Appendix E
Evaluation of Forest Practice Effects on Landslides and Erosion in the Chehalis Basin

FOREST PRACTICES IN THE CHEHALIS BASIN

Date: August 1, 2016
To: Chrissy Bailey, Washington State Department of Ecology
From: Kathy Vanderwal Dubé, Watershed GeoDynamics
CC: Jim Kramer, Ruckelshaus Center; Robert Montgomery, and Heather Page, Anchor QEA, LLC
Re: Evaluation of Forest Practice Effects on Landslides and Erosion in the Chehalis Basin

Introduction

A joint scoping comment letter on the Chehalis Basin Strategy State Environmental Policy Act (SEPA) Programmatic Environmental Impact Statement (EIS) was submitted by American Rivers, Trout Unlimited, and Washington Environmental Council on October 19, 2015. This memorandum addresses one part of the excerpted comments provided by the joint parties (as follows)—the effects of forest practices on landslides and erosion:

> ***Forest Practices*** *– The forest hydrology literature suggest that forest practices have a significant effect on … contribution of river sediment due to landslides and erosion. Because a large portion of the Chehalis basin is used for industrial-scale forestry, forest practices may have a major impact on the problems and needs addressed by this PEIS…*

- *Evaluate the potential for forest practices in the Chehalis basin to exacerbate landslides and contribution of sediment to the Chehalis River and its tributaries (American Rivers et al. 2015).*

It should be noted that the joint parties' comment also requested information on the hydrologic (flooding and low-flow) effects of forest practices; information pertaining to hydrologic effects is provided in a separate memorandum prepared by Perry et al. (2016). It should also be noted that this memorandum is not intended to result in specific recommendations for changes to forest practices in the EIS; instead, it focuses on past and current Forest Practices Rules and where, and to what extent, forest practices could be evaluated for modification in the future. Forest Practices Rules related to aquatic resources can be changed in three ways (legislation, litigation, and through the Adaptive Management Program), and recommendations of this nature are outside the scope of the EIS.

There is a large body of information regarding the effects of forest practices on mass wasting and erosion, including a summary of the effects of forest practices and historical and current forest practice regulations in the Chehalis Basin, which was prepared as part of the Chehalis Basin watershed studies in 2012 and updated in 2014 (Rodgers and Walters 2014). The following sections summarize:

- Current understanding of the effects of past forest practices on mass wasting and erosion, both generally and in the Chehalis Basin
- Evolution of Washington State Forest Practices Rules and regulations through time to address mass wasting and erosion

For more detailed information on these topics, the reader is referred to the full text of the Rodgers and Walters (2014) report.

A number of comments were received on the May 18, 2016 draft of this memorandum. The confirmation letter of comment receipt is provided as Attachment A, and the full text of the comment letters are provided as Attachment B.

Landslides and Erosion in Forested Environments

Landslides are a natural occurrence in steep forested environments (Guthrie and Evans 2004; Turner et al. 2010). Most landslides in forested areas of Western Washington occur during high-intensity storms when rain, often in combination with melting snow (e.g., rain-on-snow events), saturates surface soil layers or contributes to streamflow, which can undercut the toes of adjacent landslide areas. Factors affecting slope failure include the following:

- Geology/soil characteristics – strength, cohesion, infiltration capacity, and underlying material runoff
- Slope conditions – gradient, convergence, length, and aspect
- Vegetation – root strength and vegetation density
- Earthquake loading

The majority of active landslides in the Chehalis Basin are shallow slumps, debris avalanches, and debris flows that move the surficial soil layers (generally 3 to 5 feet deep) and associated trees and vegetation rapidly down slope (Laprade 1994; Russell 1995; Ward and Russell 1994; Sarikhan et al. 2008). If the landslide is close to a stream, the soil and debris can enter the stream, supplying rock, soil, and large woody material to the stream system. The debris avalanches or flows can turn into debris torrents in steep stream channels and scour the channel and adjacent riparian areas. Landslides are an important source of boulders, cobbles, gravel, and large woody material to streams and rivers in the Pacific Northwest (Guthrie and Evans 2004). These elements provide diverse aquatic habitat, such as spawning, rearing, and holding habitat for fish and other aquatic life, but an oversupply of sediment or debris can threaten public safety or be detrimental to water quality or aquatic habitat.

Potential Effects of Forest Practices on Landslides and Erosion

Forest practices, including timber harvesting and road building, have the potential to increase landslides and surface erosion by disturbing soils, changing infiltration capacity, removing root strength, decreasing canopy interception, and changing slope and surface runoff patterns. Many studies have documented increases in landslides and surface erosion resulting from timber harvesting and road building (Dragovich et al. 1993; Dyrness 1967; Guthrie and Evans 2004; Jakob 2000; Ketcheson and Froehlich 1978; Montgomery et al. 2000; Robison et al. 1999; Swanson and Dyrness 1975; Swanson et al. 1987; Swanston 1974).

The largest increases in landslides and surface erosion have been associated with road building on steep slopes (Amaranthus et al. 1985; Megahan and Kidd 1972). The cut and fill slopes formed by the road prism can fail, road drainage can be directed onto marginally stable slopes, or stream crossing culverts can plug and saturate road fill. Landslide risk can be increased in even-age harvested areas by removal of trees, resulting in a decrease in root strength, loss of canopy interception, and evapotranspiration (Amaranthus et al. 1985; Dragovich et al. 1993; Montgomery et al. 2000; Roering et al. 2003). As stated previously, if hillslope landslides reach the stream network, they can deliver soil, rocks, and woody material to streams.

Surface erosion from roads is influenced by soil compaction, which reduces infiltration and results in road runoff, gullies formed or deepened by the interception of cutslope drainage, and soil disturbance and breakdown of the aggregate surface from traffic on unpaved roads (Bilby et al. 1989; Foltz 1996; Luce and Black 1999; Ketcheson and Megahan 1996; Megahan and Kidd 1972; Paulson 1997; Reid 1981; Reid and Dunne 1984; Sullivan and Duncan 1980; Swanson et al. 1987; Toth 2000). Runoff from road surface erosion conveys primarily fine-grained sediment (sand, silt, clay); if roads are hydrologically connected to streams, the sediment can enter surface waters. Two studies found that an average of 10% to 11% of the total road length in commercial forestlands in Washington is hydrologically connected to the stream network (Dubé et al. 2010; Martin 2009).

Effects of Forest Practices on Landslides in the Chehalis Basin

During the past 20 years, there have been numerous investigations of the effects of forest practices on landslides in the Chehalis Basin. These studies have included the effects of harvest practice changes that were implemented through time, including rule changes in 1982, the 1990s, and major changes in 2001—these changes are described in more detail later in this memorandum. Some studies differentiated between harvest units that were harvested under the different Forest Practices Rules and some did not.

Watershed analyses were conducted in the Stillman Creek, Upper Skookumchuck, Chehalis Headwaters, and West Satsop watershed analysis units (WAUs) in the mid-1990s (Laprade 1994; Russell 1995; Ward and Russell 1994; O'Connor 1996). The Mass Wasting Module in the Stillman Creek, Upper Skookumchuck, and Chehalis Headwaters watershed analyses included an analysis of the number and volume of landslides associated with roads, harvest units, and un-harvested areas based on historical aerial photographs from approximately the 1950s to the 1990s, and thus reflect the effects of road building, harvesting practices, and storms during that period. All three of these mass wasting analyses found an increase in landslides associated with forest roads, and, to a much lesser extent recent harvest units (0 to 20 years old), during large storm events. The Chehalis Headwaters analysis found that older roads constructed using sidecast[1] methods were much more susceptible to mass wasting than newer roads constructed using endhaul methods, suggesting that the changes to road-building practices reduced landslide occurrence (Ward and Russell 1994). Watershed-specific prescriptions, which included road improvements to reduce instabilities and geologic reviews and avoidance of harvest on landforms mapped as highly unstable slopes as part of the Mass Wasting Modules, were instituted in all four watersheds (e.g., Stillman Creek, Upper Skookumchuck, Chehalis Headwaters, and West Satsop). In addition, in several of the watersheds, prescriptions or recommendations for riparian leave areas and/or limits to the amount of harvest in the rain-on-snow zone (i.e., to ensure that a specified percentage of sub-watersheds were hydrologically mature) could also result in fewer landslides if these areas overlapped unstable slopes.

A review of the three 1994 to 1995 watershed analyses (Stillman Creek, Upper Skookumchuck, and Chehalis Headwaters) was made in 1999, following the procedures for review every 5 years. This review included the effects of the December 1994 storm and the February 1996 storm, which was the largest on record at that time and was estimated to be a 100-year storm event. The mass wasting re-analysis inventoried slides using the 1997 aerial photographs. There were fewer landslides following that 100-year flood event than in the 1994 aerial photograph period, even though the storm magnitude was lower in the 1994 period. This suggests that Forest Practices Rules that were enacted in 1982 to address landslide-prone areas and the watershed analysis prescriptions were effective at reducing landslides, particularly road-related landslides. In addition to the aerial photograph analysis of the WAUs, a total of 13 harvest units in the Chehalis Headwaters and three harvest units in the Stillman WAU were harvested between 1994 to 1997 under the watershed analysis prescriptions in areas that included unstable slopes. Geologic reviews were conducted for all of these areas, and no landslides had occurred in any of these 16 harvest units. While this may be a small sample size, and no statistical analysis could be made, the review authors concluded that the watershed-specific prescriptions were effective at reducing mass wasting associated with road building and timber harvesting.

On December 3, 2007, an unprecedented storm occurred in Western Washington and Oregon, with extremely high levels of precipitation (up to 175% of the 100-year flood event 24-hour rainfall) in parts of the Willapa Hills and upper Chehalis Basin watershed. This catastrophic event resulted in thousands

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[1] Sidecast road construction methods include pushing material cut from the road bed over the downslope side of the road. Endhaul road construction methods minimize sidecast by excavating the majority of the road into the hillslope and hauling excavated material to a stable disposal location.

of landslides and millions of cubic yards of sediment and woody material delivered to streams (Sarikhan et al. 2008). Following the storm, numerous investigations were conducted to evaluate the relationship between forest practices and the 2007 landslides (Sarikhan et al. 2008; Stewart et al. 2013; Turner et al. 2010; Murphy et al. 2013). The authors and reviewers of the studies did not always interpret the study design or data in the same ways, and often reached somewhat different conclusions on the role that forest practices had on landslide initiation in the watershed resulting from the 2007 storm. The 2007 storm occurred approximately 6 years after adoption of new Forest Practices Rules (adopted in 2001, see discussion in the following section), so older harvest units would have been harvested under less restrictive rules for analysis and avoidance of unstable slopes. Some of the studies of the 2007 storm looked at all harvest units (older and newer rules) and some only looked at areas harvested since adoption of the 2001 rules.

Initial reports on the influence of forest practices on landslides resulting from the 2007 storm event were based on aerial (plane) surveys immediately following the storm (Sarikhan et al. 2008; later interpreted by Entrix 2009), and suggested that landslides in the Chehalis Basin watershed were densest in areas of highest precipitation underlain by basalt of the Crescent Formation. Sarikhan et al. (2008) found that initiation points for the majority of landslides were in recent clearcuts (0 to 5 years old) and sub-mature timber (15 to 50 years old) and were associated with roads, with few initiation points in young stands (5 to 15 years old) and mature timber (50 years old or more). However, they caution that their data were based on an aerial inventory; Brardinoni et al. (2003) found that landslide inventories based on aerial photographs in coastal British Columbia omit up to 85% of landslides that exist on the ground in heavily timbered areas due to forest cover obscuring the landslides. Therefore, the analysis of initiation points by Sarikhan and Entrix based on aerial surveys likely missed landslides in areas covered by mature timber and are likely not fully reliable.

Turner et al. (2010) conducted an aerial photograph inventory following the 2007 storm on 152,000 hectares (375,600 acres) of forestlands within the Willapa Hills, concentrating on areas that had been previously harvested. The study area included parts of the Chehalis Basin watershed. They followed this with ground-based inventories to identify the percentage of missed landslides on 3,977 hectares (9,827 acres) of land covering different age classes and rainfall intensities, and determined that 39% of field-detected landslides were not seen on the aerial photographs; detection likelihood decreased with increased stand age and narrower landslide width. Turner et al. concluded that few landslides occurred in harvested areas with less than 100% of the 100-year rainfall. In harvested areas with more than 100% of the 100-year rainfall, more landslides occurred on slopes with gradients of more than 70%. In areas with more than 150% of the 100-year rainfall, past harvest units with trees in the 0- to 10-year age class had a higher density of landslides than those in older age classes (greater than 10 years).

Stewart et al. (2013) investigated the effects of the 2007 storm on a 91-square-mile (236-square-kilometer) study area that encompassed land managed for timber production in the

Willapa Hills. The study area included parts of the Chehalis Basin watershed. They identified landslides through an on-the-ground inventory. They concluded that the majority (82%) of the landslides resulting from the 2007 storm occurred on hillslopes and the remainder (18%) on forest roads. They found no statistically significant difference in landslide density or volume among roads that were below, up to, or above current forest road-building and maintenance standards. Stewart et al. also concluded that avoiding clearcuts on unstable terrain (termed Rule-Identified Landforms [RILs]) reduced landslide density and volume. They also suggested that there were many landslides that initiated on terrain that did not meet the current RIL/unstable slope criteria. They did not find a correlation between landslides and geology or precipitation intensity, a finding different from Sarikhan et al. (2008) or Turner et al. (2010), but this may have been influenced by the selection of sample areas. Several minority reports were included in the Stewart et al. report by reviewers with dissenting opinions on the ability of the study to reach the conclusions it did due to the study design and what the reviewers felt was an insufficient amount of data collection. One primary concern was that the study area contained a landscape that was harvested under Forest Practices Rules from both pre- and post-2001 rule timeframes, and with a variety of road-building practices in place since the 1950s and before; therefore, it was not possible to make statements about the effectiveness of current rules based on the mix of treatments.

Though the extreme nature of the 2007 storm obliterated the majority of the landslide initiation points, a further investigation of the Stewart data by Murphy et al. (2013) evaluated 103 of the harvest units. They visited landslides in the field and suggested that more than half (69%) of the hillslope landslides potentially originated from lands that are not currently considered unstable (forest practices RILs) under current Forest Practices Rules. They suggested, "Given the majority of landslides initiated on non-RILs and landslides initiating from probable RILs that had no harvest on them at all (per field observations), it may be that the concentrated magnitude of the December 2007 storm event and its effects eclipsed the protection standards provided by Forest Practices Rules." However, other reviewers suggested that some of the non-RIL landslides were initiated by streams undercutting the toe of the slope, or that some of the areas identified as non-RIL could have initiated on unstable slopes (RIL), but this could not be determined because the landslides obliterated the slope.

The 2007 storm included extremely high precipitation in a small portion of the upper Chehalis and Stillman Creek basins, with high precipitation in other portions of the Chehalis Basin that resulted in thousands of landslides in areas of the most intense rainfall. An objective of the different investigations of the 2007 storm, as discussed previously, was to determine the effects of forest practices on landslide rates. Some major challenges with any study of landslides are that the timing, intensity, or location of a large storm event that triggers landslides cannot be controlled, and timber harvesting practices change through time so the landscape includes a mix of areas harvested under older and newer regulations. Study design also plays an important role in the ability to draw defensible conclusions about cause and effect. The studies of the 2007 storm had some conflicting conclusions and are the subject of ongoing debate. Initial observations (e.g., Sarikahan et al 2008 and Entrix 2009) suggested that the majority of landslides were in recent clearcuts, but these observations were made based on aerial observations and did not include ground-based surveys that would have been able to identify landslides in areas of regenerating or mature timber.

Turner et al (2010) and Stewart et al. (2013) used ground-based surveys, but had different study designs and statistical analyses, and reached somewhat differing conclusions. Turner et al. found that landslides occurred in harvested areas, primarily in areas of the most severe precipitation and on the steepest slopes, and under these severe conditions there were statistically more landslides in areas of 0- to 10-year-old trees (e.g., recent harvest). Stewart et al. concluded that reducing harvest on unstable slopes reduced landslide density, but did not find a statistically significant correlation between landslide occurrence and geology or precipitation intensity, perhaps due to sample size. The conflicting study conclusions and continuing debate over the effectiveness of past and current Forest Practices Rules at reducing landslides during that event make it difficult to reach a definitive conclusion on how effective the current rules are during an extreme storm event. However, it is clear that timber harvesting or poorly designed roads on marginally stable slopes are more likely to result in landslides during normal storm events until harvest areas gain sufficient root strength to help stabilize the slope. Current Forest Practices Rules are designed to avoid harvesting and road building on unstable slopes. The 1999 5-year review of the three watershed analyses showed that there were fewer landslides during the 1996 (approximately 100-year) storm than during previous periods with less intense storms, suggesting that the prescriptions that limited harvesting/road construction and improved existing roads on unstable landforms may be effective at reducing mass wasting during large storm events. Because watershed-wide studies of landsliding by necessity look at the effects of large storm events on areas harvested under both past and current rules, and studies must wait for a large storm event to occur, the effectiveness of current Forest Practices Rules is difficult to test directly.

Initial large-scale modeling of future changes to the climate suggest that there may be an increase in the intense rainfall and storm events that are often associated with landslides (Warner et al. 2015; Snover et al. 2013); however, there is variability in these results between different models. The University of Washington Climate Impact Group is currently modeling potential climate change for the Chehalis Basin and also found large variability in potential model results. Many climate change modelers suggest that there could be an increase in the frequency and intensity of heavy rains as the climate warms, which could increase landslide magnitude and frequency (Mauger et al. 2016).

Forest Practices Rules Related to Landslides and Erosion in the Chehalis Basin

Approximately 84% of the Chehalis Basin watershed land area is comprised of land managed for forest practices (Rodgers and Walters 2014). Most of these managed forestlands are subject to the Washington Forest Practices Act and regulations, with a small portion subject to federal or tribal authority. Forest Practices Rules related to landslides and erosion have changed through time to reflect ongoing research and understanding of how forest road building and timber harvesting affect landslides and erosion. There are legacy effects of past road building and timber harvesting activities across the Chehalis Basin watershed.

The 1974 Washington Forest Practices Act was the first step in regulating forestry activities on state and private forestland. The 1974 act was designed to protect the environment and to be flexible, allowing changes through time to reflect new information (i.e., adaptive management). Several changes to Forest Practices Rules regarding landslides and erosion have taken place during the years to continue to improve the identification and avoidance of harvest and road building on unstable slopes (Rodgers and Walters 2014), including the following:

- 1982 – Rules to address "excessively steep or landslide prone slopes"
- 1987 and 1988 – New rules to protect riparian areas and for adaptive management
- 1992 – New rules to address cumulative effects through watershed analyses (including a specific mass wasting analysis that analyzed the effects of forest practices on a watershed scale), and rules related to operations on unstable slopes
- 2001 – Major changes to Forest Practices Rules (Washington Administrative Code [WAC] 222-16-050(1)(d)(i)) were adopted, including tools for identifying unstable slopes, training, and updated forest road construction and maintenance requirements
  - The Forest Practices Adaptive Management Program was set up, including provisions for ongoing research and recommendations for rule changes through the Timber, Fish, and Wildlife (TFW) Policy Committee and the Cooperative Monitoring, Evaluation, and Research (CMER) Committee
- 2011 – In response to analyses of the effects of the December 2007 storm, the Forest Practices Board amended the Watershed Analysis rules and associated guidance to reinforce the existing process and timing for 5-year reviews of the mass wasting prescriptions developed by watershed analyses
  - Three watersheds in the Chehalis Basin (Stillman Creek, Upper Skookumchuck, and Chehalis Headwaters) had been operating under watershed analysis prescriptions, which specified road building and harvesting rules for mass wasting units that were mapped on a watershed-scale based on conditions in the mid-1990s (when the watershed analyses were written)
  - The Stillman Creek and Chehalis Headwaters analyses were not reviewed or updated in 2011, so forest practices in these areas are now governed by Forest Practices Rules, which specify analysis of unstable landforms on each harvest unit by a qualified expert
- 2014/2015 – The Forest Practices Board amended the rule addressing Forest Practices Applications/Notifications (FPAs/Ns) to clarify the requirements for providing additional geologic information to classify FPAs on or around unstable slopes. In addition, the Forest Practices

Board manual providing guidance to forest landowners on how to evaluate unstable slopes was updated in 2015

Current Forest Practices Rules related to landslides include the following:

- Board Manual Section 16 (dated November 2015) includes information on how to recognize landslides, slope form, potentially unstable slopes, and landforms in areas of proposed forest practices activities; procedures and resources for assessing potentially unstable areas for both general practitioners and qualified experts; and guidance on expert-level office review, field assessments, and geotechnical reports. This manual describes the types of RILs and how to identify them using remote screening tools (e.g., topographic maps, aerial photographs, Light Detection and Ranging [LiDAR], and publicly available screening tools) and during field surveys of areas proposed for harvesting or road building[2].
- FPA/N Form, Questions 10 and 11 (updated May 9, 2014) includes the requirement that the applicant evaluate whether any potentially unstable slopes or landforms are within or adjacent to the forest practice application area; if so, a Slope Stability Information Form is filled out that describes how these areas were assessed (using Board Manual Section 16).
- SEPA policies for potentially unstable slopes and landforms (WAC 222-10-030) relating to road construction or harvesting on potentially unstable slopes or landforms include the requirement that forest practices and roads on potentially unstable slopes or landforms must include information prepared by a qualified expert about the likelihood that the action will contribute to movement or instability, the likelihood that the action will threaten public safety, the likelihood of delivery of sediment or debris to a public resource, and possible mitigation for identified hazards and risks.
- The Washington Department of Natural Resources (DNR) may require landowners to provide additional geologic information (WAC 222-20-010(9)) if there are potentially unstable slopes or landforms in or around the area of their application.
- Road Maintenance and Abandonment Plans (RMAPs) include a forest road inventory and schedule for required road maintenance to bring roads up to current WAC 222-24-052 standards to minimize road instability, erosion, and hydrologic connectivity. An RMAP (and associated road upgrades implemented according to the schedule in the RMAP) is required for large forest landowners for all lands on their ownership; small forest landowners may submit a RMAP or upgrade their roads to WAC 222-24-052 standards as they implement harvests using those roads. Most large landowners in the Chehalis Basin are on target to complete necessary upgrades by October 31, 2016 (DNR estimates 85% of roads upgraded by this date); the remaining landowners are scheduled to complete the upgrades by 2021 (Turley 2016).

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[2] The manual can be found here: http://file.dnr.wa.gov/publications/bc_fpb_manual_section16.pdf.

Research and monitoring on landslides and erosion related to forest practices continues both within the Chehalis Basin watershed and on a state-wide basis through the CMER work plan in the Unstable Slopes Rule Group and the Roads Rule Group, and non-CMER research. These efforts are part of the Adaptive Management Program that will continue to use technical information and peer-reviewed studies to produce science-based recommendations to the Forest Practices Board regarding landslides and erosion. Current projects underway include the following:

- Forming a technical committee to evaluate gaps in the science regarding glacial deep-seated landslides and groundwater recharge areas
- Reviewing unstable slopes research strategy, including deep-seated landslides and groundwater recharge area
- Initiating the Unstable Slopes Criteria Project to evaluate unstable areas with a high probability of impacting public resources
  - The project will evaluate the degree to which the current rule-identified landforms and the board manual identify potentially unstable areas with a high probability of impacting public resources and public safety
  - The project will focus on the adequacy of existing criteria for slope gradient, slope curvature, and probability for delivery
- Conducting Road Prescription-Scale Effectiveness Monitoring to evaluate road best management practices, available science, and research alternatives regarding road erosion and delivery of water and sediment from roads to streams, which will be implemented in the 2018 fiscal year

Conclusions

A large portion of the Chehalis Basin watershed is managed for forest practices. Mass wasting and erosion are natural processes in steep, forested basins and provide sediment and large woody material to streams, creating diverse aquatic habitat conditions. Excessive landslides or erosion can result in large amounts of sediment or debris delivery to streams and threaten public resources, degrade water quality and aquatic habitat, or increase downstream flood impacts.

Forest practices activities, including road building and even-age timber harvesting, can contribute to the increase in landslides during large storm events. Forest Practices Rules and guidance have evolved over time to reduce the influence of forest practices activities on landslides in Washington as the understanding of the effects road construction and timber harvesting activities have on landslides has improved. Analyses of landslides as part of watershed analyses in four WAUs in the Chehalis Basin watershed showed fewer landslides during the approximately 100-year storm event in 1996 than during the 1987 to 1994 period, despite the large storm event. Although this encompasses only one large storm event, the results suggest that Forest Practices Rules aimed at reducing landslides associated with timber harvesting and roads enacted in 1982, 1987, and 1992 may be effective at reducing some of the potential increase in landslides from forest practices. The December 2007 storm was a catastrophic event, particularly in parts of the upper Chehalis Basin and Stillman Creek watersheds that experienced up to 175% of the 100-year 24-hour rainfall. This event produced thousands of landslides on both recently harvested and older-timbered hillslopes, and delivered millions of cubic yards of sediment and debris to streams and rivers in the upper watershed.

As mentioned previously, the studies of the 2007 storm for the Chehalis Basin had some conflicting conclusions and are the subject of ongoing debate, making it difficult to reach a definitive conclusion on how effective the current rules are during an extreme storm event. However, it is clear that timber harvesting or poorly designed roads on marginally stable slopes are more likely to result in landslides during normal storm events until harvested areas gain sufficient root strength to help stabilize the slope. It is also clear that changes in forest practices to avoid harvesting and road building on unstable ground has improved the management of areas to reduce the potential of landslides. It is not clear how much the risk of landslides caused by forest practices has been reduced during extreme events. It is also not clear how close the current Forest Practices Rules are to achieving the mass wasting target—avoiding an increase in mass wasting over natural background rates caused from new harvests on high-risk sites (e.g., RIL) at a landscape scale.

New Forest Practices Rules have been implemented as a result of ongoing TFW/CMER research and recommendations (TFW 2014) through the Adaptive Management Program. This ongoing program includes measures developed from scientific data collected from the 2007 storm in the Chehalis Basin, as well as an ongoing research and monitoring strategy on unstable slopes (Rodgers and Walters 2014). Some parties have expressed concern that the Adaptive Management Program is not effective because it requires consensus between parties. In some cases, consensus can be difficult to achieve and has resulted in protracted discussions of study plans, study results, and recommendations for rule changes, resulting in delays in meeting some scheduled landslide-related CMER research milestones (Hicks 2016).

The existing process to modify Forest Practices Rules regarding unstable slopes and landslides includes the following:

- Research of identified landslide issues through the Unstable Slopes Rule Group and the Roads Rule Group, and non-CMER research
- Recommendations from the Rule Groups to CMER for potential changes to Forest Practices Rules
- Evaluation by CMER and TFW of research results and recommended changes to Forest Practices Rules and, if approved, forwarding recommended changes on to the DNR Forest Practices Board for revision of rules and/or the forest practice application and evaluation process

Recent (2011, 2014, and 2015) changes to Forest Practices Rules and application procedures pertaining to landslides and unstable slopes have been made through this process, and current research projects will likely recommend additional changes.

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Attachment A: Confirmation Letter

August 1, 2016

Re: Comments on May 18, 2016, draft memorandum, Evaluation of Forest Practice Effects on Landslides and Erosion in the Chehalis Basin

Dear Reviewers,

Thank you for providing comments on the draft memorandum. Comments were received from the Quinault Indian Nation, Washington Department of Natural Resources, the Washington Environmental Council, and the Washington Forest Protection Association. The following changes have been made:

- Clarification that the memorandum does not address potential future modifications to forest practices because modifications are outside the scope of the programmatic EIS.
- Clarification of the 1999 re-analysis of Watershed Analysis.
- Clarification of the mix of harvest rules (pre-2001 and post-2001) at the time of the 2007 storm.
- Addition of a brief discussion of potential effects of climate change on landslides.
- Clarification of timing for completion of Road Maintenance and Abandonment Plans work in the Chehalis Basin.
- Addition of discussion of differing opinions regarding effectiveness and timeliness of Adaptive Management rule changes.
- Minor editorial corrections.

The full text of comment letters are included as an attachment to the memorandum.

Very truly yours,

Kathy Vanderwal Dubé
Geologist

52542 Canna Court, Homer, AK 99603 (425)241-1045 kdube@watershedgeodynamics.com

Attachment B: Comments

Quinault Indian Nation

Quinault Indian Nation

POST OFFICE BOX 189 • TAHOLAH, WASHINGTON 98587 • TELEPHONE (360) 276-8211

June 2, 2016

Chrissy Bailey, EIS Project Manager
Washington State Department of Ecology

By email to: chrb461@ecy.wa.gov

Dear Ms. Bailey,

The Quinault Indian Nation (QIN) provides the following comments, with supporting documentation, on the Memo entitled "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion," by Kathy Vanderwal Dubé, Watershed GeoDynamics, dated May 16, 2016. These comments were prepared at the QIN's request by the Washington Forest Law Center.

It is important to note that comments regarding mitigation are only within the context of the Washington State Environmental Policy Act (SEPA) and do not bind the Quinault Indian Nation to agreeing to proposed mitigation in either the SEPA context, or in relation to impacts to its reserved treaty rights.

Thank you for your consideration of these comments. Please let me know if you have questions.

Sincerely,

Larry Goodell, Jr.
Treaty Habitat Policy Spokesperson
Quinault Indian Nation

cc: Jim Kramer, Chehalis Basin Strategy, Facilitator/Project Manager
Heather Page, Senior Manager Environmental Planner Anchor QEA
Tom Clingman, Department of Ecology, Policy and Legislative Lead, Shorelands and Environmental Assistance Program

WASHINGTON FOREST LAW CENTER

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June 2, 2016

Sent via electronic mail

Chrissy Bailey
Chehalis Basin Strategy Programmatic EIS
Washington Department of Ecology
300 Desmond Drive SE
Lacey, WA 98503
chrb461@ecy.wa.gov

Re: Comments on "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion."

Dear Ms. Bailey:

The Washington Forest Law Center submits the following comments on behalf of the Quinault Indian Nation, regarding the document titled "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion." The Quinault Indian Nation ("Nation") has usual and accustomed fishing grounds in the Chehalis Basin and as a result Federal treaty rights to harvest salmon, and a significant interest in the protection and restoration of salmon habitat in the near- and long-term.

While the "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion" document ("Report") provides a helpful overview of several major studies conducted in the region, it falls short of the requested analysis. The Nation respectfully requests that environmental review of the Chehalis Basin Flood Strategy include analysis of the extent of sediment delivery likely to occur as a result of forest practices, the impact of that sediment on hydrology and salmon habitat, and mitigation measures that may be implemented to reduce delivery. The Nation has continuing concern that forest practices in the Chehalis Basin cause delivery of sediment to water in excess of background rates, with resulting harm to fish habitat and increased risk of flooding. The Chehalis Basin Project provides a valuable opportunity to reduce the frequency and severity of flood events by implementing modifications to forest practices. That mitigation would help accomplish project goals, benefit fish and wildlife habitat, and increase carbon sequestration.

The Nation's core concern with the Report is that it does not answer the questions posed. The tasks of the Report were to "[e]valuate the potential for forest practices in the Chehalis basin to exacerbate landslides and contribution of sediment to the Chehalis River and its tributaries," and if such potential exists, to "develop a suite of modifications to those practices that mitigate the adverse effects. Include a suite of forest practice modifications in the alternative elements being considered." *See* Report at 1. This two-step approach reflects the structure of an environmental impact statement, which is required to identify significant impacts and discuss the means of reducing or avoiding those impacts through mitigation measures. WAC 197-11-430; RCW 43.21C.030; RCW 43.21C.031. The Report unfortunately does not adequately address either issue.

The Report does not come to any overall conclusion regarding the potential for forestry to exacerbate landslides and contribute sediment to the Chehalis River. While the Report at one point notes that "it is clear that harvest or poorly designed roads on marginally stable slopes are more likely to result in landslides during normal storm events until harvest areas gain sufficient root strength to help stabilize the slope," the Report goes on to state that "[i]t is also clear that changes in forest practices have improved the management of areas to reduce the potential of landslides" and "[i]t is also not clear how close the current Forest Practices Rules are to achieving the mass wasting target: avoid an increase in mass wasting over natural background rates caused from new harvests on high-risk sites (e.g., RIL) at a landscape scale." Report at 10. The conclusion appears to be that forest practices do increase potential for landslides and sediment delivery, but that the potential is reduced to some unknown amount by existing rules. That relativistic analysis fails to answer the pertinent question: to what extent do forest practices contribute to mass wasting and delivery of sediment in the Chehalis Basin?[1] By focusing on major landslides, the Report also fails to evaluate or reach conclusions regarding increases in sediment delivery through erosion, small slope failures, and sediment delivery from logging roads that cumulatively impact river processes.

The Report does not address the issue of mitigation at all, and has no discussion of the requested "suite of modifications to [forest] practices that mitigate the adverse effects." That omission misses a valuable opportunity to potentially decrease rates of flooding in the Chehalis Basin using cost-effective and environmentally beneficial modifications to forest practices. The adage "an ounce of prevention is worth a pound of cure" is apt—the most cost-effective path forward may very likely include limiting or modifying forest practices such that flood control downstream is unnecessary over the long-term. Mitigating impacts by modifying logging would likely result in reduced rates of landslides, reduced sediment delivery, delayed and reduced runoff and peak flows, decreased water temperatures (as a result of increased shade in headwater streams), improved salmon habitat, improved climate resilience, and increased carbon sequestration.

In sum, the Nation strongly believes that an adequate EIS must acknowledge that forest practices increase the likelihood of mass wasting and sediment delivery in the Chehalis Basin, and fully evaluate an alternative which includes mitigation through modification of forest practices. The analysis should rest on a comprehensive review of best available science. In the remainder of

[1] A long history of studies strongly suggests that logging, even under Forest Practices Rules, elevates landscape level risk of landslides and erosion. Please see attached "Amicus Brief of Geologists," submitted to the Washington Supreme Court, referencing many studies.

this letter, the Nation sets forth specific suggestions for improving the analysis of the impacts of forest practices and provides examples of mitigation measures.

Climate Change

A meaningful analysis of the impacts of forestry over time must take into account climate change. Several studies conclude that in the coming decades, soil saturation will increase with increased rain fall. Extreme weather events have likely already increased in frequency and severity as a result of climate change and will continue to do so.[2] Indeed, the "Review of the Potential Effects of Forest Practices on Stream Flow in the Chehalis River Basin" analysis concludes that "climate change is projected to increase the frequency of [bankfull] flows, as well as both the frequency and intensity of atmospheric river events, known to be the cause of the most extreme floods in western Washington."

Increased severity of rain storms combined with increased soil saturation and other impacts of climate change are likely to result in significant increases in landslides, including those exacerbated by forest practices. The University of Washington's Climate Impacts Group has published a detailed report which includes analysis of "mechanisms linking climate with landslides, erosion, and sediment transport." That report concludes that "[c]limate change is expected to increase the likelihood of landslides in winter and early spring and decrease the likelihood in summer. Although there are no published projections for changing landslide hazards in the Puget Sound region, changes in the climate drivers of landslides point to changes in the frequency and size of landslides. Landslide prone areas are expected to become less stable in winter as more precipitation falls as rain rather than snow, temperatures rise, soil water content increases, and as heavy rainfall events become more intense."[3] Given these projections, analysis of the impacts of forestry over time must take into account climate change.

The Nation respectfully requests that any analysis of impacts of forest practices fully analyze those impacts in the context of climate change and resulting increased risk of landslides. The Department of Ecology provides helpful resources to assist in that evaluation.[4] The Nation also provides the cited studies and additional materials as attachments to this letter.

Reliance on Forest Practices Rules and Adaptive Management

The Report concludes that "[n]ew Forest Practices Rules have been and will continue to be implemented as a result of ongoing TFW/CMER research and recommendations (TFW 2014) through the Adaptive Management Program." Report at 10. The Report references the Adaptive

[2] *Climate Change Impacts in Washington State: Technical Summaries for Decision Makers*, at ES-2. *See also* Madsen, T., and E. Figdor, 2007; *When it rains, it pours: global warming and the rising frequency of extreme precipitation in the United States*. Report prepared for Environment California Research and Policy Center.
[3] Mauger, G.S., J.H. Casola, H.A. Morgan, R.L. Strauch, B. Jones, B. Curry, T.M. Busch Isaksen, L. Whitely Binder, M.B. Krosby, and A.K. Snover, 2015. *State of Knowledge: Climate Change in Puget Sound*. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. doi:10.7915/CIG93777D at 5-2 to 5-5.
[4] *Please see* http://www.ecy.wa.gov/programs/sea/sepa/climatechange/index.htm.

Management Program as a "robust" process that has made changes where necessary and will continue to do so in order to prevent causation of landslides or delivery of sediment.

While significant funds are dedicated to the Adaptive Management Program and several important studies have been completed, the conclusion that regulatory changes will occur as necessary is not supported by evidence. According to the Department of Ecology, "[c]onflict over project purposes, methods, and results occurring both at CMER and TFW Policy remain a prime factor for project delays. Simply getting agreement over testing the existing rules in a study has become a source of protracted conflict."[5] There have been no substantive rule changes resulting from the Adaptive Management Program relating to steep and unstable slopes, despite nearly a decade of study and debate. The response to the "Mass Wasting Prescription Effectiveness Monitoring Study" (April 2012; Vers. 8a) and the "Southern Willapa Hills Retrospective" (January 2013) was the repeal of the steep and unstable slopes module of watershed analysis.

The Adaptive Management Program's consensus process makes any update to Forest Practices Rules exceedingly difficult and unlikely. As noted in the Report, even the completed studies are the subject of ongoing dispute via majority and minority reports. No modifications have been made to the identification of "rule identified landforms" or construction of roads through the adaptive management process, despite the continued occurrence of forest practices related landslides. Rather, the referenced "Road Abandonment and Maintenance Program" has been significantly delayed, and the required "Clean Water Act Milestones" are approximately a decade behind schedule. The referenced rule change relating to DNR's ability to request geotechnical reports only confirms existing authority, and did not go through adaptive management.

The Report cites the development of an updated Forest Practices Board Manual as further evidence of the effectiveness of adaptive management. However, updates to the Board Manual do not go through adaptive management, *see* WAC 222-12-090, and consists of guidelines implementing existing rules rather than substantive and enforceable requirements.

The Report assumes that Forest Practices Rules are not only regularly updated, but that they are implemented and followed correctly. There is strong evidence that this is not the case. While DNR's compliance monitoring program does not review slope prescriptions, it has recently found compliance rates of 52 to 69 percent on forest practices applications west of the Cascade Crest.[6]

In sum, evidence does not support a conclusion that the Adaptive Management Program has prevented landslides or delivery of sediment or will do so in the future. While a tribal representative participates in the Adaptive Management Program and the Quinault supports ongoing study, it is incorrect and misleading to suggest that the adaptive management process is likely to lead to prevention of landslides or sediment delivery. The Nation respectfully requests

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[5] CWA Assurances Update (submitted in attached materials).

[6] Compliance report for 2012-2013. That report and others are available here: http://www.dnr.wa.gov/programs-and-services/forest-practices/rule-implementation.

that the environmental review focus on concrete and achievable mitigation measures rather than relying on a consensus process that is unlikely to produce timely protections in the Chehalis Basin.

Watershed Analysis

The Report notes that a "1999 5-year review of the three watershed analyses showed that there were fewer landslides during the 1996 (approximately 100-year) storm event than during previous periods with less intense storms, suggesting that the prescriptions that limited harvesting and improved roads on unstable landforms may be effective at reducing mass wasting during large storm events." The Report relies on this review as the primary evidence for the fact that Forest Practices Rules prevent mass wasting and sediment delivery.

There are several problems with that evaluation. First, as noted in the Report, the 5-year review has a very small sample size such that its results are not significant. It therefore should not be relied upon for the broad conclusion that prescriptions are effective. Second, the prescriptions studied in the review were from watershed analyses that have since lapsed and are no longer in place. Any reliance on the review must compare the prescriptions that were in place with standard rules. Third, the Report bases its reliance on the watershed analysis review on the conclusion that "[b]ecause all field-based studies of landsliding by necessity look at the effects of large storm events on areas harvested under past rules, the effectiveness of current Forest Practices Rules cannot be tested directly." The current rules have been in place for over fifteen years. Data resulting from the 2007 and 2009 storms can isolate areas logged under different rule regimes, as noted in the Report. Direct study is certainly possible.

The Nation does not agree that a 5-year review of watershed analyses provides evidence that forest practices conducted under current rules do not exacerbate mass wasting or contribute to sediment delivery.

Mitigation

There are many promising mechanisms available to reduce the occurrence of forest practices-related landslides and erosion. The Nation requests that further environmental review thoroughly review mitigation alternatives.

One method would be to use a more precautionary screening tool, as is discussed in a recent article in *Geomorphology*.[7] These screens, retroactively applied to past landslide events, have demonstrated effectiveness at identifying unstable slopes that fall outside of current "rule identified landforms."

Other mitigation methods include implementation of larger buffers around headwater streams, use of thinning prescriptions rather than clearcut logging, and increased road abandonment. These methods would help to protect the ability of remaining forest to intercept rainfall, leave

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[7] Whittaker, K.A. and D. McShane, *Comparison of slope instability screening tools following a large storm event and application to forest management and policy*. Geomorphology 145–146 (2012) 115–122.

some roots intact to preserve slope stability, and decrease rates of runoff. Project funds could be used to purchase conservation easements that put into place lower impact logging regimes. Such mitigation efforts would also be useful in offsetting any impacts to salmon resulting from other aspects of the project.

A promising form of mitigation is the use of carbon credits to purchase critical forested areas in the Chehalis Basin. The Washington Environmental Council and Nisqually Land Trust recently partnered with Microsoft and Natural Capital Partners to complete a 520 acre project that will enhance forest habitat, provide carbon sequestration, and enhance water quality. The Nisqually Land Trust purchased and owns the property, and Microsoft purchased the carbon credit once the credits had been reviewed and properly verified.[8] Similar mitigation efforts employed in the Chehalis Basin project would not only provide valuable mitigation in reducing the likelihood of landslides and erosion, but could also be used as mitigation for emissions related to the project and to satisfy the requirements of State law. State agencies are required to evaluate greenhouse gas emissions and the resulting climate impacts of agency actions under the State Environmental Policy Act ("SEPA"). *See, e.g.*, Veto Message Statement on E2SSB 6406 at 1 (May 2, 2012) (Governor's statement "that the subjects of climate change and greenhouse gases will be considered in the environmental analysis required at the threshold determination stage of the SEPA process and in the environmental analysis required in a SEPA environmental impact statement"); State Dep't of Ecology, Q&A: SEPA and Greenhouse Gas Emissions ("Consideration of greenhouse gases under SEPA is appropriate because they have an environmental impact."). In 2008, the Legislature established a scheme for the state to limit and reduce greenhouse gas emissions and participate in a future regional multi-sector carbon trading system. *See* RCW 70.235.005. The 2008 Greenhouse Gas Emissions Law requires Washington to reduce its overall greenhouse gas emissions to 1990 levels by the year 2020. RCW 70.235.020(1)(a)(i). Purchasing timber rights on forest land would sequester carbon, helping to meet the requirements of SEPA and RCW 70.235. Intact forests would also restore natural processes that dampen peak flows.

