, p. 719)
541 *Pike et al. (2010, p. 719). The authors cite McCabe et al. (2007) for this information.
542 *Pike et al. (2010, p. 719)
543 *Pike et al. (2010, p. 719)
544 *Pike et al. (2010, p. 719). The authors cite McCabe et al. (2007) for this information.
545 *Tohver and Hamlet. (2010, p. 8)
546 *Tohver and Hamlet. (2010, p. 8)
547 *Tohver and Hamlet. (2010, p. 8)

13) showing an overlap in the locations of warmer, transient basins with a progressive increase in flood risk through the 21st century.[548]

- Rain-dominant watersheds are predicted to experience small changes in flood frequency, and Washington's coldest snowmelt-dominated basins, where mean winter temperatures in the historic period were less than 23°F (< −5°C), are predicted to experience a reduction in flooding that has historically been observed during exceptionally heavy snowmelt periods in late-spring and early summer.[549] However, a more recent analysis by Tohver and Hamlet (2010) projects higher winter temperatures and precipitation regimes create conditions favoring elevated flood risk in snowmelt basins.[550] The discrepancy between Mantua, Tohver, and Hamlet's (2010) analysis and Tohver and Hamlet (2010) is attributable to the differences in spatial variability of average changes depicted by the two downscaling methods.[551]
- Hydrologic models indicate that warming trends will reduce snowpack, thereby decreasing the risk of springtime snowmelt-driven floods in some areas.[552]

Projected increases in flooding magnitude in western Washington generally become larger, with the same sign from the 2020s to the 2080s, with the greatest impacts occurring at the end of the twenty-first century.[553] Emissions scenarios also play a strong role in the rate of change in flooding magnitudes, with the changes for A1B emissions in the 2040s being similar to those for the B1 emissions in the 2080s.[554] At Ross Dam on the Skagit River, projections are as follows:

- By the 2020s: Magnitudes of the 20-, 50-, and 100-year-return flood events are projected to increase 1, 10, and 15%, respectively, under the B1 scenario (compared to a 1916-2006 baseline).[555]
- By the 2040s: Magnitudes of the 20-, 50-, and 100-year-return flood events are projected to increase 5, 15, and 22%, respectively, under the B1 scenario (compared to a 1916-2006 baseline).[556]

A case study of Portland (OR) shows that climate change will bring more frequent storm events with a return period of less than twenty-five years, which means that nuisance flooding is likely to become more common at road cross-sections that have a history of chronic flooding.[557]

Klamath Basin (southcentral Oregon and northwestern California)

Utilizing annual maximum- and minimum-week runoff as metrics of acute runoff events, projected trends in annual maximum-week runoff may vary by subbasin.[558] For example, the northeastern upper reaches (e.g., Williamson River below Sprague River) show results where annual maximum-week runoff remains relatively stable through the 21st century.[559] In contrast, runoff locations located further downstream and including a greater

[548] *Tohver and Hamlet. (2010, p. 8)
[549] *Mantua, Tohver and Hamlet. (2010, p. 201, 204)
[550] *Tohver and Hamlet. (2010, p. 7)
[551] *Tohver and Hamlet. (2010, p. 7)
[552] *Mantua, Tohver and Hamlet. (2010, p. 204). The authors cite Elsner et al. (2010) for this information.
[553] *Mantua, Tohver and Hamlet. (2010, p. 204)
[554] *Mantua, Tohver and Hamlet. (2010, p. 204)
[555] *Seattle City Light. *Appendix N. Climate Change.* (2010, p. 7). The authors cite CIG (2010) for this information.
[556] *Seattle City Light. (2010, p. 7). The authors cite CIG (2010) for this information.
[557] *Chang and Jones. (2010, p. 95). The authors cite Chang et al. (2010a) for this information.
[558] *Reclamation. (2011, p. 75)
[559] *Reclamation. (2011, p. 75)

portion of the lower basin (e.g., Klamath River near Klamath, California) show gradually increasing annual maximum-week runoff.[560]

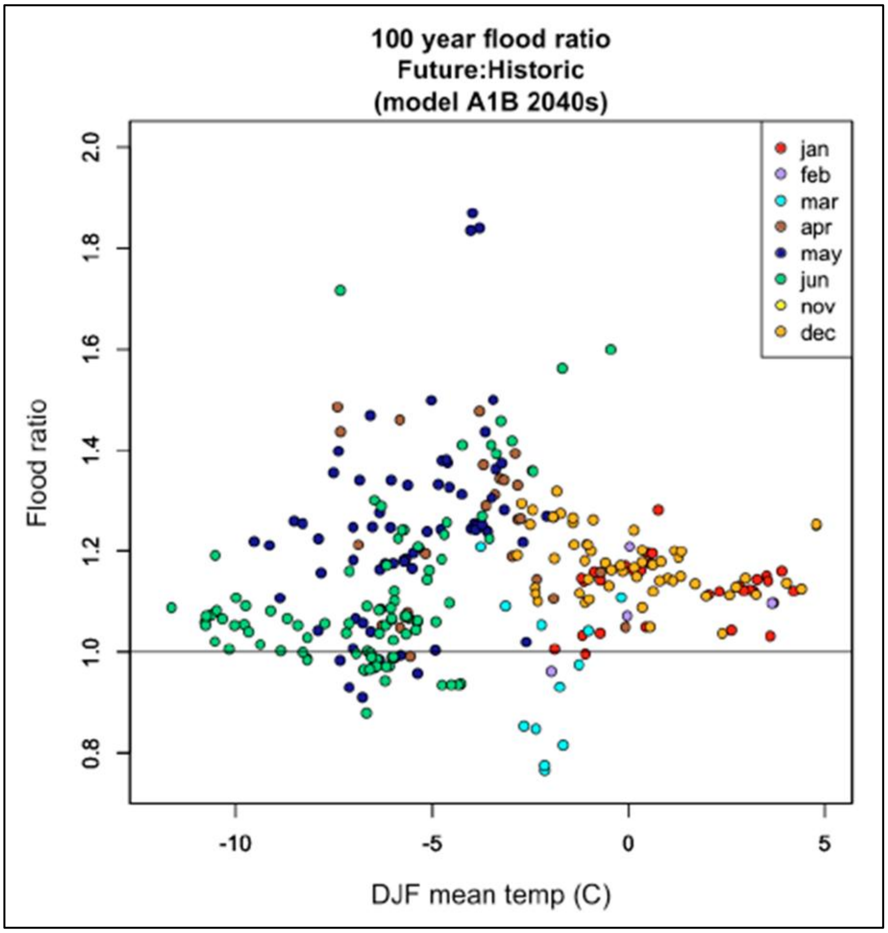

Figure 13. Average changes in the simulated 100-year flood for 297 river locations in the Pacific Northwest for the 2040s A1B scenario, expressed as a ratio of the future 100-year flood divided by the historical 100-year flood (y-axis). The x-axis shows the average DJF temperature for each river basin. *Source: Hamlet, A.F., citing Tohver and Hamlet (2010).*

Information Gaps

Information on observed trends in British Columbia, as well as southcentral and southeast Alaska, is needed. Information is also needed for future projections in all jurisdictions except Washington.

560 *Reclamation. (2011, p. 75)

4. INCREASED WATER TEMPERATURE

Box 13. Summary of observed trends and future projections for increased water temperature.

Observed Trends

- In western Washington, most maximum August stream temperatures remained below 68°F (20°C; the upper threshold for salmon survival) from 1970 to 1999. Stations along the Columbia River reported generally higher maximum temperature.[561]
- Increases in maximum stream temperature have been observed on the Rogue and Willamette Rivers (OR), and increases in the 7-day average daily maximum temperature were observed in the Portland, OR area.[562]

Future Projections

- In British Columbia's Fraser River basin, an increase in the frequency of stream temperatures exceeding 68°F (20°C) is projected.[563]
- In Washington, by the 2080s, stream temperatures are projected to increase by 3.6 to 9°F (2-5°C) under the B1 and A1B scenarios.[564]
- In the Tualatin River near Portland, Oregon, stream temperatures in excess of 68°F (20°C) are projected for the upper segments of the river.[565]

Note to the reader: In Boxes, we summarize the published and grey literature. The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

Hydrologic and physical dynamics of water temperature and climate change

The thermal regime of water bodies is mainly determined by the local weather[566] and climate. A shift in climate variables such as air temperature, radiation, cloud cover, wind or humidity will influence these heat fluxes and thus alter the heat balance of lakes and rivers.[567] Higher air temperatures, for example, are likely to increase water temperatures.[568]

Major controls on stream temperature are riparian vegetation (through shading) and streamflow (which influences heat exchange).[569] Thus, climate warming may also increase stream temperatures by reducing riparian vegetation, or by reducing snowpack and spring and summer discharges.[570] Projected hydrologic changes in some areas may produce lower streamflow in late summer, and also less groundwater discharge.[571] Both of these influences could promote higher late-summer water temperatures.[572] Similarly, physical considerations and empirical evidence consistently indicate that summer stream temperatures should increase as a result of glacier retreat; however, the

[561] Mantua et al. (2010)
[562] Chang and Jones (2010)
[563] Pike et al. (2010)
[564] Mantua et al. (2010)
[565] Chang and Jones (2010). The authors cite Chang and Lawler (2010) for this information.
[566] Nickus et al. (2010, p. 45)
[567] Nickus et al. (2010, p. 45)
[568] *Battin et al. *Projected impacts of climate change on salmon habitat restoration.* (2007, p. 6720)
[569] *Chang and Jones. (2010, p. 115)
[570] *Chang and Jones. (2010, p. 115)
[571] *Pike et al. (2010, p. 728)
[572] *Pike et al. (2010, p. 728)

magnitude of this change is difficult to predict.[573] Groundwater is typically cooler than stream water in summer during daytime and warmer during winter, and thus acts to moderate seasonal and diurnal (i.e. daily) stream temperature variations.[574] Deep groundwater temperatures tend to be within about 5.4°F (3°C) of mean annual air temperature.[575] It is reasonable, therefore, to assume that climate-induced groundwater warming will influence stream temperature regimes, particularly during base-flow periods when groundwater is a dominant contributor to streamflow and especially when energy inputs at the stream surface are relatively minor (e.g., at night).[576] Low elevation watersheds in areas of agricultural or urban land use, which are already temperature limited, may be most susceptible to climate-warming-induced increases in stream temperature.[577]

Observed Trends

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Figure 16 shows that most maximum August stream temperatures in western Washington from 1970 to 1999 were below 68°F (20°C), with stations along the Columbia River generally having higher maximum August stream temperatures than the remaining stations west of the Cascades.[578]

Several studies of Lake Washington (WA) have documented increased annual and seasonal water temperatures, both in the top-most layer and throughout the entire lake volume:

- **Annual:** Arhonditsis et al. (2004) conducted a statistical analysis of temperature fluctuations and found volume-weighted Lake Washington temperatures have increased on average by 0.047°F (0.026°C) per year from 1964 to 1998 (~1.6°F, or 0.9°C, during the thirty-five year period assessed).[579] Winder and Schindler (2004b) reported annual mean water temperature increased by 1.2°F (0.65°C) from 1962 to 2002, as predicted by a random-walk model.[580]
- **Seasonal:** In the study by Arhonditsis and colleagues, the warming trend was most pronounced for the epilimnion (i.e., the top-most layer in a thermally stratified lake) during the stratified period (April-September), which has warmed nearly 4°F (2.2°C) during the 35-year study period.[581] Winder and Schindler (2004b) found the epilimnion water temperature increased by 2.54°F (1.41°C) during the stratified period (April-November) and by 1.3°F (0.71°C) during the unstratified period (December-March) from 1962 to 2002.[582] In a second study by Winder and Schindler (2004a), a 2.50°F (1.39°C)

[573] *Pike et al. (2010, p. 717)
[574] *Pike et al. (2010, p. 728). The authors cite Webb and Zhang (1997) and Bogan et al. (2003) for this information.
[575] *Pike et al. (2010, p. 728). The authors cite Todd (1980) for this information.
[576] *Pike et al. (2010, p. 728)
[577] *Chang and Jones. (2010, p. 115)
[578] Mantua, Tohver and Hamlet. (2010, Fig. 1, p. 190)
[579] *Arhonditsis et al. *Effects of climatic variability on the thermal properties of Lake Washington.* (2004, p. 262-263)
[580] *Winder and Schindler. *Climatic effects on the phenology of lake processes.* (2004b, p. 1849)
[581] *Arhonditsis et al. (2004, p. 263)
[582] *Winder and Schindler. (2004b, p. 1849)

increase in water temperatures in the upper 10-m water layer from March to June from 1962 to 2002 was observed.[583]

Oregon

There is little evidence to date of increasing stream temperatures over time in Oregon, except in urban streams, where temperatures may have increased because of cumulative loss of shading from riparian vegetation associated with urban and suburban development.[584] Specific observed trends include:

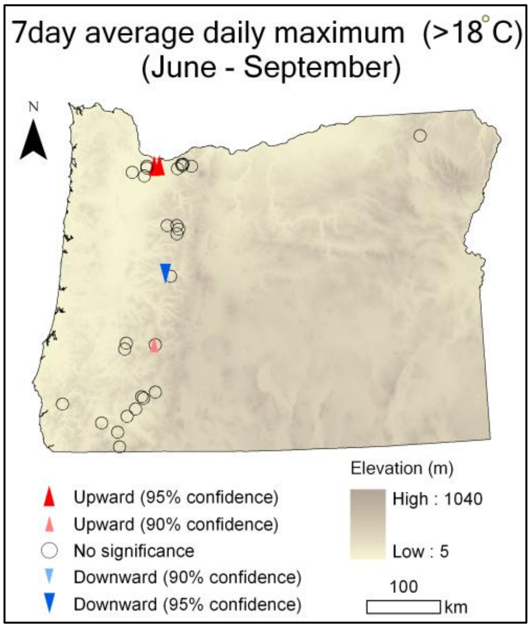

Figure 14. Trends in 7-day average daily maximum temperature for 31 stations in Oregon, 1999-2009. *Source: Reproduced from Chang and Jones. (2010, Fig. 3.25, p. 114) by authors of this report.*

- Data from three stream gauging stations in the Rogue and Willamette River basins (Rogue River near Mcleod, Blue River at Blue River, and North Santiam River at Niagara) show general increasing trends in maximum water temperature for two of the three stations, particularly in the North Santiam River.[585] High variability in August and September water temperature at Blue River appear to be associated with flow regulations in late summer months.[586]
- The 7-day average daily maximum temperature, currently used for assessing water temperature threshold for fish habitat (e.g., lethality and migration blockage conditions), increased at five stations which are all located in the Portland metropolitan area (Figure 14) from 1999 to 2009.[587] The variability of water temperature in Johnson Creek increased over the past ten-year period, suggesting that the stream frequently exceeds the threshold level of 64.4°F (18°C).[588]

Northwestern California

Temperature profiles measured regularly for two decades in Castle Lake, a small subalpine lake, have revealed large interannual differences in heat content associated with the amount of winter snowfall (prior to 1985, specific study period not provided).[589] In all years with anomalously large heat content, the snowfall was lower than average; while in all years (except 1973) with anomalously small heat contents, snowfall was higher than average.[590] ENSO events produced both anomalies, but some anomalous years were without ENSOs.[591] Hence, simple interpretations of effects from ENSO events would not be appropriate.[592]

583 *Winder and Schindler. *Climate change uncouples trophic interactions in an aquatic ecosystem.* (2004a, p. 2102)
584 *Chang and Jones. (2010, p. 118)
585 *Chang and Jones. (2010, p. 115)
586 *Chang and Jones. (2010, p. 115)
587 *Chang and Jones. (2010, p. 116)
588 *Chang and Jones. (2010, p. 116)
589 *Melack et al. (1997, p. 983). The authors cite Strub et al. (1985) for this information.
590 *Melack et al. (1997, p. 983)
591 *Melack et al. (1997, p. 983)
592 *Melack et al. (1997, p. 983)

Future Projections

Regional

A warmer future can be expected to directly increase the seasonal water temperatures of most running water ecosystems, with greater effects at more northerly (poleward) latitudes.[593] Warm-season river temperatures usually closely approximate air temperatures, typically with a time lag of weeks or less, although streams and smaller rivers with a large component of groundwater or meltwater may be considerably cooler than summer air temperatures.[594]

Southcentral and Southeast Alaska

While effects will vary regionally, impacts to Alaska's freshwater ecosystems are generally expected to include warmer summer stream temperatures.[595]

British Columbia

Streamflow scenarios for sub-basins of the Fraser River suggest an increase in the spatial and temporal frequency of temperatures exceeding 68°F (20°C), particularly below the confluence with the Thompson River.[596] Morrison et al. (2002) used a conceptual model of catchment hydrology (the University of British Columbia Watershed Model), in conjunction with projections of future temperature and precipitation, to generate scenarios for streamflow for sub-basins of the Fraser River.[597] They then used these climate and streamflow projections, together with a model of energy exchanges and water flow in the Fraser River stream network, to simulate stream temperatures.[598]

Washington

Stream temperature modeling by Mantua et al. (2010) predicts significant increases in water temperatures (T_w, estimated maximum stream temperature) statewide for both A1B and B1 emissions scenarios (compared to a 1970-1999 baseline; see Figure 15).[599] For both A1B and B1 emissions scenarios in the 2020s, annual maximum T_w at most stations included in the study is projected to rise less than 1.8°F (1°C); by the 2080s, many stations on both the east and west side of the Cascades warm by 3.6 to 9°F (2-5°C).[600] Water temperatures projected under the A1B emissions scenarios become progressively warmer than those projected under the B1 emissions, and by the 2080s the differences are ~1.8°F (~1°C; note that projected summertime air temperatures under A1B emissions are, on average, 3.24°F, or 1.8°C, warmer than those under B1 emissions for the 2080s).[601]

[593] Allan, Palmer and Poff. (2005, p. 282)
[594] Allan, Palmer and Poff. (2005, p. 282)
[595] *AK-DEC. (2010, p. 5-2)
[596] *Pike et al. (2010, p. 729). The authors are summarizing the work of Morrison et al. (2002).
[597] *Pike et al. (2010, p. 729). The authors are summarizing the work of Morrison et al. (2002).
[598] *Pike et al. (2010, p. 729). The authors are summarizing the work of Morrison et al. (2002).
[599] *Mantua, Tohver and Hamlet. (2010, p. 196)
[600] *Mantua, Tohver and Hamlet. (2010, p. 197-198)
[601] *Mantua, Tohver and Hamlet. (2010, p. 198)

Oregon

Future changes in stream temperature in response to climate change in Oregon will depend on the degree to which warming results in a reduction of late summer streamflow and how warming influences riparian vegetation.[602] Water temperature is projected to rise as air temperature increases in the 21st century, particularly in urban streams where natural riparian vegetation is typically lacking.[603] A decline in summer streamflow is expected to exacerbate water temperature increases.[604] Chang and Jones (2010) summarize the results of a study evaluating the number of days that 7-day daily average water temperature exceeds 68°F (20°C) between May 15 and October 15 in the mainstem of the Tualatin River located near the Portland metropolitan area:[605]

- Under the baseline scenario (no dates provided), only the lower segments of the drainage experience water temperature above 68°F (20°C).[606]
- Under 5% flow reduction and 2.7°F (1.5°C) air temperature rise scenarios (representing the 2040s), segments with water temperatures in excess of 68°F (20°C) for more than sixty days expand to include some upstream areas.[607]
- Under 10% flow reduction and 5.4°F (3°C) air temperature rise scenarios (which represents the 2070s), they expand further into upstream areas.[608]
- Riparian vegetation scenarios have the most direct impact on middle segments of the drainage under the highest warming scenario.[609] As noted previously, major controls on stream temperature are riparian vegetation (through shading) and streamflow (which influences heat exchange).[610]

Northwestern California

Information needed.

Information Gaps

Information on observed trends in British Columbia, southcentral and southeast Alaska, and northwestern California is needed. Information is also needed for future projections in northwestern California and southcentral and southeast Alaska. Studies using physically based modeling approaches are also needed, as many of the projections currently available are based on statistical models that do not incorporate changes in water temperature due to changes in groundwater, interannual snowpack, or glaciers.

[602] *Chang and Jones. (2010, p. 116)
[603] *Chang and Jones. (2010, p. 132)
[604] *Chang and Jones. (2010, p. 132)
[605] *Chang and Jones. (2010, p. 115). The authors are summarizing the results of Chang and Lawler (2010). Results are based on CE-QUAL-W2 simulations for 154 segments in the lower Tualatin River under three combinations of temperature, flow, and riparian scenarios.
[606] *Chang and Jones. (2010, p. 116)
[607] *Chang and Jones. (2010, p. 116)
[608] *Chang and Jones. (2010, p. 116)
[609] *Chang and Jones. (2010, p. 116)
[610] *Chang and Jones. (2010, p. 115)

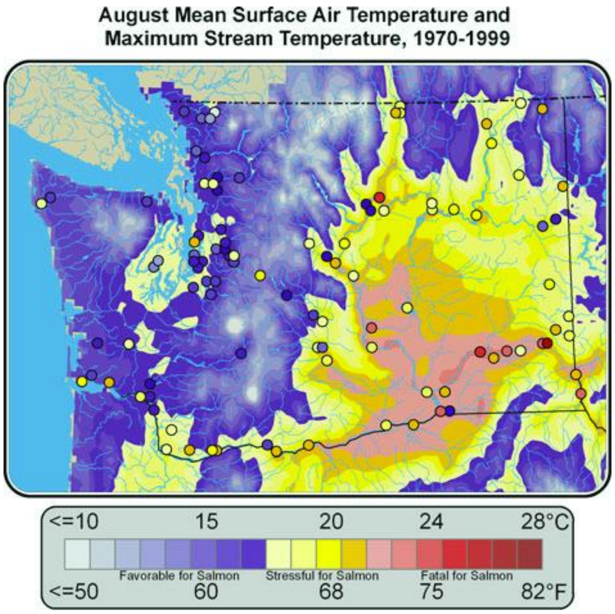

Figure 16. *Color shading* shows the historic (1970-1999) mean surface air temperatures for August, and *shaded circles* show the simulated mean of the annual maximum for weekly water temperatures for select locations. Figure: Robert Norheim *Source: Reproduced from Mantua, Tohver and Hamlet. (2010, Fig. 1, p. 190) by authors of this report.*

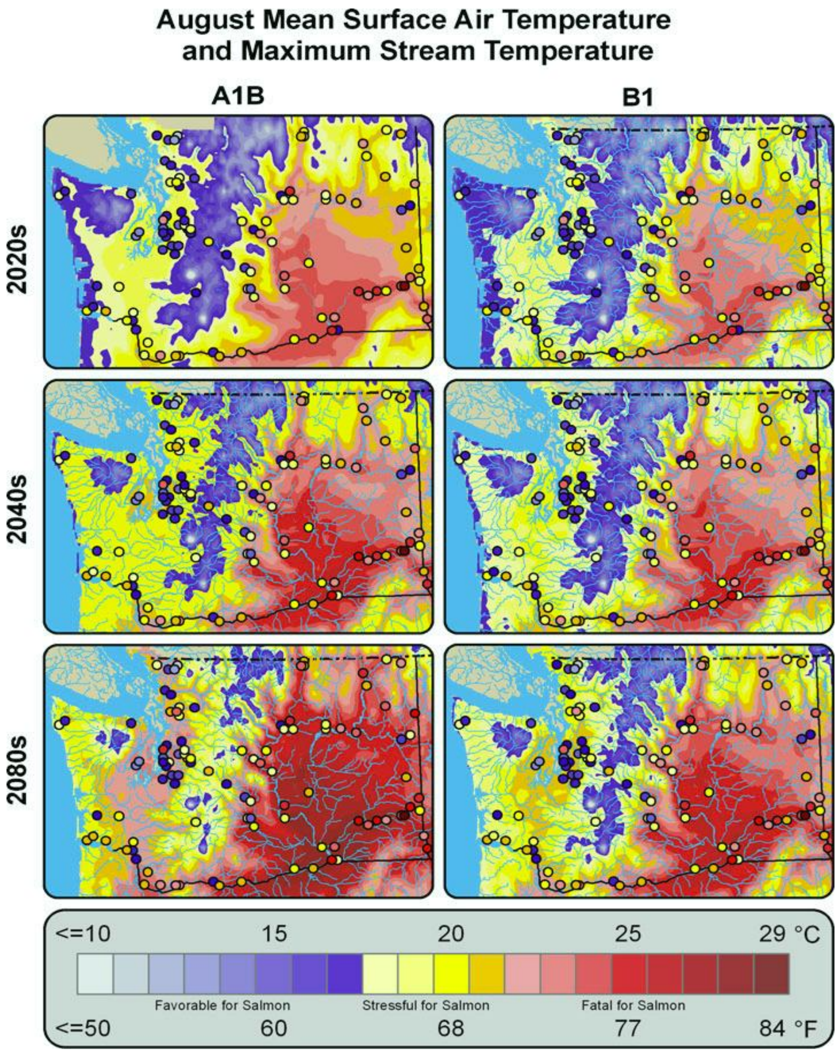

Figure 15. *Color shading* shows the mean surface air temperatures for August for the 2020s (top), 2040s (middle) and 2080s (bottom) and *shaded circles* show the simulated mean of the annual maximum for weekly water temperatures for select locations. Multi-model composite averages based on the A1B emissions are in the *left panels*, and those for B1 emissions are in the *right panels.* Figure: Robert Norheim

Source: Reproduced from Mantua, Tohver and Hamlet. (2010, Fig. 2, p. 97) by authors of this report.

5. CHANGES IN WATER QUALITY

Box 14. Summary of observed trends and future projections for changes in water quality.

Observed Trends

- For the Fraser River, water chemistry along the length of the main stem in different seasons shows changes in turbidity, total phosphorus, and iron are positively related to discharge, and five variables (chloride, calcium, sodium, reactive silica, and sulfate) are negatively associated with discharge.[611]
- Nitrogen-based nutrients are generally low in the Rogue and lower Klamath Rivers (OR and CA, respectively).[612]
- Phosphorus-based nutrients are generally low in the lower Klamath River, are approximately 38% higher in the Rogue River than the lower Klamath River, and are approximately 60% higher in the Columbia River, both near Portland (OR) and upstream near Hanford (WA), than the Klamath River.[613]

Future Projections

- Water quality projections are limited and vary widely for the NPLCC region.
  - In areas where increased flows are projected, nutrient contaminants may be diluted (e.g. northwest BC).[614]
  - However, increased flows may also increase sediment nutrient loads (e.g. during winter in the Tualatin Basin, OR).[615]
  - And while lower summer flows may decrease nutrient sediment loads, projected increases in development or other stressors may counteract projected decreases.[616]

Note to the reader: In Boxes, we summarize the published and grey literature. The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

Climatic and hydrologic dynamics influencing water quality

The most important factors that influence the effects of climate change on water quality are increases in atmospheric and water temperatures and changes in the timing and amount of streamflow.[617] Higher water temperatures will enhance the transfer of volatile and semi-volatile compounds (e.g., ammonia, mercury, dioxins, pesticides) from surface water bodies to the atmosphere.[618] Higher surface water temperatures will also promote algal blooms and increase the bacteria and fungi content.[619] For example, higher concentrations of phosphorus, along with warmer temperatures, can promote algal blooms that reduce water quality.[620]

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[611] Reynoldson et al. "Fraser River Basin." In *Rivers of North America.* (2005, p. 705). The authors cite Whitfield (1983) and Whitfield and Schreier (1982) for this information.
[612] Carter and Resh. "Pacific Coast Rivers of the Coterminous United States." In *Rivers of North America.* (2005)
[613] Stanford et al. "Columbia River Basin." In *Rivers of North America.* (2005); Carter and Resh. (2005)
[614] Pike et al. (2010)
[615] Chang & Jones. (2010)
[616] Chang & Jones. (2010)
[617] *Pike et al. (2010, p. 728)
[618] *Kundzewicz et al. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Freshwater resources and their management.* (2007, p. 188). The authors cite Schindler (2001) for this information.
[619] *Kundzewicz et al. (2007, p. 188). The authors cite Hall et al. (2002) and Kumagai et al. (2003) for information on algal blooms and Environment Canada (2001) for information on bacteria and fungi content.
[620] *Pike et al. (2010, p. 731). The authors cite Schindler et al. (2008) for this information.

Increasing nutrients and sediments due to higher runoff, coupled with lower water levels, will negatively affect water quality, possibly rendering a source unusable unless special treatment is introduced.[621] In regions where intense rainfall is expected to increase, pollutants (pesticides, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies.[622] More intense rainfall will also lead to an increase in suspended solids (turbidity) in lakes and reservoirs due to soil fluvial erosion, and pollutants will be introduced. [623] Lowering of the water levels in rivers and lakes will lead to the re-suspension of bottom sediments and liberating compounds, with negative effects on water supplies.[624] Further, as streamflows decline, the capacity of freshwaters to dilute chemical loadings will be reduced.[625] In areas where amounts of surface water and groundwater recharge are projected to decrease, water quality will also decrease due to lower dilution. [626]

Recent IPCC publications provided only cursory details on the effects of climate change on water quality.[627] Limited predictions in this area may be partly related to the challenge of separating the potential effects of climate change on water quality from those of land and water use on surface and ground waters.[628]

Observed Trends

Southcentral and Southeast Alaska

Information needed.

British Columbia

For the Fraser River, water chemistry along the length of the main stem in different seasons shows changes in turbidity, total phosphorus, and iron are positively related to discharge, and five variables (chloride, calcium, sodium, reactive silica, and sulfate) are negatively associated with discharge.[629] Three zones in the Fraser River have been identified from the water chemistry: a headwater zone that extends only as far as Red Pass (~43 miles, or 70 km, from the source), a midstream zone from Red Pass to between Prince George and Quesnel, and a downstream zone .[630]

[621] *Kundzewicz et al. (2007, p. 188). The authors cite Hamilton et al. (2001) for information on water quality and Environment Canada (2004) for information on the possibility of unusable sources and introduction of special treatments.
[622] *Kundzewicz et al. (2007, p. 188). The authors cite Fisher (2000), Boorman (2003b), and Environment Canada (2004) for this information.
[623] *Kundzewicz et al. (2007, p. 188). The authors cite Leemans and Kleidon (2002) for information on soil fluvial erosion and Mimikou et al. (2000), Neff et al. (2000),and Bouraoui et al. (2004) for information on pollutant introduction.
[624] *Kundzewicz et al. (2007, p. 188). The authors cite Atkinson et al. (1999) for this information.
[625] Pike et al. (2010, p. 730). The authors cite Schindler (2001) for this information.
[626] *Kundzewicz et al. (2007, p. 189). The authors cite Environment Canada (2004) for this information.
[627] *Pike et al. (2010, p. 728). The authors cite Kundzewicz et al. (2007) and Bates et al. (2008) for this information.
[628] *Pike et al. (2010, p. 728)
[629] *Reynoldson et al. (2005, p. 705). The authors cite Whitfield (1983) and Whitfield & Schreier (1982) for this information.
[630] Reynoldson et al. (2005, p. 705). The authors cite Whitfield (1983) for this information.

For the downstream zone, the mean ranges for water quality are:

- Turbidity: 19.0 to 25.0 JTU;
- Specific conductivity: 114 to 139 µS/cm;
- Alkalinity: 47 to 61 mg/L as $CaCO_3$;
- Hardness: 53 to 67 mg/L as $CaCO_3$;
- Chloride: 1.1 to 1.5 mg/L;
- Silica: 3.9 to 5.6 mg/L; and
- Sodium: 2.1 to 2.7 mg/L.[631]

Washington and Oregon

For the Columbia River, water-quality records of the U.S. Geological Survey from 1993 to 2003 provide the following average measures at the Beaver Army Terminal downstream of Portland, Oregon:

- Turbidity: 8.2 NTU;
- Specific conductance: 135.4 µs/cm;
- Alkalinity: 51.9 mg/L as $CaCO_3$;
- NO_3-N: 0.26 mg/L;
- Phosphorus (total): 0.06 mg/L;
- Calcium: 13.9 mg/L;
- Magnesium: 4.0 mg/L;
- Sulfate (water, filtered): 8.9 mg/L;
- Cadmium (water, filtered): 0.05 µg/L;
- Lead (water, filtered): 0.55 µg/L;
- Aluminum (water, filtered): 12.09 µg/L;
- Arsenic: 1.05 µg/L;
- DDE: 0.005 µg/L;
- Dieldrin: 0.002 µg/L; and,
- PCB: 0.15 µg/L.[632]

Values were similar at a monitoring site upstream near Hanford at Richland, Washington, for the same time period.[633]

The waters of the Rogue River in Oregon are quite soft and somewhat alkaline, with an average hardness of 41 mg/L $CaCO_3$ and a pH of 7.5.[634] Conductivity is also low, with average conductance of approximately 100 µS/cm.[635] Dissolved oxygen is very near saturation and averages 10.5 mg/L.[636] Nutrients in the Rogue are also low.[637] Nitrogen as dissolved NO_3-N + NO_2-N is approximately 0.135 mg/L and PO_4-P is 0.051 mg/L.[638]

[631] *Reynoldson et al. (2005, p. 705)
[632] *Stanford et al. (2005, p. 625)
[633] *Stanford et al. (2005, p. 625-626)
[634] *Carter and Resh. (2005, p. 571)
[635] *Carter and Resh. (2005, p. 571)
[636] *Carter and Resh. (2005, p. 571)
[637] *Carter and Resh. (2005, p. 571)
[638] *Carter and Resh. (2005, p. 571)

Northwestern California

For the Klamath River near the town of Klamath, on the coast, total hardness is 70 mg/L as $CaCO_3$ and conductivity is about 170 µS/cm.[639] The waters are alkaline, averaging approximately a pH of 8, and are well oxygenated (dissolved oxygen 10 mg/L).[640] Nutrients are generally low, with dissolved NO_3-N + NO_2-N about 0.155 mg/L and PO_4-P averaging 0.037 mg/L.[641]

Future Projections

Southcentral and Southeast Alaska

Information needed.

British Columbia

Some of the effects of climate change on water quality may be mitigated in regions such as the Peace Basin (northeast B.C.) and northwest British Columbia, where increases in summer precipitation and an overall wetter climate are predicted.[642] For example, increased flows may potentially result in increased dilution of some nutrient contaminants, offsetting the effects of temperature increases and the associated evaporative demand.[643] In some instances, greater dilution of pollutants may actually result in a positive effect on water quality.[644] Similarly, an increase in the dilution capacity of streams may occur during the spring freshet in regions with predicted increases in winter precipitation.[645] However, a counterbalancing effect may become evident on any water quality improvements because of an increase in stream power and non-point source pollutant loadings to watercourses.[646]

Washington

Information needed.

Oregon

As sediment and phosphorus loadings typically increase during high flow events, changes in flow variability are expected to alter temporal variability of sediment and phosphorus loadings.[647] A case study in the Tualatin River basin of Oregon illustrates that winter sediment nutrient loadings are expected to increase under climate change scenarios as winter flows are projected to increase.[648] Although diminished summer flow is likely to reduce summer nutrient loading, the annual load is expected to increase further with urban development scenarios.[649] However, conservation-oriented development could reduce erosion and phosphorus loading substantially compared to conventional development.[650] The combination of climate change and urban development scenarios generally produce hydrological and water quality results that track the results from climate change alone,

639 *Carter and Resh. (2005, p. 565)
640 *Carter and Resh. (2005, p. 565)
641 *Carter and Resh. (2005, p. 565)
642 *Pike et al. (2010, p. 731)
643 *Pike et al. (2010, p. 731)
644 *Pike et al. (2010, p. 731)
645 *Pike et al. (2010, p. 731)
646 *Pike et al. (2010, p. 731)
647 *Chang and Jones. (2010, p. 118)
648 *Chang and Jones. (2010, p. 118). The authors cite Praskievicz and Chang (2011) for this information.
649 *Chang and Jones. (2010, p. 118)
650 *Chang and Jones. (2010, p. 119)

suggesting that the water resource impacts from climate change are more significant than those from land use change in the Tualatin River Basin.[651] The development and conservation scenarios do differ in their hydrological and water quality outcomes, thus representing a potential opportunity for local adaptation to climate change by pursuit of sustainable forms of urban development.[652]

Northwestern California

Information needed.

Information Gaps

Information is needed for observed trends in water pollution and water quality throughout the NPLCC region, as the information presented here refers to select rivers throughout the region. Information on future projections in northwestern California, Washington, and southcentral and southeast Alaska is also needed.

[651] *Chang and Jones. (2010, p. 119)
[652] *Chang and Jones. (2010, p. 119)

6. ALTERED GROUNDWATER LEVELS, RECHARGE, AND SALINITY

Box 15. Summary of observed trends and future projections for altered groundwater levels, recharge, and salinity.

Observed Trends

- In the lower Fraser Valley (BC), groundwater levels tend to be higher during La Niña years and lower during El Niño years.[653]
- Small absolute decreases in water level, generally in upland areas, were observed in the Abbotsford-Sumas Aquifer (BC) (study period not provided).[654]
- In Island County (WA) in 2005, nine percent of wells showed positive indications of saltwater intrusion.[655]

Future Projections

- Saltwater intrusion will be exacerbated in coastal water tables influenced by the ocean or tides.[656] On the Gulf Islands (BC), the interface between seawater and fresh groundwater will move further inland.[657]
- In Oregon, the timing of groundwater recharge will increase winter flow and reduce late season flow.[658]

Note to the reader: In Boxes, we summarize the published and grey literature. The rest of the report is constructed by combining sentences, typically verbatim, from published and grey literature. Please see the Preface: Production and Methodology for further information on this approach.

Hydrologic dynamics of groundwater and climate change

Groundwater originates as precipitation that infiltrates deeply into the ground and replenishes water storage in deep soil layers and/or underground aquifers; this is known as groundwater recharge.[659] Spatial and temporal variations in groundwater levels are caused by both human and natural factors.[660] Human factors often involve groundwater extraction (e.g., pumping and irrigation) or land use change (urbanization or deforestation).[661] Natural factors may include the effects of tides on coastal aquifers, the influence of seasonal variations in precipitation and recharge, and the effects of longer-duration climatic cycles.[662]

Because groundwater systems are recharged by precipitation, they are sensitive to changes in the amount, timing, and form of precipitation.[663] Groundwater levels can lag in response to climate variation.[664] Groundwater

[653] Pike et al. (2010)
[654] Pike et al. (2010). The authors cite Scibek and Allen (2006a) for this information.
[655] Huppert et al. (2009).
[656] Chang & Jones. (2010)
[657] Pike et al. (2010)
[658] Chang & Jones. (2010)
[659] *Chang & Jones. (2010, p. 99)
[660] *Pike et al. (2010, p. 704)
[661] *Pike et al. (2010, p. 704)
[662] *Pike et al. (2010, p. 704)
[663] *Chang and Jones. (2010, p. 100)

discharge is an important component of streamflow along with surface runoff.[665] The portion of streamflow supplied by groundwater is known as baseflow.[666] Most critically, groundwater is the principal source of streamflow in the late summer and fall in some regions (e.g., Pacific Northwest) when there is little precipitation or snowmelt to supply runoff.[667]

Observed Trends

Southcentral and Southeast Alaska

Information needed.

British Columbia

The potential effects of climate change on groundwater levels and recharge in the Lower Mainland and coastal regions generate fewer concerns than in other areas of British Columbia.[668] However, relatively little research has been directed toward the effects of climate change on groundwater in British Columbia.[669] Unraveling the complexity of causal factors is confounded by climate variability; however, analysis of groundwater hydrographs in combination with climate and streamflow data offers some insight.[670] Key findings include:

- Fleming and Quilty (2006) found that, in the lower Fraser Valley, groundwater levels tend to be higher during La Niña years and lower during El Niño years because of the associated variations in precipitation and recharge.[671] The study investigated groundwater and stream hydrographs at four observation wells.[672]
- Results of a larger study conducted by Moore et al. (2007) indicate that groundwater levels have decreased over the areas examined, whereas winter precipitation and recharge increased over a 20–30 year period (specific years and locations not provided).[673] This study correlated groundwater levels with nearby streamflow and precipitation records.[674] The results are highly variable, however, and likely related to differences in aquifer properties, surface water–groundwater interactions, and the effects of water withdrawals.[675]
- A modeling study of the Abottsford-Sumas Aquifer indicates only small absolute decreases in water levels, which are generally limited to upland areas (study period not provided).[676] However, lower groundwater levels will result in decreased base flow during low flow periods, which may have a negative influence on fish habitat.[677]

[664] *Pike et al. (2010, p. 705)
[665] *Chang and Jones. (2010, p. 99)
[666] *Chang and Jones. (2010, p. 99)
[667] *Chang and Jones. (2010, p. 99)
[668] *Pike et al. (2010, p. 718).
[669] *Pike et al. (2010, p. 718). The authors cite Allen (2009) for this information.
[670] *Pike et al. (2010, p. 705)
[671] *Pike et al. (2010, p. 705). The authors are summarizing the work of Fleming and Quilty (2006).
[672] *Pike et al. (2010, p. 705). The authors are summarizing the work of Fleming and Quilty (2006).
[673] *Pike et al. (2010, p. 705). Pike et al. are summarizing the results of Moore et al.
[674] *Pike et al. (2010, p. 705). Pike et al. are summarizing the results of Moore et al.
[675] *Pike et al. (2010, p. 705). The authors cite [Moore, R.D., D.M. Allen, and K. Stahl 2007. Climate change and low flows: influences of groundwater and glaciers. Nat. Resour. Can., Can. Climate Action Fund, Ottawa, Ont. Can. Climate Action Fund Proj. No. A875. Unpubl. report.] for this information.
[676] *Pike et al. (2010, p. 718). The authors cite Scibek and Allen (2006a) for this information.
[677] *Pike et al. (2010, p. 718).

Washington

In some areas of Washington State saltwater intrusion is already a concern due to excessive pumping of the aquifers.[678] For example, in a study by Island County Environmental Health in 2005, out of 379 wells surveyed, 242 showed no evidence of intrusion (~64%), 101 showed inconclusive indications of intrusion (~27%), and 36 showed positive indications of intrusion (~9%).[679]

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska

Information needed.

British Columbia

For aquifers on the Gulf Islands and in other coastal locations, concerns about decreasing recharge and declining water levels are related to the potential for saltwater intrusion, a problem that may be compounded by rising sea levels.[680] In combination, a decrease in groundwater recharge and increase in sea level will cause the interface between seawater and fresh groundwater to move further inland, potentially increasing aquifer salinity to a point where its water is not fit for human consumption or use in irrigation.[681]

Washington

Information needed.

Oregon

The principal mechanisms for change in groundwater are expected increases in evapotranspiration, which will decrease groundwater recharge, and increased pumping of water from groundwater wells to compensate for increased evapotranspiration.[682] Secondary mechanisms include small changes in groundwater resulting from small projected changes in precipitation and localized changes in sea level in coastal areas.[683] Projected changes include:

- The timing of groundwater recharge will shift in the same manner as runoff.[684] The shift in timing of recharge will affect groundwater-dominated streams, increasing winter flow and reducing late season flow.[685]

[678] *Huppert et al. *Impacts of climate change on the coasts of Washington State*. (2009, p. 298)
[679] *Huppert et al. (2009, p. 299)
[680] *Pike et al. (2010, p. 718). The authors cite Rivera et al. (2004) for information on saltwater intrusion and Allen (2009) for information on rising sea levels.
[681] *Pike et al. (2010, p. 718).
[682] *Chang and Jones. (2010, p. 108)
[683] *Chang and Jones. (2010, p. 108)
[684] *Chang and Jones. (2010, p. 105)

- A rise in mean sea level will result in a comparable rise in water-table elevations in sand dune aquifers as well as alluvial aquifers hydraulically connected to tidally influenced estuaries.[686] Sea level rise will exacerbate any existing saltwater intrusion problems.[687]

Groundwater is typically cooler than stream water in summer during daytime and warmer during winter, and thus acts to moderate seasonal and diurnal (i.e. daily) stream temperature variations.[688] In particular, groundwater discharge from permeable upland areas has the potential to moderate the effects of warming to some degree.[689] This is because the groundwater system acts as a reservoir, storing seasonally variable recharge and releasing it to streams at a more constant rate throughout the year.[690] Groundwater is much less likely to moderate the effects of climate change on streams originating in lowland settings than streams originating in permeable uplands for several reasons.[691] Recharge rates in lowland areas are generally less because of the smaller amount of precipitation, groundwater discharge to streams from lowland areas is generally less than in upland areas, and groundwater originating in lowlands generally makes up a smaller component of streamflow.[692]

Northwestern California

Information needed.

Information Gaps

Information is needed on observed trends in groundwater in all jurisdictions except British Columbia. Information is also needed for future groundwater projections in southcentral and southeast Alaska, Washington, and northwestern California.

[685] *Chang and Jones. (2010, p. 105). The authors cite Manga (1997) and Tague et al. (2008) for this information.
[686] *Chang and Jones. (2010, p. 104)
[687] *Chang and Jones. (2010, p. 104)
[688] *Pike et al. (2010, p. 728). The authors cite Webb and Zhang (1997) and Bogan et al. (2003) for this information.
[689] *Chang and Jones. (2010, p. 105). The authors cite Tague et al. (2008), Tague and Grant (2009), Chang and Jung (2010), and Mayer and Naman (2010) as examples for this information.
[690] *Chang and Jones. (2010, p. 105)
[691] *Chang and Jones. (2010, p. 106)
[692] *Chang and Jones. (2010, p. 106)

IV. IMPLICATIONS FOR FRESHWATER ECOSYSTEMS

Changing climate is already having an impact on the physical, chemical and biological characteristics of freshwater ecosystems, both directly through changes in air temperature and precipitation and indirectly through interaction with other stressors (Figure 17).[693] Based on a search of the scientific and grey literature, the following implications of climate change for freshwater ecosystems in the NPLCC region have been identified:

1. Altered nutrient cycling and productivity
2. Changes to stratification and eutrophication
3. Changes to water input, level, and area
4. Changes to the length and date of seasonal ice cover
5. Habitat loss, degradation, and conversion

Trends toward warmer air temperatures, increased precipitation variability, decreased snowpack, and increased wildfire activity are already linked to warming streams and rivers, altered stream hydrologies, and increased channel disturbance from flooding and post-fire landslides and debris flows.[694]

Lakes differ widely in size, depth, transparency, and nutrient availability, characteristics that fundamentally determine how each lake will be affected by climate change.[695] In general, however, warmer air temperatures are likely to lead to increasing water temperatures, which, in turn, can lower water level and oxygen content.[696] Further, climate change will impact lake hydrology through effects on residence time and water level as well as through receptors and sources of streamflow.[697]

The vulnerability of wetlands to changes in climate depends on their position within hydrologic landscapes.[698] Hydrologic landscapes are defined by the flow characteristics of ground water and surface water and by the interaction of atmospheric water, surface water, and ground water for any given locality or region.[699] In general, the vulnerability of all wetlands to climate change fall between two extremes: those dependent primarily on precipitation for their water supply are highly vulnerable, and those dependent primarily on discharge from regional ground water flow systems are the least vulnerable, because of the buffering capacity of large ground water flow systems to climate change.[700]

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[693] *Nickus et al. "Direct impacts of climate change on freshwater ecosystems." In *Climate Change Impacts on Freshwater Ecosystems.* (2010, p. 60)
[694] *Isaak et al. *Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network.* (2010, p. 1350). The authors cite Abatzoglou and Redmond (2007) and IPCC (2007) for information on warmer air temperatures; Hamlet et al. (2007) for information on increased precipitation variability; Hamlet et al. (2005) and Mote et al. (2005) for information on decreased snowpack; Westerling et al. (2006) and Morgan et al. (2008) for information on increased wildlife activity; Peterson and Kitchell (2001), Morrison et al. (2002), and Bartholow (2005) for information on warming streams and rivers; Stewart et al. (2005), Barnett et al. (2008), and Luce and Holden (2009) for information on altered stream hydrologies; and, Miller et al. (2003), Istanbulluoglu et al. (2004), and Hamlet and Lettenmaier (2007) for information on increased channel disturbance from flooding and post-fire landslides and debris flows.
[695] *Kling et al. *Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems.* (2003, p. 21)
[696] *Kling et al. (2003, Fig. 17, p. 42)
[697] *Verdonschot et al. (2010, p. 69)
[698] *Winter. *The vulnerability of wetlands to climate change: a hydrologic perspective.* (2000, p. 305)
[699] *Winter. (2000, p. 305)
[700] *Winter. (2000, p. 305)

The following structure will be used to present information on the implications of climate change for the NPLCC region's freshwater ecosystems:

- **Observed Trends –** observed changes for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. A few sections also include information on changes observed across the NPLCC region.
- **Future Projections –** projected direction and/or magnitude of change for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. A few sections also include information on changes observed globally.
- **Information Gaps –** information and research needs identified by reviewers and literature searches.