Thank you for your consideration of these comments. Despite serious concerns with the content of the "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion" report, the Quinault Indian Nation remains a committed stakeholder in the Chehalis Basin Flood Strategy going forward, and is eager to provide any requested assistance. Please contact me if you have any questions, feedback, or would like more materials. I can be reached at 206-223-4088 x. 7 or wgolding@wflc.org.

Sincerely,

Wyatt Golding

Staff Attorney

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[8] https://wecprotects.org/first-forest-project-in-washington-state-to-meet-california-carbon-standards/

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Memorandum

April 27, 2016

TO: Forest Practices Board

FROM: Mark Hicks, Ecology Forest Practices Lead

SUBJECT: Clean Water Act Milestone Update

The Washington State Department of Ecology (Ecology) committed to provide the Forest Practices Board (Board) with periodic updates on the progress being made to meet milestones established for retaining the Clean Water Act (CWA) Assurances for the forest practices rules and associated programs. Our last update to the Board occurred at your May 2015 Board meeting.

Under Washington state law (Chapter 90.48 RCW) forest practices rules are to be developed so as to achieve compliance with the state water quality standards and the federal Clean Water Act (CWA). The CWA assurances establish that the state's forest practices rules and programs, as updated through a formal Adaptive Management Program (AMP), will be used as the primary mechanism for bringing and maintaining forested watersheds in compliance with the state water quality standards. The CWA assurances were originally granted in 1999 as part of the Forests and Fish Report (FFR). Those original assurances were to last for only a ten year period. After conducting a review of the program and hearing from stakeholders that they were committed to making the program work, Ecology conditionally extended the assurances for another ten years. This extension was based on the expectation that the program meet a list of process improvements and performance objectives. These are the milestones reported on in this update.

During this past year none of the remaining Non-CMER Project Milestones were completed or had a change in status, and three milestones remain off track. These include resolving disputes with identifying the uppermost point of perennial flow, orchestrating an independent review of the AMP, and assessing the risk from small forest landowner roads.

Also during this period, one CMER research milestone was completed, and two were downgraded based on a slowed pace, or no work having been initiated, and inadequate time remaining to meet the milestone. Two studies of particular concern are the examination of the effectiveness of the Rule Identified Landforms (RIL), and the eastside Type N effectiveness monitoring study. The Technical Writing & Implementation Group formed to develop the RIL study has stopped all work and effectively disbanded. The eastside Type N study should have been put into the field in 2013, and yet CMER has still not been able to identify a study design cooperators will all approve.

The Lean revisions and their approach for gaining step-wise buy-in of both CMER and Policy has clearly not resulted in the intended improvements. Conflict over project purposes, methods, and results occurring both at CMER and TFW Policy remain a prime factor for project delays. Simply getting agreement over testing the existing rules in a study has become a source of protracted conflict.

The 2009 CWA Assurance milestones were established to create a path of steady improvement. The milestones were intended to spur efforts to gather critical information to assess the effectiveness of the rules in protecting water quality as mandated by state law. Equally important, was the intent to encourage process changes that would lead to cooperators working more productively together to create a durable and effective research program to test and adjust the rules long-term. With three years remaining until the last of the 2009 corrective milestones becomes due, and key milestones more than four years behind schedule, the desired outcome remains elusive.

Ecology is urging the Board and the leaders of the various caucuses to encourage renewed commitment to the cooperative principles of TFW, and the agreement to work together to test and adjust the rules where necessary, and to do so with a shared commitment to meet the four goals of the agreement: **1**) to meet the Clean Water Act; **2**) to comply with the ESA; **3**) to ensure harvestable supplies of fish; and **4**) to meet the above resource goals in a manner that will maintain an economically viable timber industry in the state. This renewed commitment needs to be transmitted clearly to all levels of our AMP, all the way down to the people assigned to participate on Science Advisory Groups (SAGs), and the program's ad hoc workgroups.

Enclosed are two tables showing the CWA milestones and summarizing their current status. The first table shows the non-CMER project milestones. These milestones are implemented outside of the CMER research program and are largely within the control of the Forest Practices Operations Section of the Department of Natural Resources (DNR), or the Timber Fish and Wildlife Policy Committee (Policy). The second table lays out the progress being made on the CMER research study milestones. Changes in status occurring since your last briefing are highlighted in red font for your convenience.

Please contact Mark Hicks, Ecology Forest Practices Lead, if you have any questions or concerns at: mark.hicks@ecy.wa.gov or (360) 407-6477.

Attachments (2)

Summary of CWA Assurances Milestones and current status:

Non-CMER Project Milestones		
	Summarized Description of Milestone	**Status as of April 2016[1]**
2009	July 2009: CMER budget and work plan will reflect CWA priorities.	**Completed** October 2010
	September 2009: Identify a strategy to secure stable, adequate, long-term funding for the AMP.	**Completed** October 2010
	October 2009: Complete Charter for the Compliance Monitoring Stakeholder Guidance Committee.	**Completed** December 2009
	December 2009: Initiate a process for flagging CMER projects that are having trouble with their design or implementation.	**Completed** November 2010
	December 2009: Compliance Monitoring Program to develop plans and timelines for assessing compliance with rule elements such as water typing, shade, wetlands, haul roads and channel migration zones.	**Completed** March 2010
	December 2009: Evaluate the existing process for resolving field disputes and identify improvements that can be made within existing statutory authorities and review times.	**Completed** November 2010
	December 2009: Complete training sessions on the AMP protocols and standards for CMER, and Policy, and offer to provide this training to the Board. Identify and implement changes to improve performance or clarity at the soonest practical time.	**Underway** Initial training completed and a training regime has largely been incorporated into the AMP for new Board and Policy members as an ongoing program. The AMP portion of the new Forest Practices Board member training was expanded to include new training materials. Issues identified for improvement were added to the Policy and CMER task lists for future action in 2010. Since that time Policy has reviewed FFR Schedule L1 research questions for both the Type N and the Unstable Slopes Research Programs. CMER has additionally updated 6 chapters of its' Protocol and Standards Manual and is working on Chapter 7. Policy is in the process of revisiting its task list to ensure that issues previously noted as important to improve the program will be reaffirmed addressed.
2010	January 2010: Ensure opportunities during regional RMAP annual reviews to obtain input from Ecology, WDFW, and tribes, on road work priorities.	**Completed** September 2011

Non-CMER Project Milestones		
	Summarized Description of Milestone	**Status as of April 2016[1]**
	February 2010: Develop a prioritization strategy for water type modification review.	**Completed** March 2013
	March 2010: Establish online guidance that clarifies existing policies and procedures pertaining to water typing.	**Completed** March 2013
	June 2010: Review existing procedures and recommended any improvements needed to effectively track compliance at the individual landowner level.	**Completed** November 2010
	June 2010: Establish a framework for certification and refresher courses for all participants responsible for regulatory or CMP assessments.	**Completed** September 2013
	July 2010: Assess primary issues associated with riparian noncompliance (using the CMP data) and formulate a program of training, guidance, and enforcement believed capable of substantially increasing the compliance rate.	**Completed** August 2012
	July 2010: Ecology in Partnership with DNR and in consultation with the SFL advisory committee will develop a plan for evaluating the risk posed by SFL roads for the delivery of sediment to waters of the state.	**Off Track** DNR tried to get a sense of the risk by conducting a pilot project in its' NW Region. A draft report was shared with Ecology October 2014. Approximately 92% of SFLs did not respond or denied access to DNR. Of the 76 roads surveyed, most were reported as functioning appropriately, with 11% delivering sediment to streams. DNR initiated additional SFL outreach efforts on a statewide basis in 2015 in an effort to conduct a more comprehensive roads assessment. The results of this assessment may be provided to Ecology and the public soon. However, without the jurisdictional authority to conduct a representative survey, fully satisfying this milestone may not be possible.
	July 2010: Develop a strategy to examine the effectiveness of the Type N rules in protecting water quality at the soonest possible time that includes: a) Rank and fund Type N studies as highest priorities for research, b) Resolve issue with identifying the uppermost point of perennial flow by July 2012, and c) Complete a comprehensive literature review examining effect of buffering headwater streams by September 2012.	**Off Track** A strategy was developed, and Policy and its' technical subgroups were working to implement the strategy. Conflict over providing default distances for defining the UMPPF stalled implementation, then the Forest Practices Board made Type F and mass wasting Policy priorities. This resulted in Policy setting aside work on completing the Type N milestone. Ecology agreed that due to the limited capacity of Policy, they needed to temporarily suspend work on resolving the

Non-CMER Project Milestones		
	Summarized Description of Milestone	**Status as of April 2016[1]**
		Type N milestone in order to succeed in meeting the new Board priorities. But this work remains necessary and overdue.
	October 2010: Conduct an initial assessment of trends in compliance and enforcement actions taken at the individual landowner level.	**Completed** November 2010
	October 2010: Design a sampling plan to gather baseline information sufficient to reasonably assess the success of alternate plan process.	**Completed** December 2014 DNR satisfied this milestone by releasing an Alternate Plan Guidance memo (12-10-14) designed to strengthen the overall process for issuing alternate plans. Success depends on how well the new directives are translated into action. DNR completed training in all Regions regarding rule, alternate plan board manual and memo guidance. DNR has also committed to refresher training as needed for Alternate Plans. Ecology would like to work with DNR to evaluate how well the guidance is being implemented.
	December 2010: Initiate process of obtaining an independent review of the Adaptive Management Program.	**Off Track** Policy support for this review waned after the state auditor's office dropped its plans to begin a review in FY 2012. Policy is hoping internally derived changes (e.g. shorter timeline for dispute resolution and the lean process being piloted by CMER) can create enough improvements to negate the need for this milestone. No improvements are evident at this time. Policy representatives included a requirement for a process audit in draft AMP funding legislation in 2014, but that bill did not pass.
2011	December 2011: Complete an evaluation of the relative success of the water type change review strategy.	**Completed** March 2013
	December 2011: Provide more complete summary information on progress of industrial landowner RMAPs.	**Completed** September 2011
2012	October 2012: Reassess if the procedures being used to track enforcement actions at the individual land owner's level provides sufficient information to potentially remove assurances or otherwise take corrective action.	**Completed** June 2012

Non-CMER Project Milestones		
	Summarized Description of Milestone	**Status as of April 2016**[1]
	Initiate a program to assess compliance with the Unstable Slopes rules.	**Ongoing** DNR is evaluating alternative pathways to satisfying this milestone other than using the standard post-harvest compliance monitoring framework. The DNR Compliance Monitoring Program is presently evaluating its ability to include an assessment of unstable slopes rule compliance in the program. A pilot study will be conducted in 2016. Implementation of the assessment is targeted for 2017.
2013	November 2013: Prepare a summary report that assesses the progress of SFLs in bringing their roads into compliance with road best management practices, and any general risk to water quality posed by relying on the checklist RMAP process for SFLs.	**Off Track** Discussed above for Oct 2010 survey milestone.

CMER Research Milestones		
	Description of Milestone	**Status as of April 2016**[1]
2009	Complete: Hardwood Conversion – Temperature Case Study	**Completed** June 2010 Completed as data report.
	Study Design: Wetland Mitigation Effectiveness	**Completed** October 2010 Draft pilot study plan was developed then project de-prioritized in response to concerns raised about study limitations.
2010	Study Design: Type N Experimental in Incompetent Lithology	**Completed** August 2011
	Complete: Mass Wasting Prescription-Scale Monitoring	**Completed** June 2012 Study delivered in dispute to Policy with Majority Minority Reports. Dispute resolved in late 2013 by Policy.
	Scope: Mass Wasting Landscape-Scale Effectiveness	**Off Track** No work has occurred. Policy moved this project to the hold list pending review as part of developing the unstable slopes research strategy. It was also omitted from the MPS list that went to the Board. Policy should discuss this with the next review of the MPS.
	Scope: Eastside Type N Effectiveness	**Completed** November 2013
2011	Complete: Solar Radiation/Effective Shade	**Completed** June 2012
	Complete: Bull Trout Overlay Temperature	**Completed** May 2014
	Implement: Type N Experimental in Incompetent Lithology	**On Track** Preharvest monitoring is complete and all experimental basins were harvested on time.
	Study Design: Mass Wasting Landscape-Scale Effectiveness	**Off Track**

CMER Research Milestones		
	Description of Milestone	**Status as of April 2016[1]**
		Described above for 2010 scoping milestone.
2012	Complete: Buffer Integrity-Shade Effectiveness	**Underway** This study was in dispute over concerns arising from the Spring 2013 Independent Scientific Peer Review (ISPR). Final report has been edited and may be submitted again to ISPR in March 2016.
	Literature Synthesis: Forested Wetlands Literature Synthesis	**Completed** January 2015
	Scoping: Examine the effectiveness of the RILs in representing slopes at risk of mass wasting.	**Not Progressing** Policy approved project objectives and critical questions June 2016 to guide scope of study. Work subsequently stopped due to the inability of TWIG members to meet and develop study design alternatives. One outside expert left due to the problems, but work may be reinitiated soon.
	Study Design: Eastside Type N Effectiveness	**Underway** Completed supplemental field work in 2014 to help in developing a study design in 2015. TWIG submitted two draft study designs for CMER review. Issues of concern continue to be raised in early 2016 over what is being measured and the prescriptions proposed for testing. Efforts to involve Policy in resolving conflicts at the CMER level have been unsuccessful.
2013	Scoping: Forested Wetlands Effectiveness Study	**Underway** Policy approved revised problem statement, study objectives, and research questions January 2016. The TWIG is beginning work to develop study design alternatives.
	Wetlands Program Research Strategy	**Completed** April 2016. Incorporated into proposed revisions to CMER workplan going to Policy for approval
	Scope: Road Prescription-Scale Effectiveness Monitoring	**Underway** TWIG first met in June 2014, developed documents to guide project purpose. Document using Best Available Science to support recommended study design

CMER Research Milestones		
	Description of Milestone	**Status as of April 2016[1]**
		alternatives going to Policy in February 2016.
	Study Design: Examine the effectiveness of the RILs in representing slopes at risk of mass wasting.	**Earlier Stage Underway** Project discussed above for 2012 scoping stage.
	Implement: Eastside Type N Effectiveness	**Earlier Stage Underway** Project discussed above for 2012 study design stage.
2014	Complete: Type N Experimental in Basalt Lithology	**Underway** This study is steadily progressing, but the pace slowed well behind expectations as the study report chapters are finalized and moved through the ISPR process. Study appears likely to be completed in 2018.
	Study Design: Road Prescription-Scale Effectiveness Monitoring	**Earlier Stage Underway** Project discussed above for the 2013 scoping stage.
	Scope: Type F Experimental Buffer Treatment	**Completed** December 2015 A study design alternative was selected by TFW Policy. TWIG will now need to develop a study design.
	Implementation: Examine the effectiveness of the RILs in representing slopes at risk of mass wasting	**Earlier Stage Underway** Project discussed above for 2012 scoping stage.
	Study Design: Forested Wetlands Effectiveness Study	**Earlier Stage Underway** Project discussed above for 2013 scoping stage.
2015	Complete: First Cycle of Extensive Temperature Monitoring	**Underway** Of the four strata: one stratum is complete and two are in ISPR. Problems using the DNR hydro layer to find Type Np study streams on the eastside thwarted efforts to find sites for the final strata. Policy decided not to fund temperature monitoring on the final strata and deprioritized temperature trend monitoring for the others. Final

CMER Research Milestones		
Description of Milestone		**Status as of April 2016[1]**
		reports on the three tested strata expected to be complete in spring 2016.
	Scope: Watershed Scale Assess. of Cumulative Effects	**Off Track**
	Scope: Amphibians in Intermittent Streams (Phase III)	**Not Progressing** Project milestone exists only if needed to fill research gaps left from Type N Experimental in Basalt Lithology.
2017	Study design: Watershed Scale Assess. of Cumulative Effects	**Off Track**
	Study Design: Amphibians in Intermittent Streams (Phase III)	**Not Progressing** Project discussed above for 2015 scoping state.
2018	Complete: Roads Sub-basin Effectiveness	**Earlier Stage Underway** Resample for trend analysis planned for 2022. This later project timeline does not conflict with the intention of this milestone. Ecology agrees it's prudent to wait until RMAP time extensions have ended before conducting further trend sampling. RMAP programs implemented through DNR Forest Practices Operations may also negate the need for this follow-up sample of progress in fixing roads.
	Implement: Watershed Scale Assess. of Cumulative Effects	**Off Track**
	Complete: Type N Experimental in Incompetent Lithology	**On Track**
2019	Complete: Eastside Type N Effectiveness	**Earlier Stage Underway** Project discussed above for 2012 study design stage.

[1] **Status terminology:**

"Completed" - means milestone has been satisfied (includes those both on schedule and late).

"On Track" - means work is occurring that appears likely to satisfy milestone on schedule.

"Underway" - means work towards milestone is actively proceeding, but likely off schedule.

"Earlier Stage Underway" – means project initiated, but is at an earlier stage then the listed milestone.

"Not Progressing" - means no work has begun, or work initiated has effectively stopped.

"Off Track" - means: **1)** No work has begun and inadequate time remains, **2)** key stakeholders are not interested in completing the milestone, or **3)** attempt at solution was inadequate and no further effort at developing an acceptable solution is planned.

State of Knowledge Report

Climate Change Impacts and Adaptation in Washington State:
Technical Summaries for Decision Makers

Prepared by the

Climate Impacts Group
University of Washington

December 2013

COLLEGE OF THE ENVIRONMENT
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This report is available for download at:

- Full report: http://cses.washington.edu/db/pdf/snoveretalsok816.pdf
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Jan 28, 2014	Figure 4-1 temperature scale values corrected
March 31, 2014	Chapter 2 – table: corrected glacier endnote number references; Chapter 6 – table: corrected typo in projected changes for 100 year flood event for snow dominant watersheds; added 7Q10 definition for low flows
May 5, 2014	Page 7-4: Updated citation and reference period for content in first bullet

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EXECUTIVE SUMMARY

This State of Knowledge Report, *Climate Change Impacts and Adaptation in Washington State,* summarizes existing knowledge about the likely effects of climate change on Washington State and the Pacific Northwest,[A] with an emphasis on research since 2007.[B] This report provides technical summaries detailing observed and projected changes for Washington's climate, water resources, forests, species and ecosystems, coasts and ocean, infrastructure, agriculture, and human health in an easy-to-read summary format designed to complement the foundational literature from which it draws. This literature includes recent major international, United States, and Pacific Northwest assessment reports, especially two recent efforts associated with the Third U.S. National Climate Assessment,[C] scientific journal articles, and agency reports. This report also describes climate change adaptation activities underway across the state and data resources available to support local adaptation efforts.

A rapidly growing body of research has strengthened and added local detail to previous knowledge about the causes and consequences of climate change. *(Sections 1 and 2)* Human activities have increased atmospheric levels of greenhouse gases (carbon dioxide, methane, and nitrous oxide) to levels unprecedented in at least the past 800,000 years. The Earth's climate system is warming, global sea level is rising, snow and ice are declining, and ocean chemistry and climate extremes are changing. From the global scale to the scale of the western U.S., many of these changes can be attributed to human causes.

> *Human influence on the climate system is clear…Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. (IPCC 2013)*

Observed changes in regional climate, water resources, and coastal conditions are consistent with expected human-caused trends, despite large natural variations. *(Section 2)* Washington and the Pacific Northwest have experienced long-

A Whenever possible, this report focuses on information about observed and projected changes that are specific to Washington State. In cases where Washington-specific results were unavailable, information is provided relative to the Pacific Northwest as a whole. Because many characteristics of Washington's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region, results for Washington State are expected to generally align with those provided for the Pacific Northwest, with potential for some variation at any specific location.

B Research since 2007 is emphasized in order to capture major contributions to global and regional climate science since release of the fourth global climate change assessment report by the Intergovernmental Panel on Climate Change (IPCC) in 2007. Findings from the IPCC's fifth assessment report, released in September 2013, and from the U.S. National Climate Assessment are included where possible. These and other recent scientific assessment reports most salient to understanding the consequences of climate change for Washington State are described in Appendix 1.

term warming, a lengthening of the frost-free season, and more frequent nighttime heat waves. Sea level is rising along most of Washington's coast,[D] coastal ocean acidity has increased, glacial area and spring snowpack have declined, and peak streamflows in many rivers have shifted earlier. These long-term changes are consistent with those observed globally as a result of human-caused climate change. Still, natural climate variability will continue to result in short-term trends opposite those expected from climate change, as evidenced by recent regional cooling and increases in spring snowpack.

Significant changes in the Earth's climate system and the climate of the Pacific Northwest are projected for the 21st century and beyond as a result of greenhouse gas emissions (Box ES-1, Figure ES-1)**.** *(Sections 3 through 5)* All scenarios indicate continued warming. Projected changes prior to mid-century are largely inevitable, driven by the warming that is already "in the pipeline" due to past emissions of greenhouse gases. In contrast, current and future choices about greenhouse gas emissions will have a significant effect on the amount of warming that occurs after about the 2050s. For example, global warming projected for the end of the century ranges from +1.8°F (range: +0.5°F to +3.1°F), if greenhouse gases are aggressively reduced, to +6.7°F (range: +4.7°F to +8.6°F) under a high "business as usual" emissions scenario.[E][1]

Box ES-1. Projected changes in key Pacific Northwest climate variables.

- *Average annual temperature, for 2050s*: +4.3°F (range: +2.0 to +6.7°F) for a low greenhouse gas scenario or +5.8°F (range: +3.1 to +8.5°F) for a high greenhouse gas scenario (both relative to 1950-1999).
- *Extreme precipitation, for 2050s:* number of days with more than one inch of rain increases +13% (±7%) for a high greenhouse gas scenario (relative to 1971-2000).
- *Average April 1 snowpack in Washington State, for 2040s:* -38 to -46% for a low and a medium greenhouse gas scenario (relative to 1916-2006).
- *Sea level in Washington State, for 2100:* +4 to +56 inches for low to high greenhouse gas scenarios (relative to 2000). Local amounts of sea level rise will vary.
- *Ocean acidity, for 2100:* +38 to +41% for a low greenhouse gas scenario and +100 to +109% for a high greenhouse gas scenario (relative to 1986-2005).

See Sections 3 and 6 for more detailed projections and additional time periods.

C The Northwest chapter of the U.S. National Climate Assessment (scheduled for release in spring 2014) and *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities* (2013; edited by M.M. Dalton, P.W. Mote, and A.K. Snover, Washington, D.C.: Island Press, 271 pp.), a more detailed report developed to support the key findings presented in the Northwest chapter.

D Although *regional* sea level is rising in concert with global sea level rise, *local* sea level change also reflects variations in vertical land motion resulting from plate tectonics and other processes. As a result, sea level is currently falling in some Washington locations.

E These changes are for the period 2081-2100 relative to 1986-2005. The lower amount of warming is for the RCP 2.6 scenario, which requires that global emissions be reduced to about a 50% of 1990 levels by 2050 and for total

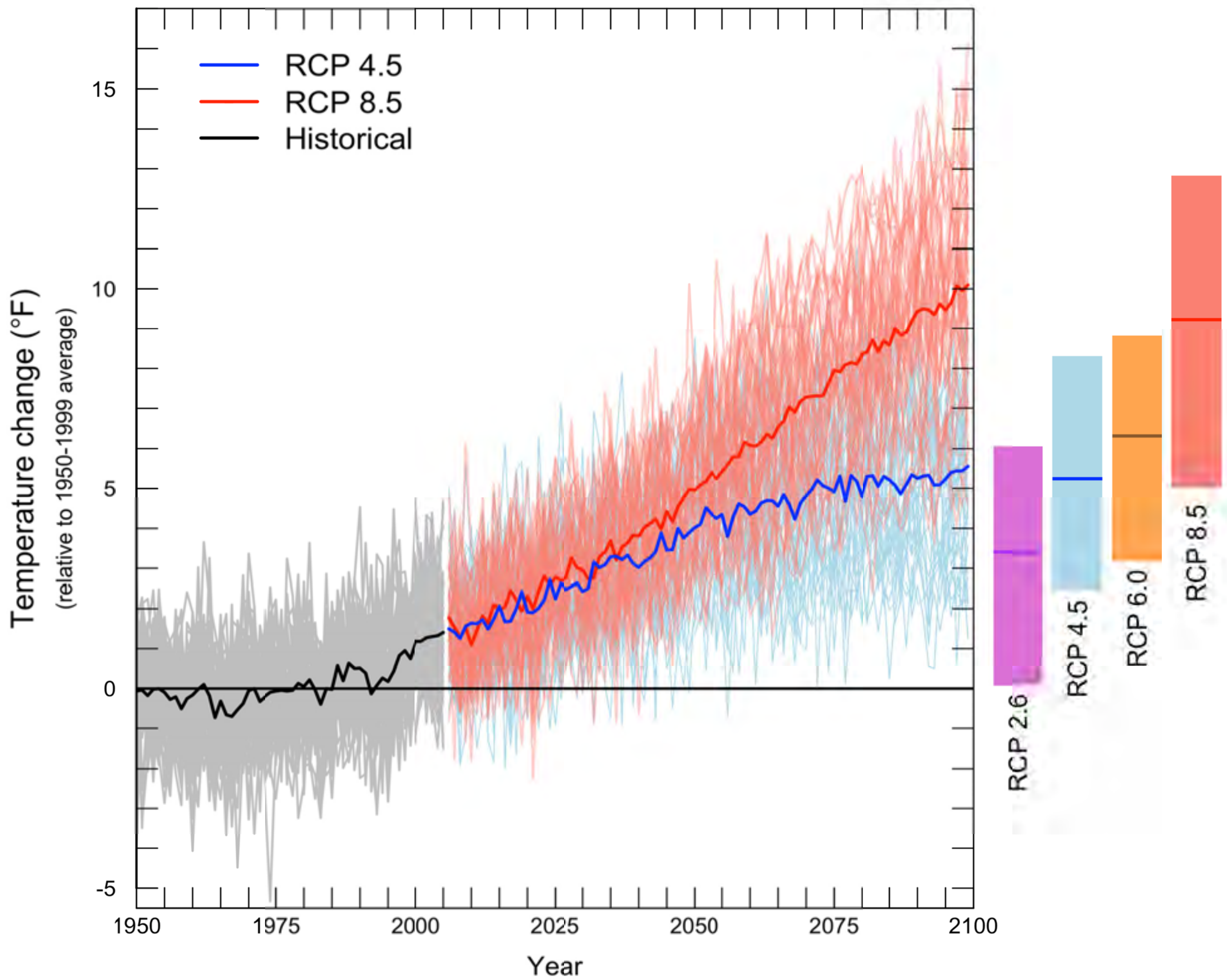

Figure ES-1. All scenarios project warming for the 21st century. The graph shows average yearly temperatures for the Pacific Northwest relative to the average for 1950-1999 (gray horizontal line). The black line shows the average simulated temperature for 1950–2011, while the grey lines show individual model results for the same time period. Thin colored lines show individual model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5 – see Section 3 for details), and thick colored lines show the average among models projections for each scenario. Bars to the right of the plot show the mean, minimum, and maximum change projected for each of the four emissions scenarios for 2081-2100, ranging from a very low (RCP 2.6) to a high (RCP 8.5) scenario. Note that the bars are lower than the endpoints from the graph, because they represent the average for the final two decades of the century, rather than the final value at 2100. *Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.[1]*

net emissions to become near or below zero in the final decades of the 21st century. The higher amount of warming is for the RCP 8.5 scenario, which assumes continued increases in greenhouse gas emissions through the end of the 21st century. See Section 3 for more on greenhouse gas scenarios.

Projected regional warming and sea level rise are expected to bring new conditions to Washington State. By mid-century, Washington is likely to regularly experience average annual temperatures that exceed the warmest conditions observed in the 20th century. Washington is also expected to experience more heat waves and more severe heavy rainfall events, despite relatively small changes in annual and seasonal precipitation amounts.

These and other local changes are expected to result in a wide range of impacts for Washington's communities, economy, and natural systems. *(Sections 6-12)* These include projected changes in water resources, forests, species and ecosystems, oceans and coasts, infrastructure, agriculture, and human health.

Hydrology and Water Resources (Section 6). Washington's water resources will be affected by projected declines in snowpack, increasing stream temperatures, decreasing summer minimum streamflows, and widespread changes in streamflow timing and flood risk. These changes increase the potential for more frequent summer water shortages in some basins (e.g., the Yakima basin) and for some water uses (e.g., irrigated agriculture or instream flow management), particularly in fully allocated watersheds with little management flexibility. Changes in water management to alleviate impacts on one sector, such as hydropower production, irrigation or municipal supply, or instream flows for fish, could exacerbate impacts on other sectors.[2]

Forests (Section 7). Washington's forests are likely to experience significant changes in the establishment, growth, and distribution of tree species as a result of increasing temperatures, declining snowpack, and changes in soil moisture. A rise in forest mortality is also expected due to increasing wildfire, insect outbreaks, and diseases.[3] The projected changes could affect both the spatial distribution and overall productivity of many ecologically and economically important Pacific Northwest tree species, including Douglas-fir, ponderosa pine, lodgepole pine, and whitebark pine.

Species and Ecosystems (Section 8). Areas of suitable climate for many plants and animals are projected to shift considerably by the end of the 21st century. Many species may be unable to move fast enough to keep up, resulting in local species losses[4] and changes in the composition of plant and animal communities. Challenges are expected for many federally-listed endangered and threatened species dependent on coldwater habitat, including salmon, trout, and steelhead. Projected impacts on other habitat types in Washington State, including wetlands, sagebrush-steppe, prairies, alpine tundra and subalpine habitats, would affect species dependent on those habitats.

Coasts and Oceans (Section 9). Sea level is projected to rise in most areas[F] of the state, increasing the likelihood for permanent inundation of low-lying areas, higher tidal and storm surge reach, flooding, erosion, and changes and loss of habitat. Sea level rise, rising coastal ocean temperatures, and ocean acidification will also affect the geographical range, abundance, and diversity of Pacific Coast marine species. These include key components of the marine food web (phytoplankton and zooplankton) as well as juvenile Chinook salmon and commercially important species such as Pacific mackerel, Pacific hake, oysters, mussels, English sole, and yellowtail rockfish. [5]

Climate change can make today's extreme events more common. For example, two feet of sea level rise in Olympia could turn today's 100-year flood into an annual event.

Built Infrastructure (Section 10). Climate change is expected to affect the longevity and performance of built infrastructure in Washington State. Most climate change impacts are likely to increase the potential for damage and service disruptions, although some risks (such as snow-related highway maintenance and closures) may decrease. Higher operating costs and reduced asset life are also expected. Sea level rise and increased river flooding are important causes of impacts on infrastructure located near the coast or current floodplains.

Agriculture (Section 11). Washington crops and livestock will be affected by climate change via increasing temperatures and water stress, declining availability of irrigation water, rising atmospheric carbon dioxide, and changing pressures from pests, weeds, and pathogens. Some impacts on agriculture may be beneficial while others may lead to losses – the consequences will be different for different cropping systems and locations. While impacts on some locations and subsectors may be significant, most agricultural systems are highly adaptable. As a result, the overall vulnerability of Washington's agricultural sector to climate change is expected to be low. However, given the combination of increasing water demands and decreasing supply in summer, water stress will continue to be a key vulnerability going forward.

Human Health (Section 12). Climate change is expected to affect both the physical and mental health of Washington's residents by altering the frequency, duration, or intensity of climate-related hazards to which individuals and communities are exposed. Health impacts include higher rates of heat-related illnesses (e.g., heat exhaustion and stroke); respiratory illnesses (e.g., allergies, asthma); vector-, water-, and food-borne diseases; and mental health stress (e.g., depression, anxiety). These impacts can lead to increased absences from schools and work, emergency room visits, hospitalizations, and deaths.

[F] Recent research projects +4 to +56 inches of sea level rise by 2100 for Washington State, compared to 2000, which will be modulated by local vertical land movement. The potential for continued decline in local sea level for the Northwest Olympic Peninsula cannot be ruled out at this time. For more information, see Section 5.

While climate change is expected to have important consequences for most sectors, key areas of risk have been identified. According to analyses completed for the U.S. National Climate Assessment, priority issues of concern for the Pacific Northwest are:

- Changes in the natural timing of water availability, due to the impacts of warming on snow accumulation and melt, reducing water supply for many competing demands and causing far-reaching ecological and socioeconomic consequences;
- Coastal consequences of sea level rise, river flooding, coastal storms, erosion, inundation, and changes in the coastal ocean including increasing ocean acidity;
- Additional forest mortality and long-term transformation of forest landscapes, caused by the combined impacts of increasing wildfire, insect outbreaks, and tree diseases.[6]

These key risk areas, identified because of their likely significant consequences for the regional economy, infrastructure, natural systems, and human health, are also relevant to Washington State.

Box ES-2. A sampling of Washington communities, government agencies, and organizations preparing for the local effects of a changing climate.

- *Washington State:* Departments of Ecology, Transportation, Natural Resources, Fish and Wildlife, Health, Agriculture, Office of the Insurance Commissioner.
- *Local governments:* King County, Seattle, Anacortes, Olympia, Sound Transit, Port of Bellingham, Port of Seattle.
- *Federal agencies:* U.S. Army Corps of Engineers, Bureau of Reclamation, Bonneville Power Administration, U.S. Forest Service, National Park Service.
- *Tribal governments*: Swinomish Indian Tribal Community, Jamestown S'Klallam Tribe.

Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change. Washington State—one of 15 U.S. states with a state adaptation plan [G][7] — has been identified as one of "the best states when it comes to planning for climate change." [H] Innovative partnerships are linking science, management, and planning across jurisdictions, helping a growing number of communities and organizations in the public and private sector to begin adapting to climate change (Box ES-2).

[G] *Preparing for Climate Change: Washington State's Integrated Climate Response Strategy* includes recommended adaptation actions for a range of sectors important to Washington State. These recommendations were developed through a year-long, multi-stakeholder collaboration among agencies, non-government organizations, and academic institutions. More information is available at: www.ecy.wa.gov/climatechange/ipa_responsestrategy.htm.

[H] http://www.nrdc.org/water/readiness/

The growth in adaptation efforts across the state has been stimulated by increasing awareness of the potential implications of climate change, the recognition that climate risks can be reduced by advance action, and the availability of locally-specific climate data, tools, and technical guidance to support adaptation planning. However, most efforts are still in the initial stages of assessing potential climate impacts and developing response plans; few have begun the challenging work of implementing adaptive responses. As more entities act to reduce their climate risks, new knowledge gaps and decision support needs will emerge. Building a climate resilient Washington will require effectively and efficiently meeting those needs.

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[1] (IPCC) Intergovernmental Panel on Climate Change. 2013. Working Group 1, Summary for Policymakers. Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

[2] Payne, J. T. et al., 2004. Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, *62*(1-3), 233-256. doi: 10.1023/B:CLIM.0000013694.18154.d6

[3] Littell, J. S. et al., 2013. Forest ecosystems: Vegetation, disturbance, and economics. Chapter 5 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*. Washington, D.C.: Island Press.

[4] Groffman, P. M. et al. (In review). Ecosystems, Biodiversity, and Ecosystem Services. Chapter 8 in the *Third U.S. National Climate Assessment*, scheduled for release in early 2014, January 2013 review draft. Available at: http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-chap8-ecosystems.pdf

[5] Reeder, W.S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities, Washington D.C.: Island Press.

[6] Mote, P.M. et al.. (In review). The Northwest. Chapter 21 in the *Third U.S. National Climate Assessment*, scheduled for release in early 2014, January 2013 review draft. Available at: http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-chap21-northwest.pdf

[7] Center for Climate and Energy Solutions. 2013. State and Local Climate Adaptation Map, as of December 9, 2013. Available at: http://www.c2es.org/us-states-regions/policy-maps/adaptation.

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SECTION 1

How Are Global and National Climate Changing?

Global and national temperatures have increased throughout much of the 20th century. Global sea level is rising, the oceans are warming, and ocean chemistry is changing. Many aspects of the earth's physical and biological systems are changing in ways consistent with human-caused warming. Natural variability continues to result in short-term periods that are warmer or cooler than the long-term average. Recent studies have made use of longer observational records and investigated trends in greater detail. These studies have provided new and stronger evidence that warming trends are largely due to human activities.

1. **The Earth's climate is continuing to warm, sea level is rising, and the oceans are changing.** Since the 1950s, many of the observed changes are unprecedented over decades to millennia.[1]

    - *Increasing global temperatures.* Average global temperature increased +1.5°F between 1880 and 2012 (Figure 1-1; Table 1-1). Globally, heat waves and heavy rainfall events have become more frequent since 1950 and cold snaps are becoming rarer.[A][1]

    - *Northern Hemisphere warming.* Each of the last three decades has been successively warmer than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years.[1]

    - *Rising sea level.* Global sea level has risen about +7 inches since 1901. The rate of global mean sea level rise has accelerated during the last two centuries.[1]

    - *Increasing ocean temperatures.* Ocean surface waters (top 250 ft.) warmed by +0.6 to +0.9°F from 1971 to 2009 (global average). Warming trends are evident at nearly all depths in the ocean.[1]

    - *Ocean acidification.* The acidity of the ocean has increased by about +26% since 1750. The current rate of acidification is nearly ten times faster than any time in the past 50 million years.[B][1][2]

2. **The U.S. is experiencing similar changes in climate.**

    - *Increasing U.S. temperature.* U.S. average temperature increased about +1.5°F since record keeping began in 1895, with different rates of warming in different locations (Figure 1-2).[3]

[A] In this section, trends are only reported if they are statistically significant at the 90% level or more.

[B] Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

Observed Change in Temperature, 1901-2012

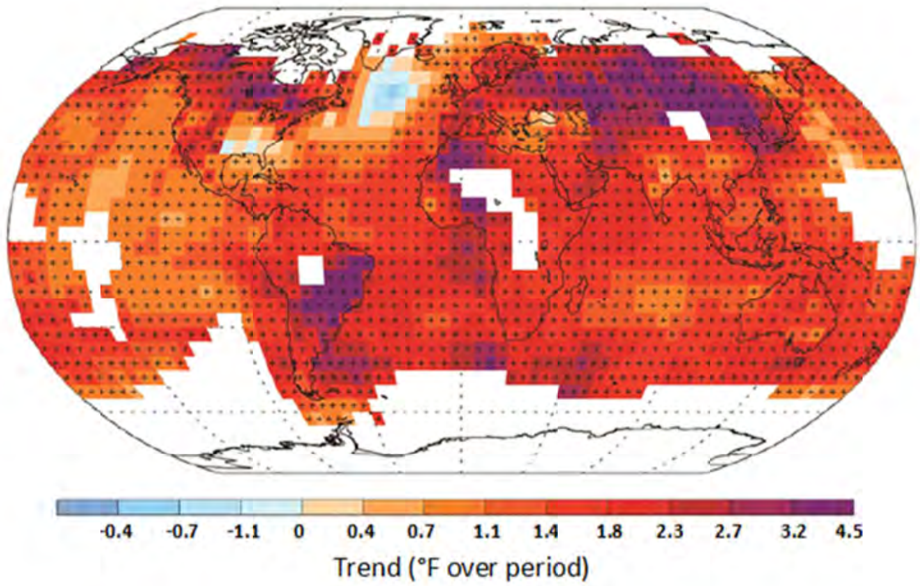

Figure 1-1. Significant warming has been observed in most locations. Observed changes in air temperature at the Earth's surface between 1901 and 2012. Red and purple colors indicate places that warmed while blue colors indicate places that cooled. White areas indicate places where data were insufficient to permit a robust trend estimate. The '+' signs indicate grid boxes where the direction of the trend is statistically significant. *Figure and caption adapted from IPCC 2013 (Figure SPM1.b).*[1]

Observed U.S. Temperature Change from 1901-1960 to 1991-2011

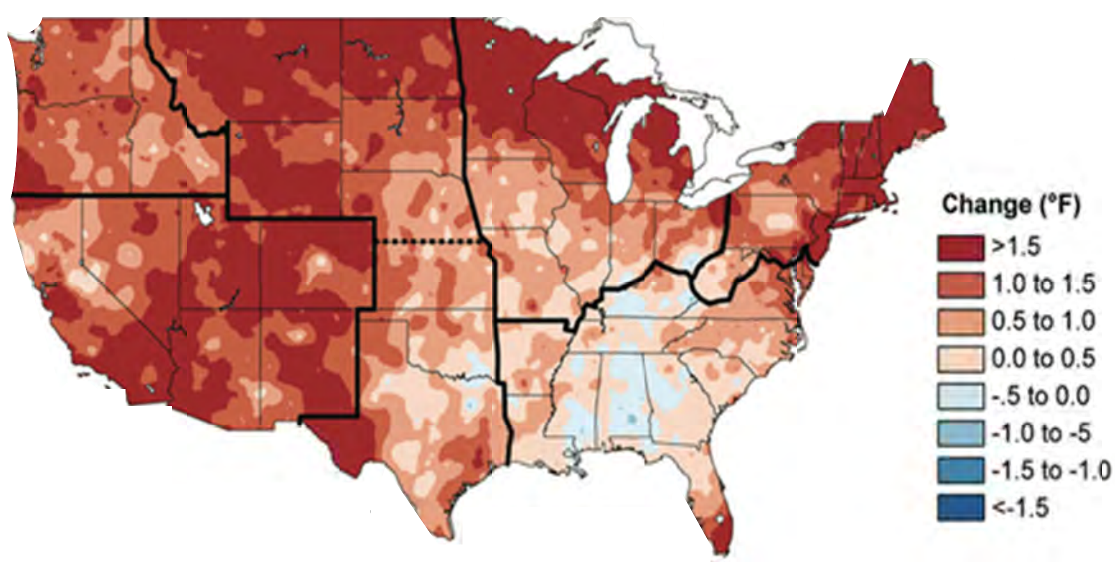

Figure 1-2. Warming has been observed for much of the continental U.S**.** Red colors indicate places that warmed while blue colors indicate places that cooled. In both cases this was calculated as the difference in temperature between the average for 1991-2011 and average temperature for 1901-1960. *Figure and caption adapted from Ch. 2 in Draft 2014 U.S. National Climate Assessment*[3]

- *More heavy rainfall events.* Heavy downpours are increasing in most regions of the U.S., especially over the last three to five decades, although trends for the Pacific Northwest are ambiguous.[3][4]

- *Longer frost-free season.* The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s. During 1991-2011, the average frost-free season was about 10 days longer than during 1901-1960. The largest increases for this period occurred in the western U.S.[3][4]

3. **Evidence of change is increasingly visible throughout Earth's physical and biological systems.**

- *Widespread declines in glaciers, sea ice, and ice sheets.* Glaciers around the world have become smaller, on average, and Greenland and Antarctica are losing ice overall.[1] Summertime minimum Arctic sea ice extent decreased more than −40% between 1978 and 2012 (relative to the median for 1979-2000), recovering slightly in 2013.[5] Annual average Antarctic sea ice extent increased by +4 to +6% between 1979 and 2012.[6]

- *Declining U.S. ice and snow.* Rising temperatures across the U.S. have reduced lake ice, sea ice, glaciers, and seasonal snow cover over the last few decades.[7] In the Great Lakes, for example, total winter ice coverage decreased substantially between the early 1970s and 2010.[8]

- *Shifting species ranges.* Plant and animal ranges are shifting northward (in the Northern Hemisphere) and to higher elevations (Section 8 of this report).[9][10]

4. **The role of human activities in changing global climate is becoming clearer.**

- *Continued increases in greenhouse gas emissions.* Globally, greenhouse gases emissions are higher and increasing more rapidly since 2000 than during the 1990s.[1]

- *Rising concentrations of greenhouse gases.* The atmospheric concentration of carbon dioxide (CO_2) increased +40% between 1750 and 2011 as a result of human activities, nearly reaching 400 ppm in 2013. Atmospheric concentrations of CO_2, methane, and nitrous oxide have increased to levels unprecedented in at least 800,000 years.[1]

- *Identifying and quantifying human influence.* Human influence is becoming increasingly detectable in the observed warming of the atmosphere and ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes.

    - The IPCC now estimates that "more than half of the observed increase in global average surface [air] temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together."[1]

- The effects of human emissions of greenhouse gases must be included in order for models to correctly simulate the observed 20th century pattern of warming.[1][11]

- Studies conducted at the scale of the western U.S. have attributed some of the observed increases in temperature, decreases in snowpack, and shifts in the timing of peak streamflows to human influence.[12][13][14]

5. Natural climate variability continues to contribute to shorter-term (annual to decades-long) periods that are warmer or cooler than the long-term average.

- *Short-term trends can differ from long-term trends.* There have been periods of accelerated warming and even slight cooling at global and regional scales throughout the course of the 20th century due, in part, to important patterns of natural climate variability such as El Niño, La Niña, and the Pacific Decadal Oscillation.[1]

- *Trends based on shorter periods of time can be misleading.* Due to natural variability, short-term trends can differ substantially from long-term trends.

- *Recent warming "hiatus" is associated with natural variability that favors cool conditions.* The slower rate of global average warming observed for 1998-2012 has coincided with a higher rate of warming at greater depths in the oceans and a dominance of La Niña and the cool phase of the Pacific Decadal Oscillation, two large-scale natural patterns of climate variability that favor cooler surface temperatures in large parts of the world.[1]

- *All climate model scenarios project warming over the course of the 21st century*.[1] The amount of warming observed at any given location and point in time will depend on the combined influences of human-caused global warming and natural climate variations. This means that long-term warming projected for this century will be punctuated by shorter periods of reduced warming, or even cooling, as well as periods of accelerated warming, for both the globe as a whole and for specific places like Washington State.

For more details on observed changes in global and national climate, see Table 1-1.

Table 1-1. Observed trends in national and global climate.

Variable and Region	Observed Change
Global Greenhouse Gas Emissions	Increasing ▪ Emissions increased +3.2% per year between 2000 and 2009. This rate was notably higher than in previous decades; emissions increased at a rate of +1.0% per year during the 1990s.[1] ▪ The atmospheric concentration of carbon dioxide (CO_2) increased +40% between 1750 and 2011 as a result of human activities.[1] ▪ Atmospheric concentrations of CO_2, methane, and nitrous oxide have increased to levels unprecedented in at least 800,000 years.[1]
Temperature	
Average Annual: Global	Warming: +1.5°F (+1.2 to +1.9°F; 1880-2012)[1]
Average Annual: U.S.	Warming: +1.5°F (1895-2011)[3][4] Greatest warming in winter and spring[3]
Extremes	More heat events and fewer cold events globally (1950-2012). No significant trends for the U.S.[C][1][4]
Precipitation	
Annual: Global	No significant trend (1901-2012). Trends vary with location[1]
Annual: U.S.	Slightly wetter (1900-2011) ▪ +5% increase in annual precipitation over the U.S. ▪ Largest increase (+9%) in Midwest ▪ No significant trend for the Pacific Northwest.[3]
Heavy Precipitation: Global	Increasing; more frequent high rainfall events since 1950[1]
Heavy Precipitation: U.S.	Increasing overall (1901-2011), although highly variable by region. ▪ Greatest increase regionally: Midwest and Northeast[3] ▪ Since 1991, all regions have experienced a greater than normal occurrence of extreme events relative to the 1901-2011 average. ▪ Significant trends observed for Southwest (decreasing) and Midwest (increasing), other U.S. regions do not have statistically significant trends.[D][4]

[C] Nationally, the 1930s remain the decade with the highest number of extreme heat events when averaged over the U.S., followed by 2001-2011. In the western U.S., however, the 2000s are the decade with the highest number of extreme heat events.

[D] Extreme events were defined as the number of 2-day extreme precipitation events exceeding a 1 in 5-year recurrence interval for the period of 1901-2011.

Variable and Region	***Observed Change***
Snow and Ice	
Glaciers, Sea Ice, and Land-based Ice Sheets	Ice coverage is shrinking overall, with some growth in sea ice in the Antarctic ▪ Melting ice from glaciers, Greenland and Antarctica contributed +0.6 to +1.1 inches to sea level rise from 1971 to 2009[1]
Arctic Sea Ice	Decreasing ▪ Average annual extent: decreased −3.5 to −4.1%/decade (1979-2012)[1] ▪ Average summer minimum extent: decreased −9.4 to −13.6%/decade (1979-2012)[1]
Snow Cover: Northern Hemisphere	Decreasing ▪ Total area covered by snow in spring (March-April) decreased by −0.8 to −2.4%/decade (1967-2012)[1]
Oceans	
Ocean Temperature: Global	Warming ▪ +0.16 to +0.23°F warming in the upper ocean (top 250 ft.; 1979-2010)[1] ▪ Over the past 40 years (1971-2010), the oceans have absorbed more than 90% of the excess energy trapped by greenhouse gases emitted due to human activities.[1]
Sea Level: Global	Rising, although amount and rate of rise varies by location and over time. ▪ Rate of rise accelerated between 1993 and 2010, although similarly high rates are likely to have occurred between 1930 and 1950. +0.6 to +0.7 in./decade (1901-2010)[1] +0.7 to +0.9 in./decade (1971-2010)[1]
Ocean Acidification	Increasing acidity. Global ocean acidity has increased by +26% since the beginning of the industrial era (~1750) (this is equivalent to a decline in pH of −0.1) [1][2]

[1] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

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[4] Kunkel et al., 2013. *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. Climate of the Contiguous United States*, NOAA Technical Report NESDIS 142-9, NOAA National Environmental Satellite, Data, and Information Service, Washington, D.C.

[5] NSIDC, 2012. Arctic sea ice reaches lowest extent for the year and the satellite record. The National Snow and Ice Data Center, as cited in Walsh, J. , D. Wuebbles, et al. (2014).

[6] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis: Technical Summary,* available at: http://www.ipcc.ch/report/ar5/wg1/#.UluMuxCz4zo; see also Turner, J., T.J. Bracegirdle, T. Phillips, G.J. Marshall, J.S. Hosking. 2013. An Initial Assessment of Antarctic Sea Ice Extent in the CMIP5 Models. *J. Climate,* 26, 1473–1484, doi:10.1175/JCLI-D-12-00068.1

[7] Arctic Monitoring and Assessment Programme. 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Cambridge University Press, as cited in Walsh, J. , D. Wuebbles, et al. (in press).

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SECTION 2

How Is Pacific Northwest Climate Changing?

The Pacific Northwest is experiencing a suite of long-term changes that are consistent with those observed globally as a result of human-caused climate change. These include increasing temperatures, a longer frost-free season, decreased glacial area and spring snowpack, earlier peak streamflows in many rivers and rising sea level at most locations. Natural variability can result in short-term trends that are opposite those expected from climate change, as evidenced by recent regional cooling and increases in spring snowpack. Recent studies have investigated trends in greater detail, and clarified the role of variability, in particular regarding changes in extremes, sea level rise, ocean acidification, and snow.

1. Washington and the Pacific Northwest have experienced long-term warming, a lengthening of the frost-free season, and more frequent nighttime heat waves.[1]

- *Increasing temperatures.* The Pacific Northwest warmed about +1.3°F between 1895 and 2011, with statistically-significant warming occurring in all seasons except for spring.[A][1][2] This trend is robust: similar 20th century trends are obtained using different analytical approaches.[3] All but five of the years from 1980 to 2011 were warmer than the 1901-1960 average (Figure 2-1, Table 2-1).[1]

- *Frost-free season.* The frost-free season (and the associated growing season) has lengthened by 35 days (±6 days) from 1895 to 2011.[2]

- *Heat waves.* Nighttime heat events have become more frequent west of the Cascade Mountains in Oregon and Washington (1901-2009).[4] For the Pacific Northwest as a whole there has been no significant trend in daytime heat events or cold events for 1895-2011.

- *Short-term trends.* The Pacific Northwest's highly variable climate often results in short-term cooling trends, as well as warming trends larger than the long-term average (Figure 2-1). The cooling observed from about 2000 to 2011, for example, is similar to cooling observed at other times in the 20th century, despite overall long-term warming.

- *Challenges in assessing trends.* Estimates of temperature changes over time can be affected by changes in the location and number of measurements made and in the instruments used to make the measurements. The temperature datasets reported here include corrections for these factors,[5] and there is no published evidence that these issues affect long-term regional trends in temperature.[6]

[A] In this section, trends are only reported if they are statistically significant at the 90% level or more.

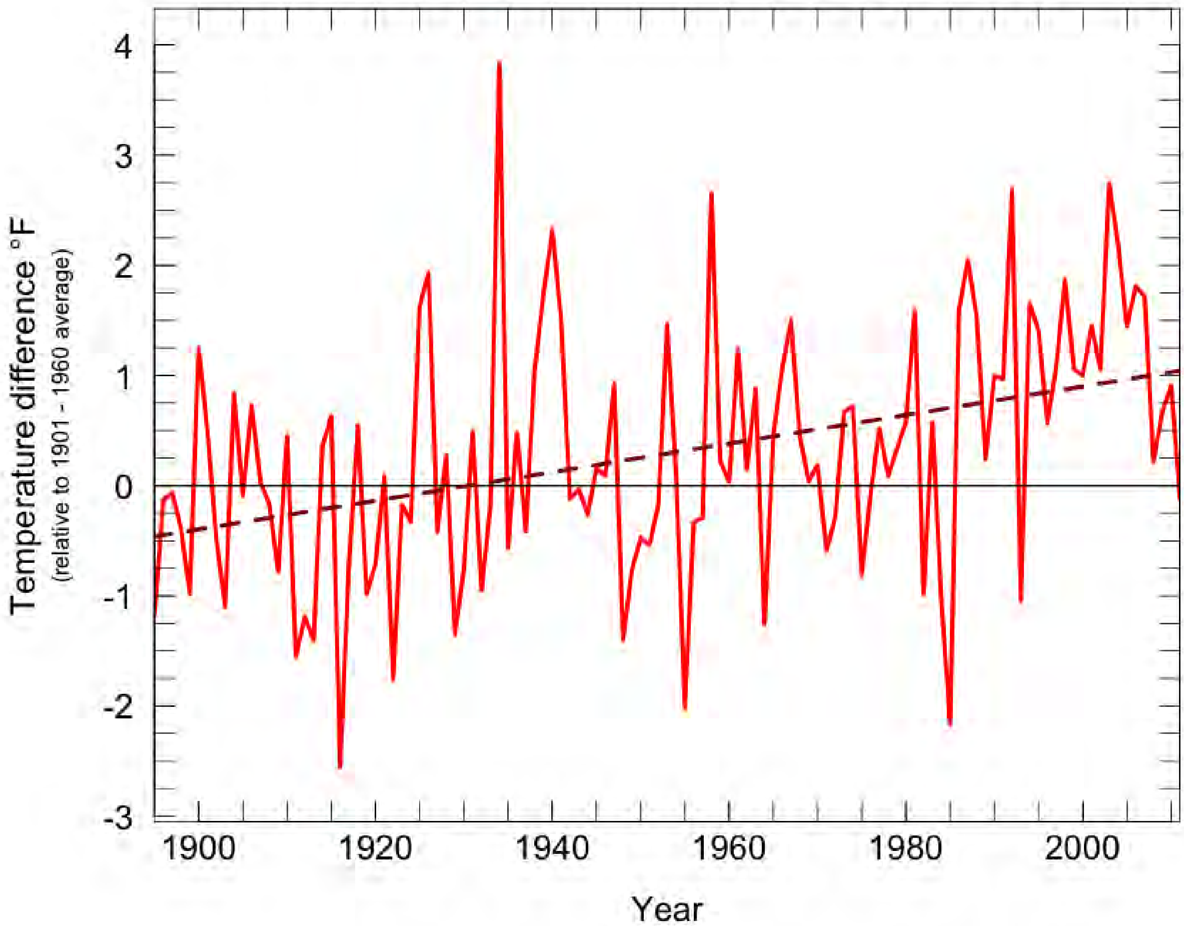

Figure 2-1. Rising temperatures in the Pacific Northwest. Average annual temperature (red line) shown relative to the 1901–1960 average (indicated by the solid horizontal line). The dashed line is the fitted trend, indicating the +0.13°F/decade warming for 1895-2011. *Data source: Kunkel et al. 2013.*[2]

2. **Sea level is rising along some parts of the Washington coastline and falling in others due to the combination of global sea level rise and local vertical land movement.**

- *Local sea level rise.* Although on average sea level is rising in the region, local sea level change is modulated by vertical land motion, in response to tectonics and other processes. Current observations of local sea level changes range from a decline along the northwest Olympic peninsula, a region experiencing uplift, to sea level rise in parts of the Puget Sound and the outer coast where land is subsiding.[7][8]

- *Year-to-year variability.* Local sea level is affected by shorter-term variations in addition to long-term changes in sea level associated with global warming. For example, El Niño conditions can temporarily increase regional sea level up to about a foot during winter months.[9][10]

3. **There has been no discernible long-term trend in Pacific Northwest precipitation.**

   - *Annual precipitation.* There is no statistically-significant trend towards wetter *or* drier conditions in Pacific Northwest precipitation for the period 1895-2011.[2]

   - *Year-to-year variability.* Natural variability has a large influence on regional precipitation, causing ongoing fluctuations between wet years and dry years and wet decades and dry decades.

   - *Heavy downpours.* Trends in heavy precipitation events are ambiguous for the Pacific Northwest. Most studies find modest increasing trends, but most are not statistically-significant, and results depend on the dates and methods of the analysis.[2][11][12][13]

4. **Long-term changes in snow, ice and streamflows reflect the influence of warming.**

   - *Spring snowpack.* Spring snowpack fluctuates substantially from year-to-year, but declined overall in the Washington Cascades from the mid-20th century to 2006.[14][15] This trend is due primarily to increasing regional temperature and reflects the influence of both climate variability and climate change.[16][17] Natural variability can dominate over shorter time scales, resulting (for example) in an increase in spring snow accumulation in recent decades.[14]

   - *Glaciers.* About two-thirds of the glaciated area in the lower 48 states (174 out of 266 sq. miles) is in Washington.[18] Although there are some exceptions, most Washington glaciers are in decline. Declines range from a 7% loss of average glacier area in the North Cascades (1958-1998)[19] to a 49% decline in average area on Mt. Adams (1904-2006).[20]

   - *Streamflow timing.* The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Pacific Northwest (observed over the period 1948-2002) as a result of decreased snow accumulation and earlier spring melt.[21]

5. **The coastal ocean is acidifying, but ocean temperatures show no strong trends.**

   - *Ocean acidification*. The chemistry of the ocean along the Washington coast has changed due to the absorption of excess CO_2 from the atmosphere. Local conditions are also affected by variations and trends in upwelling of deeper Pacific Ocean water that is low in pH and high in nutrients, deliveries of nutrients and organic carbon from land, and absorption of other important acidifying atmospheric gases. Conditions vary by location and from season to season, but appear to have already reached levels that can affect some species.[B][8][22]

[B] Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

- *Coastal ocean temperature.* The long-term trend in coastal ocean temperatures has been small compared to the considerable variations in ocean temperatures that occur from season-to-season, year-to-year, and decade-to-decade. These variations result from both local effects, such as winds and upwelling, to remote effects, such as El Niño. No warming has been detected for the general region of the Pacific Ocean offshore of North America,[23] but warming has been detected for the Strait of Georgia[C] and off the west coast of Vancouver Island.[24]

For more details on observed changes in Pacific Northwest climate, see Table 2-1.

Additional Resources

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- Trends in temperature, precipitation, and snowpack for individual weather stations across the Pacific Northwest: http://www.climate.washington.edu/trendanalysis/
- Trends in temperature and precipitation for Washington state and specific regions within the state: http://charts.srcc.lsu.edu/trends/
- Centralized resource for observed climate in the Western U.S.: http://www.wrcc.dri.edu/

[C] The Strait of Georgia is located north of the Puget Sound, between Vancouver Island and British Columbia.

Table 2-1. Observed trends in Pacific Northwest climate.

Variable	***Observed Change*** [A]
Temperature	
Annual	Warming: +0.13°F/decade (1895-2011)[1][2]
Seasonal	Warming in most seasons *Winter* Warming: +0.20°F/decade (1895-2011)[2] *Spring* No significant trend (1895 – 2011)[2] *Summer* Warming: +0.12°F/decade (1895–2011)[2] *Fall* Warming: +0.10°F/decade (1895–2011)[2]
Extremes	Statistically-significant increase in nighttime heat events west of the Cascade Mountains in Oregon and Washington (1901-2009).[4] No significant trends in daytime heat events or cold events (1895-2011).[2]
Freeze-free Season	Lengthening: +3 days/decade (1895–2011)[D][2]
Precipitation	
Annual	No significant trend (1895–2011)[1][2]
Extremes	Ambiguous: Studies find different trends depending on the dates and methods of the analysis[2][11][12][13]
Hydrology	
Snowpack	Long-term declines, recent increases. ▪ Washington Cascades snowpack decreased by about −25% between the mid-20th century and 2006, with a range of −15 to −35% depending on the starting date of the trend analysis (which ranged from about 1930 to 1970)[14][15] ▪ Snowpack in recent decades (1976–2007) has increased but the change is not statistically significant and most likely the result of natural variability.[14]
Glaciers	Declining overall ▪ North Cascades: −7% decline in glacier area (1958-1998)[19] ▪ Mt. Rainier: −14% decline in glacier volume (1970-2007)[25] ▪ Mt. Adams: −49% decline in glacier area (1904-2006)[20] ▪ Olympic Mountains: No published studies on long-term trends.
Annual Streamflow Volume	Declining in some locations Trends in annual streamflow are relatively small in comparison to year-to-year variability. A study of 43 streamflow gauges in the Pacific Northwest found declining trends (1948-2006), ranging from no change to −20% for individual locations.[26]

[D] Number of days between the last freeze of spring and first freeze of fall.

Variable	Observed Change [A]
Timing of Peak Streamflow	Shifting earlier, depending on location ▪ Spring peak streamflow in the Pacific Northwest has shifted earlier in snowmelt-influenced rivers – the shift ranges from no change to about 20 days earlier (1948-2002).[21]
Coastal Ocean	
Ocean Temperature	Varies with location ▪ Over the larger region offshore of North America: no significant warming in ocean surface temperatures (1900-2008)[23] ▪ In the Strait of Georgia and West of Vancouver Island: significant warming observed. Average for top 330 ft: +0.4°F/decade (1970-2005)[24]
Ocean Acidification	Acidifying ▪ Ocean waters on the outer coast of Washington and the Puget Sound have become about +10 to +40% more acidic since 1800 (decline in pH of −0.05 to −0.15).[27]
Sea Level Change	Mostly rising; varies with location ▪ Friday Harbor, WA: +0.4 in./decade (1934-2008) ▪ Neah Bay, WA: −0.7 in./decade (1934-2008) ▪ Seattle, WA: +0.8 in./decade (1900-2008) ▪ Astoria, OR: −0.1 in./decade (1925-2008)[28]

[1] Mote, P.W. et al., 2013. Climate: Variability and Change in the Past and the Future. Chapter 2, 25-40, in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

[2] Kunkel, K.E. et al., 2013. *Part 6. Climate of the Northwest U.S.*, NOAA Technical Report NESDIS 142-6.

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SECTION 3

Making Sense of the New Climate Change Scenarios

The speed with which the climate will change and the total amount of change projected depend on the amount of greenhouse gas emissions and the response of the climate to those emissions. To make projections, climate scientists use greenhouse gas scenarios – "what if" scenarios of plausible future emissions – to drive global climate model simulations of the earth's climate. Both the greenhouse gas scenarios and global climate models are periodically updated as the science of climate change advances. The most recent projections for 21st century climate change (IPCC 2013)[1] align with and confirm earlier projections (e.g., IPCC 2007).[2]

1. **How much and how fast climate changes occur depends on both the amount of greenhouse gas emissions and how the climate changes in response to those emissions.** As a result, projecting future climate requires making assumptions about future greenhouse gas emissions and then modeling the climate's response to those emissions. Irreducible uncertainty in both climate and future greenhouse gas emissions means that projections of future climate will always involve a range of scenarios.

   - *Since it is impossible to predict exactly how much greenhouse gases will be emitted,* scientists use greenhouse gas scenarios to consider the implications of a range of different future conditions.

   - *We can't know which scenario is more likely.* Since we are unable to predict the future, we can't say with certainty which scenario is most likely to occur.

   - *It is important to consider a range of potential outcomes.* There is no "best" scenario, and the appropriate range of scenarios depends on the specific climate impact under consideration. Deciding which scenario(s) to use involves clarifying how climate affects a particular decision and what level of risk is acceptable.

   - *Projections will continue to be updated over time.* As the science of climate change progresses, new greenhouse gas scenarios and updated climate models will inevitably replace the current climate projections.

2. **New greenhouse gas scenarios used in IPCC 2013[1][3] range from an extremely low emissions scenario involving aggressive emissions reductions to a high "business as usual" scenario with substantial continued growth in greenhouse gases.** Although these scenarios were created in a different way and span a wider range of possible 21st century emissions, many of them are similar to scenarios used in previous assessments (Table 3-1, Figures 3-1 and 3-2).[A][4]

[A] The newest scenarios, used in the 2013 IPCC report, are referred to as Representative Concentration Pathways (RCPs; Van Vuuren et al. 2011[3]). The previous greenhouse gas scenarios, used in the 2001 and 2007 IPCC reports, are described in the Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000[4]).

Table 3-1. Previous greenhouse gas scenarios have close analogues in the new scenarios.

New scenarios	***Scenario characteristics***	***Comparison to old scenarios***	***Description used in this report***
RCP 2.6	An extremely low scenario that reflects aggressive greenhouse gas reduction and sequestration efforts	No analogue in previous scenarios	“Very Low”
RCP 4.5	A low scenario in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter	Very close to B1 by 2100, but higher emissions at mid-century	“Low”
RCP 6.0	A medium scenario in which greenhouse gas emissions increase gradually until stabilizing in the final decades of the 21st century	Similar to A1B by 2100, but closer to B1 at mid-century	“Medium”
RCP 8.5	A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century	Nearly identical to A1FI[B]	"High”

- *The old scenarios have close analogues in the new scenarios*. For example, the A1B scenario – used as the high-end scenario in many Pacific Northwest impacts assessments – is similar to the newer RCP 6.0 scenario by 2100, though closer to the RCP 8.5 scenario at mid-century.

- *In both cases, the high end is a “business as usual” scenario (RCP 8.5, SRES A1FI)* in which emissions of greenhouse gases continue to increase until the end of the 21st century, and atmospheric CO_2 concentrations more than triple by 2100 relative to pre-industrial levels.

- *The new scenarios include an aggressive mitigation scenario (RCP 2.6),* which would require about a 50% reduction in global emissions by 2050 relative to 1990 levels, and near or below zero net emissions in the final decades of the 21st century.

- *All scenarios result in similar warming until about mid-century.* Prior to mid-century, projected changes in climate are largely driven by the warming that is “in the pipeline” – warming to which we are already committed given past emissions of greenhouse gases. In contrast, warming after mid-century is strongly dependent on the amount of greenhouse gases emitted in the coming decades.

- *Greenhouse gas scenarios are consistent with recent global emissions.* Globally, greenhouse gas emissions are higher and increasing more rapidly since 2000 than during the 1990s (Figure 3-1).[1]

[B] The A2 greenhouse gas scenario is between the RCP 6.0 and 8.5 scenarios.

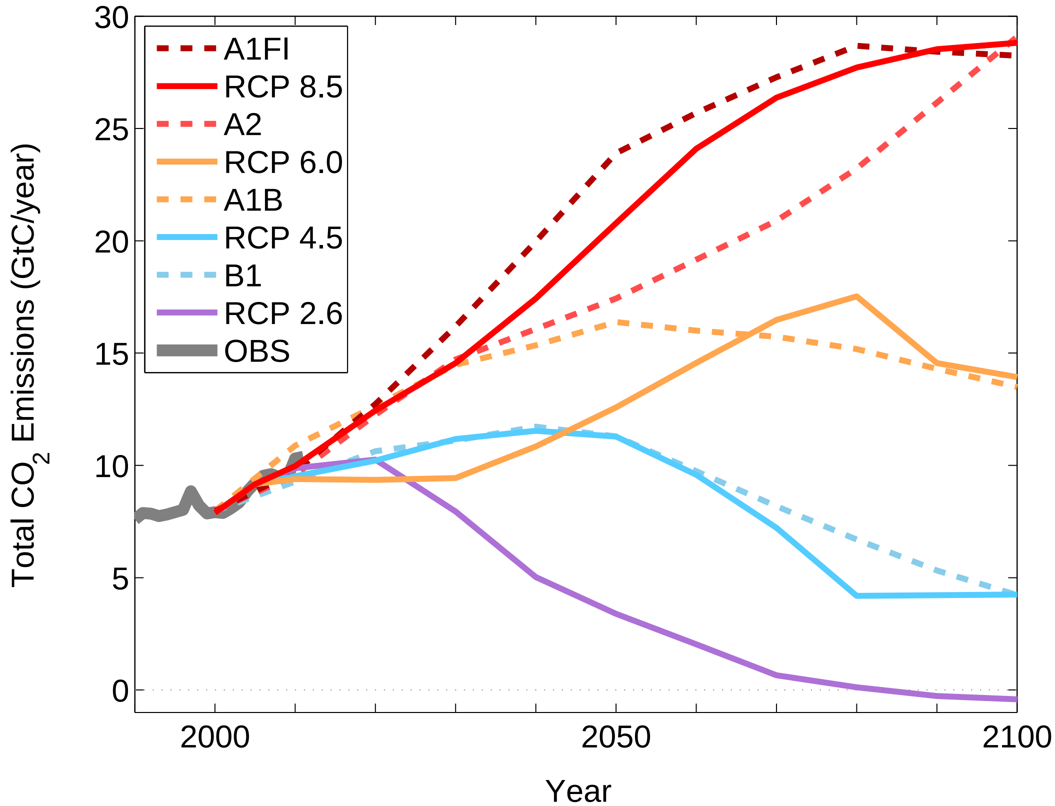

Figure 3-1. Future greenhouse gas scenarios range from aggressive reductions to large increases in greenhouse gas emissions. The figure shows annual total CO_2 emissions in Gigatons of Carbon (GtC). Though not the only greenhouse gas, CO_2 emissions are the dominant driver of global warming. The old greenhouse gas scenarios (dashed lines) have close analogs in the new scenarios (solid lines) – similar scenarios are plotted using similar colors. Actual emissions for 1990-2010 are shown in grey. Year-to-year emissions of greenhouse gases, shown in this graph, accumulate in the atmosphere, causing CO_2 concentrations to rise, as shown in Figure 3-2. Scenarios with higher emissions cause atmospheric concentrations to rise rapidly, while lower scenarios cause concentrations to rise more slowly or decline. *Figure source: Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://tntcat.iiasa.ac.at:8787/RcpDb[3] and http://sedac.ciesin.columbia.edu/ddc/sres/[4]).*

3. **New climate change projections (IPCC 2013) also use new versions of climate models that simulate changes in the Earth's climate.** More models are included in the new projections, and they are improved relative to older models.[5][6]

- *New climate models project similar climate changes for the same amount of greenhouse gas emissions.* Differences between warming projections for the 2007 and 2013 IPCC reports are mostly due to differences in greenhouse gas scenarios.[5][7]

- *The range among climate model projections may not encompass the full range of potential future climate changes.* The range among climate model simulations provides an estimate of the uncertainty in projections, but it is important to note that future changes in climate could be outside of the range projected by existing climate models.

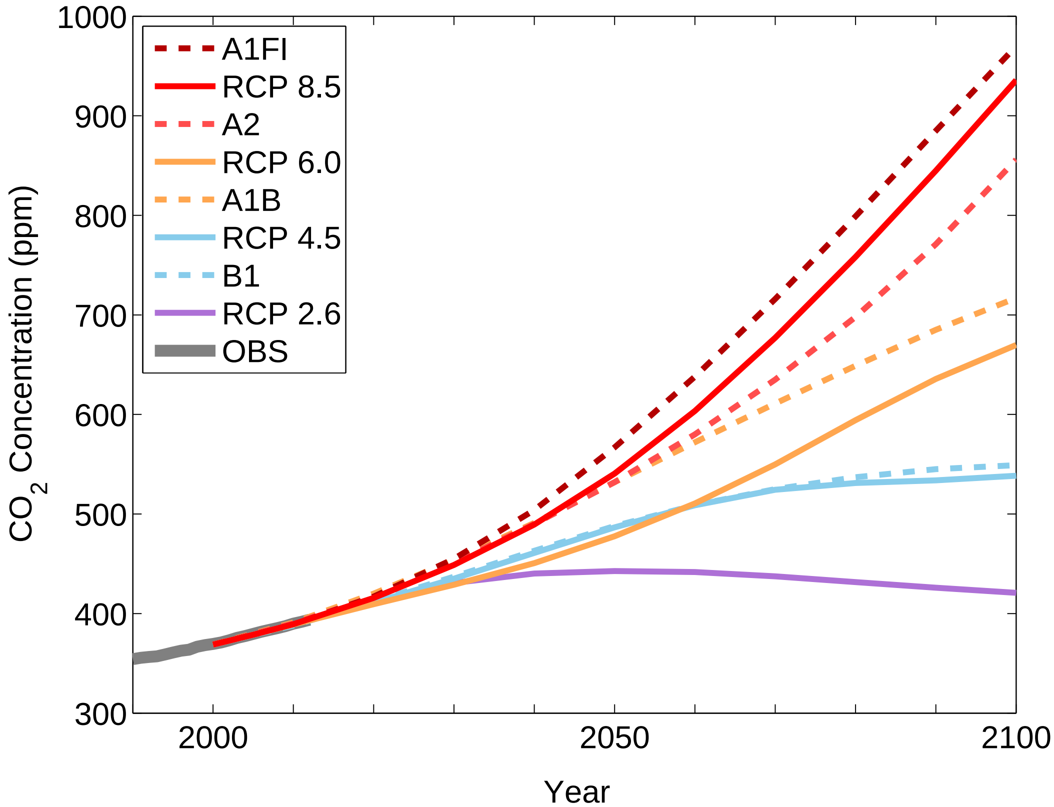

Figure 3-2. All scenarios assume continued growth in atmospheric levels of greenhouse gases for the next few decades. The figure shows total CO_2 concentration, in parts per million (ppm), for each greenhouse gas scenario. Though not the only greenhouse gas, CO_2 emissions are the dominant driver of global warming. The old greenhouse gas scenarios (dashed lines) have close analogs in the new scenarios (solid lines) – similar scenarios are plotted using similar colors. Actual concentrations for 1990-2010 are shown in grey. *Figure source: Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://tntcat.iiasa.ac.at:8787/RcpDb[3] and http://sedac.ciesin.columbia.edu/ddc/sres/[4]).*

4. Implications for Pacific Northwest climate projections and climate impacts assessments.[C]

- *Projected Pacific Northwest climate change is similar for new (IPCC 2013) and old (IPCC 2007) scenarios of medium and low greenhouse gas emissions.* The Washington Climate Change Impacts Assessment (WACCIA)[8] and many regional climate impact studies largely used the A1B and B1 greenhouse gas scenarios. These are comparable to RCP 6.0 and RCP 4.5, respectively, at the end of the century, in terms of both greenhouse gas concentrations (Table 3-1) and resultant changes in Pacific Northwest climate (Section 5, Figure 5-2).

[C] See Section 5 (Figure 5-2) for a comparison of projected Pacific Northwest temperature change under the old and new scenarios.

- *Newer scenarios for very low and high greenhouse gas emissions result in a wider range in projected late-century warming for the Pacific Northwest. Previous regional assessments have typically considered a narrower range of greenhouse gas scenarios.*
    - The new scenarios include an aggressive greenhouse gas mitigation scenario (RCP 2.6), which assumes much lower emissions than in other scenarios. The older projections do not include a comparable scenario.
    - The highest scenarios commonly used in many previous climate impacts assessments (A1B, A2) are much lower than the high-end scenario in the new projections (RCP 8.5).
- *The importance of differences between the old and new climate change projections will depend on the specific impact under consideration and the sensitivity of the decision being made.* For example, projected changes in annual average temperature are likely to differ by less than 1°F under similar greenhouse gas scenarios from IPCC 2007 and 2013, while projected changes in annual average precipitation are likely to differ by only a few percentage points (Section 5, Figure 5-2). Other differences between the scenarios have not yet been explored.

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[1] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

[2] (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[3] Van Vuuren, D. P. et al., 2011. The representative concentration pathways: An overview. *Climatic Change* 109(1-2): 5-31.

[4] Nakicenovic, N. et al., 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, U.K., 599 pp. Available online at: http://www.grida.no/climate/ipcc/emission/index.htm

[5] Taylor, K. E. et al., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485-498. doi:10.1175/BAMS-D-11-00094.1

[6] Knutti, R. et al., 2013. Climate model genealogy: Generation CMIP5 and how we got there. *Geophys. Res. Lett*, *40*, 1194-1199. doi:10.1002/grl.50256

[7] Andrews, T. et al., 2012. Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models. *Geophysical Research Letters*, *39*(9). doi: 10.1029/2012GL051607

[8] Climate Impacts Group, 2009. The Washington Climate Change Impacts Assessment, M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. Available at: http://www.cses.washington.edu/db/pdf/wacciareport681.pdf

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SECTION 4

How Are Global and National Climate Projected to Change?

Greenhouse gas emissions are projected to increase global and national average temperatures, precipitation, sea level, and ocean acidity. More extreme heat and heavy rainfall events are also likely. The amount of change that actually occurs will depend on the amount of future greenhouse gas emissions and will vary by location. The most recent projections for 21st century climate change (IPCC 2013) [1] align with and confirm earlier projections (e.g., IPCC 2007), [2] although new estimates indicate faster rates of sea level rise during this century and in the centuries to come.

1. **Significant warming is projected for the 21st century as a result of greenhouse gases emitted from human activities.[1]** The amount of warming that occurs from about mid-century onward depends on the amount of greenhouse gases emitted in the coming decades. Natural variability is expected to remain an important feature of global and regional climate, at times amplifying and at other times counteracting the long-term trends caused by rising greenhouse gas emissions.

    - *Continued rise in global temperatures.* Warming is projected to continue throughout the 21st century. Higher emissions of greenhouse gases will result in greater warming (Figure 4-1; Table 4-1). Projected warming for 2081-2100 (relative to 1986-2005) ranges from +1.8°F (range: +0.5°F to +3.1°F) for a scenario that assumes aggressive reductions in greenhouse gas emissions to +6.7°F (range: +4.7°F to +8.6°F) for a high "business as usual" emissions scenario.[A][B] Heat waves are projected to continue to become more prevalent and cold snaps less frequent.[1]

    - *Ocean warming.* The oceans will continue to warm, and heat will penetrate from the surface to the deep ocean. Projected warming in the top 330 feet of the ocean is +1.1°F to +3.6°F for 2081-2100 relative to 1986-2005.[1]

    - *Past emissions have committed the climate to ongoing changes, regardless of future emissions.* Current and past greenhouse gas emissions have already caused warming that will continue into the 21st century and persist for several centuries or longer.[3] To keep global temperature increases between +0.5 and +3.1°F (by 2081-2100 relative to 1986-2005), net greenhouse gas emissions would have to be reduced by about 50% by 2050 (relative to 1990 emissions), and to near or below zero in the final decades of the 21st century.[4]

[A] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

[B] The RCP 2.6 (very low) and RCP 8.5 (high) scenarios.

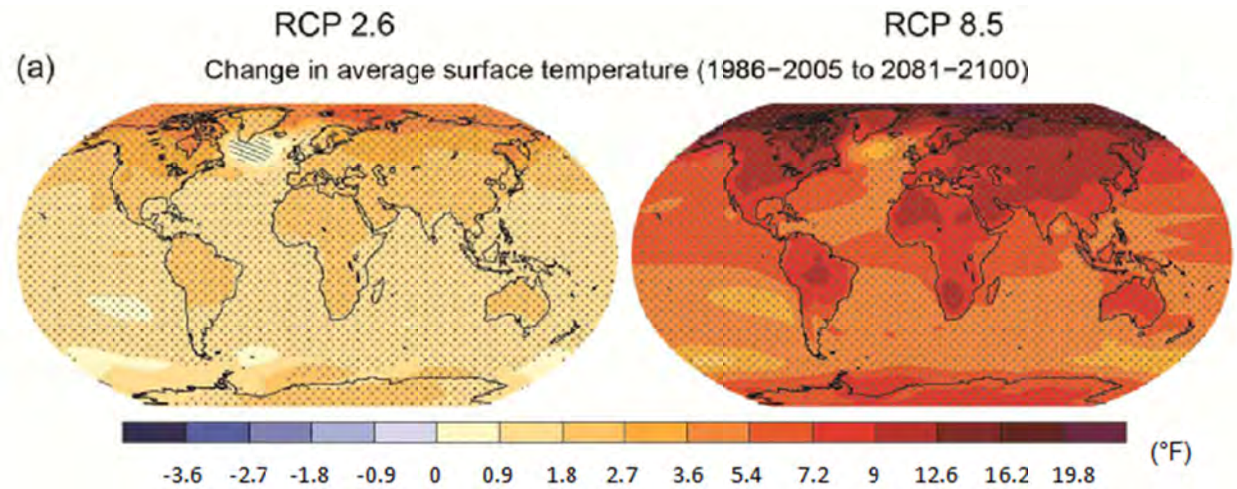

Figure 4-1. All scenarios project warming for the 21st century**.** Projected changes in annual average air temperature at the Earth's surface for 2081-2100 (relative to 1986-2005) for a very low (RCP2.6) and high (RCP8.5) greenhouse gas scenario, from an average of global climate models. Stippling indicates regions where at least 90% of models agree on the direction of change. *Figure and caption adapted from IPCC 2013, Figure SPM.8.[1]*

2. **Global warming will be accompanied by changes in precipitation, continued decreases in glaciers and ice sheets, continued sea level rise, and increasing ocean acidity.**

    - *Modest increases in global average precipitation.* Changes in precipitation will vary by location and are less certain than those in temperature. Overall, global average precipitation is projected to increase modestly, by +0.6 to +1.6% per °F for most greenhouse gas scenarios.[C][4] In general, historically dry regions and seasons are expected to get drier and historically wet regions and seasons are expected to get wetter. Heavy rainfall events are projected to become more intense over most mid-latitude land areas, including much of the continental U.S.

    - *Declining ice, snow, and glaciers.* Arctic sea ice, Northern Hemisphere spring snow cover, and the vast majority of glaciers will continue to shrink with warming. Many models project that the Arctic could be nearly ice free in September by mid-century, if greenhouse gas emissions continue to rise significantly.[1]

    - *Continued rise in sea level.* Global mean sea level is projected to rise by +11 to +38 inches by the end of the 21st century (2100, relative to 1986-2005), according to the IPCC,[D][1] and +20 to +55 inches (relative to the year 2000), according to a National

[C] Specifically, for the RCP 4.5, 6.0, and 8.5 greenhouse gas scenarios

[D] Sea level rise projections vary depending on the greenhouse gas emissions scenarios used. The average and associated ranges reported in Church et al. 2013 are +17 in. (range: 11-24 in.) for the very low (RCP 2.6) greenhouse gas scenario to +29 in. (range: 21-38 in.) for the high (RCP 8.5) greenhouse gas scenario.

Research Council report.[E][5] In all scenarios, 21st century global sea level is projected to rise faster than it has in recent decades (1971-2010).[4] Sea level rise will continue to rise for several centuries after 2100 as the ocean and ice sheets continue to respond to changes in global temperatures.[3][4]

- *Ocean acidification.* The acidity of the ocean is projected to increase by +38 to +109%[F][1] by 2100 relative to 1986-2005 (or increase roughly +150 to +200% relative to pre-industrial levels)[6] as global oceans continue to absorb carbon dioxide from the atmosphere.

3. **The most recent projections for 21st century climate change (IPCC 2013)[1] align with and confirm earlier projections (e.g., IPCC 2007),[2] although new estimates indicate faster rates of sea level rise during this century and in the centuries to come.**

- *Close agreement in many areas.* Projected changes in temperature, precipitation, snow cover, and ocean acidification closely match the projections from 2007. Differences in warming projections are largely a result of differences between among greenhouse gas scenarios.

- *Exploring the consequences of aggressive greenhouse gas reductions.* The 2013 IPCC report includes a greenhouse gas scenario that requires aggressive reductions in global carbon dioxide emissions, and therefore indicates a lower amount of warming than for the low end of the scenarios used in the 2007 report, which assumed no greenhouse gas reduction efforts.