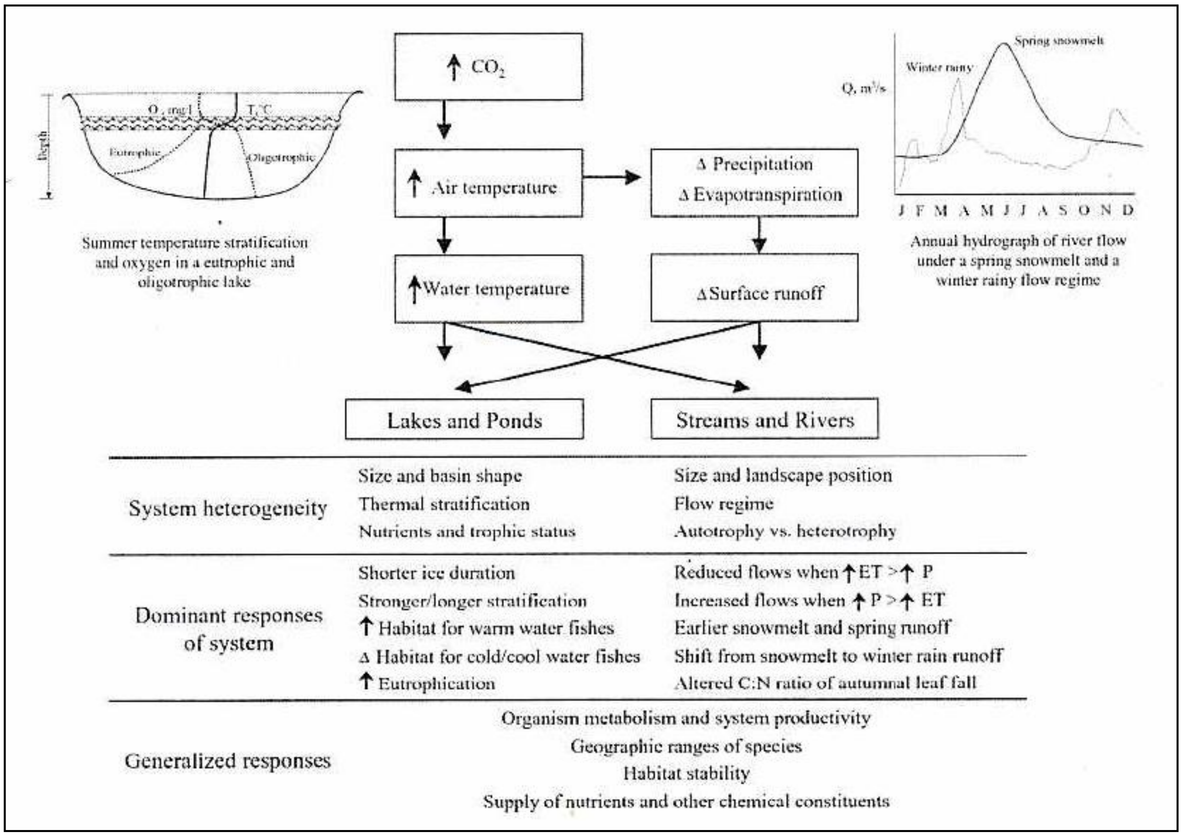

Figure 17. Linkages between atmospheric increases in CO_2 and environmental drivers of temperature and precipitation that regulate many physical and ecological processes in lakes and ponds (left) and rivers and streams (right). Studies of climate change impacts on lakes have emphasized responses to warming, which are affected by vertical temperature stratification. Studies of climate change impacts on rivers have emphasized responses to altered flow regime, including changes to magnitude, frequency, duration, and timing of discharge events. Some biological indicators shown at the bottom of the figure are general.
Source: Allan, Palmer, and Poff. (2005, Fig. 17.1, p. 277)

1. ALTERED NUTRIENT CYCLING AND PRODUCTIVITY

The productivity of inland freshwater ecosystems will be significantly altered by increases in water temperatures.[701] The metabolic rates of organisms and the overall productivity of ecosystems are directly regulated by temperature.[702] Warmer waters are naturally more productive, but the particular species that flourish may be undesirable or even harmful.[703] Changes in precipitation and runoff modify the amount and quality of habitat for aquatic organisms, and thus, they indirectly influence ecosystem productivity and diversity.[704] Further, higher temperatures may raise the rate of mineralization of organic matter in catchment soils, releasing carbon, phosphorus and nitrogen, and particulate phosphorus input may also be raised from increased erosion of catchment soils.[705] Increased nutrient loading, coupled with water temperature increases, could thereby increase autochthonous productivity and greater autochthonous biogenic contributions to the sediment.[706]

In lake ecosystems, research indicates that the longer ice-free periods and higher surface water temperatures expected in the future will spur greater algal growth.[707] Other aspects of climate change, however, may offset these productivity gains.[708] Cloudy days can lower productivity by making less light available for algal photosynthesis.[709] For example, cloud cover has increased in the Great Lakes region recently, but future trends in cloudiness are not clear.[710]

Increased primary productivity could also be limited or even reversed by a decline in availability of nutrients, primarily nitrogen and phosphorus, necessary for plant growth.[711] Predicted reductions in runoff and a general drying of watersheds during summer are likely to reduce the amounts of phosphorus and other dissolved materials that streams carry into lakes.[712] Finally, prolonged or stronger stratification can also lead to lower primary production in lakes by preventing the mixing that brings nutrients from bottom waters and sediments up into surface waters.[713]

Effects of nutrient enrichment in streams are highly variable, due to questions about which primary nutrient (nitrogen or phosphorus) is limiting, shading (light availability), water clarity, flow regime, and available substrate for periphyton (a broad organismal assemblage composed of attached algae, bacteria, their secretions, associated detritus, and various species of microinvertebrates) growth.[714] For example, forested streams are highly dependent upon inputs of terrestrial organic matter, especially leaf fall, for their energy supply, and so shifts in terrestrial vegetation and changes in leaf chemistry provide another, quite intricate set of pathways by which

[701] *Poff, Brinson and Day. *Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States.* (2002, p. iii)
[702] *Poff, Brinson and Day. (2002, p. iv)
[703] *Poff, Brinson and Day. (2002, p. iii)
[704] *Poff, Brinson and Day. (2002, p. iii)
[705] *Verdonschot et al. (2010, p. 69-70)
[706] *Verdonschot et al. (2010, p. 70)
[707] *Kling et al. (2003, p. 25). The authors cite Fee et al. (1992) and Regier, Holmes and Pauly (1990) for this information.
[708] *Kling et al. (2003, p. 25)
[709] *Kling et al. (2003, p. 25). The authors cite Adams, Meinke and Kratz (1993) for this information.
[710] *Kling et al. (2003, p. 25)
[711] *Kling et al. (2003, p. 25)
[712] *Kling et al. (2003, p. 25). The authors cite Magnuson et al. (1997) and Schindler et al. (1996) for this information.
[713] *Kling et al. (2003, p. 25). The authors cite Boyce et al. (1993) and Peeters et al. (2002) for this information.
[714] *U. S. EPA. *Climate Change Effects on Stream and River Biological Indicators: A Preliminary Analysis (EPA/600/R-07/085)*. (2008a, p. 1-8). The authors cite Dodds and Welch (2000) as an example for this information.

stream biota and ecosystems can be affected.[715] Altered carbon-to-nitrogen ratios of the leaves likely will reduce palatability, temperature changes will affect leaf processing rates, and floods may export leaf matter before it can be processed.[716] These interactions are complex and potentially offsetting, making the overall impact of climate on this energy supply difficult to predict.[717]

Hydrology is an important factor in determining levels of productivity, decomposition, and nutrient cycling in wetlands.[718] Whether precipitation increases or decreases, all of these functions will be affected.[719] Warmer temperatures in large bodies of water could boost productivity in the associated wetlands but would affect the mix of species that could thrive.[720] Finally, warmer temperatures will increase the rates at which plants decompose, affecting the amount of organic material buried on the marsh floor.[721]

Observed Trends

Regional

Pacific salmon (*Oncorhynchus* spp.) annually contribute large amounts of organic material to fresh waters of the North Pacific rim when they spawn and die.[722] This "fertilizer effect" can influence bottom-up ecosystem processes such as primary production, decomposition, and mineral cycling and top-down processes involving competition and predation.[723] For example, salmon transport marine-derived nitrogen to the rivers in which they reproduce.[724] Thus, the nutrients and energy provided by spawning salmon appear to increase freshwater and terrestrial ecosystem productivity, and may subsidize otherwise nutrient-poor Pacific Northwest ecosystems.[725] As riparian forests affect the quality of instream habitat through shading, sediment and nutrient filtration, and production of large woody debris (LWD), this fertilization process (i.e., spawning salmon as a source of nutrients to the freshwater ecosystem) serves not only to enhance riparian production, but may also act as a positive feedback mechanism by which salmon-borne nutrients improve spawning and rearing habitat for subsequent salmon generations and maintain the long-term productivity of river corridors along the Pacific coast of North America.[726]

[715] *Allan, Palmer and Poff. (2005, p. 277)
[716] *Allan, Palmer and Poff. (2005, p. 285). The authors cite Rier and Tuchman (2002) and Tuchman et al. (2002, 2003) for this information.
[717] *Allan, Palmer and Poff. (2005, p. 285). The authors refer the reader to Fig. 17.5 in the cited report.
[718] *U.S.Congress, Office of Technology Assessment (OTA). *Preparing for an Uncertain Climate--Volume II, OTA-O-568: Chapter 4: Wetlands.* (1993, Box-4G, p. 175)
[719] *OTA. (1993, Box-4G, p. 175)
[720] *OTA. (1993, Box-4G, p. 175)
[721] *OTA. (1993, Box-4G, p. 175)
[722] *Chaloner et al. *Marine carbon and nitrogen in southeastern Alaska food webs: evidence from artificial and natural streams.* (2002, p. 1258). The authors cite Levy (1997) for this information.
[723] *Darimont et al. *Salmon for terrestrial protected areas.* (2010, p. 2). The authors cite Zhang et al. (2003), Mitchell and Lamberti (2005), Hocking and REimchen (2009) as examples for information on bottom-up ecosystem processes and Ben-David et al. (2004), Gende and Quinn (2004) and Darimont et al. (2008) as examples for information on top-down processes.
[724] *Helfield and Naiman. *Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity.* (2001, p. 2403)
[725] *Chaloner et al. (2002, p. 1258). The authors cite Willson et al. (1998), Wipfli et al. (1998), and Cederholm et al. (1999) for information on freshwater and terrestrial ecosystem productivity, and Polis et al. (1997), Cederholm et al. (1999), and Gresh et al. (2000) for information on subsidizing Pacific Northwest ecosystems.
[726] *Helfield and Naiman. (2001, p. 2403)

Another principal concept describes salmon as ecosystem engineers.[727] Salmon modify creek substrates while spawning and suspend nutrient-rich sediments and salmon eggs in the water column, resulting in substantive nutrient export to estuaries and downstream lakes.[728] This process can alter the production of biofilm, rates of detrital processing, and the seasonal abundance of freshwater consumers.[729] Collectively, these observations suggest that spawning activity can represent a key component of coupled marine–freshwater nutrient cycling.[730]

Southcentral and Southeast Alaska

Despite the extent of peatlands that occur within Pacific coastal temperate rainforest watersheds, there is little information describing how dissolved organic matter (DOM) storage and export patterns are related to soil saturation and temperature in the region.[731] In 2004 and 2005, D'Amore et al. (2010) measured soil water tables, soil temperatures and redox potential and compared these measurements to fluctuations in dissolved organic carbon (DOC) and nitrogen (DON) concentrations in a forested wetland and sloping bog in southeast Alaska (near the mouth of McGinnis Creek) to address this key information gap.[732] Key findings include:

- DOC concentrations ranged from 5 to 140 mg C l^{-1} (milligrams carbon per liter) in wetland soils, 11 to 46 mg C l^{-1} in streams, and varied greatly in response to changes in water table, redox potential and soil temperature.[733]
    - Mean stream DOC concentrations at the slope bog site ranged from 11.8 to 41.2 mg C l^{-1}.[734]
    - At the forested wetland site, there was a consistent outlet streamwater DOC concentration of approximately 30 mg C l^{-1} maintained throughout the measurement period despite more variable and higher concentrations in the soil.[735]
- DON concentrations ranged from 0.03 to 2.4 mg N l^{-1} (milligrams nitrogen per liter) in wetland soils, 0.2 to 0.6 mg N l^{-1} in streams and concentrations also reflected seasonal changes in physical measures.[736]
    - Streamwater DON concentrations at the slope bog site were consistently about 0.5 mg N l^{-1} throughout the measurement period.[737] The concentrations of DON in the outlet stream at the slope bog site ranged from 0.2 to 0.6 mg N l^{-1}.[738]
    - At the forested wetland site, the outlet stream DON concentration was approximately 0.5 mg N l^{-1} throughout the measurement period.[739]

[727] *Darimont et al. (2010, p. 2)
[728] *Darimont et al. (2010, p. 2). The authors cite Moore et al. (2007, 2008) for this information.
[729] *Darimont et al. (2010, p. 2)
[730] *Darimont et al. (2010, p. 2). The authors cite Mitchell and Lamberti (2005) and Lessard and Merritt (2006) for this information.
[731] *D'Amore et al. *Controls on dissolved organic matter concentrations in soils and streams from a forested wetland and sloping bog in southeast Alaska.* (2010, p. 249)
[732] *D'Amore et al. (2010, p. 249)
[733] *D'Amore et al. (2010, p. 249)
[734] *D'Amore et al. (2010, p. 256)
[735] *D'Amore et al. (2010, p. 257)
[736] *D'Amore et al. (2010, p. 249)
[737] *D'Amore et al. (2010, p. 257)
[738] *D'Amore et al. (2010, p. 256)
[739] *D'Amore et al. (2010, p. 257)

- Depth to water table and soil temperature were significant factors related to the concentration of DOC in forested wetland soils and streams, while soil temperature was a significant factor that influenced stream DOC and DON concentrations.[740]
- Comparing soil solution and stream DOM concentrations indicated that nitrogen is retained in bogs, while both dilution and biotic/abiotic retention mechanisms control DOM export in forested wetlands.[741]

The role of salmon in freshwater ecosystem nutrient cycling and productivity has also been assessed:

- Isotopic analyses conducted by Helfield and Naiman (2001) indicate that trees and shrubs near spawning streams derive 22–24% of their foliar nitrogen (N) from spawning salmon.[742] As a consequence of this nutrient subsidy, growth rates are significantly increased in Sitka spruce (*Picea sitchensis*) near spawning streams.[743]
- Wipfli et al. (1998) studied artificial and natural streams in southeast Alaska and found that total macroinvertebrate densities were up to eight and twenty-five times higher in carcass-enriched areas of artificial and natural streams, respectively; Chironomidae midges, *Baetis* and *Cinygmula* mayflies, and *Zapada* stoneflies were the most abundant taxa.[744] The authors conclude increased biofilm in Margaret Creek (AK) and macroinvertebrate abundance in both systems suggest that salmon carcasses elevated freshwater productivity.[745]
- Chaloner et al. (2002) studied the contribution of salmon carcasses to the amount and distribution of marine carbon and nitrogen at the same site as Wipfli and colleagues (1998).[746] The assimilation of marine-derived nitrogen by aquatic organisms and subsequent isotopic enrichment were similar in experimentally and naturally carcass-enriched streams.[747] Their results suggest that pathways of marine-derived nitrogen incorporation into stream food webs include both consumption of salmon material by macroinvertebrates and fish and uptake of mineralized marine-derived nitrogen by biofilm.[748]

<u>British Columbia</u>

Information needed

<u>Washington</u>

Bilby et al. (1998) state the availability of organic matter and nutrients transported from the marine environment to streams by spawning salmon was increased in two small streams in southwestern Washington by adding salmon carcasses from a nearby hatchery.[749] Stable isotope analysis indicated that the proportion of marine-derived nitrogen in the muscle tissue of juvenile salmonids increased as much as thirty-nine percent following

[740] *D'Amore et al.. (2010, p. 249)
[741] *D'Amore et al. (2010, p. 249)
[742] *Helfield and Naiman. (2001, p. 2403)
[743] *Helfield and Naiman. (2001, p. 2403)
[744] *Wipfli et al. *Influence of salmon carcasses on stream productivity: response of biofilm and benthic macroinvertebrates in southeastern Alaska, USA.* (1998, p. 1503)
[745] *Wipfli et al. (1998, p. 1503)
[746] *Chaloner et al. (2002).
[747] *Chaloner et al. (2002, p. 1257). The authors cite Levy (1997) for this information.
[748] *Chaloner et al. (2002, p. 1257). The authors cite Levy (1997) for this information.
[749] *Bilby et al. *Response of juvenile coho salmon (Oncorhynchus kisutch) and steelhead (Oncorhynchus mykiss) to the addition of salmon carcasses to two streams in southwestern Washington, U.S.A.* (1998, p. 1909)

carcass placement.[750] Results suggest that eggs and carcasses of adult salmon provide a very important resource during a period when other food items are often scarce.[751]

Oregon

Information needed.

Northwestern California

In Castle Lake, in years with incomplete vertical mixing, productivity is often less than in years with spring holomixis (i.e., complete mixing).[752] A 27-year record (specific date range not provided) of summer primary productivity had no long-term trend, but considerable interannual variability, with extreme years often occurring when ENSOs occurred.[753] Further statistical analysis of interactions between the early summer productivity and climate revealed negative associations with the time of ice-out and total precipitation preceding the spring bloom.[754] The time of ice-out sets the length of the growing season, and total precipitation affects flushing rates.[755]

Future Projections

Global

Experimental data suggest that rates of soil dissolved organic carbon (DOC) production are increased under higher temperatures and in response to a shift from anaerobic to aerobic conditions in saturated soils.[756] A study by Tipping et al. (1999) also indicated that climatic warming will increase the production of potentially soluble organic matter.[757] On the other hand, more severe drying during droughts may have the opposite effect on DOC leaching; field manipulation experiments on podsolic heathland soils in Wales (i.e., a type of soil common to Western Europe, created by long-term clearing of natural forest and woodland vegetation via grazing or burning, such that heathland, a dwarf-shrub habitat, develops) showed decreasing microbial activity and DOC concentrations in response to experimental drought, with increased DOC observed following soil re-wetting.[758]

Dissolved inorganic nitrogen (as nitrate, NO_3^-) levels may decrease if rates of denitrification are increased (e.g., by higher temperatures and lower oxygen), which could be important given increasing levels of nitrogen deposition.[759] On the other hand, if discharge and sediment transport increase, then the downstream movement of nitrogen (as ammonium, $NH_4^{\pm}$) and phosphorus (as phosphate, PO_4^{3-}) may increase.[760]

In general in lakes, short residence times mean that pollutants such as excess nutrients from point sources are flushed out of the lake ecosystem, whereas with decreasing precipitation and longer residence times, they will accumulate, with likely changes in phytoplankton communities and in food-web composition and structure.[761] In

[750] *Bilby et al. (1998, p. 1909)
[751] *Bilby et al. (1998, p. 1909)
[752] *Melack et al. (1997, p. 983). The authors cite Goldman and de Amezaga (1984) for this information.
[753] *Melack et al. (1997, p. 983). The authors cite Jassby and Goldman (1992) for this information.
[754] *Melack et al. (1997, p. 983). The authors cite Goldman et al. (1989) and Jassby et al. (1990) for this information.
[755] *Melack et al. (1997, p. 983)
[756] *Nickus et al. (2010, p. 60). The authors cite Clark et al. (2009) for this information.
[757] *Nickus et al. (2010, p. 60)
[758] *Nickus et al. (2010, p. 60). The authors cite Toberman et al. (2008) for this information.
[759] *Palmer et al. *Wild and Scenic Rivers.* (2008, p. 31). The authors cite Baron et al. (2000) for this information.
[760] *Palmer et al. (2008, p. 31).
[761] *Verdonschot et al. (2010, p. 69). The authors cite Schindler et al. (1990, 1996) and Hillbricht-Ilkowska (2002) for information on likely changes to phytoplankton communities.

lakes with long residence times internal processes may become more important (e.g., sorbing to particles, uptake by biota).[762] Further, higher flows can cause higher turbidity in lakes, which reduces the light penetration crucial to the health of some forms of aquatic life.[763] On the other hand, where surface flows decline, erosion rates and sediment transport may drop, and lake clarity may improve but this may increase the concentration of pollutants.[764]

Southcentral and Southeast Alaska

There is some evidence for increased dissolved organic matter (DOM) export from peatlands to aquatic ecosystems due to climate warming in Great Britain.[765] While there is also evidence that decreased sulfate deposition may also be a factor, the potential that stored soil organic matter may be exported as DOM through increased microbial activity and decomposition under warmer conditions is of concern in the coastal temperate rainforest.[766] Increased DOM concentrations in the soils could be exported via shallow subsurface flowpaths, which could intensify with increased precipitation.[767] However, increased precipitation may also inhibit decomposition and subsequent DOM production.[768] Therefore, understanding how DOM concentrations vary in response to seasonal changes in soil temperature and saturation is important for elucidating DOM cycling in peatlands of the coastal temperate rainforest.[769] The results can help calibrate regional watershed carbon flux models to predict the potential impacts of climate shifts and management activities on future wetland soil and stream DOM concentrations in coastal temperate rainforest watersheds.[770]

In arctic and subarctic North America, increased rates of decomposition and increased water residence time are predicted to increase primary and secondary productivity, yet it is not clear that these increases in production will be adequate to make up for the increased metabolic demand of higher temperatures for fishes.[771] Climatic warming could result in substantial changes in the mixing properties of many high latitude and mid-latitude lakes which, in turn, would produce large effects on deep-water dissolved oxygen concentrations and on primary productivity via effects on nutrient supplies and exposure of phytoplankton to light.[772] Although these effects are expected to be highly dependent on the morphometric (i.e., size and shape) characteristics of individual lakes and are difficult to predict, at high latitudes the effects are likely to result in higher primary productivity.[773]

[762] *Verdonschot et al. (2010, p. 69)
[763] *Nelson et al. *In hot water: water management strategies to weather the effects of global warming.* (2007, p. 12). The authors cite Murdoch et al. (2000) for this information.
[764] *Nelson et al. (2007, p. 12)
[765] *D'Amore et al. (2010, p. 250). The authors cite Freeman et al. (2001) and Worrall et al. (2004) for this information.
[766] *D'Amore et al. (2010, p. 250). The authors cite Evans et al. (2006) for information on sulfate deposition and Nadelhoffer et al. (1991) and Evans et al. (1999) for information on the export of soil organic matter as dissolved organic matter via increased microbial activity and decomposition under warmer conditions.
[767] *D'Amore et al. (2010, p. 250). The authors cite Dalva and Moore (1991), Qualls (2000), and Emili and Price (2006) for this information.
[768] *D'Amore et al. (2010, p. 250)
[769] *D'Amore et al. (2010, p. 250)
[770] *D'Amore et al. (2010, p. 249)
[771] *Meyer et al. *Impacts of climate change on aquatic ecosystem functioning and health.* (1999, p. 1375-1376). The authors cite Rouse et al. (1997) for this information.
[772] *Meyer et al. (1999, p. 1376). The authors cite Hostetler and Small (1999) for information on mixing properties in high- and mid-latitude lakes.
[773] *Meyer et al. (1999, p. 1376)

British Columbia

With an increase in temperature and longer ice-free periods, streams that do not have current nutrient limitations may increase in productivity.[774] Increased water temperatures could affect metabolic rates and increase biological activity and decomposition.[775] In aquatic systems with sufficient nutrient and oxygen supplies, an increase in biological productivity can increase nutrient cycling and possibly accelerate eutrophication.[776] However, it is likely that in aquatic systems currently stressed by high biological oxygen demand any subsequent increase in water temperatures could decrease biological productivity as a result of a decline in the oxygen-holding capacity of the water.[777] Alternatively, in regions or specific water bodies where temperatures are below thermal optima for fish or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival.[778] One reviewer noted increased water temperatures may promote changes in diversity as well.[779]

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Evaluation of the potential effects of global warming on primary productivity in montane lakes is possible by linking GCM projections of climate change with a model of lacustrine (i.e., lake) productivity.[780] Byron and Goldman (1990) attempted such an approach by using almost three decades of limnological data from Castle Lake to develop a regression model that related algal productivity to regional temperature and precipitation.[781] When used in combination with GCM calculations of temperature and precipitation under doubled CO_2 concentrations, their model predicted increased algal productivity.[782] These increases were driven by the GCM-projected higher temperatures, which were linked to earlier melt and a longer growing season.[783] Because the GCMs calculated January-May precipitation as being similar to historical records, no effect of doubled CO_2 on runoff was observed; this result deserves additional study using newer, regional predictions of climate change.[784]

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends in British Columbia and Oregon and future projections in Washington and Oregon.

[774] *Austin et al. *Taking Nature's Pulse: The Status of Biodiversity in British Columbia.* (2008, p. 189). The authors cite Tyedmers and Ward (2007) for this information.
[775] *Pike et al. (2010, p. 729)
[776] *Pike et al. (2010, p. 729). The authors cite Murdoch et al. (2000) for this information.
[777] *Pike et al. (2010, p. 729)
[778] *Pike et al. (2010, p. 729)
[779] Comment from reviewer, April 2011.
[780] *Melack et al. (1997, p. 983)
[781] *Melack et al. (1997, p. 983). The authors of the cited report are summarizing the work of Byron and Goldman (1990).
[782] *Melack et al. (1997, p. 983)
[783] *Melack et al. (1997, p. 983)
[784] *Melack et al. (1997, p. 983)

2. CHANGES TO STRATIFICATION AND EUTROPHICATION

Climate change expressed by increased water temperatures is expected to enhance the symptoms of eutrophication (i.e. the process of nutrient enrichment leading to dense algae growth.[785]) through increases in primary production and declines in oxygen storage capacity.[786] Model studies predict that lake temperatures, especially in the epilimnion (i.e., the top-most layer in a thermally stratified lake), will increase with increasing air temperature, so that temperature profiles, thermal stability and mixing patterns are expected to change as a result of climate change.[787]

Fluctuations in lake surface water temperatures are transported downwards by vertical mixing, and can reach the deep waters when the thermal stratification is weak.[788] In particular, the hypolimnetic temperatures of deep lakes, which are determined by winter meteorological conditions, and the amount of heat reaching deep-water layers before the onset of thermal stratification may act as a “climate memory.”[789] Increasing air temperatures may thus lead to a progressive rise in deep-water temperatures, as found, for instance, by Ambrosetti & Barbanti (1999) for lakes in Northern Italy. [790]

Observed Trends

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

As described previously (Chapter III Section 4), spring water temperatures in Lake Washington have shown significant warming trends.[791] This trend affected the onset of spring thermal stratification in Lake Washington, which showed a significant advancement of spring warming trends from 1962 to 2002.[792] Stratification onset now occurs twenty-one days earlier than it did four decades ago.[793]

Oregon

Information needed.

Northwestern California

Information needed.

[785] Brooks et al. (2003, p. 263)
[786] *New Hampshire Dept. of Environmental Services (2003), *Environmental Fact Sheet: Lake or Pond – What is the Difference?*
[787] *Nickus et al. (2010, p. 45). The authors cite Hondzon & Stefan (1993) and Stefan et al. (1998) as examples.
[788] *Nickus et al. (2010, p. 46)
[789] *Nickus et al. (2010, p. 46)
[790] *Nickus et al. (2010, p. 46)
[791] *Winder and Schindler. (2004a, p. 2102)
[792] *Winder and Schindler. (2004a, p. 2102)
[793] *Winder and Schindler. (2004a, p. 2102)

Future Projectons

Global

Lakes may experience a longer stratification period in summer and a single circulation period in winter.[794] This could enhance eutrophication and lead to oxygen depletion in deep zones during summer, eliminating refuges for coldwater-adapted fish species.[795] In addition, warming may increase the potential for the production of nuisance algae and eliminate deep, cool refuge areas for large fish.[796] Phytoplankton production may increase with higher temperatures due to increased nutrient availability, and eutrophication problems may thereby become more severe.[797] Further, declines in surface water flows result in longer residence times for chemicals entering lakes.[798] This is of greatest importance for biologically reactive chemicals (e.g., phosphorus) for which longer residence times can result in increased biological reaction and increased potential for eutrophication.[799]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed for both observed trends and future projections in eutrophication and stratification.

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[794] *Euro-Limpacs. *Climate Change and Freshwater (website).* (2011)
[795] * Euro-Limpacs. (2011)
[796] *New Hampshire Dept. of Environmental Services (2003), *Environmental Fact Sheet: Lake or Pond – What is the Difference?*
[797] *Verdonschot et al. (2010, p. 69). The authors cite Mooij et al. (2005) for this information.
[798] *Pike et al. (2010, p. 731). The authors cite Whitehead et al. (2009) for this information.
[799] *Pike et al. (2010, p. 731). The authors cite Schindler (2001) for this information.

3. CHANGES TO WATER INPUT, LEVEL, AND AREA

Increased air temperatures may speed evaporation of surface water from wetlands (and from runoff and water bodies that supply wetlands) and could increase the rate at which wetland plants lose water through evaporation and transpiration if the warmer temperatures are not accompanied by increased rainfall.[800] Drying is most likely to occur at the edges of wetlands and could reduce the size or extent of inland wetlands.[801] Earlier ice-out and snowmelt may shorten wet periods, especially in ephemeral wetlands.[802]

Flow exerts a strong control on stream temperature, and flow reductions will likely exacerbate stream temperature increases caused by increased incoming longwave (i.e. infrared) and sensible heat (i.e. heat energy transferred between the surface and air when there is a difference in temperature between them).[803] If warmer temperatures produce a shift from snow to rain in higher or more northerly basins, this could reduce summer base flows in streams; in turn, habitat for invertebrates and fish would decrease and there would be less recharge into riparian groundwater tables that support tree communities.[804] Changes in flood risk are likely to result in substantial changes in sediment transport and channel formation processes, and are also likely to affect ecological processes that are sensitive to changes in the probability distributions of high flow events.[805]

Snow-fed rivers and streams are likely to have less water in summer, which may diminish the quantity and quality of wildlife habitat.[806] However, as one reviewer noted, this trend will vary by location and season.[807]

Winter (2000) lists the following examples of adverse effects to the water supply of riparian wetlands: (1) reduction of precipitation in headwaters areas, (2) reduction of groundwater contribution to the stream, and (3) increase in transpiration from valley bottom vegetation.[808] Wetlands fed by regional groundwater sources may have relatively sustained water inputs, and therefore be somewhat buffered from changes in climate.[809] However, small systems fed by local groundwater discharge may be more vulnerable because of their small watersheds.[810]

Observed Trends

Southcentral and Southeast Alaska

Across the southern two-thirds of Alaska, the area of closed-basin lakes (lakes without stream inputs and outputs) has decreased over the past fifty years.[811] This is likely due to the greater evaporation and thawing of permafrost that result from warming.[812] As noted previously, the NPLCC region contains little permafrost.

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[800] *OTA. (1993, Box 4G, p. 175)
[801] *OTA. (1993, Box 4G, p. 175)
[802] Kling. (2003, Table 5, p. 28)
[803] *Luce and Holden. (2009, p. 5)
[804] Poff, Brinson and Day. (2002)
[805] *Hamlet and Lettenmaier. (2007, p. 16)
[806] *PRBO. (2011, p. 10)
[807] Comment by reviewer, April 2011.
[808] Winter. (2000)
[809] Winter. (2000)
[810] Winter. (2000)
[811] *US-GCRP. (2009, p. 141)
[812] *US-GCRP. (2009, p. 141). The authors cite Klein et al. (2005) and Riordan et al. (2006) for this information.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Global

One of the most direct effects will be reduced lake levels, although areas that become wetter could have higher lake levels.[813] Increases in evapotranspiration brought about by higher temperatures, longer growing seasons, and extended ice-free periods, unless offset by equal or greater increases in precipitation, are likely to result in reduced lake levels and river inputs.[814] A decline in water level due to decreased precipitation may cause changes in the nutrient status and acidity of lakes with low buffering capacities.[815] In cases where precipitation and evapotranspiration both increase, lake levels might change little but water residence time in lakes would be expected to be shortened.[816]

Permanent lowering of lake levels will expose more shoreline, possibly harming productive littoral (near-shore) zones and coastal wetlands of the Great Lakes.[817] Many of these lake-fringing wetlands may become isolated, reducing habitat for fish that require wetlands for spawning and nursery habitat.[818] The effects of water-level reductions in smaller lakes could be equally profound.[819]

[813] *Poff, Brinson and Day. (2002, p. 15)
[814] *Allan, Palmer and Poff. (2005, p. 279)
[815] *Verdonschot et al. (2010, p. 69). The authors cite Carvalho and Moss (1999) for this information.
[816] *Allan, Palmer and Poff. (2005, p. 279)
[817] *Poff, Brinson and Day. (2002, p. 17). The authors cite Magnuson et al. (1997) for this information.
[818] *Poff, Brinson and Day. (2002, p. 17). The authors cite Brazner and Magnuson (1994) for this information.
[819] *Poff, Brinson and Day. (2002, p. 17)

Box 16. Multiple stressors in wetlands: climate change, and human and natural disturbance.

Any wetland already degraded as a result of human actions (e.g., pollution, water diversion, fragmentation) may be particularly vulnerable to climate change impacts. By 1997, the conterminous United States had lost more than half of the estimated 221 million acres (89.5 million hectares) of wetlands it contained at the time of European settlement (~115.5 million acres, or ~46.7 million hectares, lost). The potential for climate change to spur further losses and degradation could pose a significant threat to valued functions of wetlands.

The impacts of climate change will overlay current disturbances, further reducing the ability of riparian wetlands to perform functions such as stream bank maintenance, erosion reduction, flood buffering, and filtration of sediments and nutrients. Warmer temperatures may increase the susceptibility of seasonal wetlands to drought and fire, which would degrade vegetation and habitat. Areas that become drier due to changes in precipitation and soil moisture could experience greater disturbance than those that become wetter.

Disease and insect outbreaks are also projected to be affected by climate change. These ecological disturbance processes may then affect related riparian processes. Further, ecosystems may become more susceptible to invasion as temperatures warm, precipitation regimes fluctuate, and nutrient flows change, hampering the ability of the ecosystem to promote native species biodiversity. For information on disturbance due to invasive and non-native species, please see Chapter V Section 4. *Altered interaction with invasive and non-native species.*

Even if it does not become the primary driver of wetland loss, climate change is also likely to aggravate stresses such as agriculture, development, and pollution. Anthropogenic responses to climate change will also affect riparian wetlands; if conditions become drier, human demands for groundwater and surface water will increase, decreasing the amount of water available in aquifers to feed wetland systems.

Sources: Dahl. (2000); Pike et al. (2010); Poff, Brinson, and Day. (2002); U.S. Congress, Office of Technology Assessment. (1993); U.S. EPA. (2008b).

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Pacific Northwest

In Oregon (as well as transient rain-snow basins throughout the western U.S.), lower order streams in transient rain-snow basins will be the most vulnerable to rising summer air temperature and diminished low flow; a new dam or reservoir might be required to maintain environmental flow in summer.[820]

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends and future projections for specific lakes and wetlands, as well as regional assessments.

[820] *Chang and Jones. (2010, p. 132)

4. CHANGES TO THE LENGTH AND DATE OF SEASONAL ICE COVER

High-latitude rivers and lakes develop an ice cover in winter.[821] Although the area and volume are small compared to other components of the cryosphere (which consists of snow, river and lake ice, sea ice, glaciers and ice caps, ice shelves and ice sheets, and frozen ground[822]), this ice plays an important role in freshwater ecosystems, winter transportation, bridge and pipeline crossings, etc.[823] Changes in the thickness and duration of these ice covers can therefore have consequences for both the natural environment and human activities.[824] According to IPCC (2007), freeze-up is defined conceptually as the time at which a continuous and immobile ice-cover forms, while break-up is generally the time when open water becomes extensive in a lake or when the ice-cover starts to move downstream in a river.[825]

Major variables affecting duration and thickness of lake and river ice are air temperature, wind, snow depth, heat content of the water body and rate and temperature of potential inflows.[826] Dates of freeze-up and ice break-up have proved to be good indicators of climate variability at local to regional scales, and as a response to large-scale atmospheric forcing.[827] As climate changes, and air temperatures, particularly in the winter, tend to increase, these shifts should be reflected in ice-cover.[828]

Observed Trends

Regional

Several authors have used the correlation of ice-cover dates and air temperature to translate shifts in freeze-up and break-up into estimated changes in air temperature.[829] A typical value for lakes at mid-latitude is a four- to five-day shift in mean freeze-up or break-up dates for each degree Celsius change in mean autumn or spring temperatures.[830] Relationships tend to be stronger for freezing dates and in colder climates.[831]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Increasing temperatures have affected the length and date of seasonal lake ice cover.[832] A Canada-wide study showed significantly earlier lake "ice-free" dates for the 1951–2000 period.[833] In several British Columbia lakes,

[821] *Lemke et al. (2007, p. 342)
[822] *Lemke et al. (2007, p. 339)
[823] *Lemke et al. (2007, p. 342)
[824] *Lemke et al. (2007, p. 342)
[825] *Nickus et al. (2010, p. 51)
[826] *Nickus et al. (2010, p. 51)
[827] *Nickus et al. (2010, p. 51). The authors cite Walsh (1995), Livingstone (1999, 2000), Yoo & D'Odorico (2002), and Blenckner et al. (2004) as examples for this information.
[828] *Nickus et al. (2010, p. 51)
[829] *Nickus et al. (2010, p. 51). The authors cite Palecki and Barry (1986), Roberston et al. (1992), Assel and Robertson (1995), and Magnusion et al. (2000) as examples for this information.
[830] *Nickus et al. (2010, p. 51)
[831] *Nickus et al. (2010, p. 51). The authors cite Walsh (1995) for this information.
[832] *Pike et al. (2010, p. 703)
[833] *Pike et al. (2010, p. 703). The authors cite Duguay et al. (2006) for this information.

the first melt date and ice-free date was two to eight days earlier per decade from 1945 to 1993, whereas the duration of ice cover decreased by up to forty-eight days over the 1976–2005 period.[834]

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Ecological processes in montane lakes such as Castle Lake may be strongly influenced by climatic conditions, and, therefore, be sensitive to changes in climate caused by global warming.[835] For example, during the extraordinary El Niño of 1983, Castle Lake remained frozen until early July and summer primary productivity was only twenty-five percent of the long-term average.[836]

Future Projections

Global

Climate change will reduce the spatial and seasonal extent of ice cover on lakes, which may influence community and invasion processes by increasing light levels for aquatic plants, reducing the occurrence of low oxygen conditions in winter, and exposing aquatic organisms to longer periods of predation from terrestrial predators.[837] For example, longer ice-free periods potentially lengthen the growing season for algae and aquatic macrophytes.[838] On the other hand, shorter ice cover periods can be a mixed blessing for fish.[839] Reduced ice will lessen the severity of winter oxygen depletion in many small inland lakes, thus significantly reducing winter kill in many fish populations.[840] However, small species uniquely adapted to live in winterkill lakes go extinct locally when predatory fishes are able to invade and persist in lakes that previously experienced winterkill.[841]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

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[834] *Pike et al. (2010, p. 703). The authors cite B.C. Ministry of Environment (2002) and Rodenhuis et al. (2007) for this information.
[835] *Melack et al. (1997, p. 983)
[836] *Melack et al. (1997, p. 983). The authors cite Strub et al. (1985) for this information.
[837] *Rahel and Olden. *Assessing the effects of climate change on aquatic invasive species.* (2008, p. 525). The authors cite Magnuson et al. (2000) for information on climate change and reduced extent of ice cover on lakes in the northern hemisphere.
[838] *Verdonschot et al. "Climate change and the hydrology and morphology of freshwater ecosystems." In *Climate Change Impacts on Freshwater Ecosystems.* (2010, p. 69)
[839] *Kling et al. (2003, p. 23)
[840] *Kling et al. (2003, p. 23). The authors cite Stefan, Fang and Eaton (2001) for information on the severity of winter oxygen depletion in small inland lakes.
[841] *Kling et al. (2003, p. 23-24). The authors cite Jackson and Mandrak (2002) for this information.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends in specific lakes and rivers, as well as future projections throughout the region.

5. HABITAT LOSS, DEGRADATION, AND CONVERSION

Climate change could affect the distribution and condition of U.S. wetlands by reducing the area they cover and potentially altering the assemblages of plant and animal species they support.[842] In many areas, the direct effects of climate change may not overtake existing sources of degradation and loss as the dominant threat to wetlands in the near term, but will likely exacerbate current trends of loss and degradation.[843]

In areas that become drier, the edges of wetlands will start to recede.[844] Some small or seasonal streams and their associated wetlands could disappear altogether.[845] In a drier climate, peat-based wetlands would be especially hard-hit as the highly organic soils undergo oxidation and subsidence, thus altering drainage patterns, topography, and exposure to fire.[846] In a more humid climate, precipitation-dominated wetlands could expand, assuming no barriers from competing land uses.[847] Further, riparian wetlands have some capacity to adapt to a changing climate by migrating along river edges up- and downstream as well as up- and down-slope to follow the water.[848] However, in those areas subject to hotter and drier conditions, rivers are likely to shrink, so migration will likely involve retreat rather than expansion.[849] Overall, in areas where increases in precipitation are greater than evapotranspiration losses due to higher temperatures, wetlands may expand, while increases in precipitation less than evapotranspiration increases, stable precipitation, or declining precipitation would cause may cause rivers to shrink and wetlands to retreat in a warmer climate.[850]

The patterns of water depth, and the duration, frequency, and seasonality of flooding together constitute a wetland's hydroperiod, which determines its vegetation composition, habitat for aquatic organisms, and other ecosystem characteristics.[851] Vegetation on wetlands can be forests, shrubs, mosses, grasses, and sedges.[852] Regional wetland types range from wet meadows and forested wetlands to fens, bogs, slope wetlands, seeps, and riparian wetlands, among others.[853] Longer growing seasons with warmer temperatures likely will result in faster growth.[854] Those conditions also will favor more rapid decomposition and a transition of bog and forested wetlands to forests with larger stature trees.[855] Although glaciers and snow fields currently provide habitat for only a few species, the loss of snowpack with warming may allow (alpine) vegetation establishment in these areas, leading to improved habitat conditions for other high elevation wildlife species.[856] In the short term, vegetation establishment will be limited to areas with substrate that is favorable to rapid soil development, such as

842 *OTA. (1993, p. 172)
843 *OTA. (1993, p. 179)
844 *OTA. (1993, p. 172)
845 *OTA. (1993, p. 184)
846 *Poff, Brinson and Day. (2002, p. 20)
847 *Poff, Brinson and Day. (2002, p. 20)
848 *OTA. (1993, p. 184-185)
849 *OTA. (1993, p. 185)
850 OTA. (1993)
851 *Poff, Brinson and Day. (2002, p. 18-19). The authors refer the reader to Box 2 in the cited report.
852 *Brooks et al. (2003, p. 120)
853 U.S. Army Corps of Engineers (2008) *Interim Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Western Mountains, Valleys, and Coast Region.* US ACoE: Washington D.C. ERDC/EL TR-08-13. 154 pp. Available online at: < http://www.usace.army.mil/CECW/Documents/cecwo/reg/west_mt_intersupp.pdf>
854 *Kelly et al. (2007, p. 51)
855 *Kelly et al. (2007, p. 51)
856 Halofsky et al. (in press)

shallow-gradient slopes with deep layers of fine-grained glacial till.[857] The flora of alpine wetlands, restricted to the highest peaks in the continental United States, are particularly vulnerable because an increase in temperature will eliminate species that require cold thermal regimes.[858]

Although CO_2 could potentially enhance photosynthesis and productivity for some wetland plants, the effects of increased atmospheric CO_2 concentrations on wetland plant communities in general are difficult to predict.[859] Some groups of plants are more responsive to higher CO_2 concentrations than others because of fundamental physiological differences.[860] However, it is difficult to generalize about the effects of CO_2 on wetlands because of uncertainty about changes in other important factors such as water use efficiency, insect and fungal damage, and soil bacterial activity.[861]

Further, as vegetation composition in the watershed responds to climate change, so too will the amounts of water intercepted, evaporated, and transpired, thus altering snow accumulation and melt processes, water balance, groundwater recharge, and ultimately streamflow and mass wasting processes.[862] For example, increases in the length of the snow-free season and changes in atmospheric evaporative demand are likely to increase plant transpiration, assuming soil water is available.[863]

Observed Trends

Southcentral and Southeast Alaska

As precipitation in southeastern Alaska shifts toward increased rain and less snow, more water will run off the landscape rather than being stored.[864] Meadows and bogs may dry as a result.[865] At the same time, wetlands may become more forested and productive.[866]As in bogs, alpine tundra is likely to shrink as lower-altitude and lower-latitude edges dry.[867]

In a modeling and connectivity study by Murphy et al. (2010), Alaska’s current biome types were predicted using SNAP climate data (Figure 18). Simulated, rather than actual, climate data were used to represent existing conditions in part because actual data for the 2000–2009 decade were not yet available during the modeling for this project in 2008 and 2009.[868]

[857] Halofsky et al (in press)
[858] *Poff, Brinson and Day. (2002, p. 23)
[859] OTA. (1993)
[860] *Poff, Brinson and Day. (2002, p. 19)
[861] *Poff, Brinson and Day. (2002, p. 19). The authors cite Thompson and Drake (1994) for this information.
[862] *Pike et al. (2010, p. 713)
[863] *Pike et al. (2010, p. 713)
[864] *Kelly et al. (2007, p. 53)
[865] *Kelly et al. (2007, p. 53)
[866] *Kelly et al. (2007, p. 53)
[867] *OTA. (1993, p. 185)
[868] *Murphy et al. *Connecting Alaska landscapes into the future: Results from an interagency climate modeling, land management and conservation project. Final Report*. (August 2010, p. 15)

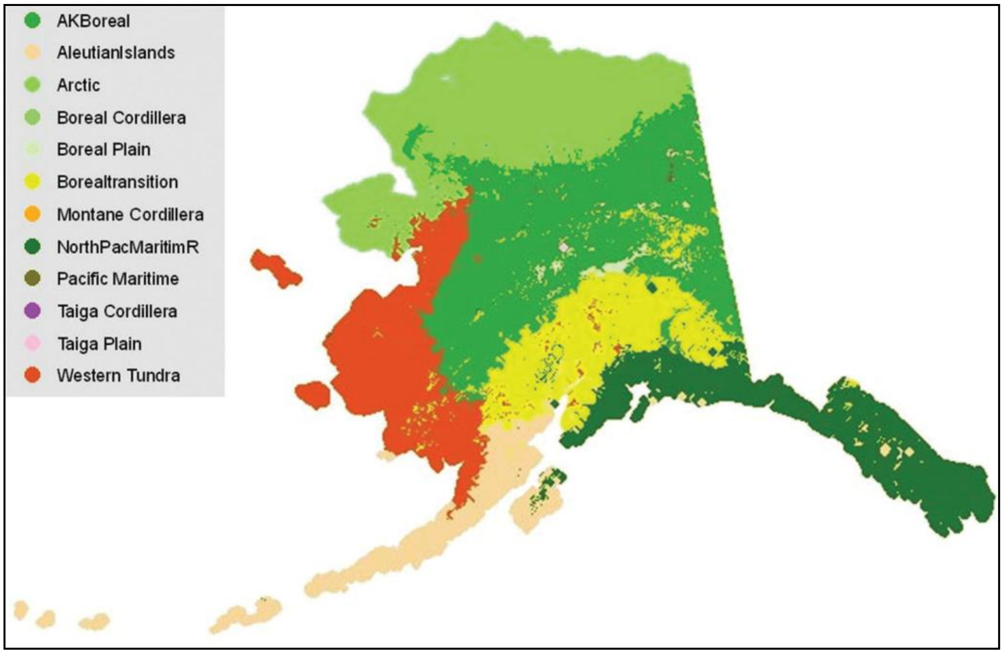

Figure 18. Current biome types as predicted by SNAP climate data. This map shows the best fit for each 2 km pixel in Alaska for 2000–2009 climate projection data, based on climate envelopes for pre-defined biomes and ecoregions in Alaska and Canada. *Source: Reproduced from Murphy et al. (August 2010, Fig. 4, p. 16) by authors of this report.*

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska, and British Columbia

The abundant peatlands in arctic and subarctic North America are vulnerable to changes in water table depth influenced by permafrost melting and altered water balances.[869] A changing climate can shift them from a net sink to a net source for CO_2.[870] In arctic and subarctic North America, reduction in ice-jams on rivers are predicted to result in loss of river delta lakes.[871]

[869] *Meyer et al. (1999, p. 1376)
[870] *Meyer et al. (1999, p. 1376)
[871] *Meyer et al. (1999, p. 1376)

Murphy et al. (2010) projected spatial shift in potential biomes for three future periods: 2030-2039, 2060-2069, and 2090-2099.[872] Climate data inputs were all based on the midrange (A1B) emissions scenario for the Scenarios Network for Alaska Planning (SNAP's) Composite GCM, and included mean monthly temperatures and precipitation for the months of June and December for the decades 2000-2009, 2030-2039, 2060-2069, and 2090-2099.[873] Figure 19 shows results from 2090-2099.

By 2069, projections indicate marked northward shifts, almost complete change in western coastal regions, and some Canadian biomes moving in from the east.[874] It is important to note that these shifts represent **potential** rather than actual biome shift, since in many cases it is unconfirmed that seed dispersal, soil formation, and other functional changes could occur at the same rate as climate change (emphasis in original).[875] In addition, much of southeast Alaska may be in the process of shifting from North Pacific Maritime to Canadian Pacific Maritime—again, as constrained by functional barriers (Box 17).[876]

The model suggests that two-thirds of Alaska will experience a potential biome shift in climate this century, although shifts are occurring at temporally and spatially different rates across the landscape.[877] Not surprisingly, the three most southern biomes (Boreal Transition, Aleutian Islands, and North Pacific Maritime) were the only biomes with climate envelopes that occur in greater distribution through the next century.[878] Using Marxan, Murphy and colleagues find that, in general, the Boreal Transition, Aleutian, and Northern Pacific Maritime regions in the southeast portions of the state are more likely to be resilient to change (Figure 20).[879]

Box 17. Vegetation in the North Pacific Maritime and Canadian Pacific Maritime regions.

Alaska's North Pacific Maritime biome extends along the north and east shores of the Gulf of Alaska. Old-growth forests of Sitka spruce, hemlock, and cedar are found in the Alexander Archipelago. Hemlock extends to the end of the Kenai Peninsula, while cedar extends to Prince William Sound. Wetlands are found throughout the region. As elevation increases, upper forests are replaced by a narrow subalpine zone of alder and herbaceous meadow. Alpine tundra and bedrock or ice are found at the highest elevations.

Canada's Pacific Maritime Ecozone includes the mainland Pacific coast and offshore islands of British Columbia. Mixtures of western red cedar, yellow cedar, western hemlock, Douglas-fir, amabilis fir, mountain hemlock, Sitka spruce, and alder comprise the region's temperate coastal forests. Amabilis fir is more common in the north, and Douglas-fir is found largely in the extreme southern portion of the ecozone. Ecosystems range from low-elevation coastal rainforest (mild, humid) to higher-elevation, cool boreal and alpine conditions. Mountain hemlock tends to populate higher elevations.

Source: Murphy et al. (August 2010, p. 65-66, 68-69).

[872] *Murphy et al. (August 2010, p. 14)
[873] *Murphy et al. (August 2010, p. 14)
[874] *Murphy et al. (August 2010, p. 21)
[875] *Murphy et al. (August 2010, p. 21)
[876] *Murphy et al. (August 2010, p. 21)
[877] *Murphy et al. (August 2010, p. 21)
[878] *Murphy et al. (August 2010, p. 21)
[879] *Murphy et al. (August 2010, p. 29)

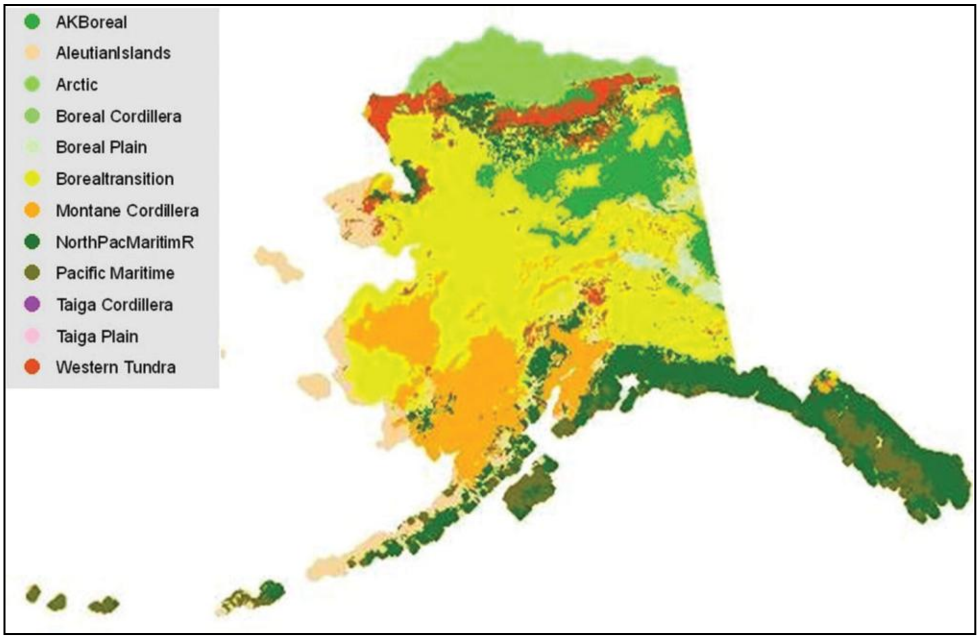

Figure 19. Projected potential biomes for 2090-2099. The Arctic, Alaska Boreal, and Western Tundra biomes are all greatly diminished, in favor of the Montane Cordillera and Boreal Transition. In addition, nearly half of southeast Alaska has shifted from North Pacific Maritime to the Canadian Pacific Maritime.
Source: Reproduced from Murphy et al. (August 2010, Fig. 7, p. 19) by authors of this report.

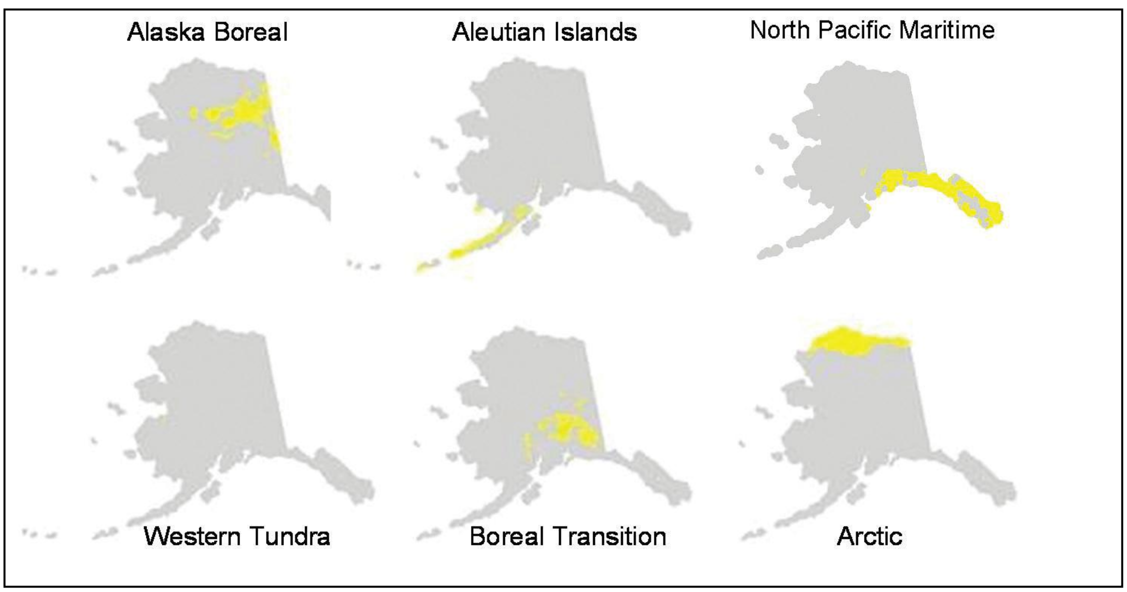

Figure 20. Biome refugia. Areas shaded in yellow are projected to see no change in potential biome by the end of the twenty-first century. Thus, these regions may be more ecologically resilient to climate change and may serve as refugia for species assemblages from each biome.
Source: Reproduced from Murphy et al. (August 2010, Fig. 11, p. 25) by authors of this report.

Washington

In the Queets River, and other coastal rivers, variability in sediment delivery, discharge and benthic shear stress determine the structure, composition and spatial distribution of riparian vegetation.[880] Climatically induced changes in the hydrological regime are expected to have substantial consequences for riparian forests, in terms of their structure, biogeochemical processes and resiliency.[881] Much of the possible variability is apparent in the species, and their life history strategies in the temperate coastal rainforest.[882] Rivers with high discharge favor willow, sexually reproducing black cottonwood and many exotic species.[883] In contrast, rivers with little variability favor more upland species such as western hemlock, sitka spruce and Douglas fir, asexually reproducing cottonwood and less exotic species.[884]

Box 18. Sediment Accumulation Rate (SAR): Observed trends and future projections.

The Sediment Accumulation Rate (SAR) indicates the rate of sediment accumulation over space and time. Verdonschot et al. (2010) note the SAR affects lake morphology and the characteristics of lake habitats, as well as physical and chemical stratification. All of these factors affect the distribution of aquatic flora and fauna, particularly in lake shoreline areas. Over the last 100 years (specific study period not provided), an increase in SAR has been observed in many lakes. Increased biogenic sedimentation from eutrophication and accelerated catchment soil erosion, caused by changes in land use and management, contributed to the observed increase in SAR. Climate change, through increases in winter run-off, may increase the suspended sediment load to lakes, which could lead to increases in the SAR. Similarly, increases in catchment soil erosion induced by more rainfall or increased frequency of extreme events (e.g., summer droughts, winter storms), may increase allochthonous input to lakes and as a result, may increase the SAR.

Source: Verdonschot et al. (2010, p. 70)

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here.

880 *Melack et al. (1997, p. 985). The authors cite Fetherston et al. (1995) for this information.
881 *Melack et al. (1997, p. 985). The authors cite Naiman et al. (1993) for this information.
882 *Melack et al. (1997, p. 985). The authors cite Naiman and Anderson (1997) for this information.
883 *Melack et al. (1997, p. 985). The authors cite DeFerrari and Naiman (1994) for this information.
884 *Melack et al. (1997, p. 985)

V. IMPLICATIONS FOR FRESHWATER SPECIES , POPULATIONS, AND BIOLOGICAL COMMUNITIES

Climate change at global and regional scales is predicted to alter species distributions, life histories, community composition, and ecosystem function.[885] The broad categories of climate change impacts on species composition and ecosystems are gradually becoming better defined, however the full implications of these types of changes, particularly at the site level, are still unknown and could be unique to each case.[886] For increases in global average temperature exceeding 2.7 to 4.5°F (1.5 to 2.5°C) and in concomitant atmospheric CO_2 concentrations, there are projected to be major changes in ecosystem structure and function, species' ecological interactions and shifts in species' geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services, e.g. water and food supply.[887] Based on a search of the scientific and grey literature, the following implications of climate change for species, populations, and biological communities in the NPLCC region have been identified:

1. Shifts in species range and distribution
2. Altered phenology and development
3. Shifts in community composition, competition, and survival
4. Altered interaction with non-native and invasive species

The following structure will be used to present information on the implications of climate change for the NPLCC region's species, populations, and biological communities.:

- **Observed Trends –** observed changes for southcentral and southeast Alaska, British Columbia,[888] Washington, Oregon, and northwestern California. A few sections also include information on changes observed globally or across the NPLCC region.
- **Future Projections –** projected direction and/or magnitude of change for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California. Some sections also include information on global future projections.
- **Information Gaps –** information and research needs identified by reviewers and literature searches.

Chapter VI discusses implications for key fish, amphibians, and macroinvertebrates in the NPLCC region.

Almost every alteration in a species' environment – whether natural or human-induced, biotic or abiotic – is a potential source of new or intensified directional selection on traits important for fitness.[889] In biology, the term *fitness* describes the sum of processes occurring throughout life history, often used as a measure of an individual's ability to reproduce or the chance an individual will leave more offspring than other individuals. When faced with

[885] *McLaughlin et al. *Climate change hastens population extinctions.* (2002, p. 6070). The authors cite Gates (1993), Graham & Grimm (1990), McCarty (2001), Hughes (2000), and Kappelle et al. (1999) for this information.
[886] *Burgiel and Muir. *Invasive species, climate change and ecosystem-based adaptation: Addressing multiple drivers of global change.* (2010, p. 10)
[887] *IPCC. *Climate Change 2007: Synthesis Report.* (2007, p. 48)
[888] At time of publishing, Austin et al. (2008, p. 189) state there has been no comprehensive evaluation of the potential effects of climate change on B.C.'s freshwater ecosystems, though impacts on salmon and other freshwater fish have received attention. Austin et al. cite Nelitz et al. (2007) and Tyedmers and Ward (2001) for information on salmon and other freshwater fish.
[889] *Gienapp et al. *Climate change and evolution: disentangling environmental and genetic responses.* (2008, p. 167)

new selection pressures – such as those imposed by ongoing climate change – populations can respond basically in three ways: [890]

- They can evade by dispersing to suitable habitats elsewhere;
- They can remain in the habitat and adjust to the changed conditions by means of phenotypic plasticity without altering their genetic constitution; or,
- They can adapt to the changed conditions by means of genetic changes through the process of evolution.[891]

While evading will lead to local extinction but persistence elsewhere, phenotypic plasticity (i.e., production of multiple phenotypes from a single genotype) and genetic adaptation can prevent local extinction.[892] Disentangling microevolutionary responses (i.e., genetic responses) from plastic responses is important for several reasons:

- Phenotypic plasticity provides an important mechanism to cope with changing environmental conditions, but there are limits to plastic responses and they are unlikely to provide long-term solutions for challenges faced by populations experiencing continued directional environmental change.[893] This limitation becomes important when environmental change progresses to a point where plastic responses cannot anymore mitigate loss of fitness.[894]
- Coping with climate change via plastic responses is possible only as long as the relationship between existing reaction norm (i.e., the pattern of phenotypic expression of a single genotype across a range of environments) and fitness remains unchanged over time.[895] However, this seems unlikely in the case of climate change.[896]
- A wide diversity of organisms express phenotypic plasticity in response to biotic and abiotic aspects of their environments.[897] The ability of plasticity to stabilize a population is strongly dependent on the lag between the induction time of a plastic response and the timing of environmental changes[898] As the lag time increases, the ability of plasticity to stabilize a population decreases, increasing the amplitude of population fluctuations.[899]
- Results of theoretical treatments suggest the predicted rate of climate warming may be too rapid for many populations to sustain continued response.[900]

[890] Gienapp et al. (2008, p. 167). The authors cite Houghton et al. (2001) and Jones et al. (2001) for information on ongoing climate change, and Holt (1990) and Davis et al. (2005) as examples of the three population responses.
[891] *Gienapp et al. (2008, p. 167)
[892] *Gienapp et al. (2008, p. 167)
[893] *Gienapp et al. (2008, p. 168). The authors cite Bradshaw (1965) and Przybylo et al (2000) as examples of coping with changing environmental conditions, and de Jong (2005), Pigliucci (1996), and DeWitt et al . (1998) for information on limits to plastic responses.
[894] *Gienapp et al. (2008, p. 168)
[895] *Gienapp et al. (2008, p. 168)
[896] *Gienapp et al. (2008, p. 168)
[897] *Miner et al. (2005, p. 685). The authors cite Karban and Baldwin (Eds.) (1997), Tollrain and Harvell (Eds.) (1999), Sultan (2000), Pigliucci (2001), DeWitt and Scheiner (Eds.) (2004) and Young et al. (2003) for this information.
[898] *Miner et al. (2005, p. 688). The authors cite Underwood (199), Abrams and Matsuda (2004), and Padilla nd Adolph (1996) for this information.
[899] *Miner et al. (2005, p. 688). The authors cite Underwood (199), Abrams and Matsuda (2004), and Padilla nd Adolph (1996) for this information.
[900] *Gienapp et al. (2008, p. 168). The authors cite Lynch & Lande (1993), Bürger & Lynch (1995), Lynch 1996, and Gomulkiewicz & Holt (1995) for this information.