- *Higher sea level rise projections.* The updated sea level rise projections are about +40% higher, in large part because the new report includes projected changes in ice sheet flow, which were omitted in the 2007 IPCC report.

- *New findings about Greenland.* The Greenland ice sheet may be more easily destabilized by warming than previously thought. Studies indicate that the threshold for initiating a near-complete loss of Greenland ice is a global warming of +2°F to +7°F relative to pre-industrial, well within the projected warming for 2100. This would result in a sea level rise of more than 20 feet over the next one thousand years or more.[4]

- *Antarctic ice sheet stability.* The stability of large Antarctic marine ice sheets in a warmer climate is uncertain; their breakup could also lead to several additional feet of sea level rise, though probably not in this century.

E The IPCC projections are lower than those from the National Research Council (NRC 2012),[5] especially at the high end of the range. The two studies employed different analytical approaches and different assumptions about future greenhouse gas emissions.

F Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

4. The United States is also projected to experience warming, modest changes in precipitation, and continued sea level rise.

- *Warming.* Continued warming of +3°F to +11°F by the end of this century (2070-2099), relative to recent decades (1971-1999; Figure 4-2).[G][7][8]

- *Variable changes in precipitation.* Precipitation changes will vary by location and season. Winter and spring precipitation are expected to increase in the northern U.S. while summer precipitation is projected to decrease throughout the U.S.[7]

- *More extreme events.* Heavy rains and heat waves will continue to become more frequent.[7] Climate models currently project increases in the frequency and intensity of the strongest Atlantic hurricanes, although there is large uncertainty about these conclusions given the numerous factors that influence the formation of hurricanes.[7]

- *Continued rise in sea level.* Averaged over the U.S., sea level is projected to rise in response to global sea level rise.[7] Locally, sea level rise will vary from place to place due to differences in the rate of vertical land movement, ocean currents, and other factors.

- *Impacts on human and natural systems.* Projected changes in U.S. climate are expected to: increase damage to infrastructure as a result of higher storm surge, increased flooding, and extreme heat events; increase the likelihood of water shortages and competition for water among agricultural, municipal, and environmental uses; and reduce the capacity of ecosystems to moderate the consequences of disturbances such as droughts, floods, and severe storms, among other impacts. Impacts on U.S. agriculture are expected to become more problematic after mid-century as temperature increases and precipitation extremes are further intensified.[9]

For more details on projected global and national changes in climate, see Table 4-1.

[G] U.S. temperature projections from the 2007 IPCC report[2] differ somewhat from the projections presented in IPCC 2013[1] because of the different greenhouse gas scenarios (see Section 3 of this report) and historical base periods used (1971-99 vs. 1986-2005).

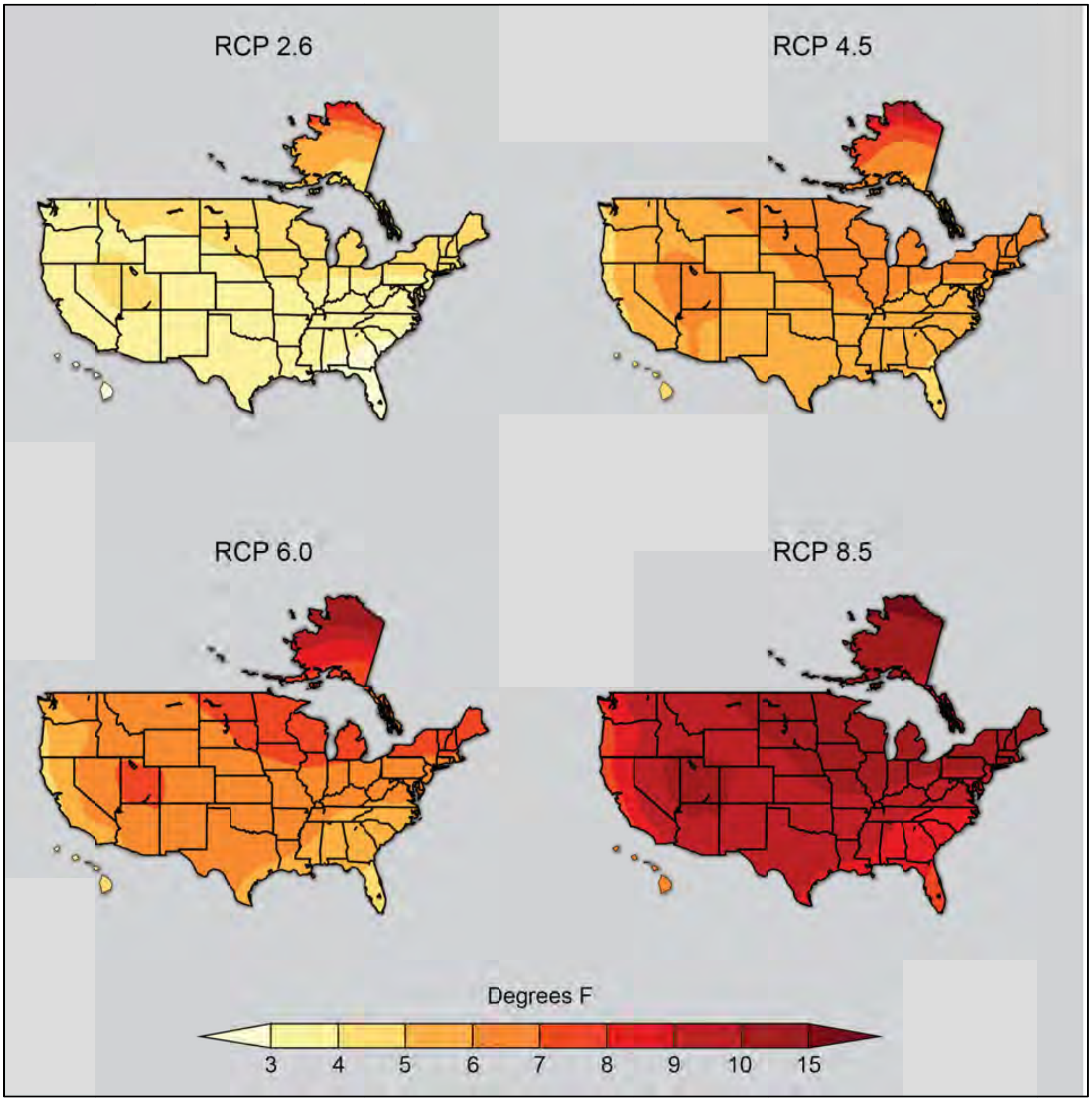

Figure 4-2. All scenarios project warming for the U.S.; the amount of warming depends on the amount of greenhouse gases emitted in the coming decades. Projected changes in annual average air temperature for the U.S. at the Earth's surface for the later part of this century (2071-2099) relative to 1971-2000 for the four greenhouse gas scenarios used to project global changes in IPCC 2013. RCP 2.6 (top left) is a very low greenhouse gas scenario that assumes rapid reductions in emissions – about a 50% cut from 1990 levels by 2050. RCP 8.5 (bottom right) is a high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century. Also shown are temperature changes (°F) for a low scenario (RCP 4.5, top right) and a medium scenario (RCP 6.0, bottom left). For more details on greenhouse gas scenarios, see Section 3 of this report. *Figure and caption adapted from Walsh et al., (in press).*[7]

Table 4-1. Projected changes in global and national climate.

<table>
<tr><th>Variable and Region</th><th>Projected Long-term Change</th></tr>
<tr><td>Temperature</td><td></td></tr>
<tr><td>Global</td><td>Warming

Warming projected for all greenhouse gas scenarios; amount of warming depends on the amount of greenhouse gases emitted.
Projected change for 2081-2100 relative to 1986-2005:
Very low emissions (RCP 2.6): +1.8°F (range: 0.5°F to 3.1°F)
High emissions (RCP 8.5): +6.7°F (range: 4.7°F to 8.6°F)[1]
Spatial pattern of warming varies. More warming is projected over land than over oceans, and the Arctic is projected to warm more rapidly than the global average.
</td></tr>
<tr><td>U.S.</td><td>Warming

Warming is projected for all scenarios for the end of the century (2070-2099, relative to 1971-1999):
Low emissions (B1): +3 to +6°F
High emissions (A2): +5 to +11°F[8]
Spatial pattern of warming varies. In the continental U.S., the inland West and upper Midwest are projected to warm more rapidly than the coasts.[7]
</td></tr>
<tr><td>Extremes</td><td>Increasing extreme heat events and decreasing extreme cold events globally and nationally.

Projected change for the U.S. for the 2050s (2041-2070, relative to 1980-2000), under a high emissions scenario (A2):

Increase in number days above 95°F. Greatest increases occur in the southern U.S. and the Midwest.[4]
Decrease in number of days below 10°F. Greatest decreases occur in the interior West, upper Midwest, and Northeast.[4]

</td></tr>
<tr><td>Precipitation</td><td></td></tr>
<tr><td>Global</td><td>Decreases in annual precipitation at mid-latitudes and in the subtropics, increases at high-latitudes and parts of the tropics.</td></tr>
<tr><td>U.S.</td><td>Changes vary by season, location, and time period.

Projected changes for mid-century (2041-2070; relative to 1971-2000) under a high emissions scenario (A2):[4]

Increasing winter precipitation in most of the U.S., including much of the Northwest.
Increasing spring/fall precipitation in most of the U.S., except the Southwest, where decreases are projected.
Decreasing summer precipitation in the Northwest and Southwest, and parts of the Midwest and East.

</td></tr>
</table>

Variable and Region	Projected Long-term Change
Heavy Precipitation	Increasing, but varies by location. ▪ Globally, more frequent and more intense extreme precipitation events expected by the end of this century over most of the mid-latitude land areas and wet tropical regions. ▪ Within the U.S., heavy rainfall events projected to become more frequent. Greatest increases expected in Alaska, the Northeast, and the Northwest.[4]
Snow and Ice	
Glaciers	Continued losses, on average, globally and nationally. Global average projections for 2081-2100, relative to 1986-2005: Very low emissions (RCP 2.6): −15 to −55% decline High emissions (RCP 8.5): −35 to −85% decline[1]
Arctic Sea Ice	Decreasing ▪ Projected decline in total area covered by Arctic sea ice for 2081-2100 relative to 1986-2005 (range from RCP 2.6 to RCP 8.5): February: −8 to −34% September: −43 to −94%[1]
Northern Hemisphere Snow Cover	Decreasing ▪ Projected change in spring (March-April) snow extent for 2081-2100 (relative to 1986-2005) from a very low (RCP 2.6) to a high (RCP 8.5) greenhouse gas scenario: −7 to −25%[1]
Oceans	
Ocean Temperature	Warming ▪ Projected warming greatest near the surface and generally decreasing with depth. Projected change for 2081-2100 relative to 1986-2005: Top 330 ft (RCP 2.6 to RCP 8.5): +1.1 to +3.6°F Top 3,300 ft (RCP 2.6 to RCP 8.5): +0.5 to +1.1°F[1]
Global Sea Level	Rising globally and nationally, on average, although rate and direction of change will vary by location. ▪ Projections of global average sea level:[D] *IPCC (2081-2100 relative to 1986-2005):* Very low emissions (RCP 2.6): +17 in. (range: +11 to +24 in.) High emissions (RCP 8.5): +29 in. (range: +21 to +38 in.) [1] *National Research Council (2100 relative to 2000):* Range from low (B1) to high (A1FI) emissions scenario: +20 to +56 in.[5] ▪ No projected range specific to the U.S. as a whole (projections are for specific regions within the U.S.)

Variable and Region	***Projected Long-term Change***
Ocean Acidification	Global ocean acidity is projected to increase by 2100 for all scenarios (relative to 1986-2005).[1] Low emissions (RCP 4.5): +38 to +41% *(decrease in pH: 0.14-0.15)* High emissions (RCP 8.5): +100 to +109% *(decrease in pH: 0.30-0.32)*

[1] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

[2] (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[3] Solomon, S. et al., 2009. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences*, 106(6), 1704-1709.

[4] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis: Technical Summary*, available at: http://www.ipcc.ch/report/ar5/wg1/#.UluMuxCz4zo

[5] (NRC) National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press, 2012.

[6] Feely, R.A. et al., 2009. Ocean acidification: Present conditions and future changes in a high-CO2 world. *Oceanography* 22(4):36–47, http://dx.doi.org/10.5670/oceanog.2009.95.

[7] Walsh, J., D. Wuebbles, et al. (in press). Our Changing Climate. Chapter 2 in the draft 2014 U.S. National Climate Assessment, http://ncadac.globalchange.gov/.

[8] Kunkel et al. 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. *Climate of the Contiguous United States,* NOAA Technical Report NESDIS 142-9, NOAA National Environmental Satellite, Data, and Information Service, Washington, D.C.

[9] (NCADAC) National Climate Assessment and Development Advisory Committee. 2014. U.S. National Climate Assessment, http://ncadac.globalchange.gov/.

SECTION 5

How is Pacific Northwest Climate Projected to Change?

Continued increases in average annual and seasonal Pacific Northwest temperatures are projected as a result of global warming, as well as increases in extreme heat. Projected changes in annual precipitation are small, although heavy rainfall events are projected to become more severe. Regionally, sea level will continue to rise in concert with global sea level. Locally, sea level is projected to rise in most locations, with the amount of rise varying by location and over time. Natural variability will continue to influence shorter-term (up to several decades) climate trends. New climate change projections are very similar to previous projections when similar greenhouse gas emissions are assumed.

1. **The Pacific Northwest is projected to warm rapidly during the 21st century, relative to 20th century average climate, as a result of greenhouse gases emitted from human activities.[A]** The actual amount of warming that occurs in the Pacific Northwest after about 2050 depends on the amount of greenhouse gases emitted globally in coming decades.[1]

   - *Continued rise in annual average temperature.* Warming is projected to continue throughout the 21st century (Figure 5-1). For the 2050s[B] relative to 1950-1999, temperature is projected to rise +5.8°F (range: +3.1 to +8.5°F) for a high greenhouse gas scenario (RCP8.5).[C][D] Much higher warming is possible after mid-century (Figure 5-1, Table 5-1).[1] Lower emissions of greenhouse gases will result in less warming.

   - *Warming is projected for all seasons.* The warming projected for summer is slightly larger than for other seasons.[1][2]

   - *More extreme heat.* There is strong agreement among climate models that extreme heat events will become more frequent while extreme cold events will become less frequent.[1]

   - *Ongoing variability.* Natural variability will remain an important feature of global and regional climate, at times amplifying or counteracting the long-term trends caused by rising greenhouse gas emissions. Important modes of natural variability for the Pacific Northwest include the El Niño/Southern Oscillation (i.e., El Niño and La Niña) and the Pacific Decadal Oscillation.

   - *The size of projected change is large compared to observed variability.* The Pacific Northwest is likely to regularly experience average annual temperatures by mid-century that exceed what was observed in the 20th century.[E][1]

[A] Many characteristics of Washington's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Washington State are therefore expected to generally align with those provided for the Pacific Northwest, with potential for some variation at any specific location.

[B] Specifically, "2050s" refers to the 30-year average spanning from 2041 to 2070. Note that this section focuses on changes for the 2050s, because this is the only time period for which there are published results for the Pacific Northwest from the 2013 IPCC[2] projections.

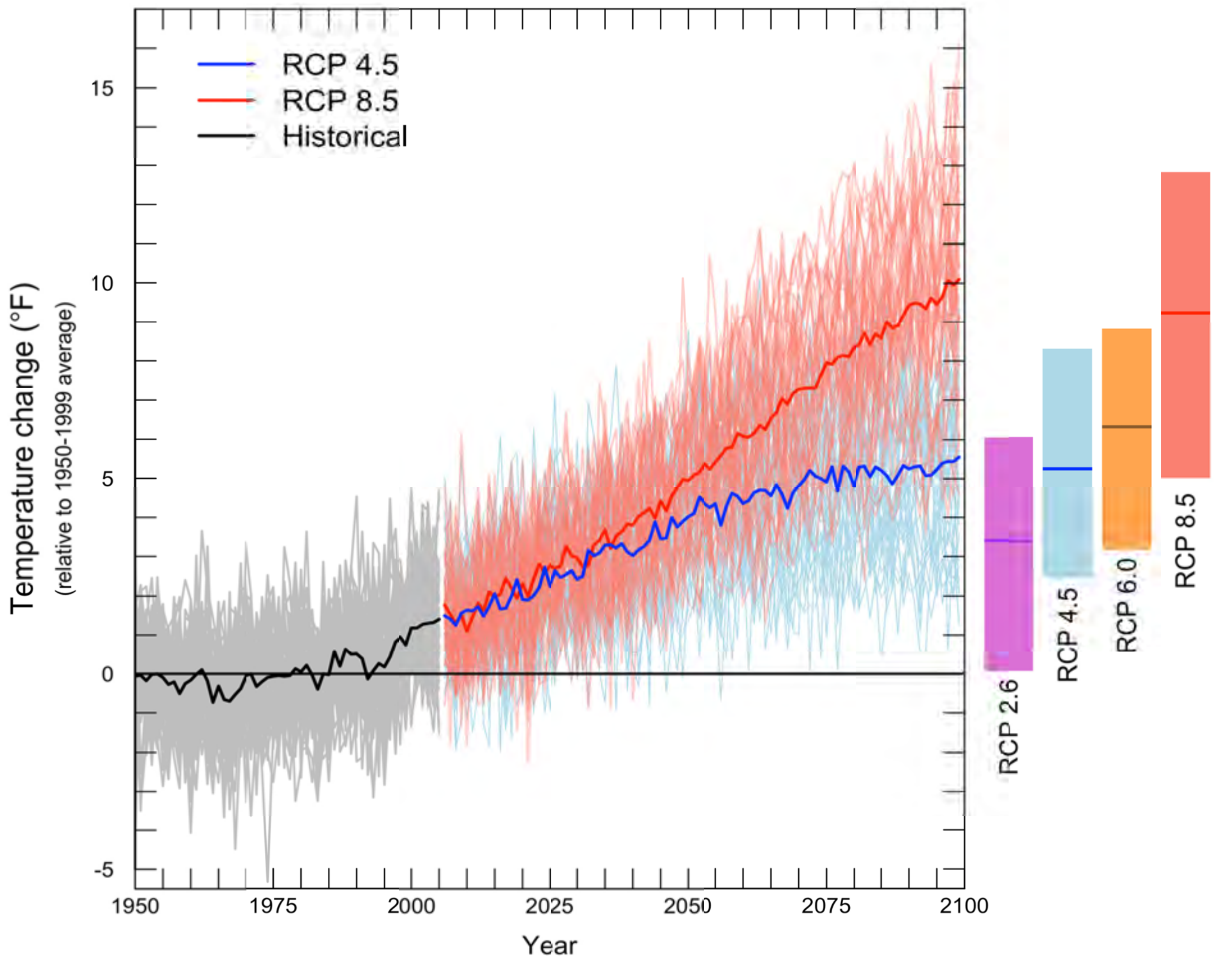

Figure 5-1. All scenarios project warming for the 21st century. The graph shows average yearly temperatures for the Pacific Northwest relative to the average for 1950-1999 (gray horizontal line). The black line shows the average simulated temperature for 1950–2011, while the grey lines show individual model results for the same time period. Thin colored lines show individual model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5 – see Section 3 for details), and thick colored lines show the average among models projections for each scenario. Bars to the right of the plot show the mean, minimum, and maximum change projected for each of the four emissions scenarios for 2081-2100, ranging from a very low (RCP 2.6) to a high (RCP 8.5) scenario. Note that the bars are lower than the endpoints from the graph, because they represent the average for the final two decades of the century, rather than the final value at 2100. *Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.*[2]

C Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for details.

D Scenarios used in this report range from a low (RCP 4.5) to a high (RCP 8.5) greenhouse gas scenario (both of which are used in the recent IPCC report,[2] see Section 3). The implications of the lowest greenhouse gas scenario – RCP 2.6, which assumes aggressive reductions in emissions – are not discussed in the text of this section

2. Changes in annual and seasonal precipitation will continue to be primarily driven by year-to-year variations rather than long-term trends, but heavy rainfall events are projected to become more severe.

- *Small changes in annual precipitation.* Projected changes in total annual precipitation are small (relative to variability)[F] and show increases or decreases depending on models, which project a change of −4% to +14% for the 2050s[D] (relative to 1950-1999).[1]

- *Seasonal changes in precipitation are mixed.* Most models project drier summers, with an average model projection of −6% to −8% for the 2050s for a low and a high greenhouse gas scenario, respectively (2041-2070, relative to 1950-1999).[D][G][2] Some individual model projections show as much as a −30% decrease in summer precipitation. A majority of models project increases in winter, spring, and fall precipitation for this same time period, ranging from +2 to +7%, on average.[1]

- *Increasing precipitation extremes.* Heavy rainfall events are projected to become more severe by mid-century. Specifically, the number of days with more than 1 inch of rain is projected to increase by +13% (±7%) for the 2050s (relative to 1971-2000) for a high greenhouse gas scenario.[H][3]

- *Size of projected change is smaller than observed variability.* Projected changes in annual and seasonal precipitation are generally small – throughout the 21st century – compared to the range of precipitation caused by natural variability. In addition, projected changes are not consistent for all scenarios: some models project increases while others project decreases.[1]

3. Washington's coast will be affected by sea level rise, warmer ocean temperatures, and changing ocean chemistry.

- *Coastal areas in Washington will experience sea level rise, although some areas may continue to experience decreases due to trends in vertical land movement.* According to a recent report by the National Research Council, sea level is projected to rise an additional +4 to +56 inches in Washington by 2100 (relative to 2000).[4] Locally, however, sea level will increase by different amounts in different places. Previous research projects a decline

because there are no published projections for the Pacific Northwest based on this scenario. In order to illustrate the full range of projections, Figures 5-1 and 5-2 nonetheless show results from the very low (RCP 2.6) greenhouse gas scenario, among other scenarios ranging up to the highest (RCP 8.5) scenario.

E Specifically, all scenarios project that, by mid-century (2041-2070), annual temperatures will be warmer than the warmest year historically (1950-1999).

F Year-to-year variations in precipitation are about ±10 to 15%, on average.

G The RCP 4.5 (low) and RCP 8.5 (high) greenhouse gas scenarios (see Section 3 for more details).

H Projection based on regional climate model simulations, from the North American Regional Climate Change Program (NARCCAP) multi-model ensemble (http://www.narccap.ucar.edu). These simulations are based on results from 6 different regional models driven by 4 different global model projections, all based on the A2 greenhouse gas scenario, which is slightly lower than the RCP 8.5 scenario used in IPCC 2013. Values denote the average and the standard deviation among model projections. Results are averaged over a large area and may not be applicable to a given locale in Washington State.

in sea level for the northwest Olympic Peninsula through 2100, for scenarios that assume very low rates of global sea level rise and high rates of vertical uplift.[5][6] These projections differ from the NRC projections due to different study approaches. Although most global projections would result in sea level rise for the northwest Olympic Peninsula, it is not yet possible to conclusively rule out a decline in sea level for that region.

- *Short-term sea level variations can temporarily offset or accelerate trends.* Sea level can be temporarily elevated or depressed by up to a foot in winter as a result of natural periodic cycles in climate patterns such as El Niño and the Pacific Decadal Oscillation.[4] This variability will continue in the future.

- *Coastal ocean temperatures are projected to increase.* Ocean surface temperatures offshore of Washington are projected to rise by about +2°F by the 2040s (2030-2059, relative to 1970-1999) for a medium greenhouse gas scenario.[I][7] Projected changes in winter sea surface temperatures in the North Pacific are expected to be as large as the range of natural variability by 2030-2050 (relative to 1950-1999) under a medium greenhouse gas scenario.[J][8] However, coastal ocean temperatures are strongly affected by coastal upwelling of colder water from ocean depths, and by large scale climate variability such as El Niño – current research is unclear as to how these might be altered by climate change.

- *Acidification of Washington's marine waters is projected to continue.* The acidity of Washington's coastal waters is projected to increase due to increases in global ocean acidity (+38 to +109%[K] by 2100 relative to 1986-2005,[2] or roughly +150 to +200% relative to pre-industrial levels)[9]. Local conditions are also affected by seasonal upwelling of deeper Pacific Ocean water that is low in pH and high in nutrients, transport of nutrients and organic carbon from land, and oceanic absorption of other acidifying atmospheric gases.

4. The new climate projections[1] are very similar to the climate projections from 2007[7] when similar rates of greenhouse gas emissions are assumed.

- *Projected Pacific Northwest climate change is similar for new (IPCC 2013)[2] and old (IPCC 2007)[10] scenarios of medium and low greenhouse gas emissions.*[C] The Washington Climate Change Impacts Assessment (WACCIA)[11] and many regional climate impact studies largely used the A1B and B1 greenhouse gas scenarios. These are comparable to RCP 6.0 and RCP 4.5, respectively, at the end of the century, in terms of both greenhouse gas concentrations (see Section 3) and resultant changes in NW climate (Figure 5-2).

I The A1B greenhouse gas scenario. See Section 3 for more details about scenarios.

J Based on analyses of 10 global climate models and the A1B greenhouse gas scenario.

K Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Global ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines a liquid's acidity) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

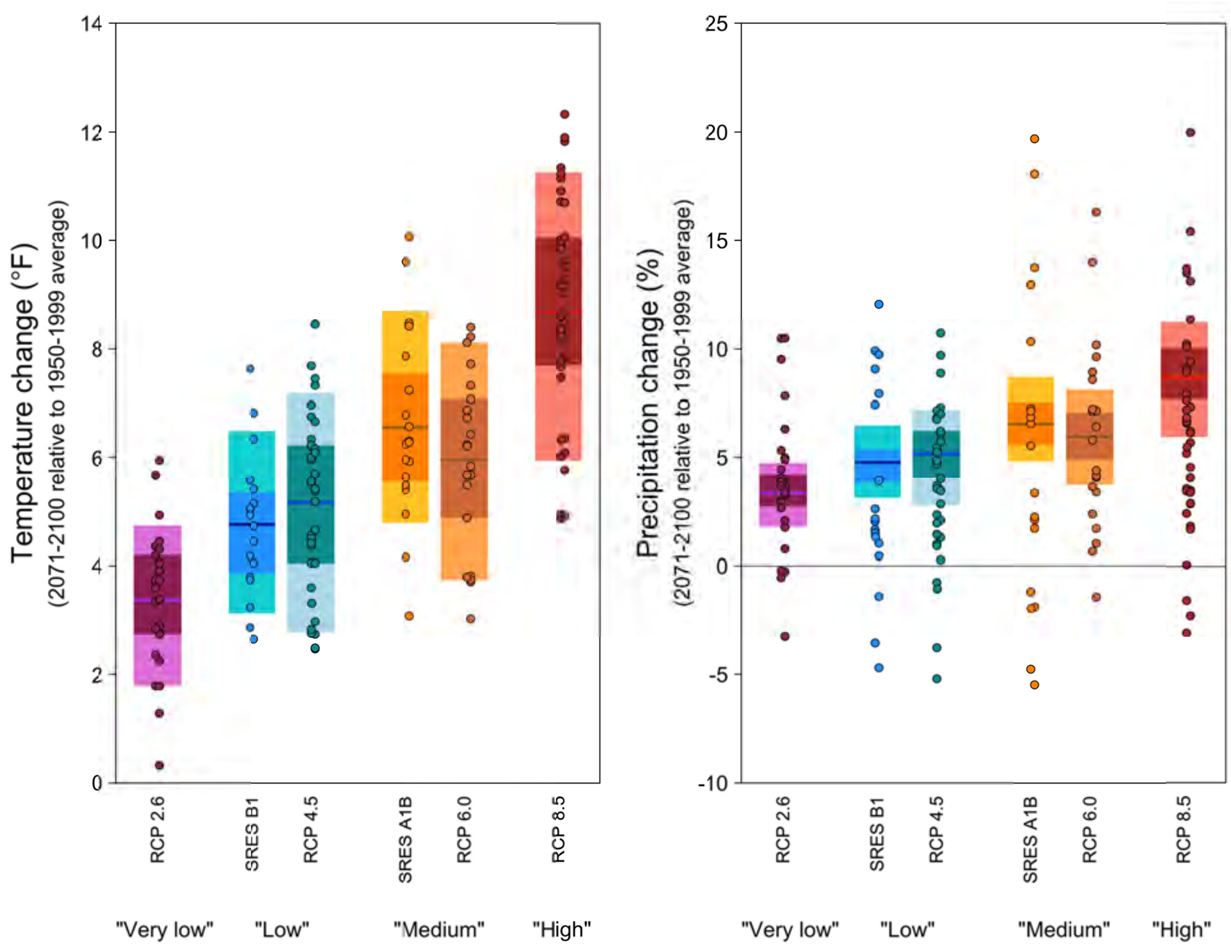

Figure 5-2. Differences among climate change projections for the Pacific Northwest are primarily due to differences among greenhouse gas scenarios. Projected changes in average annual temperature (left) and precipitation (right) for the Pacific Northwest for the 2080s (2071-2100, relative to 1950-1999). Projections are shown for all four new scenarios: RCP 2.6 ("very low"), 4.5 ("low"), 6.0 ("medium"), and 8.5 ("high"), along with the older projections based on the B1 ("low") and A1B ("medium") scenarios used in many Pacific Northwest impacts assessments. Individual climate model projections for each scenario are shown using colored dots. Boxes show the average projected change (in °F for temperature and percent change for precipitation), along with the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile values among all climate model projections. The black horizontal line on the precipitation graph denotes zero change. *Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.[2] and figures 2.5b and 2.6 of Mote et al., 2013.[1]*

- *Newer scenarios for very low and high greenhouse gas emissions result in a wider range among late-century warming projections for the Pacific Northwest.* Previous regional assessments have typically considered a narrower range of greenhouse gas scenarios.
    - The new scenarios include an aggressive mitigation scenario (RCP 2.6), which would require about a 50% reduction in global emissions by 2050 relative to 1990 levels and near or below zero net emissions in the final decades of the 21st century. The older projections do not include a comparable scenario.
    - The highest scenarios commonly used in previous climate impacts assessments (A1B, A2) are much lower than the high-end scenario in the new projections (RCP 8.5).
- *The importance of differences between the old and new climate change projections will depend on the specific impact under consideration and the sensitivity of the decision being made.* For example, projected changes in annual average precipitation are likely to differ by less than 1°F under similar greenhouse gas scenarios from IPCC 2007 and 2013, while projected changes in annual average precipitation are likely to differ by only a few percentage points (Figure 5-2). Other differences between the scenarios have not yet been explored.

For more details on projected changes in Pacific Northwest climate, see Table 5-1 at the end of this section. See next page for additional resources for evaluating regional climate change projections.

Additional Resources for Evaluating Regional Climate Change Projections

The following resources provide location-specific information about climate change impacts to support identification and reduction of risks associated with a changing climate. Some resources are designed so that any user can easily browse, view, and download products; others assume more technical knowledge.

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. These are based on projections in IPCC 2007.[10] http://warm.atmos.washington.edu/2860,[11] http://cses.washington.edu/cig/.

- **Climate scenarios for the Western U.S.** This dataset provides future projections of daily temperature, precipitation, humidity, insolation and wind at a spatial resolution of about 2.5 miles, using new statistical downscaling methods and the new climate projections included in IPCC 2013.[2][11] http://nimbus.cos.uidaho.edu/MACA/

- **Fine scale climate scenarios for the lower 48 states.** Produced by NASA, this dataset provides future projections of monthly temperature and precipitation at a spatial resolution of about half a mile, using updated statistical downscaling methods and the new climate projections included in IPCC 2013.[2][13] https://portal.nccs.nasa.gov/portal_home/published/NEX.html

- **Regional climate model projections for the Pacific Northwest.** Dynamically downscaled data are being developed at the Climate Impacts Group based on projections from both IPCC 2007[10] and 2013.[2] The data are produced using regional climate model simulations over the state of Washington and surrounding region, at a spatial resolution of about 9 miles. Among other advantages, these data are more accurate for projecting changes in extremes.[14][15]

- **Regional climate model projections for the Western U.S.** This dataset includes a large ensemble of regional climate model projections, based on a high greenhouse gas scenario (A2). Simulations are archived for numerous different regional and global climate models, all at a spatial resolution of about 30 miles. These are based on projections in IPCC 2007. [10] http://narccap.ucar.edu/

Table 5-1. Projected changes in the climate of Washington and the Pacific Northwest.

Variable	***Projected Long-term Change***
Temperature	
Annual	Warming ▪ Warming projected for *all* greenhouse gas scenarios; amount of warming depends on the amount of greenhouse gases emitted. ▪ Projected change in Pacific Northwest[A] average annual temperature for the 2050s (2041-2070),[B] relative to the average for 1950-1999: Low emissions (RCP 4.5): +4.3°F (range: 2.0 to 6.7°F) High emissions (RCP 8.5): +5.8°F (range 3.1 to 8.5°F)[D][1]
Seasonal	Warming in all seasons for 2041-2070, relative to 1950-1999: *Winter* Low emissions (RCP 4.5): +4.5°F (range: 1.6 to 7.2°F) High emissions (RCP 8.5): +5.8°F (range 2.3 to 9.2°F) *Spring* Low emissions (RCP 4.5): +4.3°F (range: 0.9 to 7.4°F) High emissions (RCP 8.5): +5.4°F (range 1.8 to 8.3°F) *Summer* Low emissions (RCP 4.5): +4.7°F (range: 2.3 to 7.4°F) High emissions (RCP 8.5): +6.5°F (range 3.4 to 9.4°F) *Fall* Low emissions (RCP 4.5): +4.0°F (range: 1.4 to 5.8°F) High emissions (RCP 8.5): +5.6°F (range 2.9 to 8.3°F)[1]
Geography of Change	Overall, warming is expected to be fairly uniform across Washington State. However, there is slightly greater warming projected for the interior – east of the Cascade range.[1]
Extremes	More frequent extreme heat events and less frequent extreme cold events ▪ Projected changes in Pacific Northwest annual temperature extremes for 2041-2070, relative to 1971-2000, for a high greenhouse gas scenario:[L][3] Length of freeze-free period: +35 days (± 6 days) Number of days above 90°F: +8 days (± 7 days) Number of nights below 10°F: −8 days (± 5 days) Heating degree days: −15% (± 2%)[M] Cooling degree days: +105% (± 98%) Growing degree days (base 50°F): +51% (± 14%)

L Projection based on regional climate model simulations under a high greenhouse gas scenario (A2).[H]

M Cooling and heating degree days are measurements used in energy markets to estimate demand. In the United States, a cooling degree day is counted for each degree the average temperature for a day moves above 75°F. For example, if the average temperature for the day was 80°F, that would count as 5 cooling degree days. One heating degree day is counted for each degree that average daily temperature falls below 65°F.

Variable	*Projected Long-term Change*
Precipitation	
Annual	Small changes ▪ Annual changes for all models are small relative to year-to-year variability. ▪ For all greenhouse gas scenarios, some models project wetter conditions while others project drier conditions. ▪ Projected change in annual Pacific Northwest precipitation for the 2050s (2041-2070,[B] relative to 1950-1999): Low emissions (RCP 4.5): −4.3 to +10.1% High emissions (RCP 8.5): −4.7 to +13.5%[D][1]
Seasonal	Projected changes vary seasonally. ▪ A majority of models project increases in winter, spring, and fall precipitation for the Pacific Northwest for mid-century, as well as decreasing summer precipitation. ▪ For all scenarios and seasons, some models project wetter conditions while others project drier conditions. ▪ Projected summer drying is more consistent among models. Some models project more than a 30% decrease in summer precipitation for the 2050s (2041-2070, relative to 1950-1999), although the average projected change for summer is notably smaller: −6 to −8% for a low (RCP 4.5) and high (RCP 8.5) greenhouse gas scenario, respectively.[1]
Geography of Change	Changes in precipitation are expected to be different from place to place.
Heavy Precipitation	Increasing ▪ Heavy rainfall events are expected to occur more frequently. ▪ Projected changes in Pacific Northwest precipitation extremes for 2041-2070, (relative to 1971-2000) for a high greenhouse gas scenario:[H][3] Number of days with rain > 1 inch: +13% (±7%) Number of days with rain > 3 inches: +22% (±22%)
Oceans	
Ocean Temperature	Warming ▪ Ocean surface temperatures off the coast of Washington[N] are projected to warm by +2.2°F by the 2040s (2030-2059, relative to 1970-1999).[4] ▪ Projections of coastal ocean temperatures are unclear due to limited understanding of changes in coastal upwelling and the large influence of natural variability.
Sea Level Change	Rising in general, although considerable variations from location to location due to different rates of subsidence or uplift of land areas. ▪ Regionally, sea level is projected to rise substantially under all

[N] Projected change in sea surface temperature for model grid points near the coast between 46° and 49°N.

Variable	Projected Long-term Change
	greenhouse gas scenarios. Locally, however, sea level can rise or fall relative to land due to vertical uplift of land surfaces, primarily as a consequence of the high tectonic activity of the Pacific Northwest. ▪ Projected sea level rise (for 2100 relative to 2000): Seattle, WA: +4 to +56 inches Newport, OR: +5 to +56 inches[O][4]
Ocean Acidification	Increasing acidity ▪ Regionally, coastal ocean acidity is projected to increase in tandem with global ocean acidification (see Section 4).[2]

[1] Mote, P. W. et al., 2013. Climate: Variability and Change in the Past and the Future. Chapter 2, 25-40, in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

[2] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

[3] Kunkel, K. E. et al., 2013: *Part 6. Climate of the Northwest U.S.*, NOAA Technical Report NESDIS 142-6.

[4] National Research Council. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press, 2012.

[5] Mote, P.W. et al. 2008. *Sea Level Rise in the Coastal Waters of Washington State*. Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, and the Washington Department of Ecology, Lacey, WA.

[6] Reeder, W. S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities, Washington D.C.: Island Press.

[7] Mote, P. W., and E.P. Salathé. 2010. Future climate in the Pacific Northwest*.* *Climatic Change* 102(1-2): 29-50, doi: 10.1007/s10584-010-9848-z.

[8] Overland, J. E., and M. Wang. 2007. Future climate of the North Pacific Ocean. *Eos*, *Transactions American Geophysical Union*, 88, 178, 182. doi: 10.1029/2007EO160003, 178, 182.

[9] Feely, R. A. et al., 2009. Ocean acidification: Present conditions and future changes in a high-CO_2 world. *Oceanography* 22(4):36–47, doi:10.5670/oceanog.2009.95.

[10] (IPCC) Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[11] Climate Impacts Group, 2009. *The Washington Climate Change Impacts Assessment*, M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington.

[12] Abatzoglou, J. T. and T. J. Brown T.J., 2011. A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology* 32(5), 772-780. doi:10.1002/joc.2313

[13] Thrasher, B. et al., 2013. Downscaled Climate Projections Suitable for Resource Management. *Eos Transactions, American Geophysical Union*, *94*(37), 321-323.

[14] Salathe Jr, E. P. et al., 2010. Regional climate model projections for the State of Washington. *Climatic Change*, *102*(1-2), 51-75.

[15] Salathé Jr, E. P. et al., 2013: *Estimates of 21st century flood risk in the Pacific Northwest based on regional climate model simulations.* Water Resources Research (in review).

O Range includes uncertainty in the estimated rate of melt for glaciers and ice sheets, vertical land motion, and greenhouse gas scenarios, spanning from the B1 (low emissions, similar to RCP 4.5) to the A1FI (high emissions, similar to RCP 8.5) greenhouse gas scenarios.

SECTION 6

How Will Climate Change Affect Water in Washington?

Washington is projected to experience decreases in snowpack, increases in stream temperatures, and widespread changes in streamflow timing, flooding, and summer minimum flows. Annual streamflow volumes are not projected to change substantially. Climate change is projected to result in more frequent summer water shortages in some basins, while others remain unaffected – vulnerability is likely greatest in fully allocated watersheds with little management flexibility. Recent research has largely confirmed previous research, but has contributed increased understanding of the local- and water-use specific implications of climate change. New datasets provide a comprehensive set of projections that can support long-range planning.

1. **As is the case for much of the western U.S., Washington is projected to experience decreasing snowpack, a shifting balance between snow and rain, increasing stream temperatures, and changes in streamflow timing, flooding, and summer minimum flows.** The largest changes are projected for mid-elevation basins with significant snow accumulation (today's so-called "mixed rain and snow" watersheds; Figures 6-1 and 6-2, Table 6-1).[A][1]

   Drivers of change: Temperature and precipitation

   - *All scenarios project continued warming* during this century, and most scenarios project that this warming will be outside of the range of historical variations by mid-century (Section 3 of this report). As a consequence, there is high confidence in the warming-related changes in water resources.

   - *Projected changes in precipitation are mixed.* Changes in precipitation are less clear, and are generally projected to be smaller than natural year-to-year variability. As a result, there is much lower confidence in the precipitation-dependent changes in water resources.

   Natural water storage

   - *Declining snowpack.* Average spring snowpack in Washington is projected to decline by −56 to −70% by the 2080s (2070-2099, relative to 1916-2006).[B][C][D][2]

[A] Watersheds are classified based on the proportion of precipitation that falls as snow versus rain during winter (October-March). "Rain dominant" basins (i.e., watersheds with warm winter temperatures), receive less than 10% of winter precipitation as snow. In contrast, colder watersheds are classified as "snow dominant" if they receive more than 40% of winter precipitation as snow. "Mixed rain and snow" basins are middle elevation basins, near the current snowline, that receive between 10 and 40% of winter precipitation as snow. These different basin types will experience different impacts of climate change. Washington watershed classifications are shown in Figure 6-1.

[B] These numbers indicate changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Northwest.