- Although microevolutionary adaptations are generally envisioned to be ubiquitous and are a requisite for coping with environmental changes in the long run, no clear picture has yet emerged as to how effective microevolution will be in mitigating consequences of ongoing environmental changes.[901] One meta-analysis of 866 papers (published between 1899 and January 2006) concluded that although evolutionary responses have been documented (mainly in insects), there is little evidence that observed genetic shifts are of the type or magnitude to prevent predicted species extinctions.[902]

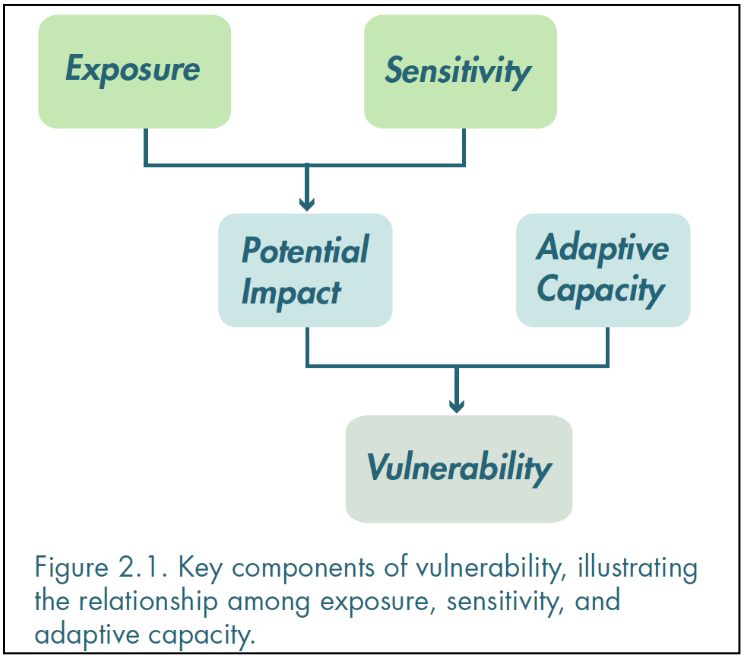

Figure 21. Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity. *Source: Reproduced from Glick, Stein, and Edelson. (2011b, Fig. 2.1, p. 20) by authors of this report.*

Increased risk of extinction due to climate change occurs where species possess biological traits or characteristics that make them particularly susceptible to change, and simultaneously occur in areas where climatic changes are most extreme (Figure 22)[903] as well as where geography or existing stressors increase vulnerability. Considering the degree of change (i.e., exposure) a species or system is projected to experience, along with its likely response (i.e., sensitivity) to those changes, determines the potential impact.[904] Understanding the likely consequences (i.e., vulnerability), however, requires further consideration of the ability for the species or system to reduce or moderate those potential impacts (i.e., its adaptive capacity) (Figure 21).[905]

[901] *Gienapp et al. (2008, p. 168). The authors cite Hendry & Kinnison 2001 and references therein for information on ubiquity of microevolutionary adaptations and cite Stockwell et al. (2003) and Davis et al. (2005) as examples for information on microevolutionary adaptations as a requisite for coping with environmental change in the long run.
[902] *Parmesan. (2006, p. 657)
[903] *Foden et al. *Species susceptibility to climate change impacts.* (2008, p. Sec1:2)
[904] *Glick, Stein, and Edelson. (2011b, p. 20)
[905] *Glick, Stein, and Edelson. (2011b, p. 20)

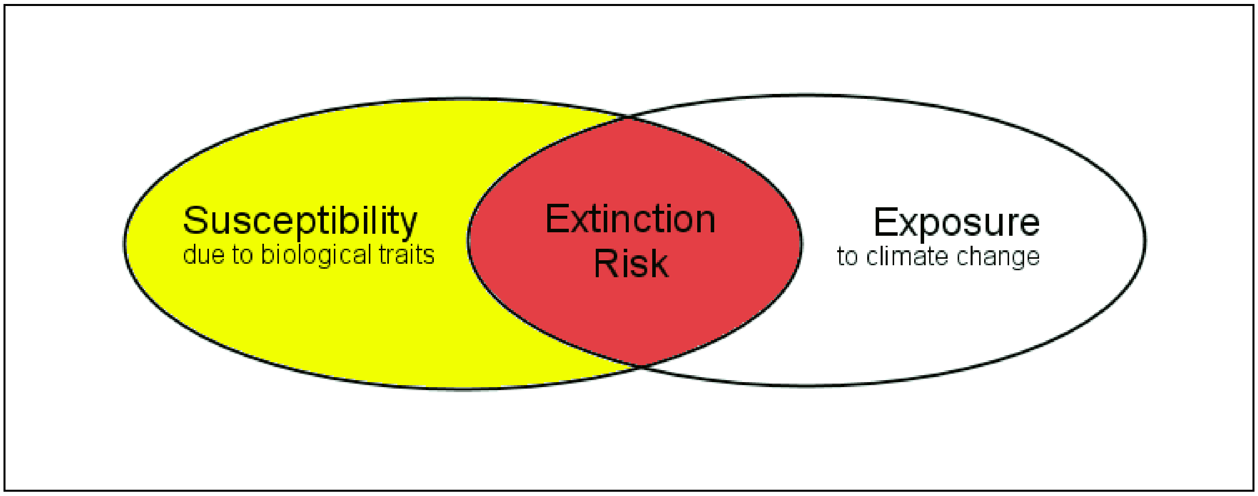

Figure 22. Increased risk of extinction due to climate change occurs where species possess biological traits or characteristics that make them particularly susceptible to change, and simultaneously occur in areas where climatic changes are most extreme. *Source: Reproduced from Foden et al. (2008, Sec1:2) by authors of this report.*

1. SHIFTS IN SPECIES RANGE AND DISTRIBUTION

A strong case can be made that future climate warming will alter the extent of habitat available for cold-, cool-, and warm-water organisms depending upon region, and result in range expansions and contractions.[906] Species at the southern extent of their geographical distribution (in the north temperate zone) will shift northward and face local extirpation at their southern limit, while expanding at the northern limit of their range.[907] Further, physical constraints such as drainage patterns, waterfalls, and land-locked areas play a large role in determining the boundaries of a species' range and the rate at which it may respond to changing conditions.[908] For example, the impacts of climate-induced habitat shifts may be pronounced in stream ecosystems where biota are often ectothermic (body temperatures strongly influenced by external sources of heat) and movements are constrained to linear networks that are easily fragmented by thermal or structural barriers.[909]

Observed Trends

Southcentral and Southeast Alaska

In a modeling and connectivity study by Murphy et al. (2010), four species with very different connectivity issues were selected for evaluation.[910] Caribou were selected to represent mammal species with few migration constraints; Alaska marmot were selected to represent mammals with limited range and migration capability; trumpeter swans were selected to investigate how statewide landscape connectivity issues would apply to breeding bird populations; and reed canary grass was selected as an invasive plant species that uses the human footprint on the landscape for initial dispersal and may benefit from a warming climate.[911] The latter three – Alaska marmot, trumpeter swan, and reed canary grass – are currently found in the NPLCC region. Alaska marmot and trumpeter swan are discussed in this Section, while reed canary grass is discussed in Section 4 (Altered interaction with invasive and non-native species) of this Chapter.

The Alaska marmot *(Marmota broweri)*, a relic species from the Beringia Ice Age, has limited adaptability and dispersal ability and thus makes an excellent case study for connectivity and habitat loss for endemics (native species) in arctic environments.[912] Data for thirty-four known occurrences of Alaska marmots were provided by the Alaska National Heritage Program, based on various sources including the Gunderson collections.[913] Murphy and colleagues used SNAP climate data for June and December mean temperature and precipitation for 2000–2009 to develop a climate envelope and current potential distribution based on known occurrence sites.[914] However, terrain roughness was also added as a covariate.[915] Rockiness, steepness, and associated biophysical

906 *Allan, Palmer and Poff. (2005, p. 279)
907 *Allan, Palmer and Poff. (2005, p. 279-280)
908 *Kling et al. (2003, p. 53)
909 *Isaak et al. (2010, p. 1350). The authors cite Pörtner and Farrell (2008) for information on climate-induced habitat shifts in stream ecosystems and Fagan (2002) for information on constraints to movement.
910 Murphy et al. (August 2010, p. 32)
911 *Murphy et al. (August 2010, p. 32)
912 *Murphy et al. (August 2010, p. 35). The authors cite Gunderson et al. (2009) for information on adaptability and dispersal ability.
913 *Murphy et al. (August 2010, p. 35). The authors cite Gunderson et al. (2009) for information on the Gunderson collections.
914 *Murphy et al. (August 2010, p. 36)
915 *Murphy et al. (August 2010, p. 36)

features are of great importance to marmot habitat, since Alaska marmots use rock piles for cover.[916] It cannot be presumed that the species is absent from areas for which no data exist (Figure 23).[917]

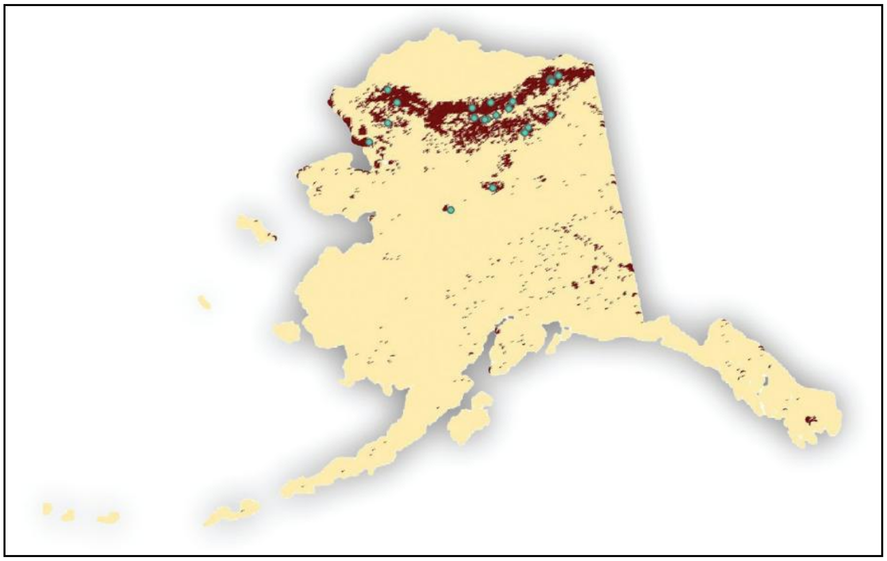

Figure 23. Known Alaska marmot distribution and modeled current distribution. Since no absence data exist, it cannot be assumed that marmots do not also inhabit similar habitat in which no confirmed presence data are available.
Source: Reproduced from Murphy et al. (August 2010, Fig. 19, p. 36) by authors of this report.

The trumpeter swan *(Cygnus buccinator)* was selected as a species of interest because, like many other birds species in the state, it is migratory.[918] As such, statewide connectivity of habitat may not be an issue for them.[919] However, quantity and quality of habitat are pertinent to the survival of this species.[920] Swans are limited, in part, by summer season length to fledge their young.[921] Trumpeter swans in Alaska require 138 ice-free days to fledge their young successfully.[922] Figure 25 shows the current and projected range for trumpeter swans.

British Columbia

Information needed.

Washington, Oregon, and Northwestern California

The bull trout *Salvelinus confluentus* is believed to be among the most thermally sensitive species in coldwater habitats in western North America.[923] Dunham, Rieman, and Chandler (2003) developed models of thermal habitat associations using two data sets representing a geographically diverse range of sites and sampling methods in the western U.S.[924] The concordance in parameter estimates and cross validation both within and between data sets indicates a consistent relationship between temperature and the occurrence of small bull trout throughout the

[916] *Murphy et al. (August 2010, p. 36)
[917] *Murphy et al. (August 2010, p. 35)
[918] *Murphy et al. (August 2010, p. 38)
[919] *Murphy et al. (August 2010, p. 38)
[920] *Murphy et al. (August 2010, p. 38)
[921] *Murphy et al. (August 2010, p. 38)
[922] *Murphy et al. (August 2010, p. 38). The authors cite Mitchell (1994) for this information.
[923] *Dunham, Rieman and Chandler. *Influences of temperature and environmental variables on the distribution of bull trout within streams at the southern margin of its range.* (2003, p. 894)
[924] *Dunham, Rieman and Chandler. (2003, p. 894)

southern margin of the species' range.[925] In both data sets, maximum temperature was strongly associated with the distribution of bull trout:[926]

- In both cases, the probability of the occurrence of bull trout exceeded fifty percent when the maximum daily temperature was less than 57.2 to 60.8°F (14-16°C), a result that is consistent with recent laboratory-based thermal tolerances.[927]

However, Crimmins et al. (2011) note the assumption that temperature is the principal factor defining species' distributions ignores the fact that many species are constrained by energy and water availability,[928] as well as by interactions with other species or the availability of key resources such as nesting or foraging habitat. Consequently, considering changes in temperature alone may be inadequate for understanding distributional shifts of plant and animal species,[929] although additional research is needed. For example, by comparing the altitudinal distributions of sixty-four plant species between the 1930s (historical period: 1920-1949) and present-day (modern period: 1976-2005) within California, Crimmins et al. (2011) show that climate changes have resulted in a significant downward shift in species' optimum elevations.[930] Specifically, they found significant downhill shifts in optimum elevations (mean difference = -88.2 m, $t = -2.49$, df = 63, $P = 0.016$), with a higher proportion of species shifting their distributions downhill [proportion (p) = 0.72, 95% confidence interval = 0.59 to 0.82] than uphill [$p = 0.28$, 95% confidence interval = 0.18 to 0.41).[931]

Future Projections

<u>Southcentral and Southeast Alaska</u>

Using the covariates mentioned above (see "Observed trends: Southcentral and Southeast Alaska"), results from Random Forests™ modeling showed shrinking range size for the Alaska marmot (A1B scenario; Figure 24).[932] Statewide, total range area shrank by 27% by 2039, 81% by 2069, and 87% by 2099, as compared with present estimated range size (2000-2099).[933] In addition, previously contiguous habitat areas became disconnected.[934]

[925] *Dunham, Rieman and Chandler. (2003, p. 898)
[926] *Dunham, Rieman and Chandler. (2003, p. 894)
[927] *Dunham, Rieman and Chandler. (2003, p. 894)
[928] *Crimmins et al. *Changes in climatic water balance drive downhill shifts in plant species' optimum elevations.* (2011, p. 324). The authors cite Stephenson (1990) and Stephenson (1998) for this information.
[929] *Crimmins et al. (2011, p. 324)
[930] *Crimmins et al. (2011, p. 324)
[931] *Crimmins et al. (2011, p. 325). The authors refer to the reader to Fig. 3 in the cited report.
[932] *Murphy et al. (August 2010, p. 36)
[933] *Murphy et al. (August 2010, p. 36)
[934] *Murphy et al. (August 2010, p. 36)

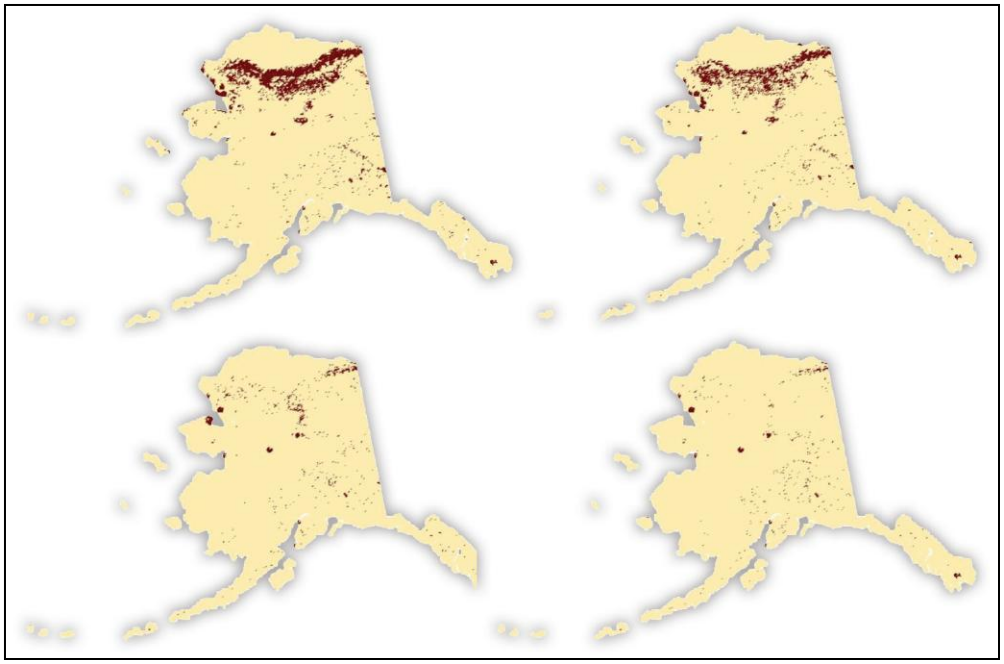

Figure 24. Projected Alaska marmot distribution. Marmot range is expected to diminish sharply as climate warms and alpine habitat shrinks. *Source: Reproduced from Murphy et al. (August 2010, Fig. 20, p. 37) by authors of this report.*

Using the same methodology and climate data described for modeling biomes (see Chapter IV Section 5 in this report), Murphy and colleagues modeled potential shifts in swan climate-linked habitat, using SNAP temperature and precipitation data for summer and winter for the current decade and three future decades (2000–2009, 2030–2039, 2060–2069, and 2090–2099).[935] Model results showed distribution expanding west and north (Figure 25), but did not predict movement into the Arctic.[936] It should be noted that this shift might be happening already.[937] Since biologists cannot easily distinguish tundra versus trumpeter swans from the air, mixing is probably occurring already at the interface between habitats along the northern and western parts of the range.[938]

[935] *Murphy et al. (August 2010, p. 38)
[936] *Murphy et al. (August 2010, p. 38)
[937] *Murphy et al. (August 2010, p. 38)
[938] *Murphy et al. (August 2010, p. 38)

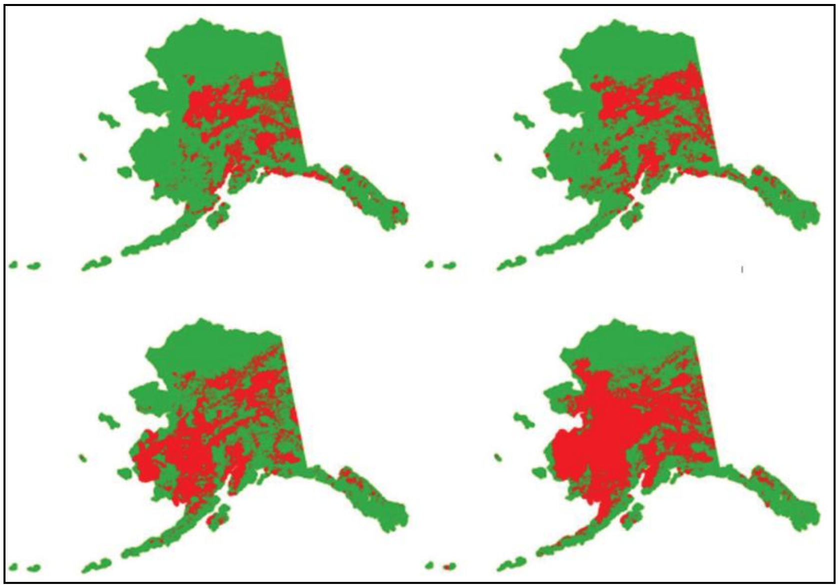

Figure 25. Potential expansion of trumpeter swan habitat. These predictions are based on 138-day ice-free season, summer and winter climate envelopes, as predicted by SNAP climate projections, and a competitive filter of non-forested biomes to represent tundra swans (not included in this figure). Trumpeter swans are predicted to shift their range northward and westward over the course of this century. Red indicates trumpeters present. Green indicates trumpeters absent.
Source: Reproduced from Murphy et al. (August 2010, Fig. 21, p. 39) by authors of this report.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends in British Columbia and for future projections in British Columbia, Washington, Oregon, and northwestern California.

2. ALTERED PHENOLOGY AND DEVELOPMENT

Given that species interactions can strongly determine the structure and dynamics of many natural communities, some of the most profound effects of climate change are likely to be driven by changes in the timing of biotic interactions between species.[939] The effects of these altered interactions can be as strong as or stronger than the direct abiotic effects of climate change.[940]

Many organisms alter the timing of their seasonal activities in response to climate change, whether it be flowering in plants, budding of trees, emergence of insects or breeding in birds.[941] Despite this ability of some species to shift the timing of seasonal events, some species may still suffer if their phenological response differs from the response of organisms at lower levels of the food chain (or on which they depend in some other way, e.g. a pollinator-flower relationship),[942] leading to a mismatch between the timing of reproduction and the main food supply or between other time-dependent events such as the concurrence of flowering and pollinator presence.[943] This mistiming can have a clear effect on species population dynamics and ecosystem functioning.[944]

Observed Trends

Global

Numerous ecological studies have now pointed to an important general pattern of species' responses to climate change around the world: on average, seasonal life-history events such as leaf unfolding, flowering, insect emergence, or the arrival of migratory birds are occurring earlier than they have in the historical past.[945] For example, Parmesan and Yohe (2003) report global meta-analyses documented significant mean advancement of spring events by 2.3 days per decade,[946] with a bootstrapped 95% confidence interval of 1.7-3.2 days advancement per decade (significant at $P < 0.05$).[947] Despite this prevailing trend, however, it has also become evident that species within the same community often show variable phenological responses to climate change.[948]

[939] *Yang and Rudolf. *Phenology, ontogeny and the effects of climate change on the timing of species interactions.* (2010, p. 1)
[940] *Yang and Rudolf. (2010, p. 1). The authors cite Parmesan (2006) for this information.
[941] *Both et al. *Climate change and population declines in a long-distance migratory bird.* (2006, p. 81). The authors cite Walther et al. (2002), Parmesan and Yohe (2003), and Root et al. (2003) for this information. One reviewer noted that while spring events tend to shift earlier, fall events tend to shift later.
[942] *Both et al. (2006, p. 81). The authors cite Visser and Both (2005), Stenseth et al. (2002), Merila et al. (2001), Both and Visser (2001), Visser et al. (1998), and Visser and Holleman (2001) for this information.
[943] *Both et al. (2006, p. 81). The authors cite Visser et al. (2004) for this information.
[944] *Both et al. (2006, p. 81). The authors cite Stenseth et al. (2002) and McLaughlin et al. (2002) for this information.
[945] *Yang and Rudolf. (2010, p. 1)
[946] *Parmesan and Yohe. *A globally coherent fingerprint of climate change impacts across natural systems*. (2003, p. 37). The authors cite Dunn & Winkler (1999), Walther et al. (2002), Parmesan & Yohe (2003), and Gordo & Sanz (2005) for this information.
[947] *Parmesan and Yohe. (2003, p. 38)
[948] *Yang and Rudolf. (2010, p. 1). The authors cite Visser & Both (2005), Miller-Rushing & Primack (2008), and Both et al. (2009) for this information.

In a literature review of 866 papers (published between 1899 and January 2006) documenting changes through time in species or systems that could, in whole or part, be attributed to climate change, Parmesan (2006) concludes with the following summary points:[949]

- The advance of spring events (bud burst, flowering, breaking hibernation, migrating, breeding) has been documented on all but one continent and in all major oceans for all well-studied marine, freshwater, and terrestrial groups.[950]
- Variation in phenological response between interacting species has already resulted in increasing asynchrony in predator-prey and insect-plant systems, with mostly negative consequences.[951]
- Poleward range shifts have been documented for individual species, as have expansions of warm-adapted communities, on all continents and in most of the major oceans for all well-studied plant and animal groups.[952]
- These observed changes have been mechanistically linked to local or regional climate change through long-term correlations between climate and biological variation, experimental manipulations in the field and laboratory, and basic physiological research.[953]
- Shifts in abundances and ranges of parasites and their vectors are beginning to influence human disease dynamics.[954]
- Range-restricted species, particularly polar and mountaintop species, show more-severe range contractions than other groups and have been the first groups in which whole species have gone extinct due to recent climate change.[955] Tropical coral reefs and amphibians are the taxonomic groups most negatively impacted.[956]
- Although evolutionary responses have been documented (mainly in insects), there is little evidence that observed genetic shifts are of the type or magnitude to prevent predicted species extinctions.[957]

Regional

In addition to a key role played by salmon in ecological interactions, coevolutionary association with other species is also evident.[958] For example, there is evidence that aquatic insects may time their emergence from streams as adults such that they avoid disturbance caused by spawning salmon.[959] It has also been shown that the timing of lactation in mink (*Mustela vison*)—which is decoupled from that predicted by latitude—occurs during salmon spawning periods.[960] Salmon availability can also increase niche diversity within consumer populations, which is important because foraging behavior is a central and influential trait on which natural selection can act.[961] Salmon have also been linked to the maintenance of a rare polymorphic trait; recent evidence indicated that the

[949] Parmesan. *Ecological and evolutionary responses to recent climate change.* (2006, p. 640)
[950] *Parmesan. (2006, p. 657)
[951] *Parmesan. (2006, p. 657)
[952] *Parmesan. (2006, p. 657)
[953] *Parmesan. (2006, p. 657)
[954] *Parmesan. (2006, p. 657)
[955] *Parmesan. (2006, p. 657)
[956] *Parmesan. (2006, p. 657)
[957] *Parmesan. (2006, p. 657)
[958] *Darimont et al. (2010, p. 2)
[959] *Darimont et al. (2010, p. 2). The authors cite Moore and Schindler (2010) for this information.
[960] *Darimont et al. (2010, p. 2). The authors cite Ben-David (1997) for this information.
[961] *Darimont et al. (2010, p. 2). The authors cite Hocking et al. (2007) and Darimont et al. (2009a) for information on niche diversity within consumer populations.

unusual white phase of the black bear (*Ursus americanus*) in coastal British Columbia, Canada might be a salmon specialist.[962]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

In Lake Washington since 1976 (study period: 1962-2002), the dominant zooplankton species have been the rotifer *Keratella cochlearis*, the cladoceran *Daphnia pulicaria*, and the two copepod species *Cyclops biscuspidatus thomasi* and *Leptodiaptomus ashlandi*.[963] As described below, a long-term decline in *Daphnia* populations, the keystone herbivore, is associated with an expanding temporal mismatch with the spring diatom bloom and may have severe consequences for resource flow to upper trophic levels.[964]

Changes in the timing of thermal stratification in Lake Washington were transmitted through primary producers to herbivorous zooplankton.[965] However, the ability to respond to changes in the timing of phytoplankton blooms differed among zooplankton species.[966] The timing of the spring phytoplankton bloom changed in accordance with earlier stratification and has advanced twenty-seven days over the entire study period (1962–2002), or twenty days over the period 1977–2002, when the trophic state of Lake Washington was stable.[967] *Keratella* and *Daphnia* show a pronounced seasonal succession that coincides with or lags the phytoplankton spring bloom:[968]

- The phenology of the herbivorous rotifer *Keratella* paralleled the advance in timing of the phytoplankton peak.[969] More precisely, a significant trend towards earlier timing of peak densities was observed for *Keratella*, which advanced twenty-one days between 1962 and 1995.[970] Therefore, the temporal offset in this predator–prey relationship did not exhibit any long-term trends (slope = 0.18 ± 0.51, $P = 0.50$).[971]
- In distinct contrast, a growing mismatch between peak algal densities and *Daphnia* populations in the water column has developed since 1977.[972] More precisely, the timing of the annual spring peaks of *Daphnia* exhibited no significant trend over the period from 1977 to 2002.[973] Therefore, the offset in timing between the peak of the spring diatom bloom and the peak of the spring *Daphnia* bloom has increased significantly over the past twenty-six years (slope 1.57 ± 0.8, $P < 0.001$), corresponding to a significant long-term decline in spring/summer *Daphnia* densities.[974]

[962] *Darimont et al. (2010, p. 2). The authors cite Klinka and Reimchen (2009) for this information.
[963] *Winder and Schindler. (2004a, p. 2101)
[964] *Winder and Schindler. (2004a, p. 2100)
[965] *Winder and Schindler. (2004a, p. 2103)
[966] *Winder and Schindler. (2004a, p. 2103)
[967] *Winder and Schindler. (2004a, p. 2102-2103)
[968] *Winder and Schindler. (2004a, p. 2101). The authors refer the reader to Fig. 1B in the cited report.
[969] *Winder and Schindler. (2004a, p. 2103)
[970] *Winder and Schindler. (2004a, p. 2103). The authors refer the reader to Fig. 2C in the cited report.
[971] *Winder and Schindler. (2004a, p. 2103). The authors refer the reader to Fig. 2C in the cited report.
[972] *Winder and Schindler. (2004a, p. 2103)
[973] *Winder and Schindler. (2004a, p. 2103). The authors refer the reader to Fig. 2D in the cited report.
[974] *Winder and Schindler. (2004a, p. 2103). The authors refer the reader to Fig. 2D for the timing offset and to Fig. 3D and Fig. 3F for the decline in spring/summer *Daphnia* densities in the cited report.

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Global

In general, the populations that are most mistimed are expected to decline most in number.[975] However, one reviewer noted some species may be able to shift the species on which they depend.[976]

Temperatures and hydrological patterns can control the timing of seasonal events such as reproduction and key life history stages (i.e., phenology). For example, for fishes dependent on water temperature for spawning cues, the spawning time of fishes may shift earlier if river waters begin to warm earlier in the spring.[977] In snowmelt-dominated areas, the lifecycles of many species have evolved around predictable springtime peak flows whereas, in rain dominant areas, species life cycles have evolved around predictable wintertime peak flows.[978]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends in all jurisdictions except Washington and for species- and community-specific studies of future projections throughout the region.

[975] *Both et al. (2006, p. 81)
[976] Comment from reviewer. (June 2011)
[977] *Palmer et al. (2008, p. 30). The authors cite Hilborn et al. (2003) for this information.
[978] Mara Zimmerman, Washington Department of Fish and Wildlife. (Personal communication)

3. SHIFTS IN COMMUNITY COMPOSITION, COMPETITION, AND SURVIVAL

Changes in baseline conditions of aquatic ecosystems could influence the outcomes of competition between species with differential temperature tolerances, as well as affect the necessary habitat requirements and survivability of sensitive species.[979] Temperatures that commonly exceed physiological thresholds or lethal limits will presumably set relatively hard limits to species occurrence, although variation in life history and behavior (including phenotypic plasticity), such as the increasing exploitation of thermal refugia, may mitigate hard constraints.[980] For example, fish and amphibian species will experience increased stream and lake temperatures that will affect their food supply and fitness (e.g. reproductive fitness and survival).[981] Further, for fish, amphibians, and water-dispersed plants, habitat fragmentation due to dams or the isolation of tributaries due to drought conditions may result in local extirpations.[982] Particle size and hydraulic forces are major determinants of stream biodiversity (both the numbers and composition of algae, invertebrates, and fish) and excessive bottom erosion is well known to decrease abundances and lead to dominance by a few taxa.[983] Further, physiological stress and increased predation resulting from crowding (less depth means less habitat), combined with habitat fragmentation in stream networks (isolated pools), may dramatically reduce survival and constrain dispersal.[984] However, in very small, eutrophic lakes, by contrast, prolonged ice cover prevents the lake from absorbing oxygen from the atmosphere, and depletion of dissolved oxygen in winter often causes die-backs in fish populations.[985] In these lakes, climate warming may enhance survival of fish in winter.[986]

Observed Trends

<u>Regional</u>

There is evidence that winter avifauna in North America has responded to climate change by shifting their distribution poleward.[987] However, how these changes have been manifested within community composition and structure has yet to be determined.[988] To address this information gap, La Sorte et al. (2009) examined trends in three community attributes from 1975 to 2001 for assemblages of terrestrial winter avifauna in North America.[989] The attributes include species richness and two attributes summarized at the assemblage level: average body mass and average geographical occupancy.[990] Their findings indicate:

- After accounting for possible effects of land-use change and survey effort, a general trend of increasing species richness, average body mass, and average geographical occupancy for assemblages of terrestrial winter avifauna in North America from 1975 to 2001 is indicated.[991]

979 *Pike et al. (2010, p. 729). The authors cite Schindler (2001) for this information.
980 *Rieman and Isaak. *Climate change, aquatic ecosystems, and fishes in the Rocky Mountain West: implications and alternatives for management.* (2010, p. 14). The authors cite Crozier and others (2008) and Keefer and others (2009) as examples for this information.
981 CA-NRA. (2009)
982 *Palmer et al. (2008, p. 30). The authors cite Dynesius et al. (2004) and Palmer et al. (2008) for this information.
983 *Palmer et al. (2008, p. 31). The authors cite Allan (1995) for this information.
984 *Palmer et al. (2008, p. 31). The authors cite Poff (2002) for this information.
985 *Poff, Brinson and Day. (2002, p. 14)
986 *Poff, Brinson and Day. (2002, p. 14). The authors cite Fang and Stefan (2000) for this information.
987 *La Sorte et al. (2009, p. 3167). The authors cite La Sorte and Thompson (2007) for this information.
988 *La Sorte et al. (2009, p. 3167)
989 *La Sorte et al. (2009, p. 3167)
990 *La Sorte et al. (2009, p. 3167)
991 *La Sorte et al. (2009, p. 3170)

- Modern global climate change is associated with community-level changes that cannot be comprehensively predicted using spatial ecological associations.[992] This outcome suggests that space-for-time substitution has limited applicability as a predictive tool under climate change and also suggests that species within communities are responding in a non-uniform manner to climate change.[993]

Southcentral and Southeast Alaska

The Kittlitz's murrelet (*Brachyramphus brevirostris*) has been reported to be experiencing an annual estimated decline of around eighteen percent, attributed primarily to climate change, although the specific causes of its decline have not been determined.[994] Kittlitz's murrelet feeds in waters around tidewater glaciers and is considered a critically endangered species as glaciers recede.[995] The southcentral Alaska landscape is one of its primary areas.[996]

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Future Projections

Global

River temperature is a main determinant of community composition, and a general increase in temperature could cause communities to migrate upstream, or invasive species to spread.[997] More precisely, it could cause community composition in a given location to shift towards warmer-adapted species due to changes in survival, reproduction, competitive dominance, and other factors that shift community composition.[998]

Warmer water can increase growth rates and stimulate ecosystem production.[999] For example, assuming no change in food resources, invertebrate production of streams and rivers may increase, potentially yielding more food for fish.[1000] However, higher water temperatures will also increase the rate of microbial activity and thus the rate of

[992] *La Sorte et al. (2009, p. 3171)
[993] *La Sorte et al. (2009, p. 3171)
[994] *Haufler, Mehl and Yeats. (2010, p. 17)
[995] *Haufler, Mehl and Yeats. *Climate change: anticipated effects on ecosystem services and potential actions by the Alaska Region, U.S. Forest Service.* (2010, p. 17)
[996] *Haufler, Mehl and Yeats. (2010, p. 17)
[997] *Euro-Limpacs (N.D.), *Climate Change and Freshwater* (website).
[998] Comment from reviewer. (June 2011)
[999] *Poff, Brinson and Day. (2002, p. 7)
[1000] *Poff, Brinson and Day. (2002, p. 7)

decomposition of organic material, which may result in less food being available for invertebrates and ultimately fish.[1001] In either case, warmer water holds less dissolved oxygen, so water quality will be reduced for organisms such as invertebrates and fish that have a high oxygen demand.[1002]

In general, nutrient enrichment leads to changes in the algal and diatom community composition of a stream, and sometimes, in some streams, to increased production and chlorophyll concentrations, leading to changes in primary invertebrate consumers which could cascade through the community.[1003] Reduction in salmonid populations in river systems may decrease food for forest-dwellers such as bears and impact nutrient cycling and terrestrial food webs.[1004]

Predictions of climate-induced population extinctions are supported by geographic range shifts that correspond to climatic warming, but few extinctions have been linked mechanistically to climate change.[1005]

Southcentral and Southeast Alaska, and British Columbia

In arctic and subarctic North America, top predators (grayling and lake trout) appear particularly vulnerable to climate change, and reductions in their abundance would likely have effects throughout the food web.[1006]

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Information is especially needed for observed trends everywhere but southcentral and southeast Alaska and for future projections throughout the region.

[1001] *Poff, Brinson and Day. (2002, p. 7). The authors cite Meyer and Edwards (1991) for this information.
[1002] *Poff, Brinson and Day. (2002, p. 7)
[1003] *U. S. EPA. (2008a, p. 1-8). The authors cite Gafner and Robinson (2007) as an example of the effects of nutrient enrichment on primary invertebrate consumers. The authors cite Power (1990) and Rosemond et al. (1993) for information on changes cascading through the community.
[1004] *Austin et al. (2008, p. 189). Austin et al. refer the reader to Section 2.5.1.3-F, p. 121 in their report. They also cite Compass Resource Management (2007) for information on major climate change impacts in B.C.
[1005] *McLaughlin et al. (2002, p. 6070)
[1006] *Meyer et al. (1999, p. 1376)

Table 11. Summary of possible responses of common categories of stream and river biological fish indicators to climate-related changes in water temperature and hydrologic regime

Source: Modified from U.S. EPA. Climate Change Effects on Stream and River Biological Indicators: A Preliminary Analysis. (2008, Table 3-1, p. 3-4) by authors of this report.

Category	***Expected climate change effects/sensitivities***	***References***
Richness and abundance measures	May have initial increase in diversity as more warm-water assemblages replace cool- or cold-water species. Habitat availability is expected to be diminished by altered flow regimes with an associated loss of diversity. If barriers to dispersal limit community replacements, richness also may decline. May also, for example, lose spring spawners (e.g., some salmon species) due to changes in timing of spring flows. Abundance of warm-water species may increase, while coldwater species may decrease.	Xenopoulos and Lodge, 2006; Xenopoulos et al., 2005; Poff et al., 2002; Grimm et al., 1997; Hayhoe et al., 2007; Wehrly et al., 2003
Composition measures	Expect fish community compositional changes resulting from losses of cold- and/or cool-water fishes (e.g., brook trout, dace and bleak), and increases in warm-water fishes (e.g., chub and barbell).	Daufresne et al., 2003; Mohseni et al., 2003; Schindler, 2001; Covich et al., 1997; Moore et al., 1997; Rahel et al., 1996, Eaton and Scheller, 1996
Tolerance/ intolerance measures	Loss of temperature-sensitive cold- and cool-water species will decrease intolerant measures, increase tolerant measures.	Mohseni et al., 2003; Moore et al., 1997; Rahel et al., 1996; Eaton and Scheller, 1996
Feeding measures	Shift in food sources through attrition of lower trophic levels (and changes in community composition) will affect higher trophic levels, including top carnivores.	Schindler et al., 2005; Melack et al., 1997
Habitat measures	Changes in habitat features and connectivity fosters hybridization and drift in species gene pool.	Matsubara et al., 2001; Heggenes and Roed, 2006

4. ALTERED INTERACTION WITH INVASIVE AND NON-NATIVE SPECIES

Both invasive species and climate change are major ecosystems stressors.[1007] Although not well understood, particularly in aquatic ecosystems, the interaction of these stressors may exacerbate (or mitigate) the effects of each other.[1008] Some end-of-21st-century climates will include conditions not experienced at present (‘‘novel’’ climates).[1009] Regions over much of the globe are likely to develop novel communities,[1010] which could occur independent of novel climates. As temperatures warm, precipitation regimes fluctuate, and nutrient flows change, ecosystems may lose their ability to support a diverse set of native species, becoming more vulnerable to invasion (from both native and non-native species) as new resources become available.[1011]

Climate change will have direct and second order impacts that facilitate the introduction, establishment, and/or spread of invasive species.[1012] Climate change may enhance environmental conditions for some species in some locations with the following consequences:

- New species are now able to survive in new or existing locations,
- Known invasive species expand their range into new territories, and
- Species that currently are not considered invasive may become invasive and cause significant impacts.[1013]

Climate change impacts, such as warming temperatures and changes in CO_2 concentrations, are likely to increase opportunities for invasive species because of their adaptability to disturbance and to a broader range of biogeographic conditions and environmental controls.[1014] Recent accelerated warming of high-latitude environments has increased the chances that species being transported from lower latitudes are able to establish themselves and spread.[1015] Warmer air and water temperatures may also facilitate movement of species along previously inaccessible pathways of spread, both natural and human-made.[1016] Further, a rising number of species are expanding their ranges, often with large-scale impacts on ecosystems at the destination.[1017] The impacts of those invasive species may be more severe as they increase both in numbers and extent, and as they compete for diminishing resources such as water.[1018]

Invasive species can compromise the ability of intact ecosystems to sequester carbon which helps offset greenhouse gas emissions.[1019] Thus, invasive species can increase the vulnerability of ecosystems to other climate-related stressors and also reduce their potential to sequester greenhouse gases.[1020]

[1007] *U. S. EPA. (2008b, p. 4-1)
[1008] *U. S. EPA. (2008b, p. 4-1)
[1009] *Williams, Jackson and Kutzbach. *Projected distributions of novel and disappearing climates by 2100 AD.* (2007, p. 5738)
[1010] *Williams, Jackson and Kutzbach. (2007, p. 475)
[1011] *U. S. EPA. (2008b, p. 2-14). The authors cite Melbourne et al. (2007), Byers and Noonburg (2003), and Davis et al. (2000) for this information.
[1012] *Burgiel and Muir. *Invasive species, climate change and ecosystem-based adaptation: Addressing multiple drivers of global change.* (2010, p. 5)
[1013] *U.S. EPA. *Effects of Climate Change on Aquatic Invasive Species and Implications for Management and Research [EPA/600/R-08/014]*. (2008, p. 2-14)
[1014] *Burgiel and Muir. (2010, p. 4)
[1015] *Hoegh-Guldberg and Bruno. (2010, p. 1527). The authors cite Stachowicz et al. (2002) for this information.
[1016] *Burgiel and Muir. (2010, p. 4)
[1017] *Hoegh-Guldberg and Bruno. (2010, p. 1527)
[1018] *Burgiel and Muir. (2010, p. 4)
[1019] *Burgiel and Muir. (2010, p. 8)

Note: Given the multitude of invasive and non-native species in the NPLCC region and the need for a more in-depth discussion of which species are of most significant concern due to climate change, this section compiles general information on a few species. The focus groups planned for 2011 and 2012 will ultimately guide which invasive and non-native species are described in the final report.

Observed Trends

Southcentral and Southeast Alaska

In a modeling and connectivity study, Murphy et al. (2010) selected reed canary grass (*Phalaris arundinacea*) as a case study because it represents an aggressive invasive species.[1021] It is already established on the Kenai Peninsula and elsewhere, and is projected to spread along road and trail systems, and along river systems statewide.[1022] Because it clogs waterways, it can have a profound effect on riparian ecosystems.[1023] Dispersal of reed canary grass is clearly through roads and streams, although some isolated road systems are not yet impacted.[1024]

British Columbia

Information needed.

Pacific Northwest and Northwestern California

Tamarisk (*Tamarix* spp.) are estimated to occupy approximately 650,000 ha (1.6 million acres) of primarily riparian floodplain habitat in twenty-three western states.[1025] Although eight to twelve species were introduced and have been found in the west, only about four species are highly invasive.[1026] Detrimental effects documented or proposed in association with tamarisk invasion are numerous and include decreased stream flow, excessive water use, loss of native biodiversity, effects on primary consumers and food web structure, salinization issues, and changes in channel morphology.[1027]

Based on a presence database, populations of tamarisk species are prevalent in the northwestern United States, most notably east of the Cascade Mountains.[1028] Major population centers are limited to the warmest and driest environments found in the Northern Basin and Range (43% of presence grid cells), Columbia Plateau (33%), and central Snake River Plain (22%).[1029] All other ecoregions had < 2% tamarisk presence grid cells.[1030] The presence database used in this study does not represent a complete or randomized field survey, and data could be biased toward larger, accessible, and known populations of tamarisk.[1031] Currently, major population centers in

[1020] *Burgiel and Muir. (2010, p. 5)
[1021] *Murphy et al. (August 2010, p. 40)
[1022] *Murphy et al. (August 2010, p. 40)
[1023] *Murphy et al. (August 2010, p. 40). The authors cite Zedler and Kercher (1994) for this information.
[1024] *Murphy et al. (August 2010, p. 40)
[1025] *Kerns et al. (2009, p. 200). The authors cite Zavaleta (2000a) for this information.
[1026] *Kerns et al. (2009, p. 200). The authors cite Gaskin and Schaal (2002) for this information.
[1027] *Kerns et al. (2009, p. 201). The authors cite Bailey et al. (2001), Birken and Cooper (2006), DiTomaso (1998), Kennedy et al. (2005), Ladenberger et al. (2006), and Shafroth et al. (2005) for this information.
[1028] *Kerns et al. (2009, p. 206). The authors refer the reader to Fig. 1in the cited report.
[1029] *Kerns et al. (2009, p. 206-207)
[1030] *Kerns et al. (2009, p. 207)
[1031] *Kerns et al. (2009, p. 207)

Washington, Oregon, and Idaho are limited to the warmest and driest environments in the central Snake River Plain, Columbia Plateau, and Northern Basin and Range.[1032]

Oregon Sea Grant's (2008) identification guide provides information on over thirty freshwater organisms, freshwater and riparian plants, and fish that are already established or likely to become established in the Pacific Northwest:[1033]

- Freshwater organisms include nutria, feral swine, zebra and quagga mussel, Asian clam, New Zealand mudsnail, bullfrog, red-eared slider, rusty crayfish, ringed and virile crayfish, and red swamp crayfish.
- Freshwater and riparian plants include hydrilla, Brazilian elodea, milfoil, giant salvinia, didymo, yellow flag iris, reed canarygrass, purple loosestrife, and knotweed.
- Fish include Asian leaping carp, Atlantic salmon, other nonnative anadromous fish, and nonnative carp, panfish, gamefish, trout, catfish, aquarium and ornamental fish, mosquitofish, tui chub, and northern snakehead.

Future Projections

Southcentral and Southeast Alaska

As with Murphy and colleagues' other models described in previous sections, the known occurrences of reed canary grass (*P. arundinacea*) were mapped and sites were linked with SNAP climate data for June and December 2000-2009.[1034] Using this training data, Murphy and colleagues extrapolated the potential habitat for the species for three future time steps (2030–2039, 2060–2069, and 2090–2099; see Figure 26).[1035] The predictions are very conservative since they do not account for spread via water.[1036] In addition, the models do not take into account the potential spread by airplanes (terrestrial and floatplanes).[1037]

[1032] *Kerns et al. (2009, p. 200)
[1033] Wiedemer and Chan. *On the lookout for aquatic invaders: Identification guide for the Pacific Northwest.* (2008)
[1034] *Murphy et al. (August 2010, p. 40)
[1035] *Murphy et al. (August 2010, p. 40)
[1036] *Murphy et al. (August 2010, p. 40)
[1037] *Murphy et al. (August 2010, p. 40)

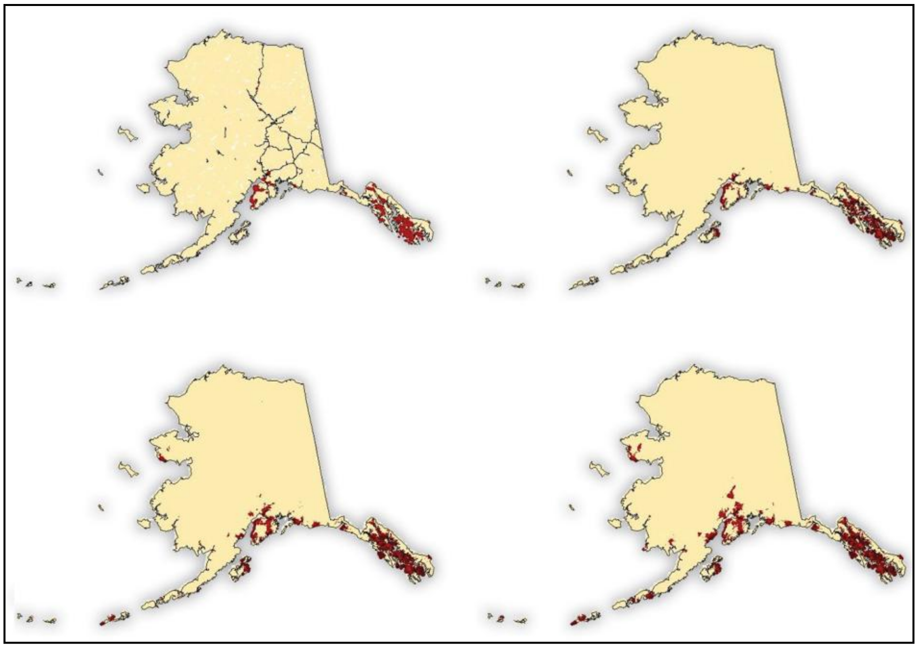

Figure 26. Potential spread of reed canary grass, using climate and all-season roads as predictors. Inclusion of waterways, proposed roads, and trails would be likely to broaden the modeled range of this invasive species. See Technical Addendum VIII in the cite report. Top left: Known occurrences and existing roads. Top right: 2030-2039. Bottom left: 2060-2069. Bottom right: 2090-2099. *Source: Reproduced from Murphy et al. (August 2010, Fig. 22, p. 41) by authors of this report.*

In addition, current and future range map scenarios were created for sixteen invasive plant species in Alaska.[1038] Twelve of these species currently inhabit, or could inhabit, southcentral and southeast Alaska (Table 12).

Table 12. Invasive plant species modeled in southcentral and southeast Alaska.
Table created by authors of this report.

• Garlic mustard (*Alliaria petiolata* (M. Bieb.) Cavara & Grande) • Leafy spurge (*Euphorbia esula* L) • Giant hogweed (*Heracleum mantegazzianum* Sommier & Levier) • Hydrilla (*Hydrilla* spp. *Rich.*, mainly *H. verticillata* (L. f.) Royle) • Ornamental jewelweed (*Impatiens glandulifera* Royle) • Purple loosestrife (*Lythrum salicaria* L.)	• Eurasian watermilfoil (*Myriophyllum spicatum* L.) • White waterlily (*Nymphaea alba* L.) • Reed canarygrass (*Phalaris arundinacea* L) • Knotweed complex (*Polygonum sachalinense* F. Schmidt ex Maxim., *P. ×bohemicum* (J. Chrtek & Chrtkovß) Zika & Jacobson [cuspidatum × sachalinense], *P. cuspidatum* Siebold & Zucc.) • Common tansy (*Tanacetum vulgare* L.) • Scentless false mayweed (*Tripleurospermum perforatum* (Mérat) M. Lainz)

Species distributions were modeled using two different predictive models (DIVA-GIS and MaxEnt), two different future climates (Hadley and CCC), two emissions scenarios (A2, high and B2, low), for current climate plus three time steps (2020, 2050, 2080). All species show an increase in range over time,

[1038] HDR. *Invasive Plant Species Response to Climate Change in Alaska: Bioclimatic models of current and predicted future changes (pdf).* (2009, p. 2) particularly aquatic species including hydrilla (*Hydrilla* spp.), Eurasian watermilfoil (*Myriophyllum spicatum* L.), and white waterlily (*Nymphaea alba* L.).[1039] Range maps across all climate scenarios and all species studied are available at http://alaska.fws.gov/fisheries/invasive/reports_maps.htm#distribution_maps (accessed 4.21.2011).

British Columbia

In British Columbia, alien warm-water fish species, such as smallmouth and largemouth bass (*Micropterus dolomieu* and *M. salmoides*) and yellow perch (*Perca flavescens*), may thrive as water temperatures increase.[1040] These species may out-compete and/or prey on cold-water native species.[1041]

Pacific Northwest

Water hyacinth in Washington is thought to be limited in its ability to become established because of the state's cold winters.[1042] As increasing temperatures warm water bodies in the region, the waters of Washington may be more suitable to water hyacinth, allowing the plant to become widely established.[1043]

Tamarisk (*Tamarix* spp.) species are shrubs or small trees considered by some to be among the most aggressively invasive and potentially detrimental exotic plants in the United States.[1044] Kerns et al. (2009) obtained distribution data for the northwest (Oregon, Washington, and Idaho), developed a habitat suitability map, and projected changes in habitat due to climate change in a smaller case study area using downscaled climate data.[1045] Key results include:

- Although considerable uncertainty exists regarding future climate change, a two- to ten-fold increase in highly suitable tamarisk habitat is projected by the end of the 21st century.[1046]
- Habitat suitability model results indicate twenty-one percent of the region supports suitable tamarisk habitat.[1047] Less than one percent of these areas are occupied by tamarisk; the remainder is highly vulnerable to invasion.[1048]

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here.

[1039] *HDR. (2009, p. 2)
[1040] *Austin et al. (2008, p. 192). The authors cite Compass Resource Management (2007) for information on major climate impacts in B.C.
[1041] *Austin et al. (2008, p. 192)
[1042] *U. S. EPA. (2008b, p. C-25). The authors cite Washington Department of Fish and Wildlife (2001) for this information.
[1043] *U. S. EPA. (2008b, p. C-25)
[1044] *Kerns et al. *Modeling Tamarisk (Tamarix* spp.*) habitat and climate change effects in the northwestern United States.* (2009, p. 200)
[1045] *Kerns et al. (2009, p. 200)
[1046] *Kerns et al. (2009, p. 200)
[1047] *Kerns et al. (2009, p. 200)
[1048] *Kerns et al. (2009, p. 200)

VI. IMPLICATIONS FOR KEY FISH, AMPHIBIANS, AND MACROINVERTEBRATES

The combination of increased temperatures and decreased late-summer base flows (low flows) could increase the stress for fish and other aquatic biota in the future.[1049] Low flows can cause a reduction in habitat availability, food production, and water quality, and can heighten the effects of ice on smaller streams during the winter time.[1050] For example, the drying of streams into isolated pools crowds organisms and results in reduced dissolved oxygen levels.[1051] Stream and river biological fish indicators will respond to climate change influences on water temperature and hydrologic regime in a number of ways, as summarized in Table 16.

Based on a search of the scientific and grey literature, sufficient information is available to discuss observed trends and future projections in the NPLCC region for:

1. Pacific lamprey
2. Pacific salmon
3. Amphibians
4. Macroinvertebrates

The following structure will be used to present information on the implications of climate change for fish, amphibians, and macroinvertebrates in the NPLCC region:

- **Observed Trends –** observed changes for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California.
- **Future Projections –** projected direction and/or magnitude of change for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California.
- **Information Gaps –** information and research needs identified by reviewers and literature searches.