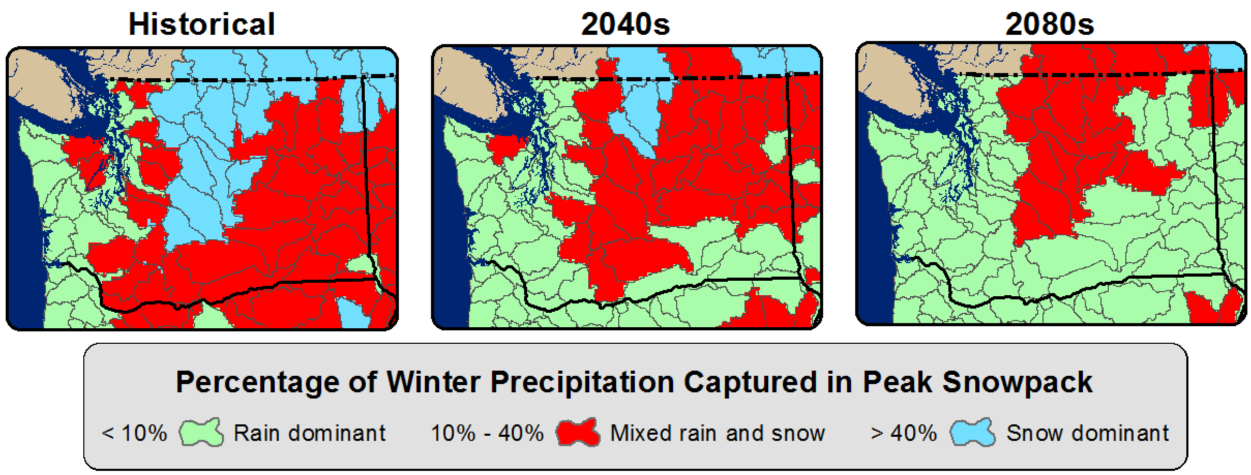

Figure 6-1. Changing hydrology with warming. Maps above indicate current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Graphs below indicate current and future average monthly streamflow for these watershed types. Both compare average historical conditions (1916-2006) and projected future conditions for two time periods, the 2040s (2030-2059) and the 2080s (2070-2099), under a medium greenhouse gas scenario (A1B). Green shading in the maps indicates *warm ("rain-dominant") watersheds*, which receive little winter precipitation in the form of snow. In these basins, streamflow peaks during during winter months and warming is projected to have little effect (below, left). Blue indicates *cold ("snow-dominant") watersheds,* that is, cold basins that receive more than 40% of their winter precipitation as snow. Depending on elevation, these basins are likely to experience increasing winter precipitation as rain and increased winter flows (below, right). The most sensitive basins to warming are the *watersheds that are near the current snowline ("mixed rain and snow")*, shown in red. These are middle elevation basins that receive a mixture of rain and snow in the winter, and are projected to experience significant increases in winter flows and decreases in spring flows as a result of warming (below, center). *Source: Hamlet et al., 2013.*[3]

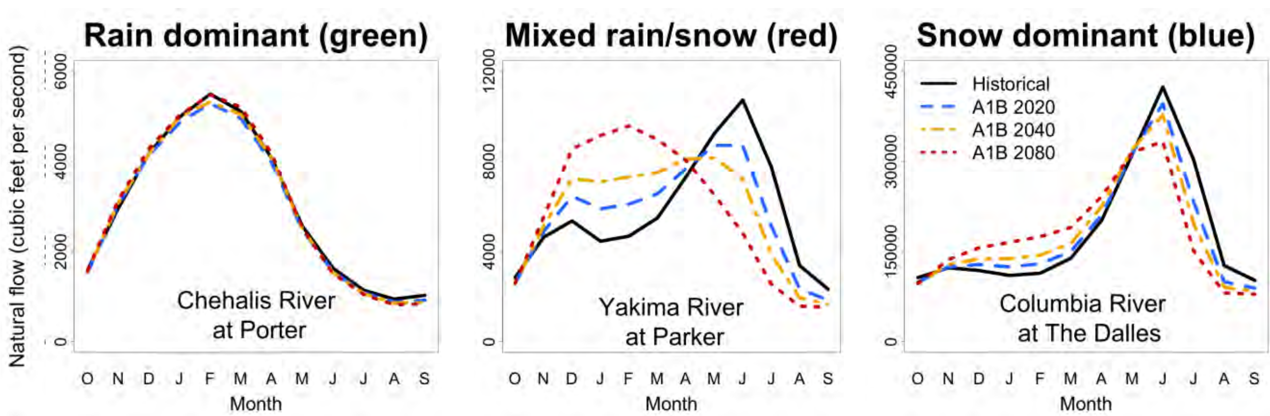

Figure 6-2. Changes in the seasonality of streamflow for three example watersheds in the Pacific Northwest: The Chehalis River, a warm basin (left); the Columbia River, a cold basin with source waters at high elevations (right) and the Yakima River, a middle-elevation basin near the current snowline (middle). *Source: Elsner et al., 2010.*[2]

- *Shrinking glaciers.* There are no published projections of Northwest glacier response to climate change, although most Northwest glaciers are in decline (Section 2) and one study found that only 2 of the 12 North Cascades glaciers with annual measurements are expected to survive the current climate.[4] In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.[5]

Watershed type and streamflow conditions

- *Changing watershed type*. The dominant form of precipitation in most Washington watersheds will be rainfall by the end of the 21st century (Figure 6-1). In contrast, many have historically been strongly influenced by snowfall in winter. The one exception is the North Cascades, where snow accumulation is projected to remain important through 2100.

- *Earlier streamflow timing.* The spring peak in streamflow is projected to occur earlier in mixed-rain and snow and snow dominant basins (see red and blue shading in Figure 6-1). For instance, peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1917-2006) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt) and the Yakima basin (Figure 6-2).[D][2]

- *Small increase in annual streamflow.* Annual streamflow is projected to increase by +4.0 to +6.2% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999). These changes are likely to be dwarfed by natural year-to-year variations in streamflow totals through the end of the century.[D][2]

- *Increasing winter streamflow*. Winter streamflow is projected to increase by +25 to +34% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999).[D][2]

- *Declining summer streamflow*. Summer streamflow is projected to decrease by −34 to −44% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999).[D][2]

- *Increasing stream temperatures.* Stream temperatures are projected to increase in response to warming and decreases in summer streamflow. Projections for 124 stream temperature locations across the state find that more sites will experience temperatures that elevate stress for adult salmon.[6] Many will exceed thermal tolerances for the entire summer season by 2080 (2070-2099), despite rarely being in excess of these temperatures in the recent past.[7]

[C] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

[D] Average projected change for ten global climate models, averaged over Washington State. Range spans from a low (B1) to a medium (A1B) greenhouse gas scenario.

Streamflow extremes

- *Flooding*
  - *Projected changes range from modest decreases to large increases in extreme river flows depending on location and watershed type.* The highest river flows are generally expected to increase in rain-dominant and in mixed rain and snow watersheds. Some snow dominant watersheds will see flood increases, while others experience decreases. Projections for specific Washington locations can be found here: http://warm.atmos.washington.edu/2860/products/sites/.
  - *Increases in heavy rainfall events could further increase flood risk.* Heavy rainfall events are projected to become more severe by mid-century (Section 3 of this report). On average in the Northwest, the number of days with more than 1 inch of rain is projected to increase by +13% (±7%) for the 2050s relative to 1971-2000.[8] Preliminary results suggest an increase in the number of heavy rain events occurring in early fall.[9] These changes may result in more severe flooding in rain dominant and mixed rain and snow basins.
  - *Changes in flood management may not be sufficient to mitigate increases in flood risk.* In the upper Skagit basin, for instance, with current flood management practices, the 100-year flood is projected to increase by 24% by the 2080s (2070-2099, relative to 1916-2006)[E]; simulations indicate that changes in water management can only mitigate 7% of this projected increase.[10]
  - *Sea level rise will exacerbate coastal river flooding*. Higher sea level can increase the extent and depth of flooding by making it harder for flood waters in rivers and streams to drain to the ocean or Puget Sound. Initial research on this issue suggests that the amount of area flooded in the Skagit would increase by up to 74% by the 2080s when accounting for the combined effects of sea level rise and larger floods.[11]
- *Minimum flows.* Low summer streamflow conditions are projected to become more severe in about 80% of watersheds across Washington State. Rain dominant and mixed rain and snow basins show the greatest and most consistent decreases in minimum flows, while changes for snow dominant basins are smaller. Changes are more pronounced west of the Cascade mountains because there is "less water to lose" east of the Cascades – historical conditions are already very arid in interior Washington.[F][12]

2. **Year-to-year variability will continue to cause some periods that are abnormally wet, and others that are abnormally dry.** For the foreseeable future, Washington will continue to experience years and decades with conditions that temporarily mask or amplify the projected changes in water resources (Figure 6-3), even as long-term trends continue.

[E] Projected change based on the ECHAM5 global climate model and the A1B greenhouse gas scenario.
[F] Results for a low (B1) and medium (A1B) greenhouse gas scenario for 112 medium-sized watersheds in Washington.

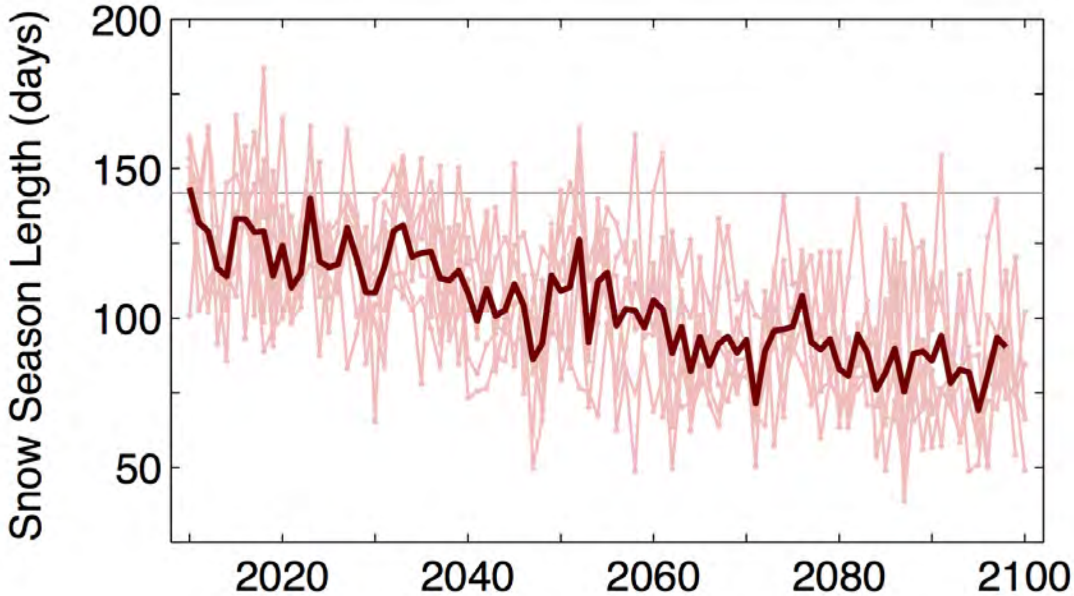

Figure 6-3. Shorter snow season with warming; large year-to-year variability. Projected length of the snow season, in days, for middle elevations (4,000 to 5,000 ft) for the Cascade mountains in Oregon and Washington. The plot shows projected snow season length from seven individual climate models (thin pink lines) and the average among all models (thick red line) for a medium greenhouse gas scenario (A1B). For comparison, the average snow season length for 1950-1999 was 142 days (shown as the gray horizontal line). Although the length of the snow season is clearly expected to decrease significantly over this century, individual years with substantially longer or shorter snow seasons than the general declining trend are also expected to occur. *Data source: Hamlet et al. 2013*[B]

3. **These changes will have far-reaching consequences for people, infrastructure and ecosystems across the state.** Climate change impacts on water resources will pose increasing challenges in the decades ahead. The examples below indicate the potential sector-specific consequences of climate change in the absence of management adjustments to reduce impacts. Although not included in these projections, changes in water management to alleviate impacts on one sector – i.e., hydropower production, irrigation or municipal supply, or instream flows for fish – could exacerbate impacts on other sectors.[13]

   - *Irrigation water supply.* In the Yakima basin, warming is projected to increase the frequency of water shortage years – i.e., years in which water delivery is curtailed due to insufficient streamflow – from 14% of years historically (1940-2005) to 43-68% of years by the 2080s (2070-2099).[D][14]

   - *Hydropower production.* In response to increases in winter and decreases in summer streamflow, hydropower production in the Columbia River basin is projected to increase by +7 to +10% in winter and decrease by −18 to −21% in summer by the 2080s (2070-2099, relative to 1917-2006).[D][15] Regional power planners have expressed concerns over the existing hydroelectric system's potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints.[16][17]

- *Fish and aquatic ecosystems.* Warming streams, declining summer flows, and increasing flood risk are all expected to negatively affect coldwater fish populations such as salmon[18] and trout.[19] Trout populations in the western US are projected to experience a decline of −33 to −77% in suitable habitat area by the 2080s (2070-2099, relative to 1985-2004) under a high greenhouse gas scenario.[G][19] Warming streams are projected to negatively affect salmon health, migration, and survival (see above).

- *Flood protection and stormwater management.* Increases in flooding can increase the cost of protecting and maintaining infrastructure, affect water quality via increasing sediment and nutrient loads, and result in increased landslide risk (Section 10).[20]

- *Municipal water supply.* Assuming no change in demand, new sources of supply or significant changes in operating procedures, water supply for Everett is projected to remain near 100% reliability (no water shortages) through the 2080s (2070-2099, relative to 1917-2006) and decrease to 63-96% for Tacoma under low and medium greenhouse gas scenarios.[H][21] Climate change is also projected to increase demand.[22][23] For Seattle, supply is projected to exceed demand in nearly all years, and the City has identified no or low-cost system modifications to mitigate climate change-related supply reductions, keeping supply above demand under all climate change scenarios examined.[I][22]

- *Shortened ski season.* Historically (1971-2000), Washington ski areas have experienced warm winters (average December-February temperature above freezing) anywhere from 0 to 33% of the time, depending on location. In response to a warming of +3.6°F – the lower end of the range projected for mid-century (Section 3) – warm winters would occur 33 to 77% of the time.[J][26]

- *Small increase in irrigation demand projected for eastern Washington*. Forecasted eastern Washington water demand in the 2030s (2020-2049, relative to 1977-2006) indicates a small increase in demand for irrigation (+4% assuming historical cropping patterns, for a mid-range future climate scenario.[K][27]

- *Small increases in municipal demand projected for the greater Seattle area*. Municipal demand in Seattle is projected to increase by 1% in 2025, 2% in 2050, and 5% in 2075

[G] Change in the length of stream habitat that is suitable to one of the following four trout species: cutthroat (*Oncorhynchus clarkia)*, brook (*Salvelinus fontinalis)*, brown (*Salmo trutta)*, and rainbow (*Oncorhynchus mykiss)*.

[H] Average water supply reliability projected by ten global climate models. Range stems from a combination of variations among two different reservoirs supplying water to Tacoma, as well as a low (B1) and medium (A1B) greenhouse gas scenario.

[I] These results are based on a simplified analysis using projections from IPCC 2007.[25] Seattle Public Utilities is currently updating their assessment using 40 new projections from the 2013 IPCC report.[24]

[J] The ski areas evaluated for Washington State were: Bluewood, Mt. Spokane, Mt. Baker, Crystal Mountain, Mission Ridge, White Pass, the Summit at Snoqualmie, Stevens Pass, and Hurricane Ridge.

[K] Projected change is based on a low greenhouse gas scenario (B1) obtained using the HADCM global climate model, which was found to be near the middle of the range among projections for 2030. This projection does not include potential changes in the crop mix in response to climate change, which would likely reduce the impacts on water supply.

(relative to 2000), assuming current population forecasts and no new conservation measures, based on a high greenhouse gas scenario.[L][22]

- *Greatest vulnerability in highly allocated basins with little management flexibility*. Vulnerability to projected changes in snowmelt timing is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated mixed rain and snow watersheds with existing conflicts among users of summer water. In contrast, vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins), where institutional arrangements are simple, and current natural and human demands rarely exceed current water availability.[H][28][29][30][31]

4. **Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change on water resources.** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

River flooding

- *Preparing King County infrastructure for projected flooding increases:*
    - *Levee improvements and relocation of at-risk structures.* King County formed a new Flood Control District in 2007 to increase capacity for addressing regional flood risks due to climate change and other factors, increasing local funding for flood risk reduction efforts ten-fold.[32]
    - *Widening bridge spans.* King County has replaced 15 short span bridges with wider span structures (including the Tolt Bridge over the Snoqualmie River) and 42 small culverts with large box culverts. These changes will increase resilience to major flooding.[M]
- *Addressing extreme flood risk to Interstate-5 in Skagit County.* A federally funded pilot project will support development of a series of site-specific adaptation options to improve the resilience of Interstate 5 and state routes in the Skagit basin. These will complement flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

Drinking water supply

- *Ensuring supply exceeds demand for Seattle.* Seattle has undertaken numerous evaluations of climate change impacts and potential response options, including identifying no or low-cost system modifications to mitigate climate change-related supply reductions and demand increases. The City's analysis indicates that no new source of water supply is needed before 2060 and that, under the warmest scenario considered,

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[L] Projection based on the IPSL global climate model coupled with a high greenhouse gas scenario (A2).
[M] Presentation by Matt Kuharic, Senior Climate Change Specialist, King County Department of Natural Resources and Parks to the Washington State Climate Change Impacts Steering Committee, April 27, 2010.

available supply would exceed forecasted demand if all modifications are implemented. Depending on the relative timing of system modifications and climate change impacts, climate change could increase the frequency of requests to customers to curtail water use.[22]

- *Redesigning the Anacortes Water Treatment Plant.* Climate change projections for increased flooding and sediment loading in the Skagit River led to design changes for the City of Anacortes' new $65 million water treatment plant (under construction in 2013). The altered design includes elevated structures, water-tight construction with minimal structural penetrations and no electrical control equipment below the current 100-year flood elevation, and more effective sediment removal processes.[33][34]

Long-range water planning

- *The Yakima basin long-term water management plan.* Development of the Yakima River Basin Integrated Water Resource Management Plan included an evaluation of the likely efficacy of a suite of water management strategies and storage options under various climate change scenarios. While the Integrated Plan improves basin water supply conditions for all scenarios considered, specific outcomes will be very different under different climate conditions. Under the "moderately adverse" climate change scenario[N] and demand growth, supplies for proratable irrigation districts would be 61% in a severe one-year drought with the Integrated Plan, as opposed to 27% without (compared to 37% during the one-year drought in 2005).[35]

- *Long-range water resources planning in the Columbia Basin.* The U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Bonneville Power Administration collaborated on an assessment of climate change impacts on Columbia River Basin hydrology and water management to support decisions on the Columbia River Treaty and future biological opinions. The three federal agencies are integrating new climate change data derived from this work into their ongoing modeling and planning efforts.[36]

For more details on projected impacts on Water Resources, see Table 6-1.

[N] Corresponds to the low end of the range projected for mid-century (Section 3).

Additional Resources for Evaluating Hydrologic Impacts
The following resources provide location-specific information about climate change impacts to support identification and reduction of risks associated with a changing climate.

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. http://warm.atmos.washington.edu/2860,[3] http://cses.washington.edu/cig/

- **Water supply and demand forecast.** The *Columbia River Basin long-term water supply and demand forecast*[K] provides historical data and projected changes in water supply and agricultural demand as a result of climate change. Other demand forecasts (municipal, hydropower, and instream flows) do not incorporate climate change. Results are available for each individual Water Resource Inventory Area (WRIA) in eastern Washington and the Columbia River basin as a whole. http://www.ecy.wa.gov/programs/wr/cwp/forecast/forecast.html

Table 6-1. Projected changes in water resources.

Variable	*Projected Long-term Change*
Snow	
Snowpack	Declines ▪ Declines projected for *all* greenhouse gas scenarios; specific amount depends on the amount of greenhouse gases emitted. ▪ Projected change in Washington-average April 1st snowpack[B]; range from a low to a medium greenhouse gas scenario): 2040s (2030-2059, relative to 1916-2006): −38 to −46% 2080s (2070-2099, relative to 1916-2006): −56 to −70%[D][2]
Glaciers	Declines expected, but there are no published projections for Northwest glacier response to climate change. ▪ An evaluation of current glacier status found that only 2 of the 12 North Cascades glaciers with annual measurements are expected to survive the current climate.[4] ▪ In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.[5]
Streamflow	
Annual	Mixed, but most models project a small increase in annual streamflow, on average for Washington State. ▪ Total annual streamflow is projected to increase slightly. 2040s (2030-2059, relative to 1917-2006): +2.1 to +2.5% 2080s (2070-2099, relative to 1917-2006): +4.0 to +6.2%[D][2] ▪ Changes are small relative to year-to-year variability in streamflow, and models disagree on the direction of change.
Winter	Mixed, but most models project an increase in winter streamflow, on average for Washington State. ▪ Winter (Oct-Mar) streamflow change: 2040s (2030-2059, relative to 1917-2006): +20 to +16% 2080s (2070-2099, relative to 1917-2006): +25 to +34%[D][2] ▪ Changes are small relative to year-to-year variability in winter streamflow, and models disagree on the direction of change.
Summer	Mixed, but most models project a decrease in summer streamflow, on average for Washington State. ▪ Summer (Apr-Sep) streamflow change: 2040s (2030-2059, relative to 1917-2006): −30 to −23% 2080s (2070-2099, relative to 1917-2006): −44 to −34%[D][2] ▪ Changes are small relative to year-to-year variability in summer streamflow, and models disagree on the direction of change.

Variable	*Projected Long-term Change*
Streamflow timing	Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers in the Northwest. ▪ Peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1917-2006) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt) and the Yakima basin.[D][2]
Stream temperatures	Warming ▪ By the 2080s (2070-2099, relative to 1970-1999)[O], more stream locations are projected to experience weekly summer stream temperatures stressful to adjust salmon (in excess of 67°F):[6] Eastern Washington: 19% more sites Western Washington: 16% more sites ▪ Many stream locations projected to exceed 70°F for the entire summer season by 2080 – resulting in waters that are warm enough to impede migration and increase the risk of fish kills.[7]
Flooding	Increases in most watersheds ▪ Projected changes in streamflow volume associated with the 100 year (1% annual probability) flood event, by basin type, in Washington State for the 2080s (2070-2099, relative to 1916-2006): Rain dominant watersheds: +18% (range: +11 to +26%) Mixed rain-snow watersheds: +32% (range: −33 to +132%) Snow dominant watersheds: −2% (range: −15 to +22%)[F][P][12] ▪ Projected changes in heavy rainfall (Section 3 of this report) are not included in the above projections. Preliminary research indicates an increase in the proportion of heavy rain events occurring in early fall. Both changes will likely increase flood risk in rain dominant and mixed rain and snow watersheds, especially west of the Cascade crest.[9]
Minimum flows	Decreased flow in most watersheds ▪ Projected changes for changes in 7Q10 flows,[Q] by basin type, in Washington State for the 2080s (2070-2099, relative to 1916-2006): Rain dominant watersheds: −14% (−44 to −3%) Mixed rain-snow watersheds: −15% (−60 to +14%) Snow dominant watersheds: −6% (−12 to +4%)[F][P][12]

O Average projected change for 124 stream locations across Washington State. Projections are made using ten global climate models and a medium greenhouse gas scenario (A1B).

P Watersheds were defined as rain dominant if the average winter temperature (Dec-Feb) was greater than 35.6°F (+2°C), mixed rain and snow if the average winter temperature (Dec-Feb) was between 21.2 and 35.6°F (-6 to +2°C), and snow dominant if the average winter temperature (Dec-Feb) was below 21.2°F (-6°C).

Q The 7Q10 flow is the lowest 7-day average flow that occurs on average once every 10 years. 7Q10 flows are a common standard for defining low flow for the purpose of setting permit discharge limits.

Variable	*Projected Long-term Change*
Water Resources	
Irrigation water supply	Increase in water short years in the Yakima River basin, in which water delivery is curtailed to junior water rights growers. ▪ Likelihood of shortfalls: Historical (1975-2004): 14% 2020s (2010-2039): 24 to 27% 2040s (2030-2059): 31 to 33% 2080s (2070-2099): 43 to 68%[D][14]
Hydropower production	Increase in winter, decrease in summer ▪ Average change for the Columbia River basin for the 2080s (2070-2099, relative to 1917-2006): Winter increase: +8 to +11% Summer decrease: −17 to −21%[D][15] ▪ Annual average cost of lost hydropower for 2030 (relative to 2010) is projected to be $120 million[R], although estimates range from a slight gain in revenue to much larger losses.[16]
Fish and Aquatic Ecosystems	Decline in interior western U.S. trout populations for the 2080s (2070-2099, relative to 1985-2004) for a high greenhouse gas scenario: Suitable habitat extent: −47% (−35 to −77%)[G][19] Warming stream temperatures are projected to negatively affect salmon health, migration, and survival (see above).
Municipal Water Supply	Changes in climate affect municipal water supply reliability differently for the three cities of Everett, Seattle, and Tacoma. ▪ Historically, all three cities have had at least 99% reliability, meaning that at most 1% of years experience water delivery shortfalls. ▪ Assuming no changes in demand, new sources of supply or significant changes in operating procedures, projected reliability for the 2080s (2070-2099, relative to 1917-2006): Everett: 100% Tacoma: 63 to 96%[H][21] ▪ For Seattle, supply is projected to exceed demand in nearly all years, and the City has identified no or low-cost system modifications to mitigate climate change-related supply reductions, keeping supply above demand under all climate change scenarios examined.[I][22]
Ski Season	More warm winters ▪ Probability of a warm winter (average Dec-Feb temperature above freezing) for Washington State ski resorts:

[R] Estimated using an intermediate climate change scenario for the 2040s (2030-2059), and linearly interpolating the changes in temperature and precipitation to 2030.

	Historic (1971-2000): 0 to 33%, depending on location With +3.6°F[S] warming: 33 to 77%[26]
Changing Water Demand	Small increase projected for the near term for the Columbia River basin ▪ Irrigation demand projected to increase by +4% in eastern Washington by the 2030s (2020-2049; relative to 1977-2006), for a low greenhouse gas scenario.[K][27] Small increases in municipal demand projected for the greater Seattle area. ▪ Municipal demand is projected to increase by 1% in 2025, 2% in 2050, and 5% in 2075 (relative to 2000), assuming current population forecasts and no new conservation measures, based on a high greenhouse gas scenario.[L][22]

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SECTION 7

How Will Climate Change Affect Forests in Washington?

Climate change is expected to transform Washington's forests over the long term by affecting the establishment, growth, and distribution of forest plant species, and by increasing disturbances such as fire, insect outbreaks, and disease.[1] While direct impacts of climate change on tree species (e.g., productivity, distribution) are important, the large projected increases in fire suggest that indirect impacts of climate change through disturbance are likely to be greater and more immediate agents of change for Washington forests. Recent research has provided projected impacts on several Washington forest species and types, as well as on disturbances, particularly fire and insect outbreaks.

1. **The spatial distribution of suitable climate for many ecologically and economically important tree species in Washington may change considerably by the end of the 21st century, and some vegetation types, such as subalpine forests, may become very limited in their ranges.**[A][1]

    - *Area of climatic suitability for Douglas-fir is projected to decline.* Climate is projected to become unfavorable for Douglas-fir over 32% of its current range in Washington by the 2060s, relative to 1961-1990, under a medium greenhouse gas scenario.[B] Areas of climatic suitability for Douglas-fir are projected to decline most noticeably at lower elevations, especially in the Okanagan Highlands and the south Puget Sound/southern Olympics.[C][2]

    - *Area of climatic suitability for pine species are projected to decline*. Only 15% of the area currently suitable for three pine species in Washington (ponderosa pine, lodgepole pine, and whitebark pine) is projected to remain suitable for all three by the 2060s, relative to 1961-1990, under a medium greenhouse gas scenario, while 85% of their current range is projected to become climatically unsuitable for one or more of the three species (Figure 7-1).[C][2]

    - *Area of climatic suitability for subalpine forest is projected to decline*. Suitable climate

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A Much of the material in this document is derived or directly quoted from *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*[1] and Littell et al. 2010.[2] Impacts on specific species and ecosystems described in this document represent examples rather than an exhaustive list of potential regional impacts. In describing potential impacts, we have used the term "projected" where future impacts have been estimated quantitatively (e.g., using models or experiments) and explicitly incorporate climate models and greenhouse gas scenarios (which we report in associated footnotes), and the term "may" where future impacts have been inferred from available biological information and projected climatic changes.

B Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to RCP 2.6; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

C Using results from two global climate models (HadCM3GGa1 and CGCM2) under a scenario that assumes a 1%/year increase in greenhouse gas emissions. This scenario closely resembles the current medium greenhouse gas scenario (RCP 6.0), with the exception that its late 21st century emissions are higher.

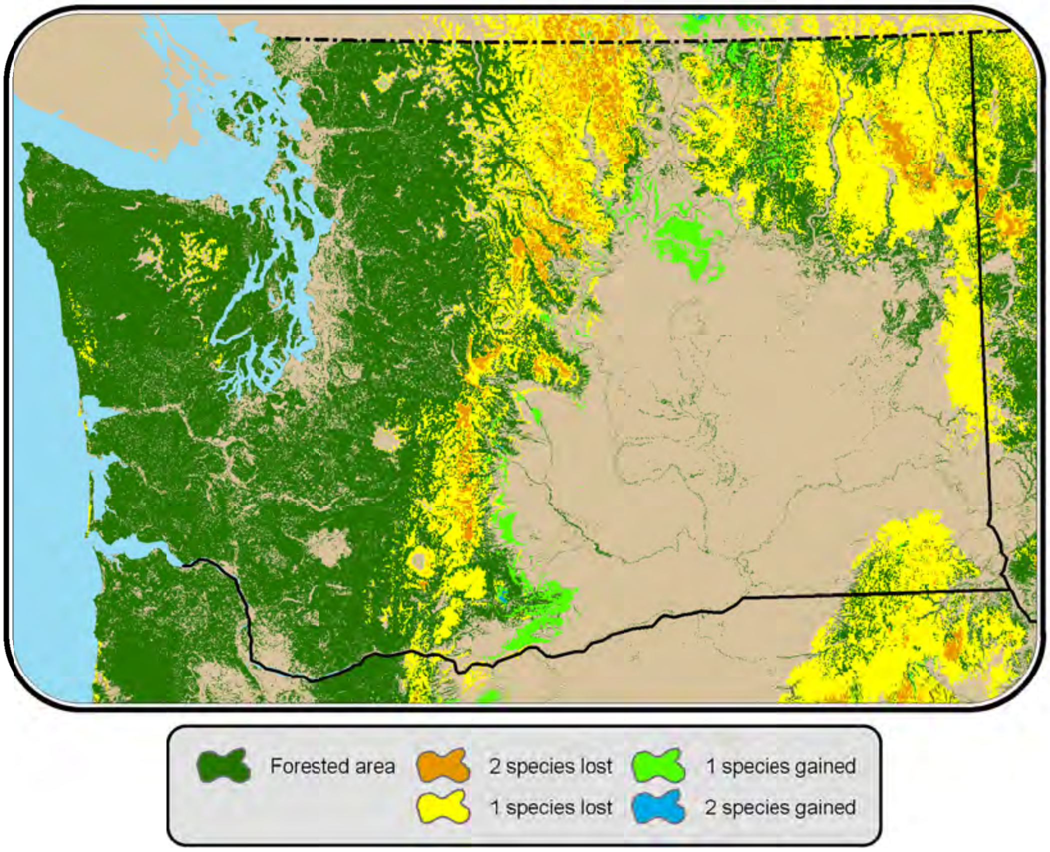

Figure 7-1. Projected changes in climatic suitability for three Washington pine species (ponderosa pine, lodgepole pine, and whitebark pine) by the 2060s relative to 1961-1990, under a medium greenhouse gas scenario.[B][C] Decreases indicate places where climate will be no longer suitable for some species, whereas increases indicate places where climate is currently unsuitable for some species but may be suitable in the 2060s. Reproduced from Littell et al. (2010).[2]

for subalpine forest in Washington is projected to decline substantially in area under a high greenhouse gas scenario.[D][3] Areas of climatic suitability may decline for high-elevation populations of whitebark pine, Brewer spruce, Engelmann spruce, and subalpine fir in the Pacific Northwest.[1]

- *Further research is needed concerning additional species and vegetation types.* Most existing research has focused on economically important species such as Douglas-fir and vulnerable vegetation types such as subalpine forest. Additional projections are needed for a wider range of tree species and forest types.

2. **Changes in forest structure and composition will be driven primarily by disturbance.** Because forests take many years to regenerate, stand-replacing disturbances caused by fire,

[D] Changes from historical (1971–2000) to future (2070–2099) modeled using MC1 vegetation model projections based on three global climate models (CSIRO-Mk3, Hadley CM3, and MIROC 3.2 medres) under a high (A2) greenhouse gas scenario.

insects, and disease will result in more rapid changes to forests than suggested by projections of future species range shifts.[1]

3. **Climate change may affect the productivity of Washington forests.** Given projections of warmer, possibly drier summers in Washington, tree growth may increase where trees are currently energy-limited (e.g., higher elevations) and decrease where trees are currently water-limited (e.g., drier areas).[1]

4. **Washington forests are likely to become increasingly water-limited, with episodes of drought increasing in area and intensity.** This is likely to lower forest productivity in some areas, while also increasing vulnerability to disturbance (e.g., fire, insects, pathogens).

    - *Area of severely water-limited forest is projected to increase.* Under a medium greenhouse gas scenario, the area of Washington forest where tree growth is limited by water availability is projected to increase (relative to 1970-1999) by +32% in the 2020s, with an additional +12% increase in both the 2040s and 2080s. Severely water-limited forests are projected to occur on the east side of the Cascade Range and in the northeastern part of the state.[E][2]

5. **Drier, warmer conditions are likely to increase the annual area burned by forest fires.[F]** This is because projected decreases in summer precipitation and increases in summer temperatures would reduce moisture of existing fuels, facilitating fire, while earlier snowmelt should lead to earlier onset of the fire season.[2]

    - *Annual area burned is projected to increase.* Compared to the median annual area burned in the Northwest during 1916-2006 (0.5 million acres), one set of fire models projects an increase to 0.8 million acres in the 2020s, 1.1 million acres in the 2040s, and 2 million acres in the 2080s, under a medium greenhouse gas scenario.[G][2] Another set of models projects +76% to +310% increases in annual area burned for the Northwest from 1971-2000 to 2070-2099 under a high greenhouse gas scenario.[D][3]

    - *Increases in area burned are projected to vary across the region.* For example, in forested ecosystems (Western and Eastern Cascades, Okanogan Highlands, and Blue Mountains), annual area burned is projected to increase by about a factor of 4 by the 2040s, compared to 1980-2006, under a medium greenhouse gas scenario. In non-forested areas (Columbia Basin and Palouse Prairie), annual area burned is projected to increase on average by about a factor of 2.[G][2]

[E] Based on hydrologic simulations of annual precipitation and summer potential evapotranspiration, which were averaged over 20 global climate models and a low (B1) and medium (A1B) greenhouse gas scenario. Energy-limited forests were defined as those where annual precipitation exceeds summer evapotranspiration, and water-limited forests were defined as those where summer potential evapotranspiration exceeds annual precipitation.

[F] Compared to area burned, there is much less quantitative information about the likely consequences of climate change for forest fire frequency, severity, and intensity (Littell et al. 2013).[1]

[G] Average of area burned calculated separately for climate simulated by two global climate models (CGCM3 and ECHAM5) under a medium (A1B) greenhouse gas scenario.

- *Fires may occur in areas where they have been rare in the past.* While it is difficult to project future fire risk for wetter regions (e.g., Puget Trough, Olympic Mountains) with low historical annual area burned, it is expected that rising summer temperatures, lower soil moisture, and higher evaporation rates could result in more area burned in western Washington forests that have not traditionally been considered fire-prone.[2] One set of projections estimates that annual area burned for Northwest forests west of the Cascade Range crest will be about +150% to +1000% higher in 2070-2099 compared to 1971-2000, under a high greenhouse gas scenario.[D][3]

- *Further research is needed.* In particular, models are needed that account for climate-fire severity relationships and provide projections of future fire severity as a function of climate change.

6. **Insect outbreaks are likely to change in frequency and affected area, as forests become more susceptible due to climatic stressors (e.g., drought), and areas climatically suitable for outbreaks shift**.

   - *The area of forest susceptible to mountain pine beetle outbreaks is projected to first increase then decrease.* Under a medium greenhouse gas scenario, area susceptible to mountain pine beetle outbreak is projected to first increase (+27% higher in 2001-2030 compared to 1961-1990) as warming exposes higher elevation forests to the pine beetle, but then decrease (−49 to −58% lower by 2071-2100) as temperatures exceed the beetle's thermal optimum.[H][4]

   - *Ranges of other bark beetles may also decrease.* Ranges of some bark beetles (e.g., pine engraver beetle) may decrease due to climatic conditions less favorable for outbreaks.[1]

   - *Further research is needed into how other insects may respond to climate change.* Anticipating future impacts will require better understanding the role of climate in other insects' (e.g., spruce and fir beetles or defoliators) life cycles and host vulnerabilities.

7. **Climate change is likely to influence forest disease outbreaks, but because climatic influences are likely to be species- and host-specific, generalizations are difficult to make.[5]**

   - *Climate change is projected to increase Northwest forests' susceptibility to several diseases.* With warmer future temperatures, risk of forest damage from yellow-cedar decline and Cytospora canker of alder may be high if annual precipitation decreases, while risk of forest damage from dwarf mistletoes and *Armillaria* root disease may be high whether precipitation increases or decreases.[5] Several studies have suggested that future increases in temperature and precipitation may lead to increased risk of sudden oak

[H] Historical (1961-1990) temperatures were used to predict current climatic suitability for outbreaks. Future (2001–2030, 2071–2100) temperature suitability estimated for one future climate scenario (CRCM) assuming a high (A2) greenhouse gas scenario.

death in the Northwest.[5][6] In addition, swiss needle cast is projected to have increased capacity to affect Douglas-fir in Northwest forests by 2050, under a low greenhouse gas scenario.[I][7]

8. **Climate change may affect the ability of Washington's forests to sequester carbon by increasing disturbances such as fire, which may alter the amount of carbon stored in soils and vegetation.[1]**

   - *Increased annual area burned is projected to lower the amount of carbon stored in Washington forests.* By 2040, increasing burn area in Washington is projected to reduce the amount of carbon stored by forests by 17 to 37%.[J][8]

   - *Changes in carbon stores may vary regionally.* Forests of the western Cascades are projected to be more sensitive to climate-driven increases in fire, and thus projected changes in carbon dynamics, than forests of the eastern Cascades.[J][8]

9. **Due to recent research, scientific understanding of impacts has advanced and the specificity and quality of projections has increased.** Almost all of the impacts described in this document have been quantified since 2010, and include finer spatial and temporal resolution than previous analyses, as well as additional detail on impacts to particular species.

   - *New information for Washington and the Northwest includes the following:*

     - Projected changes in areas of climatic suitability for forest species (e.g., Douglas fir), and forest types (e.g., subalpine forest).
     - Projected changes in annual area burned.
     - Projected changes in ability of forests to store carbon.

   - *Available studies are still limited to a relatively small proportion of Washington forest species and disturbance processes.* Projections for a wider variety of tree species and forest types are needed, as well as more sophisticated models of fire and disease.

10. **Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change on forests.** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

    - *Science-management partnerships have been established to approach adaptation to climate change.*[1] For example, the *North Cascadia Adaptation Partnership* is a Forest

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I Projection based on continuing winter temperature increases for the Pacific Northwest of approximately 0.72°F/decade through 2050 (for a total increase of 3.6°F, which is near the average projected warming for mid-century in the Pacific Northwest, assuming a low greenhouse gas scenario).

J Based on estimates of historical and future carbon carrying capacity of forest types based on potential productivity, maximum carbon storage, historical fire regimes, and projections of 21st century area burned from Littell et al. 2010.[2]

Service - National Park Service collaboration that joined with city, state, tribal, and federal partners to increase awareness of climate change, assess the vulnerability of cultural and natural resources, and incorporate climate change adaptation into current management of federal lands in the North Cascades region. More information is available at Northcascadia.org.

- *A guidebook has been developed to assist with developing adaptation options for national forests, including those in Washington*. Responding To Climate Change In National Forests: A Guidebook for Developing Adaptation Options includes both strategies and approaches to strategy development.[9]

- *Climate adaptation strategies have been or are being developed for specific national forests.* A completed example is: Adapting to Climate Change at Olympic National Forest and Olympic National Park.[10]

Additional Resources for Evaluating Changes in Forests

The following resources provide local information about hydrologic conditions and water availability and demand to support assessment of climate impacts on forested ecosystems, and on forest management and forest uses.

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, plant water demand, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. http://warm.atmos.washington.edu/2860,[11] http://cses.washington.edu/cig/

- **Data Basin,** a science-based mapping and analysis platform that aggregates, describes and shares datasets, maps and galleries of information of relevance to forest and disturbance change in the Pacific Northwest. http://databasin.org/

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Section 8

How Will Climate Change Affect Plants and Animals in Washington?

Climate change is expected to cause significant changes in plant and animal distributions and communities, and may threaten the some of the region's iconic species.[A] The timing of biological events, such as spring budburst and migration, will shift for many species. Sea level rise is projected to displace coastal habitats and the species that depend on them. Ocean acidification will negatively impact marine species and ecosystems, particularly shellfish. Recent studies have provided projections specific to Pacific Northwest species and ecosystems, and significantly more detail on the impacts of ocean acidification on Washington's marine species.

1. **The spatial distributions of suitable climate for many species of plants and animals are projected to change considerably by the end of the 21st century.** Many species may be unable to move fast enough to keep up with shifting areas of climatic suitability, which may result in local extirpations. Both range shifts and local extirpations are likely to lead to changes in the composition of Washington's biological communities.[1]

   - *Areas of suitable climate for alpine and subalpine species are projected to significantly decline.* Suitable climate for alpine tundra and subalpine vegetation in Washington is projected to decline substantially in area or disappear by the end of the century under a high greenhouse gas scenario.[B][C][2] These reductions may negatively affect associated wildlife species, such as American pika.[3] Areas of contiguous habitat for Pacific Northwest populations of wolverine[D][4] and American marten[E][5] are projected to significantly decrease by the late 21st century under a medium greenhouse gas scenario.

   - *Areas of suitable climate for several Washington tree species are projected to decline.* For example, climate is projected to become unfavorable for Douglas-fir over 32% of its

[A] Impacts on specific species and ecosystems described in this document represent examples rather than an exhaustive list of potential regional impacts. In describing potential impacts, we have used the term "projected" where future impacts have been estimated quantitatively (e.g., using models or experiments) and explicitly incorporate climate models and greenhouse gas scenarios (which we report in associated footnotes), and the term "may" where future impacts have been inferred from available biological information and projected climatic changes.

[B] Changes from historical (1971–2000) to future (2070–2099) modeled using MC1 vegetation model projections based on CSIRO-Mk3, Hadley CM3, and MIROC 3.2 medres global climate models under the SRES-A2 greenhouse gas scenario.

[C] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

[D] Models of future (2070-2099) wolverine connectivity based on projected late spring snow cover under 10 global climate models and the A1B greenhouse gas scenario.