[1049] *Pike et al. (2010, p. 730)
[1050] *Pike et al. (2010, p. 730). The authors cite Bradford and Heinonen (2008) for this information.
[1051] *Poff, Brinson and Day. (2002, p. 12)

1. PACIFIC LAMPREY (*LAMPETRA TRIDENTATA*)

Pacific lamprey co-occur with Pacific salmon and they have a similar life cycle to Pacific salmon (i.e., anadromy, living in both salt and freshwater, and semelparity, reproducing once in a lifetime).[1052] After ceasing their parasitic stage in the ocean, Pacific lamprey return to freshwater during the spring (April–June), and then begin their initial upstream migration during the summer (July–September), before overwintering during October–March.[1053] Like other anadromous lampreys, Pacific lamprey do not feed during this prolonged freshwater residency and somatic energy reserves fuel sexual maturation.[1054] As a result, Pacific lamprey shrink in body size prior to maturing, spawning, and then dying the following spring (April–July).[1055]

This section focuses on climate change impacts during the freshwater phase of lamprey life history. For information on climate change impacts in the marine phase of their life history, please see the companion report *Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature (Phase 1 Draft Final Report).*

Observed Trends

<u>Regional</u>

In recent decades, anadromous Pacific lampreys along the west coast of North America, have experienced broad-based population declines and regional extirpations.[1056] These declines parallel those of Pacific salmonids (*Oncorhynchus* spp.), perhaps because the two groups share widely sympatric (i.e. occurring in the same or overlapping geographic areas) distributions and similar anadromous life histories.[1057]

<u>Southcentral and Southeast Alaska</u>

Information needed.

<u>British Columbia</u>

Information needed.

[1052] *Clemens et al. *Do summer temperatures trigger spring maturation in Pacific lamprety, Entosphenus tridentatus.* (2009, p. 418)
[1053] *Clemens et al. (2009, p. 418). The authors cite Beamish (1980) for information on spring, and Scott and Crossman (1973) for information on summer and overwintering.
[1054] *Clemens et al. (2009, p. 418). The authors cite Kott (1971), Beamish et al. (1979), and Larsen (1980) for information on other anadromous lamprey; Beamish (1980) and Whyte et al. (1993) for information on feeding during freshwater residency; and, Kott (1971), Beamish et al. (1979), and Larsen (1980) for information on somatic energy reserves fueling sexual maturation.
[1055] *Clemens et al. (2009, p. 418). The authors cite Beamish (1980) and Whyte et al. (1993) for information on shrinking in body size, and Beamish (1980) and Pletcher (1963, as cited in Scott & Crossman, 1973) for information on maturing, spawning, and dying in spring.
[1056] *Keefer et al. *Variability in migration timing of adult Pacific lamprety (Lampetra tridentata) in the Columbia River, U.S.A.* (2009, p. 254). The authors cite Beamish and Northcote (1989), Kostow (2002), and Moser and Close (2003) for this information.
[1057] *Keefer et al. (2009, p. 254). The authors cite Scott and Crossman (1973), Simpson and Wallace (1978), and Moyle (2002) for information on sympatric distributions, and McDowall (2001) and Quinn and Myers (2004) for information on Anadromous life histories.

Washington and Oregon

At the Bonneville Dam, Keefer et al. (2009) found that lamprey run timing shifted progressively earlier from 1939 to 2007, coincident with decreasing Columbia River discharge and increasing water temperature.[1058] In a 41-year time series of adult lamprey counts in the Columbia River, migration timing was earliest in warm, low-discharge years and latest in cold, highflow years.[1059] However, as one reviewer noted, this may be an example of behavioral adaptation to climatic change, not simply vulnerability to negative impacts.[1060] Key findings include:

- Threshold temperatures associated with run timing were similar throughout the dataset despite significant impoundment-related warming, suggesting that temperature-dependent migration cues have been temporally stable.[1061]
- In both historical (1939–1969) and recent (1998–2007) periods, very few lampreys passed Bonneville Dam before water temperatures reached 59°F (15°C) and the midpoint of the run typically passed by about 66°F (~19°C).[1062]

A lamprey passage study by Vella et al. (1999a and 1999b) revealed that up to eighty percent of radio-tagged lamprey failed to pass Bonneville Dam.[1063] The cause for this apparent passage failure has yet to be determined, and potential reasons could be behavioral disorientation, swim performance limitations, physiological stress or exhaustion, depletion of energy reserves, thermal stress, or a combination of any of these factors.[1064]

In a laboratory study of stream temperature and maturation in Pacific lamprey (*Entosphenus tridentatus*) collected from the Willamette River near Oregon City (OR), Clemens et al. (2009) hypothesize that warm, summer temperatures (>68°F, 20°C) would accentuate shrinkage in body size, and expedite sexual maturation and subsequent death.[1065] The results confirmed predictions:

- Lamprey from a warm water group (68-75.2°F, 20-24°C; mean 71.2°F, 21.8°C) showed significantly greater proportional decreases in body weight following the summer temperature treatments than fish from a cool water group (56.5°F, 13.6°C).[1066]
- A greater proportion of warm water fish sexually matured (100%) and died (97%) the following spring than cool water fish (53% sexually mature, 61% died).[1067]
- Females tended to mature and die earlier than males, most obviously in the warm water group.[1068]

[1058] *Keefer et al. (2009, p. 258)
[1059] *Keefer et al. (2009, p. 253)
[1060] Comment from Reviewer (June 2011).
[1061] *Keefer et al. (2009, p. 253)
[1062] *Keefer et al. (2009, p. 261)
[1063] *ISAB. *Climate change impacts on Columbia River Basin Fish and Wildlife (pdf).* (2007, p. 47). The authors cite Vella et al. (1999a, 1999b) for this information.
[1064] *ISAB. (2007, p. 47)
[1065] *Clemens et al. (2009, p. 418)
[1066] *Clemens et al. (2009, p. 418)
[1067] *Clemens et al. (2009, p. 418)
[1068] *Clemens et al. (2009, p. 418)

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Future projections for Pacific lamprey are needed. Additional studies throughout the NPLCC region are needed to supplement the information on observed trends presented here. Research on the freshwater life stages of anadromous Pacific lamprey, including projected effects of climate change, is especially needed.

2. PACIFIC SALMON (*ONCORHYNCHUS* SPP.)

Pacific salmon have complex life histories that span diverse environments across the Pacific Rim.[1069] Pacific salmon as a group occupy habitats that range from the Beaufort Sea where they occur in relatively small numbers to San Francisco Bay where they are nearly extirpated.[1070] They spawn in fall in fresh water and their embryos incubate in the gravel during the winter and emerge in spring.[1071] Juveniles then spend days to years in habitats ranging from small creeks to large rivers, and small ponds to large lakes.[1072] Most juveniles then migrate downriver, through estuaries and coastal waters, to the ocean.[1073] These "anadromous" individuals spend anywhere from a few months to as much as seven years at sea, before migrating back to spawn and die at their natal sites in fresh water.[1074] This great diversity of environments and behaviors suggests that climate change could influence selection on multiple traits in multiple phases of the life cycle.[1075]

The primary climate change impacts on anadromous fishes in the freshwater phase of their life history are increased water temperature and altered streamflow (Figure 27); for information on climate change impacts in the marine phase of their life history, please see the companion report *Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature (Phase 1 Draft Final Report).*

Water temperatures fundamentally affect the health and distribution of salmon and steelhead.[1076] An increase of even a few degrees above optimum range can change migration timing, reduce growth rates, reduce available oxygen, and increase susceptibility to toxins, parasites, predators, and disease (Box 19).[1077]

Streamflow changes due to global warming will have large effects on salmon, especially coupled with warmer temperatures.[1078] Reduced summer flows exacerbate warmer temperatures and make it even more difficult for adult salmon to pass obstacles in their struggle to reach their natal spawning grounds.[1079] In extreme cases, low flows will stop fish short of their spawning grounds.[1080] Excessively high flows in winter, due to rapid melting or increased rainfall, can cause "scouring" events that wash away the gravel beds salmon use as nesting sites.[1081] And once spawning occurs, reduced flows can dewater nests, exposing eggs to the elements.[1082]

1069 *Crozier et al. *Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon.* (2008, p. 253). The authors cite Groot and Margolis (1991) and Quinn (2005) for this information.
1070 *Bryant. (2009, p. 184). The author cites Craig and Haldorson (1986), Nehlson (1997), and Groot and Margolis (1991) for this information.
1071 *Crozier et al. (2008, p. 253)
1072 *Crozier et al. (2008, p. 253-254)
1073 *Crozier et al. (2008, p. 254)
1074 *Crozier et al. (2008, p. 254)
1075 *Crozier et al. (2008, p. 254)
1076 *Martin and Glick. *A great wave rising: solutions for Columbia and Snake River salmon in the age of global warming.* (2008, p. 13)
1077 *Martin and Glick. (2008, p. 13). The authors cite Poole et al. (2001) for this information.
1078 *Martin and Glick. (2008, p. 14)
1079 *Martin and Glick. (2008, p. 14)
1080 *Martin and Glick. (2008, p. 14)
1081 *Martin and Glick. (2008, p. 14). The authors cite Spence et al. (1996) for this information.
1082 *Martin and Glick. (2008, p. 14)

Box 19. Thresholds & Salmon.

Threshold crossings occur when changes in a system exceed the adaptive capacity of the system to adjust to change. Environmental managers have a pressing need for information about ecosystem thresholds because of the potentially high-stakes consequences of exceeding them, which may limit future management actions, force policy choices, and in some circumstances be non-reversible. Effects of crossing climate change-related thresholds might include extirpation or extinction of species or expansion of nonnative invasive species. Maximum weekly temperature thresholds and ranges for salmon species (based on the EPA's 2007 guidance for all salmon species) include:

- 55.4 to 58.1°F (13-14.5°C) is the range for spawning, rearing, and migration
- 59.9 to 67.1°F (15.5-19.5°C) is the range for elevated disease risk in adults
- 68.9 to 70.7°F (20.5-21.5°C) is the threshold for adult lethality
- Greater than 70.7°F (21.5°C) is the threshold for juvenile lethality

Sources: Baron et al. (2009); Groffman et al. (2006); Mantua et al. (2010); U.S. Climate Change Science Program (2009).

Observed Trends

Southcentral and Southeast Alaska

Please see Chapter IV Section 1 for information on salmon in this region.

British Columbia and Washington

Natural origin abundance of most Evolutionarily Significant Units/Distinct Population Segments (ESUs/DPSs) has increased since the original status reviews in the mid-1990s, but declined since the time of the last status review in 2005.[1083] Crossin et al. (2008) tested the hypothesis that exposure of sockeye to higher temperatures, ~64°F (18°C) and above, reduces migration success compared with that of sockeye exposed to a lower temperature.[1084] Late-run sockeye from the Weaver Creek (BC) population were caught en route to spawning grounds and were experimentally exposed to temperatures that have commonly been encountered by early migrants (~64°F, 18°C) and to temperatures historically encountered by normal-timed fish (50°F, 10°C).[1085] These temperatures also bracket the optimal temperature for swimming performance (57-59°F, 14-15°C) for this population.[1086] The holding temperature also spanned a threshold for *Parvicapsula minibicornis* infection (a kidney parasite implicated in the mortality of early-migrating Fraser River sockeye salmon).[1087] The temperature experienced during treatment had a significant effect on survival:

- Thirty-one fish (62%) survived at 50°F (10°C; 15 females and 16 males) and,

[1083] *Ford. *Status review update for Pacific salmon and steelhead listed under the Endangered Species Act: Northwest. Draft.* (2010, p. 5)
[1084] *Crossin et al. *Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration.* (2008, p. 128)
[1085] *Crossin et al. (2008, p. 128). The authors cite Patterson et al. (2007) for information on normal-timed fish.
[1086] *Crossin et al. (2008, p. 128). The authors cite Lee et al. (2003) for this information.
[1087] *Crossin et al. (2008, p. 128). The authors cite Wagner et al. (2005) for this information.

- Seventeen fish (34%) at ~64°F (18°C; 8 females and nine males).[1088]

The expression of *P. minibicornis* in moribund fish (dead < 2 hours) was temperature-dependent:[1089]

- The kidneys of ~64°F-treated fish (18°C ; N=14) had significantly higher levels of *P. minibicornis* than 50°F-treated fish (10°C; N=13, P = 0.002).[1090]
- The infection scores were maximal (25) in seven of the fourteen fish that were exposed to ~64°F (18°C) and that had accrued more than 350 degree days (i.e., the cumulative freshwater temperature experienced by the fish; ~400 degree days is the cumulative temperature threshold for full expression of *P. minibicornis*), whereas none of the 50°F (10°C) fish showed histological evidence of infection.[1091]

Exposure to high but sublethal temperatures had a negative effect on migratory performance and survival in both sexes after their release back into the Fraser River:[1092]

- Eight of thirteen (62%) of control salmon and twenty-one of thirty-one (68%) of 50°F (10°C) salmon reached spawning areas.[1093]
- The ~64°F (18°C) fish were half as successful (6 of 17; 35%).[1094]
- The only physiological difference between treatments was a change in gill Na^+, K^+-ATPase activity.[1095] This drop correlated negatively with travel times for the ~64°F-treated males (18°C).[1096]
- Reproductive-hormone levels and stress measures did not differ between treatments but showed significant correlations with individual travel times.[1097]

In an earlier study of temperature and flow effects on salmon in the Fraser River watershed, Morrison, Quick and Foreman (2002) concluded:

- Water temperatures between 71.6 and 75.2°F (22-24°C) over a period of several days can be fatal for salmon.[1098]
- Temperatures over 75.2°F (24°C) can cause death within a few hours.[1099]
- Even water temperatures as low as 68°F (20°C) can have an adverse effect on spawning success rates.[1100]
- On the migration route back to the spawning beds the [sockeye] salmon are sensitive to the river water temperatures and there is a strong correlation between pre-spawning mortality and high river temperature.[1101]

[1088] *Crossin et al. (2008, p. 131)
[1089] *Crossin et al. (2008, p. 131)
[1090] *Crossin et al. (2008, p. 131)
[1091] *Crossin et al. (2008, p. 131)
[1092] *Crossin et al. (2008, p. 133)
[1093] *Crossin et al. (2008, p. 127)
[1094] *Crossin et al. (2008, p. 127)
[1095] *Crossin et al. (2008, p. 127)
[1096] *Crossin et al. (2008, p. 127)
[1097] *Crossin et al. (2008, p. 127)
[1098] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Servizi and Jansen (1977) for this information.
[1099] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Bouke et al. (1975) for this information.
[1100] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Gilhousen (1990) for this information.

Alternatively, in regions or specific water bodies where temperatures are below thermal optima for fish or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival.[1102] Even minor temperature increments can change egg hatch dates and increase seasonal growth and instream survival in juvenile salmon.[1103] At Carnation Creek on the west coast of Vancouver Island, minor changes in stream temperatures in the fall and winter due to forest harvesting profoundly affected salmonid populations, accelerating egg and alevin development rates, emergence timing, seasonal growth, and the timing of seaward migration.[1104]

Mantua et al. (2010) report upper thermal tolerance of cutthroat and rainbow trout, and pink, chum, coho, and Chinook salmon (Table 13).

Table 13. Maximum weekly temperature upper thermal tolerances for salmonids

Species	*Upper thermal tolerances (°F with °C in parentheses)*
Cutthroat trout (*Oncorhynchus clarki*)	73.9 (23.3)
Rainbow trout (steelhead; *O. mykiss*)	75.2 (24.0)
Chum salmon (*O. keta*)	67.6 (19.8)
Pink salmon (*O. gorbuscha*)	69.8 (21)
Coho salmon (*O. kisutch*)	74.1 (23.4)
Chinook salmon (*O. tshawytscha*)	75.2 (24)

Based on the 95th percentile of maximum weekly mean temperatures where fish presence was observed (Eaton and Scheller, 1996) *Source: Reproduced from Mantua, Tohver, and Hamlet. (2010, Table 2, p. 194) by authors of this report.*

Oregon and Northwestern California

The Klamath River and its tributaries support populations of anadromous fish species with economic, ecological, and cultural importance.[1105] Coho salmon (*Oncorhynchus kisutch*, Southern Oregon/Northern California Coasts Evolutionarily Significant Unit) are listed as threatened under the U.S. Endangered Species Act.[1106] In addition, steelhead trout (*Oncorhynchus mykiss*) and Chinook salmon (*Oncorhynchus tshawytscha*) in the lower Klamath Basin are of special concern.[1107] Habitat degradation, over-exploitation, and reductions in water quality and quantity have been implicated in declines of these species.[1108] In particular, low late-summer and early fall streamflow in several tributaries is a major factor limiting survival of juvenile coho salmon.[1109] Increasing late-summer tributary flow is a major objective

[1101] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Gilhousen (1990), Rand and Hinch (1998), and Williams (2000) for this information.
[1102] *Pike et al. (2010, p. 730)
[1103] *Pike et al. (2010, p. 730)
[1104] *Pike et al. (2010, p. 730). The authors cite Tschaplinksi et al. (2004) for this information.
[1105] *Van Kirk and Naman. (2008, p. 1036)
[1106] *Van Kirk and Naman. (2008, p. 1036). The authors cite Good et al. (2005) for this information.
[1107] *Van Kirk and Naman. (2008, p. 1036-1037). The authors cite Nehlsen et al. (1991) for this information.
[1108] *Van Kirk and Naman. (2008, p. 1037). The authors cite Nehlsen et al. (1991), Brown et al. (1994), and Good et al. (2005) for this information.
[1109] *Van Kirk and Naman. (2008, p. 1037). The authors cite NRC (2003) and CDFG (2004) for this information.

of coho salmon recovery efforts, particularly in the Scott River (CA), the most important coho salmon spawning and rearing stream in the basin.[1110]

Future Projections

Southcentral and Southeast Alaska

Southeast Alaska supports a diverse set of salmonids that depend on freshwater ecosystems.[1111] The five Pacific salmon include pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), coho (*O. kisutch*), sockeye (*O. nerka*), and chinook (*O. tshawytscha*) salmon.[1112] Life history strategies of anadromous salmonids in Alaska separate into two groups on the basis of how they use the freshwater environment; general patterns are shown in Figure 27.[1113] Extreme variation occurs within the group, however, and these variations are significant in as much as they illustrate the plasticity of salmonids to adapt to a range of environmental conditions and may be important in an environment of rapidly changing climatic conditions.[1114]

Pacific salmon as a group occupy habitats that range from the Beaufort Sea where they occur in relatively small numbers to San Francisco Bay where they are nearly extirpated.[1115] Furthermore, they have been introduced to diverse geographic locations in both the northern and southern hemispheres.[1116] They readily exploit new habitats opened with fish ladders and major changes in watersheds.[1117] These characteristics suggest that Pacific salmon in southeast Alaska may be fairly resilient in the face of global temperature increases.[1118] If the temperatures in southeast Alaska increase by 3.6 to 7.2°F (2–4°C), then the climate might be similar to that in southern British Columbia or Washington State.[1119] Both locations have climates that are generally favorable to Pacific salmon and have or had robust salmon stocks.[1120] As noted earlier in this report, Alaska-wide average annual air temperature is projected to increase 5-13°F (2.8-7.2°C) after 2050.[1121]

In southcentral Alaska, several major systems of lakes support large runs of sockeye salmon and include the Kenai, Tustamena and Skilak lakes, all glacially influenced.[1122] Climate-induced increases in glacial runoff into these lakes in summer could cause concomitant increases in turbidity and reductions in primary productivity.[1123] The offsetting effects of a shorter period of ice cover and warmer water

[1110] *Van Kirk and Naman. (2008, p. 1037). The authors cite Brown et al. (1994), NRC (2003), and CDFG (2004) for this information.
[1111] *Bryant. *Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska.* (2009, p. 170).
[1112] *Bryant. (2009, p. 170)
[1113] *Bryant. (2009, p. 170). The author cites Groot and Margolis (1991) for this information.
[1114] *Bryant. (2009, p. 171)
[1115] *Bryant. (2009, p. 184). The author cites Craig and Haldorson (1986), Nehlson (1997), and Groot and Margolis (1991) for this information.
[1116] *Bryant. (2009, p. 184). The author cites Quinn et al. (2001) and Hansen and Holey (2002) for this information.
[1117] *Bryant. (2009, p. 184). The author cites Hendry et al. (1998, 2000) and Bryant et al. (1999) for this information.
[1118] *Bryant. (2009, p. 184)
[1119] *Bryant. (2009, p. 184)
[1120] *Bryant. (2009, p. 184)
[1121] *US-GCRP. (2009, p. 139)
[1122] *Melack et al. (1997, p. 986)
[1123] *Melack et al. (1997, p. 986)

temperatures could enhance zooplankton and salmon fry growth.[1124] With increasing latitude, overwintering mortality becomes a significant factor in the production of salmonids.[1125] Consequently, a reduction in the length of ice cover in streams may enhance overwintering survival.[1126]

However, many of the predicted outcomes from scenarios for climate change are not favorable for anadromous salmonids.[1127] For example, increased winter flows and spring peaks may reduce salmonid egg to fry survival, particularly if the cumulative effects of altered land use are considered, e.g. increased erosion and runoff.[1128] Higher spring peaks in flow and warmer water temperatures may cause earlier emergence of fry and migration of pink and chum salmon fry to estuaries at a time when their food sources have not developed adequately.[1129] Lower summer flow may reduce the amount of suitable spawning and rearing habitat.[1130]

Bryant (2009) summarizes potential effects of climate change on anadromous salmonids in freshwater habitats of southeast Alaska (Table 14). The three major climate change variables are temperature, precipitation (hydrology), and sea level.[1131]

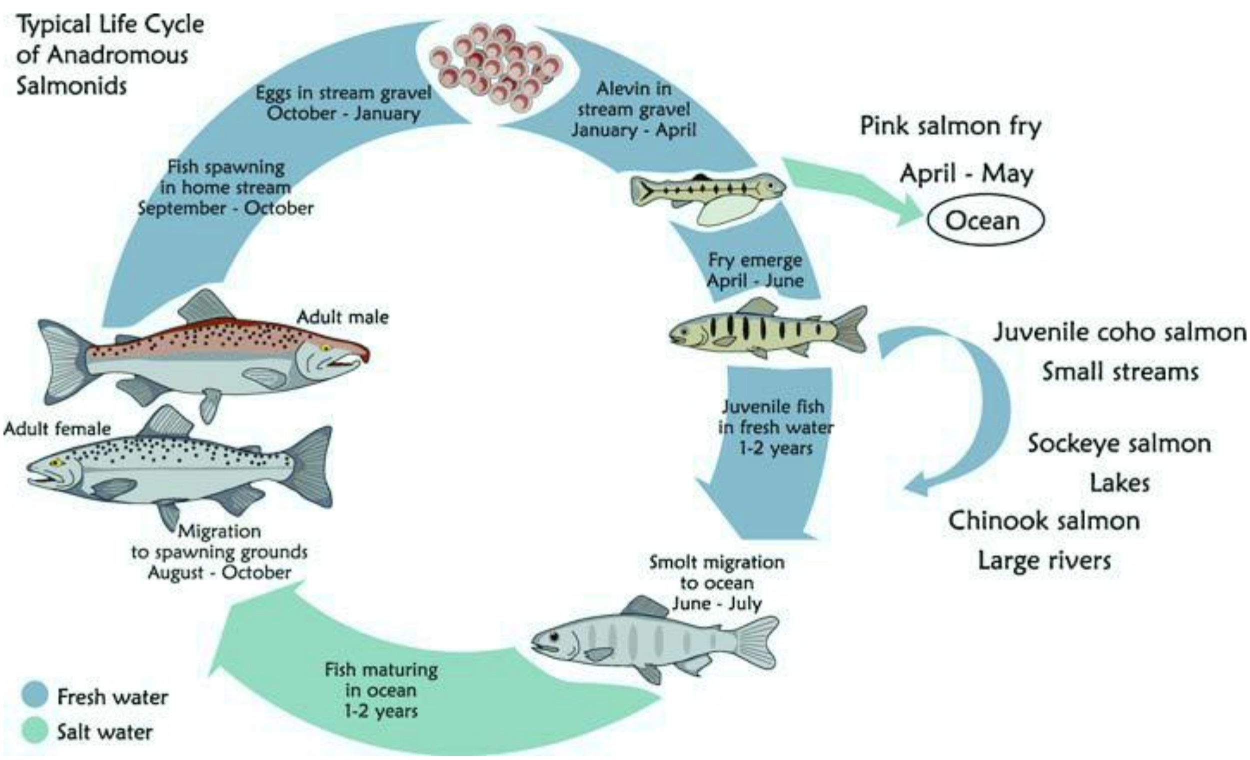

Figure 27. Life cycle strategies of the five species of salmon (*Oncorhynchus*) found in southeast Alaska with those that rear in freshwater and those that migrate directly to the ocean.
Source: Reproduced from Bryant (2009, Fig. 1, p. 171) by authors of this report.

[1124] *Melack et al. (1997, p. 986)
[1125] *Melack et al. (1997, p. 987)
[1126] *Melack et al. (1997, p. 987)
[1127] *Bryant. (2009, p. 182)
[1128] *Melack et al. (1997, p. 987)
[1129] *Melack et al. (1997, p. 987)
[1130] *Melack et al. (1997, p. 987)
[1131] *Bryant. (2009, p. 172)

Table 14. Summary of potential effects of climate change on anadromous salmonids in freshwater habitats of southeast Alaska.
Source: Reproduced from Bryant. (2009, Table 1, p. 183) by authors of this report.

Pink salmon and chum salmon

- Increased frequency and extent of pre-spawner mortality resulting from increasing temperatures and decreasing summer flows
- Earlier emergence time and entry into the marine environment with less favorable conditions for early feeding and growth
- Deterioration of spawning habitats
    - Greater upslope landslide activity increasing scour and sediment infiltration
    - Incursion of saltwater from rising sea levels into spawning areas
    - Alterations in sediment dynamics with changes in sea level
- Alterations in run timing as a result of shifts in temperature and discharge

Sockeye salmon

- Shifts in spawning time with subsequent changes in time of emergence of fry
- Spawning habitat deterioration from upslope landslides induced by increased rainfall intensity
- Changes in growth and survival resulting from alteration of trophic status of lakes
    - Shifts in zooplankton availability
    - Changes in lake physical and chemical dynamics resulting from either increases or decreases in water recharge
    - Decreasing rearing capacity and secondary production from saltwater intrusion
- Increased predation as thermal characteristics become more favorable for natural or introduced predators

Chinook salmon

- Changes in run timing forced by temperature and/or discharge regimes
- Increased stress and mortality during spawning migration resulting from loss of thermal refuges in large pools
- Deterioration of spawning habitat caused by increased frequency of upslope landslides
- Loss of rearing habitat as thermal refuges are lost

Coho salmon

- Deterioration of spawning habitat from landslides that scour spawning beds and deposit sediment on downstream spawning areas
- Changes in fry emergence timing and emigration
- Effects of climate change induced temperatures on growth and survival of juvenile coho salmon
    - Increased growth as temperatures in streams increase above 50°F (10°C) but remain below 64°F (~18°C)
    - Decreased survival as metabolic demands increase but food supplies become limited
- Loss of rearing habitats
    - Decrease in summer rearing habitats as flow decreases and pool abundance and quality decrease
    - Deterioration of off-channel habitats as temperatures exceed optimum ranges
    - Loss of off-channel habitats through more frequent high intensity rainfall events that remove instream structure and beaver dams during fall and winter
    - Intrusion of salt water into low elevation rearing areas

British Columbia

In regions or specific water bodies where temperatures are below thermal optima for fishes or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival.[1132] For example, even minor temperature increments can change egg hatch dates and increase seasonal growth and instream survival in juvenile salmon.[1133] However, trends toward decreased autumn and increased winter precipitation on the coast can lead to increased stress, followed by winter flooding and stream erosion with negative consequences for survival.[1134] An increase in annual precipitation without an increase in summer precipitation offers little benefit to species that need moisture during the hot, dry season, and summer precipitation is indeed projected to decrease.[1135]

Additional impacts to salmon in British Columbia are summarized in Table 15 and Figure 29.

Table 15. Species and life stage-specific summary of *potential* biological vulnerabilities of salmon to climate-induced changes in water flows and temperatures *Linkages among climate drivers, physical changes in freshwater habitats, and biological mechanisms are summarized in Figure 29* on page 143.
Source: Reproduced from Nelitz et al. (2007, Table 2, p. 17) by authors of this report.

Type	Eggs	Fry	Parr	Smolts	Spawners
Chinook, Coho, and Sockeye	• Scour • Stranding • Change in hatch timing • Change in sex ratio of eggs	• Change in growth rates • Thermal mortality • Oxygen stress • Change in prey density • Change in competition	• Change in growth rates • Thermal mortality • Oxygen stress • Change in prey density • Change in competition	• Increased predation and competition • Change in growth rates • Oxygen stress • Delayed outmigration • Change in age of outmigration • Change in physiological function	• Change in run timing • Increased incidence of disease • Thermal mortality • Bioenergetic stress • Increased predation
Chum and Pink	• Scour • Stranding • Change in hatch timing • Change in sex ratio of eggs				• Change in run timing • Increased incidence of disease • Thermal mortality • Bioenergetic stress • Increased predation

1132 *Pike et al. (2010, p. 730)
1133 *Pike et al. (2010, p. 730)
1134 *Austin et al. (2008, p. 184)
1135 *Austin et al. (2008, p. 184). The authors cite Pacific Climate Impacts Consortium (PCIC, no date) Climate Overview for this information.

Washington and Oregon

Mantua, Tohver, and Hamlet (2010) state that stream temperature modeling predicts significant increases in water temperatures and thermal stress for salmon statewide for both A1B and B1 emissions scenarios.[1136] For the fifty-five western Washington stations included in the study, Mantua, Tohver, and Hamlet project:

- At seventy-one percent of stations, estimated weekly maximum stream temperature (T_w) is projected to be less than 67.1°F (T_w < 19.5°C) for the 2080s, compared to eighty-seven percent of streams in the 1980s (an estimated sixteen percent decline).[1137]
- A prolonged duration of water temperatures unfavorable for salmon is predicted for the Lake Washington/Lake Union ship canal, where T_w > 69.8°F (T_w > 21°C) persisted up to ten weeks in the late 1980s.[1138]
- The expansion of the T_w > 69.8°F (T_w > 21°C) season is predicted to increase considerably for the warmer streams in western Washington like the Stillaguamish River at Arlington, where in recent years these conditions were observed zero to at most a few weeks each summer.[1139] For this station the period with T_w > 69.8°F (T_w > 21°C) lasts up to thirteen weeks by 2100 and is centered on the first week of August.[1140]

Additional impacts on salmonid species due to climate change include impacts on spawning, migration, egg incubation, and stream rearing (see also, Figure 28):

- **Spawning and migration**
  - Reductions in the volume of summer/fall low flows in transient and rainfall-dominated basins might also reduce the availability of spawning habitat for salmon populations that spawn early in the fall.[1141] In combination with increased summertime stream temperatures, reduced summertime flow is likely to increase mortality rates during spawning migrations for summer-run adults.[1142]
  - Reductions in springtime snowmelt may negatively impact the success of smolt migrations from snowmelt dominant streams where seaward migration timing has evolved to match the timing of peak snowmelt flows.[1143]
  - In the absence of thermal cues for initiating spawning migrations, temperature impacts on adult spawning migrations are projected to be most severe for stocks having summertime migrations.[1144] These include summer-run steelhead, sockeye and Chinook salmon populations in the Columbia Basin, and sockeye and Chinook salmon in the Lake Washington system.[1145]

[1136] *Mantua, Tohver and Hamlet. *Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State*. (2010, p. 196)
[1137] *Mantua, Tohver and Hamlet. (2010, p. 199)
[1138] *Mantua, Tohver and Hamlet. (2010, p. 199)
[1139] *Mantua, Tohver and Hamlet. (2010, p. 199, 201)
[1140] *Mantua, Tohver and Hamlet. (2010, p. 201)
[1141] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1142] *Mantua, Tohver and Hamlet. (2010, p. 209-210)
[1143] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1144] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1145] *Mantua, Tohver and Hamlet. (2010, p. 207)

- **Egg incubation and stream rearing, including survival rates**
  - Predicted increases in the intensity and frequency of winter flooding in Washington's transient runoff basins will negatively impact the egg-to-fry survival rates for pink, chum, sockeye, Chinook, and Coho salmon due to an increased intensity and frequency of redd and egg scouring.[1146] However, the impact of increasing winter flooding will likely vary across species or populations because redd depth is a function of fish size (deeper redds will be less vulnerable to scouring and the deposition of fine sediments). [1147]
  - Parr-to-smolt survival rates will likely be reduced for Coho and stream-type Chinook salmon and steelhead because increases in peak flows reduce the availability of slow-water habitats and cause increases in the displacement of rearing juveniles downstream of preferred habitats.[1148]
  - In combination with increased summertime stream temperatures, reduced summertime flow is likely to limit rearing habitat for salmon with stream-type life histories (wherein juveniles rear in freshwater for one or more years) (Figure 28).[1149] For example, increased stream temperatures pose risks to the quality and quantity of favorable rearing habitat for stream-type Chinook and coho salmon and steelhead (summer and winter run) throughout Washington because these stocks spend at least one summer (and for Washington's steelhead typically two summers) rearing in freshwater.[1150]

As mentioned previously, excessively high flows in winter, due to rapid melting or increased rainfall, can cause "scouring" events that wash away the gravel beds salmon use as nesting sites.[1151] This is likely to be a particular problem in transient snowmelt/rainfall basins in western Washington and Oregon that experience increased fall/winter flooding[1152] and in river reaches where channel connection to the floodplain is compromised, reducing availability of winter refugia from high flows.

Northwestern California

Information needed.

Information Gaps

Information is needed on observed trends particular to southcentral and southeast Alaska. Information is also needed for future projections throughout the NPLCC region. For example, information is needed to understand the genetic adaptation and phenotypic plasticity of salmonids in response to climate change, and the consequences for abundance, distribution, and survival.

[1146] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1147] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1148] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1149] *Mantua, Tohver and Hamlet. (2010, p. 209-210)
[1150] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1151] *Martin and Glick. (2008, p. 14). The authors cite Spence et al. (1996) for this information.
[1152] *Martin and Glick. (2008, p. 14). The authors cite Battin et al. (2007) for this information.

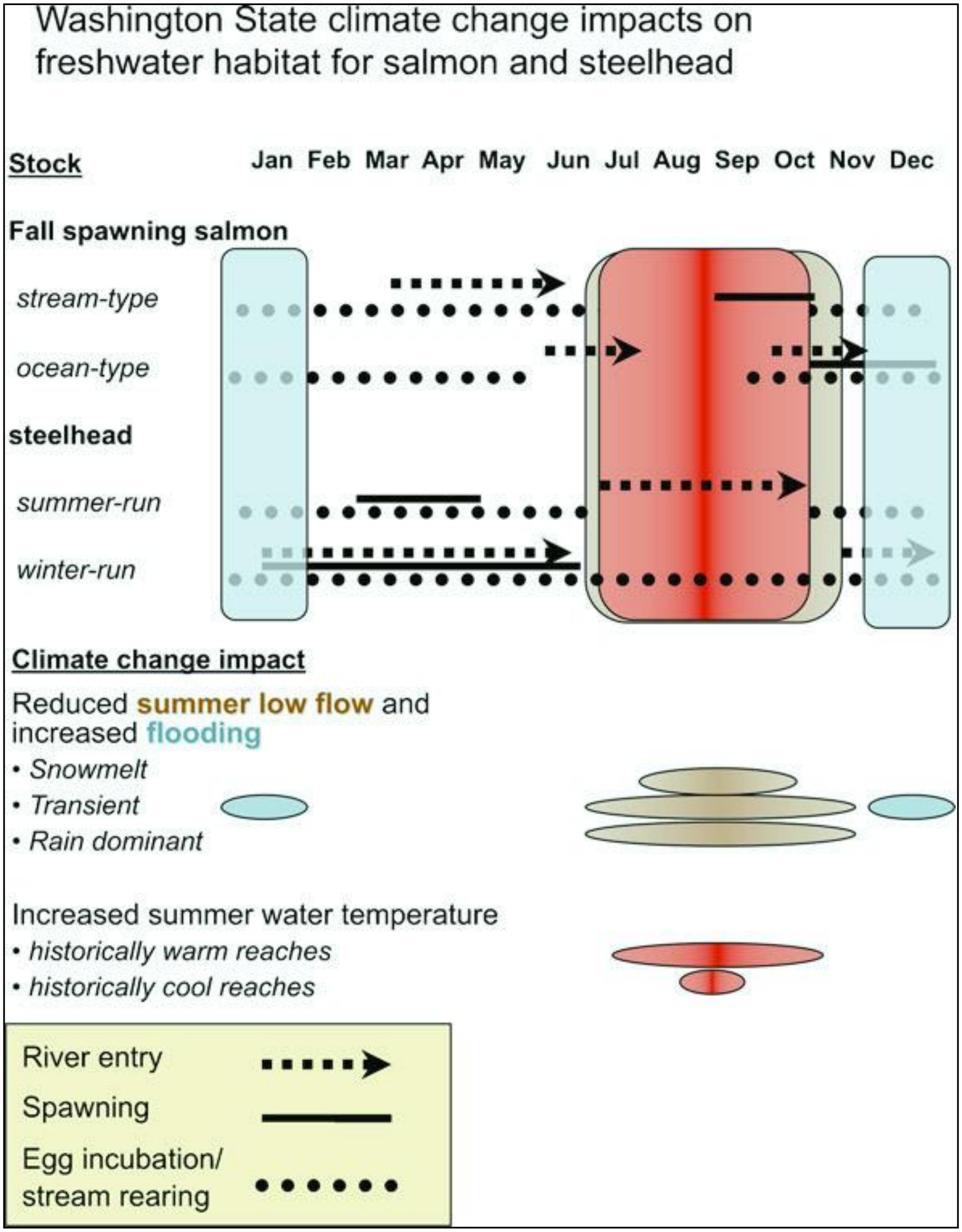

Figure 28. Summary of key climate change impacts on Washington's freshwater habitat for salmon and steelhead, how those impacts differ for streams with different hydrologic characteristics, and how the timing for different impacts compare with the life history for generalized salmon and steelhead life history types. Example life history stages are shown for adult river entry (*broken arrows*), spawning (*solid lines*), and egg incubation and rearing periods (*dotted lines*) for generalized stocks. *Tan shading* highlights periods of increased flooding, *brown shading* indicates periods with reduced summer/fall low flows, and *red shading* indicates periods with increased thermal stress *Source: Reproduced from Mantua, Tohver and Hamlet. (2010, Fig. 11, p. 208) by authors of this report.*

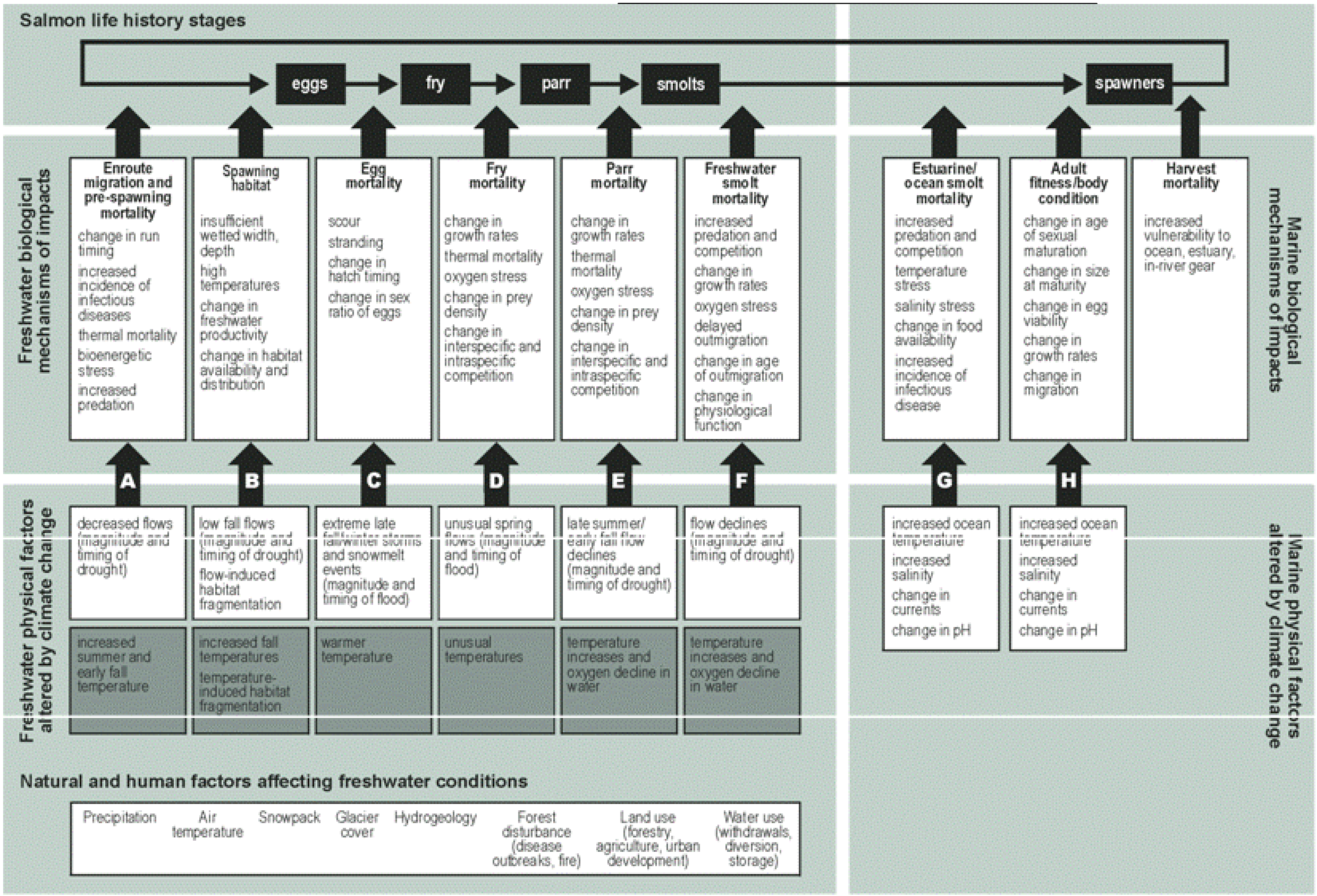

Figure 29. Conceptual diagram illustrating linkages among freshwater physical habitat factors altered by climate change (e.g., water flows and temperatures), freshwater biological mechanisms affecting survival, and life stages of salmon. *Source: Reproduced from Nelitz et al. (2007, Fig. 1, p. 15) by authors of this report.*

3. AMPHIBIANS

Amphibians may be especially sensitive to climatic change because they are ectotherms (i.e., body temperature is determined externally).[1153] Changes in ambient temperature may influence amphibian behaviors, including those related to reproduction.[1154] Potentially, changes in ambient temperature on a global scale could disrupt timing of breeding, periods of hibernation, and ability to find food.[1155]

Global warming could potentially affect amphibians at the population level and could potentially contribute to widely reported population declines.[1156] Because amphibians are key components of many ecosystems, changes in amphibian populations could affect other species within their communities, such as their predators and prey, even if these species were unaffected directly by global warming.[1157]

Global warming could also have a number of indirect effects on amphibians.[1158] For example, one potential consequence of global warming is the increased spread of infectious disease.[1159] Immune-system damage from multiple stressors could make amphibians more susceptible to pathogens whose ranges may change due to global warming.[1160] Moreover, recent evidence suggests that amphibians compromised by ultraviolet radiation are more susceptible to certain pathogens.[1161]

Observed Trends

Global

Amphibians have been shown to be undergoing precipitous declines and species extinction on a global basis, and the recent Global Amphibian Assessment has shown that out of 5743 species, 1856 (32.5%) are globally threatened.[1162] While a large percentage of these declines are attributable to direct anthropogenic effects, such as habitat loss, a substantial amount (48%) are classed as 'enigmatic' declines with no identifiable cause.[1163]

Chytridiomycosis is an emerging infectious disease of amphibians that is causing mass mortality and population declines worldwide.[1164] The causative agent, a non-hyphal zoosporic fungus, *Batrachochytrium dendrobatidis* (Bd), is a recently described species of the chytridiales which is known to infect over ninety-three species worldwide.[1165] Bosch et al. (2007) use long-term observations on amphibian population dynamics in the Peñalara

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1153 *Blaustein et al. *Amphibian breeding and climate change.* (2001, p. 1808). The authors cite Donnelly and Crump (1998) for this information.
1154 *Blaustein et al. (2001, p. 1808)
1155 *Blaustein et al. (2001, p. 1808)
1156 *Blaustein et al. (2001, p. 1808). The authors cite Blaustein and Wake (1995), Stebbins and Cohen (1995), and Ovaska (1997) as examples for this information.
1157 *Blaustein et al. (2001, p. 1808). The authors cite Burton and Likens (1975) and Blaustein (1994) for information amphibians as key components of ecosystems, and refer the reader to discussion by Donnelly and Crump (1998) for information on predator-prey interactions.
1158 *Blaustein et al. (2001, p. 1808)
1159 *Blaustein et al. (2001, p. 1808). The authors cite Cunningham et al. (1996) and Epstein (1997) for this information.
1160 *Blaustein et al. (2001, p. 1808). The authors cite Blaustein et al. (1994c) for this information.
1161 *Blaustein et al. (2001, p. 1808). The authors cite Kiesecker and Blaustein (1995) for this information.
1162 *Bosch et al. *Climate change and outbreaks of amphibian chytridiomycosis in a montane area of Central Spain; is there a link?* (2007, p. 253). The authors cite Stuart et al. (2004) for this information.
1163 *Bosch et al. (2007, p. 253). The authors cite Stuart et al. (2004) for this information. Quotes in original.
1164 *Bosch et al. (2007, p. 253). The authors cite Berger et al. (1998) and Daszak (2003) for this information.
1165 *Bosch et al. (2007, p. 253). The authors cite Longcore et al. (1999) for information on *B. dendrobatidis* and refer the reader to www.jcu.edu.au/school/phtm/PHTM/frogs/chyglob.htm for information on the number of species infected.

Natural Park, Spain, to investigate the link between climate change and chytridiomycosis.[1166] Their analysis shows a significant association between change in local climatic variables and the occurrence of chytridiomycosis within this region.[1167] Specifically, they show that rising temperature is linked to the occurrence of chytrid-related disease, consistent with the chytrid-thermal-optimum hypothesis.[1168] They show that these local variables are driven by general circulation patterns, principally the North Atlantic Oscillation.[1169]

Regional

The Global *Bd* Mapping Project provides a map of *Bd* surveillance in the United States, available at http://www.bd-maps.net/surveillance/suveil_country.php?country=US (accessed 8.29.2011). A global map is available at http://www.bd-maps.net/maps/ (accessed 8.29.2011).

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Blaustein et al. (2001) conducted an analysis of the breeding phenology of four species of North American anurans (i.e. frogs) for which they have long-term data sets.[1170] They found:

- At four sites, neither western toads nor Cascades frogs (*Rana cascadae*) showed statistically significant positive trends toward earlier breeding.[1171] However, at three of four of these sites, breeding time was associated with warmer temperatures.[1172]
- At one site, in Oregon, a trend (nonsignificant) for western toads (*Bufo boreas*) to breed increasingly early was associated with increasing temperature.[1173]

Based on Blaustein et al.'s (2001) data for North American species and a report by Reading (1998) on toads in Europe, Blaustein et al. conclude that the suggestion that amphibians in temperate regions are breeding earlier due to climate change may be premature.[1174]

In a study of downed wood microclimates near three headwater streams and their potential impact on plethodontid salamander habitat in the Oregon Coast Range, streamside and upslope maximum air temperatures measured during July 2006 along all three streams were near or exceeded 86°F (30°C), the critical thermal tolerance

1166 *Bosch et al. (2007, p. 253)
1167 *Bosch et al. (2007, p. 253)
1168 *Bosch et al. (2007, p. 253)
1169 *Bosch et al. (2007, p. 253)
1170 *Blaustein et al. (2001, p. 1804)
1171 *Blaustein et al. (2001, p. 1804)
1172 *Blaustein et al. (2001, p. 1804)
1173 *Blaustein et al. (2001, p. 1804)
1174 *Blaustein et al. (2001, p. 1808)

threshold for western plethodontid salamanders.[1175] Streamside and upslope temperatures inside small logs, large logs, and soils stayed below critical temperatures.[1176] This demonstrates the ability of soil, small logs, and large logs to protect against thermal extremes that are harmful to plethodontid salamanders.[1177] Temperature regimes are especially critical for these lungless salamanders because gas exchange and water balance occurs through the permeable surface of their skin, making them highly susceptible to dehydration.[1178]

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Likely impacts on reptiles and amphibians in Washington's Olympic Peninsula include:

- Reduction in snowpack and changes in timing of runoff with warmer temperatures will likely lead to drying of some wetland habitats, such as alpine ponds and wetlands, reducing habitat quality for dependent species such as the Cascades frog, northwestern salamander, long-toed salamander, and garter snakes.[1179]

Oregon

Oregon represents the northern margin of the range of the black salamander (*Aneides flavipunctatus*), and includes habitats that are particularly vulnerable to predicted patterns of global climate change.[1180] In particular, a change in storm patterns that alters precipitation, either annual accumulation or seasonal pattern, could affect this species.[1181] The association of this species with bioclimatic attributes was supported by Rissler and Apodaca (2007).[1182] Warming trends could increase the elevational extent of the species range and increase occupancy of north-facing slopes, and also restrict its distribution at lower elevations or south-southwest aspects.[1183] A smaller band of habitat might result if the current foothills of the Siskiyou Mountains become less suitable for the species.[1184] Also, it is possible that additional "new" habitats might become available for this species in Oregon,

[1175] *Kluber, Olson and Puettmann. *Downed wood microclimates and their potential impact on plethodontid salamander habitat in the Oregon Coast Range.* (2009, p. 25)
[1176] *Kluber, Olson and Puettmann.. (2009, p. 25)
[1177] *Kluber, Olson and Puettmann.. (2009, p. 32)
[1178] *Kluber, Olson and Puettmann.. (2009, p. 25-26)
[1179] *Halofsky et al. *Adapting to climate change at Olympic National Forest and Olympic National Park (pdf).* (n.d., p. 143)
[1180] *Olson. *Conservation Assessment for the Black Salamander (Aneides flavipunctatus) in Oregon.* (October 7, 2008, p. 13)
[1181] *Olson. (October 7, 2008, p. 13)
[1182] *Olson. (October 7, 2008, p. 13)
[1183] *Olson. (October 7, 2008, p. 13)
[1184] *Olson. (October 7, 2008, p. 13)

which is at the northern extent of the species' range.[1185] Although more extremes in conditions might forestall the ability of these animals to use habitats that on average appear suitable.[1186] Warming trends also could alter fire regimes and vegetation conditions, further restricting habitats.[1187] Indirect effects from changes of prey or predator communities are likely, but are difficult to predict.[1188] Interactions of warming trends with reduced cover from timber harvest are likely.[1189] Amelioration of climate changes may be possible by retaining canopy cover and large down wood, which moderate temperature extremes in their forested habitats.[1190]

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Studies assessing the effects of projected habitat changes (e.g., wetland extent and drying) on amphibians throughout their lifecycle are especially needed.

[1185] *Olson. (October 7, 2008, p. 13)
[1186] *Olson. (October 7, 2008, p. 13)
[1187] *Olson. (October 7, 2008, p. 13)
[1188] *Olson. (October 7, 2008, p. 13)
[1189] *Olson. (October 7, 2008, p. 13)
[1190] *Olson. (October 7, 2008, p. 13)

4. MACROINVERTEBRATES

Macroinvertebrates are organisms without a backbone, generally visible to the unaided eye.[1191]

Macroinvertebrates, as biological indicators of stream water quality, can be utilized to identify impaired waters, determine aquatic life stressors, set pollutant load reductions and indicate improvement.[1192] For example, benthic (bottom-dwelling) macroinvertebrates are sensitive to changes in temperature, precipitation, and the associated flow regimes, which should make them particularly responsive to the effects of climate change.[1193]

Observed Trends

Global

Warmer water may increase the growth rates of aquatic invertebrates and result in earlier maturation.[1194] For example:

- In a mesocosm experiment using the mayfly *Cloeon dipterum*, temperature increases alone had little effect on nymph abundance, and only small effects on body length, though emergence began earlier in the year.[1195]
- McKee and Atkinson (2000) show that for treatments with both increased temperatures and nutrients, both nymph abundance and size increase.[1196]

In general, nutrient enrichment leads to changes in the algal and diatom community composition of a stream, and sometimes, in some streams, to increased production and chlorophyll concentrations, leading to changes in primary invertebrate consumers which could cascade through the community.[1197]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

[1191] *NH-DES. *Glossary of Terms (website).* (2008)
[1192] *Kenney et al. *Benthic macroinvertebrates as indicators of water quality: the intersection of science and policy*. (2009, p. 2)
[1193] *Lawrence et al. (n.d., p. 200). The authors cite Bunn and Arthington (2002) and Lytle and Poff (2004) as examples for the sensitivity of benthic macroinvertebrates to changes in temperature, precipitation, and flow regimes.
[1194] *U. S. EPA. (2008a, p. 1-7). The authors cite Poff et al (2002) for this information.
[1195] *U. S. EPA. (2008a, p. 1-7). The authors cite McKee and Atkinson (2000) for this information.
[1196] *U. S. EPA. (2008a, p. 1-7). The authors cite McKee and Atkinson (2000) for this information.
[1197] *U. S. EPA. (2008a, p. 1-7). The authors cite Gafner and Robinson (2007) as an example of the effects of nutrient enrichment on primary invertebrate consumers. The authors cite Power (1990) and Rosemond et al. (1993) for information on changes cascading through the community.

Northwestern California

Information needed.

Future Projections

Global

Table 16 summarizes some observed and projected changes to macroinvertebrates due to climate change. Reduced stream temperature from increased contributions of glacial meltwater and decreased channel stability from changed runoff patterns and altered sediment loads, will, potentially, reduce the diversity of zoobenthic communities in glacier-fed rivers and cause an increase in the relative abundance of a number of key taxa, most notably *Diamesa* spp.[1198]

There is evidence that projected increases in CO_2 will reduce the nutritional quality of leaf litter to macroinvertebrate detritivores (i.e., organisms that obtain nutrients from decomposing organic matter, thereby contributing to decomposition and nutrient cycles).[1199] Reduced litter quality would result in lower assimilation and slower growth.[1200] While seemingly a secondary climate-change effect, changes in these processes could have food web implications: altered stream productivity that impacts fish and other consumers.[1201] In contrast to this, Bale et al. (2002) found little evidence of the direct effects of CO_2 on insect herbivores and instead discuss a range of temperature effects (including interactions with photoperiod cues) on various life history processes that affect ecological relationships.[1202]

Southcentral and Southeast Alaska

Oswood et al. (1992) considered the biogeographical implications for freshwater invertebrates of a less rigorous thermal environment at higher latitudes.[1203] Increased water temperature and decreased permafrost in areas south of the Alaska Range allow for potential redistributions of benthic invertebrate communities with the possible arrival of new predators (e.g. Megaloptera) and the loss of some cold water stenotherms at their southerly ranges.[1204] The altitudinal range of invertebrates in mountain streams may also change with the extension of some species to higher elevations and the reduction in the amount of habitat for cold water stenotherm taxa.[1205]

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

[1198] *Melack et al. (1997, p. 985)
[1199] *U. S. EPA. (2008a, p. 1-8)
[1200] *U. S. EPA. (2008a, p. 1-8). The authors cite Tuchman et al. (2002) for this information.
[1201] *U. S. EPA. (2008a, p. 1-8)
[1202] *U. S. EPA. (2008a, p. 1-8). The authors cite Bale et al. (2002) for this information.
[1203] *Melack et al. (1997, p. 985). The authors of the cited report are summarizing the work of Oswood et al. (1992).
[1204] *Melack et al. (1997, p. 985)
[1205] *Melack et al. (1997, p. 985)

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. For example, to support the use of macroinvertebrates as indicators of climate change, detailed information on the current range and distribution of macroinvertebrates (e.g., species and community composition in small geographic areas such as specific streams) is especially needed.

Table 16. Expected climate change effects and sensitivities, and potential novel indicators of climate change, in macroinvertebrates *Source: Modified from U.S. EPA (2008, Tables 3-1 & 3-2, p. 3-4 to 3-7) by authors of this report. Note: The species names Protoneumura, Nenoura, and Neumera were changed to Protonemoura (the former) and Nemoura (the latter two) in response to reviewer comments and online verification.*

Impacts	*Effects, Sensitivities, and Potential Novel Indicators*	*References*
Phenology	Early emergence of mayfly species (also stonefly and caddisfly species); Accelerated development and earlier breeding of the amphipod *Hyallela azteca*	Harper and Peckarsky, 2006; Briers et al., 2004; Gregory et al., 2000; McKee and Atkinson, 2000; Hogg et al., 1995
Longer growing season	Altered sex ratios for certain insects (e.g. trichopteran *Lepidostoma*)	Hogg and Williams (1996)
Life-stage specific	Smaller size at maturity and reduced fecundity of plecopteran *Nemoura trispinosa* and amphipod *Hyallela azteca* due to increased temperature	Turner and Williams, 2005; Hogg et al., 1995
Hydrologic sensitivity	Differential mortality of drought-intolerant mussel species (e.g., *Lampsilis straminea claibornensis*, *Villosa villosa*, *Lampsilis subangulata)* results in changes in relative abundance, extirpation of vulnerable species	Golladay et al. 2004
Measures of richness and abundance	Overall richness generally expected to decline due to temperature sensitivity and hydrologic stresses including increased flashiness, increased instances of summer low flows, drought, etc. However, replacements over time with tolerant forms may ameliorate this in some situations. Abundance or eurytolerant species may increase in some habitats.	Durance and Ormerod, 2007; Bradley and Ormerod, 2001
Measures of community composition and persistence	Compositional changes resulting from reductions in temperature and/or flow sensitive taxa (examples potentially include *Chloroperla*, *Protonemoura*, *Nemoura*, *Rhyacophila munda*, *Agabus* spp,, Hydrophilidae, and *Drusus annulatus*) and increases in less temperature and/or flow sensitive taxa (examples potentially include *Athricops*, *Potamopyrgus*, *Lepidostoma*, *Baetis niger*, *Tabanidae*, *Hydropsyche instabilis*, *Helodes marginata*, *Caenis* spp.), and/or from shifts in range; patterns of persistence or community similarity that track climatic patterns; changes may also occur in functional roles of species.	Daufresne et al., 2003; Durance and Ormerod, 2007; Bradley and Ormerod, 2001; Burgmer et al., 2007; Golladay et al., 2004; Parmesan, 2006; Hawkins et al., 1997
Measures of tolerance / intolerance	Climate-change sensitivities related to temperature or flow regime may be documented as decreases (potentially resulting from local extinctions and/or range shifts) in richness (number of taxa) of temperature or flow-regime sensitive groups. Dominance by tolerant taxa also may increase.	Daufresne et al., 2003; Durance and Ormerod, 2007; Burgmer et al., 2007; Golladay et al., 2004; Parmesan, 2006
Measures of feeding	Variable responses expected, driven by interactions between temperature, which may increase phytoplankton and periphyton productivity and thus increase associated feeding type; hydrologic factors which may decrease periphyton if habitat stability is decreased or sedimentation is increased; CO_2 concentrations, which can directly affect leaf litter composition and decomposition; and changes in riparian vegetation.	Gafner and Robinson, 2007; Dodds and Welch, 2000; Tuchman et al., 2002
Measures of habitat	Number and percent composition of clingers likely to decrease if hydrologic changes decrease habitat stability, increase embeddedness, or decrease riparian inputs of woody vegetation.	Johnson et al., 2003; Townsend et al., 1997

VII. ADAPTING TO THE EFFECTS OF CLIMATE CHANGE IN THE FRESHWATER ENVIRONMENT

This section presents adaptation actions culled from the scientific literature and interviews with experts.

In this report, "adaptation" refers to the IPCC's definition: "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities."[1206]

Many water supply sources (rivers, lakes, groundwater basins, etc.) are already over-allocated, suffer degraded water quality, and are often not in sufficient condition to support endangered species.[1207] Climate change will exacerbate these water challenges, leading to insufficient water for people and the environment and making it increasingly difficult to meet the needs of both.[1208]

Adaptation is one of two major ways in which climate-related risks can be managed (the other is mitigation, which includes strategies to reduce greenhouse gas sources and emissions, and enhance greenhouse gas sinks).[1209] Even if global greenhouse gas emissions were to be stabilized near their current levels, atmospheric concentrations would increase throughout the 21st century, and might well continue to increase slowly for several hundred years after that.[1210] Thus, mitigation can reduce climate-related risks only in the longer term.[1211] Adaptation has emerged as a necessary response to and preparation for the unavoidable impacts of global climate change.[1212]

Adaptation is in its infancy and the field is developing in a rapid and *ad hoc* fashion.[1213] However, general and specific approaches to adaptation action are emerging, as are common tenets of adaptation action.[1214] Along with these, existing conservation activities are being applied to climate change adaptation, and new activities are also being developed.[1215] The states, provinces, and tribal governments of the NPLCC region are developing climate change adaptation strategies. Each of these topics is covered in turn:

- **Framework for Adaptation Action:** A general approach and specific planning and management approaches to adaptation action, derived from published and grey literature.
- **Common Tenets of Adaptation Action:** Adaptation principles derived from the literature.
- **Climate Adaptation Actions:** Adaptation actions are organized into five broad categories, including information gathering and capacity building; monitoring and planning; infrastructure

[1206] *IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Introduction.* (2007, p. 6)
[1207] Natural Resources Defense Council (NRDC). *Climate Change and Water Resource Management: Adaptation strategies for protecting people and the environment.* (2010, p. 1)
[1208] NRDC. (2010, p. 1)
[1209] Asian Development Bank (ADB). *Climate Proofing: A risk-based approach to adaptation.* (2005, p. 7); Information on mitigation available from Parry et al. (2007, p. 878)
[1210] *ADB. (2005, p. 7)
[1211] ADB. (2005, p. 7)
[1212] *Gregg et al. (2011, p. 30)
[1213] *Gregg et al. (2011, p. 30)
[1214] ADB (2005); Gregg et al. (2011); Heller and Zavaleta (2009); NOAA. *Adapting to Climate Change: A Planning Guide for State Coastal Managers*. (2010a)
[1215] See, for example, Baron et al. (2009); Heller and Zavaleta (2009); Mawdsley, O'Malley, and Ojima (2009); NOAA. *Adapting to Climate Change: A Planning Guide for State Coastal Managers*. (2010a); U.S. EPA. *Synthesis of Adaptation Options for Coastal Areas.* (2009)

and development; governance, policy, and law; and, conservation, restoration, protection and natural resource management. The actions described represent the range of ideas suggested by the scientific literature on climate change adaptation. They are not intended as recommendations.

- **Status of Adaptation Strategies and Plans:** Brief descriptions of the development and implementation of state, provincial, and selected tribal adaptation strategies in the NPLCC region.

1. FRAMEWORK FOR ADAPTATION ACTIONS

General Approach to Adaptation Action

Adaptation actions are undertaken either to avoid or take advantage of actual and projected climate change impacts either by decreasing a system's vulnerability or increasing its resilience.[1216] This may entail reprioritizing current efforts as well as identifying new goals and objectives to reduce overall ecosystem vulnerability to climate change.[1217] The former – reprioritizing current efforts – is known as a "bottom-up" or "project-based" approach and involves integrating climate change considerations into existing management and program structures.[1218] The latter – identifying new goals and objectives – is known as a "top-down" or "landscape-based" approach and is particularly useful for broad-scale efforts, such as those conducted at regional, state, or national levels for one or more sectors.[1219]

General approaches to and principles of adaptation action in both human and natural systems have been addressed in past reports.[1220] A review of these reports indicates the approaches and adaptation principles are consolidated typically into four broad steps:

1. **Assess current and future climate change impacts and conduct a vulnerability assessment**.[1221] The vulnerability assessment may focus on a species, place, program, community, or anything else of concern to those doing the assessment, and should include exposure (the nature and degree to which a system is exposed to significant climatic variations), sensitivity (the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli), and adaptive capacity (ability of the system to respond effectively), as well as interactions with other factors, such as existing stressors or possible changes in human resource use patterns.[1222] In all cases, the assessment should begin with the overall goal of those carrying it out (e.g. sustainable fisheries management, coastal habitat protection).[1223] Further information on conducting vulnerability assessments is provided in Section 3 of this Chapter.
2. **Select conservation targets and course of action**.[1224] This step includes identifying, designing, prioritizing, and implementing management, planning, or regulatory actions and policies that reduce the vulnerabilities and/or climate change effects identified in Step 1.[1225] *Note that Steps 1 and 2 are interchanged in some reports (CIG 2007; Heller & Zavaleta 2009), and are considered iterative by others (Glick et al. 2009).*

1216 *Gregg et al. (2011, p. 29). The authors cite ADB (2005), Levin & Lubchenco (2008), Lawler (2009). Pew Center (2009).
1217 *Glick et al. (2011a, p. 7)
1218 Glick et al. (2011a, p. 7); Glick et al. (2011b, Box 1.1, p. 13)
1219 Glick et al. (2011a, p. 8); Glick et al. (2011b, Box 1.1, p. 13)
1220 *Gregg et al. (2011, p. 30)
1221 Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID (2009); CIG (2007); ADB (2005); Pew Center. (2009)
1222 *Gregg et al. (2011, p. 30)
1223 *Gregg et al. (2011, p. 30)
1224 Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID (2009); CIG (2007); Pew Center. (2009)
1225 Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID (2009); CIG (2007)

3. **Measure, evaluate, and communicate progress** through the design and implementation of monitoring programs that assess changes in the chosen parameters of management and/or policy effectiveness.[1226]
4. **Create an iterative process to reevaluate and revise the plan, policy, or program,** including assumptions.[1227]

In some reports, a wider planning process and team-building activities precede Step 1 above. For example, the process outlined in NOAA's *Adapting to Climate Change: A Planning Guide for State Coastal Managers* (2010) begins with a planning process that includes scoping the level of effort and responsibility; assessing resource needs and availability; assembling a planning team and establishing responsibilities; and, educating, engaging & involving stakeholders.[1228] The Climate Impacts Group *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* (2007) includes similar steps: scope climate change impacts in major sectors; build and maintain support to prepare for climate change by identifying a "champion" and audience, and developing and spreading a message; and, build a climate change preparedness team.[1229] The Asian Development Bank's (2005) approach begins with capacity building and provision, enhancement, and application of data, tools, and knowledge.[1230]

Specific Planning and Management Approaches to Adaptation Action

Implementing actions now to improve water quality and supplies, protect aquatic ecosystems, and improve flood management will help reduce future impacts related to climate change.[1231] One of many approaches to adaptation planning and management in the freshwater environment is that outlined in the *U.S. National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate*.

This draft *National Action Plan* includes preliminary recommendations that may change as it is further developed.[1232] The six recommendations and associated supporting actions are:

- ***Establish a planning process and organizational framework*** to adapt water resources management to a changing climate. [1233]
- ***Improve water resources and climate change information for decision-making*** by strengthening data for understanding climate change impacts on water, creating a program to align "hydroclimatic" statistics, implementing a surveillance system for tracking waterborne disease threats, providing information to identify areas likely to be inundated by sea level rise, and expediting implementation of a wetlands mapping standard.[1234]
- ***Strengthen assessment of vulnerability of water resources to climate change*** by publishing a long-term plan for Federal "downscaling" of climate model projections, developing a Federal

[1226] Gregg et al. (2011); Glick et al. (2009); Heller & Zavaleta (2009); NOAA (2010a); U.S. AID (2009); CIG (2007); ADB (2005)
[1227] Gregg et al. (2011); Glick et al. (2009); NOAA (2010a); U.S. AID (2009); CIG (2007); ADB (2005)
[1228] NOAA. (2010a)
[1229] CIG. (2007)
[1230] ADB. (2005, p. 95)
[1231] ADB. (2005, p. 7); information on mitigation is from Parry et al. (Eds). *Climate Change 2007: Impacts, Adaptation, Vulnerability: Appendix 1: Glossary.* (2007, p. 878)
[1232] Interagency Climate Change Adaptation Task Force. *National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate (Draft).* (June 2, 2011, p. 2)
[1233] Interagency Climate Change Adaptation Task Force. (June 2, 2011, Table 1, p. 4)
[1234] Interagency Climate Change Adaptation Task Force. (June 2, 2011, Table 1, p. 4)

internet portal, developing a pilot climate change/water vulnerability index, developing tools to build capacity for vulnerability assessments, assessing the vulnerability of National Forests and Grasslands, and promoting free and open access to water resources data.[1235]

- ***Improve water use efficiency*** by developing nationally consistent metrics for water use efficiency, making water use efficiency an explicit consideration in the Principles and Standards for water resources projects and in the new National Environmental Policy Act guidance on climate change, and enhancing agency coordination and creating a "toolbox" of key water efficiency practices.[1236]
- ***Support integrated water resources management*** by strengthening the role of river basin commissions in climate change adaptation, revising Federal water project planning standards to address climate change, working with States to review flood risk management and drought management planning and identify "best practices" to prepare for hydrologic extremes in a changing climate, and developing benchmarks for incorporating adaptive management into water project designs, operational procedures, and planning strategies.[1237]
- ***Educate water resource managers and build capacity*** by establishing a core training program on climate change science, focusing existing youth outreach programs on climate change and water issues, engaging land grant colleges in climate change adaptation research, and increasing graduate level fellowships in water management and climate change.[1238]

[1235] Interagency Climate Change Adaptation Task Force. *National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate (Draft).* (June 2, 2011, Table 1, p. 4)
[1236] Interagency Climate Change Adaptation Task Force. *National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate (Draft).* (June 2, 2011, Table 1, p. 4)
[1237] Interagency Climate Change Adaptation Task Force. *National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate (Draft).* (June 2, 2011, Table 1, p. 4)
[1238] Interagency Climate Change Adaptation Task Force. *National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate (Draft).* (June 2, 2011, Table 1, p. 4)

2. COMMON TENETS OF ADAPTATION ACTION

No single element or component of adaptation is a solution on its own, and there is no universally best set of solutions.[1239] Successfully adapting to climate change relies on a mixture of approaches as well as perpetual review and modification as new information comes to light, new ideas are generated, and additional changes take place.[1240] Scientists are increasingly emphasizing the concepts of maintaining or improving ecosystem resistance and resilience,[1241] as well as enabling or facilitating the ability of a species or ecosystem to change,[1242] e.g. via response or realignment.[1243] A review of the published and grey literature indicates the following are common tenets of adaptation action:

- Remove other threats and reduce non-climate stressors that interact negatively with climate change or its effects.[1244]
- Establish or increase habitat buffer zones and corridors, including adjustments to protected area design and management such as expanding reserve networks.[1245]
- Increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management (Box 20).[1246]

Four additional tenets were also found in the literature, although they were not cited universally:

- Manage for ecological function and protection of biological diversity, including restoration of habitat and system dynamics.[1247]
- Implement proactive management and restoration strategies, which may include translocations.[1248]
- Reduce local and regional climate change, e.g. via restoration, planting vegetation.[1249]
- Reduce greenhouse gas emissions.[1250]

[1239] *Gregg et al. (2011, p. 30)
[1240] *Gregg et al. (2011, p. 30)
[1241] *Glick et al. (2009, p. 12)
[1242] *Glick et al. (2009, p. 13)
[1243] *U.S. Fish and Wildlife Service. *Rising to the urgent challenge: strategic plan for responding to accelerating climate change (pdf).* (2010, Sec1:16). The authors cite Millar et al. (2007) for information on realignment.
[1244] Gregg et al. (2011); Lawler (2009); Glick et al. (2009)
[1245] Gregg et al. (2011); Lawler (2009); Glick et al. (2009)
[1246] Gregg et al. (2011); Lawler (2009); Glick et al. (2009)
[1247] Glick et al. (2009); Lawler (2009)
[1248] Glick et al. (2009); Lawler (2009)
[1249] *Gregg et al. (2011, p. 32)
[1250] *Gregg et al. (2011, p. 33)

Box 20. Managing uncertainty: Scenario-based planning and adaptive management.

Scenario-based planning: Scenario planning is a concept developed by Peterson, Cumming, & Carpenter (2003).[1251] It is a systematic method for thinking creatively about possible complex and uncertain futures.[1252] The central idea of scenario planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome.[1253] In this context, the scenarios are not predictions or forecasts but, rather, a set of *plausible* alternative future conditions.[1254] Scenario planning is appropriate for systems in which there is a lot of uncertainty that is not controllable.[1255] This approach is used by the IPCC (see Box 2 and Appendix 2 for an explanation).

Adaptive management: Adaptive management is a systematic approach for improving resource management by learning from management outcomes.[1256] It puts management actions into an experimental framework, specifying what information is needed to evaluate management success and how and when it will be used to adjust management actions.[1257] In theory, adaptive management allows for the management of highly uncertain systems.[1258] It is useful not only when the future is uncertain, but when there is uncertainty about which management approach is best or how the system being managed functions even under today's conditions.[1259] It may be particularly useful in cases where immediate action is required to address short-term and/or potentially catastrophic long-term consequences or where management actions are likely to have no regrets near-term benefits.[1260] While it is a common complaint that current environmental rules and regulations lack the flexibility needed for true adaptive management, the U.S. Department of the Interior's technical guide to adaptive management provides both suggestions for and examples of effective adaptive management in the federal context.[1261]

[1251] Glick et al. (2009, p. 18)
[1252] Peterson et al. *Scenario planning: a tool for conservation in an uncertain world*. (2003, p. 359)
[1253] Peterson et al. (2003, p. 359)
[1254] Glick et al. (2009, p. 18)
[1255] Peterson et al. (2003, p. 365)
[1256] Williams, Szaro and Shapiro. *Adaptive Management: The U.S. Department of the Interior Technical Guide.* (2009, p. 1). The authors cite Sexton et al. (1999) for this information.
[1257] Gregg et al. (2011, p. 32)
[1258] Lawler. (2009, p. 85)
[1259] Glick et al. *Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Restoration Projects.* (2011a, p. 39)
[1260] Glick et al. *Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Restoration Projects.* (2011a, p. 39). The authors cite Ojima and Corell (2009) and Climate Change Wildlife Action Plan Working Group (2008) for this information.
[1261] Glick et al. (2011b, Box 1.2, p. 15). The authors cite Williams et al. (2007) for the technical guide.

Box 21. Adaptation and Adaptive Management: Complementary but Distinct Concepts.

Adaptation and adaptive management are distinct concepts that are frequently confused with one another.[1262] As described earlier, adaptation refers to strategies designed to prepare for and cope with the effects of climate change.[1263] In contrast, adaptive management is one particular approach to management in the face of uncertainty, and is not necessarily tied to climate change (see Box 20)[1264]

Adaptation to climate change is characterized by making decisions in the face of uncertainty.[1265] Because of the uncertainties associated with predicting the effects of future climates on species and ecosystems, flexible management will almost certainly be a component of well-designed adaptation strategies.[1266] However, while the adaptive management framework is structured to enable managers to act in the face of uncertainty, other management approaches and philosophies are also designed to address different levels of uncertainty (e.g. scenario-based planning).[1267]

To summarize, adaptive management can be an important component of adaptation efforts, but not all adaptive management is climate change adaptation, nor is all climate change adaptation necessarily adaptive management.[1268]

[1262] Glick et al. (2011b, Box 1.2, p. 15).
[1263] Glick et al. (2011b, Box 1.2, p. 15).
[1264] Glick et al. (2011b, Box 1.2, p. 15).
[1265] Glick et al. (2011b, Box 1.2, p. 15).
[1266] Glick et al. (2011b, Box 1.2, p. 15).
[1267] Glick et al. (2011b, Box 1.2, p. 15).
[1268] Glick et al. (2011b, Box 1.2, p. 15).

3. CLIMATE ADAPTATION ACTIONS – INFORMATION GATHERING AND CAPACITY BUILDING

Building capacity in organizations, managers, practitioners, decision-makers, and the public can increase the ability to plan, develop, and implement adaptation strategies.[1269] There are multiple factors that can affect capacity to engage in adaptation, including generic factors such as economic resources and more specific factors such as quality and quantity of information, and training and technological resources.[1270] The sections below describe components of information gathering and capacity building.

Conduct/gather additional research, data, and products

Gathering research, data, and products on actual and projected climate change impacts is critical to supporting adaptation action.[1271] Models and research products have predicted a range of plausible scenarios; as these tools are refined, many indicate that the extent and magnitude of climate impacts may be greater than previously thought.[1272] Incorporating the best available science, traditional ecological knowledge, and citizen science efforts may improve climate adaptation decisions.[1273] For example, the Climate Action Knowledge Exchange (CAKE) is aimed at building a shared knowledge base for managing natural systems in the face of rapid climate change[1274] and the Climate Ready Water Utilities (CRWU) Toolbox provides access to resources containing climate-related information relevant to the water sector.[1275]

Create/enhance technological resources

Technological resources can make adaptation action easier and more accessible.[1276] These resources include the tools that can support information exchange, modeling of vulnerability and risk, and decision-making.[1277] These resources can help planners, managers, scientists, and policy makers to identify priority species and areas for conservation, generate inundation and hazard maps, and ascertain organizations and communities that have successfully implemented adaptation strategies.[1278]

Conduct vulnerability assessments and studies

Vulnerability assessments help practitioners evaluate potential effects of climatic changes on ecosystems, species, human communities, and other areas of concern.[1279] Vulnerability assessments and studies can identify impacts of concern, a range of scenarios that depend on the frequency and magnitude of changes, who and what is at risk from these impacts, and what can be done to reduce vulnerability and increase

[1269] *Gregg et al. (2011, p. 46)
[1270] *Gregg et al. (2011, p. 46)
[1271] *Gregg et al. (2011, p. 53)
[1272] *Gregg et al. (2011, p. 53)
[1273] *Gregg et al. (2011, p. 53)
[1274] * Climate Action Knowledge Exchange (CAKE). *About.* (2011). Available at http://www.cakex.org/about (accessed 8.22.2011).
[1275] * U.S. EPA. *Climate Ready Water Utilities Toolbox.* (August 5, 2011). Available at http://www.epa.gov/safewater/watersecurity/climate/toolbox.html (accessed 8.22.2011).
[1276] *Gregg et al. (2011, p. 70)
[1277] *Gregg et al. (2011, p. 70)
[1278] *Gregg et al. (2011, p. 70)
[1279] *Gregg et al. (2011, p. 54)

resilience.[1280] Specifically, climate change vulnerability assessments provide two essential components to adaptation planning:

- Identifying *which* species or ecosystems are likely to be most strongly affected by projected changes; and
- Understanding *why* these resources are likely to be vulnerable, including the interaction between climate shifts and existing stressors.[1281]

Determining *which* resources are most vulnerable enables managers to better set priorities for conservation action, while understanding *why* they are vulnerable provides a basis for developing appropriate management and conservation responses (emphasis in original). [1282] In other words, they can provide a factual underpinning for differentiating between species and systems likely to decline and likely to thrive, but do not in themselves dictate adaptation strategies and management responses.[1283] This emphasizes the fact that a vulnerability assessment is not an endpoint, but a source of information that can be incorporated into planning and decision-making.[1284]

Vulnerability is a function of exposure and sensitivity to change as well as adaptive capacity, which can all vary greatly depending on geography, genetic or species diversity, resources, and other factors.[1285] Vulnerability assessments are, therefore, structured around assessments of these distinct components.[1286] Furthermore, because vulnerability assessments should elucidate the specific factors that contribute to a species' or habitat's vulnerability, they can help managers identify options for reducing that vulnerability through management and conservation actions.[1287] In some cases there may be practical management options, but in other cases the factors leading to vulnerability may be very difficult or simply not feasible to address.[1288] This is an important consideration in selecting conservation targets and objectives.[1289] The key steps and associated actions for assessing vulnerability to climate change are listed in Table 17.

The EPA's Climate Ready Estuaries program compiled best practices and lessons learned for vulnerability assessment efforts including:

- Recognize that non-climate drivers, such as development, pollution, and population growth, often exacerbate climate change vulnerabilities.[1290]
- When working with limited data, use readily available scientific best professional judgment to help support decision-making.[1291] Surveying both local and regional experts and stakeholders can assist in building knowledge, as they have access to some of the most up-to-date information and research.[1292]

[1280] *Gregg et al. (2011, p. 54)
[1281] *Glick et al. (2011b, p. 1)
[1282] *Glick et al. (2011b, p. 1)
[1283] *Glick et al. (2011b, p. 3)
[1284] *Glick et al. (2011b, p. 77)
[1285] *Gregg et al. (2011, p. 54)
[1286] *Glick et al. (2011b, p. 2)
[1287] *Glick et al. (2011b, p. 77)
[1288] *Glick et al. (2011b, p. 77)
[1289] *Glick et al. (2011b, p. 77)
[1290] *U.S. EPA. *Lessons Learned from the Climate Ready Estuaries Program*. (2011, p. 2)
[1291] *U.S. EPA. (2011, p. 2)
[1292] *U.S. EPA. (2011, p. 2)

- Focus on emergency and disaster management, which is one area National Estuary Programs can work with local and state governments to incorporate climate change issues.[1293] *For further information on emergency and disaster management, please see "Invest in/enhance emergency services planning and training" in this Section and "Develop a disaster preparedness plan" in Section 6 of this Chapter*.
- Collaborate with and use local partners, such as universities, non-profits, Sea Grants, and National Estuarine Research Reserves to fill information gaps.[1294]
- Determine scope – vulnerability assessments do not necessarily have to be broad in scope.[1295] Focusing on the vulnerability of a specific resource may generate momentum for adaptation.[1296] This lesson is echoed by Glick et al.'s "landscaped-based" and "project-based" approach to climate-smart conservation, described previously (see Section 1 in this Chapter).[1297]

Table 17. Key Steps for Assessing Vulnerability to Climate Change.

Key Steps	*Associated Actions*
Determine objectives and scope	• Identify audience, user requirements, and needed products • Engage key internal and external stakeholders • Establish and agree on goals and objectives • Identify suitable assessment targets • Determine appropriate spatial and temporal scales • Select assessment approach based on targets, user needs, and available resources
Gather relevant data and expertise	• Review existing literature on assessment targets and climate impacts • Reach out to subject experts on target species or systems • Obtain or develop climatic projections, focusing on ecologically relevant variables and suitable spatial and temporal scales • Obtain or develop ecological response projections
Assess components of vulnerability	• Evaluate climate sensitivity of assessment targets • Determine likely exposure of targets to climatic/ecological change • Consider adaptive capacity of targets that can moderate potential impact • Estimate overall vulnerability of targets • Document level of confidence or uncertainty in assessments
Apply assessment in adaptation planning	• Explore why specific targets are vulnerable to inform possible adaptation responses • Consider how targets might fare under various management and climatic scenarios • Share assessment results with stakeholders and decision-makers • Use results to advance development of adaptation strategies and plans

Source: Modified from Glick et al. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. (2011b, Box 2.1, p. 19).

[1293] *U.S. EPA. (2011, p. 2)
[1294] *U.S. EPA. (2011, p. 2)
[1295] *U.S. EPA. (2011, p. 2)
[1296] *U.S. EPA. (2011, p. 2)
[1297] Glick et al. (2011a, p. 7)

Conduct scenario planning exercises

Scenario planning involves the creation of a series of scenarios specifically for the planning process in question, as well as narratives to accompany those scenarios.[1298] It also involves the use of those scenarios for evaluating policy/management options.[1299] Scenario planning allows participants to identify actions that work well across multiple scenarios, to discover options for dealing with uncertainty, and can improve adaptive management (and adaptation).[1300]

Increase organizational capacity

Sufficient organizational capacity is needed to support adaptation activities at all levels of government.[1301] This strategy includes improving the resources, tools, knowledge, and institutional support required to increase organizational capacity.[1302]

Create/host adaptation training and planning workshops

While many researchers, conservation practitioners, and resource managers understand the reality of climate change, they are often still challenged by what actions to take.[1303] As a result, the conservation and resource management community needs assistance developing its thinking on dealing with climate change, finding the information or data it needs to make informed decisions, and finding people to interact with on this topic as individuals develop their own approaches.[1304] Training and planning workshops can provide context, guidance, and practical examples of how adaptation is being addressed on-the-ground.[1305]

Provide new job training for people whose livelihoods are threatened by climate change

This strategy directly addresses the potential economic consequences of global climate change.[1306] Increased water temperatures and ocean acidification will severely impact fisheries, aquaculture, and ecotourism and recreation based on natural resources.[1307]

Create new institutions (training staff, establishing committees)

Creating committees and advisory bodies and having properly trained staff can institutionalize climate change considerations within an organization.[1308] Technical experts, scientists, and other staff can contribute important knowledge and recommendations to support governmental decision-making on climate adaptation.[1309]

1298 *Gregg et al. (2011, p. 59)
1299 *Gregg et al. (2011, p. 59)
1300 *Gregg et al. (2011, p. 59). The authors cite Peterson (2003) for this information.
1301 *Gregg et al. (2011, p. 48)
1302 *Gregg et al. (2011, p. 48)
1303 *Gregg et al. (2011, p. 56)
1304 *Gregg et al. (2011, p. 56)
1305 *Gregg et al. (2011, p. 56)
1306 *Gregg et al. (2011, p. 55)
1307 *Gregg et al. (2011, p. 55)
1308 *Gregg et al. (2011, p. 46)
1309 *Gregg et al. (2011, p. 46)

Coordinate planning and management across institutional boundaries

Many climate change impacts will affect multiple jurisdictions at once whether the effects are felt at local, regional, national, or international scales.[1310] Because climatic variability is not confined by political or social boundaries, cross-jurisdictional coordination of planning and management can improve adaptation efforts.[1311] Increased cooperation may include information sharing, improved communication, and establishing formal partnerships to share resources, funds, and knowledge.[1312]

Invest in/enhance emergency services planning and training

Climate change is expected to increase risks to public health and safety throughout North America.[1313] Warmer temperatures and changes in precipitation patterns will likely increase incidences of wildfires and drought, pests and diseases, and intense heat waves.[1314] Integrating climate change concerns into emergency services planning and training, including police, fire and rescue, and emergency medical services, will be important to limit public health and safety risks.[1315]

Create stakeholder engagement processes

As mentioned previously, gaining public buy-in for adaptation can be critical to ensuring the effectiveness of any strategy.[1316] Engaging stakeholders can occur in a variety of ways; for example, participating in meetings and workshops, one-on-one interactions, and websites, among others.[1317] Activities like interactive, participatory discussions, problem solving sessions, and role-playing exercises have been used to engage stakeholders in climate adaptation.[1318] The EPA's Climate Ready Estuaries program compiled best practices and lessons learned for stakeholder engagement efforts including:

- Leverage existing efforts.[1319]
- Focus on local issues.[1320] Presenting local evidence of climate change (e.g., changes in seasonal events or animal behavior, local projections of wetland loss) to local officials and the general public is often a useful approach to build support for adaptation.[1321]
- Link climate change adaptation messages to clean water supply and stormwater drainage.[1322] This can be an effective way to engage local decision-makers, as constituents are increasingly concerned about these issues.[1323]
- Target entities most responsible for construction and maintenance of public infrastructure (e.g., municipalities, counties or regional authorities) first to encourage greater willingness to engage

[1310] *Gregg et al. (2011, p. 49)
[1311] *Gregg et al. (2011, p. 49)
[1312] *Gregg et al. (2011, p. 49)
[1313] *Gregg et al. (2011, p. 50)
[1314] *Gregg et al. (2011, p. 50)
[1315] *Gregg et al. (2011, p. 50)
[1316] *Gregg et al. (2011, p. 57)
[1317] *Gregg et al. (2011, p. 57)
[1318] *Gregg et al. (2011, p. 57)
[1319] *U.S. EPA. (2011, p. 3)
[1320] *U.S. EPA. (2011, p. 3)
[1321] *U.S. EPA. (2011, p. 3)
[1322] *U.S. EPA. (2011, p. 3)
[1323] *U.S. EPA. (2011, p. 3)

on the impacts of sea-level rise due to the significant fiscal implication of infrastructure loss or damage.[1324]

- Conduct meetings or phone calls with key stakeholders to help identify what stakeholders are already working on and their key needs for undertaking climate change adaptation.[1325]

Increase/improve public awareness, education, and outreach efforts

This strategy relates to improving the links between science, management, decision-making, and public awareness.[1326] These efforts may be in the form of presentations and workshops, print and internet media, steering and advisory committees, and traditional educational venues.[1327] More interactive approaches tend to be better at ensuring a two-way flow of information, recognizing that scientists must learn from managers, policy makers, and the public as well as vice-versa.[1328] Enabling managers and decision-makers to incorporate climate adaptation into practice requires that the appropriate science be available in useable forms when needed.[1329] The broader public also needs to be engaged in climate adaptation and be made aware of the potential ways that climate change may affect the economy, natural resources, livelihoods, health, and well-being.[1330] Gaining public buy-in may increase political and social capital to support climate adaptation action at local, regional, national, and international levels.[1331]

[1324] *U.S. EPA. (2011, p. 3)
[1325] *U.S. EPA. (2011, p. 3)
[1326] *Gregg et al. (2011, p. 51)
[1327] *Gregg et al. (2011, p. 51)
[1328] *Gregg et al. (2011, p. 51)
[1329] *Gregg et al. (2011, p. 51)
[1330] *Gregg et al. (2011, p. 51-52)
[1331] *Gregg et al. (2011, p. 52)

4. CLIMATE ADAPTATION ACTIONS – MONITORING AND PLANNING

The sections below describe components of monitoring and planning.

Evaluate existing monitoring programs for wildlife and key ecosystem components

Monitoring systems provide information that managers can use to adjust or modify their activities through the process of adaptive management.[1332] This approach would evaluate the current state of the systems that collect, analyze, and interpret environmental information.[1333] It would determine how programs will need to be modified to provide management-relevant information on the effects of climate change and what new monitoring systems will need to be established in order to address gaps in knowledge of climate effects.[1334] The costs to adapt existing monitoring systems and develop new monitoring systems are likely to be high.[1335] In many cases this will probably require new legislation and regulations, and possibly new tools and approaches to monitoring.[1336] It will also require better integration and coordination across existing monitoring programs.[1337]

Improve coordinated management and monitoring of wetlands

Three options for improving coordinated management and monitoring of wetlands are:

- Promote climate-smart integrated resource management at the watershed level by offering financial and other incentives[1338]
- Use legislative reauthorizations to explore new ways to protect biodiversity and ecosystems in light of climate change and to integrate preservation and restoration[1339]
- Support research on the impacts of climate change (and the effectiveness of various management options) on wetlands[1340]

Incorporate predicted climate change impacts into species and land management

Information about actual and potential climate change impacts can be of benefit to land and natural resource managers in making decisions and taking actions.[1341] Climate change is not addressed in many existing natural resource plan documents.[1342] This strategy would use existing natural resource planning mechanisms to inform decision-making on a broad spectrum of natural resource management topics.[1343] Many existing natural resource plans already contain provisions for updates and revisions, which could

[1332] *Heinz Center (2008, p. 29). The authors cite Walters (1986), Margoluis and Salafsky (1998), and Williams, Szaro, and Shapiro (2007) for this information.
[1333] *Heinz Center (2008, p. 29). The authors cite Walters (1986), Margoluis and Salafsky (1998), and Williams, Szaro, and Shapiro (2007) for this information.
[1334] *Heinz Center (2008, p. 29)
[1335] *Heinz Center (2008, p. 30)
[1336] *Heinz Center (2008, p. 30)
[1337] *Heinz Center (2008, p. 30). The authors cite The Heinz Center (2006) for this information.
[1338] *OTA. (1993, p. 197)
[1339] *OTA. (1993, p. 197)
[1340] *OTA. (1993, p. 197)
[1341] *Heinz Center (2008, p. 30)
[1342] *Heinz Center (2008, p. 30). The authors cite Hannah, Midgley and Millar (2002) for information on existing natural resource plan documents, and Mawsdsley (unpublished data) for information on endangered species recovery plans and State Wildlife Action Plans.
[1343] *Heinz Center (2008, p. 30)

provide a mechanism for incorporating information about climate change effects and adaptation strategies.[1344]

The problems with this approach are mainly practical at present: there is a definite cost associated with revisiting and revising management plans; in practice, many resource management plans are updated infrequently.[1345] While detailed predictions of potential climate change effects have only been available for a small subset of species and areas,[1346] considerable progress is being made in down-scaling of climate information for use at more local levels.[1347] Below, three examples are provided for incorporating predicted climate change impacts into species and land management:

- **Incorporate climate change into wetland restoration planning:** To incorporate climate change into wetland restoration planning, one option is to establish wetland reference sites to document the impacts of climate change and to determine the effectiveness of management and adjustment strategies.[1348] Another option is to develop protection and adjustment tools through the use of "pilots."[1349] In all cases, monitoring success and failures[1350] and actively making the results of studies broadly available to the public and other practitioners[1351] is suggested.
- **Incorporate climate change considerations into aquatic invasive species management plans:** The process could be initiated by conducting facilitated meetings and/or workshops to identify specific management strategies and research needs to inform management strategies.[1352] State (or other jurisdictions) councils also could work with one another to share information on climate-related data across regions.[1353] Coordination and information sharing among states (or other jurisdictions) will also facilitate the implementation of activities that are adapted to climate change effects.[1354] State and federal agencies (as well as other jurisdictions) also could collaborate in areas such as aquatic invasive species data collection, specifically where the spatial scale of the biological and environmental data needed by the federal government may be more efficiently collected by a state.[1355] In turn, the data provided to the federal government by states (or other jurisdictions) may be used in modeling scenarios that also would benefit state aquatic invasive species management efforts.[1356]

  Please see the description of "Prevent establishment of aquatic invasive species" found in the section "Manage aquatic and riparian invasive and non-native species in a changing climate" for information on additional methods for incorporating climate change in aquatic invasive species management efforts.

[1344] *Heinz Center (2008, p. 30)
[1345] *Heinz Center (2008, p. 30-31)
[1346] Heinz Center (2008, p. 31). The authors cite The Heinz Center (2007) for this information.
[1347] *Bridging the Gap: Downscaling Climate Models to Inform Management Actions.* Workshop held November 3, 2010. Documents available at www.dfg.ca.gov/climatechange/downscaling-workshop/ (accessed 7.10.2011).
[1348] *Association of State Wetland Managers (ASWM). *Recommendations for a National Wetlands and Climate Change Initiative.* (2009, p. 12)
[1349] *ASWM. (2009, p. 12)
[1350] *ASWM. (2009, p. 12)
[1351] *ASWM. (2009, p. 12)
[1352] *U.S. EPA. (2008b, p. 4-2)
[1353] *U.S. EPA. (2008b, p. 4-2)
[1354] *U.S. EPA. (2008b, p. 4-2)
[1355] *U.S. EPA. (2008b, p. 4-2)
[1356] *U.S. EPA. (2008b, p. 4-2)

- **Incorporate climate change considerations into Ecosystem-Based Management (EBM):** EBM is an integrated approach to management that considers the entire ecosystem, including humans.[1357] The goal of ecosystem-based management is to maintain an ecosystem in a healthy, productive and resilient condition so that it can provide the services humans want and need.[1358] Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity or concern; it considers the cumulative impacts of different sectors.[1359] Specifically, ecosystem-based management:
    - Emphasizes the protection of ecosystem structure, functioning, and key processes;
    - Is place-based in focusing on a specific ecosystem and the range of activities affecting it;
    - Explicitly accounts for the interconnectedness within systems, recognizing the importance of interactions between many target species or key services and other non-target species;
    - Acknowledges interconnectedness among systems, such as between air, land and sea; and
    - Integrates ecological, social, economic, and institutional perspectives, recognizing their strong interdependences.[1360]

Develop dynamic landscape conservation plans

Dynamic landscape conservation plans include information on fixed and dynamic spatial elements, along with management guidelines for target species, genetic resources, and ecosystems within the planning areas.[1361] Fixed spatial elements include protected areas where the land use is fully natural.[1362] Dynamic spatial elements include all other areas within the landscape matrix, where land use may change over time.[1363] The plan includes a desired future condition for each element, based on predicted shifts in distribution of species and other ecosystem components, as well as any intermediate steps that may be necessary to transition between current and future condition.[1364] The management guidelines suggest mechanisms and tools for management (such as land acquisition, riparian plantings, or other wildlife-friendly farming practices) and specific government agencies responsible for implementation.[1365] The actual planning activities required to develop these plans are likely to be compatible with other local or regional-scale planning projects such as State Wildlife Action Plans or watershed management plans.[1366] However, planning efforts can be resource-intensive.[1367] Recommendations such as suggesting that certain spatial elements (i.e., areas of land or water) will need to be converted from human uses to “natural” management are likely to prove controversial.[1368]

[1357] *West Coast EBM Network. *Community-based management of coastal ecosystems: Highlights and lessons of success from the West Coast Ecosystem-Based Management Network (pdf).* (2010, p. 2)
[1358] *West Coast EBM Network. (2010, p. 2)
[1359] *West Coast EBM Network. (2010, p. 2)
[1360] *West Coast EBM Network. (2010, p. 2) The authors cite McLeod et al. (2005) for this information.
[1361] *Heinz Center (2008, p. 31). The authors cite Hannah and Hansen (2005) for this information.
[1362] *Heinz Center (2008, p. 31)
[1363] *Heinz Center (2008, p. 31)
[1364] *Heinz Center (2008, p. 31)
[1365] *Heinz Center (2008, p. 31)
[1366] *Heinz Center (2008, p. 31)
[1367] *Heinz Center (2008, p. 31)
[1368] *Heinz Center (2008, p. 31)

Develop/implement adaptive management policies and plans

Because of the uncertainty about climate change, its effects, and appropriate management responses, adaptive management policies and plans can play an important role in climate change adaptation (although adaptive management is not inherently linked to climate adaptation, see Box 21).[1369] Adaptive management involves testing hypotheses about system function and management efficacy and adjusting behavior and actions based on experience and actual changes.[1370] These decisions can be either active or passive; active adaptive management involves experimenting with multiple options in order to determine the best strategy, while passive adaptive management requires selecting and implementing one option and monitoring to determine if changes are needed.[1371]

For example, the Climate Resilience Evaluation and Awareness Tool (CREAT) allows users to evaluate potential impacts of climate change on their water utility and to evaluate adaptation options to address these impacts using both traditional risk assessment and scenario-based decision-making.[1372] CREAT provides libraries of drinking water and wastewater utility assets (e.g., water resources, treatment plants, pump stations) that could be impacted by climate change, possible climate change-related threats (e.g., flooding, drought, water quality), and adaptive measures that can be implemented to reduce the impacts of climate change.[1373] The tool guides users through identifying threats based on regional differences in climate change projections and designing adaptation plans based on the types of threats being considered.[1374] Following assessment, CREAT provides a series of risk reduction and cost reports that will allow the user to evaluate various adaptation options as part of long-term planning.[1375]

Changes to land use planning and zoning

This may include restricting or prohibiting development in erosion zones, redefining riverine flood hazard zones, or increasing shoreline setbacks.[1376] It may be difficult to attain agreement among all parties.[1377] Redefining riverine flood hazard zones to match projected expansion of flooding frequency and extent protects riverine systems and zones, but may impact flood insurance or require changing zoning ordinances, which can be difficult.[1378]

Integrate floodplain management and reservoir operations using Ecosystem-Based Adaptation

Ecosystem-based adaptation, or EBA, refers to the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change.[1379] At a recent conference held by the American Water Resources Association, Opperman et al. (2011) outlined a

[1369] *Gregg et al. (2011, p. 71)
[1370] *Gregg et al. (2011, p. 71)
[1371] *Gregg et al. (2011, p. 71)
[1372] *U.S. EPA. *Climate Resilience Evaluation and Awareness Tool (CREAT) (website).* (2011)
[1373] *U.S. EPA. *Climate Resilience Evaluation and Awareness Tool (CREAT) (website).* (2011)
[1374] *U.S. EPA. *Climate Resilience Evaluation and Awareness Tool (CREAT) (website).* (2011)
[1375] *U.S. EPA. *Climate Resilience Evaluation and Awareness Tool (CREAT) (website).* (2011)
[1376] *U.S. EPA. *Synthesis of Adaptation Options for Coastal Areas*. (2009, p. 14)
[1377] *U.S. EPA. (2009, p. 14)
[1378] *U.S. EPA. (2009, p. 14)
[1379] *Opperman et al. *Integrated floodplain-reservoir management as an ecosystem-based adaptation strategy to climate change (conference proceedings).* (April 18-20, 2011, p. 2) The authors cite IUCN (2009) for the definition of ecosystem-based adaptation.

rationale for integrated floodplain-reservoir management as an ecosystem-based adaptation (EBA) strategy to climate change.

Large-scale floodplain reconnection below dams can enable a reduction of reservoir flood-storage space, essentially transferring flood-storage functions from the reservoir to the downstream floodplain.[1380] By liberating some or all of a reservoir's flood-control storage, the reservoir can provide greater benefits in the form of increased hydropower, enhanced water-supply reliability, and environmental flows.[1381] Through this integration, floodplain reconnection serves as an EBA strategy for both flood risk and drought risk.[1382] This approach attaches economic value to floodplains, in the form of the increased reservoir benefits they facilitate by managing floodwater, and thus can provide revenue for funding floodplain restoration.[1383]

Though the integration of floodplain management and reservoir operations is not a panacea, Opperman et al. recommend the investigation of the full range of benefits from floodplain reconnection as an EBA strategy in already developed systems, as well as greater appreciation for the multiple benefits—including to the resiliency of water-management systems—provided by functioning, flooding floodplains in regions undergoing development of infrastructure.[1384]

Community planning

Local-level planning and involvement are key to achieving on-the-ground implementation of adaptation strategies.[1385] Although international and national action are needed to address broad policies and reform, community planning and management have greater effects on local resources through land use planning and zoning.[1386] Building local capacity is especially important for dealing with disaster risk management and gaining stakeholder support for action.[1387]

Ensure that wildlife and biodiversity needs are considered as part of the broader societal adaptation process

Modern wildlife professionals and natural resource managers are aware that management activities take place within a broader societal context, and that the broader society must be supportive in order for management to succeed.[1388] Managers can take proactive steps to engage local and regional government entities in adaptation planning, thereby ensuring that the needs of wildlife and natural resources are included at the start of these discussions.[1389]

[1380] *Opperman et al. (April 18-20, 2011, p. 7)
[1381] *Opperman et al. (April 18-20, 2011, p. 3)
[1382] *Opperman et al. (April 18-20, 2011, p. 3)
[1383] *Opperman et al. (April 18-20, 2011, p. 3)
[1384] *Opperman et al. (April 18-20, 2011, p. 3)
[1385] *Gregg et al. (2011, p. 62)
[1386] *Gregg et al. (2011, p. 62)
[1387] *Gregg et al. (2011, p. 62)
[1388] *Heinz Center (2008, p. 32)
[1389] *Heinz Center (2008, p. 32)

5. CLIMATE ADAPTATION ACTIONS – INFRASTRUCTURE AND DEVELOPMENT

The sections below address threats to the built environment and other infrastructure from climate change impacts in the freshwater environment.

Make infrastructure resistant or resilient to climate change

This strategy involves the consideration of climate change in both the planning of new or retrofitting of existing infrastructure, including stormwater systems, transportation, water supply, or buildings.[1390] Three examples are provided here:

- **Incorporate wetland protection into infrastructure planning:** The incorporation of wetland protection in transportation planning, sewer utilities, and other infrastructure planning helps protect infrastructure.[1391] It may also help maintain water quality and preserve habitat for vulnerable species.[1392]
- **Manage realignment and deliberately realign engineering structures:** Realignment of engineering structures affecting rivers, estuaries, and coastlines could reduce engineering costs, protect ecosystems and estuaries, and allow for natural migration of rivers.[1393] However, it can be costly.[1394]
- **Develop adaptive stormwater management practices:** *Please see the following adaptation action "Develop more effective stormwater infrastructure" for information on adaptive stormwater management practices.*

Develop more effective stormwater infrastructure

In general, the purpose of stormwater management is to control the amount of pollutants, sediments, and nutrients entering water bodies through precipitation-generated runoff.[1395] However, it also plays an important role in preventing damage to the built environment and the natural systems that protect it.[1396] Existing drainage systems may be ill-equipped to handle the amount of stormwater runoff that will accompany the more intense rainfall events expected in the future.[1397]

Adaptive stormwater management practices such as removing impervious surface and replacing undersized culverts minimize pollutant and nutrient overloading of existing wetlands.[1398] Further, promoting natural buffers and adequately sizing culverts preserves natural sediment flow and protects water quality of downstream reaches.[1399] Effective stormwater infrastructure could reduce future

[1390] *Gregg et al. (2011, p. 61)
[1391] *U.S. EPA. (2009, p. 13)
[1392] *U.S. EPA. (2009, p. 13)
[1393] *U.S. EPA. (2009, p. 11)
[1394] *U.S. EPA. (2009, p. 11)
[1395] *NOAA. (2010a, p. 93)
[1396] *NOAA. (2010a, p. 93)
[1397] *NOAA. (2010a, p. 93)
[1398] *U. S. EPA. (2009, p. 20)
[1399] *U. S. EPA. (2009, p. 15)

occurrences of severe erosion[1400] and maintain or improve water quality. However, they may require costly improvements.[1401] Additional modifications include:

- Updating stormwater regulations,
- Incorporating green infrastructure (*please see "Green infrastructure and low-impact development" in this section for further information*),
- Limiting/removing impervious surfaces,
- Acquiring easements for new and wider drainage ditches,
- Implementing and enforcing stream dumping regulations,
- Improving carrying and storage capacity of streams, channels, and basins through ongoing maintenance,
- Installing larger pipes and culverts (*Please see the section "Maintain, restore, or create stream and watershed connectivity" for information on improved culvert design.*),
- Adding pumps,
- Creating retention and detention basins, and
- Converting culverts to bridges.[1402]
- Phase out all combined sewer systems in the region.[1403]

Green infrastructure and low-impact development

As it relates to water resource management and protection, "green infrastructure" is a comprehensive approach that promotes the use of natural and built systems to improve infiltration, evapotranspiration, capture, and reuse of stormwater at regional, community, and site scales.[1404] It uses soil and vegetation in lieu of or in addition to the "hard" or "gray" infrastructure typically used to divert, store, and treat stormwater.[1405] Some aspects of green infrastructure will need to be managed through regulations (e.g., land use, building codes) and land acquisition programs; others will be most effective when promoted through outreach, education, and training.[1406]

In general, regional green infrastructure is an interconnected network of natural lands and waters that provide essential environmental functions (e.g., wetlands, floodplains, and forests) and the buffers that protect them.[1407] Examples of community and site-level green infrastructure practices that may help coastal communities adapt to climate change include:

- Vegetated swales and median strips,
- Urban forestry,
- Porous pavement,
- Rain gardens,
- Green roofs,

[1400] *Palmer et al. (2008, p. 33)
[1401] *U. S. EPA. (2009, p. 20)
[1402] *NOAA. (2010a, p. 93-94). The authors note that since some modifications and enhancements could encourage growth in the short-term, growth controls may also be needed.
[1403] Comment from reviewer (June 2011).
[1404] *NOAA. (2010a, p. 94)
[1405] *NOAA. (2010a, p. 94)
[1406] *NOAA. (2010a, p. 94)
[1407] *NOAA. (2010a, p. 95)

- Rain barrels and cisterns, and
- Downspout disconnection.[1408]

By helping to maintain and restore natural hydrology and removing nutrients, pathogens, and pollutants from stormwater, these approaches:

- Improve water quality and groundwater recharge,
- Reduce stormwater flooding,
- Protect ecosystems,
- Provide habitat,
- Provide recreational opportunities, and
- Improve aesthetics.[1409]

Build storage capacity

Damming rivers for conservation purposes is a controversial concept.[1410] They may provide managers with the ability to store water and manage river flows (timing, volume, temperature) to best suit the needs of salmon.[1411] In watersheds without sufficient water storage (natural or not), damming rivers may be an idea worth discussing.[1412] There are many arguments against building more dams including: the barrier to fish passage (both adults and out-migrating smolts), the impact on species besides salmon, and the impacts on the geomorphology of the river.[1413] Dam construction is also expensive.

[1408] *NOAA. (2010a, p. 95)
[1409] *NOAA. (2010a, p. 95)
[1410] *Nelitz et al. *Helping Pacific Salmon Survive the Impact of Climate Change on Freshwater Habitats.* (2007, p. 101)
[1411] *Nelitz et al. (2007, p. 101)
[1412] *Nelitz et al. (2007, p. 101)
[1413] *Nelitz et al. (2007, p. 101)

6. CLIMATE ADAPTATION ACTIONS – GOVERNANCE, POLICY, AND LAW

Local, regional, and national governments play important roles in many climate change policies and provide support to resource managers, conservation practitioners, and communities.[1414] Many projected climate impacts will have transboundary effects and require multilateral adaptation efforts.[1415] The sections below describe components of governance, policy, and law.

Note: Governance is not distinguished clearly from policy and law, as evidenced by the incorporation of policy and/or law into wide-ranging definitions of governance.[1416]

Develop a disaster preparedness plan

Coastal hazards, such as erosion, landslides, and extreme weather events, can harm people and property; climate change is projected to exacerbate these effects in both frequency and magnitude.[1417] Disaster preparedness plans can help coastal communities identify risks and vulnerabilities and develop options for response and recovery.[1418]

Maintain adequate financial resources for adaptation

Economic barriers are frequently cited by groups as reasons for not taking adaptation action.[1419] If adaptation activities focus on building climate change into existing efforts or frameworks (e.g., incorporating climate projections into bridge designs or harvest limits), ensuring adequate financing for adaptation means simply ensuring that project budgets reflect any needed additional funding (e.g. more materials needed for a higher bridge, or downscaled climate model scenarios for use in planning).[1420] Climate adaptation actions undertaken as a new and distinct set of activities (e.g., scenario planning exercises) will require new and distinct funding.[1421]

Some adaptation actions require up-front financial investment but more than pay for themselves in reduced long-term expenditures, meaning that grants or loans may be appropriate sources of financing.[1422] Grants can also provide short-term funds for strategy development and testing, but over the longer term it is important to diversify, for instance by building support for governmental adaptation funding, forging new partnerships, or reworking organizational budgets.[1423] Establishing endowments (e.g., the $90 million provincial endowment that established the Pacific Institute for Climate Solutions in British Columbia) can provide more stable funding than year-by-year funding.[1424] Increased and sustainable funding sources can

[1414] *Gregg et al. (2011, p. 67)
[1415] *Gregg et al. (2011, p. 67)
[1416] United Nations Economic and Social Council. Committee of Experts on Public Administration (Fifth Session). *Definition of basic concepts and terminologies in governance and public administration (pdf, website).* (2006).
[1417] *Gregg et al. (2011, p. 68)
[1418] *Gregg et al. (2011, p. 68)
[1419] *Gregg et al. (2011, p. 69)
[1420] *Gregg et al. (2011, p. 69)
[1421] *Gregg et al. (2011, p. 69)
[1422] *Gregg et al. (2011, p. 69)
[1423] *Gregg et al. (2011, p. 69)
[1424] *Gregg et al. (2011, p. 69)

help organizations and governments overcome financial constraints and adapt to changing environmental conditions.[1425]

Review existing laws, regulations, and policies

This strategy would initiate a review of all applicable laws, regulations, and other public policies related to wildlife management, natural resource management, and biodiversity conservation.[1426] Many of these laws and regulations are decades old, and most were developed before climate change became a significant concern.[1427] Actually addressing the deficiencies that are identified through these reviews may be difficult without significant political will to overcome institutional inertia.[1428] There will likely be significant concern expressed from all sides about any sweeping revisions to existing laws and regulations.[1429]

Create new or enhance existing policy

Legislation, regulations, agreements, and enforcement policies at local, regional, national, and international levels can be created or enhanced to support climate adaptation action.[1430] New legislative tools or regulations may be necessary to address specific climate change impacts.[1431] For example, given that existing wildlife and biodiversity legislation is often decades old, new legislative or regulatory approaches may very well be needed to address specific effects or challenges associated with climate change.[1432] Another example concerns in-stream flow rights: where in-stream flow rights do not currently exist, laws that define in-stream water flow as a legitimate and legal use of water could be passed. The obvious benefit of maintaining in-stream flows is to aquatic ecosystems. There are also opportunities to use existing regulatory frameworks to support conservation and management efforts to decrease the vulnerability of natural and human systems,[1433] provided that the program managers are given the flexibility needed to directly address climate threats.[1434]

[1425] *Gregg et al. (2011, p. 69)
[1426] *Heinz Center. (2008, p. 33)
[1427] *Heinz Center. (2008, p. 33)
[1428] *Heinz Center. (2008, p. 33)
[1429] *Heinz Center. (2008, p. 33)
[1430] *Gregg et al. (2011, p. 72)
[1431] *Heinz Center. (2008, p. 34)
[1432] *Heinz Center. (2008, p. 34)
[1433] *Gregg et al. (2011, p. 72)
[1434] *Heinz Center. (2008, p. 34)

Additional actions

The following adaptation actions for governance, policy, and law were found in the literature, but were not discussed in detail or are described elsewhere in this report:

- Create permitting rules that constrain locations for landfills, hazardous waste dumps, mine tailings, and toxic chemical facilities[1435]
- Floodplain zoning: *Please see the section "Reduce effects of increased flooding and extreme flow" for an explanation of floodplain zoning.*
- Flood hazard mapping: *Please see the section "Reduce effects of increased flooding and extreme flow" for an explanation of flood hazard mapping.*

[1435] *U.S. EPA. (2009, p. 10)

7. CLIMATE ADAPTATION ACTIONS – SPECIES AND HABITAT CONSERVATION, RESTORATION, PROTECTION AND NATURAL RESOURCE MANAGEMENT

Addressing adaptation in management and conservation is necessary to deal with the actual and potential effects of climate change on ecosystems and the functions and services they provide.[1436] Climate change may have negative *and* positive effects on wildlife and habitat.[1437] Managers and conservation practitioners can decrease ecosystem vulnerability by directly addressing expected climate change effects in policies and plans or by reducing the stressors that can exacerbate climate impacts.[1438] The sections below describe components of species and habitat conservation, restoration, protection, and natural resource management to consider to address potential climate change impacts.