[E] Models of future marten connectivity based on upward shifts of current temperatures by approximately 325, 650, 985, 1310, and 1640 ft from the current optimum elevation of 4920 ft, which correspond to a low to medium increase in temperature by 2081-2100, relative to 1950-1999.

current range in Washington by the 2060s relative to 1961-1990, under a medium greenhouse gas scenario.[F][6] Only 15% of the area currently suitable for three pine species in Washington (ponderosa pine, lodgepole pine, and whitebark pine) is projected to remain suitable for all three by the 2060s relative to 1961-1990, under a medium greenhouse gas scenario, while 85% of their current range is projected to become climatically unsuitable for one or more of the three species. [F][6]

- *Area of suitable climate for sagebrush-steppe vegetation is projected to decline.* Sagebrush-steppe ecosystems in eastern Washington are projected to decline in extent by the 2080s (2070-2099), relative to 1970-1999, under a high greenhouse gas scenario.[B][2] This has negative implications for associated wildlife, such as greater sage grouse and pygmy rabbit.

- *Climate change may lead to reductions in the extent of wetlands and ponds.* Reduced snowpack and altered runoff timing may contribute to the drying of many ponds and wetland habitats across the Pacific Northwest.[7]

- *Climate change may result in the expansion of prairies.* Projected increases in summer drought may result in an expansion of Pacific Northwest prairies. Projected increases in winter precipitation may lead to the expansion of wetland prairies on poorly drained soils in areas such as the South Puget Sound.[8] However, high levels of human land use in future areas of climatic suitability may limit opportunities for expansion.

2. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, will continue to shift, leading to significant impacts on species and habitats.[1]** For example, some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds.[9] There are currently few studies on such impacts specific to the Pacific Northwest.

3. **Climate change will affect biodiversity through major ecosystem disturbances, including fire, drought, and flooding.[1]** For example, climate change may increase the risk of severe, stand-replacing fires, which may negatively impact species associated with old-growth forest, such as marbled murrelets and northern spotted owls. Species that thrive in conditions after severe fires, such as the northern flicker and hairy woodpecker, may benefit under an altered fire regime.[1]

4. **Climate change may promote the spread of invasive species.[1]** This will include both native invasive species (e.g., western juniper) moving beyond their historical ranges, and non-native species (e.g., cheat grass) increasing due to improved conditions. Moreover, responses of invasive species to climate change will vary, so that some may benefit while others will not.[1]

F Using results from the HadCM3GGa1 and CGCM2 global climate models (GCMs) under a scenario that assumes a 1%/year increase in greenhouse gas emissions. This scenario closely resembles the RCP 6.0 scenario, with the exception that late 21st century emissions are higher.

- *Some invasive species are projected to benefit from climate change.* For example, changes in salinity due to sea level rise may facilitate invasion by non-native species better adapted to salinity variations, such as the invasive New Zealand mud snail, which has been found in the Columbia River estuary.[G][10]

- *Some invasive species may not benefit from climate change.* For example, suitable habitat for cheatgrass is projected to increase in some areas of the Pacific Northwest and decrease in others by 2100, relative to 1971-2000, under a medium greenhouse gas scenario; its future distribution will be strongly influenced by future changes in precipitation.[H] [11]

5. **Changes in the timing and quantity of streamflows, together with increasing stream temperatures, are projected to cause significant changes in freshwater aquatic species and ecosystems.[7]**

- *Suitable stream temperatures for aquatic species may shift upstream.* Suitable stream temperatures for many aquatic species across the Pacific Northwest could shift a few to nearly one hundred miles upstream, with smaller changes seen along steep streams, and larger changes along relatively flat streams.[I][12]

- *Rising stream temperatures and altered streamflows will likely reduce the reproductive success of many Washington salmon populations, though impacts will vary by location.* Relative to 20th century conditions, under a low-warming scenario, juvenile salmon growth rates by mid-21st century are projected to be lower in the Columbia Basin, but unchanged or greater in coastal and mountain streams. [J][13] By the 2080s (2070-2099, relative to 1970-1999), for a medium emissions scenario, the duration of summertime stream temperatures that cause thermal stress and migration barriers to salmon is projected to at least double for many areas in eastern Washington and along the lower Columbia River.[K][14] Earlier spring runoff may alter migration timing and survival rates for salmon smolts in snowmelt-dominated streams.[14]

- *Steelhead vulnerability to climate change varies across the region.* Steelhead vulnerability to streamflow change at mid-century (2030-2059) relative to 1970-1999 under a medium greenhouse gas scenario is projected to be high in northeastern Washington and Cascade Mountain rivers (both east and west side), and lowest in coastal rivers. Vulnerability to stream temperature change is projected to be high in eastern and

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[G] Based on experiment demonstrating increased salinity tolerance of New Zealand mud snails from the Columbia River estuary compared to those found in a freshwater lake.
[H] Based on bioclimatic envelope models under the SRES A1B greenhouse gas scenario and 10 general circulation models for 2100.
[I] Assuming a warming of 3.6°F, which is near the average projected warming for mid-century in the Pacific Northwest, under a low greenhouse gas scenario.
[J] Fish growth from winter to summer was projected with temperature-dependent models of egg development and juvenile growth using empirical temperature data from 115 sites.
[K] Based on the average of 10 climate models run under the A1B emissions scenario.

southwest Washington, but low in most Cascade Mountain rivers.[L][15][16]

6. **Rising sea levels are projected to displace many coastal habitats and the species that depend on them**. Most of the region's important coastal habitats have already been damaged or destroyed by extensive dredging, coastal modifications, pollution, and other development. Natural barriers and coastal modifications such as dikes and seawalls may significantly impede the ability of habitats to migrate inland to accommodate sea-level rise.[17]

    - *Sea level rise is projected to cause reductions in the extents of many coastal habitats*. By 2100, under a medium greenhouse gas scenario, sea level rise in Washington and Oregon is projected to result in the loss of as much as 44% of tidal flat, 13% of inland freshwater marsh, 25% of tidal fresh marsh, 61% of tidal swamp, and 65% of estuarine beaches.[M][17]

    - *Sea level rise is projected to change the composition of many existing coastal habitats*. By 2100 in Washington and Oregon, under a medium greenhouse gas scenario, 52% of brackish marsh is projected to be converted to tidal flats, transitional marsh and saltmarsh; 11% of inland swamp is projected to be inundated with salt water; and 2% of undeveloped land is projected to be inundated or eroded to form other habitat types.[M][17]

7. **Ocean acidification is expected to threaten coastal and marine species and ecosystems.**

    - *Ocean acidification is likely to reduce shellfish populations.* By the end of the century, ocean acidification is projected to result in a 40% reduction, globally, in the rate at which mollusks (e.g., mussels and oysters) form shells, as well as a 17% decline in growth, and a 34% decline in survival.[N][18]

    - *Ocean acidification may negatively impact some fish species.* By 2028, ocean acidification impacts on shellfish and plankton are projected to result in a 10–80% decline in the abundance of commercially important groundfish on the US west coast, including English sole, arrowtooth flounder, and yellowtail rockfish, owing to the loss of shelled prey items from their diet. [O][19]

L Based on Elsner et al.'s (2010)[16] historical and future hydrologic projections, which stem from an average of 20 global climate models and the A1B greenhouse gas scenario.

M Based on a 27.3-inch global sea-level rise by 2100 relative to 1980-1999 (projected under a medium greenhouse gas scenario) and the Sea Level Affecting Marshes Model (SLAMM) applied to 11 coastal sites in Puget Sound and along the Pacific Coast in southwestern Washington and northwestern Oregon. Projected changes in habitat are relative to total habitat amounts in 2007.

N Based on statistical synthesis of results from 228 experimental assessments of responses of marine organisms to acidification, with end-of-century projections based on 0.5 unit reduction in global average ocean surface pH relative to current pH. This is higher than the change projected for 2100 by the IPCC (0.30 to 0.32 unit reduction under the high RCP 8.5 scenario, for 2081-2100 relative to 1986-2005) and also higher than the projections of Feely et al. 2009 (0.4 to 0.48 unit reduction, under a high (A2) greenhouse gas scenario, for 2095 relative to pre-industrial (1875) levels).

O Relative to 2009 (with baseline conditions established 1995-2005), and based on a 20-year model run of the Atlantis ecosystem model, using four scenarios treating acidification as a range of additional mortality rates on shelled plankton and benthos groups.

- *Ocean acidification may benefit some species*. For example, seagrasses may experience increased growth rates with elevated ocean carbon dioxide levels.[20]

8. **Increasing sea surface temperatures may alter the ranges, types, and abundances of Pacific Northwest marine species.** However, projections specific to waters off of Washington and the Pacific Northwest are currently limited relative to terrestrial and freshwater studies.[21]

9. **As a result of recent research, scientific understanding of the biological impacts of anthropogenic climate change in Washington State has advanced and the specificity of projections has increased.**

    - *Ocean acidification has become a primary area of study and concern.* Ocean acidification has only recently been widely recognized as a concern, and there has been a tremendous increase in studies documenting projected impacts.

    - *Changes in suitable climate have been projected for several species and habitat types.* However, many of these are for economically important species such as Douglas-fir and salmon, and projected climate impacts on most Washington species and ecosystems remain understudied.

10. **Various Washington communities, government agencies, and organizations are preparing for the impacts of climate change on plants and animals.[22]** Examples include:

    - *The Pacific Northwest Vulnerability Assessment* is a collaboration among researchers, managers, and planners from Pacific Northwest universities, agencies, and non-government organizations. It will soon be releasing products indicating the potential effects of future climate change on regional species and habitats. More information is available at: Climatevulnerability.org

    - *The Washington Wildlife Habitat Connectivity Working Group* (WHCWG) is a large collaborative effort to identify opportunities for maintaining and restoring landscape connectivity in Washington. Increasing connectivity is a key recommendation of the *Washington State Integrated Climate Change Response Strategy*.[P] WHCWG products offer tools for implementing this recommendation. More information is available at: waconnected.org.

    - The new *Washington Ocean Acidification Center* at the University of Washington (funded by the State Legislature in summer 2013) will coordinate scientific research, monitoring and data-sharing related to ocean acidification, and work with partners in state and federal agencies, tribes, industries, and academic institutions to link ocean-acidification science with decision-making.

[P] Available at: http://www.ecy.wa.gov/climatechange/ipa_responsestrategy.htm

- The Washington Department of Fish & Wildlife (WDFW) is developing a *Climate Adaptation Handbook* designed to provide practical, hands on guidance for integrating climate considerations into WDFW activities.

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SECTION 9

How Will Climate Change Affect the Coast and Ocean in Washington?

A major driver of climate change impacts on Washington's coasts is sea level rise, which is expected to affect most locations in Washington State. Key impacts include inundation of low-lying areas, increased storm surge reach, flooding, erosion, and changes and loss of habitat types. These impacts are likely to affect a wide range of communities, species, and infrastructure. Since 2007, studies have provided more regional specificity about how coastal ocean conditions may change in the Pacific Northwest, particularly with respect to sea level rise and ocean acidification.

1. **Changes in Pacific Northwest coastal waters are strongly influenced by changes in global sea level and ocean conditions.**[1] Global sea level is projected to increase by +11 to +38 inches by 2100 (relative to 1986-2005), depending on the amount of 21st century greenhouse gas emissions.[A][2] This will cause Washington's marine waters to rise, although how much change occurs at a specific location depends on a variety of local factors, as described below. Additionally, coastal sea surface temperatures and the acidity of Washington's marine waters are projected to increase.[B][3][4]

2. **Sea level is projected to continue rising in Washington through the 21st century, increasing by +4 to +56 inches by 2100, relative to 2000.**[5]

   - *Multiple factors affect local sea level.* The amount of sea level change at a given location and time will depend both on how much global sea level rises and on local factors such as seasonal wind patterns, vertical land movement associated with plate tectonics, and sediment compaction. These local factors may result in higher or lower amounts of local sea level rise (or even declining sea level) relative to global projections depending on the rate and direction of change in these local factors.

   - *Sea level rise is expected to continue in most of Washington's coastal areas (Table 9-1).* Most areas in Washington are expected to experience sea level rise through 2100. This includes the Puget Sound region and the central and southern outer coast.[6]

   - *A few locations may experience declining sea level.* Previous research indicates that declining sea level is possible in the Northwest Olympic Peninsula if the rate of global sea level rise is very low and if the rate of uplift caused by plate tectonics continues to exceed the rate of global sea level rise.[6] Although most *current* global projections would result in sea level rise for the northwest Olympic Peninsula, it is not yet possible to conclusively rule out a decline in sea level for that region.

[A] Sea level rise projections vary with greenhouse gas scenarios. The average and associated ranges reported in IPCC 2013[2] are +17 in. (range: +11 to +24 in.) for the very low (RCP 2.6) greenhouse gas scenario to +29 in. (range: +21 to +38 in.) for the very high (RCP 8.5) scenario. See Section 3 for more details on greenhouse gas scenarios and Sections 4 and 5 for more on global and Pacific Northwest sea level rise projections.

[B] See Section 5 for more on projected changes in regional sea surface temperatures and ocean acidity.

Table 9-1. Sea level rise projections for Washington State and sub-regions. Projections are in inches, for 2030, 2050, and 2100 (relative to 2000), from two regionally-specific studies: Mote et al 2008[6] and NRC 2012[5]. Values shown are the central (for NRC 2012), or medium (for Mote et al. 2008) projections, with the projected range shown in parentheses. *Table and caption adapted from Reeder et al. 2013.[1]*

Domain	2030	2050	2100
Washington State (NRC 2012)[C],[D]	+3 inches *(-2 to +9 in.)*	+7 inches *(-1 to +19 in.)*	+24 inches *(+4 to +56 in.)*
Puget Sound (Mote et al. 2008)[E]	---	+ 6 inches *(+3 to +22 in.)*	+13 inches *(+6 to +50 in.)*
NW Olympic Peninsula (Mote et al. 2008)	---	0 inches *(-5 to +14 in.)*	+2 inches *(-9 to +35 in.)*
Central & Southern WA Coast (Mote et al. 2008)	---	+5 inches *(+1 to +18 in.)*	+11 inches *(+2 to +43 in.)*

- *Sea level rise is not expected to occur in a consistent, linear fashion*. Episodes of faster and slower rise, as well as periods of no rise, are likely due in part to natural variability, especially as you move to regional (e.g., the Pacific Northwest) and smaller scales.[7]

3. **Sea level rise increases the potential for higher tidal/storm surge reach and increased coastal inundation, erosion, and flooding.** Even small amounts of sea level rise can shift the risk of coastal hazards in potentially significant ways.

    - *Sea level rise will permanently inundate low-lying areas.* Where and how much inundation occurs will depend on the rate of sea level rise and shoreline characteristics. Communities and organizations that have mapped sea level rise inundation zones include the City of Olympia,[8] City of Seattle, King County,[9] the National Wildlife Federation (mapped for Puget Sound, southwestern Washington, and northwestern Oregon), [10] the Swinomish Indian Tribal Community,[11] and the Jamestown S'Klallam Tribe.[12]

C Calculated for the latitude of Seattle, Washington (NRC 2012).[5] The mean value reported in NRC 2012 is based on the A1B greenhouse gas emissions scenario. The range values are projections for a low (B1) to a high (A1FI) greenhouse gas emissions scenario. See Section 3 for more details on greenhouse gas scenarios.

D Regional comparisons between Mote et al. 2008[6] and NRC 2012 differ due to the different approaches taken by the studies to estimate global sea level rise and local influences on the relative rate of rise. Also, Mote et al. 2008 does not provide projections for 2030 and NRC 2012 did not provide projections for sub-regions of Washington State.

E The sub-regional sea level rise projections for Washington State in Mote et al. 2008 integrate projected changes in global sea level rise, potential changes in wind direction (which can push waves onshore or off shore for prolonged periods of time depending on wind direction), and different rates of vertical land motion. Low to high projections for each of these components were used to develop the low, medium, and high sub-regional sea level rise estimates. The global sea level rise projections used in these calculations range are based on a low greenhouse gas scenario (B1; for the low projection), a high greenhouse gas scenario (A1FI; for the high projection), and an average of six greenhouse gas emissions scenarios (B1 through A1FI; for the medium projection). See Section 3 for more details on greenhouse gas scenarios.

- *Sea level rise will exacerbate coastal river flooding*. Higher sea level can increase the extent and depth of flooding by making it harder for flood waters in rivers and streams to drain to the ocean or Puget Sound. Projected increases in both the size and frequency of high river flows due to climate change will compound this risk.[13]

- *Sea level rise increases the frequency of today's extreme tidal/storm surge events.* Higher sea level amplifies the inland reach and impact of high tides and storm surge, increasing the likelihood of today's extreme coastal events. For example, +6 inches of sea level rise[F] in Olympia shifts the probability of occurrence for the 100-year flood event from a 1% annual chance to 5.5% annual chance (1-in-18 year) event.[8] With +24 inches of sea level rise,[G] the 100-year flood event would become an annual event (Table 9-2).

- *Sea level rise can increase coastal erosion.* Higher sea level and storm surge reach exposes more areas to erosion, which can affect the stability of coastal infrastructure. For example, analysis of beach erosion rates in Oregon for the period 1967-2002 found that significant beach erosion occurred in areas where relative sea level (north-central Oregon) increased. In contrast, beaches were relatively stable in areas experiencing sea level decline (e.g., along the southern Oregon coast, where the rate of uplift is greater than observed sea level rise).[14]

Table 9-2. Impact of sea level rise on the probability of today's 100-year coastal flood event in Olympia, WA. As sea level rises, the probability of today's 100-year flood event increases from a 1% annual probability to a 100% probability if sea level rises +24 inches or more. *Figure and caption adapted from Simpson 2012.[8]*

Sea level rise amount	**0 inches**	**+3 inches**	**+6 inches**	**+12 inches**	**+24 inches**	**+50 inches**
Return frequency for a storm tide reaching the current 100-year flood level	100-yr event	40-yr event	18-yr event	2-yr event	< 1-yr event	<< 1-yr event
Equivalent annual probability of occurrence	1%	2.5%	5.5%	50%	100%	100%

F A +6 inch increase in regional sea level is currently near the average value (+6.5 inches) projected in NRC 2012 for Seattle for 2050, and within the range of values projected for Seattle as early as 2030 (range of -1.5 in. to +8.8 in.). See Table 9-1 for more detail.

G A +24 inch increase in sea level is currently the average value (+24.3 inches) projected in NRC 2012 for Seattle for 2100 (range: +4 in. to +56 in.). See Table 9-1 for more detail.

4. Sea level rise and changes in coastal ocean conditions[H] impact human, plant, and animal communities in important ways.

- *Economic and cultural impacts on human communities are expected.* Efforts to better understand and adapt to coastal impacts are occurring in a variety of organizations and coastal communities.

  - *Projected impacts.* Impacts on human communities include the potential for increased damage to coastal infrastructure from storm surge or flooding [8][9][15] permanent inundation of important commercial and industrial areas, [8][11][16] loss of culturally important sites,[11] and impacts on commercial fishing and shellfish harvesting.[1]

  - *Adapting to sea level rise.* Adaptive decisions based on sea level rise projections have already been made by the City of Olympia,[17] City of Seattle,[I] King County,[18] Port of Bellingham,[19] and the Swinomish Indian Tribal Community.[20] Analyses of sea level rise impacts have also been completed by the Port of Seattle,[21] the Jamestown S'Klallam Tribe,[12] and Sound Transit.[J] For more on some of these efforts, see this Section 10 on infrastructure and the built environment.

- *Sea level rise and changes in the marine environment will affect the geographical range, abundance, and diversity of Pacific Coast marine species and habitats.*[K][22]

  - *Coastal habitats.* Increased inundation and erosion due to sea level rise are expected to cause habitat loss and shifts in habitat types. Locations more likely to experience habitat loss include low-lying areas, locations with highly erodible sediments, and areas where inland migration of coastal habitats is hindered by bluffs or human development. Vulnerable habitat types include coastal wetlands, tide flats, and beaches.[10]

  - *Coastal species.* Species potentially affected by sea level rise and changes in ocean conditions include key components of the marine foodweb (phytoplankton and zooplankton) as well as juvenile Chinook salmon and commercially important species such as Pacific mackerel (*Scomber japonicus*), Pacific hake (*Merluccius productus*), oysters, mussels (*Mytilus edulis*), English sole (*Pleuronectes vetulus*), and yellowtail rockfish (*Sebastes flavidus*).[4][23] A species' ability to adapt to climate change will vary based on physiology and life cycle traits. How quickly climate changes, how large the change is, and the impact of other non-climate stressors such as fishing or pollution will also influence adaptive capacity.

H This includes changes sea surface temperature, salinity, pH, ocean circulation patterns and other factors that can affect species.

I See http://sdotblog.seattle.gov/2013/01/23/sea-level-and-the-seawall/ for more details on how the Seattle Department of Transportation evaluated sea level rise projections for the new Seattle sea wall.

J As announced by the U.S. Federal Transit Administration, http://www.fta.dot.gov/sitemap_14228.html. Final project report scheduled for release by FTA in winter 2014.

K For more on impacts to Pacific Northwest species and ecosystems, including projected percentage losses of specific coastal habitat types, see Section 8 on species and ecosystems.

Additional Resources for Evaluating Coastal Impacts. The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **NOAA Tides and Currents** (http://tidesandcurrents.noaa.gov/): for information on observed trends in sea level
- **NOAA Coastal Services Center** (https://csc.noaa.gov/): provides technical information and support for managing coastal hazards. Tools and products include:
    - *Sea Level Rise Viewer:* creates maps of potential impacts of sea level rise along the coast and provides related information and data for community officials.
    - *Coastal County Snapshots:* allows users to develop customizable PDF fact sheets with information on a county's exposure and resilience to flooding; its dependence on the ocean for a healthy economy; and the benefits received from a county's wetlands.
    - *Coastal LiDAR:* a clearinghouse of LiDAR datasets contributed by many different entities and groups that can be used for mapping sea level rise inundation.
- **Georgetown Climate Center Adaptation Clearinghouse: Rising Seas and Flooding** (http://www.georgetownclimate.org/adaptation/rising-seas-and-flooding): provides links to a variety of case studies and regulatory analyses related to sea level rise.

[1] Reeder, W.S. et al. 2014. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

[2] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

[3] Mote, P.W. and E.P. Salathé. 2010. Future climate in the Pacific Northwest. *Climatic Change* 102(1-2): 29-50, doi: 10.1007/s10584-010-9848-z.

[4] Feely, R.A. et al. (eds.). 2012. *Scientific Summary of Ocean Acidification in Washington State Marine Waters*. NOAA OAR Special Report. Seattle, Washington.

[5] (NRC) National Research Council 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.* Washington, DC: The National Academies Press.

[6] Mote, P.W. et al. 2008. *Sea Level Rise in the Coastal Waters of Washington State*. Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington and the Washington Department of Ecology, Lacey, Washington.

[7] Bromirski, P. D. et al. 2011. Dynamical suppression of sea level rise along the Pacific Coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research* 116: C07005. doi: 10.1029/2010JC006759.

[8] Simpson, D.P. 2012. *City Of Olympia Engineered Response to Sea Level Rise*. Technical report prepared by Coast Harbor Engineering for the City of Olympia, Public Works Department, Planning and Engineering.

[9] King County Wastewater Treatment Division. 2008. *Vulnerability of Major Wastewater Facilities to Flooding From Sea Level Rise.* Report prepared by the King County Wastewater Treatment Division, Department of Natural Resources and Parks. July 2008. 13 pp.

[10] Glick, P. et al. 2007. *Sea-Level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon*. National Wildlife Federation.

[11] Swinomish Indian Tribal Community. 2010. *Swinomish Climate Change Initiative: Climate Adaptation Action Plan.* La Conner, WA.

[12] Jamestown S'Klallam Tribe. 2013. *Climate Change Vulnerability Assessment and Adaptation Plan.* Petersen, S. and J. Bell (eds). A collaboration between the Jamestown S'Klallam Tribe and Adaptation International.

[13] Tohver, I. et al. 2013. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. *Journal of the American Water Resources Association*, In press.

[14] Ruggiero, P. et al. In press. *National Assessment of Shoreline Change: Historical Shoreline Change along the Pacific Northwest Coast.* US Geological Survey Open-File Report 2012–1007, 55 pp.

[15] Washington State Department of Transportation. 2011. Climate Impacts Vulnerability Assessment. Report prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, Olympia, Washington.

[16] Seattle Public Utilities Sea Level Rise Map, released January 2013, available at: http://www.seattle.gov/util/AboutUs/SPU_&_the_Environment/ClimateChangeProgram/index.htm , accessed November 8, 2013

[17] "Addressing Sea Level Rise and Flooding in Olympia" case study, prepared for the Successful Adaptation in the Coastal Sector: Washington Practitioners Workshop, sponsored by the Climate Impacts Group at the University of Washington, March 20, 2013.

[18] King County. 2013. *2012 Annual Report of King County's Climate Change, Energy, Green Building and Environmental Purchasing Programs*. Seattle, WA.

[19] "Adapting to Sea Level Rise at the Port of Bellingham" case study, prepared for the Successful Adaptation in the Coastal Sector: Washington Practitioners Workshop, sponsored by the Climate Impacts Group at the University of Washington, March 20, 2013.

[20] "The Swinomish Indian Tribal Community" case study, prepared for the Successful Adaptation in the Coastal Sector: Washington Practitioners Workshop, sponsored by the Climate Impacts Group at the University of Washington, March 20, 2013.

[21] Huang, M. 2012. *Planning for Sea Level Rise: The Current State of Science, Vulnerability of Port of Seattle Properties to Sea Level Rise, and Possible Adaptation Strategies.* Report prepared for the Port of Seattle, WA.

[22] Tillmann, P. and D. Siemann. 2011. *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 Final Report.* Produced by the National Wildlife Federation for the U.S. Fish and Wildlife Service North Pacific Landscape Conservation Cooperative.

[23] Kaplan, I.C. et al. 2010. Fishing catch shares in the face of global change: A framework for integrating cumulative impacts and single species management. *Canadian Journal of Fisheries and Aquatic Sciences* 67 (12): 1968–1982. doi: 10.1139/F10-118.

SECTION 10

How Will Climate Change Affect Infrastructure in Washington?

Climate change is expected to increase the potential for infrastructure damage and service disruptions, and may also lead to higher operating costs and reduced asset life. Some minor benefits may also be realized, including the potential for fewer snow-related road closures. The specific nature of impacts on infrastructure will vary depending on infrastructure location, age, design tolerances, and other factors. Studies completed since 2007 have increased our understanding of how climate change may affect transportation and coastal infrastructure in Washington State. However, more detailed studies are needed to assess potential costs and to understand the implications for asset management.

1. **Most climate change impacts are likely to increase the potential for damage and service disruptions to infrastructure in Washington State, although some risks may decrease.** Studies to date on infrastructure impacts in Washington State and the Northwest have primarily focused on transportation infrastructure and coastal infrastructure (particularly as it relates to sea level rise). In general:

    - *Most climate change impacts evaluated are expected to increase risks to infrastructure.* Impacts that can increase risks to infrastructure include projections for more frequent or more severe flooding, extreme heat, extreme precipitation, storm surge, salt water intrusion, mudslides, erosion, wildfire, and inundation of low-lying areas.[1][2][3] Projected changes in extreme events are more likely to damage infrastructure than are changes in average conditions. [1][2][3]

    - *Some climate change impacts may slightly decrease risks or otherwise create minor benefits.* Projections for lower winter snowpack and warmer winter temperatures may decrease the frequency of snow-related closures on mountain highways.[1][2] However, extreme snowfall events will still occur, requiring continued maintenance of emergency response capacity.[2] Warmer spring and fall temperatures may extend the construction season, possibly improving cost efficiencies.

    - *Understanding the specific nature of climate change impacts on infrastructure often requires detailed, locally-specific studies.* Similar types of infrastructure can have very different responses to climate change, depending on its specific location, age, and how it is designed, maintained, and operated.[1][3] For example, while a small amount (+3 inches) of sea level rise may have important effects on flooding and stormwater management in Olympia, sea level rise impacts on State-owned coastal transportation infrastructure do not begin to emerge until much higher amounts (>+2 feet) of sea level rise occur.

2. Analysis by the Washington State Department of Transportation (WSDOT) finds that the majority of State-owned and operated transportation infrastructure is resilient to a range of projected climate change impacts, including sea level rise under +2 feet.[3]

However, all regions of the State include transportation infrastructure identified by WSDOT as being moderately or highly vulnerable to climate change (Figure 10-1).

- *Climate change exacerbates many issues already affecting WSDOT infrastructure*. This includes unstable slopes, flooding, and coastal erosion. In many cases, areas most likely to be affected by climate change are areas already experiencing problems or on "watch lists," such as bridges or roads that are being undercut by fast moving waters ("scour critical" transportation infrastructure) or chronic environmental deficiency sites.[A][3]

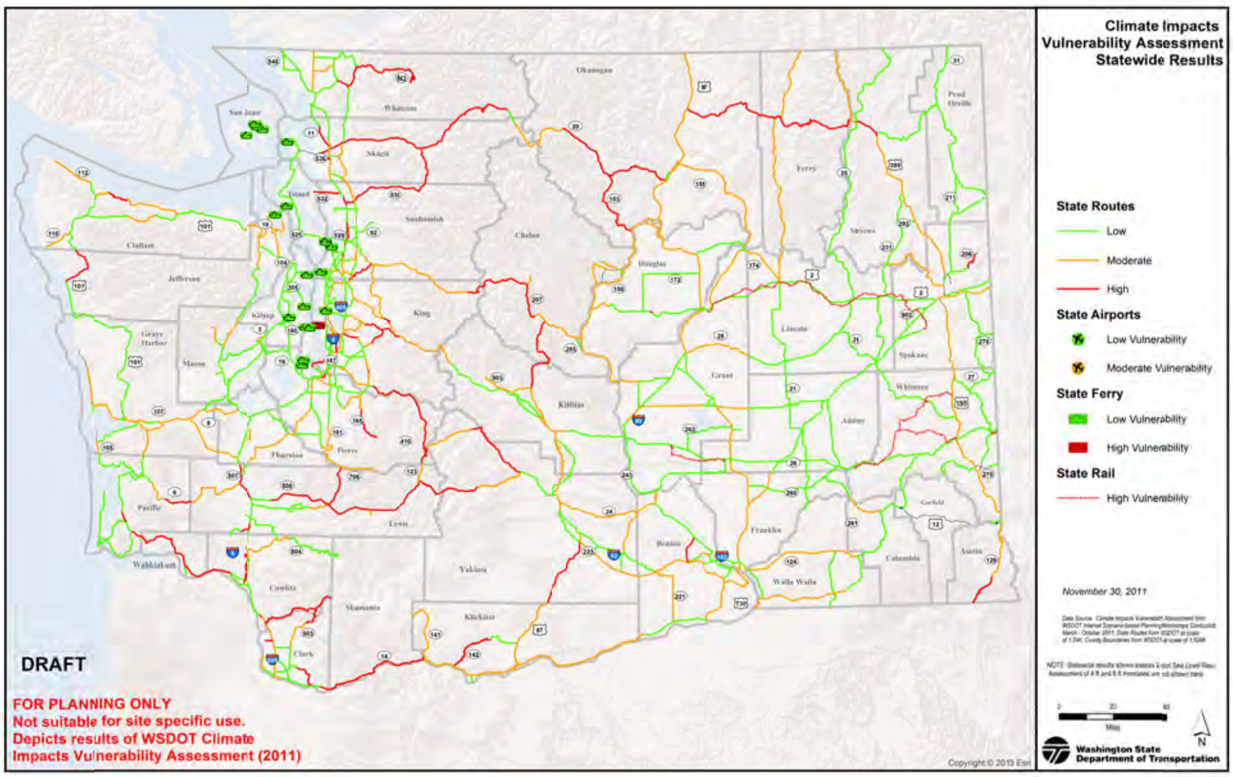

Figure 10-1. Summary of WSDOT's climate impacts vulnerability assessment for State-owned infrastructure. Results are for a range of temperature and precipitation changes and +2 feet of sea level rise. Red denotes roads or facilities that may be vulnerable to catastrophic failure along some portion of the road or at the facility. Yellow denotes roads or facilities that could experience temporary operational failures at one or more locations. Green indicates roads that could experience little or negligible impact. *Figure source: WSDOT 2011[3]*

[A] Chronic environmental deficiencies (CED) are locations along the state highway system where recent, frequent, and chronic maintenance repairs to the state transportation system are causing impacts to fish and fish habitat.

- *Climate change impacts on state highway, ferry, aviation, and rail operations may result in more frequent travel delays, closures, and re-routes.* For example, projected increases in wildfires and the potential for more dust storms tied to drought may cause more frequent temporary closures of airports and roads due to decreased visibility.

- *Vulnerability to climate change is higher in certain locations.* State-owned infrastructure is most likely to be impacted by climate change when located:

  - in the mountains,
  - above or below steep slopes,
  - in low-lying areas subject to flooding,
  - along rivers that are aggrading[B] due to glacier melt, and
  - in low-lying coastal areas subject to inundation from sea level rise.[3]

- *Many ongoing infrastructure improvements benefit climate resilience.* Many infrastructure improvements made for other reasons, such as seismic retrofits, fish passage improvements, culvert replacement, and drilled shaft bridges, also make infrastructure more resistant to climate change impacts.[3]

- *Newer infrastructure is generally more resilient to climate impacts, although the resilience of individual pieces of infrastructure can be affected by vulnerabilities in other parts of the system.* For example, most of WSDOT's newer bridges were found to be resistant to climate change impacts, including some that were resilient to up to +4 feet of sea level rise.[3] Road approaches to bridges are often more vulnerable than the bridges themselves, however.[3] As infrastructure ages, it becomes more vulnerable to extreme weather events and other climate related stressors affecting the structure.[1]

3. **Sea level rise increases the potential for damage to stormwater and wastewater systems, ports, and other public and private coastal infrastructure**.[C] Studies to date have focused on infrastructure in the Puget Sound region. Similar impacts are likely on the outer coast, however.

   - *Coastal wastewater and stormwater collection systems are likely to experience more problems with saltwater intrusion, corrosion, flooding, and inundation.*

     - *King County.* Sea level rise is projected to temporarily or permanently inundate three or more King County Wastewater Treatment Division facilities as early as 2050, depending on the combined effects of different sea level rise projections and the return frequency of specific storms sizes.[D][4] The County has also identified 20

B Aggrading refers to the raising of a stream or river bed due to sediment deposition. Glacial recession can cause aggradation below a glacier by exposing unstable sediments to erosion by rain or other factors.

C See Section 5 and Section 9 for more details on projected sea level rise.

D Periodic or permanent inundation of the Division's three lowest facilities occurs as early as 2050 with +1.8 feet (22 inches) of sea level rise and a +2.3 foot storm surge, currently considered a 50% probability (once every 2 years) storm surge event. As many as 14 facilities would be periodically or permanently inundated by 2100 with +4.17 feet of sea level rise (currently near the high-end of projections for Puget Sound) and a +3.2 foot storm surge (today's 1% annual probability storm surge).

facilities that are at risk of saltwater inflow into the conveyance system due to sea level rise, high tides, and storm surge by 2050.[5][6] This additional inflow can increase the volume of wastewater that has to be conveyed and treated, shortening equipment lifespan and increasing treatment costs.[7] King County estimates the current cost of treating saltwater already entering the system[E] during high tides to be $0.5 to $1.0 million annually.[F]

- *City of Olympia.* Modest amounts of sea level rise (as little as +3 inches) increase the likelihood that saltwater will enter the city's combined sewer system and be conveyed to the Lacey, Olympia, Tumwater, and Thurston County (LOTT) wastewater plant for treatment, potentially increasing operating costs.[8]

- *Low-lying urban and commercial infrastructure is likely to experience more frequent flooding or permanent inundation due to sea level rise.*

  - *Swinomish Indian Tribal Community.* Approximately 15% (over 1,100 acres) of Swinomish Indian Tribal Community Reservation lands are potentially at risk of inundation from sea level rise, including the tribe's primary economic development zone at the north end of Fidalgo Island and more than $100 million in residential and non-residential/commercial structures.[9]

  - *City of Olympia.* A small amount of sea level rise greatly increases the probability of flooding in downtown Olympia, potentially affecting public infrastructure, high-density development, and the City's historic district (Figure 10-2).[8][10]

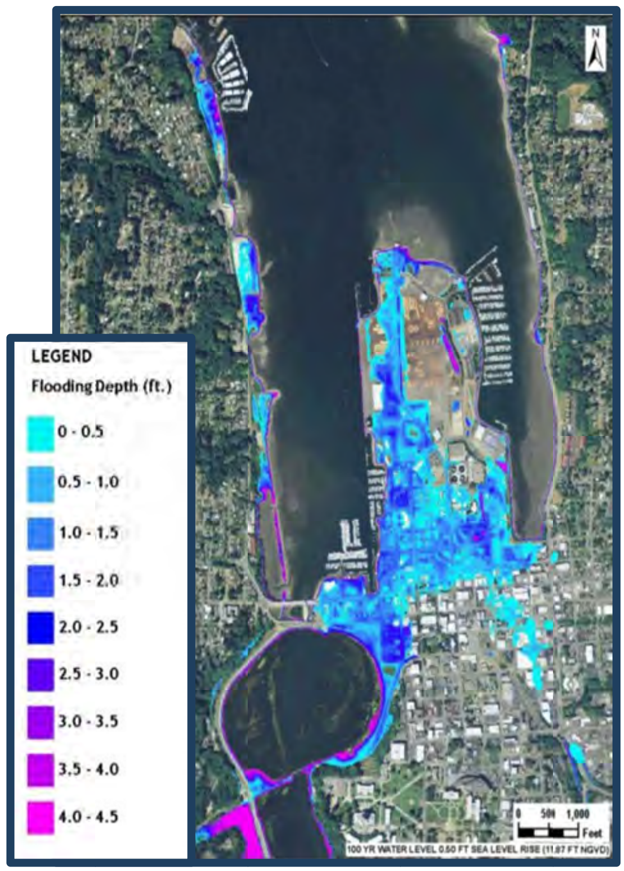

Figure 10-2. Projected flooding in the City of Olympia during a 100-year flood event with +6 inches of sea level rise. The projected depth of flood waters ranges from less than 6 inches to 4.5 feet, as indicated by the map colors. *Figure source: Simpson 2012*

E Sources for saltwater intrusion are leaky gates, overflow weirs, groundwater infiltration, and local sewer connections. Intrusion already occurs during high tides in the industrial area along the Duwamish Waterway, the Downtown Seattle Waterfront, and the Salmon Bay area near the Ballard Locks.[7]

F This cost estimate is specifically for saltwater treatment at the West Point Treatment Plant and does not include the cost of repairing and replacing damaged equipment. King County estimates that 3 to 6 million gallons of salt water enters the system each day, totaling about 1 to 2 billion gallons each year.[7]

    - A +3-inch rise in sea level makes it impractical to use common emergency response measures (sand bags and sealing catch basins) to control flooding associated with the 1-in-10 year (10% annual chance) flood event.[8]
    - A +6-inch rise in sea level shifts the probability of occurrence for the 100-year flood event in Olympia from a 1% to a 5.5% annual chance event.[8]

- *Port operations and infrastructure, including access to port facilities, are likely to be affected by sea level rise and increased coastal flooding.*[11][12] Climate-related impacts in other parts of the world[G] may also affect Washington's marine trades, although little is known about the specific nature and potential size of those impacts on port business.[1][11]

  - *Direct sea level rise impacts identified by the Port of Seattle:*[11]

    - Increasing rates of corrosion in docks and other infrastructure (e.g., piles, pile caps, and beams) exposed to saltwater more frequently as a result of sea level rise and increased tidal and storm surge reach.
    - Increased difficulty draining stormwater from port facilities due to increasing extreme precipitation and sea level rise.
    - Increased storm surge damage to port facilities.

  - *Impacts on low-lying areas serving Port of Seattle facilities.* Low-lying rail yards and roads serving the Port of Seattle are vulnerable to permanent inundation if sea level rise is +3 feet or greater. Lower amounts of sea level rise would likely result in more frequent temporary flooding of low-lying rail yards and roads. These impacts may affect the movement of goods in and out of port facilities regardless of how the port adapts its own infrastructure.[12]

4. **Projected increases in river flooding increase the risk of damage and service interruptions for infrastructure located in or near current floodplains.** In coastal drainages, sea level rise can exacerbate existing flood risks.[H]

   - *Larger flood events can reduce the effectiveness of existing levees and tide gates.* Flood flows in the Skagit basin are expected to more frequently exceed the design capacity of many of the basin's current dikes and levees, which are designed to the current 30-year return interval.[13] Sea level rise is also expected to reduce the effectiveness of tide gates for draining low lying cropland in the Skagit Valley.[13]

   - *The ability of dams to mitigate increasing flood risk may be limited.* Initial research for the Skagit basin suggests that reducing community vulnerability to increasing flood risk

[G] Reduced sea ice in Alaska and the Arctic is likely to extend the shipping season and create new opportunities for shipping, although it is unknown at this time if, when, and how these changes could affect Washington's ports. Climate impacts on trading partners in Asia may also affect traffic in and out of Washington's shipping ports, although it is not known how traffic would be affected specifically.

[H] Higher sea level can increase the extent and depth of flooding by making it harder for flood waters in rivers and streams to drain to the ocean or Puget Sound. Because of this, even modest river flooding can produce larger flood impacts in the lower portion of a river basin in the future relative to today's flood events.

and sea level rise will be more effective if those efforts focus primarily on improving management of the floodplain rather than on increasing flood storage in headwater dams (e.g., Upper Baker Dam).[I][13] This is because most of the streamflows causing the increased flood risk originate *below* the headwater dams.

- *Climate change increases the risk of flooding in Green River communities.* By the 2080s, streamflow volume for the 100-year (1%) flood event in the Green River as measured at Auburn could increase +15% to +76% relative to historical (1916-2006) climate for a medium greenhouse gas scenario.[J] A change of this upper magnitude shifts the probability of today's 1-in-500 year (0.2% annual probability) flood event on the Green River to a 1-in-100 year (1% annual probability) flood event.[14] Potential inundation mapping of the current 500-year flood event by the U.S. Army Corps of Engineers projects flood depths of 0-15 feet in the Kent-Auburn area.[K] This could affect residential and commercial properties, local roads, access to SR 167, and rail services in the area.