Maintain, restore, or increase in-stream flow to address changes in snowpack, runoff, and streamflow regimes

The available evidence suggests that climate change may have profound impacts on water resource availability.[1439] Climate change will affect not only initial surface runoff into a stream system, but also rates of evaporative loss, seepage to groundwater aquifers, recharge from those aquifers and rates of consumptive use from irrigation withdrawals along the entire stream system.[1440] Hydrologic analyses of plausible climate change scenarios indicate possible substantial reductions in streamflows in some areas, increased flood frequencies in other areas, and changes in the seasonal pattern of flows, with reduced summer flows likely in many mountainous and northern river basins.[1441]

<u>Assess barriers to determine the potential for improving flow</u>

Assessment of barriers such as dams and diversion structures to determine the potential for improving flow[1442] may include the following activities:

- Develop reservoir release options with dam managers and/or design structures for temporary storage of flood waters before they reach the reservoir.[1443]
- Remove dams in areas with high evaporation, and consider methods to divert water to groundwater storage to provide for later use.[1444]
- Adjust outlet height on dam to release high quality water to downstream rivers (e.g., deeper waters are typically cooler than surface waters).[1445] With large changes in reservoir water levels,

[1436] *Gregg et al. (2011, p. 35)
[1437] *Gregg et al. (2011, p. 35)
[1438] *Gregg et al. (2011, p. 35)
[1439] *Miller et al. *Water allocation in a changing climate: institutions and adaptation*. (1997, p. 157)
[1440] *Miller et al. (1997, p. 167)
[1441] *Miller et al. (1997, p. 157). The authors cite Schaake (1990), Waggoner (1990), and Duell (1992) for this information.
[1442] *Nelson et al. (2007, p. 41)
[1443] *Palmer et al. (2008, p. 34)
[1444] *Palmer et al. (2008, p. 34)
[1445] *Palmer et al. (2008, p. 34)

the outlet height on dams may need adjusting to ensure high quality water to downstream rivers.[1446]

- Maintain the natural flow regime through managing dam flow releases upstream (e.g. through option agreements with willing partners) to protect flora and fauna in drier downstream reaches, or to prevent losses from extreme flooding.[1447] Water releases from dams and transporting fish may be necessary short-term solutions in times of drought or extreme low flows.[1448]
- Manage water storage and withdrawals to smooth the supply of available water throughout the year.[1449]
- Improve culvert design. *Please see the section "Maintain, restore, or create stream and watershed connectivity" for information on improved culvert design.*

Adapt water rights

The prospect of climate changes makes it more important to give explicit attention to the tradeoff between the initial costs of clarifying the rights of multiple water users and the future costs of conflicts that may arise if water availability changes.[1450] The desires of competing water users for certainty, flexibility and protection of environmental values must now be accommodated within the context of increasing hydrologic uncertainty.[1451] This suggests a number of factors that policymakers could consider in the upcoming decades as water statutes are modified, as adjudications are carried out, and as decisions are made regarding water transfers, issuance of new permits and protection of environmental values:[1452]

- **Improve the predictability of the limits of individual rights under a variety of possible climatic conditions:** It may be valuable to define limits on allowable consumptive use as a basis for reducing the adverse impacts of climate change on junior users and instream flows.[1453] For example, state regulations could specify consumptive use thresholds at which owners of existing water rights could reasonably be required to modify their diversions and application practices as climatic conditions change.[1454] State water authorities should explicitly incorporate such conditions in the specification of any new water rights.[1455]
- **Further document and clarify consumptive use rights:** The prospect of climate change suggests that it may be valuable to better document water withdrawals and consumptive uses, as well as natural variations in streamflows and groundwater levels.[1456] Such efforts should be targeted at reducing the basis for future disputes and providing adequate information for water transfers should water scarcity become more prevalent.[1457]
- **Better integrate groundwater and surface water rights:** In planning for the integration of groundwater and surface water rights, water authorities should give attention to how the

[1446] *Palmer et al. (2008, p. 36)
[1447] *Palmer et al. (2008, p. 33)
[1448] *Lawler (2009, p. 87). The authors cite Palmer et al. (2008) for this information.
[1449] *Palmer et al. (2008, p. 33)
[1450] *Miller et al. (1997, p. 170)
[1451] *Miller et al. (1997, p. 170)
[1452] *Miller et al. (1997, p. 170)
[1453] *Miller et al. (1997, p. 170)
[1454] *Miller et al. (1997, p. 170)
[1455] *Miller et al. (1997, p. 170)
[1456] *Miller et al. (1997, p. 171)
[1457] *Miller et al. (1997, p. 171)

hydrologic interactions between groundwater and surface water sources may be affected by a range of possible future changes in the local and regional climate.[1458]

- **Create flexibility to move water to more valuable uses:** Flexibility in water allocation can be achieved either through markets or through administrative action.[1459] The key is to ensure that the method chosen provides a fair and efficient means of moving some aspect of the water resource to a more valuable use.[1460]
- **Purchase or lease water rights:** The purchase or lease of water rights to enhance flow management options can be a valuable tool.[1461] For example, the establishment of dry-year option agreements with willing private partners can ensure that flows during droughts remain sufficient to protect critical habitats and maintain water quality.[1462] A strengthening of environmental flow programs and water use permit conditions to maintain natural flow conditions will also be critical.[1463]
- **Enhance the ability to condition rights in a fair and efficient manner to provide appropriate protection for environmental values:** Authorities could specifically condition new water rights to alert users to possible future modification of the rights and to explicitly spell out the climatic and environmental conditions under which such modifications can be expected.[1464] In addition, it would be valuable to develop clear policy statements regarding modifications of established rights in the event of future climate change or long-run drought, together with explicitly stated standards of evidence that will be used to determine when hydrologic conditions have changed sufficiently to warrant implementation of the regulations.[1465] Open discussion of the criteria by which policy options should be evaluated will also be valuable.[1466]

Create and preserve a water supply “safety margin”

The possibility of conflicts between competing water users might be reduced if instream flows are explicitly treated as a buffer to be used to absorb the impact of changing climatic conditions.[1467] Rather than setting a single minimum flow standard to be used as a target for avoiding serious adverse impacts on fisheries and other aquatic resources, a range of environmentally desirable flow levels could be defined.[1468] The lower level might serve as a trigger for water authorities to enhance instream flows by purchasing water or implementing restrictions on existing rights, while the upper level would be used as the target for conditioning new rights.[1469] For example, administrators could grant new permits subject to the condition that they not deplete streamflows beyond the upper flow- level target.[1470] If flows increase, water users could fully exercise the new rights.[1471] If flows decline, the impact would fall first on the

[1458] *Miller et al. (1997, p. 171)
[1459] *Miller et al. (1997, p. 172)
[1460] *Miller et al. (1997, p. 172)
[1461] *Palmer et al. (2008, p. 36-37)
[1462] *Palmer et al. (2008, p. 37)
[1463] *Palmer et al. (2008, p. 37)
[1464] *Miller et al. (1997, p. 174)
[1465] *Miller et al. (1997, p. 174)
[1466] *Miller et al. (1997, p. 174)
[1467] *Miller et al. (1997, p. 174)
[1468] *Miller et al. (1997, p. 174)
[1469] *Miller et al. (1997, p. 174)
[1470] *Miller et al. (1997, p. 174)
[1471] *Miller et al. (1997, p. 174)

conditioned permits, then on the buffer and finally on current water uses.[1472] Where water is already fully appropriated, authorities could create such a buffer by purchasing water rights from willing sellers to reduce existing consumptive uses (see the previous adaptation action *"Adapt water rights"* for further information on purchasing water rights).[1473] Where unappropriated water is available, they could more easily create such a buffer by incorporating appropriate conditions in the definition of new rights and by closing some streams to new appropriations unless and until there is considerable evidence that wetter conditions are likely to prevail.[1474]

<u>Implement low impact irrigation practices</u>

Low impact irrigation practices include optimizing irrigation timing and implementing drip irrigation. Optimized irrigation timing involves managing the daily timing of irrigation to minimize evaporation during warm periods and waste during rain.[1475] For example, in a pilot project on the Nicola River (at Kilchena, British Columbia), a number of mini irrigation monitoring stations were installed to track soil moisture and weather conditions.[1476] The monitoring station is linked to the farmer's phone so they know when the fields need to be irrigated.[1477]

Drip irrigation technology has the potential to at least double the crop yield per unit of water.[1478] However, drip irrigation does not necessarily save water when considered from a basin scale.[1479] In an integrated basin-scale analysis of the Upper Rio Grande Basin of North America, Ward & Pulido-Velazquez (2008) conclude adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge.[1480]

<u>Divert water from other locations</u>

Like dams, diversions are very controversial and may provide managers with the ability to store water and manage river flows (timing, volume, temperature) to best suit the needs of salmon.[1481] However there are major impacts to both the area where the water is removed and the area where the water is diverted to.[1482]

<u>Additional actions</u>

The following adaptation actions for maintaining, restoring, or increasing in-stream flow were found in the literature, but were not discussed in detail, or they are described elsewhere in this report:

- Maintain free-flowing rivers[1483]
- Reduce water extraction[1484]

[1472] *Miller et al. (1997, p. 174)
[1473] *Miller et al. (1997, p. 174)
[1474] *Miller et al. (1997, p. 174)
[1475] *Nelitz et al. (2007, p. 100)
[1476] *Nelitz et al. (2007, p. 100)
[1477] *Nelitz et al. (2007, p. 100)
[1478] *Nelitz et al. (2007, p. 100). The authors cite Postel (2000) for this information.
[1479] *Ward and Pulido-Velazquez. *Water conservation in irrigation can increase water use*. (2008, p. 18219). The authors cite Molden (2007) for this information.
[1480] *Ward and Pulido-Velazquez. (2008, p. 18215)
[1481] *Nelitz et al. (2007, p. 102)
[1482] *Nelitz et al. (2007, p. 102)
[1483] *Nelson et al. (2007, p. 41)
[1484] *Lawler. (2009, p. 87). The authors cite Hansen et al. (2003) for this information.

- Place snow fences to increase snowpack[1485] and/or alter snowpack patterns
- Disconnect road drainage from stream networks to restore natural patterns of flow.[1486]
- Minimize ground disturbance and land-use changes that reduce groundwater recharge, and implement Best Management Practices that encourage groundwater recharge from impervious and disturbed areas.[1487]
- Support and restore healthy beaver populations: *Please see the section "Maintain and restore wetlands and riparian areas" for an explanation of supporting and restoring beaver populations.*
- Restore riparian habitat: *Please see the section "Maintain and restore wetlands and riparian areas" for an explanation of restoring riparian habitat*

Case Study 1. Willamette Water 2100: Anticipating water scarcity and informing integrative water system response in the Pacific Northwest.

Climate impacts addressed: Changes in snowpack, runoff, groundwater and streamflow regimes

Description: In October 2010, faculty from Oregon State University, the University of Oregon, and Portland State University began a five-year project to evaluate how climate change, population growth, and economic growth will alter the availability and the use of water in the Willamette River Basin on a decadal to centennial timescale. The National Science Foundation sponsored project provides a means to ask "what if" questions about climate impacts on the hydrologic system and freshwater ecosystems. It has four objectives: identify and quantify the linkages and feedbacks among hydrologic, ecological, and socioeconomic dimensions of the water system; determine where and when human activities and climate change will create water scarcities; evaluate a broad range of strategies that could enable this region to prevent, mitigate, or adapt to water scarcities; and, lastly to create a transferable method of predicting where climate change will create water scarcities and where those scarcities will exert the strongest impacts on human society. The project team is using Envision, a modeling framework developed at OSU, to visualize and assess alternative future scenarios. Envision integrates a geographic information system with hydrological, ecological, and socio-economic process models, and user-defined policies that guide land and water management decisions parcel-by-parcel. As Envision steps through time, it generates maps and datasets depicting the interaction of policies with the changing conditions forecasted by the hydrologic, ecological and socio-economic models. The project includes a "stakeholders learning and action network" (SLAN) of agricultural and municipal water users, local public officials and natural resources professionals from federal, state, and local agencies. Currently, the SLAN is meeting with the team scientists to inform and critique the modeling framework and develop realistic policy scenarios. In future years, the SLAN will help analyze model results and convey results to their constituents.

Sources: Personal interview (June 2011); Willamette Water 2100.
http://water.oregonstate.edu/ww2100 (accessed 6.29.2011).; Envision.
http://envision.bioe.orst.edu<http://envision.bioe.orst.edu/> (accessed 6.29.2011).

[1485] *Lawler. (2009, p. 89). The authors cite Hansen et al. (2003) for this information.
[1486] *Furniss et al. (2010, p. 51)
[1487] *Furniss et al. (2010, p. 51)

Reduce effects of increased flooding and extreme flow

Restore the natural capacity of rivers to buffer climate change impacts

Establishing or restoring ecological buffer zones (buffers) along streams and other water bodies may be done through a variety of methods including land acquisition around rivers[1488] (*Please see the section "Maintain, restore, or create stream and watershed connectivity" for information on land acquisition*), levee setbacks to free the floodplain of infrastructure,[1489] and supporting healthy beaver populations *(Please see the section "Maintain and restore wetlands and riparian areas" for an explanation of supporting and restoring beaver populations)*.

Buffers are similar to setbacks (and may be included within setbacks), but are typically designed to protect the natural, rather than the built, environment.[1490] By protecting natural resources, buffers protect the natural and beneficial functions those resources provide.[1491]

Specifically, buffers are land use regulations designed to reduce the impacts of land uses (e.g., development) on natural resources by providing a transition zone between a resource and human activities.[1492] Typically, buffers are maintained in their natural vegetative state and activities such as vegetation removal, soil disturbance, and construction are restricted or prohibited.[1493]

The effectiveness of any buffer will depend on several factors, including size, elevation, vegetation, slope, soil, permitted activities, adjacent land uses, stormwater flow, and erosion rate.[1494] In addition, effectiveness will also be dependent on property owner compliance and the monitoring and enforcement of buffer regulations.[1495] If drafting new or revised buffer regulations, consider these characteristics as well as how buffers, and the natural resources they protect, might be affected by climate change in the next century.[1496]

> ***Zoning*** can be used to regulate parcel use, density of development, building dimensions, setbacks, impervious surfaces, type of construction, landscaping, etc. It can also be used to regulate where development can and cannot take place. ***Subdivision regulations*** go beyond zoning regulations. They may limit the subdivision of land in inappropriate areas; specify characteristics such as size, shape, orientation, and layout; set standards for infrastructure, open space, buffers, landscaping, and access/egress; and require hazard assessments and the consideration of impacts on neighboring lands.
>
> *Source: NOAA. Adapting to climate change: A planning guide for state coastal managers. (2010a, p. 65-66).*

Protective services (i.e. benefits) include providing habitat and connectivity; minimizing erosion and flooding by stabilizing soil, providing flood storage, and reducing flood velocities; and improving water quality through filtration of harmful sediment, pollutants,

[1488] Palmer et al. (2008, p. 33)
[1489] Palmer et al. (2008, p. 33)
[1490] *NOAA. (2010a, p. 85)
[1491] *NOAA. (2010a, p. 85)
[1492] *NOAA. (2010a, p. 85)
[1493] *NOAA. (2010a, p. 85-86)
[1494] *NOAA. (2010a, p. 86)
[1495] *NOAA. (2010a, p. 86)
[1496] *NOAA. (2010a, p. 86)

and nutrients.[1497] As climate changes, buffers will also be able to support inland wetland migration as well as carbon sequestration.[1498]

Floodplain zoning

Intended to create a healthy, safe, and orderly community while balancing a diversity of interests, ideally as envisioned by a comprehensive plan, zoning is one of the most commonly used methods of regulating land use.[1499]

Floodplain zoning is an example of a zoning application that, if thoughtfully drafted, can provide multiple benefits.[1500] In addition to protecting life and property (and reducing economic risk to communities, states, and the federal government), benefits of floodplain zoning can include resource conservation, open space preservation, public access, and water-quality protection.[1501] Floodplain regulations that just meet the minimum requirements of the National Flood Insurance Program are more focused on how to build safely in the floodplain and may not provide the additional benefits.[1502]

Current regulations may need to be revised to accommodate for new conditions.[1503] A state may want to encourage local governments to review the adequacy of their zoning, make changes and additions as appropriate, and to consider climate change in future zoning decisions.[1504] As the need for new districts arises, model language can help ease the process and advance state interests.[1505]

Flood hazard mapping

Flood hazard maps are prepared for areas adjacent to water bodies to provide land owners, insurers and regulators with information on their risks of flooding from a variety of environmental conditions.[1506] Flood hazard maps are used to plan for and reduce impacts from the riverine and coastal flooding that would likely result from cyclones, heavy rains, storm surges, extreme tides, and tsunamis.[1507] Once the maps are generated, the information can be incorporated into risk reduction procedures (including evacuation and community-based disaster risk reduction plans) or adaptation measures (e.g., construction of flood control structures; establishment of warning systems; formulation of development policies and standards such as setbacks, zoning, building codes, etc.).[1508] Flood hazard maps can also be used to guide development away from sensitive habitats in floodplains, maintain critical ecosystem services (such as flood storage in wetlands), maintain the natural and beneficial function of floodplains, protect public lands, guide development to low hazard areas, and reduce impacts to development.[1509]

1497 *NOAA. (2010a, p. 85)
1498 *NOAA. (2010a, p. 86)
1499 *NOAA. (2010a, p. 65)
1500 *NOAA. (2010a, p. 65)
1501 *NOAA. (2010a, p. 65)
1502 *NOAA. (2010a, p. 65)
1503 *NOAA. (2010a, p. 66)
1504 *NOAA. (2010a, p. 66)
1505 *NOAA. (2010a, p. 66)
1506 *USAID. *Adapting to coastal climate change: A guidebook for development planners.* (2009, p. 127)
1507 *USAID. (2009, p. 127)
1508 *USAID. (2009, p. 127)
1509 *USAID. (2009, p. 127, 129)

The mapping of flood hazards typically begins by taking observed data or historic information on previous events and combining it with hypothetical information about future events to predict the potential magnitude of flood waters.[1510] This can be done with the use of engineering computer models or through participatory mapping.[1511] Before mapping flood hazards, deciding how the information will be used by communities and governments will determine the technical requirements of the mapping activity and help make a match between budget and the scope of the mapping effort.[1512]

Additional actions

The following adaptation actions for reducing the effects of increased flooding and extreme flow were found in the literature, but are not described in detail or are described elsewhere in this report:

- Remove sediment from reservoirs to increase water storage capacity in short-term[1513]
- Create wetlands and off-channel basins for water storage during times of extreme flows:[1514] This may prevent excess water from reaching reservoirs and reduce downstream flows[1515] and reduce erosion during high flow periods.[1516]
- Close road segments[1517]
- Design culverts to improve connectivity and mobility, e.g. oversize new and replacement culverts:[1518] *Please see the section "Maintain, restore, or create stream and watershed connectivity" for information on improved culvert design.*
- Integrate floodplain management and reservoir operations using Ecosystem-Based Adaptation. *Please see the section "Monitoring, planning, infrastructure, and development" for information on integrating floodplain management and reservoir operations with Ecosystem-Based Adaptation.*

Moderate or reduce water temperature

Release cold water from lakes or reservoirs

Using cold water pools to maintain cooler river temperature is a strategy that is used extensively in California and has been tried with varying degrees of success in BC. [1519] For example, temperature control curtains are a tool to enable the withdrawal of cooler water from a reservoir with thermal stratification and are being used in the Trinity River Reservoir, CA.[1520] They may be a cost effective way of selectively withdrawing cooler water from a reservoir with thermal stratification.[1521] In Cameron Lake (Vancouver Island, BC), a computer system monitors river temperatures and releases water from the weir on the lake

[1510] *USAID. (2009, p. 128)
[1511] *USAID. (2009, p. 128)
[1512] *USAID. (2009, p. 128)
[1513] *Lawler. (2009, p. 87). The authors cite Palmer et al. (2008) for this information.
[1514] *Lawler. (2009, p. 87). The authors cite Palmer et al. (2008) for this information.
[1515] *Lawler. (2009, p. 87). The authors cite Palmer et al. (2008) for this information.
[1516] *Palmer et al. (2008, p. 33)
[1517] *Hayward et al. *Managing fish and wildlife habitat in the face of climate change: USDA Forest Service perspective.* (2009, p. 104)
[1518] *Hayward et al. (2009, p. 104)
[1519] *Nelitz et al. (2007, p. 104)
[1520] *Nelitz et al. (2007, p. 104)
[1521] *Nelitz et al. (2007, p. 104). The authors cite Vermeyen (1997) for this information.

as needed during critical spawning times.[1522] This has resulted in summer water temperatures that are more tolerable to salmon.[1523] Considerations for the use of cold water releases from lakes or reservoirs to reduce water temperatures include:

- There may only be a local effect on temperature[1524]
- Effect on the ecosystem, colder is not always better for all species or communities[1525]
- Engineering challenges & costs of maintaining and accessing cold water source[1526]
- Climate change is expected to result in ecosystems shifting from glacierized or snow dominated to snow or rain dominated.[1527] These changes (i.e. less snow melt and more rain) will affect the cold water source and the methods used to maintain a cold water supply.[1528] For example, a reduction of snowmelt in the Trinity River watershed would mean that greater carryover storage (minimum water level in the reservoir) would be necessary as lowering the level too far warms the reservoir.[1529]

Low-impact forestry practices

A reduction in stream shade is the dominant mechanism by which forestry activities can increase stream temperature.[1530] Maintaining stream shade at natural levels can prevent harvesting-related stream heating.[1531] Riparian buffer strips of approximately 98 feet (~30 m) were found to provide sufficient shading and prevent increases in stream temperature.[1532] However, a recent study of Flat Branch, a perennial second-order tributary of the Tallulah River Watershed in Georgia, found no significant difference in summertime mean or minimum temperature between cut and uncut areas, although a small but statistically significant increase in monthly summer maximum stream water temperature occurred within the cut area following harvest.[1533] Water temperatures were not different from reference levels at the below-cut site.[1534]

Transplant stocks or species to take advantage of differences in physiological characteristics[1535]

A possible strategy given increasing stream temperatures is to transplant temperature tolerant stocks or species to warmer streams.[1536] This strategy could be controversial as it risks the ability to maintain unique stocks (and could result in a decrease in biodiversity or an increase in "non-native" species).[1537]

[1522] *Nelitz et al. (2007, p. 104). The authors cite Vermeyen (1997) for this information.
[1523] *Nelitz et al. (2007, p. 104). The authors cite Vermeyen (1997) for this information.
[1524] *Nelitz et al. (2007, p. 104)
[1525] *Nelitz et al. (2007, p. 104)
[1526] *Nelitz et al. (2007, p. 104)
[1527] *Nelitz et al. (2007, p. 104). The authors cite Stahl (2007) for this information.
[1528] *Nelitz et al. (2007, p. 104)
[1529] *Nelitz et al. (2007, p. 104). The authors cite Deas (1997) for this information.
[1530] *Teti. *Shade and Stream Temperature (website).* (2003/04, p. 4)
[1531] *Teti. (2003/04, p. 1)
[1532] *Shrimpton et al. *Removal of the riparian zone during forest harvesting increases stream temperature: are the effects cumulative downstream?* (2000, p. 534)
[1533] *Clinton et al. *Flat Branch Monitoring Project: Stream water temperature and sediment responses to forest cutting in the riparian zone.* (2010, p. 3)
[1534] *Clinton et al. (2010, p. 3)
[1535] *Nelitz et al. (2007, p. 40)
[1536] *Nelitz et al. (2007, p. 99)
[1537] *Nelitz et al. (2007, p. 99)

Experience with transplanting stocks for enhancement has had limited success, so this strategy may be difficult to implement.[1538] Information on species and stock specific environmental thresholds, ranges and ecology is critical to informing management actions.[1539]

Build a groundwater-fed side channel

Groundwater injection to surface waters moderates water temperature and provides flows in rearing channels.[1540] Groundwater-fed side channels are less prone to winter scouring of eggs and juveniles.[1541] They also provide a water supply through the summer.[1542] Considerations to include in building a groundwater-fed side channel include:

- Groundwater source, sufficient space and the right slope, substrate (gravel; clay, sand, and silt do not work)[1543]
- If set up properly, groundwater channels are self-fed and therefore self- sustaining.[1544]

Additional actions

The following adaptation actions for moderating or reducing water temperature were found in the literature, but are not described in detail or are described elsewhere in this report:

- Identify and protect existing thermal refugia[1545]
- Manipulate run-timing to avoid peak temperatures[1546]
- Support and protect ground water resources in the watershed through monitoring and regulation of groundwater extraction and pumping[1547]
- Riparian restoration: Maintaining riparian vegetation is particularly important to help maintain cool stream temperatures.[1548] *Please see the section "Maintain and restore wetlands and riparian areas" for information on riparian restoration.*
- Floodplain restoration: *Please see the previous section "Reduce effects of increased flooding and extreme flow" for information on restoring the natural capacity of rivers to buffer climate change impacts.*
- Protect headwaters: *Please see the section "Preserve habitat for vulnerable species" for information on protecting headwaters.*

Maintain or improve water quality

As described in Chapter 3 Section 5, the most important factors that influence the effects of climate change on water quality are increases in atmospheric and water temperatures and changes in the timing

[1538] *Nelitz et al. (2007, p. 99)
[1539] *Nelitz et al. (2007, p. 99)
[1540] *Nelitz et al. (2007, p. 105)
[1541] *Nelitz et al. (2007, p. 105)
[1542] *Nelitz et al. (2007, p. 105)
[1543] *Nelitz et al. (2007, p. 105)
[1544] *Nelitz et al. (2007, p. 105)
[1545] *Lawler. (2009, p. 87). The authors cite Hansen et al. (2003) this information.
[1546] *Nelitz et al. (2007, p. 99)
[1547] Comment from reviewer (June 2011)
[1548] *Nelitz et al. (2007, p. 106)

and amount of streamflow.[1549] For example, higher surface water temperatures will promote algal blooms and increase the bacteria and fungi content.[1550] In regions where intense rainfall is expected to increase, pollutants (pesticides, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies.[1551]

Implement low-impact forestry practices

For example, maintain riparian buffers, avoid steep slopes, and minimize the use of chemicals.[1552] Management of logging roads is another option.[1553] For example:

- Design to minimize sediment input[1554]
- Use crushed rock to reduce surface erosion[1555]
- Install adequate drainage structures and stream crossings[1556]
- Deactivate old logging roads and restore land to its original condition[1557]

Additional actions

The following adaptation actions for maintaining or improving water quality were found in the literature, but were not described in detail or are described elsewhere in this report:

- Develop more effective stormwater infrastructure *e see the section "Climate adaptation actions – infrastructure and development" for information*. *Pleas on effective stormwater infrastructure.*
- Green infrastructure and low-impact development (LID). *Please see the section "Climate adaptation actions – infrastructure and development" for information on green infrastructure and LID.*
- Support/restore healthy beaver populations. *Please see the section "Maintain and restore riparian areas" for information on healthy beaver populations. It follows the next action/*

Address climate change impacts on glaciers

As one reviewer noted, actions to address climate change impacts on glacier size and abundance are provocative and highly unlikely to be implemented in this region (e.g. spread foam or cloth covering on glaciers in the summer).[1558]

[1549] *Pike et al. (2010, p. 728)
[1550] *Kundzewicz et al. (2007, p. 188). The authors cite Hall et al. (2002) and Kumagai et al. (2003) for information on algal blooms and Environment Canada (2001) for information on bacteria and fungi content.
[1551] *Kundzewicz et al. (2007, p. 188). The authors cite Fisher (2000), Boorman (2003b), and Environment Canada (2004) for this information.
[1552] *Nelitz et al. (2007, p. 106)
[1553] *Nelitz et al. (2007, p. 106)
[1554] *Nelitz et al. (2007, p. 106)
[1555] *Nelitz et al. (2007, p. 106). The authors cite Roni et al. (2001) for this information.
[1556] *Nelitz et al. (2007, p. 106)
[1557] *Nelitz et al. (2007, p. 106)
[1558] Personal communication with reviewer, April 2011; Orlove. *Glacier retreat: reviewing the limits of human adaptation to climate change*. (2009, p. 28)

Maintain and restore riparian areas

The riparian ecosystem is particularly important given climate change, since riparian vegetation provides shade which helps to cool tributaries.[1559] In addition, riparian vegetation provides a source of large woody debris which improves the quality of rearing habitat and provides habitat for a number of other wildlife species.[1560]

Restore riparian habitat

River restoration projects can be used to achieve a variety of goals, such as stabilizing eroding banks, repairing in-stream habitat, or promoting fish passages from areas with high temperatures and less precipitation.[1561] However, riparian restoration without ecosystem function restored may require periodic intervention as well as expensive actions such as floodplain grading.[1562] Thus, it is important to conserve the watershed function.[1563] Conserving habitat may be less expensive and more effective than restoring habitat.[1564]

A study by Battin et al. (2007) indicates the success of riparian/watershed restoration may vary based on the elevation of the area to be restored and the climate change impacts projected for the region.[1565] Battin et al. note that projects that rely on the preservation of relatively undisturbed high-elevation streams that derive a significant proportion of their flow from snowmelt may be especially vulnerable to climate change (e.g., the Snohomish Basin in WA), and the intuitively appealing idea that high-elevation watersheds should be the top priority for restoration and preservation in the face of climate change may prove to be incorrect in the region.[1566] However, watersheds at elevations and latitudes higher than those considered in the study may continue to receive most of their winter precipitation as snow and thus respond differently to climate change.[1567] For further information on this study, please see Case Study 4.

Riparian restoration activities may include:

- **Channel reconfiguration, dam removal or retrofit, floodplain restoration, dam-based flow management, and/or bank stabilization:**[1568] Restoring slope stability, for example, prevents slides, erosion, and fine sediment deposition.[1569] It can be done before starting habitat improvements in the main channel.[1570]
- **Restore connectivity with floodplain and channel meander capacity:** One benefit is to create diverse riparian habitat for wildlife, vegetation, and bird species and to provide winter refugia for anadromous fish.[1571]

[1559] *Nelitz et al. (2007, p. 109)
[1560] *Nelitz et al. (2007, p. 109)
[1561] *Palmer et al. (2008, p. 33)
[1562] *Nelitz et al. (2007). The authors cite Orr et al. (2006) for this information.
[1563] *Nelitz et al. (2007, p. 100)
[1564] *Nelitz et al. (2007, p. 100)
[1565] *Battin et al. (2007)
[1566] *Battin et al. (2007, p. 6724)
[1567] *Battin et al. (2007, p. 6724)
[1568] *Lawler. (2009, p. 87)
[1569] *Nelitz et al. (2007, p. 107). The authors cite Hartman et al. (1996) for this information.
[1570] *Nelitz et al. (2007, p. 107). The authors cite Hartman et al. (1996) for this information.
[1571] Comment from reviewer (June 2011).

- **Plant riparian vegetation to restore large woody debris and boulders in stream channels to create deeper pools:**[1572] Planting riparian vegetation provides a long-term source for woody debris and ensures adequate flows to ensure the natural hydrological processes occur to maintain sediment budgets and channel complexity.[1573] It takes fifteen to twenty years to see habitat effects of riparian planting.[1574] A detailed understanding of the timing of seed dispersal and recruitment requirements is needed in order to best determine which plants are most suitable and how to manage the flows most effectively.[1575] There may be tradeoffs between species in terms of the shade they provide and the water they require.[1576] Re-establishing successional processes for pioneer species would require channel meandering with formation of new alluvial surfaces and flow regimes that mimic the natural frequency and timing.[1577] In terms of where to focus riparian planting, interviews conducted by Nelitz et al. (2007) suggest the focus for riparian planting should be in the tributaries.[1578] The impact of shading on large rivers is minimal.[1579] Tributaries will remain cooler with sufficient shading and this will flow into the mainstem providing cold water refuges in the mainstem.[1580] These are used by adult migrating fish as holding areas and they can move between these in order to find an appropriate spawning area.[1581] In terms of specific species to plant, Roni et al. (2002; as cited in Nelitz et al., 2007) suggest planting conifers in riparian zones after disturbances because they provide a better long-term source of woody debris.[1582]
- **Instream habitat enhancement:** There is evidence that instream habitat enhancement may be effective for increasing freshwater productivity for some species.[1583] However they tend to have limited persistence and they should be employed only where short term enhancement is needed.[1584] A more holistic approach is needed in the long term, restoring ecological function so that the instream enhancements are unnecessary (e.g. restore large woody debris).[1585]
- **Additional riparian restoration activities**
    - Use drought-tolerant plant varieties to help protect riparian buffers.[1586]
    - Minimize temperature increases by maintaining well-shaded riparian areas and limiting groundwater withdrawals.[1587]

1572 *TU. *Healing Troubled Waters: Preparing trout and salmon for a changing climate.* (2007, p. 11)
1573 *Nelitz et al. (2007, p. 107). The authors cite USFWS and HVT (1999) for this information.
1574 *Nelitz et al. (2007, p. 109)
1575 *Nelitz et al. (2007, p. 109)
1576 *Nelitz et al. (2007, p. 109)
1577 *Nelitz et al. (2007, p. 109). The authors cite Orr et al. (2006) for this information.
1578 *Nelitz et al. (2007, p. 109). The authors cite Nina Hemphill, Trinity River Restoration Program, pers. comm. for this information.
1579 *Nelitz et al. (2007, p. 109). The authors cite Al von Finster, Fisheries and Oceans Canada, pers. comm. for this information.
1580 *Nelitz et al. (2007, p. 109)
1581 *Nelitz et al. (2007, p. 109). The authors cite Nina Hemphill, Trinity River Restoration Program, pers. comm. for this information.
1582 *Nelitz et al. (2007, p. 109)
1583 *Nelitz et al. (2007, p. 107). The authors cite Roni et al. (2002), Lacey et al. (2004), and Ward et al. (2006) for this information.
1584 *Nelitz et al. (2007, p. 107). The authors cite Roni et al. (2002) for this information.
1585 *Nelitz et al. (2007, p. 107)
1586 *Palmer et al. (2008, p. 33)
1587 *Furniss et al. (2010, p. 51)

- Avoid over-grazing (elk, moose, deer) either via hunting or by restoring populations of predators (e.g. wolves).[1588]
- Prevent excessive livestock grazing and damage to riparian vegetation through exclusion and/or proper grazing management such as rest-rotation.[1589]
- Restore beaver populations[1590]

Protect the assets of Wild and Scenic Rivers

The Wild and Scenic River System was created to protect and preserve the biological, ecological, historic, scenic and other “remarkable” values of U.S. rivers.[1591] In light of climate change impacts and their anticipated effects on habitat, biodiversity, and other ecological assets, it may be useful to emphasize such natural values when designating new Wild and Scenic Rivers.[1592] In addition, where two outstandingly remarkable values are in conflict within the same designated river—as sometimes happens, for example, between habitat and recreational values—an open and fair process in which climate change impacts are considered needs to be used to evaluate the priorities.[1593] Given limited financial and human resources, Palmer et al. (2008) identify actions for the protection of Wild and Scenic River assets under conditions of climatic change:

- Increase monitoring capabilities in order to acquire adequate baseline information on water flows and water quality, thus enabling river managers to prioritize actions and evaluate effectiveness.[1594]
- Increase forecasting capabilities and develop comprehensive scenarios so that the spectrum of possible impacts, and their magnitude, can reasonably be anticipated.[1595]
- Strengthen collaborative relationships among federal, state, and local resource agencies and stakeholders to facilitate the implementation of adaptive river management strategies.[1596] For example, because the agencies administering Wild and Scenic Rivers have little or no authority over dam operations, a proactive collaboration among the agencies involved – at federal, state, and local levels – is critical.[1597]
- Forge partnerships and develop mechanisms to ensure environmental flows for Wild and Scenic Rivers in basins that experience water stress.[1598]
- Work with land use planners to minimize additional development on parcels of land adjacent to Wild and Scenic Rivers, and optimally to acquire floodplains and nearby lands that are not currently federally owned or ensure they are placed in protected status.[1599]
- Build flexibility and adaptive capacity into the Comprehensive River Management Plans for Wild and Scenic Rivers, and update these plans regularly to reflect new information and scientific understanding.[1600]

[1588] Comments from reviewers. (June & July 2011)
[1589] Comment from reviewer. (July 2011)
[1590] Comment from reviewer. (June 2011)
[1591] *Palmer et al. (2008, p. 37)
[1592] *Palmer et al. (2008, p. 37)
[1593] *Palmer et al. (2008, p. 37)
[1594] *Palmer et al. (2008, p. 38)
[1595] *Palmer et al. (2008, p. 38)
[1596] *Palmer et al. (2008, p. 38)
[1597] *Palmer et al. (2008, p. 36)
[1598] *Palmer et al. (2008, p. 38)
[1599] *Palmer et al. (2008, p. 38)

Support/restore healthy beaver populations

Beavers are ecosystem engineers because their building activities can change, maintain, or create habitats by modulating the availability of resources of both biotic and abiotic materials for themselves and for other species.[1601] Similarly, their foraging activity also alters organic material availability, thus creating habitat for other species, because tree felling by beavers for feeding purposes rarely entails the consumption of the whole plant material.[1602] The strength (i.e., magnitude and nature) of beaver impact varies from site to site, depending on the geographical location, relief, and the impounded habitat type.[1603] Consequently, they may not be significant controlling agents of the ecosystem in all parts of their distribution.[1604] According to the Washington Department of Fish and Wildlife (2004), beaver can be reintroduced to any watershed where they have been extirpated within the following parameters:

- The channel is less than 3% slope to minimize dam blow-outs;
- The water supply is perennial or beaver are released on ephemeral streams during a period with sufficient water to create a dam and lodge;
- The stream geomorphology is such that beaver activities will be supported. For example beaver do not seem to colonize as well in volcanic stream systems due to the instability of the channel;
- Beaver will not cause unacceptable damage to public or private property or facilities;
- There is an adequate food source (at least 18 acres of willow or 6 acres of *Populus* species within 100 feet (~30 meters) of the stream) and dam building materials;
- Their activities will not conflict with other management prescriptions, such as endangered species management or instream flow issues;
- The valley is at least 60 feet (~18 meters) wide (150 feet, or ~46 meters, or more is best); and,
- The site is below 6,000 feet (~1828 meters) elevation. The short growing season and heavy snowfall above this elevation may be limiting factors for beaver.[1605]

Implement low-impact livestock grazing practices

Low-impact livestock grazing techniques can include:

- Riparian fencing;
- Rotational grazing;
- Offstream water development (prevents cattle from needing to directly access the river);
- Brush and woody vegetation control/removal;
- Rangeland Water Quality Management Plan;
- Riparian restoration *(Please see the section "Maintain and restore wetlands and riparian areas" for information on riparian restoration.);*

[1600] *Palmer et al. (2008, p. 38)
[1601] *Rosell et al. *Ecological impact of beavers Castor fiber and Castor canadensis and their ability to modify ecosystems.* (2005, p. 248). The authors cite Jones, Lawton & Shachak (1994) and Gurney and Lawton (1996) for this information.
[1602] *Rosell et al. (2005, p. 248)
[1603] *Rosell et al. (2005, p. 248)
[1604] *Rosell et al. (2005, p. 248)
[1605] *WA-DFW. *2004 Stream Habitat Restoration Guidelines: Final Draft: Beaver Re-introduction.* (2004, p. 3). The authors cite McKinstry and Anderson (1999) for problem areas to avoid as well as benefits that landowners feel they receive from beaver. The authors cite Vore et al. (1993) for information on food source, valley width, and maximum elevation.

- Controlled burning; and,
- Native perennial grass restoration.[1606]

Maintain and restore wetlands

Promote or sustain wetland accretion and nourishment

Four options for promoting or sustaining wetland accretion and nourishment are:

- Divert sediments to nourish wetlands.[1607]
- Adopt buffers to reduce potential for erosion and pollution, to keep water temperatures low, and to allow migration of plants and animals.[1608]
- Flood storage to reduce erosion and wash out events: *Please see "Reduced effects of increased flooding and extreme flow) for further information on flood storage.*
- Water recharges to keep water temperatures low and prevent wetland drying: *Please see "Maintain, restore, or increase in-stream flow to address changes in snowpack, runoff, and streamflow regimes" and "Moderate or reduce water temperature" for further information.*

Facilitate wetland migration

Wetland migration is facilitated by identifying wetlands most able to migrate, the sites to which they could migrate, and acquiring lands important for migration (including buffer zones).[1609] Requiring building setbacks from coastal and riparian wetlands is another option,[1610] as is reducing Federal subsidies such as U.S. Coastal Zone Management Act funds and flood insurance in areas that have not established setback or "planned retreat" policies.[1611]

Protect existing wetlands

Existing wetlands may be protected by augmenting and coordinating monitoring of wetlands to test and refine hypotheses about climate change, its effects, and the effectiveness of various management options.[1612] A number of existing and potential Federal policy and regulatory actions are available, including:

- Implement and oversee the no-net-loss policy;
- Expand coverage and strengthen enforcement of U.S. Clean Water Act Section 404 to protect all wetlands and to account for plausible effects of climate change;
- Design Federal projects to incorporate climate change predictions and safeguard water and sediment flow to wetlands; and,
- Eliminate Federal incentives for wetland destruction.[1613]

[1606] *Nelitz et al. (2007, p. 106)
[1607] *ASWM. (2009, p. 12)
[1608] *ASWM. (2009, p. 11)
[1609] *OTA. (1993, p. 197)
[1610] *OTA. (1993, p. 197)
[1611] *OTA. (1993, p. 197)
[1612] *OTA. (1993, p. 197)
[1613] *OTA. (1993, p. 197)

Requiring direct payments or traded obligations and acquiring key wetlands that may be lost soon are additional options.[1614] For example, developing a list of high-priority wetlands within an integrated resource management framework would help direct funds to areas and wetland types that are either insufficiently protected now or that could be especially vulnerable to climate change.[1615]For further information on prioritizing wetlands with large carbon stores, please see the adaptation action that follows this one *"Prioritize retention/protection of wetlands with large carbon stores."*

Prioritize retention/protection of wetlands with large carbon stores

Unless already known, wetland prioritization could begin by identifying wetlands with strong restoration potential under climate change conditions.[1616] For example, wetlands with deep carbon deposits could be identified and targeted for acquisition or more stringent regulations.[1617] Another route is to use existing watershed plans and other land use planning to determine the processes and actions needed to increase the resistance and resilience of wetlands and watersheds in the face of climate change.[1618] The Association of State Wetland Managers (2009) suggests regulatory agencies at all levels of government should amend regulations to better protect wetland carbon stores.[1619] Further, permittees should be required to estimate carbon impacts in seeking permits, and mitigation and compensation measures should be required.[1620]

Additional actions

The following adaptation actions for maintaining and restoring wetlands were found in the literature, but are described elsewhere in this report:

- Restore degraded or converted wetlands: Restoration of degraded or converted wetlands may include removal of hard engineering structures that degrade wetlands and restoration of more naturally regulated water and sediment flow.[1621] Fully funding existing restoration programs helps facilitate wetland restoration.[1622]
- Improve coordinated management and monitoring: *Please see the section "Climate adaptation actions – monitoring and planning" for information on improving coordinated management and monitoring.*
- Incorporate climate change into wetland restoration planning: *Please see the section "Climate adaptation actions – monitoring and planning" for information on incorporating climate change into wetland restoration planning.*
- Promote wetland connectivity and persistence: *Please see the section "Maintain, restore, or create stream and watershed connectivity" for information on promoting wetland connectivity and persistence.*

[1614] *OTA. (1993, p. 199)
[1615] *OTA. (1993, p. 199)
[1616] *ASWM. (2009, p. 11)
[1617] *ASWM. (2009, p. 11)
[1618] *ASWM. (2009, p. 12)
[1619] *ASWM. (2009, p. 12)
[1620] *ASWM. (2009, p. 12)
[1621] *OTA. (1993, p. 197)
[1622] *OTA. (1993, p. 197)

Maintain and restore lake shorelines

Note to the reader: These actions are culled from a City of Seattle guidebook, and can be applied to homes all around Lake Washington (WA).[1623] Additionally, most of the information is relevant to Lake Samammish (WA),[1624] and may be relevant for similar lakes in other areas of the NPLCC.

The actions listed here are examples of alternatives to armored shorelines (e.g. concrete, riprap, sheetpile, or another type of bulkhead) known as Green Shorelines.[1625] A cost-comparison of armored and Green shorelines is found in Table 19, and a decision-tree for selecting one or more of the actions described below can be found in Figure 30 (see p. 199 and 200, respectively).

<u>Install or restore full beaches</u>

On the right site (see Figure 30), beach restoration can be straightforward:[1626]

1. **Remove the bulkhead:** The costs of removing a bulkhead depend on the site's accessibility and the type of bulkhead, as shown in Table 18.

Table 18. Bulkhead removal costs per linear foot.
Reproduced from Seattle Department of Planning and Development (DPD). (n.d., p. 25) by authors of this report.

Site Access	*Bulkhead material (removal)*		
	Wood	Riprap	Concrete
Accessible from land and water	$30-40	$45-60	$95-110
Accessible from water only	$40-55	$55-80	$100-125

2. **Lay back the slope to a stable angle:** Beach slope is a critical component of a successful restoration project.[1627] A well-designed slope provides resistance to erosion, reducing the need for maintenance.[1628] Slopes of 7:1 or flatter are ideal (seven horizontal feet for each vertical foot), but slopes up to 4:1 can be stable in some circumstances.[1629]
3. **Add appropriate gravel and plants:** New beaches should be made of an appropriate gravel material.[1630] Although people tend to think of sand when they think of shorelines, sand erodes quickly in most parts of Lake Washington.[1631] Instead, use clean, well-rounded gravel 1/8" to 2" size – specifics will depend on wave energy and your proximity to known sockeye spawning grounds.[1632] Contact the Washington State Department of Fish and Wildlife to learn about

[1623] *Seattle-DPD. *Green Shorelines: Bulkhead Alternatives for a Healthier Lake Washington.* (n.d., p. 2)
[1624] *Seattle-DPD. (n.d., p. 2)
[1625] *Seattle-DPD. (n.d.)
[1626] *Seattle-DPD. (n.d., p. 6)
[1627] *Seattle-DPD. (n.d., p. 7)
[1628] *Seattle-DPD. (n.d., p. 7)
[1629] *Seattle-DPD. (n.d., p. 7)
[1630] *Seattle-DPD. (n.d., p. 7)
[1631] *Seattle-DPD. (n.d., p. 7)
[1632] *Seattle-DPD. (n.d., p. 7)

requirements.[1633] If sand is desired it should either be placed well above the water line or physically separated from the gravel beach using stone or wood.[1634]

Additionally, a successful design for a restored beach must address how the beach will meet neighboring properties.[1635] This is not a concern if neighbors already have or are restoring their own beaches, but it is necessary to plan how the edges of a beach will meet any neighboring bulkheads.[1636] There are two strategies for meeting adjacent bulkheads:

- Install rocks, wood, plantings, or concrete walls at the edges of your beach to reinforce the transition area from beach to bulkhead – these areas will be subject to greater erosive forces.[1637]
- Add extra fill below the water line at the edges of the property – this protects the beach from the erosive forces of neighboring bulkheads and protects the bulkheads from undercutting.[1638] For shoreline restoration purposes, twenty-five cubic yards of fill are allowed outright in the water so long as they do not create dry land.[1639] More may be approved depending on site conditions.[1640]

Some erosion to beaches is normal over time.[1641] This can be offset by beach nourishment, the periodic addition of gravel.[1642] When a project is designed and installed properly, some nourishment is likely to be necessary every five to ten years.[1643] To make beach nourishment easier, it is ideal to include periodic fill as part of the maintenance plan in the initial construction permit.[1644] This can help avoid needing to obtain a local permit to add gravel to the beach in the future.[1645] If nourishment is not covered in the initial permit, a shoreline exemption for each instance of beach nourishment will need to be obtained.[1646] Time and costs for this process depends on the local jurisdiction.[1647]

<u>Install or restore beach coves</u>

A beach cove is a beach along a portion of a property's waterfront, flanked on both sides with hard structural elements.[1648] This is a useful strategy to improve habitat quality and water access while keeping armoring if it is necessary.[1649] Like full beaches, beach coves should use appropriately sized gravel, and typically not sand.[1650] Beach nourishment will be needed with about the same frequency as with a full beach restoration (every five to ten years), but less fill is needed since the beach area is smaller.[1651]

1633 *Seattle-DPD. (n.d., p. 7)
1634 *Seattle-DPD. (n.d., p. 7)
1635 *Seattle-DPD. (n.d., p. 7)
1636 *Seattle-DPD. (n.d., p. 7)
1637 *Seattle-DPD. (n.d., p. 7)
1638 *Seattle-DPD. (n.d., p. 7)
1639 *Seattle-DPD. (n.d., p. 7)
1640 *Seattle-DPD. (n.d., p. 7)
1641 *Seattle-DPD. (n.d., p. 7)
1642 *Seattle-DPD. (n.d., p. 7)
1643 *Seattle-DPD. (n.d., p. 7)
1644 *Seattle-DPD. (n.d., p. 7)
1645 *Seattle-DPD. (n.d., p. 7)
1646 *Seattle-DPD. (n.d., p. 7)
1647 *Seattle-DPD. (n.d., p. 7)
1648 *Seattle-DPD. (n.d., p. 8)
1649 *Seattle-DPD. (n.d., p. 8)
1650 *Seattle-DPD. (n.d., p. 8)
1651 *Seattle-DPD. (n.d., p. 8)

Localized erosion can occur where the bulkhead meets the beach on either side of the cove.[1652] Two techniques that help prevent this from happening include:

- Angling the ends of the bulkhead away from the water to dissipate wave energy and decrease erosion, and
- Adding extra gravel fill below the water line to help prevent undercutting of the bulkhead.[1653]

As with full beaches, beach cove slopes should typically be no steeper than 4:1, i.e. four horizontal feet to one vertical foot (7:1 is a good goal, but steeper slopes can be stable when appropriate materials are used).[1654] Beach coves provide less shoreline for wading and other beach activities, and they do less to improve habitat.[1655] While fish biologists have observed juvenile salmon using pocket beaches around Lake Washington, research suggests that the fish gravitate to larger beaches and plantings when they are available.[1656]

Set back bulkheads

If there is not an adequate setback between the water line and the house, a bulkhead may be necessary to protect houses or other structures.[1657] In many cases, however, the bulkhead can be moved back from the high water mark, providing benefits to the homeowner and the lake ecosystem.[1658] Part of the bulkhead can be set back to create a reinforced beach cove, or the whole thing can be set back to create a new beach all across the shoreline.[1659]

Whether setting a bulkhead back or replacing it in the same location, angling back the batter (the slope of the bulkhead) is generally a good idea.[1660] With every wave that hits it, a vertical bulkhead reflects most of the wave energy back into the lake.[1661] This leads to turbulence and erosion, which results in deeper water at the bulkhead’s base.[1662] A sloped bulkhead does a better job of absorbing and dissipating energy, creating less erosion and lengthening the service life of the investment.[1663] For Lake Washington, engineers generally recommend a bulkhead slope of 3:1 where site constraints will allow it.[1664]

Install logs

Logs can provide strategically placed “hard engineering” structural reinforcement while complementing the aesthetic of a more natural beach project, and, in some cases, enhancing ecological function.[1665] Logs

[1652] *Seattle-DPD. (n.d., p. 8)
[1653] *Seattle-DPD. (n.d., p. 8)
[1654] *Seattle-DPD. (n.d., p. 8)
[1655] *Seattle-DPD. (n.d., p. 8)
[1656] *Seattle-DPD. (n.d., p. 8)
[1657] *Seattle-DPD. (n.d., p. 10)
[1658] *Seattle-DPD. (n.d., p. 10)
[1659] *Seattle-DPD. (n.d., p. 10)
[1660] *Seattle-DPD. (n.d., p. 11)
[1661] *Seattle-DPD. (n.d., p. 11)
[1662] *Seattle-DPD. (n.d., p. 11)
[1663] *Seattle-DPD. (n.d., p. 11)
[1664] *Seattle-DPD. (n.d., p. 11)
[1665] *Seattle-DPD. (n.d., p. 12)

must be anchored securely in place.[1666] There are several ways to secure a log, but it is most commonly done using duckbill anchors and cables or by partially burying the log.[1667]

Logs used for habitat enhancement should be as complex as possible, with root wads and some branches still attached.[1668] Some restoration efforts have installed logs perpendicular to the shoreline to enhance fish habitat.[1669] Logs in the water can improve nearshore habitat by creating salmon refuge areas.[1670] However, they should not extend beyond a depth of two feet (~0.6 meters) below ordinary high water.[1671] Anything beyond this is thought to create habitat for predator fish species that prey on salmon.[1672] In some cases, logs are not allowed to extend horizontally beyond the water line, since they can interfere with natural movement of sediments.[1673]

<u>Install or restore vegetated buffers</u>

Diverse shoreline plantings contribute to aquatic habitat in several important ways:

1. Vegetation provides diffuse shade to the water's edge, creating conditions that help juvenile fish blend in with their surroundings;
2. They restore natural food web processes to the shoreline – plants are home to insects and other small organisms, which become fish food when they fall into the water;
3. They provide twigs, branches and leaves, which create important refuges from birds and bigger fish; and,
4. Planted strips protect water quality by filtering excess nutrients and other contaminants from stormwater.[1674]

Considerations for planting vegetated buffers include:

- **Buffer width:** This depends on what your lot can accommodate.[1675] While bigger is better, even a few feet can provide benefits.[1676] For most new residences along Lake Washington, Seattle requires at least a 25' building setback.[1677] This means a 5-10' vegetated buffer can easily fit on most sites, and 15-20' is often feasible.[1678]
- **Type and location of plants:** Native plants are ideal, not only because they often have lower water and maintenance needs, but also because they help draw birds and beneficial insects to the yard.[1679] Ideally, shrubs and perennials should be directly adjacent to the water's edge, overhanging the lake wherever possible.[1680] When a property has a bulkhead, however, trees and

[1666] *Seattle-DPD. (n.d., p. 13)
[1667] *Seattle-DPD. (n.d., p. 13)
[1668] *Seattle-DPD. (n.d., p. 13)
[1669] *Seattle-DPD. (n.d., p. 13)
[1670] *Seattle-DPD. (n.d., p. 13)
[1671] *Seattle-DPD. (n.d., p. 13)
[1672] *Seattle-DPD. (n.d., p. 13)
[1673] *Seattle-DPD. (n.d., p. 13)
[1674] *Seattle-DPD. (n.d., p. 14)
[1675] *Seattle-DPD. (n.d., p. 14)
[1676] *Seattle-DPD. (n.d., p. 14)
[1677] *Seattle-DPD. (n.d., p. 14)
[1678] *Seattle-DPD. (n.d., p. 15)
[1679] *Seattle-DPD. (n.d., p. 14)
[1680] *Seattle-DPD. (n.d., p. 14)

large shrubs need to be sited carefully to prevent damage to shoreline armoring.[1681] Black cottonwood, for example, is an ideal tree to plant next to beach areas, but its vigorous root system could cause problems for a riprap bulkhead.[1682]

- **Use of emergent plants:** Emergent plants provide excellent habitat and erosion control, but they often struggle on Lake Washington due to the lake's unusual hydrological conditions – the lake's water level is managed at the Ballard Locks such that high water occurs in the summer and low water occurs in the winter.[1683] Emergent plants may work well in protected parts of Lake Washington, or areas with shallow nearshore slopes.[1684]
- **Permitting:** As long as all plants are placed above the high water mark, no permits are necessary to plant shoreline vegetation.[1685]

Conduct slope bioengineering

Slope bioengineering is a term used for an array of different techniques that use plant material as a self-renewing, ecologically sustainable way to hold soil and gravel in place.[1686] These "soft engineering" techniques are commonly used in parks and natural areas for ecological restoration projects, but they may also be used on residential properties.[1687] Cuttings should be collected from an approved site – in Washington, the city parks department or Department of Natural Resources can be contacted for information.[1688] Permits are required for any slope bioengineering installations at or below ordinary high water.[1689] Examples of these techniques include:

- **Live stakes:** Live stakes are a key element of almost all bioengineering projects.[1690] These are cuttings from plants that will grow roots when inserted into moist ground.[1691] Willows, dogwoods, and other shoreline species adapted to reproduce through cuttings are all viable candidates.[1692] Live stakes can be a simple and cost-effective way to bind soil in place and provide plant cover.[1693]
- **Fascines:** Fascines are long bundles of thin branches, tightly bound with twine.[1694] They are partially buried in trenches parallel to incoming waves and "nailed" into place with live stakes.[1695] These thick masses of branches provide immediate structural support, catch sediment coming from upslope, and can establish their own roots and new growth.[1696] Since they are usually

[1681] *Seattle-DPD. (n.d., p. 14)
[1682] *Seattle-DPD. (n.d., p. 14)
[1683] *Seattle-DPD. (n.d., p. 14)
[1684] *Seattle-DPD. (n.d., p. 14)
[1685] *Seattle-DPD. (n.d., p. 14)
[1686] *Seattle-DPD. (n.d., p. 16)
[1687] *Seattle-DPD. (n.d., p. 16)
[1688] *Seattle-DPD. (n.d., p. 17)
[1689] *Seattle-DPD. (n.d., p. 17)
[1690] *Seattle-DPD. (n.d., p. 17)
[1691] *Seattle-DPD. (n.d., p. 17)
[1692] *Seattle-DPD. (n.d., p. 17)
[1693] *Seattle-DPD. (n.d., p. 17)
[1694] *Seattle-DPD. (n.d., p. 17)
[1695] *Seattle-DPD. (n.d., p. 17)
[1696] *Seattle-DPD. (n.d., p. 17)

composed of several different species, the resultant growth comes in as a thicket of mixed plants.[1697] For this reason, fascines should be placed carefully to avoid blocking views.[1698]

- **Live revetment:** Live revetment is used to stabilize steep banks.[1699] Geotextile fabric holds earth-filled terraces in place.[1700] Further structural support is provided by live stakes driven through the fabric.[1701]

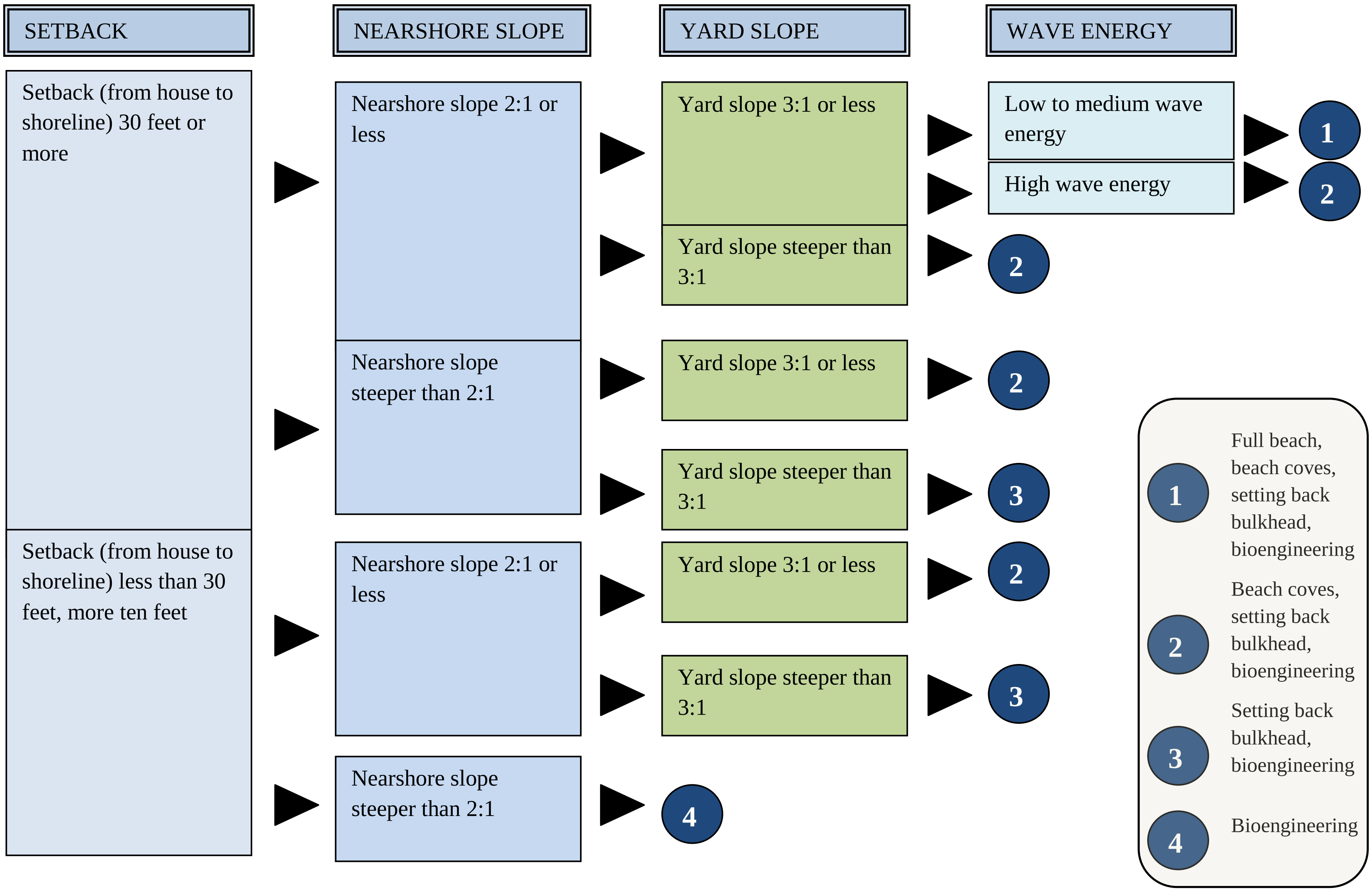
Table 19. Shoreline construction costs (as of 2008).
Reproduced from Seattle DPD (n.d., p. 25) by authors of this report.

	Conventional Treatments		**Green Shorelines**		
Cost Category	***Solid bulkheads***	***Riprap***	***Beach Establishment***	***Slope bioengineering***	***Docks***
Capital Costs (per linear foot, except where indicated otherwise)	Average rock or concrete bulkhead is $350 to $400, sheetpile is $800+	Average riprapped bank is $125 to $200 feet	Average beach establishment is $200 to $500	Average bioengineering project is $200 to $500	Average new dock costs $100 to $130 per square foot
Design and Permitting	10-15% of capital costs for larger projects (greater than $100K), 20-25% for smaller projects		7-12% of capital costs for larger projects (greater than $100K), 15-20% for smaller projects		Similar to bulkheads
Maintenance	No maintenance is usually required for 25-50 year life span of projects		Sand replenishment at a 1-5 year frequency, gravel at a 5-10 years, both $3 to $6 per square foot of beach – with proper maintenance, project can last indefinitely		Similar to bulkheads

1697 *Seattle-DPD. (n.d., p. 17)
1698 *Seattle-DPD. (n.d., p. 17)
1699 *Seattle-DPD. (n.d., p. 17)
1700 *Seattle-DPD. (n.d., p. 17)
1701 *Seattle-DPD. (n.d., p. 17)

Figure 30. Green Shorelines Decision Tree *Reproduced from Seattle DPD (n.d., p. 21) by authors of this report.*

Notes: The use of plant buffers or logs is a viable option for any site, including those that employ hard engineering such as bulkheads. Sites with less than a ten foot setback are not included on this decision tree, because in most cases they will depend on concrete, sheetpile, or riprap.



Maintain, restore, or create stream and watershed connectivity

These strategies address the fragmentation, drying, and/or loss of wetlands and wetland habitat due to increased air temperatures, reduced soil moisture, and other stressors.

Promote connectivity and persistence in streams, wetlands, floodplains, and watersheds

Connectivity and persistence can be promoted in a number of ways. For example, re-establishing and maintaining corridors permits migration of plant and animal species.[1702] Since drainage is only partially regulated at federal, state and local levels, controlling wetland drainage would better protect wetland functions and values, as well as protecting carbon stores and carbon sequestering ability.[1703] Similarly, installing water control structures at the outlets of freshwater wetlands may help maintain water levels during dry periods; however, it may be quite expensive, will require maintenance, and will interrupt natural successional cycles.[1704]

In other areas of the watershed, e.g. in streams and floodplains, the following strategies are also available:

- Protect and restore longitudinal connectivity of stream systems to provide species with access to habitats that may be disconnected by changes in flow regime.[1705]
- Improve lateral channel-floodplain connectivity where human disturbance has isolated channels.[1706]

Move dikes back from rivers

Constraints such as dikes prevent natural alluvial processes including meandering, scouring, flooding and sediment transport and create channelized simple rivers.[1707] Setting dikes back allows rivers to meander naturally, restoring connectivity of the river channel to the floodplain.[1708] Complex river channels have significantly more habitat for a range of species and are necessary to maintain ecosystem function.[1709] This strategy is easier in less developed regions, where the floodplain land is not owned by private owners and there are fewer concerns with flooding.[1710] In the Trinity River (CA), dikes are being removed and floodplains are being bought in order to allow the natural alluvial processes to occur.[1711] *For further information on adaptation actions for barriers such as dikes, see "Maintain, restore, or increase in-stream flow to address changes in snowpack, runoff, and streamflow regimes" in this Chapter. For further information on floodplain and wetland restoration, please see "Reduce effects of increased flooding and extreme flow" and "Maintain and restore wetlands," respectively, in this Chapter.*

[1702] *ASWM. (2009, p. 11-12)
[1703] *ASWM. (2009, p. 12)
[1704] *ASWM. (2009, p. 12)
[1705] *Furniss et al. (2010, p. 51)
[1706] *Furniss et al. (2010, p. 51)
[1707] *Nelitz et al. (2007, p. 109). The authors cite USFWS and HVT (1999), and Howie Wright, Okanagan Nation Alliance, pers. comm. for this information.
[1708] *Nelitz et al. (2007, p. 109)
[1709] *Nelitz et al. (2007, p. 109)
[1710] *Nelitz et al. (2007, p. 109)
[1711] *Nelitz et al. (2007, p. 109). The authors cite USFWS and HVT (1999), and Howie Wright, Okanagan Nation Alliance, pers. comm. for this information.

Remove perched culverts or other artificial obstructions

One way to increase amount of freshwater habitats is by removing barriers (e.g., culverts) to allow access to previously utilized areas as well as to areas that may not have had salmon (and other species) previously.[1712] This strategy is used throughout the Pacific Northwest and in California where individual projects are tracked by a FishXing project team (see www.stream.fs.fed.us/fishxing/case.html, accessed 7.10.2011).[1713]

Considerations for culvert removal or redesign include:

- Culverts designed for adult passage often create water velocities that exceed juvenile salmon swimming abilities and prevent juvenile fish from reaching important rearing areas.[1714]
- Smooth culverts lacking roughness or baffles normally impair juvenile fish passage except at very low slopes.[1715]
- Culverts may affect coho in particular because they tend to use smaller streams where there is not as much flow.[1716]
- Culverts affect the movement of nutrients up and downstream.[1717]

Networks of protected areas

Extensive networks of protected areas provide the most efficient way of conserving biodiversity in the face of climate change.[1718] An integrated approach for both freshwater and terrestrial ecosystems is likely to be the most fruitful avenue for conserving wholesale biodiversity in reserve networks.[1719] Given that currently protected areas are typically delineated based on the representation of terrestrial ecosystems and a low number of taxonomic groups (e.g. vascular plants and terrestrial vertebrates), it is unclear if freshwater biodiversity is adequately protected in current protected areas network, and if future shifts in freshwater species' ranges could be accommodated by these areas.[1720] To be efficient for freshwater organisms, protected areas should be based on the characteristics of freshwater ecosystems and the requirements of freshwater organisms.[1721] For example, taking a catchment perspective instead of strict conservation of terrestrial areas that can be easily bounded and protected would be more desirable for conserving freshwater biodiversity.[1722]

[1712] *Nelitz et al. (2007, p. 108)
[1713] *Nelitz et al. (2007, p. 108). The authors cite Nina Hemphill, Trinity River Restoration Program, pers. comm. for this information.
[1714] *Nelitz et al. (2007, p. 108). The authors cite Furniss et al. (1991) for this information.
[1715] *Nelitz et al. (2007, p. 108). The authors cite Robison (1999) as cited in Roni et al. (2002) for this information.
[1716] *Nelitz et al. (2007, p. 108). The authors cite Roni et al. (2002) for this information.
[1717] *Nelitz et al. (2007, p. 108). The authors cite Roni et al. (2002) for this information.
[1718] *Heino, Virkkala and Toivonen. *Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions.* (2009, p. 49)
[1719] *Heino, Virkkala and Toivonen. (2009, p. 49). The authors cite Abell (2002) for this information.
[1720] *Heino, Virkkala and Toivonen. (2009, p. 49)
[1721] *Heino, Virkkala and Toivonen. (2009, p. 49). The authors cite Saunders, Meeuwig, and Vincent (2002), Toivonen, Leikola and Kallio (2004), and Abell et al. (2007) for this information.
[1722] *Heino, Virkkala and Toivonen. (2009, p. 49). The authors cite Dudgeon et al. (2006) for this information.

Dispersal corridors

Dispersal corridors are vital for species to track changes in climatic conditions.[1723] This is especially relevant for freshwater organisms that rely on rivers and streams for successful dispersal among water bodies.[1724] Even for more highly dispersive species (e.g. insects with a winged terrestrial adult stage and small organisms that survive passive overland dispersal), the distances between suitable water bodies are likely to be important with regard to their chances of tracking climate change.[1725] In the natural settings of formerly glaciated northern regions, for example, lakes are typically numerous and generally highly interconnected by streams, facilitating the movements of species in response to climate change after these northern regions have been reached by freshwater species.[1726]

Management of the matrix between protected areas

Because a great majority of freshwater ecosystems are located outside protected areas and affect those in protected areas, the matrix and its adaptive management is likely to be as important as the protection of new areas for biodiversity conservation.[1727] This would entail planning land use so that harmful influences from built-up areas, agriculture, and forestry do not degrade the state of freshwater ecosystems.[1728]

Land exchange and acquisition

Land acquisition may enhance floodplain extent and buffer river segments from impacts in the surrounding watershed, and could provide replication in space of at-risk habitats and refugia for species.[1729] For example, where Wild and Scenic Rivers contain naturally occurring refugia, additional river reaches could be acquired.[1730]

A land exchange program, such as a conservation easement, typically transfers some development and management options – such as the right to subdivide or to cut trees – from the landowner to a nonprofit or governmental organization that holds those rights.[1731] The landowner reserves certain rights, such as the right to build additional homes or add roads and also continues to own the property and manage it within the bounds set by the easement.[1732] The easement holder is responsible for monitoring and enforcing easement specifications.[1733] A conservation easement program is likely to be most effective when it has strong

> ***A conservation easement*** is a legal agreement between a landowner and a land trust or government agency that can be used to restrict development in sensitive and hazard-prone areas. A conservation easement program is likely to be most effective when it has strong planning and outreach components that identify lands that would benefit from easements and inform property owners about easements and their benefits.
> *Source: NOAA. (2010a, p. 67-68)*

[1723] *Heino, Virkkala and Toivonen. (2009, p. 49)
[1724] *Heino, Virkkala and Toivonen. (2009, p. 49)
[1725] *Heino, Virkkala and Toivonen. (2009, p. 49)
[1726] *Heino, Virkkala and Toivonen. (2009, p. 49). The authors cite Poff et al. (2002) for this information.
[1727] *Heino, Virkkala and Toivonen. (2009, p. 50)
[1728] *Heino, Virkkala and Toivonen. (2009, p. 50)
[1729] *Palmer et al. (2008, p. 34)
[1730] *Palmer et al. (2008, p. 33)
[1731] *Merenlender et al. *Land trusts and conservation easements: Who is conserving what for whom?* (2004, p. 67)
[1732] *Merenlender et al. (2004, p. 67)

planning and outreach components that identify lands that would benefit from easements and inform property owners about easements and their benefits.[1734]

Landowners who donate their easement may be eligible for federal or state tax breaks.[1735] Easements typically apply in perpetuity and are passed on from owner to owner.[1736] Most are placed on individual properties, but they may also be placed on subdivisions or coordinated at a regional scale (e.g., to more effectively manage a strip of land or accommodate wetland migration).[1737]

Case Study 2. Limits to floodplain development: the National Flood Insurance Program and National Marine Fisheries Service Biological Opinion, Puget Sound, WA.

Climate impacts addressed: Increased flooding. Changes in snowpack, runoff, and streamflow regimes. Increased water pollution and corresponding changes in water quality. Increased water temperature.

Description: The National Flood Insurance Program was created by Congress to provide flood insurance for properties that private insurers were unwilling to cover. One of the primary goals of the program is to reduce long-term vulnerability to floods. However, the government-subsidized insurance, combined with sometimes inaccurate floodplain maps and inadequate risk reduction requirements, has instead resulted in continued floodplain development and redevelopment in flood risk areas and degraded habitat for fish and wildlife, including federally protected species under the Endangered Species Act. For example, the National Marine Fisheries Service released a Biological Opinion in 2008 stating that floodplain development supported by the National Flood Insurance Program in Puget Sound (WA) is jeopardizing the continued existence of Puget Sound Chinook salmon, Puget Sound steelhead, Hood Canal summer-run chum salmon, and Southern Resident killer whales, and is likely to adversely modify Puget Sound Chinook salmon, Hood Canal summer-run chum salmon, and Southern Resident killer whale critical habitat. To be ESA-compliant, the National Flood Insurance Program must prevent further harm to salmon habitat by including enhanced development restrictions in the floodway, channel migration zone and riparian buffer area. These development restrictions create an opportunity to restore valuable floodplain functions and reconnect floodplains to upland stream and riparian habitats, thereby improving water quality, preserving habitat for vulnerable species, and reducing flood risk from increasingly severe storms.

Sources: *National Marine Fisheries Service. (September 22, 2008). Puget Sound Biological Opinion; Hewes & Fahlund. (2011). Weathering Change: Policy reforms that save money and make communities safer.*

[1733] *Merenlender et al. (2004, p. 67)
[1734] *NOAA. (2010a, p. 68)
[1735] *NOAA. (2010a, p. 68)
[1736] *NOAA. (2010a, p. 68)
[1737] *NOAA. (2010a, p. 68)

Preserve habitat for vulnerable species

Protect large and environmentally heterogeneous areas

Because large and heterogeneous areas are more likely to incorporate a wider array of different types of lentic (e.g. lakes and ponds) and lotic (e.g. streams and rivers) ecosystems than smaller and more homogenous areas, this approach should lead to preservation of much of regional freshwater biodiversity.[1738] Large protected areas should also accommodate larger parts of whole catchments that are of vital importance for the functioning of freshwater ecosystems and harboring diverse ecological communities.[1739] More heterogeneous protected areas, for example, in terms of mountainous and lowland areas would also provide possibilities for freshwater organisms to track suitable temperature conditions following climate change.[1740] *Please see the section "Maintain, restore, or create stream and watershed connectivity" for additional methods that may allow freshwater organisms to track suitable temperature conditions.*

Support open-space preservation and conservation

Open space preservation and conservation can be accomplished through the management of lands dedicated as open space through a number of the measures, e.g. zoning, redevelopment restrictions, acquisition, easements, setbacks, and buffers (*Please see the sections "Reduce the effects of increased flooding and extreme flow" for information on floodplain zoning, easements, and buffers and "Maintain, restore, or create stream and watershed connectivity" for information on land acquisition*).[1741] While there are costs associated with the management of open space, the public expenditures may be lower than if the land was developed and the provision of full services was required.[1742] Management costs could be defrayed by transferring the title to a nonprofit conservation organization.[1743]

Open space management plans can be developed to guide the acquisition and use of open space in a manner that fulfills multiple community objectives (e.g., trails, athletic fields, campgrounds, community gardens, wildlife refuges, environmental education centers, etc.).[1744] Any such plan should consider the impacts and consequences of climate change, sea level rise and flooding in particular, to ensure that investments are wisely made (land purchase as well as use and amenity placement).[1745] Open space management should also consider the key role of open space in green infrastructure and wetland migration programs (*Please see the section "Maintain or improve water quality" for information on green infrastructure and "Maintain and restore wetlands" for information on wetland migration.*).[1746]

[1738] *Heino, Virkkala and Toivonen. (2009, p. 49)
[1739] *Heino, Virkkala and Toivonen. (2009, p. 49). The authors cite Pringle (2001) and Dudgeon et al. (2006) for this information.
[1740] *Heino, Virkkala and Toivonen. (2009, p. 49)
[1741] *NOAA. (2010a, p. 86)
[1742] *NOAA. (2010a, p. 86)
[1743] *NOAA. (2010a, p. 86)
[1744] *NOAA. (2010a, p. 86-87)
[1745] *NOAA. (2010a, p. 87)
[1746] *NOAA. (2010a, p. 87)

Case Study 3. Climate Change and the Salmon Stronghold Approach.

Climate stressors addressed: Changes in snowpack, runoff, and streamflow regimes. Increased water pollution and corresponding changes in water quality. Increased water temperature.

Description Since 2008, a consortium of federal, state, private, and tribal partners has been collaborating to identify "wild salmon strongholds" throughout California, Oregon, Washington, and Idaho. Salmon strongholds refer to a watershed or watersheds that meet(s) biological criteria for abundance, productivity, genetic and life history diversity, habitat quality, and other biological attributes necessary to sustain viable wild salmon populations across their range. In addition to containing key areas of refugia and populations that can anchor regional salmon recovery efforts, strongholds promote a range of vital ecosystem services – including clean water, carbon sequestration, flood control, and recreation to name just a few. Because they contain extensive intact habitats, which promote a wide range of life history and genetic diversity, strongholds also represent some of the most resilient salmon ecosystems in the face of changing watershed conditions. Among the many changes confronting the rivers of California and the Pacific Northwest, altered streamflow regimes, increasing water temperatures, and shifting food webs pose some of the greatest threats to wild salmon populations.

The identification of salmon strongholds is part of a broader effort being led by the North American Salmon Stronghold Partnership to protect a network of the healthiest remaining wild Pacific salmon ecosystems in North America to ensure the long term survival of salmon, steelhead, and the many species that depend on them. The effort seeks to complement ongoing recovery efforts by promoting greater investment in preventative, proactive conservation strategies in and across strongholds. Emerging climate change science and downscaling models that can "localize" regional climate impacts are vital to informing these strategies. While the designation of strongholds represents a snapshot in time (i.e., it reflects population and habitat conditions today), stronghold partners are taking the necessary steps to ensure strongholds resilient to climate change are protected and strong populations sustained. They plan to use downscaled, local climate change models and the predicted responses of stronghold watersheds to most effectively invest scarce resources across the expansive salmon landscape.

Source: *Personal interview (June 2011); North American Salmon Stronghold Partnership Charter, http://www.wildsalmoncenter.org/programs/north_america/strongholds.php (accessed 6.29.2011).*

Restore riparian habitat

Please see the section "Maintain and restore wetlands and riparian areas" for an explanation of restoring riparian habitat. Listed here are some benefits of riparian habitat restoration for species:

- Increasing physical habitat heterogeneity in channels supports diverse biotic assemblages.[1747] Aquatic fauna may benefit from an increase in physical habitat heterogeneity in the channel,[1748] and replanting or widening any degraded riparian buffers may protect river fauna by providing more shade and maintaining sources of allochthonous (i.e. originating from outside the aquatic system) input.[1749]

[1747] *Palmer et al. (2008, p. 33)
[1748] *Palmer et al. (2008, p. 35). The authors cite Brown (2003) for this information.
[1749] *Palmer et al. (2008, p. 35). The authors cite Palmer et al. (2005) for this information.

- Planting riparian vegetation provides fish and other organisms with refugia.[1750]
- Creating side channels and adjacent wetlands provides refugia for species during droughts and floods.[1751]
- A focus on increasing genetic diversity and population size through plantings or via stocking fish may increase the adaptive capacity of species.[1752]
- Increasing quality of freshwater habitat and hence increasing survival to offset increased mortality due to climate change may help salmon survive climate change.[1753]

Engineer streams and off-channel areas to create artificial habitats that replace lost or degraded rearing habitats

Engineered streams are constructed as natural type channels that meander over a location to maximize functional stream surface area, with variable stream widths that contain the natural components of salmon rearing habitat (pools, riffles, runs, deep ponds).[1754] For example, deep pools provide thermal refuge for adult holding or juvenile rearing.[1755] A pilot engineered stream on the Dungeness River (WA) has had production efficiencies as high as ten fingerlings per square meter, representing more than seventy percent survival of eggs.[1756] Engineered streams cost from $10,000 to $50,000 per kilometer and require ongoing maintenance.[1757]

Spawning channels for sockeye, chum, and pinks have been successful in providing spawning habitat and increasing productivity (e.g., Weaver Creek Channel in the Harrison Lake Basin, BC).[1758] Considerations for creating side channel spawning and rearing habitat include:

- Sufficient woody debris and other sources of instream cover;
- Ensure entrance does not run dry;
- Optimal pond size and depth; and
- High elevation habitats may be particularly important given climate change.[1759] The Yurok Tribe is working to provide tributary habitat, particularly high elevation as a strategy to help endangered coho in the Trinity River (CA).[1760]

Clean gravels

Ideally spawning gravel is free of silt and sand so water can percolate through the redds bringing oxygen to the eggs.[1761] Spawning gravel can be cleaned, but is expensive and fresh sediment may be deposited

[1750] *Palmer et al. (2008, p. 33)
[1751] *Palmer et al. (2008, p. 33)
[1752] *Palmer et al. (2008, p. 35)
[1753] *Nelitz et al. (2007, p. 107). The authors cite Ward et al. (2006) and Nina Hemphill, Trinity River Restoration Program, pers. comm.. for this information.
[1754] *Nelitz et al. (2007, p. 106)
[1755] *Nelitz et al. (2007, p. 108)
[1756] *Nelitz et al. (2007, p. 106). The authors cite Brannon (2006) for this information.
[1757] *Nelitz et al. (2007, p. 106)
[1758] *Nelitz et al. (2007, p. 106)
[1759] *Nelitz et al. (2007, p. 108)
[1760] *Nelitz et al. (2007, p. 108)
[1761] *Nelitz et al. (2007, p. 108)

with later high flows.[1762] This strategy has been tried with limited success in BC in the Horsefly and Nadina Rivers.[1763]

Case Study 4. Projected impacts of climate change on salmon habitat restoration, Snohomish Basin, WA.

Climate impacts addressed: Changes in snowpack, runoff, and streamflow regimes; Increased flooding and extreme flow; Increased water temperatures; Changes in water quality

Description: To investigate possible interactions between the impacts of climate change and habitat restoration, Battin et al. (2007) modeled Chinook salmon (*Oncorhynchus tshawytscha*) population dynamics in the Snohomish River basin under a variety of future climate and habitat conditions. Using the A2 scenario and two models chosen for their ability to reproduce 20th century hydrologic conditions in the Puget Sound (GFDL R30, HadCM3), they projected changes in spawning Chinook salmon abundance between 2000 and 2050 under three future land-use scenarios (Table A, below). In all model and land-use scenario combinations, projected declines in salmon abundance are lessened as a fuller suite of restoration targets are met; in one case, salmon abundance increases by 19%. The projected changes in salmon abundance vary spatially. In general, the largest declines in abundance are projected at high elevations and more moderate declines and increases in abundance are projected at low- and mid-elevations across all models and land-use scenarios. In contrast, hydrologic impacts are affected little by the choice of land-use scenario and climate models project basin-wide increases in incubation peak flows and pre-spawning temperatures and decreases in spawning flows. The largest hydrologic changes tended to be projected to occur at higher elevations, which consist primarily of federally protected lands and relatively pristine streams where there is little potential for habitat restoration or degradation. Battin et al. state that "model results suggest that, because climate impacts on hydrology are greatest in the highest-elevation basins, and restoration impacts are concentrated at lower elevations, the combined effect of climate change and restoration will be to shift salmon distributions to lower elevations" (p. 6722). Battin et al. conclude that in basins similar to the Snohomish River basin "salmon recovery plans that enhance lower-elevation habitats are likely to be more successful over the next 50 years than those that target the higher-elevation basins likely to experience the greatest snow-rain transition" (p. 6720).

Source: Battin et al. *Projected impacts of climate change on salmon habitat restoration.* (2007). See Figures 3 and 5 in the cited report (p. 6723) for a visual depiction of the results summarized here.

Table A. Basin-wide total percent change in spawning Chinook salmon abundance between 2000 and 2050

Model	***Current land-use*** *(no change from 2001 conditions)*	***Moderate restoration*** *(completion of current restoration projects but no further restoration)*	***Full restoration*** *(all restoration targets in the restoration plan are met)*
GFDL R30	-40	-27	-5
HadCM3	-20	-5	+19

1762 *Nelitz et al. (2007, p. 108)
1763 *Nelitz et al. (2007, p. 108)

Establish environmental flow regimes

Operating water storage facilities in a 'fish friendly' manner, by changing the storage and release patterns to account for fish needs is a successful strategy that is being widely used for Pacific salmon.[1764] Considerations include:

- Need sufficient flow and appropriate (e.g., low enough) temperatures for spawners of various species and life history stages, which return at different times of the year;
- Dam releases can be used to make out-migration conditions more favorable; and,
- Timing of increased flows is also important for both establishing and scouring riparian vegetation as well as driving geomorphological processes.[1765]

Improve fish passage

Fish passage devices can improve survival of adults migrating upstream to spawning areas, and juveniles outmigrating to the ocean.[1766] Downstream fish passage technology includes various types of turbines.[1767] Examples of upstream fish passage technology include:

- Fish ladders;
- Improved culvert design *(Please see the section "Maintain, restore, or create stream and watershed connectivity" for an explanation of improved culvert design.);*
- Vertical slot;
- Roughened channels;
- Hybrid fishways; and,
- Mechanical fishways.[1768]

There is a large body of evidence describing how fish passage over hydropower devices can be improved.[1769] For example, the Electrical Power Research Institute has written a Manual of Upstream and Downstream Fish Passage and Protection Technologies for Hydroelectric Application.[1770]

Build better docks

On lakes, overwater structures change underwater light conditions, affecting the behavior of juvenile salmon and their predators.[1771] The following actions can be taken to decrease the impact on sensitive shoreline habitat and species:

- Use grated decking with openings that allow light to pass through;
- Make ramps and walkways narrower, ideally four feet or less for walkways and three feet or less for ramps;

[1764] *Nelitz et al. (2007, p. 103)
[1765] *Nelitz et al. (2007, p. 103)
[1766] *Nelitz et al. (2007, p. 105)
[1767] *Nelitz et al. (2007, p. 105)
[1768] *Nelitz et al. (2007, p. 105)
[1769] *Nelitz et al. (2007, p. 105)
[1770] *Nelitz et al. (2007, p. 105). A PDF (~4 MB) of the manual can be downloaded at http://my.epri.com/portal/server.pt?space=CommunityPage&cached=true&parentname=ObjMgr&parentid=2&control=SetCommunity&CommunityID=404&RaiseDocID=000000000001005392&RaiseDocType=Abstract_id (accessed 5.19.2011).
[1771] *Seattle-DPD. (n.d., p. 22)

- Avoid using "skirts," i.e. boards on the sides of the dock that extend down to the water (multiple agencies prohibit skirts because of their effects on light in the nearshore area);
- Design the dock such that the bottom of the entire structure is at least eighteen inches above ordinary high water;
- Use structural beams such as glu-lams, which allow longer spans between piles; and,
- Avoid overwater lights that will be on all night.[1772]

In addition, there are measures that can be taken during construction, including careful selection of wood preservatives for any lumber that will have contact with the water (or, use untreated wood), using decking materials that will not require toxic finishes and cleaning agents, scheduling construction during approved work windows, and working with a contractor who is conscientious about preventing spills and minimizing disturbance of sediments (i.e., following Best Management Practices).[1773]

<u>Enrich streams or lakes with nutrients</u>

Add inorganic nitrogen and phosphorus to freshwater environments by using artificial fertilizers or hatchery salmon carcasses.[1774] In BC, surveys indicated decreases of nutrients in watersheds where populations have not been enhanced by hatchery supplementation, fertilization, construction of spawning channels, or other mitigating action.[1775] Considerations for enriching streams or lakes with nutrients include:

- Nutrient concentrations at point of application and downstream,
- Influence of urban areas where nutrient loadings may already be artificially high,
- Application of hatchery carcasses to a site several times through the spawning season rather than all at once, and
- Consider reductions in harvest prior to artificial enhancement of nutrients.[1776]

<u>Conserve freshwater biodiversity</u>[1777]

Freshwater biodiversity may be conserved by reintroducing native species,[1778] reevaluating conservation and recovery programs,[1779] or by increasing genetic diversity through planting or by stocking fish.[1780] Reintroducing native species is highly desirable for species that are prevented from tracking climate change due to human-made dispersal barriers, such as dams, or limited dispersal ability.[1781] It may be desirable to introduce native species that play key roles in ecosystems.[1782] Amongst such species are predatory fish species that are also favored for sport fishing, and species that may be considered as

[1772] *Seattle-DPD. (n.d., p. 23)
[1773] *Seattle-DPD. (n.d., p. 23)
[1774] *Nelitz et al. (2007, p. 107)
[1775] *Nelitz et al. (2007, p. 107). The authors cite Larkin and Slaney (1999) as cited in Roni et al. (2002) for this information.
[1776] *Nelitz et al. (2007, p. 107)
[1777] *Spittlehouse and Stewart. *Adaptation to climate change in forest management.* (2003, Table 1, p. 3)
[1778] *Heino et al. *Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions.* (2009, p. 50)
[1779] *Spittlehouse and Stewart. (2003, p. 8)
[1780] *Palmer et al. (2008, p. 33)
[1781] *Heino, Virkkala and Toivonen. (2009, p. 50)
[1782] *Heino, Virkkala and Toivonen. (2009, p. 50). The authors cite Hunter (2007) for this information.

ecosystem engineers that participate in processes important to a suite of other species.[1783] However, it is likely to be unsuitable for most freshwater species due to economic constraints and practical difficulties in breeding and moving living organisms.[1784] The reevaluation of conservation and recovery programs is suggested in light of the possibility that the long-term preservation of some rare species may only be possible in artificial reserves or arboreta. [1785]

Case Study 5. Citizen scientists monitor for climate change effects: the Salmon Watcher Program, WA.

Climate impacts addressed: Changes in snowpack, runoff, and streamflow regimes. Increased water temperature.

Description: The Salmon Watcher Program, founded in 1996, trains citizen scientists to monitor the status of salmon populations in streams and rivers throughout King and Snohomish counties in Washington state, focusing mainly on the Lake Washington watershed. Volunteers learn to identify different salmonid species, including Chinook, coho, sockeye, kokanee, and chum. Volunteers then record the species and number of salmon at assigned streams twice a week between September and December (spawning season). Information is also collected on any barriers to salmon passage in the water. The information collected is then passed on to scientists so that they can determine fluctuations in populations; scientists can then use these data sets to identify variability. This project is one of the case studies in the U.S. Global Change Research Program's Climate Change, Wildlife, and Wildlands Toolkit for Formal and Informal Educators, developed to aid educators in communicating how climate change will affect the environment and how people can become "climate stewards."

Source: *Climate Adaptation Knowledge Exchange, http://www.cakex.org/case-studies/852 (accessed May 20, 2011); King County. Salmon Watcher Program. http://www.kingcounty.gov/environment/animalsandplants/salmon-and-trout/salmon-watchers.aspx (accessed May 22, 2011).*

Monitor to determine when and what changes are occurring[1786]

Since many organisms respond to climatic variability and trends, some of these responses may be useful as indicators of climate change.[1787] Golladay et al. (2004) suggest that wetland invertebrates could be divided into four response guilds to indicate hydrologic status that may be adaptable to river/stream systems.[1788] Changes in density-weighted ratios of the following response guilds could be used as indicators of climate driven changes in hydrologic conditions over time:[1789]

- Overwintering residents that disperse passively, including snails, mollusks, amphipods, and crayfish;
- Overwintering spring recruits that require water availability for reproduction, including midges and some beetles;

[1783] *Heino, Virkkala and Toivonen. (2009, p. 50). The authors cite Jones, Lawton and Shachak (1994) for this information.
[1784] *Heino, Virkkala and Toivonen. (2009, p. 50)
[1785] *Spittlehouse and Stewart. (2003, p. 8)
[1786] *Spittlehouse and Stewart. (2003, Table 1, p. 3)
[1787] *U. S. EPA. (2008a, p. 1-9)
[1788] *U. S. EPA. (2008a, p. 1-9)
[1789] *U. S. EPA. (2008a, p. 1-9)

- Overwintering summer recruits that only need saturated sediment for reproduction, including dragonflies, mosquitoes, and phantom midges; and
- Non-wintering spring migrants that generally require surface water for overwintering, including most water bugs and some water beetles.[1790]

Cold-water fish species, and salmon species in particular, may be good indicators of climate-change effects in streams and rivers.[1791] To use a salmon species or any fish species as an indicator, one must be sure not to count or include fish that may have been stocked rather than occur naturally in a particular stream or river.[1792] Species with widespread ranges and high thermal tolerance such as largemouth bass, carp, channel catfish, and bluegills would generally not be good indicators of climate impacts since they are relatively insensitive and their ranges extend south into Mexico.[1793] Another possible effect of increased water temperatures is to reduce dissolved oxygen levels in stream waters.[1794] Darter species are sensitive to benthic oxygen depletion because they feed and reproduce in benthic habitats, making them another potential indicator of climate change.[1795] Monitoring changes in community composition, including shifts from cold- and cool-water dominated systems to warm-water communities, may be another good indicator for the following reasons:[1796]

- It is expected that cool-water and warm-water fishes will be able to invade freshwater habitats at higher latitudes, while cold-water fish will disappear from low latitude limits of their distribution where summer temperatures already reach fish maximum thermal tolerances.[1797]
- In east-west drainages fish may not be able to find thermal refuge and may experience local extinctions.[1798]
- Cold-water fish that do persist at higher altitudes and latitudes may not experience as many winter stresses, and their ranges may expand with increased duration of optimal temperatures.[1799]

Beyond categorization of existing biological indicators as sensitive/insensitive to climate change effects, there are biological metrics that could be considered for incorporation into bioassessment programs that are not currently measured on a routine basis in most existing programs.[1800] Such “novel” indicators are considered specifically because of their sensitivity to climate change effects – most have been predicted or observed in the literature as biological responses to directional climate change, especially increases in water temperature.[1801] Table 20 summarizes examples of such “novel” biological indicators.[1802]

1790 *U. S. EPA. (2008a, p. 1-9)
1791 *U. S. EPA. (2008a, p. 1-11)
1792 *U. S. EPA. (2008a, p. 1-11)
1793 *U. S. EPA. (2008a, p. 1-11)
1794 *U. S. EPA. (2008a, p. 1-11)
1795 *U. S. EPA. (2008a, p. 1-11). The authors cite U.S. EPA (1999) for information on the sensitivity of darter species to benthic oxygen depletion due to their feeding and reproductive habits.
1796 *U. S. EPA. (2008a, p. 1-9)
1797 *U. S. EPA. (2008a, p. 1-9). The authors cite Carpenter et al. (1992) and Tyedmers and Ward (2001) for this information.
1798 *U. S. EPA. (2008a, p. 1-9). The authors cite Carpenter et al. (1992) for this information.
1799 *U. S. EPA. (2008a, p. 1-9). The authors cite Carpenter et al. (1992) and Tyedmers and Melack et al. (1997) for this information.
1800 *U. S. EPA. (2008a, p. 3-5)
1801 *U. S. EPA. (2008a, p. 3-5)
1802 *U. S. EPA. (2008a, p. 3-5)

Considerations for ongoing evaluation of potential novel indicators and their role in adaptation of bioassessment programs include:

- Many of the metrics are more difficult or time- and resource-consuming to measure, especially on a routine basis.[1803]
- Some metrics require sampling techniques and timing or frequency of sampling that are quite different from the commonly applied bioassessment approaches.[1804]
- The potential sensitivity to other (conventional) stressors, in addition to their responsiveness to climate change, will affect how they might be incorporated into a monitoring design and analysis approach.[1805]

Additional actions

The following adaptation actions for preserving habitat for vulnerable species were found in the literature, but are not described in detail or are described elsewhere in this report:

- Study and better understand species that are expected to migrate north and upslope in order to determine which ones are most likely to support wetland functions and values given climate change.[1806]
- Establish programs to move isolated populations of species of interest that become stranded when water levels drop.[1807]
- Install irrigation screens to prevent fish from being pulled into the irrigation system.[1808]
- Maintain representative forest types across environmental gradients; protect primary forests (established forests are often able to survive extensive periods of unfavorable climates and this inertia could extend the time period over which adaptation could take place[1809]
- Establish special protection for multiple headwater reaches that support keystone processes or sensitive species.[1810] Since headwaters often support rare and sensitive species, protecting multiple small headwaters will provide "insurance" against regional species loss if losses occur in one or a few tributaries.[1811]
- Maintain connectivity in a varied, dynamic landscape:[1812] *Please see the section "Maintain, restore, or create stream and watershed connectivity" for actions that minimize fragmentation of habitat and maintain connectivity.*

[1803] *U. S. EPA. (2008a, p. 3-8)
[1804] *U. S. EPA. (2008a, p. 3-8)
[1805] *U. S. EPA. (2008a, p. 3-8)
[1806] *ASWM. (2009, p. 12)
[1807] *Palmer et al. (2008, p. 33)
[1808] *Nelitz et al. (2007, p. 100)
[1809] *Spittlehouse and Stewart. (2003, p. 10)
[1810] *Palmer et al. (2008, p. 33)
[1811] *Palmer et al. (2008, p. 34-35)
[1812] *Spittlehouse and Stewart. (2003, Table 1, p. 3)

Table 20. Novel indicators that may be sensitive to climate change.
Modified from U.S. EPA (2008a, Table 3-2, p. 3-6 to 3-7) by authors of this report. Table continues on following page.

Category	***Metric***	***Comments***	***References***
Phenology	Timing of emergence of mayfly species (also stonefly and caddis species)	Indirect effects on timing of salmonid feeding regime	Harper and Peckarsky, 2006; Briers et al., 2004; Gregory et al., 2000; McKee and Atkinson, 2000
	Timing of trout spawning in warmer water		Cooney et al., 2005
	Rate of development and timing of breeding of the amphipod *Hyallela azteca*		Hogg et al., 1995
Longer growing season	Algal productivity	In northern areas a response to decreased ice cover and increased light penetration	Flanagan et al., 2003
	Number of reproductive periods of amphipod species		Hogg et al., 1995
Life-stage specific	Sex ratios for certain insects (e.g. trichopteran *Lepidostoma*)		Hogg and Williams, 1996
	Smaller size at maturity and reduced fecundity of plecopteran *Nenoura trispinosa* and amphipod *Hyallela azteca*	From increased temperature	Turner and Williams, 2005; Hogg et al., 1995
	Decreased salmon egg to fry survival	Increased turbidity from eroded sediment due to increased precipitation	Melack et al., 1997
Temperature sensitivity	Reduced size of sockeye salmon	Reduced growth and increased mortality in higher temperatures as well as to lower plankton productivity	Melack et al., 1997
	Increased growth rate of juvenile salmon in Alaska		Schindler et al., 2005

	Decreased growth rate of trout		Jensen et al., 2000
Hydrologic sensitivity	Decreased survival of eggs of autumn-spawning salmon (e.g. dolly varden, brook trout, coho salmon)	Results in decreased abundance of autumn-spawning species, and/or change in relative composition between spring and autumn spawners	Gibson et al., 2005
	Decreased fry survival of pink and chum salmon due to earlier (late winter to early spring) peak flows	Earlier emergence and migration of pink and chum salmon fry to estuaries at a time when their food sources have not developed adequately	Melack et al., 1997
	Differential mortality of drought-intolerant mussel species (e.g. *Lampsilis straminea claibornensis*, *Villosa villosa*, *Lampsilis subangulata)*	Results in changes in relative abundance, extirpation of vulnerable species	Golladay et al., 2004

Manage and prevent the establishment of aquatic and riparian invasive and non-native species in a changing climate

Despite the uncertainties in climate change, aquatic invasive species management plays a critical role in overall ecosystem management and should be planned and implemented in a manner that is flexible and considers and monitors for potential changes.[1813]

Prevention measures are implemented to avoid the introduction and establishment of invasive species and are widely recognized as the most effective and cost-efficient tools for combating invasive species.[1814] Addressing invasive species through prevention mechanisms such as early detection and eradication will be less costly over the long-term than post-entry maintenance and control activities that depend on continued commitment and resources as well as on development of successful, targeted control mechanisms.[1815] Thus, prevention activities are key tools for successfully addressing invasive species, and states (or provinces, Tribes, and First Nations) with limited resources may maximize the use of scarce invasive species funds by investing in prevention efforts.[1816] Numerous strategies and measures may be used to manage and prevent the establishment of potentially harmful aquatic /riparian invasive and non-native species, including those described below.

[1813] *NOAA. (2010a, p. 92)
[1814] *U. S. EPA. (2008b, p. 2-12). The authors cite Keller et al. (2007), Leung et al. (2002), NISC (2001) and Wittenberg and Cock (2001) for this information.
[1815] *U. S. EPA. (2008b, p. 2-12 to 2-13). The authors cite Simberloff (2003) and Mack et al. (2000) for this information.
[1816] *U. S. EPA. (2008b, p. 2-13)

Monitoring, mapping and/or survey efforts to identify and mitigate invasive species threats

To address the potential effects of climate change, continued and new monitoring will be necessary to update information systems with data that allow evaluation of those effects.[1817] Monitoring efforts may need to be modified to focus on weakened or changing ecosystems that are more vulnerable to invasion.[1818] Further, monitoring and survey efforts may be used to identify species that are encroaching as a result of expanding ranges.[1819] Adapting monitoring may mean sampling at different temporal or spatial frequencies, or using different sampling techniques.[1820] For example, monitoring to detect range changes may require sampling the distributional and altitudinal edges of species ranges.[1821] This may benefit from acquiring the ability to distinguish between range shifts and species invasions (e.g. decide if plant or animal species migration into an area due to increased temperatures, sea level rise or other climate change factors is to be considered "invasive").[1822]

Adapt information management activities

An information management system will have to support rapid and accurate discovery of data, correlate and synthesize data from many sources, and present the results of data synthesis that meets the needs of users.[1823] In addition to data on species movement and establishment, information on ecosystem conditions—e.g., water temperatures, chemical composition, and salinity levels, where applicable—should also be monitored and evaluated to fully assess invasive-species threats in the context of a changing climate.[1824] Any existing or planned information systems for aquatic invasive species should incorporate information on climate change and its effects on invasive species and have the ability to be updated with monitoring information in order to assess the occurrence of effects.[1825] As more information on effects of climate change on aquatic invasive species becomes available, information systems will require the capacity to be updated.[1826] Then more targeted research may be done that can provide more specific recommendations for aquatic invasive species management in a changing climate.[1827]

Adapt Early Detection and Rapid Response (EDRR) protocols and emergency powers

EDRR refers to efforts that identify and control or eradicate new infestations before they reach severe levels.[1828] Because even the most effective barriers to entry will at some point be breached, EDRR is an important element in preventing and controlling invasive species problems.[1829] In addition to surveying and/or mapping to detect infestations, EDRR efforts may include emergency powers for state agencies to implement control measures quickly and restoration to decrease vulnerability to re-establishment of the

[1817] *U. S. EPA. (2008b, p. 2-15). The authors cite Lee et al. (2008) for this information.
[1818] *U. S. EPA. (2008b, p. 2-14)
[1819] *U. S. EPA. (2008b, p. 2-14)
[1820] *U. S. EPA. (2008b, p. 2-15). The authors cite Hellmann et al. (2008) for this information.
[1821] *U. S. EPA. (2008b, p. 2-15).
[1822] *ASWM. (2009, p. 11)
[1823] *U. S. EPA. (2008b, p. 2-16)
[1824] *U. S. EPA. (2008b, p. 2-16 to 2-17)
[1825] *U. S. EPA. (2008b, p. 2-17). The authors cite Lee et al. (2008) for this information.
[1826] *U. S. EPA. (2008b, p. 2-17)
[1827] *U. S. EPA. (2008b, p. 2-17)
[1828] *U. S. EPA. (2008b, p. 2-15)
[1829] *U. S. EPA. (2008b, p. 2-15)

invading species.[1830] Comprehensive EDRR plans identify participating and lead agencies, potential regulatory requirements for control, and other EDRR protocols.[1831] The effectiveness of EDRR efforts may be improved by monitoring both for the establishment of new infestations as well as for changing conditions in order to better predict which systems may become vulnerable to invasion.[1832]

The Hazard Analysis and Critical Control Points (HACCP) planning framework

Another important prevention tool for invasive species managers is the HACCP planning framework.[1833] As a part of the HACCP planning process, natural resource managers identify potential invasive species and possible points of entry that could result from management activities.[1834] Managers also focus on specific pathways and develop best management practices to prevent these species from being introduced.[1835] This planning framework helps managers assess risk and make more strategic decisions.[1836]

Evaluate vectors for the ability to transmit species under changing conditions

Vectors also may be influenced by changes in climate and should be evaluated for the ability to transmit species under changing conditions.[1837] For example, seaways may remain open for longer periods during the year due to warming temperatures; thus, shipping and boating traffic, a major vector for species such as the zebra mussel, also may increase.[1838] To begin to address these concerns, pathway analysis and species prediction models should be modified to include climate change parameters.[1839]

Precautionary measures and quarantines

Climate changes resulting in increased storm surge and flooding increase the risk of species escape from aquaculture facilities.[1840] In light of these changes, aquaculture facilities may need to take additional precautionary measures against escapes or establishment (e.g., use only triploids, stock only one sex, or use sterile hybrids) or to use only native species.[1841]

Regulation of certain species (e.g. introduction, import, or release requirements)

States may need to alert inspection and border control agencies to new invasive threats, and related inspection priorities may need to be re-assessed in light of these impending threats and pathways.[1842] Import/introduction/release requirements should be based on risk assessments that account for how changing conditions will affect the potential for an area to be invaded.[1843]

[1830] *U. S. EPA. (2008b, p. 2-15)
[1831] *U. S. EPA. (2008b, p. 2-15)
[1832] *U. S. EPA. (2008b, p. 2-15)
[1833] *U. S. EPA. (2008b, p. 2-13)
[1834] *U. S. EPA. (2008b, p. 2-13)
[1835] *U. S. EPA. (2008b, p. 2-13)
[1836] *U. S. EPA. (2008b, p. 2-13)
[1837] *U. S. EPA. (2008b, p. 2-14)
[1838] *U. S. EPA. (2008b, p. 2-14)
[1839] *U. S. EPA. (2008b, p. 2-14)
[1840] *U. S. EPA. (2008b, p. 2-14)
[1841] *U. S. EPA. (2008b, p. 2-14)
[1842] *U. S. EPA. (2008b, p. 2-14)
[1843] *U. S. EPA. (2008b, p. 2-14)

Re-evaluate ongoing land and water management activities

Ongoing land and water management activities should be re-evaluated for their potential to provide new invasion pathways.[1844] For example, waterway engineers could examine passage between water bodies that were historically separated, create barriers to passages, and consider aquatic invasive species spread before re-filling or reconnecting waterways.[1845] In addition, a re-evaluation of appropriate control measures may be necessary in order to make efficient use of state (or provincial, Tribal, First Nations) investments in aquatic invasive species management.[1846] Changing conditions, such as warmer waters, extreme weather events, salt water intrusion, and/or changes in water chemistry, may affect the success of "tried and true" biological, chemical, or mechanical control measures.[1847]

Adapt restoration activities

Restoration of natural systems is critical to preventing re-introduction of an invasive species once it has been eradicated or controlled.[1848] Because healthy ecosystems may be less vulnerable to invasion, restored ecosystems also may be less vulnerable future invasions, thus providing some insurance to investments in invasive species prevention, Early Detection and Rapid Response, and other control measures.[1849] Given that climate change is expected to alter native species and habitats and other ecosystem attributes, restoration designs should emphasize restoration of ecosystem processes (e.g. sediment and nutrient transport, export of woody debris, river-floodplain connections) that were originally disrupted and may have facilitated the establishment of aquatic invasive species.[1850] Restoration projects should include analyses of which native species may thrive in, or at least tolerate, future climate-change conditions and avoid those species that may not be as well suited to future conditions.[1851] In addition, restoration projects may actively remove invasive species that threaten key native species[1852] and undesirable plant species may be controlled through vegetation management treatments.[1853] *Please see the section "Maintain and restore wetlands and riparian areas" for further information on riparian restoration activities.*

Adapt education efforts to increase public awareness regarding particular species and/or pathways[1854]

Many states (or provinces, Tribes, First Nations) conduct public awareness campaigns to inform the public, decision-makers, and other stakeholders about ways to prevent the introduction and spread of invasive species.[1855] Aquatic invasive species outreach campaigns can use their existing efforts to educate the public about new invasive species threats due to climate change.[1856]

1844 *U. S. EPA. (2008b, p. 2-14)
1845 *U. S. EPA. (2008b, p. 2-14). The authors cite Rahel and Olden (2008) for this information.
1846 *U. S. EPA. (2008b, p. 2-16)
1847 *U. S. EPA. (2008b, p. 2-15)
1848 *U. S. EPA. (2008b, p. 2-16)
1849 *U. S. EPA. (2008b, p. 2-16). The authors cite Vitousek et al. (1996) for this information.
1850 *U. S. EPA. (2008b, p. 2-16)
1851 *U. S. EPA. (2008b, p. 2-16)
1852 *Palmer et al. (2008, p. 33)
1853 *Spittlehouse and Stewart. (2003, p. 10)
1854 *U. S. EPA. (2008b, p. 2-13)
1855 *U. S. EPA. (2008b, p. 2-17)
1856 *U. S. EPA. (2008b, p. 2-17)

Additional actions

An additional action is to incorporate climate change considerations into aquatic invasive species management plans. *Please see the section "Climate adaptation actions – monitoring and planning" for information on incorporating climate change into aquatic invasive species management plans.*

8. STATUS OF ADAPTATION STRATEGIES AND PLANS IN THE STATES, PROVINCES, AND SELECTED TRIBAL NATIONS OF THE NPLCC

Alaska

To address the impacts of climate change on Alaska, Governor Sarah Palin signed Administrative Order 238 on September 14, 2007, which established and charged the Alaska Climate Change Sub-Cabinet to advise the Office of the Governor on the preparation and implementation of a comprehensive Alaska Climate Change Strategy (AO 238).[1857] The Adaptation Advisory Group (AAG) was charged with evaluating and developing options to adapt to climate change.[1858] The Final Report Submitted by the Adaptation Advisory Group to the Alaska Climate Change Sub-Cabinet was released in January 2010. The types of recommendations made by the AAG vary.[1859] The options cover four broad sectors (public infrastructure, health and culture, natural systems, and economic activities) and range from new systems approaches and institutional structures to adoption of new or revised policies, initiatives, and other actions.[1860] The Sub-Cabinet will consider these, as well as recommendations from the Immediate Action Work Group, the Mitigation Advisory Group, and the Research Needs Work Group in the context of other complementary efforts.[1861] A comprehensive Climate Change Strategy for Alaska will then be drafted for consideration by the Governor.[1862]

Yukon Territory

Within the Yukon Territory (186,272 mi^2, 482,443 km^2),[1863] the only land within the NPLCC region is that covered by the Kluane National Park and Preserve (8,487 $miles^2$, 21, 980 km^2; ~4.6% of total area in Yukon Territory),[1864] located in the southwest corner of the Territory. Parks Canada lists impacts in its Pacific Coast parks largely consistent with those described in this report for the region: higher temperatures, a moderate increase in winter precipitation and drier summers, increased ocean surface temperatures, greater storm intensity, and altered ocean currents (please see relevant sections of this report for further information).[1865] Information on climate change adaptation planning for the Kluane National Park and Preserve was limited; however, information on adaptation planning by the Government of Yukon is described below.