- *More sediment and flood debris in coastal rivers could affect port and ferry facilities.* Increased river flooding and reduced snow and ice cover in mountain watersheds is projected to increase the amount of sediment and flood debris carried by coastal rivers.[13] As a result, more frequent dredging near port facilities and ferry terminals is likely to be needed.[3][11] Damage to port facilities and ferry terminals is also possible due to the potential for more flood debris.[3]

5. **Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change on infrastructure.** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

   - *Increasing the resilience of State-owned transportation infrastructure:*

     - *Considering climate change and extreme weather events in project-level environmental review.* WSDOT is integrating the results of its vulnerability assessment into the environmental review of proposed projects. For example, the

I Preliminary results based on use of an integrated daily time step reservoir operations model built for the Skagit River Basin. The model simulated current operating policies for historical streamflow conditions and for projected flow for the 2040s and 2080s associated with the Echam5 global climate model run with the A1B greenhouse gas emissions scenario. For more on climate scenarios, see Section 3 of this report.

J Range based on data from the University of Washington Climate Impacts Group's Columbia Basin Climate Change Scenarios Project website (http://warm.atmos.washington.edu/2860/) for the A1B greenhouse gas emissions scenario. Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These scenarios are described in this report as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

K See "Potential Inundation, Shown as Simulated Water Depth, in Kent for a Peak Flow at Auburn Gage of 25,000 cubic feet Per Second" map produced by the U.S. Army Corps of Engineers. Existing levees are assumed to be intact but the map does not reflect ongoing levee fortification efforts, which could reduce flood risk. Map available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx

Mukilteo Multimodal Terminal environmental impact statement evaluated impacts of sea level rise and increased rainfall.

- *Long-term planning for corridor improvements.* Recent studies for US 2, SR 516 and SR 520 include vulnerability ratings developed by WSDOT in 2011. These plans discuss the level of risk, emergency response and hazard reduction strategies, and options for increasing resilience.

- *Preparing interstate and state routes in the Skagit River basin for climate change.* A federally funded pilot project will support development of a series of site-specific adaptation options to improve the resilience of Interstate 5 and state routes in the Skagit basin (Figure 10-3). These will complement flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

- *Increasing the resilience of King County infrastructure to increased flooding and sea level rise:*

  - *Levee improvements and flood-risk reduction activities.* King County formed a new Flood Control District in 2007 to increase capacity for addressing regional flood risks due to climate change and other factors. The creation of the new District resulted in a

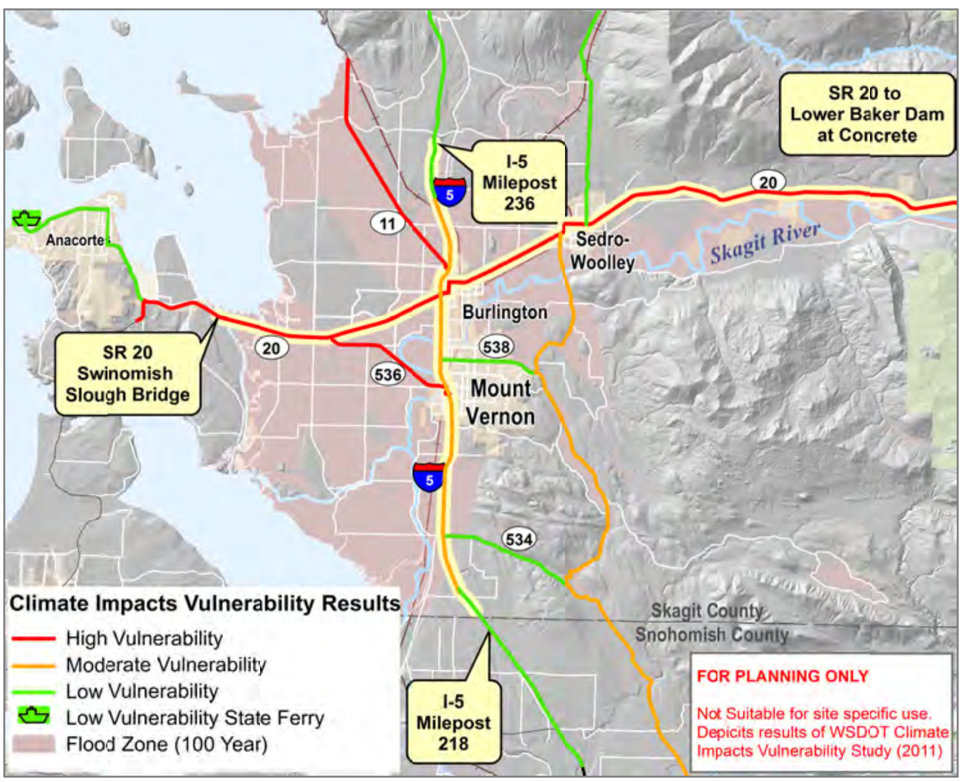

Figure 10-3. Study area for WSDOT's Preparing Interstate and State Routes in the Skagit River Basin pilot project, funded by the Federal Highway Administration. *Figure source: WSDOT.*

ten-fold increase in local funding[L] for flood risk reduction efforts. Accomplishments in 2012 included mapping flood hazards on the Sammamish River and the coastal shoreline, completing five levee repair projects and six projects that raised structures in flood zones, and purchasing sixty acres of floodplain on the Tolt, Snoqualmie, Cedar, and White rivers. Public ownership of this land and removal of structures will reduce flood risks and preclude development in these flood prone areas.[6]

  - *Widening bridge spans.* King County has replaced 15 short span bridges with wider span structures (including the Tolt Bridge over the Snoqualmie River) and 42 small culverts with large box culverts. These changes will increase resilience to major flooding. In many cases these wider structures also allow for the movement of a variety of wildlife along the river's edge during normal flows and elevated flood events thereby protecting wildlife connectivity between critical habitats.[6]

- *Redesigning the Anacortes Water Treatment Plant to reduce the potential for flooding.* Projections for increased flooding and sediment loading in the Skagit River led to design changes for the City of Anacortes' new $65 million water treatment plant (under construction in 2013). The altered design includes elevated structures, water-tight construction with minimal structural penetrations, no electrical control equipment below the (current) 100-year flood elevation, and more effective sediment removal processes.[10]

- *Planning for sea level rise in the City of Olympia.* In an effort to reduce flood risk in association with sea level rise, the City of Olympia conducted GIS mapping of projected inundation zones (shown previously in Figure 10-2), incorporated sea level rise considerations into the City's Comprehensive Plan and Shoreline Management Plan, and develops annual work plans to address key information needs.[15]

- *Planning for sea level rise at the Port of Bellingham.* Plans by the Port of Bellingham to redevelop the 228 acre Georgia Pacific site near downtown Bellingham include raising site grades approximately +3 to +6 feet in areas with high value infrastructure as a buffer against sea level rise.[16]

- *Evaluating the robustness of the Seattle sea wall design to sea level rise.* An evaluation of sea level rise impacts on design considerations for the new Seattle sea wall found that the current sea wall height would be three feet above the new still water level[M] with 50 inches of sea level rise. As a result, the City determined that it was not necessary to build a higher structure to accommodate sea level rise over the next 100 years.[N]

- *Increasing capacity to manage extreme precipitation events in Seattle.* Seattle Public Utilities' RainWatch system[O] provides operators and decisions makers with 1-hour precipitation forecasts and 1- to 48-hour rain accumulation totals that can be used to

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[L] Funding for the Flood Control District comes from a county-wide property levy of 10 cents per $1,000 assessed value. This amounts to $40 per year on a $400,000 home. The levy raises roughly $36 million a year (http://www.kingcountyfloodcontrol.org/).

[M] The Mean Higher High Water, which is the average of the highest daily tide at a place over a 19-year period.

[N] See http://sdotblog.seattle.gov/2013/01/23/sea-level-and-the-seawall/ for more details.

[O] See http://www.atmos.washington.edu/SPU/

manage extreme precipitation risks at the neighborhood- or basin-scale in real-time. RainWatch represents a "no regrets" climate change adaptation strategy by improving operations response to extreme events today and in the future.

- *Adaptation planning for multiple climate-related hazards: the Swinomish Indian Tribal Community.* The Swinomish Indian Tribal Community is implementing adaptation recommendations developed in 2010. This includes revisions to shoreline codes, development of a detailed coastal protection plan for the most vulnerable 1,100 low-lying acres on the north end of the Reservation, development of a Reservation-wide wildfire risk reduction program, and development of a system of community health indicators to measure knowledge of and impacts of climate change within the tribal community.[9]

[1] MacArthur, J. et al. 2012. *Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska.* Region X Northwest Transportation Consortium, OTREC-RR-12-01, WA-RD #772.1.

[2] Hamlet, A.F. 2011. Impacts of climate variability and climate change on transportation systems and infrastructure in the Pacific Northwest. White Paper prepared for the Western Federal Lands-Highway Division by the Climate Impacts Group, University of Washington, Seattle.

[3] (WSDOT) Washington State Department of Transportation. 2011. *Climate Impacts Vulnerability Assessment.* Report prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, Olympia, Washington.

[4] (KCWTD) King County Wastewater Treatment Division. 2008. *Vulnerability of Major Wastewater Facilities to Flooding From Sea Level Rise*. Report prepared by the King County Wastewater Treatment Division, Department of Natural Resources and Parks. Seattle, WA.

[5] (KCWTD) King County Wastewater Treatment Division. 2012. *Hydraulic Analysis of Effects of Sea-Level Rise on King County's Wastewater System*. Report prepared by the King County Wastewater Treatment Division, Department of Natural Resources and Parks. Seattle, WA.

[6] King County. 2013. *2012 Annual Report of King County's Climate Change, Energy, Green Building and Environmental Purchasing Programs*. Seattle, WA.

[7] (KCWTD) King County Wastewater Treatment Division. 2011. *Saltwater Intrusion and Infiltration into the King County Wastewater System*. Report prepared by the King County Wastewater Treatment Division, Department of Natural Resources and Parks.

[8] Simpson, D.P. 2012. *City Of Olympia Engineered Response to Sea Level Rise.* Technical report prepared by Coast Harbor Engineering for the City of Olympia, Public Works Department, Planning and Engineering.

[9] Swinomish Indian Tribal Community. 2010. *Swinomish Climate Change Initiative: Climate Adaptation Action Plan*. La Conner, WA.

[10] Reeder, W.S. et al. 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

[11] Huang, M. 2012. *Planning for Sea Level Rise: The current state of science, vulnerability of Port of Seattle properties to sea level rise, and possible adaptation strategies*. Report prepared for the Port of Seattle, WA.

[12] Huppert, D.D. et al. 2009. Impacts of climate change on the coasts of Washington State. Chapter 8 in *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate,* Climate Impacts Group, University of Washington, Seattle, Washington.

[13] Hamlet, A.F. and S-Y. Lee. 2011. *Skagit River Basin Climate Science Report*. Prepared for Envision Skagit and Skagit County. The Climate Impacts Group, University of Washington, September, 2011.

[14] (USACE) U.S. Army Corps of Engineers. 2012. *Assembly of Design Flood Hydrographs for the Green River Basin: Summary Report for Flood Plain Management Services Program*. Seattle District Army Corps of Engineers, September 2012.

[15] "Addressing Sea Level Rise and Flooding in Olympia" case study, prepared for the Successful Adaptation in the Coastal Sector: Washington Practitioners Workshop, sponsored by the Climate Impacts Group at the University of Washington, March 20, 2013.

[16] "Adapting to Sea Level Rise at the Port of Bellingham" case study, prepared for the Successful Adaptation in the Coastal Sector: Washington Practitioners Workshop, sponsored by the Climate Impacts Group at the University of Washington, March 20, 2013.

SECTION 11

How Will Climate Change Affect Agriculture in Washington?

Washington crops and livestock will be affected by climate change via warming temperatures, rising atmospheric carbon dioxide, increasing water stress, declining availability of irrigation water, and changing pressures from pests, weeds, and pathogens. Different crops and locations will experience different impacts. Because of the high adaptability in most agricultural systems, overall vulnerability is low. However, given the combination of increasing water demands and decreasing supply in summer, water stress will continue to be a key vulnerability going forward. Since 2007, new studies have quantified impacts on specific crops and locations, and evaluated the combined effects of warming and CO2. New research has also begun to integrate impacts and economic modeling as a means of assessing market influences and the potential for adaptation.

1. **Washington State agriculture is projected to be affected by warming temperatures, rising carbon dioxide (CO_2) concentrations, and changes in water availability.**[1] Some changes may be beneficial while others may lead to losses – the consequences will be different for different crops and locations (Figure 11-1). Ultimately, impacts will reflect a combination of all of the factors listed below, the specific changes in climate that will occur, and the extent and effectiveness of adaptive actions that are taken in anticipation of the effects of climate change.

   - *Warming.* The longer growing seasons and fewer winter freezes projected for the region (Section 5) will benefit many crops and allow greater flexibility in crop selection, but in some cases may result in increased incidence and severity of pests, weeds, and diseases. Warming may decrease crop yields by accelerating the rate of development, and can have negative effects on wine grapes and some species of tree fruit due to insufficient winter chilling. Warmer summer temperatures will also result in increased heat stress and greater drought stress, affecting many Northwest crops and livestock.

   - *Increasing CO_2 concentrations.* Increasing levels of atmospheric CO_2 may result in increased productivity in some crops (referred to as "CO_2 fertilization"). In the near term, if sufficient water is available, these benefits can outweigh the negative effects of warming. Invasive species may benefit as well; some as a result may gain a competitive advantage over native species and crops.

   - *Changing precipitation.* Although year-to-year variations will continue to dominate annual and seasonal changes in precipitation (Section 3 of this report), the general tendency towards wetter winters will increase water available in spring but may also impede spring planting due to wetter soils. Projected decreases in summer precipitation would result in increased water stress in both rain-fed and irrigated agriculture.

   - *Irrigation water supply.* Water supply is a chief concern for Northwest agriculture, where the growing season coincides with the dry season. Projected reductions in summer

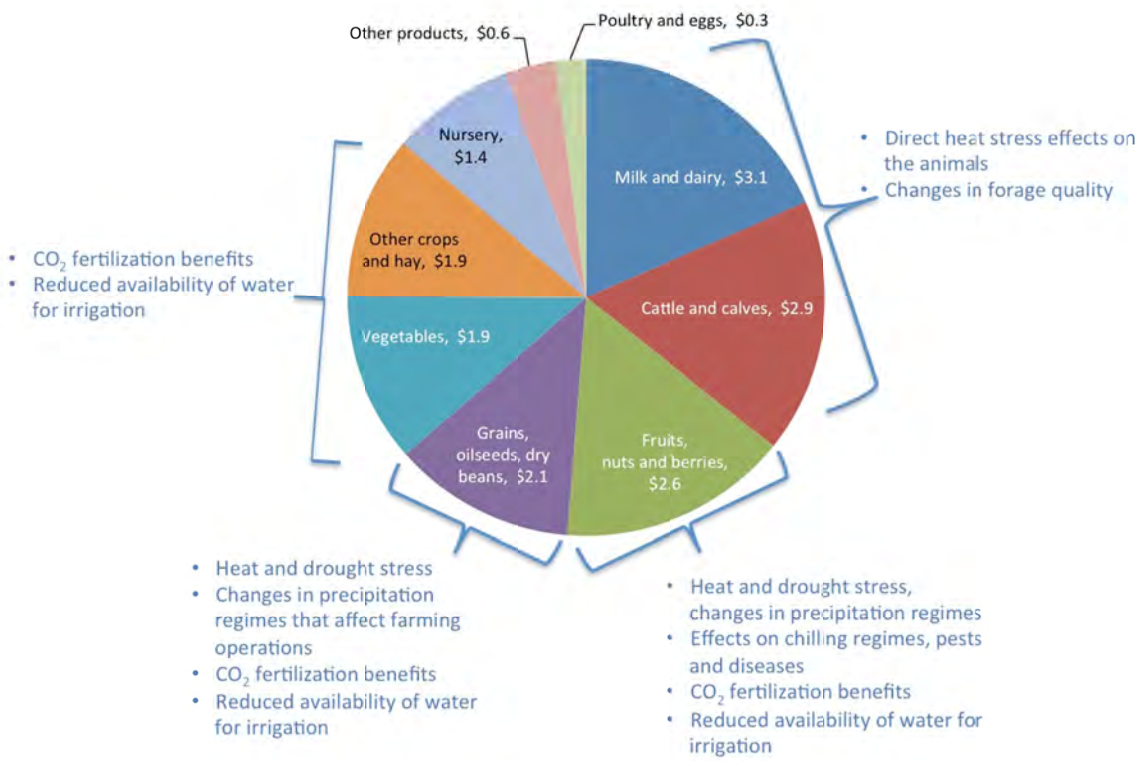

Figure 11-1. Climate change impacts on Pacific Northwest agriculture. Pacific Northwest agricultural commodities, with potential climate change impacts listed for each sector. Market values are shown in $ (billion), with a total value of $16.8 billion. *Figure source: Eigenbrode et al., 2013.*[1]

streamflow, combined with increasing evaporative demand (Section 6 of this report) will pose continued challenges to agricultural operations. In the Yakima basin, for example, water shortage years – years with curtailed water delivery to junior water rights holders – are projected to increase from 14% of years historically (1979-1999) to 43 to 68% of years by the 2080s (2070-2099) for a low and a medium greenhouse gas scenario, respectively.[A][B][2]

- *Climate extremes and fire.* Projected increases in the frequency of heat waves and heavy rainfall events (Section 5 of this report), and the area burned by wildfire (Section 7) can

[A] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

[B] Average projected change for ten global climate models. Range is from two greenhouse gas scenarios: B1 (low) and A1B (medium).

all have deleterious effects on crops and livestock and potentially increase risks of damage from pests, invasives, and disease.

- *Additional research is needed to quantify the above impacts on different crops and locations.* To date, most studies have focused on one specific crop in a handful of locations, and only consider a subset of all relevant climate impacts on production. Impacts can differ substantially for different crops and locations, and little is known about the combined effects of all of the changes listed above.

2. **Annual crops in Washington State are projected to experience a mix of increases and decreases in production, primarily in response to warmer temperatures and CO_2 fertilization.** Projections are based on changes in temperature, precipitation, and evaporative demand, but do not consider other factors such as changes in water availability and pests.[C]

   - *Winter wheat yields are projected to increase.* Projected change is +23 to +35% in four eastern Washington locations by the 2080s (2070-2099, relative to 1975-2005), under a medium greenhouse gas scenario.[D][3]

   - *Spring wheat yields are projected to either remain the same or decrease.* Projected change ranges from no change to −11% in the same four eastern Washington locations by the 2080s (2070-2099, relative to 1975-2005) for a medium greenhouse gas scenario.[D][3]

   - *Potato yields are projected to decrease slightly*. Projected declines in potato yields are small: −3% for Othello, WA by the 2080s (relative to 1975-2005) under a medium greenhouse gas scenario.[E][3] Warmer temperatures can result in lower quality potatoes.[4]

3. **Perennial crops in Washington State are projected to experience a mix of increases and decreases in response to a longer growing season, reduced winter chilling, and CO_2 fertilization.**

   - *Apple yields are projected to increase*. Under a medium greenhouse gas scenario, apples in Sunnyside Washington (near Yakima) are projected to increase in yield by +16% for the 2080s (2070-2099, relative to 1975-2005).[3] However, these results assume no change in water availability – since apples are a relatively water-intensive crop, production could be negatively affected by projected decreases in water availability (Section 6).

   - *Wine grapes require winter "chilling"; new vineyards take years to establish.* Wine grapes, especially the cool climate varieties that are typically produced in Washington –

[C] Impacts on specific crops and locations described in this document represent examples rather than an exhaustive list of potential regional impacts.

[D] Changes in crop yield were simulated for 4 eastern Washington locations: Pullman, St. John, Lind, and Odessa, using the average projection from four global climate models (PCM1, CCSM3, ECHAM5, and CGCM3) and a medium greenhouse gas scenario (A1B; see Section 3). The range in projections is a result of differences in growing season and precipitation at these four locations.

[E] Based on the average projection from four global climate models (PCM1, CCSM3, ECHAM5, and CGCM3) and a medium greenhouse gas scenario (A1B; see Section 3).

e.g., Pinot Gris, Pinot Noir – require winter "chilling" conditions in order to produce fruit of sufficient quality. Annual frost-free days are projected to decrease by −35 days on average by the 2050s (2041-2070, relative to 1970-1999) under a high greenhouse gas scenario.[F][5] There are significant costs associated with shifting to warmer grape varieties: grapes are a multi-decade investment for farmers, taking 4 to 6 years to mature and remaining productive for several decades.

4. **Pests are affected by warming, which can increase growth and reproductive success, and alter their vulnerability to predators.** Projections are limited to a small selection of species and locations, and do not include the combined effects of changing crops, predators, and other factors.

   - *Codling moth (Cydia pomonella) populations are expected to increase, affecting apples.* The codling moth, which is the main pest attacking apples in Washington, is projected to reproduce more rapidly with warming. For Sunnyside, Washington (near Yakima), warming under a medium greenhouse gas scenario is projected to cause adult moths to hatch about 2 weeks earlier and increase the fraction of the third generation hatch by +81% by the 2080s (2070-2099, relative to 1975-2005) for a medium greenhouse gas scenario.[E][3]

   - *Populations of the cereal leaf beetle (Oulema melanopus) are expected to increase*. Temperatures in the Northwest are projected to become more favorable for the invasive cereal leaf beetle. Preliminary work also indicates that the parasitoid wasp (*Tetrastichus julis*), which attacks cereal leaf beetles, may become less effective as a population control as a consequence of warmer springs.[6]

   - *Parasitic wasp (Cotesia marginiventris) populations are projected to decrease*. Reproduction by this wasp, which attacks caterpillars, including those species affecting Northwest crops, is projected to decline substantially in response to warming, potentially allowing caterpillar populations to increase.[7]

5. **Livestock are affected by climate via impacts on food sources as well as the direct effects of heat stress.** Research has generally focused on the isolated effect of warming or CO_2 fertilization in specific locations, and does not include factors such as changing water availability, fire risk, and invasive species.

   - *Rangeland grasses are expected to have increased growth but decreased digestibility.* Experiments have shown increased forage growth in grazing lands in response to both elevated CO_2 concentrations[8] and warming[9]. However, these studies also found a decrease in digestibility of grasses grown under these conditions and a changing balance of grass species, as some benefit more from the changes than others. Invasive species may also benefit from warming and rising CO_2 concentrations[10]. Warming is likely to decrease soil water availability, especially in late summer, resulting in decreased forage growth and an increased risk of fire.[11][12]

[F] Projection based on regional climate model simulations under a high greenhouse gas scenario (A2; see Section 5 of this report).[5]

- *Increases in forage and pasture crop production, decreases in digestibility.* Experiments indicate that CO_2 fertilization will result in reduced nutritional value in these crops, for instance finding up to a −14% reduction in digestibility for livestock in response to a doubling of CO_2.[13] In spite of decreases in nutritional value, alfalfa production is projected to increase by +27 to +45% in response to a doubling of CO_2 and a warming of 4.5°F.[G][14] Projected decreases in irrigation water supply (Section 6 of this report) may limit forage production.

- *Impacts on livestock are minor.* Livestock eat less in response to heat stress, are less efficient at converting feed into protein (either dairy or meat), and have reduced reproductive rates. Dairy cows in Washington are projected to produce slightly less milk in response to heat stress – about −1% less by the 2080s (2070-2099, relative to 1970-1999) for a medium greenhouse gas scenario.[15] Preliminary results project that beef cattle will mature more slowly, taking +2.2 to +2.5% longer to achieve finishing weights in response to a doubling of CO_2, which is projected to occur by about mid-century under a high greenhouse gas scenario.[16]

6. Agriculture is expected to be very adaptable to changing circumstances, although some crops and locations are more vulnerable than others.

- *Farming and ranching are inherently flexible.* Agricultural production already involves adapting to changing weather and climate conditions. This flexibility will facilitate adaptation to climate change.

- *Agriculture in the Pacific Northwest is very diverse.* The diverse climates of the Pacific Northwest host a wide range of agricultural production. This will likely facilitate adaptation, as some crops fare better than others.

- *Selective breeding and improved management practices could outpace climate impacts.* For instance, the pace of recent changes in livestock production – in response to changes in management and breeding – is much larger than existing projections of climate change impacts.[15]

- *Western Washington agriculture is likely less vulnerable than the interior.* Greater water availability, access to urban markets, and the milder climate of coastal Washington will likely make it easier for agriculture to adapt in this region. Areas in the interior, especially semi-arid regions with limited access to irrigation water, have much less capacity for adaptation.

- *Transitioning to new crops can require substantial investments in time and money.* Wine grapes and apples, for instance, require years to establish and begin generating revenue.

- *Some subsidies and conservation programs could inhibit adaptation.* Some policies and regulations – including crop subsidies, disaster assistance, conservation programs,

[G] 4.5°F is near the middle of the range projected for mid-century (2041-2070), relative to 1950-1999, under a low greenhouse gas scenario (RCP 4.5).

environmental regulations, and certain tax policies – may reduce the incentive for adaptation.

7. **Since 2007, new studies have quantified impacts on specific crops and locations, evaluated the combined effects of warming and CO_2, and begun to integrate climate impacts with economic modeling of market influences and adaptation.**

- *New advancements include the following:*
    - Improved understanding of climate impacts on specific crops and locations, and studies of impacts on new species not previously assessed.
    - More information on the combined effects of warming, CO_2 fertilization, predator-prey interactions, and other factors impacting the response of crops to climate change.
    - New efforts to integrate climate impacts modeling with economic models that consider market influences and potential for adaptation.
- *Available studies are still limited to a subset of Washington crops and locations.* Research is needed to quantify impacts on additional crop, weed, and pest species; assess the synergistic effects of multiple stressors on yields; and identify vulnerabilities in the food system and barriers to adaptation.[17]

Specific Information and Resources to Support Adaptation to Changes in Agriculture
The following resources are suggested for additional information beyond the summaries provided in this document.

- **Integrated modeling of climate change, agriculture, and economics.** The *Regional Approaches to Climate Change for Pacific Northwest Agriculture* integrates climate modeling with research and modeling of economics, crop systems, and agriculture. Driven by stakeholder needs, this research will evaluate the combined effects of climate change and adaptation on Pacific Northwest agriculture. www.reacchpna.org
- **Water supply and demand forecast.** The *Columbia River Basin long-term water supply and demand forecast*[18] provides historical data and projected changes in water supply and agricultural demand as a result of climate change. Other demand forecasts (municipal, hydropower, and instream flows) do not incorporate climate change. Results are available for each individual Water Resource Inventory Area (WRIA) in eastern Washington and the Columbia River basin as a whole. http://www.ecy.wa.gov/programs/wr/cwp/forecast/forecast.html
- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. These are based on projections in IPCC 2007.[19] http://warm.atmos.washington.edu/2860,[19] http://cses.washington.edu/cig/
- **Modeling the interactions between climate, water, carbon, and nitrogen.** The *Regional Earth System Modeling Project (BioEarth)* links global climate model projections with a regional model that simulates complex interactions between the land, water, and atmosphere, including vegetation changes, water and nutrient cycling, and agriculture. www.cereo.wsu.edu/bioearth/
- **Modeling the interactions between water resources, water quality, climate change, and human decisions.** The *Watershed Integrated Systems Dynamics Modeling (WISDM)* project is focused on agricultural and urban environments. A primary goal is to engage stakeholders in the development of scientifically sound and economically feasible water policy. www.cereo.wsu.edu/wisdm/

1 Eigenbrode, S. D. et al., 2013. Agriculture: Impacts, Adaptation, and Mitigation. Chapter 6 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

2 Vano, J. A. et al., 2010. Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. *Climatic Change*, *102*(1-2), 287-317.

3 Stöckle, C. O. et al., 2010. Assessment of climate change impact on Eastern Washington agriculture. *Climatic change*, *102*(1-2), 77-102.

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[17] Miller, M. et al., 2013. Critical research needs for successful food systems adaptation to climate change. *Journal of Agriculture, Food Systems, and Community Development, 3*(4)*,* 161-175. doi: 10.5304/jafscd.2013.034.016

[18] Yorgey, G. G. et al., 2011. *Technical Report – 2011 Columbia River Basin Long-Term Water Supply and Demand Forecast.* WA Department of Ecology, Ecy. Pub. #11-12-011.

[19] (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[20] Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean* 51(4): 392-415. doi: 10.1080/07055900.2013.819555

SECTION 12

How Will Climate Change Affect Human Health in Washington?

Studies of climate change impacts on human health in the Pacific Northwest are limited. Research to date finds that climate change is likely to increase rates of heat related illnesses (including heat exhaustion and stroke); respiratory illness (e.g., allergies, asthma); vector-, water-, and food-borne diseases; and mental health stress. These impacts can lead to increased absences from schools and work, emergency room visits, hospitalizations, and deaths. Efforts to adapt Washington's public health systems are in the early stages due in part to the limited information available to agencies.

1. **Climate change is expected to affect both the physical and mental health of Washington's residents by altering the frequency, duration, or intensity of climate-related hazards to which individuals and communities are exposed.[A][1]** In some cases (e.g., disease vectors), climate change may also lead to the introduction of new risks.

   - *Health impacts are under-studied.* A small but growing number of local studies provide more regionally-specific information about the types and scale of human health impacts likely to be experienced in the Pacific Northwest as a result of climate change. However, the area remains under-studied and no studies on the individual and societal costs of climate change impacts on human health have been done to date in the Pacific Northwest region.

   - *Health impacts stem from a wide range of projected climate change impacts.* Human health in Washington State is likely to be affected by projected increases in extreme heat events, flooding, sea level rise, drought, and forest fires; increased allergen production and summer air pollution; and changes in the types, distribution, and transmission of infectious diseases (e.g., West Nile Virus) and fungal diseases (Table 12-1).

   - *Health impacts are diverse.* Anticipated health impacts include higher rates of heat related illnesses (including heat exhaustion and stroke); respiratory illness (e.g., allergies, asthma); vector-, water-, and food-borne diseases; and mental health impacts.[1][2]These impacts can lead to increased absences from schools and work, emergency room visits, hospitalizations, and deaths.

   - *Some populations are more vulnerable to health impacts.* Vulnerable populations include those over age 65, children, poor and socially isolated individuals, the mentally ill, outdoor laborers, and those with cardiac or other underlying health problems (e.g., asthma or reduced immunity due to chemotherapy, illness, or disease).[1][2]

[A] Unless otherwise noted, material in this document is derived or directly quoted from Bethel et al. 2013,[1] prepared as part of the U.S. National Climate Assessment.

2. Washington's state and local governments are in the early stages of identifying how climate change may affect human health and public health infrastructure.

- *Washington State Dept. of Health.* The Washington State Department of Health is:

    - developing strategies to support enhanced emergency preparedness and response, specifically focused on heat waves;
    - looking at ways to enhance how the agency can track air quality and disease to detect and address public health threats; and
    - partnering with communities to build environments that manage growth, decrease urban sprawl, support efficient transportation modes, and offer protection from flooding and landslides.[3]

    The Department of Health has also developed the Washington Tracking Network (WTN), which is part of a national effort to develop better and more integrated ways of sharing environmental public health data that can be used to track and analyze climate-related health impacts over time.[B]

- *King County.* Health-related adaptation activities at King County include the following:

    - *Climate change health indicators.* King County is tracking human health and economic impact indicators to help monitor how climate change may be affecting key issues in the County.[C]

    - *Heat impacts assessment.* King County is partnering with the University of Washington to identify and plan for the impact of climate change on human health, including synthesizing data on the effects of changing temperature on illness and death in King County.[4]

[B] See https://fortress.wa.gov/doh/wtn/WTNPortal//Help/AboutTracking.aspx for more information.
[C] More information available at: http://www.kingcounty.gov/environment/climate/climate-change-resources/impacts-of-climate-change/health-economic-impacts.aspx

Table 12-1. Summary of projected Pacific Northwest climate change impacts and related projected human health impacts, based on Bethel et al. 2013[1] and other sources. More details, where available, on the projected climate change impacts listed here are included in other sections of this report. Few studies have been conducted to date on climate change impacts to human health in the Pacific Norwest. The health impacts listed here represent examples rather than an exhaustive list of potential impacts.

Projected Climate Change Impact *General Trend*	*Specific Changes Projected*	**Related Human Health Impacts**
More extreme heat events [D]	• The number and duration of days above 90°F increases throughout the state.[5] • Increases in number of days in Washington above 95°F annually range from less than 3 days to up to 10 days by 2050s, compared to 1980-2000, depending on the greenhouse gas scenario and location.[E][5]	Increased potential for:[1] • worsening of existing problems with respiratory illness, cardiovascular disease, and kidney failure; • more heat exhaustion, heart attacks, strokes, and drownings; and • more heat related deaths, although the projected numbers vary widely. Related information: • One study for the greater Seattle area projected an additional 157 annual heat-related deaths by 2045 under a moderate (A1B) greenhouse gas emissions scenario.[F][2] Another study projected only an additional 14 annual heat-related deaths in Seattle for approximately the same time period under a very high (A1FI) emissions scenario.[G][6]

D The temperature thresholds used to define an extreme heat event will vary by location. The thresholds used for Seattle and Spokane in Jackson et al. 2010 were 92.5°F and 100.6°F, respectively. For more on projected changes in extreme events, see this report's section on projected Pacific Northwest climate.

E Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 3 for more details.

F Study inclusive of King, Pierce, and Snohomish Counties. Projected change in mortality for those over age 45, relative to a base period of 1980-2006. Projections based on the average of the climate change scenarios derived from two global climate models and two greenhouse gas emissions scenarios: the PCM model run with the B1 emissions scenario and the HADCM1 model run with the A1B emissions scenario. Population levels were held constant at year 2025.

G Projected change in mortality relative to a base period of 1975-95. Projections cited here based on modeling of the A1FI greenhouse gas emissions scenario with the PCM global climate model.

Projected Climate Change Impact *General Trend*	*Specific Changes Projected*	**Related Human Health Impacts**
Increased winter flooding[H]	• More winter flooding is expected west of the Cascades. The largest projected changes are found in mid-elevation mixed rain and snow basins, which are most sensitive to warming winter and spring temperatures.[I][7] • Some higher elevation snow dominant watersheds will see increasing flooding, while others experience decreased flooding.[7]	Increased potential for:[1] • injuries and death, • exposure to hazardous and toxic substances released and spread by flooding, • respiratory illness from mold and microbial growth in flood-impacted structures, • contamination of, or disruption to, public water supplies,[8] • mental health impacts[J] associated with damage to homes, communities, places of employment.
Increased drought[H]	• Lower summer streamflows, warmer summer temperatures, and earlier spring snowmelt contribute to increased risk of drought, particularly in eastern Washington. • Drought impacts can affect food production, the potential for wildfire in forests and rangeland, water supply, and water quality.	Increased potential for:[1] • respiratory illness associated with increased forest fires (see next row), • reduced water supplies, including impacts to groundwater supplies used by private wells, and • mental health effects.

[H] For more on projected impacts on Pacific Northwest hydrology, see Section 6.

[I] Projections for specific Washington locations can be found here: http://warm.atmos.washington.edu/2860/products/sites/

[J] Mental health impacts are common to most climate change impacts. Potential mental health impacts include: emotional and psychological stress associated with weather-related trauma, including loss of homes or places of employment, financial concerns, recovery and rebuilding, family pressure, loss of leisure and recreation, loss of security; physical impacts of stress, including post-traumatic stress disorder, high blood pressure, and unhealthy coping mechanisms (e.g., increased alcohol or tobacco use, poor dietary habits); non-trauma related anxiety and depression related to feelings of losing control over a situation, or uncertainty about the future; and grief and despair over the loss, or potential loss, of culturally important resources, traditions, or places.

Projected Climate Change Impact *General Trend*	 *Specific Changes Projected*	**Related Human Health Impacts**
Increased forest fires[K]	• Most models project increases in the amount of area burned in Washington by forest fires. The projected change is less than 100% to greater than 500% by mid-century.[9] • Risk of fires is greatest east of the Cascades, but air quality around the state is affected.	Increased potential for:[1] • more asthma, bronchitis, and pneumonia hospital admissions; • missed school and work days; • mental health effects due to potential or actual loss of property and disruptions to communities. Related information: • Smoke from the 2012 wildfires in Chelan and Kittitas Counties contributed to an additional 350 hospitalizations for respiratory conditions and 3,400 student absences from school.[L] • Studies in California found that fine particulate matter concentrations in the air were higher and more toxic during wildfires that occurred in 2003 and 2007.[10]
Increased production of allergens	• The pollination season is projected to lengthen.[11][12] • The amount of allergy-causing proteins in pollen is also projected to increase.[12]	Increased potential for:[1] • more severe and longer-lasting allergy symptoms; • asthma attacks, and • missed school and work days.
Increased air pollution	• Warmer summer air temperatures are expected to lead to the production of more ground-level ozone, particularly in urban areas. This could slow air quality improvements made in recent decades in urban areas.[2]	Increased potential for:[1] • Cardiovascular disease, respiratory disorders (e.g., asthma), and mortality. Related information: • Under a high emissions scenario (A2), the annual number of additional May-September deaths due to ozone is projected to increase from 69 in 1997-2006 to 132 by mid-century in

K For more on projected impacts on Pacific Northwest forests and forest fire risk, see this report's section on forests.
L Glen Patrick, Manager of the Environmental Epidemiology, Washington State Dept. of Health, personal communication

Projected Climate Change Impact *General Trend*	 *Specific Changes Projected*	**Related Human Health Impacts**
		King County, and from 37 (1997-2006) to 74 in Spokane.[2]
Infectious, vector-born, and fungal diseases	• Higher temperatures may increase the incidence of West Nile virus. The impact of climate change on Lyme disease, hantavirus, malaria, and dengue in the PNW is unknown. [1] • Warmer ocean temperatures increase the risk of *Vibrio parahaemolyticus* outbreaks in oysters and shellfish, which can cause illness in humans. [1] • Projected increases in precipitation and flooding increase the potential for *Cryptosporidium* contamination in water supplies. [1]	Increased potential for:[1] • More illness and mortality associated with infectious diseases. The emergence of new diseases and/or expansion of existing diseases is expected to exacerbate these impacts.
Harmful Algal Blooms (HABs)	• Models project the window of opportunity for *A. catenella*, which can cause illness or death via paralytic shellfish poisoning, in Puget Sound to increase by an average of 13 days by the end of the century under a moderate (A1B) greenhouse gas emissions scenario.[13]	Increased potential for:[1] • More illness and mortality associated with infectious diseases.
Sea Level Rise	• Sea level is projected to increase +4 to +56 inches overall in Washington State by 2100, relative to 2000, although some locations may experience sea level fall because of uplift caused by plate tectonics. [M][14] • Associated impacts with the potential to impact human health include inundation of low-lying areas, increased coastal river flooding, increases in the frequency of today's extreme tidal/storm surge events, and changes in coastal habitats that may affect culturally and economically important species.	Increased potential for: [1] • Mental health stress associated with storm surge damage and loss of culturally or economically important areas to inundation, erosion, or storm surge. • Reduced drinking water quality due to saltwater intrusion into coastal aquifers and rivers.

[M] Mean value: +24 inches (± 12 inches) for a moderate (A1B) greenhouse emissions scenario for 2100, relative to 2000. The range values reported in the table are for the lowest (B1) to the highest (A1FI) greenhouse gas emissions scenarios used prior to the release of the CMIP5 RCP scenarios. For more on sea level rise and coastal impacts, see this report's sections on projected Pacific Northwest climate and projected impacts on oceans and coasts.

[1] Bethel, J. et al. 2013. Human health: Impacts and adaptation. Chapter 7 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

[2] Jackson, J.E. et al. 2010. Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. *Climatic Change* 102(1-2): 159-186, doi: 10.1007/s10584-010-9852-3.

[3] Washington State Department of Health. 2012. *Strategic Plan 2012-2016*. Olympia, WA. Available at: http://www.doh.wa.gov/Portals/1/Documents/1000/StrategicPlan2012-16.pdf

[4] King County. 2012. *Strategic Climate Action Plan.* December 2012. Seattle, WA. Available at: http://your.kingcounty.gov/dnrp/climate/documents/2012_King_County_Strategic_Climate_Action_Plan.pdf

[5] Kunkel, K. E. et al., 2013: Part 6. Climate of the Northwest U.S., NOAA Technical Report NESDIS 142-6, 76 pp.

[6] Greene, S. et al. 2011. An examination of climate change on extreme heat events and climate-mortality relationships in large U.S. Cities. *Weather, Climate, and Society* 3: 281-292. doi: 10.1175/WCAS-D-11-00055.1

[7] Tohver, I. et al., 2013. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. *Journal of the American Water Resources Association*, in press.

[8] Howard, G. and J. Bartram. 2010.*Vision 2030: The Resilience of Water Supply And Sanitation in the Face of Climate Change*, Technical report for the World Health Organization, Geneva, Switzerland.

[9] Littell, J.S., et al. 2013. Forest Ecosystems: Vegetation, Disturbance, and Economics. Chapter 5 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds*.) Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

[10] Wegesser, T.C. et al. 2009. California wildfires of 2008: Coarse and fine particulate matter toxicity. *Environmental Health Perspectives* 117 (6):893-897. doi: 10.1289/ehp.0800166.

[11] Rogers, C. A. et al. 2006. Interaction of the onset of spring and elevated atmospheric CO_2 on ragweed (*Ambrosia artemisiifolia L.*) pollen production. *Environmental Health Perspectives* 114 (6): 865-869. doi: 10.1289/ehp.8549.

[12] Singer, B. D. et al. 2005. Increasing Amb a 1 content in common ragweed (*Ambrosia artemisiifolia*) pollen as a function of rising atmospheric CO_2 concentration. *Functional Plant Biology* 32 (7): 667-670. doi: 10.1071/FP05039.

[13] Moore, S.K. et al. 2011. Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish. *Harmful Algae* 10:521-529, doi:10.1016/j.hal.2011.04.004.

[14] (NRC) National Research Council 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.* Washington, DC: The National Academies Press.

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APPENDIX

Bibliography: Key References on Climate Change

The basis for our understanding of observed and projected climate change is scientific findings published in the peer-reviewed literature. Scientists periodically convene to assess and synthesize the peer-reviewed science. These assessments serve to integrate scientific information from various sources, to emphasize the key findings, to draw broader conclusions about the state of the science and to identify significant gaps in our understanding of the climate change science and impacts. The following lists the primary syntheses useful for understanding climate change impacts. Since the peer-reviewed journal articles are the primary source for these documents, we have also included annotations for several noteworthy papers.

Synthesis Reports: Global

1. IPCC, 2013: Intergovernmental Panel on Climate Change (IPCC), *IPCC Fifth Assessment Report, Working Group I Report*

The IPCC is the leading international, scientific organization providing assessments on climate change and its projected impacts on resources and societies worldwide. Teams composed of thousands of scientists from around the world collaborate to develop periodic assessments of the current state of knowledge in climate change and its potential environmental and socioeconomic impacts. The Working Group I report ("The Physical Science Basis") consists of a synthesis of the science on global climate change. The fifth assessment report (AR5) was released in September of 2013.