The Government of Yukon Climate Change Strategy, released in 2006, sets out the government's role and key goals for its response to climate change.[1866] After its release, Environment Yukon began researching and collecting information needed to develop the Yukon Government Climate Change Action Plan, which was released February 2009.[1867] The Climate Change Strategy includes broad goals targeted at enhancing the awareness and understanding of climate change impacts, taking measures to reduce the levels of

[1857] *AK Department of Environmental Conservation. (2010, Ch 1, p. v-vi)
[1858] *AK Department of Environmental Conservation. (2010, Ch 1, p. vi)
[1859] *AK Department of Environmental Conservation. (2010, Ch 1, p. vi)
[1860] *AK Department of Environmental Conservation. (2010, Ch 1, p. vi)
[1861] *AK Department of Environmental Conservation. (2010, Ch 1, p. vi)
[1862] *AK Department of Environmental Conservation. (2010, Ch 1, p. vi)
[1863] Government of Yukon. *Executive Council Office: General Facts: Land (website).* (2011)
[1864] Parks Canada. *Kluane National Park and Preserve of Canada Management Plan*. (2010, p. 3)
[1865] *Parks Canada. *The Climate is Changing Our National Parks: Impacts on Pacific Parks (website).* (2009)
[1866] *Yukon Government. *Government of Yukon Climate Change Strategy.* (July 2006, p. 1)
[1867] *Yukon Government. *Yukon Government Climate Change Action Plan.* (February 2009, p. 9)

greenhouse gas emissions in Yukon, building environmental, social and economic systems that are able to adapt to climate change impacts and positioning Yukon as a northern leader for applied climate change research and innovation.[1868] The Action Plan, providing clear direction and action, advances the goals of the Climate Change Strategy.[1869] The four goals outlined in the Action Plan are: (1) enhance knowledge and understanding of climate change; (2) adapt to climate change; (3) reduce greenhouse gas emissions; and, (4) lead Yukon action in response to climate change.[1870]

Preparation of the Action Plan included discussions with a wide variety of government and non-government representatives, an interdepartmental workshop, working-group meetings and several external workshops.[1871] A draft of the Action Plan was circulated for public comment from May 12 to July 31, 2008 before its release in February 2009.[1872]

The Yukon government will pursue the implementation of its Climate Change Strategy in partnership and collaboration with First Nation governments, municipalities, industry, the public, the other northern territories and the provinces, the federal government and other governments around the world.[1873] Implementation of the Action Plan will involve all departments and agencies of the Yukon government.[1874] The Yukon government will also work with partners to meet the challenges and opportunities of climate change in Yukon – other governments, non-governmental organizations, industry, and the academic community.[1875]

British Columbia

Building on a framework established in 2007, British Columbia released a Climate Action Plan in 2008.[1876] The section on adaptation outlines a range of coordinated actions to help B.C. adapt to climate change, including options for investing in new ideas and solutions, protecting forests, protecting water, and building carbon smart communities.[1877] The Climate Change Adaptation Strategy addresses three main themes that provide a solid framework to address climate change impacts and adaptation: (1) build a strong foundation of knowledge and tools to help public and private decision-makers across B.C. prepare for a changing climate, (2) make adaptation a part of B.C. Government's business, ensuring that climate change impacts are considered in planning and decision-making across government, and (3) assessing risks and implementing priority adaptation actions in key climate sensitive sectors.[1878]

Washington

In the spring of 2009, Governor Gregoire signed legislation (E2SSB 5560) that included provisions for the formation of an "integrated climate change response strategy" that would "better enable state and local agencies, public and private businesses, nongovernmental organizations, and individuals to prepare

[1868] *Yukon Government. (July 2006, p. 1)
[1869] *Yukon Government. (February 2009, p. 5)
[1870] *Yukon Government. (February 2009, p. 7)
[1871] *Yukon Government. (February 2009, p. 9)
[1872] *Yukon Government. (February 2009, p. 9)
[1873] *Yukon Government. (July 2006, p. 1)
[1874] *Yukon Government. (February 2009, p. 5)
[1875] *Yukon Government. (February 2009, p. 5)
[1876] *Government of British Columbia. *Climate Action Plan*. (2008, p. 1)
[1877] Government of British Columbia. *Climate Action Plan*. (2008, p. 66-69)
[1878] *B.C. Ministry of Environment. *Climate Change Adaptation Strategy (website).* (2011)

for, address, and adapt to the impacts of climate change."[1879] The legislation directs Ecology, in partnership with the departments of Agriculture, Commerce, Fish and Wildlife, Natural Resources, and Transportation to develop an initial state strategy by December of 2011.[1880]

Four Topic Advisory Groups (TAGs) were formed to assist in developing a state strategy for how Washington can prepare for and adapt to the impacts of climate change.[1881] The TAGs are structured around four areas (built environment, infrastructure, and communities; human health and security; ecosystems, species, and habitats; natural resources) and will address a wide range of key issues that citizens, governments, and businesses will face in a changing climate.[1882] The Departments of Agriculture, Ecology, Fish and Wildlife, Health, Natural Resources, Transportation, and the University of Washington lead TAGs that examine climate change impacts and identify preparation and adaptation strategies as well as additional research needs.[1883] TAG members met regularly since their inception in early 2010 through January 2011, including three cross-cutting TAG meetings.[1884] The draft strategy will be completed in Spring 2011, followed by a period of public comment and outreach through Summer 2011.[1885] The final strategy will be submitted to the Legislature in December 2011.[1886]

Jamestown S'Klallam Tribe

In late 2009, Tribal Council approved a proposal by the Tribe's Natural Resources Department to write a formal Jamestown S'Klallam Plan for Climate Change.[1887] The purpose of the plan is to prepare for a warming climate, and to help reduce the Tribe's carbon footprint, to slow down the warming planet.[1888]

Swinomish Indian Tribal Community

In the fall of 2008 the Swinomish Indian Tribal Community started work on a landmark two-year Climate Change Initiative to study the impacts of climate change on the resources, assets, and community of the Swinomish Indian Reservation and to develop recommendations on actions to adapt to projected impacts.[1889] This followed issuance of a Proclamation by the Tribal Senate in 2007 directing action to study and assess climate change impacts on the Reservation.[1890] Under the guidance and coordination of the Swinomish Office of Planning & Community Development, the first year of the project was devoted to assessment of projected impacts, as presented in an Impact Assessment Technical Report issued in the fall of 2009.[1891] The second year of the project was focused on evaluation of strategies and options for recommended actions to counter identified impacts, which resulted in preparation and release of the

[1879] *WA Department of Ecology. *Preparing for impacts: adapting to climate change (website).* (2011)
[1880] *WA Department of Ecology. *Preparing for impacts: adapting to climate change (website).* (2011)
[1881] *WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)
[1882] *WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)
[1883] *WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)
[1884] *WA Department of Ecology. *Topic Advisory Groups (website)*. (2011)
[1885] WA Department of Ecology Topic Advisory Groups. *Integrated Climate Change Response Plan: Draft Topic Advisory Group Work Plan (unpublished internal document).* (2009)
[1886] WA Department of Ecology Topic Advisory Groups. (2009)
[1887] *Jamestown S'Klallam Tribe. *Newsletter (Vol 32, Issue 2) (pdf; website).* (2011, p. 9)
[1888] *Jamestown S'Klallam Tribe. (2011, p. 9)
[1889] *Swinomish Indian Tribal Community. *Swinomish Climate Change Initiative: Climate Adaptation Action Plan.* (2010, p. 1)
[1890] *Swinomish Indian Tribal Community. (2010, p. 1)
[1891] *Swinomish Indian Tribal Community. (2010, p. 1)

Climate Adaptation Action Plan.[1892] The ultimate goal of the project was to help ensure an enduring and climate-resilient community that can meet the challenges of anticipated impacts in the years to come.[1893]

The Action Plan discusses climate change within the context of Swinomish cultural traditions, community health, and cultural resilience, and reviews the relationship between tribal traditions and effective adaptation planning. This information, along with the climate change impacts assessed in the Technical Report and strategic evaluation of many adaptation options, was used to derive the adaptation goals, action recommendations and priorities described in the Action Plan. These are organized into four focal areas (coastal resources, upland resources, physical health, and community infrastructure and services). Strategic evaluation included assessment of six key objectives (comprehensive, sustainable, dynamic response, fiscally feasibile, non-regulatory, and meets community goals).[1894] Strategies were then screened against a number of key considerations (evaluation objectives met, existing authority and capacity versus required authority and capacity, potential internal and external partners, and timeframe anticipated for potential implementation), as well as the vulnerability and estimated risk to the system in question.[1895] At time of writing, the Swinomish are moving forward on a number of their priority actions. For example, they are seeking grants for their work, evaluating existing management plans and regulations, and assessing needed changes to building and zoning codes. A description of the Swinomish Tribe's Climate Adaptation Action Plan can be found at http://www.swinomish-nsn.gov/climate_change/Docs/SITC_CC_AdaptationActionPlan_complete.pdf (accessed 4.7. 2011).

Tulalip Tribe

The Tulalip Adaptation and Mitigation Policy Frameworks for Climate Change lists six criteria for incorporating policies and law in planning and management that allow the Tulalip Tribes to sustainably maintain healthy, resilient human communities in the face of change.[1896] These policies and law need, among other things, to be *integrated* (involve multiple independent sectors in the creation of holistic solutions that address a full range of natural and social factors), *cross-scale* (address problems at multiple scales, and devise scale-appropriate actions, working to ensure policies and actions do not defeat measures taken at any one scale), *adaptive* (monitor and respond to the effectiveness of efforts and advances in scientific and local knowledge, adapt objectives when necessary), *restorative* (use historical baselines for mitigation goals for processes that maintain healthy watersheds and communities), *participatory* (recognize stakeholder equity by including federal, state, tribal and local governments, businesses and citizens in the transparent development of baselines, objectives, and mitigation and adaptation measures), and *sustainable* (design objectives and actions on a basis of ecological and cultural sustainability, and include mechanisms to ensure the sustained financial and administrative support for their implementation).[1897]

[1892] *Swinomish Indian Tribal Community. (2010, p. 1)
[1893] *Swinomish Indian Tribal Community. (2010, p. 1)
[1894] Swinomish Indian Tribal Community. (2010, p. 38)
[1895] Swinomish Indian Tribal Community. (2010, p. 40)
[1896] *Tulalip Tribes. *Climate Change Impacts on Tribal Resources (pdf; website).* (2006, p. 2)
[1897] *Tulalip Tribes. (2006, p. 2)

Oregon

In October 2009, Governor Kulongoski of Oregon asked the directors of several state agencies, universities, research institutions and extension services to develop a climate change adaptation plan.[1898] Among other things, the plan provides a framework for state agencies to identify authorities, actions, research, and resources needed to increase Oregon's capacity to address the likely effects of a changing climate.[1899] *The Oregon Climate Change Adaptation Framework* was released in December 2010. The Framework lays out eleven expected climate-related risks, the basic adaptive capacity to deal with those risks, short-term priority actions for each risk, and several steps that will evolve into a long-term process to improve Oregon's capacity to adapt to variable and changing climate conditions.[1900]

Coquille Tribe

Building on the traditions and values of the Tribal community, the Coquille Indian Tribe is focused on developing a plan to adapt to the challenges presented by climate change and related threats to the tribe's well-being.[1901] Currently, the tribe is focused on building capacity within the Tribal government to understand the impacts of climate change, engaging the tribal community in climate change discourse, and strengthening collaboration and partnerships with non-tribal organizations within the region.[1902] The Tribe has committees in place to identify and investigate the issues, including the Climate Change Committee and the Emergency Preparedness and Disaster Mitigation Committee.[1903] The Climate Change Committee, for example, was established in 2008 and has been tasked by Tribal Council to: become familiar with the causes of climate change and consequences of climate change to the Tribe, tribal members, tribal enterprises and the outlying community; evaluate practices, policies operations and enterprises and make recommendations regarding opportunities, adaptations and mitigations regarding the climate change process as it affects the Tribe and its members; and, provide information to the Tribal membership regarding the causes, effects and prudent responses to climate change.[1904]

In addition to continuing current efforts, the Tribe is preparing a *Climate Action Plan*, a more detailed and informed plan that incorporates insight and knowledge from Tribal members, the Tribe's natural resources and planning staff, information and data from climate scientists, research and other organizations dedicated to climate issues, and the assistance and resources available from local, state and federal government.[1905] The plan will help to further identify local risks to Coquille Tribal land and natural resources, infrastructure and transportation systems, and in turn, the Tribe's culture, economy, health, and safety.[1906] Additionally, impacts to other regions of the northwest and the world that may also bring adverse local impacts will be investigated.[1907] Further information on the Coquille Tribe's efforts around climate change can be found at http://tribalclimate.uoregon.edu/files/2010/11/tribes_Coquille_web2.pdf (accessed 4.7. 2011).

[1898] *State of Oregon. *The Oregon Climate Change Adaptation Framework*. (2010, p. i)
[1899] *State of Oregon. (2010, p. i)
[1900] State of Oregon. (2010, p. i)
[1901] *Institute for Tribal Environmental Professionals. *Climate Change and the Coquille Indian Tribe: Planning for the effects of climate change and reducing greenhouse gas emissions (pdf).* (2011, p. 1)
[1902] *Institute for Tribal Environmental Professionals. (2011, p. 2)
[1903] *Institute for Tribal Environmental Professionals. (2011, p. 2)
[1904] *Institute for Tribal Environmental Professionals. (2011, p. 3)
[1905] *Institute for Tribal Environmental Professionals. (2011, p. 1)
[1906] *Institute for Tribal Environmental Professionals. (2011, p. 1)
[1907] *Institute for Tribal Environmental Professionals. (2011, p. 1)

California

California strengthened its commitment to managing the impacts from sea-level rise, increased temperatures, shifting precipitation and extreme weather events when Governor Arnold Schwarzenegger signed Executive Order (EO) S-13-08 on November 14, 2008.[1908] The order called on state agencies to develop California's first strategy to identify and prepare for these expected climate impacts.[1909] The California Natural Resources Agency (CNRA) has taken the lead in developing this adaptation strategy, working through the Climate Action Team (CAT).[1910] Seven sector-specific working groups led by twelve state agencies, boards and commissions, and numerous stakeholders were convened for this effort.[1911] The strategy proposes a comprehensive set of recommendations designed to inform and guide California decision-makers as they begin to develop policies that will protect the state, its residents and its resources from a range of climate change impacts.[1912] Four comprehensive state adaptation planning strategies were identified by all climate adaptation sectors.[1913] These strategies were intended to be in place or completed by the end of 2010.[1914]

Following a 45-day public comment period since its release as a Discussion Draft in August 2009, the CNRA and sector working groups have revised the strategy incorporating public stakeholder input.[1915] This document will be updated approximately every two years to incorporate progress in strategies and changing climate science.[1916] The current draft reviews projections for temperature, precipitation, sea-level rise, and extreme events, then evaluates climate impacts by sector.[1917]

Yurok Tribe

In 2010, the Yurok Tribe received a grant from the U.S. Environmental Protection Agency for a Climate Change Impacts Assessment and Prioritization Project.[1918] The final goal of the project is the preparation and completion of the Yurok Tribe Climate Change Prioritization Plan and an initial assessment of potential climate change impacts that will serve as a guide for future tribal climate change research and planning efforts.[1919] The project also aims to build tribal government and community capacity via technical training of the program staff and participation in national meetings.[1920] The project will engage the reservation community in potential localized changes through the production of educational materials, including a brochure outlining various opportunities to participate in local and regional climate change planning efforts.[1921]

[1908] *CA Natural Resources Agency. (2009, p. 4)
[1909] *CA Natural Resources Agency. (2009, p. 4)
[1910] *CA Natural Resources Agency. (2009, p. 4)
[1911] *CA Natural Resources Agency. (2009, p. 4)
[1912] *CA Natural Resources Agency. (2009, p. 4)
[1913] CA Natural Resources Agency. (2009, p. 23)
[1914] CA Natural Resources Agency. (2009, p. 23)
[1915] *CA Natural Resources Agency. (2009, p. 4)
[1916] *CA Natural Resources Agency. (2009, p. 4)
[1917] CA Natural Resources Agency. (2009, p. 4)
[1918] U.S. EPA. *Environmental Justice Grant Recipients in the Pacific Southwest: Yurok Tribe Project (website).* (2011)
[1919] *U.S. EPA. (2011)
[1920] *U.S. EPA. (2011)
[1921] *U.S. EPA. (2011)

VIII. NEXT STEPS

In 2011 and 2012, National Wildlife Federation (NWF), in partnership with the University of Washington Climate Impacts Group (CIG), will convene six expert focus groups to confirm, augment, and disseminate the findings of this report. Leveraging NWF's existing efforts in outreach and stakeholder engagement and CIG's expertise conducting similar focus groups, NWF will utilize a participatory, integrative approach to engage experts in focus group discussions of climate change effects and adaptation strategies in freshwater aquatic and riparian ecosystems in the NPLCC geography.

Similar to the review process used to produce this final draft report, information gathered during focus group meetings will be incorporated into this report and reviewed by focus group participants as well as others. Focus groups will address climate change at both the local- and landscape-level, incorporating expert knowledge on the major effects resulting from climate change in freshwater ecosystems, the implications for biological communities across taxa and trophic levels, and adaptive approaches to address impacts into this report to produce the first picture of landscape-wide climate change effects in these ecosystems. Further, focus groups will confirm and revise the adaptation options described in the draft reports to produce a menu of policy and management options that respond to climate change in these ecosystems, and are therefore useful and relevant to management needs across the NPLCC landscape. The final product will be the first compilation of landscape-wide climate change impacts and adaptation approaches for the NPLCC region's freshwater aquatic and riparian ecosystems.

IX. APPENDICES

1. KEY TERMS AND DEFINITIONS

A

Adaptation: adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.[1922]

Adaptive capacity: the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Adaptive management: an experimental framework composed of management actions that specifies the research and monitoring information needed to evaluate management success and stipulates how and when information will be used to revise management action.[1923] It is similar to scenario-based planning, but does not build management experiments into a model.[1924]

Aerosol: highly dispersed solid or liquid particles suspended in a gas

Anoxia: a water column devoid of oxygen

Aquatic (habitat or ecosystem): habitats or ecosystems dominated by water

Autotrophic: the capacity to perform primary production; self-feeding; able to use CO_2 as a source of carbon using chemical (chemoautotrophy) or light (photoautotrophy) energy[1925]

B

Baseflow: the level of stream discharge in the absence of recent storms[1926]

Benthic community: the community of organisms living on or near the bottom of a water body such as a river, a lake, or an ocean.[1927]

C

(Date of) **Center of mass** (of streamflow): the date at which roughly half of the mass of annual streamflow has occurred

(Date of) **Center of volume** (of streamflow): the date at which roughly half of the volume of annual streamflow has occurred

Climate: Climate in a narrow sense is usually defined as the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. Climate in a wider sense is the state, including a statistical description, of the climate system. The classical period of time is 30 years, as defined by the World Meteorological Organization (WMO).[1928]

Climate change: Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines 'climate change' as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'.[1929]

Climate change adaptation: a dynamic management strategy that involves identifying, preparing for, and responding to expected climate change in order to promote ecological resilience, maintain ecological function, and provide the necessary elements to support

[1922] *IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Introduction.* (2007, p. 6)
[1923] Gregg et al. (2011); Peterson, Cumming and Carpenter. (2003)
[1924] Peterson, Cumming and Carpenter. (2003)
[1925] Dodds & Whiles. (2010)
[1926] Dodds & Whiles. (2010)
[1927] Parry et al. (Eds.) (2007, p. 870)
[1928] Parry et al. (Eds.) (2007, p. 871)
[1929] Parry et al. (Eds.) (2007, p. 871)

biodiversity and sustainable ecosystem services.[1930]

Climate shift: a rapid change in relatively stable physical ocean properties that affects biota and ecosystems

Climate threshold: The point at which external forcing of the climate system, such as the increasing atmospheric concentration of greenhouse gases, triggers a significant climatic or environmental event which is considered unalterable, or recoverable only on very long time-scales, such as widespread bleaching of corals or a collapse of oceanic circulation systems.[1931] *See also Threshold.*

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).[1932]

D

E

Ecosystem: The interactive system formed from all living organisms and their abiotic (physical and chemical) environment within a given area. Ecosystems cover a hierarchy of spatial scales and can comprise the entire globe, biomes at the continental scale or small, well-circumscribed systems such as a small pond.[1933]

Ecosystem-Based Management (EBM): an integrated approach to management that considers the entire ecosystem, including humans. EBM emphasizes the protection of ecosystem structure, function, and key processes; focuses on a specific ecosystem and the activities affecting it; explicitly accounts for the interconnectedness within systems (e.g. between species); acknowledges interconnectedness among systems (e.g. air, land and water); and integrates ecological, social, economic, and institutional perspectives.[1934]

El Niño: the warm phase of ENSO; characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall

El Niño-Southern Oscillation (ENSO): the major source of inter-annual climate variability in the Pacific Northwest (PNW). ENSO variations are more commonly known as El Niño (the warm phase of ENSO) or La Niña (the cool phase of ENSO)

Evapotranspiration: water evaporation from soils, plant surfaces, and water bodies and water losses through plant leaves.[1935]

Exposure (to climate change): the nature and degree to which a system is exposed to significant climatic variations

Extinction (of species): the state of a species that no longer exists anywhere on Earth (includes wild and captive species)

Extirpation (of species): native species that no longer exist in the wild in any part of their original distribution area, although they may exist elsewhere

F

Firn: Old snow that has become granular and compacted (dense) as the result of various surface metamorphoses, mainly melting and refreezing but also including sublimination (i.e. the physical process by which a solid transforms

[1930] Glick et al. (2009, p. 8)
[1931] Parry et al. (Eds.) (2007, p. 872)
[1932] Parry et al. (Eds.) (2007, p. 872)
[1933] Parry et al. (Eds.) (2007, p. 874)
[1934]. West Coast EBM Network. (2010)
[1935] Brooks et al. *Hydrological Processes and Land Use.* (2003)

to a gas without going through a melting stage)[1936]

Flux: the rate of flow of energy or particles across a surface

Freshet: the annual spring rise of streams in cold climates as a result of melting snow; a flood resulting from rain or melting snow, usually applied only to small streams and to floods of minor severity; a small freshwater stream[1937]

Freshwater ecosystem: Freshwater ecosystems are aquatic systems which contain drinkable water or water of almost no salt content. Freshwater resources include lakes and ponds, rivers and streams, reservoirs, wetlands, and groundwater.[1938]

G

Glacier: A mass of land ice, formed by the further recrystallization of firn, flowing continuously from higher to lower elevations.[1939]

Gyre: a spiral oceanic surface current moving in a clockwise direction

H

Habitat: the locality or natural home in which a particular plant, animal, or group of closely associated organisms lives.[1940]

Heterotrophy: metabolic energy and growth from degradaton of organic molecules; carnivory, detritivory, herbivory, microbial decay, and omnivory[1941]

Hydric soils: soils with characteristics related to constant water inundation[1942]

Hydrologic cycle: the existence and movement of water on, in, and above the Earth; composed of sixteen components: water storage in oceans, evaporation, sublimination, evapotranspiration, water in the atmosphere, condensation, precipitation, water storage in ice and snow, snowmelt runoff to streams, surface runoff, streamflow, freshwater storage, infiltration, groundwater storage, groundwater discharge, springs; the processes and pathways involved in the circulation of water from land and water bodies to the atmosphere and back again[1943]

Hydrologic year: generally, 1 October to 30 September in the Northern Hemisphere, 1 July to 30 June in the Southern Hemisphere; the annual cycle that is associated with the natural progression of the hydrologic seasons. It commences with the start of the season of soil moisture recharge, includes the season of maximum runoff (or season of maximum groundwater recharge), if any, and concludes with the completion of the season of maximum evapotranspiration (or season of maximum soil moisture utilization)[1944]

Hydrology: the science encompassing the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground

Hypolimnion: the bottom layer of a stratified lake; below the metalimnion[1945]

Hypoxia: a water column largely deficient of dissolved oxygen; generally, a water column with less than 2.0 milligrams of oxygen per liter of water dissolved within it

I

(climate change) Impacts: the effects of climate change on natural and human systems.[1946]

J

[1936] American Meteorological Society. *Glossary of Meteorology (website).* (n.d.)
[1937] Farlex. *Freshet (website).* (2011)
[1938] U.S. EPA. *Aquatic Biodiversity: Freshwater Ecosystems (website)*. (2010)
[1939] American Meteorological Society. (n.d.)
[1940] Parry et al. (Eds.) (2007, p. 876)
[1941] Parry et al. (Eds.) (2007, p. 876)
[1942] Parry et al. (Eds.) (2007, p. 876)
[1943] Brooks et al. (2003, p. 21)
[1944] American Meteorological Society. (n.d.)
[1945] Dodds & Whiles. (2010)
[1946] Parry et al. (Eds.) (2007, p. 876)

K

L

La Niña: the cool phase of ENSO; characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall.

Lake: a very slowly flowing or nonflowing (lentic) open body of water in a depression and not in contact with the ocean (the definition includes saline lakes but excludes estuaries and other mainly marine embayments)[1947]

Littoral zone: shallow, shoreline area of a water body; the portion of benthos from zero depth to the deepest extent of rooted plants[1948]

M

Marsh: continuously or usually inundated wetland with saturated soils and emergent vegetation[1949]

Metalimnion: the intermediate zone in a stratified lake in which the temperature change with depth is rapid, below the epilimnion and above the hypolimnion; also known as the thermocline or the mesolimnion[1950]

Metapopulation: two or more geographically separated populations that interact to some degree[1951]

N

[1947] Dodds & Whiles. (2010, p. 143)
[1948] Dodds & Whiles. (2010)
[1949] Dodds & Whiles. (2010)
[1950] Dodds & Whiles. (2010)
[1951] Dodds & Whiles. (2010)

O

Oligotrophic: nutrient-poor system with relatively low primary production[1952]

P

Pacific Decadal Oscillation (PDO): long-lived El Niño-like pattern of Pacific climate variability

Periphyton: the mixed assemblage of organisms attached to solid substrates in lighted benthic habitats, including algae, bacteria, protozoa, and invertebrates; a biofilm containing algae; also called aufwuchs and microphtyobenthos[1953]

pH: activity of hydrogen ions (which is closely related to concentration), expressed as $\log_{10}$ (moles H^+ liter^{-1})[1954]; a measure of the acidity or alkalinity (i.e. basicity) of a substance, ranging on a scale of 0 to 14, where 7 is "neutral" (neither acidic nor basic). The scale is logarithmic (i.e. a substance with pH 5 is ten times more acidic than a substance with pH 6).

Phenology: the study of natural phenomena that recur periodically (e.g. development stages, migration) and their relation to climate and seasonal changes.[1955]

Phytoplankton: the plant forms of plankton

Pond: an inland body of freshwater naturally formed by processes such as glacial retreat; generally smaller and shallower than lakes.

Precipitation: the general term for rainfall, snowfall and other forms of frozen or liquid water falling from clouds

Puget Sound: a large estuary complex in the Pacific Northwest

Q

[1952] Dodds & Whiles. (2010)
[1953] Dodds & Whiles. (2010)
[1954] Dodds & Whiles. (2010)
[1955] Parry et al. (Eds.) (2007, p. 879)

R

Radiative forcing: measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system; an index of the importance of the factor as a potential climate change mechanism

Realignment adaptation: a type of adaptation typically used in already significantly disturbed systems in which the system (e.g., an organism, population, community, or ecosystem) is changed to be healthy under expected future conditions rather than returned to historical conditions

Recruitment: the number of fish entering each size or age class[1956]

Relocation: a type of adaptation in which a system (e.g., an organism, population, community, or ecosystem) is moved to a new location, either by natural processes or through human assistance (latter also known as assisted migration)

Reservoir: similar to lakes, but constructed by humans. Levels are generally controlled by an outlet at a dam. Natural lakes that have been dammed may also function as partial reservoirs.

Resilience: the amount of change or disturbance that can be absorbed by a system (e.g., an organism, population, community, or ecosystem) before the system is redefined by a different set of processes and structures; the ability of a system to recover from change or disturbance without a major phase shift

Resistance: the ability of a system (e.g. an organism, population, community, or ecosystem) to withstand a change or disturbance without significant loss of structure or function

Response adaptation: a type of adaptation that facilitates the transition of ecosystems from current, natural states to new conditions brought about by a changing climate

[1956] Dodds & Whiles. (2010)

Riffle: a rapidly flowing portion of a river or stream where the influence of the bottom can be seen at the surface[1957]

Riparian (habitat or ecosystem): related to or located near water; often a transition zone between terrestrial and aquatic habitats[1958]

Riparian buffer: an area adjacent to a stream or other water body where vegetation is left intact to reduce pollution inputs[1959]

River: the common term for a large stream.

S

Saltwater intrusion / encroachment: displacement of fresh surface water or groundwater by the advance of salt water due to its greater density; usually occurs in coastal and estuarine areas due to reducing land-based influence (e.g. from reduced runoff & associated groundwater recharge; from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative SLR).[1960]

Scenario-based planning: a systematic method that considers a variety of possible futures that include the key uncertainties in a system (as opposed to a focus on the accurate prediction of a single outcome). Scenarios are specific to the planning process, are accompanied by narratives, and are used to evaluate policy and management options. Participants are able to explore the effectiveness of various strategies, identifying actions that work well across multiple scenarios and are robust under situations of high uncertainty.[1961]

Secondary production: tissue production by heterotrophic organisms[1962]

Sensitivity (to climate change): the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.

[1957] Dodds & Whiles. (2010)
[1958] Dodds & Whiles. (2010)
[1959] Dodds & Whiles. (2010)
[1960] Parry et al. (Eds.) (2007, p. 880)
[1961] Gregg et al. (2011); Peterson, Cumming and Carpenter. (2003)
[1962] Dodds & Whiles. (2010)

Shredder: an organism that makes its living shredding organic material for food[1963]

Species diversity: generally measured as the number of species in an area and their evenness (relative abundance) [1964]

Species richness: the number of species in an area[1965]

Spring pulse onset: date of the beginning of the spring or early summer snowmelt-derived streamflow for snowmelt-dominated rivers[1966]

Stratification: density differences in water that can maintain stable layers[1967]

Stream: the water flowing in a natural channel (as distinct from a canal).[1968]

Sublittoral: bottom region between littoral and profundal zones[1969]

T

Threshold: The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.[1970] *See also climate threshold.*

Trophic cascade: influence of consumer organisms on those lower in the food web with alternating effects at each trophic level (top-down control)[1971]

Trophic state: total ecosystem productivity, including heterotrophic and autotrophic pathways[1972]

U

V

Vulnerability (to climate change): the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts. It is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Vulnerability Assessment: process of identifying, quantifying, and prioritizing the vulnerabilities in a system; a key tool for carrying out climate change adaptation planning for natural systems and informing the development and implementation of resource management practices

WXYZ

Water column: a conceptual column of water from surface to bottom sediments

Water cycle: *See hydrologic cycle*

Water year: *See hydrologic year*

Wet meadow: a meadow without open water but saturated soils[1973]

Wetland: lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water;[1974] areas inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a prevalence of vegetation adapted for life in saturated soil conditions[1975]

[1963] Dodds & Whiles. (2010)
[1964] Dodds & Whiles. (2010)
[1965] Dodds & Whiles. (2010)
[1966] Stewart, Cayan and Dettinger. (2005, p. 1138)
[1967] Dodds & Whiles. (2010)
[1968] U.S. Geological Survey. (2008)
[1969] Dodds & Whiles. (2010)
[1970] Parry et al. (Eds.) (2007, p. 882)
[1971] Dodds & Whiles. (2010)
[1972] Dodds & Whiles. (2010)
[1973] Dodds & Whiles. (2010)
[1974] U.S. Fish and Wildlife Service. (1993)
[1975] Dodds & Whiles. (2010)

2: SRES SCENARIOS AND CLIMATE MODELING

The explanation of SRES scenarios is excerpted from the IPCC's AR4 Synthesis Report (p. 44). Figure 31 was accessed online at http://sedac.ciesin.columbia.edu/ddc/sres/, December 2, 2010.

SRES scenarios

SRES refers to the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The emissions projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socio-economic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments. {WGI 10.1; WGII 2.4; WGIII TS.1, SPM}

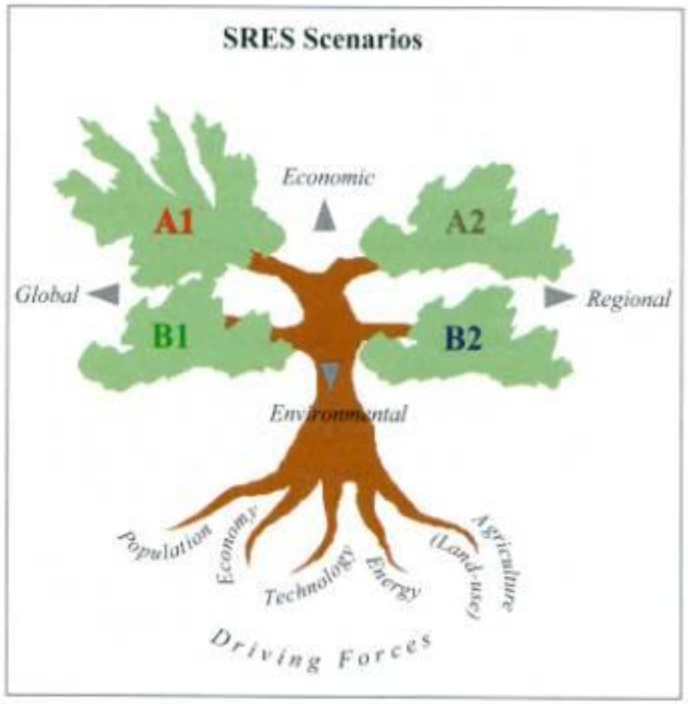


Figure 31. SRES Scenarios.

The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. No likelihood has been attached to any of the SRES scenarios. {WGIII TS.1, SPM}

Climate modeling

Global Models

Envisioning global climate in a future with much higher greenhouse gases requires the use of physically based numerical models of the ocean, atmosphere, land, and ice, often called global climate models

(GCMs) or climate system models.[1976] A common set of simulations using 21 GCMs was coordinated through the Intergovernmental Panel on Climate Change (IPCC).[1977] These models typically resolve the atmosphere with between 6,000 and 15,000 grid squares horizontally, and with between 12 and 56 atmospheric layers.[1978]

Simulations of 21st century climate require projections of future greenhouse gases and sulfate aerosols (which reflect sunlight and also promote cloud formation, thereby offsetting greenhouse gases locally), of which more than 40 were produced and six "marker" scenarios selected (B1, B2, A1, A1B, A1F1, A2) under the auspices of the IPCC.[1979] Three of these scenarios were commonly chosen for forcing the GCMs: B1, A1B, and A2.[1980] A2 produces the highest climate forcing by the end of the century, but before mid-century, none of the scenarios is consistently the highest.[1981] Though B1 is the lowest of the IPCC illustrative scenarios, it still produces changes in climate that many scientists call "dangerous" — a threshold that a growing number of political leaders have stated their intention to avoid.[1982] At the high end, scenario A1FI results in even higher climate forcing by 2100 than A2 or A1B.[1983] Mid-2000s global emissions of CO_2 exceeded even the A1FI scenario.[1984]

Downscaled Climate Models

Note: While the information described here pertains to Washington State, it is often applicable for sub-global (e.g., regional, local) modeling elsewhere.

Global climate models do not account for the atmospheric processes that determine the unique spatially heterogeneous climatic features of Washington.[1985] Statistical downscaling is based on fine-scale data derived using assumptions about how temperature and precipitation vary over complex terrain in order to interpolate the sparse station network (about 50-km spacing) to a 0.0625° grid.[1986] Information simulated by the coarse-resolution global models (with output on a 100-to-300 km grid) is then used to project the future climate.[1987] This approach represents the mean climate and local regimes quite well but does not take into account how the terrain influences individual weather systems.[1988]

Salathé, Jr. et al.'s (2010) results show that, with increased spatial resolution relative to global models, regional climate models can represent the local forcing from the complex terrain to produce more realistic spatial and temporal variability of temperature, precipitation, and snowpack in the State of

[1976] *Mote and Salathé, Jr. (2010, p. 29)
[1977] *Mote and Salathé, Jr. (2010, p. 29-30)
[1978] *Mote and Salathé, Jr. (2010, p. 30)
[1979] *Mote and Salathé, Jr. (2010, p. 30)
[1980] *Mote and Salathé, Jr. (2010, p. 30)
[1981] *Mote and Salathé, Jr. (2010, p. 30)
[1982] *Mote and Salathé, Jr. (2010, p. 31). The authors cite Schellnhuber et al. (2006) for information on changes in climate that many scientists call dangerous.
[1983] *Mote and Salathé, Jr. (2010, p. 31).
[1984] *Mote and Salathé, Jr. (2010, p. 31). The authors cite Raupach et al. (2007) for information on mid-2000s emissions and state "…we must emphasize that the scenarios used here may not span the range of possibilities" (p. 31).
[1985] *Salathé, Jr. et al. *Regional climate model projections for the State of Washington*. (2010, p. 52)
[1986] *Salathé, Jr. et al. (2010, p. 52)
[1987] *Salathé, Jr. et al. (2010, p. 52)
[1988] *Salathé, Jr. et al. (2010, p. 52)

Washington.[1989] With the ability to resolve topographic effects, more robust changes in mountain snowpack and extreme precipitation emerge.[1990] These changes are consistent between the two regional simulations despite differences in seasonal precipitation and temperature changes in the global and regional model results.[1991] It is clear that changes in the seasonal climate and the frequency of extreme events may be locally much more intense than can be inferred from statistical methods.[1992] The implication is that, while a valuable tool for regional climate impacts assessment, multi-model ensembles of global climate projections and statistical methods may under represent the local severity of climate change.[1993]

[1989] *Salathé, Jr. et al. “Regional climate model projections for the State of Washington.” In: *Washington Climate Change Impact Assessment.* (2009, p. 65)
[1990] *Salathé, Jr. et al. (2009, p. 65)
[1991] *Salathé, Jr. et al. (2009, p. 65)
[1992] *Salathé, Jr. et al. (2009, p. 65)
[1993] *Salathé, Jr. et al. (2009, p. 65)

3. MAJOR CLIMATE PATTERNS IN THE NPLCC: ENSO AND PDO

This explanation is excerpted from a webpage written by Nathan J. Mantua (Ph.D.) of the University of Washington's Joint Institute for the Study of the Atmosphere and Oceans and Climate Impacts Group. The webpage is not copied in its entirety; sections that explain climate variability and its impacts on climate in the NPLCC are emphasized. The full-text can be accessed at http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm (last accessed December 9, 2010).

Introduction

In addition to El Niño, there are other heavily researched climate patterns that exert important influences on regional climates around the world. For instance, many studies highlight the relative importance of the Pacific Decadal Oscillation and Arctic Oscillation/North Atlantic Oscillation in North American climate. Each of these major patterns--El Niño/Southern Oscillation, Pacific Decadal Oscillation, and Arctic Oscillation/North Atlantic Oscillation--has characteristic signatures in seasonally changing patterns of wind, air temperature, and precipitation; each pattern also has a typical life time for any given "event".

A PDO definition

The Pacific Decadal Oscillation, or PDO, is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). As seen with the better-known El Niño/Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in Pacific Basin and North American climate. In parallel with the ENSO phenomenon, the extreme phases of the PDO have been classified as being either *warm* or *cool*, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean.

Two main characteristics distinguish the PDO from ENSO. First, typical PDO "events" have shown remarkable persistence relative to that attributed to ENSO events - in this century, major PDO eras have persisted for 20 to 30 years (Mantua et al. 1997, Minobe 1997). Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics - the opposite is true for ENSO. Several independent studies find evidence for just two full PDO cycles in the past century (e.g. Mantua et al. 1997, Minobe 1997): cool PDO regimes prevailed from 1890-1924 and again from 1947-1976, while warm PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990's. Recent changes in Pacific climate suggest a possible reversal to cool PDO conditions in 1998, an issue that is discussed in more detail at the end of this article.

The North American climate anomalies associated with PDO warm and cool extremes are broadly similar to those connected with El Niño and La Niña (Latif and Barnett 1995, Latif and Barnett 1996, Zhang et al. 1997, Mantua et al. 1997). Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to those correlated with El Niño (Figure 4): above average winter and spring time temperatures in northwestern North America, below average temperatures in the southeastern US, above average winter and spring rainfall in the southern US and northern Mexico, and below average precipitation in the interior Pacific Northwest and Great Lakes regions. Cool phases of the PDO are simply correlated with the reverse climate anomaly patterns over North America (not shown), broadly similar to typical La Niña climate patterns. The PDO-related temperature and precipitation patterns are also strongly expressed in regional snow pack and stream flow anomalies, especially in western North America (see Cayan 1995, Mantua et al. 1997, Bitz and Battisti 1999, Nigam et al. 1999). A summary of major PDO climate anomalies are listed in Table 1.

Table 1: Summary of North American climate anomalies associated with extreme phases of the PDO.

Climate Anomalies	Warm Phase PDO	Cool Phase PDO
Ocean surface temperatures in the northeastern and tropical Pacific	Above average	Below average
October-March northwestern North American air temperatures	Above average	Below average
October-March Southeastern US air temperatures	Below average	Above average
October-March southern US/Northern Mexico precipitation	Above average	Below average
October-March Northwestern North America and Great Lakes precipitation	Below average	Above average
Northwestern North American spring time snow pack	Below average	Above average
Winter and spring time flood risk in the Pacific Northwest	Below average	Above average

An ENSO definition

This definition is excerpted from the Climate Impacts Group website El Niño/Southern Oscillation, available at http://cses.washington.edu/cig/pnwc/aboutenso.shtml (last accessed 1.18.2011)

The El Niño/Southern Oscillation (ENSO) is the major source of inter-annual climate variability in the Pacific Northwest (PNW). ENSO variations are more commonly known as **El Niño** (the warm phase of ENSO) or **La Niña** (the cool phase of ENSO).

An El Niño is characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall. A La Niña is characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall. Average years, i.e., years where there is no statistically significant deviation from average conditions at the equator, are called ENSO-neutral. Each ENSO phase typically lasts 6 to 18 months.

Although ENSO is centered in the tropics, the changes associated with El Niño and La Niña events affect climate around the world. ENSO events tend to form between April and June and typically reach full strength in December (hence the name El Niño, which is Spanish for "Little Boy" or "Christ Child"; La Niña means "Little Girl"). The ENSO influence on PNW climate is strongest from October to March; by summer, Northern Hemisphere wind patterns are such that they effectively trap ENSO-related disturbances in the tropics.

The CIG has demonstrated numerous linkages between changes in ENSO and variations in PNW climate and natural resources. El Niño winters, for example, tend to be warmer and drier than average with below normal snowpack and streamflow. La Niña winters tend to be cooler and wetter than average with above normal snowpack and streamflow. These linkages and the availability of ENSO forecasts a few months to one year in advance of the event's maturation provide resource managers opportunity to consider how a particular ENSO forecast may affect resource management choices.

Interactions between ENSO and PDO

This explanation is excerpted from the Climate Impacts Group website Impacts of Natural Climate Variability on Pacific Northwest Climate, available at http://cses.washington.edu/cig/pnwc/clvariability.shtml (last accessed 1.18.2011).

The potential for temperature and precipitation extremes increases when ENSO and PDO are in the same phases and thereby reinforce each other. This additive effect is also seen in the region's streamflow and snowpack. There is no evidence at this time to suggest that either PDO or ENSO dominates with respect to temperature and precipitation when the two climate patterns are in opposite phases (i.e., an El Niño during a cool phase PDO or a La Niña during a warm phase PDO). The opposite effects on temperature and precipitation can cancel each other out, but not in all cases and not always in the same direction. Similar effects are seen on regional streamflow.

4. RESOURCES FOR ADAPTATION PRINCIPLES AND RESPONSES TO CLIMATE CHANGE

1. **Recommendations for a National Wetlands and Climate Change Initiative.** Association of Wetland Managers, Inc. January 20, 2009. Available online at http://www.aswm.org/calendar/wetlands2008/recommendations_2008_112008.pdf (accessed January 14, 2011).

    Summary: The report discusses the role U.S. agencies, Congress, states and local governments could play in implementing a national wetlands and climate change initiative (pp. 4-6). It also includes chapters on specific measures needed to better protect and adapt coastal and estuarine lands (pp. 7-10) and freshwater wetlands (pp.10-12). It concludes with a chapter on priority management-oriented and basic research needs (pp. 13-15)

2. **A New Era for Conservation: Review of Climate Change Adaptation Literature.** Glick, Patty; Staudt, Amanda; Stein, Bruce. March 12, 2009. Report produced by the National Wildlife Federation. Available online at http://www.nwf.org/News-and-Magazines/Media-Center/Faces-of-NWF/~/media/PDFs/Global%20Warming/Reports/NWFClimateChangeAdaptationLiteratureReview.ashx (accessed January 25, 2011).

    Summary: The report reviews the common barriers to climate change adaptation (including solutions; pp. 9-13), describes five overarching principles of climate change adaptation (pp. 12-17) and provides a six-stage framework to use as a guideline for developing adaptation strategies (pp. 18-23). It also includes sector-specific adaptation strategies for forests (pp. 23-29), grasslands and shrublands (pp. 30-35), rivers, streams, and floodplains (pp. 36-43), and coasts and estuaries (pp. 44-52).

3. **Biodiversity management in the face of climate change: A review of 22 years of recommendations.** Heller, Nicole E. and Zavaleta, Erika S. 2009. *Biological Conservation.* 142: 14-32. Available online at http://people.umass.edu/gce/Heller%20and%20Zavaleta,%202009.pdf (accessed January 13, 2011).

    Summary: See Table 1 (pp. 18-22) for a list of recommendations for climate change adaptation strategies for biodiversity management.

4. **Climate change adaptation strategies for resource management and conservation planning.** Lawler, Joshua J. 2009. *Annals of the New York Academy of Sciences (The Year in Ecology and Conservation Biology).* 1162: 79-98. Available online at http://training.fws.gov/branchsites/lkm/climate_change/june_09/cc-adaptreview.pdf (accessed January 13, 2011).

    Summary: Lawler provides an overview of general strategies for addressing climate change including removing other threats and reducing additional stressors, expanding reserve networks, increasing connectivity, restoring habitat and system dynamics, adaptive management, and translocation. Specific recommendations for addressing climate change in freshwater, marine, and terrestrial systems are also provided.

5. **A review of climate-change adaptation strategies for wildlife management and biodiversity conservation.** Mawdsley, Jonathan R.; O'Malley, Robin; and Ojima, Dennis S. 2009. Available online at http://www.uwpcc.washington.edu/documents/PCC/mawdsley-etal-2009.pdf (accessed January 13, 2011). *Conservation Biology.* 23(5): 1080-1089.

    Summary: Mawdsley and colleagues describe sixteen adaptation strategies, organized by strategies related to land and water protection and management (seven strategies), direct species management (four strategies), monitoring and planning (four strategies), and reviewing and modifying existing laws, regulations, and policies regarding wildlife and natural resource management (one strategy).

6. **Preparing for climate change: a guidebook for local, regional, and state governments.** Snover, Amy K.; Whitely Binder, Lara; Lopez, Jim; and Colleagues. 2007. In association with and published by ICLEI – Local Governments for Sustainability, Oakland, CA. Available online at http://cses.washington.edu/cig/fpt/guidebook.shtml (accessed January 13, 2011).

    Summary: The guidebook provides a suggested checklist for governments on how to prepare for climate change. It includes five milestones: initiate your climate resiliency effort, conduct a climate resiliency study, set preparedness goals and develop your preparedness plan, implement your preparedness plan, and measure your progress and update your plan.

7. **Climate Savvy: Adapting conservation and resource management to a changing world.** Hansen, Lara J. and Hoffman, Jennifer R. 2011. Island Press: Washington, DC. Available online for preview and purchase at http://islandpress.org/bookstore/detailsee40.html (accessed July 13, 2011).

    Summary: Hansen and Hoffman assess the vulnerabilities of existing conservation and resource management tools to climate change, then describe how these tools can be adapted to address climate change impacts. The book begins with a general overview of climate change and its effects, and key facets of building a plan to address climate change impacts. The tools include protected areas, species-based protection, connectivity, regulating harvests, reduction of pollutants, control of invasive species, pests, and disease, restoration, and a broader rethinking of governance, policy, and regulation.

8. **U.S. natural resources and climate change: concepts and approaches for management adaptation.** West, Jordan M.; Julius, Susan H.; Kareiva, Peter; and Colleagues. 2009. *Environmental Management.* 44: 1001-1021. Available online at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2791483/pdf/267_2009_Article_9345.pdf (accessed January 13, 2011).

    Summary: West and colleagues provide several concepts and approaches for assessing impacts to support adaptation, management strategies for resilience to climate change, responding to barriers and opportunities for implementation, and advancing the nation's capability to adapt. Twelve tables provide examples of specific approaches that are in use or have been proposed (e.g. Table 5, pp. 1009, provides examples of adaptation actions that focus on restoration as a means of supporting resilience).

5. LIST OF REVIEWERS AND INTERVIEWEES

Reviewers

Alaska **Bill Hanson**, US Fish and Wildlife Service **Erin Uloth**, USDA Forest Service **Gordie Reeves**, USDA Forest Service **Greg Hayward**, USDA Forest Service **Katrina Bennett**, University of Alaska – Fairbanks **Laura Baker**, The Nature Conservancy **Rob DeVelice**, USDA Forest Service **Wayne Owen**, USDA Forest Service British Columbia **Doug Biffard**, BC Ministry of Environment **James Casey**, World Wildlife Fund – Canada **John Richardson**, University of British Columbia **Tory Stevens**, BC Ministry of Environment Washington **Alan Hamlet**, Climate Impacts Group, University of Washington **Lara Whitely Binder**, Climate Impacts Group, University of Washington **Lisa Crozier**, National Oceanic and Atmospheric Administration **Marketa Elsner**, Climate Impacts Group, University of Washington **Timothy J. Beechie**, National Oceanic and Atmospheric Administration	Oregon **Dede Olson**, USDA Forest Service **Doug Spencer**, US Fish and Wildlife Service **Keith Hatch**, Bureau of Indian Affairs **Sharon Selvaggio**, US Fish and Wildlife Service **Stan Gregory**, Oregon State University California **Amy Merrill**, Stillwater Sciences **Emily Limm**, Save the Redwoods League **Hugh Safford**, USDA Forest Service **Iris Stewart-Frey**, Santa Clara University **Joseph Furnish**, USDA Forest Service **Michael J. Furniss**, USDA Forest Service Native Alaskans, First Nations, Tribal **David Graves**, Columbia River Inter-Tribal Fish Commission **Eric Quaempts**, Umatilla Tribe **Laura Gephart**, Columbia River Inter-Tribal Fish Commission Other **Doug Inkley,** National Wildlife Federation **Garrit Voggesser**, National Wildlife Federation **Jim Murphy**, National Wildlife Federation **Michael Murray**, National Wildlife Federation

Interviewees ***(continued on next page)***

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Kathie Dello, Oregon Climate Change Research Institute, Oregon State University
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Lenise Lago, USDA Forest Service
Michael J. Hampton, USDA Forest Service
Phil Mote, Oregon Climate Change Research Institute, Oregon State University
Sara O'Brien, Defenders of Wildlife
Sharon Selvaggio, US Fish and Wildlife Service
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Tim Mayer, US Fish and Wildlife Service

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Joseph Furnish, USDA Forest Service
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Native Alaskans, First Nations, Tribal

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Bob Heinith, Columbia River Inter-Tribal Fish Commission
Bruce Jones, Northwest Indian Fisheries Commission
Charles P. O'Hara, Swinomish Indian Tribal Community
Claire Wood, Confederated Tribes of Siletz Indians

Washington **Carmen Revenga**, The Nature Conservancy **Chris Konrad**, US Geological Survey **Elizabeth Gray**, The Nature Conservancy **George Pess**, National Oceanic and Atmospheric Administration **James Schroeder**, The Nature Conservancy **Jennie Hoffman**, EcoAdapt **Jon Hoekstra**, The Nature Conservancy **Lara Whitely Binder**, Climate Impacts Group, University of Washington **Marketa Elsner**, Climate Impacts Group, University of Washington **Mary Mahaffy**, US Fish and Wildlife Service **Rachel M. Gregg**, EcoAdapt **Tim Beechie**, National Oceanic and Atmospheric Administration	**David Graves**, Columbia River Inter-Tribal Fish Commission **Ed Knight**, Swinomish Indian Tribal Community **Jim Weber**, Northwest Indian Fisheries Commission **Kyle Dittmer**, Columbia River Inter-Tribal Fish Commission **Laura Gephart**, Columbia River Inter-Tribal Fish Commission **Lilian Petershoare**, USDA Forest Service **Mike Kennedy**, Confederated Tribes of Siletz Indians **Preston Hardison**, Tulalip Tribes **Ray Paddock**, Central Council Tlingit and Haida Indian Tribes of Alaska **Reid Johnson**, Central Council Tlingit and Haida Indian Tribes of Alaska **Rishi Sharma**, Columbia River Inter-Tribal Fish Commission **Stephen Kullmann**, Wiyot Tribe **Tim Nelson**, Wiyot Tribe Other **Dave Cleaves**, USDA Forest Service **Garrit Voggesser**, National Wildlife Federation **Myra Wilensky**, National Wildlife Federation **Steve Torbit**, National Wildlife Federation

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