Link to report	http://www.ipcc.ch/report/ar5/wg1/#.UqI6miTHRow
Publishing body	IPCC (Cambridge Press)
Literature included	Contributions are supported by references to peer-reviewed and internationally available literature. Sources other than scientific journals include reports from governments, industry, research institutions, international organizations and conference proceedings. Each IPCC Working Group sets cut-off dates by which time the literature must be accepted for publication by scientific journals (~2-3 months prior to final draft completion), thereby assuring that the literature included is up-to-date.
Review process	IPCC review process includes wide participation, with hundreds of Expert Reviewers and governments invited at different stages to critique the accuracy and completeness of the scientific assessment. The review process consists of 3 stages: 1. Authors prepare a first order draft of the report based on scientific, technical and socioeconomic literature and other relevant publications. Experts from a wide

	range of views, expertise and geographical representation review the first order draft. 2. Authors prepare a second order draft based on the review comments of the first order draft. The Summary for Policymakers (SPM) is drafted at this time. Both drafts are subject to simultaneous review by experts and governments. 3. Author teams prepare the final drafts of the full report and the SPM accounting for the reviewers' comments. The final drafts are submitted to governments to for a last round of comments on the SPM. The process concludes with a plenary session where the governments meet to approve the SPM line-by-line and to accept the final report. For additional details, see "IPCC Factsheet: How does the IPCC review process work?: http://www.ipcc.ch/news_and_events/docs/factsheets/FS_review_process.pdf
Geographical domain	Global, regional (continental)
Subject matter	Climate science.
Citation	Not yet available. (Official publication date in January of 2014.

2. **IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation***

The purpose of this synthesis report is to integrate expertise in climate science, disaster risk management, and adaptation to inform decisions on reducing and managing the risks of extreme events and disasters associated with climate change.

Link to report	http://ipcc-wg2.gov/SREX/
Publishing body	IPCC (Cambridge Press)
Literature included	Contributions are supported by references to peer-reviewed and internationally available literature. Unpublished material needs citation and a copy must be provided.
Review process	Authors and review editors for special report are nominated by governments and selected by the WGI and WGII bureaus. The report and summary for policymakers (SPM) undergo an expert review and an additional expert and government review. http://ipcc-wg2.gov/SREX/ipcc-process/
Geographical domain	Global, national, regional

Subject matter	Climate science, climate impacts, adaptation and vulnerability, mitigation (very broad for state-level adaptation efforts).
Citation	Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (Eds.). (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

3. IPCC, 2007: *IPCC Fourth Assessment Report, Working Group I Report*

The IPCC is the leading international, scientific organization providing assessments on climate change and its projected impacts on resources and societies worldwide. The Working Group I report ("The Physical Science Basis") consists of a synthesis of the science on change in the global climate system. The fourth assessment report (AR4) was released in 2007.

Link to report	http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html
Publishing body	IPCC (Cambridge Press)
Literature included	Contributions are supported by references to peer-reviewed and internationally available literature. Unpublished material needs citation and a copy must be provided.
Review process	IPCC authors are directed to "seek the participation of reviewers encompassing the range of scientific, technical and socio-economic views, expertise, and geographical representation". The review process consists of 2 stages: 1. Review by experts from a range of scientific, technical and socio-economic views, expertise and geographical backgrounds, and 2. Review by governments and experts chosen to include "as wide a group of experts as possible". For additional details, see "IPCC principles, Appendix A: http://www.ipcc.ch/organization/organization_procedures.shtml
Geographical domain	Global, regional (continental)
Subject matter	Synthesis of the current state of climate science.
Citation	Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis,

K.B. Averyt, M. Tignor and H.L. Miller (eds.). (2007). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Synthesis Reports: United States

4. Kunkel, K.E. et al. 2013*: Regional Climate Trends and Scenarios for the U.S. National Assessment. Part 9. Climate of the Contiguous U.S.*

This report is one in a series of nine, eight of which cover a region of the U.S. and this one covering the contiguous U.S. This report provides a synthesis of the most recent climate science for the CONUS, based on previously published papers, datasets and model output. The reports include two components: historical climate based on core climate data and future climate conditions projected by two greenhouse gas emissions scenarios. Collectively, these reports provide the technical input for the Third National Climate Assessment.

Link to report	http://scenarios.globalchange.gov/regions
Publishing body	NOAA
Literature included	Previously published literature and datasets on historical and plausible future climate scenarios specific to the Northwest region
Review process	National Climate Assessment working group including university-based and Federal research scientists
Geographical domain	Contiguous United States
Subject matter	Documents, graphics, references to data sets, and other resources depicting a range of plausible future conditions to inform decisions and assessments of risk, vulnerability and opportunities for adaptation on a regional scale.
Citation	Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K.T. Redmond, and J.G. Dobson, 2013: Part 9. Climate of the Contiguous U.S., NOAA Technical Report NESDIS 142-9, 85 pp.

5. USGCRP 2014: US Global Change Research Program (USGCRP), *Third National Climate Assessment (NCA)*

The NCA evaluates and summarizes current climate science from the US Global Change Research Program and other sources. The report is intended to inform national priorities for future climate science research and adaptation to climate impacts. The assessment is undergoing final federal agency review (as of December 2013) and is scheduled for release in spring 2014.

Link to report	Public comment draft available at: http://ncadac.globalchange.gov/
Publishing body	National Climate Assessment Development Advisory Committee
Literature included	Synthesis reports (e.g., IPCC), peer-reviewed literature, technical inputs
Review process	Input from stakeholders that was compiled into a separate Technical Input Report (TIR) for each chapter. The entire 3rd NCA draft was released for an expert review and public comment period from January to April 2013.
Geographical domain	National and regional
Subject matter	Climate science, climate impacts, vulnerability
Citation	TBD

6. NRC 2011: National Research Council (NRC), *America's Climate Choices*

America's Climate Choices is a five report series developed by the National Research Council, as requested by Congress. Developed between 2009 and 2011, the report discusses climate change adaptation and mitigation policy as well as the relevant science and technology. The report focusing on the science of climate impacts, *Advancing the Science of Climate Change*, includes impacts by sector such as freshwater resources, agriculture, public health and transportation. The report also covers adaptation options and climate change drivers in each sector.

Link to report	http://nas-sites.org/americasclimatechoices/sample-page/panel-reports/
Publishing body	National Research Council of the National Academy of Sciences
Literature included	Peer-reviewed science and other assessments such as IPCC AR4, USGCRP's *Global Climate Change Impacts in the United States* and previous NRC reports
Review process	A different authoring panel is responsible for each report in

	the series, with outside input received from public presentations and workshops and comments submitted on the website.
Geographical domain	U.S.
Subject matter	Climate science, adaptation and mitigation policy, technology
Citation	National Research Council (2011). *America's Climate Choices*. Washington, DC: The National Academies Press.

Synthesis Reports: U.S. West Coast

7. NRC, 2012: *Sea level rise for the coasts of California, Oregon and Washington: Past, Present and Future*

Several federal and state agencies collaborated to produce this assessment of sea level rise along the West Coast of the U.S. The report, produced by the National Research Council, reviews and synthesizes the current, published research on global and regional sea levels and applies established process-based approaches to project global sea level rise through the 21st century.

Link to report	http://www.nap.edu/catalog.php?record_id=13389
Publishing body	National Academy of Sciences
Literature included	Committee reviews and synthesizes current, published research.
Review process	The NRC appointed a Report Review Committee to select experts from a variety of backgrounds to independently review the report. The review process ensures that the report meets institutional standards of objectivity, evidence and responsiveness to the study charge. Reviewers are listed in the Acknowledgements of the report.
Geographical domain	West Coast of U.S. (California, Oregon and Washington)
Subject matter	Sea level rise, coastal impacts, vulnerability – specific to coastal systems along the U.S. West Coast.
Citation	National Research Council. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press, 2012.

Synthesis Reports: Pacific Northwest

8. Kunkel, K.E. et al. 2013: ***Regional Climate Trends and Scenarios for the U.S. National Assessment. Part 6. Climate of the Northwest U.S.***

This report is one in a series of nine, eight of which cover a region of the U.S. and one cover the contiguous U.S. Each report provides a synthesis of the most recent climate science for the given region, based on previously published papers, datasets and model output. The reports include two region-specific components: historical climate based on core climate data and future climate conditions projected by two greenhouse gas emissions scenarios. These reports provide the technical input for the Third National Climate Assessment.

Link to report	http://scenarios.globalchange.gov/regions/northwest
Publishing body	NOAA
Literature included	Previously published literature and datasets on historical and plausible future climate scenarios specific to the Northwest
Review process	National Climate Assessment working group including university-based and Federal research scientists
Geographical domain	Regional (Northwest U.S.)
Subject matter	Documents, graphics, references to data sets, and other resources depicting a range of plausible future conditions to inform decisions and assessments of risk, vulnerability and opportunities for adaptation on a regional scale.
Citation	Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K.T. Redmond, and J.G. Dobson, 2013: Part 6. Climate of the Northwest U.S., NOAA Technical Report NESDIS 142-6, 76 pp.

9. Dalton et al. 2013: ***Climate Change in the Northwest: Implications for our Landscapes, Waters, and Communities***

As companion report for the Northwest chapter of the Third National Climate Assessment, the objective of this synthesis is to assess the state of knowledge about key climate impacts and consequences to multiple natural resource sectors and communities in the Northwest U.S. This report is the culmination of an iterative process involving workshops with regional stakeholders to identify climate risks and consequences in their respective sectors. This report is designed to serve as an updated resource for scientists, decision makers, stakeholders and adaption planning in the PNW.

Link to report	http://islandpress.org/ip/books/book/distributed/C/bo9111930.html

Publishing body	Island Press
Literature included	Previously published literature representing best available science on regional climate change, impacts, vulnerability assessments, mitigation and adaptation.
Review process	27 expert reviewers drawn from federal, state, tribal, private, nonprofit, universities and other regional agencies.
Geographical domain	Regional (Northwest U.S.)
Subject matter	A review of the historic, current and projected climate conditions for the Northwest region. Interactions among important sectors, and cross-sectoral topics: climate change mitigation, adaptation, education and outreach.
Citation	Dalton, M.M., P.W. Mote, and A.K. Snover. (Editors). 2013. Climate Change in the Northwest: Implications for our Landscapes, Waters, and Communities. Washington, D.C.: Island Press. 271 pp.

Synthesis Reports: Washington State

10. CIG, 2009: Climate Impacts Group (CIG), *Washington State Climate Change Impacts Assessment (WACCIA)*

The WACCIA was produced in 2009 by the Climate Impacts Group in collaboration with researchers and Washington State University and the Pacific Northwest National Laboratory, as mandated by Washington State House Bill 1303. The WACCIA reported on new research assessing climate impacts on Washington State's resources. The WACCIA involved developing updated climate change scenarios for Washington State and using these scenarios to assess the impacts of climate change on the following sectors: hydrology, water management and irrigation, energy, agriculture, salmon, forests, coasts, stormwater infrastructure, human health and adaptation.

Link to report	http://cses.washington.edu/cig/res/ia/waccia.shtml
Publishing body	Climate Impacts Group, University of Washington
Literature included	Synthesis reports (e.g., IPCC), peer-reviewed literature
Review process	Anonymous peer review: all chapters were published as a special edition in the journal *Climatic Change*.
Geographical domain	Focused on WA state, but also includes results for the full Columbia River basin.
Subject matter	Climate impacts, by sector.
Citation	Climate Impacts Group (2009). *The Washington Climate*

Change Impacts Assessment, M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington.

11. Feely et al. 2012: *Scientific Summary of Ocean Acidification in WA State Marine Waters*

This scientific summary was a collaborative effort among natural scientists from Washington and Oregon States. The purpose of this NOAA special report is to inform members of the WA Shellfish Initiative Blue Ribbon Panel on ocean acidification and to summarize and synthesize the state of knowledge with regards to the conditions and probable biological and ecological responses to changes in ocean chemistry in the estuaries and coastal waters of WA.

Link to report	https://fortress.wa.gov/ecy/publications/summarypages/1201016.html
Publishing body	NOAA OAR Special Report
Literature included	Synthesis reports (e.g., IPCC), peer-reviewed literature.
Review process	Federal scientists from NOAA, and where relevant subject matter experts at the WA State Department of Ecology
Geographical domain	Focused on WA state, but provides global overview of the mechanisms driving ocean acidification
Subject matter	Ocean acidification and related regional dynamics contributing to changes in ocean chemistry, impacts to regional marine ecosystems and to shellfish industries.
Citation	Feely, R.A., Klinger, T., Newton, J.A., Chadsey, M. [Eds.] 2012. Scientific Summary of Ocean Acidification in Washington State Marine Waters. NOAA OAR Special Report. Seattle, Washington.

Key Peer-reviewed Journal Articles and White Papers

The following list includes noteworthy references to papers that provide the foundation for the syntheses listed above.

Greenhouse gases

This study describes recent trends in global greenhouse gas emissions, including the substantial acceleration in emissions since the year 2000:

- Peters, G.P., G. Marland, C. Quéré, T. Boden, J.G. Canadell, and M.R. Raupach. 2012. Rapid growth in CO2 emissions after the 2008–2009 global financial crisis. *Nature Climate Change* 2, 2–4. 2012, doi:10.1038/nclimate1332

Temperature trends

This study investigates the impact of measurement issues (changes in location of measurements, the instruments used, or in the overall number of observing stations in operation) on estimates of long-term trends in temperature. They find that correcting for these issues generally has a small effect on estimated trends:

- Menne, M. J., Williams, C. N., & Palecki, M. A. (2010). On the reliability of the US surface temperature record. *Journal of Geophysical Research: Atmospheres (1984–2012)*, 115(D11).

Detection and attribution

These four studies evaluate role of human activity in driving recent observed changes in temperature, precipitation, snowpack, and streamflow in the Western U.S.:

- Bonfils, C., and Coauthors. 2008. Detection and attribution of temperature changes in the mountainous western United States. *Journal of Climate*, 21, 6404–6424. doi:10.1175/2008JCLI2397.1

- Barnett, T., D.W. Pierce, H. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nazawa, A, Mirin, D. Cayan, and M. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. *Science Express Reports* 10.1126/science.1152538.

- Pierce, D.W., T. Barnett, H. Hidalgo, T. Das, C. Bonfils, B.D. Santer, G. Bala, M. Dettinger, D. Cayan, A, Mirin, A.W. Wood, and T. Nazawa. 2008. Attribution of declining western U.S. snowpack to human effects. *Journal of Climate* 21(23): 6425–6444, doi:10.1175/2008JCLI2405.1.

- Hidalgo H.G., Das T., Dettinger M.D., Cayan D.R., Pierce D.W., Barnett T.P., Bala G., Mirin A., Wood A.W., Bonfils C., Santer B.D. and T. Nozawa, 2009, Detection and Attribution of Streamflow Timing Change in the Western United States, *J. Climate, 22(13): 3838-3855.*

Streamflow

This is a landmark paper summarizing observed changes in streamflow timing across Western North America for the period 1948-2002. They find that the majority of streamflow sites show a shift to earlier peak flows, with implications for summer water availability.

- Stewart, I., D. R. Cayan and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18: 1136-1155.

Sea level rise

This report consists of a synthesis of findings concerning the global and local factors contributing to sea level rise along the coasts of Washington state. The report provides summaries of sea level rise projections for 3 areas in WA state: the Puget Sound basin, Central/Southern WA coast, and the NW Olympic peninsula.

- Mote, P., Petersen, A., Reeder, S., Shipman, H., Whitely Binder, L.C. (2008). *Sea level rise in the coastal waters of Washington State.* Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington and the Washington Department of Ecology, Lacey, Washington.

This study demonstrates the potential impacts to coastal ecosystems as a result of projected sea level rise in the Puget Sound and along the Washington and northern Oregon coasts.

- Glick, P., Clough, J., and Nunley, B. 2007. Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon (Reston, VA: National Wildlife Federation).

Ocean temperatures

This study evaluates observed changes in ocean temperatures in the Strait of Georgia (North of Puget Sound) and West of Vancouver Island, and finds a statistically significant warming trend for the top 1300 ft of ocean depth.

- Masson, D., & Cummins, P. F. (2007). Temperature trends and interannual variability in the Strait of Georgia, British Columbia. *Continental shelf research*, 27(5), 634-649.

Forested and non-forested ecosystems

This study assessed the likely impacts of climate change on wildfire, tree growth, tree species distributions, and mountain pine beetle outbreaks in the Pacific Northwest.

- Littell, J.S., E.E. Oneil, D. McKenzie, J.A. Hicke, J.A. Lutz, R.A. Norheim, and M.M. Elsner. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climatic Change 102(1-2): 129-158, doi: 10.1007/s10584-010-9858-x.

This paper describes an analysis of projected climate change impacts on diverse ecosystems found in the Pacific Northwest. It provides an indication of the sensitivity of the various vegetation types to increased fire occurrence and the potential response of carbon dynamics.

- Rogers, B. M., R. P. Neilson, R. Drapek, J. M. Lenihan, J. R. Wells, D. Bachelet, and B. E. Law (2011), Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest, Journal of Geophysical Research 116: G03037.

Agriculture

This paper summarizes the current research on rangeland vulnearbilities and also provides a synopsis of anticipated impacts in the Pacific Northwest.

- Polley, H. W. et al., 2013. Climate Change and North American Rangelands: Trends, Projections, and Implications. *Rangeland Ecology and Management*, *66*(5), 493-511.

This paper argues for a more comprehensive look at food system vulnerability (i.e., "food security") — including not just agricultural production but also delivery, processing, and storage food. The paper also includes a review of existing research on impacts and adaptation.

- Miller, M. et al., 2013. Critical research needs for successful food systems adaptation to climate change. *Journal of Agriculture, Food Systems, and Community Development, 3*(4)*,* 161-175. doi: 10.5304/jafscd.2013.034.016

Water Resources

Water management in the context of climate change has been the focus of much research over the past decade. This is a classic study that highlights some of the conflicting objectives that water managers will face in attempting to mitigate the effects of climate change.

- Payne, J. T. et al., 2004. Mitigating the effects of climate change on the water resources of the Columbia River basin. Climatic Change, 62(1-3), 233-256. doi: 10.1023/B:CLIM.0000013694.18154.d6

This paper reviews the development, methods, and results of the Columbia Basin Climate Change Scenarios Project, which includes a comprehensive set of high resolution climate and hydrologic projections for the entire state of Washington, as well as summaries for 112 specific streamflow locations across the state.

- Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. Atmosphere-Ocean 51(4): 392-415. doi: 10.1080/07055900.2013.819555

Hydrologic Extremes

Much recent work has been devoted to assessing the impacts of climate change on precipitation and streamflow extremes. The following two papers present different approaches to assessing changes in extremes, both of which include results for Washington State.

- Tohver, I. et al., 2013. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. Journal of the American Water Resources Association, in press.

- Salathé, E.P. Jr et al., 2013. Estimates of 21st Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations. Submitted

The Climate Impacts Group

University of Washington

http://cses.washington.edu/cig/

IN THE SUPREME COURT OF THE STATE OF WASHINGTON

SUPREME COURT NO. 90759-5

JEROME C. HURLEY and BESSIE M. HURLEY, *et al*,

Petitioners,

v.

CAMPBELL MENASHA, LLC; *et al*.,

Respondents,

AMICUS BRIEF OF GEOLOGISTS AND GEOMORPHOLOGISTS DR. DAVID MONTGOMERY, DR. TIM ABBE, DR. SCOTT R. LINNEMAN, DR. JEFFREY D. PARSONS, DR. SCOTT F. BURNS DAN MCSHANE, JEREMY T. BUNN, ANDY ROSS, JOHN N. THOMPSON, AND KIM NINNEMANN

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I. IDENTITY OF THE AMICI

The *amici* are Dr. David Montgomery, Dr. Tim Abbe, Dr. Scott R. Linneman, Dr. Jeffrey D. Parsons, Dr. Scott F. Burns, Dan McShane, Jeremy T. Bunn, Andy Ross, John N. Thompson, and Kim Ninnemann, all geologists and/or geomorphologists with advanced degrees who have studied the interaction between forest practices and landslides. *See* Motion to File Amicus Brief.

II. LOGGING ON STEEP SLOPES, EVEN WHEN DONE WITH REASONABLE CARE, RESULTS IN A HIGHER RISK AND INCIDENCE OF LANDSLIDES

The Court of Appeals' decision states that the "parties dispute whether logging creates a risk of landslides in general." Decision at 7. There is no evidence in the record to support that statement. The only evidence in the record about logging's effect on landslide risks is that logging significantly increases the risk of landslides. As discussed below, the court's statement is contrary to peer-reviewed, scientific studies (many referenced in the record).

The special problem created by logging on steep slopes is that it is practically impossible, even if reasonable care is used, to identify precisely all areas most vulnerable to sliding if logged. The problem arises because identifying the most dangerous locations requires extensive, sub-surface investigations. It is not practical to do so across hundreds or thousands of forested acres. Sub-surface investigations are routine when much smaller areas are at issue, for instance, to assure the stability of a single building, or even a complex of buildings, to be built in one confined area on a slope. But given the vast expanse of sloped lands logged each year in this state, it is not practical to undertake that level of analysis before logging.

Instead, out of necessity, a more superficial assessment is made. But because of the limitations of that more superficial assessment, it is inevitable that some of the areas that are clearcut will be areas that create additional risks of sliding. We know this both because of textbook-level geological science and because of the numerous studies that have documented this in the field.

Screening tools (some mandated by the State) to identify potentially unstable slopes based on surface information alone have limited capacity to identify high-risk areas due to conditions hidden beneath the surface. Studies confirm that using those surface-oriented screening tools and complying with state regulations does not eliminate the risk that logging will cause a landslide. To the contrary, these studies, as well as an understanding of basic geologic principles, demonstrate that even when logging is done in compliance with regulations and with reasonable care, logging on steep slopes results in a significantly higher incidence of landslides. *See, e.g.,* CP 75–78; 1162–1163; 1170–71.

III. THE SCIENCE OF LANDSLIDES

The stability of a slope is governed by a wide variety of factors, many hidden below the surface: cohesion, permeability and porosity of the soil at various depths (including the effects of roots); the thickness and friction angle of the soil; presence or absence of subsurface water; and planes of weakness within underlying units. Accurate measurement of these parameters can only be accomplished with subsurface investigations. Absent an intensive amount of subsurface investigation, we must rely on many uncertain assumptions about the subsurface to estimate slope stability.

The harvest of timber across steep slopes brings about changes to subsurface conditions that can and do lead to landslides. Tree removal will lead to loss of apparent soil cohesion as roots binding soil particles together rot, causing the soil to lose strength and, thus, lose resistance to landslides. Removal of trees also leads to more frequent saturated soil conditions in the subsurface (due to reduced evapo-transpiration) and results in an increase in pore-water pressure. Increased pore-water pressure between soil grains reduces the resistance to landslide forces.

Reduced soil cohesion from loss of root strength and increased pore-water pressure have been well studied and documented.[1]

A particularly difficult subsurface feature to identify and/or accurately assess is a bedrock hollow. Bedrock hollows are subsurface depressions within the underlying bedrock that are filled, or partially filled, with looser material (soil) that will be significantly more likely to fail. Sometimes, these bedrock hollows are mirrored on the surface as readily apparent topographic depressions, but sometimes not. The lack of a "surface expression" for a bedrock hollow means that a ground-level review of a logging site will not be able to identify it as a potentially unstable slope.[2]

Steep slopes and bedrock hollows are less vulnerable to landsliding when covered by mature trees which maintain soil cohesion and absorb water. But logging may cause such slopes to become unstable due to greater water recharge and/or loss of root cohesion.

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1 A textbook discussion of these geologic principles as they apply to timber harvest is included in the excerpt from one of the *amici's* textbook of introductory geomorphology, attached hereto as Appendix A.

2 The heightened instability of bedrock hollows is due to the presence of the looser material and the likelihood that subsurface waters will collect in these subsurface hollows, saturating and weakening the soils.

Because some bedrock hollows and site-specific variability in other subsurface factors cannot be identified from the surface, fully evaluating the risks created by logging a steep slope would require intensive subsurface, geologic investigation. In the absence of a subsurface investigation, the logging company takes the risk that it is not logging over a particularly vulnerable slope or bedrock hollow and—if they do—that no storm large enough to trigger sliding will hit that slope before the new forest is 10 to 20 years old and regains most of the lost root cohesion.

The impact of clearcut logging on the stability of steep slopes is well established in studies that compare the frequency and magnitude of slope failures in the vicinity of recent clearcuts with landslide activity in untouched areas. These studies (dozens of them) leave no doubt that logging on steep, soil-mantled slopes increases the risk of landsliding. This point has been recognized since Alexandre Surell's famous 1840s studies of the relation between landslides and forest clearing in the French Alps.[3] More recent studies in the Pacific Northwest have quantified the role of root strength on soil reinforcement and slope stability. The results

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[3] Surell, A., re-published 1870, *A Study of the Torrents in the Department of the Upper Alps*, Translated by A. Gibney, Paris, Dunod.

of those studies support Surell's general conclusion about forest clearing increasing the probability of landslides in steep, forested terrain.

In the Pacific Northwest, landslide frequencies in areas with forest clearing have been estimated to be up to 34 times higher than natural background rates (Rood, 1984). Studies by Montgomery *et al* (2000) found landslide frequencies three to nine times higher than pre-European settlement. Timber harvest is the primary factor responsible for this difference (Sidle *et al*, 1985). These impacts were further reflected in the compilation of studies referenced in the record. CP 73 (¶b), 74, 111 (¶11). Those studies involved inventories of landslides across large and small landscapes. In each study, landscapes were coded as originating in a recently logged area (or close to a logging road) or in an area that was in its natural condition. One study found that areas with logging had twice as many landslides as the adjacent natural areas. That was the *smallest* increase found among the studies. Other studies found increases of four-fold, ten-fold and even 33-fold. *Id.* On average, the studies indicated an almost ten-fold increase in landslides on lands associated with logging.

Certainly, it is true that landslides occur naturally. As one of the respondents states, "hundreds of debris slide events happened in both logged and unlogged areas in the path of the January 2009 winter storm."

Zepp Resp. Br. at 8. But that statement hides the differences between the frequency of slides in logged and unlogged areas. As described in the in the record, the vast majority of slides occurred in recently logged areas, even though most of the landscape was not recently logged. CP 111-112.

IV. RESTATEMENT OF TORTS, §502

One of the factors to be considered in deciding whether an activity is "ultra-hazardous" is the "inability to eliminate the risk by the exercise of reasonable care." Restatement of Torts (2d), §520. The geologists and geomorphologists submitting this *amicus* brief believe that there is no doubt from a scientific perspective that this factor is present here. Absent an impractical investment in sub-surface geotechnical investigation across hundreds or thousands of acres of steep forested landscape, each year, the information necessary to identify potentially unstable slopes vulnerable to post-harvest landsliding will be limited to landform features expressed on the land surface. Many potentially unstable slopes will remain un-identified by either logging companies or regulators.

Subsurface investigations routinely done for large buildings and dams are not practical for most logging which can span hundreds of acres. There can be tremendous variation in geologic conditions across a forestry site, both on the surface and underground. It is not practical to develop the hundreds of boring holes that would be needed for each logging site to try and find all bedrock hollows (and other problematic sub-surface features). Thus, there is no practical way to identify many of the most hazardous areas.

In the absence of subsurface information, forest practice activities on steep slopes will remain inherently risky. The only way to eliminate that risk is to not log on steep slopes, however, that approach would eliminate access to and harvest of vast tracts of valuable timber. The alternative approach that has become the norm is to avoid the most obvious visible slide prone spots and assume or hope that there are no unidentified potentially unstable slopes that will fail due to tree removal or road construction; or hope that no large storm hits that slope before root cohesion in restored; or, if all else fails, hope that if slides do take place due to forest practice activities, no one is in harm's way below.

Thankfully, most logging on steep slopes takes place in areas remote from human settlement. *See, e.g.,* CP 89 (¶4.a). Consequently, in most situations, the companies can take the risk without triggering a slide that actually causes harm to anyone. But when forest practices reduce slope stability and a large storm hits before the new forest grows back and a landslide results and damages private property, it seems to us that the law should allow the persons who suffer property damage or bodily harm to recover for the harm they suffer. The logging companies profit from logging steep, soil-mantled slopes. Those companies should make good when inherently risky activity causes slopes to give way, damaging private property and, possibly, causing bodily harm or death.

The Court of Appeals recognized evidence "that even when exercising the highest degree of due care, logging in rural areas may increase the risk of landslides." Decision at 10. But the foregoing discussion demonstrates that the undisputed scientific evidence was more conclusive than that. Logging "will" increase the risk, not "may."

We reiterate, though, that some landslides occur naturally and thus we believe that the damaged party should still be responsible for proving causation. Strict liability would merely eliminate the plaintiff's burden of proving negligence. This is consistent with the petitioners' position. *See* PFR at 11, n. 7.

V. REVIEW SHOULD BE GRANTED

The geological evidence discussed above demonstrates that the Court of Appeals' decision conflicts with other decisions of this Court analyzing the factors in Section 520A. Not only is there no doubt that logging increases landslide risk, but there is no scientific basis for believing that that risk can, as a practical matter, be mitigated to anything close to background levels. The best we can practically do today results in landslide risks from logging that are vastly greater than leaving the hillsides untouched.

Likewise, the scientific evidence conflicts with the Court of Appeals' reasoning that a multiplicity of causes makes strict liability inappropriate. Decision at 10. In reality, virtually all landslides on logged slopes are caused by logging and a small minority are natural. There is no evidence in the record that any cause other than those two ever is involved. (We note that the Court of Appeals did not identify *any* causes other than natural conditions and those related to logging. *Id.*)

Finally, it should be obvious in the wake of innumerable slides apparently linked to logging activities that deciding this issue is a matter of great public importance.

DATED this 7th day of November, 2014.

Jeffrey J. Bode, WSBA 10865
Attorney for Dr. David Montgomery, Dr. Tim Abbe, Dr. Scott R. Linneman, Dr. Jeffrey D. Parsons, Dr. Scott F. Burns, Dan McShane, Jeremy T. Bunn, Andy Ross, John N. Thompson, and Kim Ninnemann.

Appendix A

Montgomery, D. R., K. M. Schmidt, W. E. Dietrich, and J. McKean. Instrumental record of debris flow initiation during natural rainfall: Implications for modeling slope stability. *Journal of Geophysical Research—Earth Surface* 114 (2009): F01031, doi: 10.1029/2008JF001078.

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Terzaghi, K. Stability of steep slopes on hard unweathered rock. *Géotechnique* 12 (1962): 251–270.

DIGGING DEEPER How Much Do Roots Contribute to Slope Stability?

Keen observers have long recognized that trees help stabilize soils on steep mountain slopes. Lyell (1853) and Marsh (1864) interpreted associations between forest cutting and mass wasting as evidence that forest clearing accelerated erosion in mountainous terrain. Since Lyell's day, the influence of root reinforcement on shallow landsliding has been well established by studies of landslide erosion under mature forest and in harvested plots, mechanistic studies of root reinforcement, and theoretical analyses based on the infinite-slope stability equation (eq. 5.8), where root strength is considered as part of the cohesion term (Sidle et al., 1985). Although roots contribute to soil strength by providing apparent cohesion and holding the soil mass together, they have a negligible effect on frictional strength. Studies from the western United States, Japan, and New Zealand all indicate that the stability of the soil mantle on steep, soil-mantled slopes depends in part on reinforcement by tree roots and that after the loss of forest cover (either by timber harvest or fire), the decay of tree roots increases the potential for slope instability, especially when soils are partly or completely saturated (Sidle et al., 1985; Bierman et al., 2005).

Root reinforcement may occur through the base of a potential landslide as roots grow into the underlying bedrock or more stable surface materials. Dense, interwoven root networks both reinforce soil and provide lateral reinforcement across potential failure scarps. Burroughs and Thomas (1977) demonstrated a rapid decline in the tensile strength of Douglas-fir roots following timber harvest in western Oregon and central Idaho and indicated the increased potential for landslides when trees were removed. Building on the Burroughs and Thomas approach, Sidle (1992) developed a quantitative model of root-strength reinforcement that combined the decay of roots after timber harvest with the regrowth of new roots [**Figure DD5.1**]. Although the decay and regrowth times vary for different tree species, a period of low root strength occurs some time between 3 and 20 years following timber harvest or fire. If a big storm occurs in

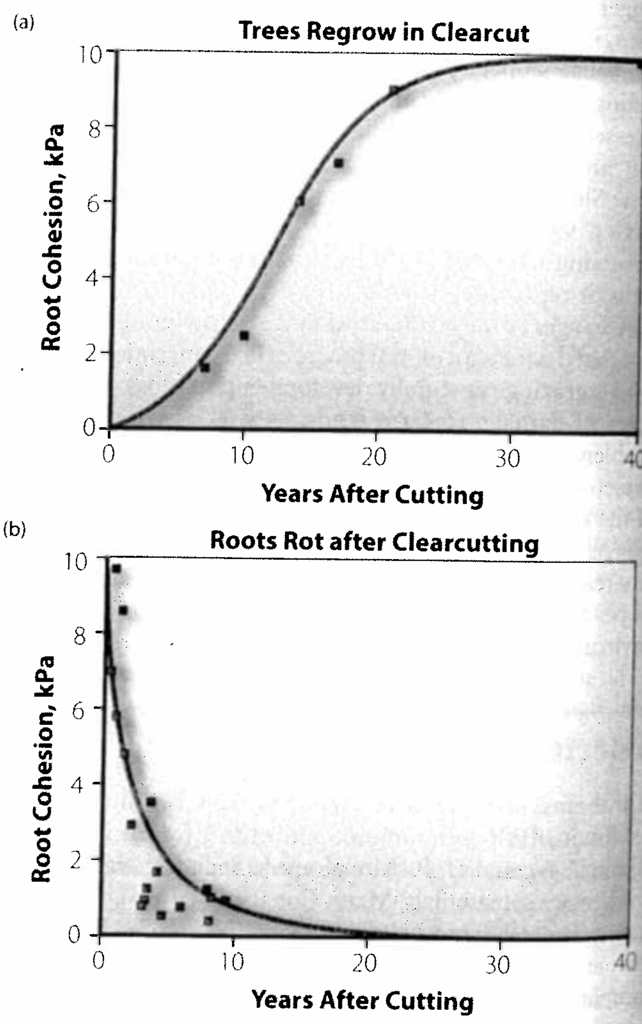

FIGURE DD5.1 Root strength changes over time as (a) trees grow in clearcuts and (b) as roots decay after trees are clear-cut. It takes about a decade after cutting for the dead roots of coastal Douglas fir trees to lose all of their strength and about 20 years for new trees to take root and develop full root strength. Planting seedlings right after harvest is a land-management strategy that reduces the chance of landsliding because new roots are growing as the old ones are decaying. [From Sidle (1992).]

this window and saturates the soil, landslides will likely follow.

Studies comparing the rate of landsliding on forested versus clear-cut slopes have reported a range of effects, from no detectable increase in landslide frequency to more than a ten-fold increase following timber harvest (Sidle et al., 1985). In a study that both analyzed a regional data set of ~3200 landslides and intensively monitored a study area, Montgomery et al. (2000) found that storms with 24-hour rainfall recurrence intervals of less than 4 years (common storms) triggered landslides in the decade after timber harvesting in the Oregon Coast Range **[Figure DD5.2]**. Comparison of these postharvest rates of landsliding with the estimated background rate implied that clear-cutting of slopes increased landsliding rates by 3 to 9 times over the natural background. This increase reflected reduced root strength as the dead roots of the cut trees rotted and weakened. Without strong roots, less soil saturation was required to induce slope failure, and thus smaller storms could trigger landslides.

Schmidt et al. (2001) measured root cohesion in soil pits and scarps of landslides triggered during large storms in February and November of 1996 in the Oregon Coast Range. They found a preponderance of broken roots in the margins of recent landslide scarps, indicating that root tensile strength contributed to stabilizing the soil (until the roots snapped) in most locations. They also found that root density, root penetration depth, and the tensile strength varied among species; the tensile strength increased nonlinearly with root diameter. The median lateral cohesion provided by roots in mature natural forest ranged from 26 to 94 kPa. It was much lower in planted, industrial forest stands, ranging from 7 to 23 kPa. In clear-cuts, the lateral root reinforcement was uniformly low, under 10 kPa **[Figure DD5.3]**.

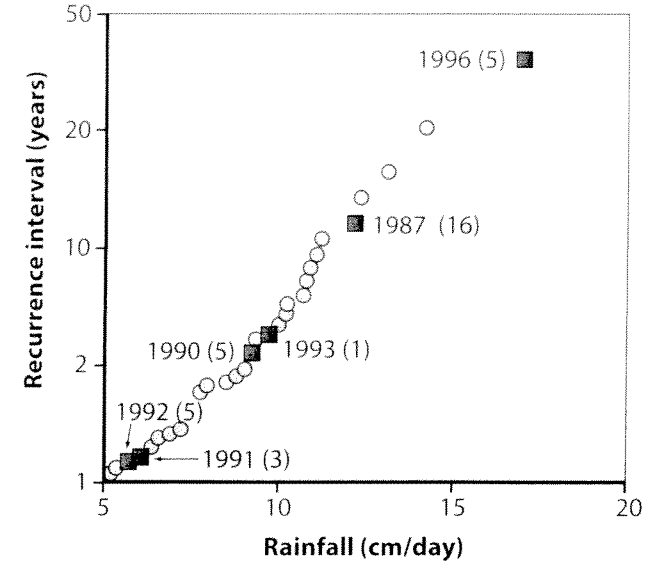

FIGURE DD5.2 Plot of recurrence intervals for 24-hour rainfall events from 1931 through 1996 (yellow circles) in a steep 0.43 km^2 study area that was clear-cut in the 1980s. Storms that occurred after clear-cutting and are known to have generated landslides are shown as blue squares. Numbers in parentheses after years indicate how many landslides occurred. Note that eight landslides occurred in this area during storms having less than 2-year recurrence intervals, all after clear-cutting. Vertical axis is logarithmic. [From Montgomery et al. (2000).]

Similar to Montgomery et al. (2000), Schmidt et al. (2001) found that a persistent reduction in root strength

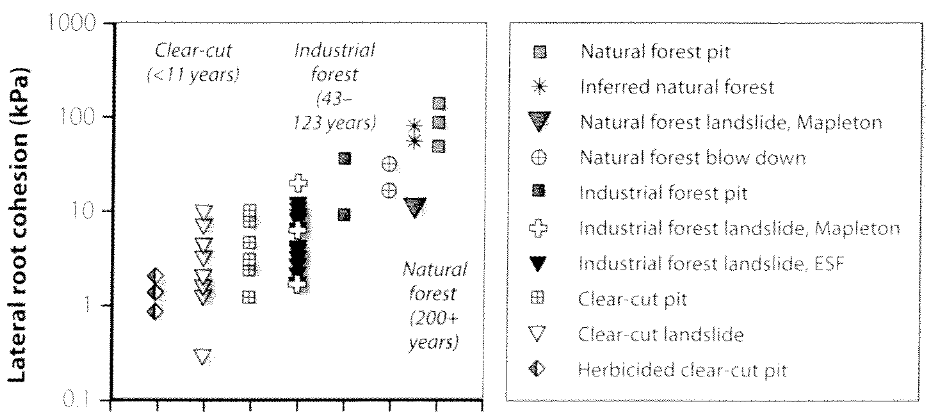

FIGURE DD5.3 In the Oregon Coast Range, not all roots provide the same amount of lateral root cohesion. Roots in clear-cuts do little to stabilize slopes. Industrial forests, those planted and managed for wood products, have roots that provide some stabilization, but the highest apparent root-cohesion values are found in mature, natural forests. [From Schmidt et al. (2001).]

DIGGING DEEPER How Much Do Roots Contribute to Slope Stability? *(continued)*

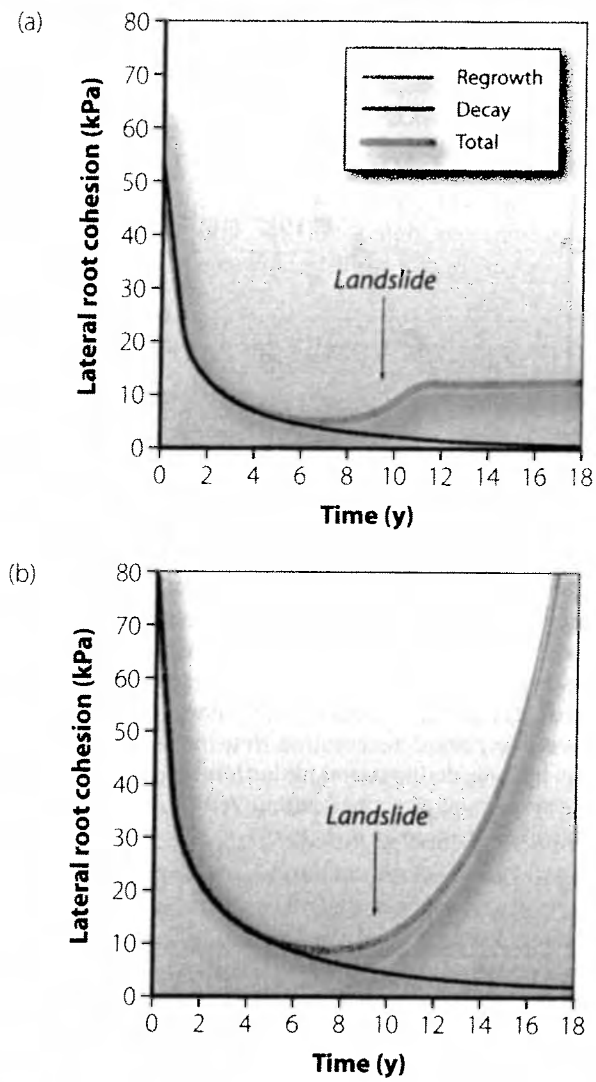

FIGURE DD5.4 Predicted total lateral root cohesion considering contributions from tree regrowth and decay of old roots for two sites that were clear-cut in 1986 and yielded landslides in 1996. Figure (a) represents a site where understory regrowth dominates vegetation. Figure (b) is a site where growth consists of abundant conifers and deciduous trees. [From Schmidt et al. (2001).]

resulting from timber harvest significantly reduced the soil moisture (m in eq. 5.8) required to trigger slope instability. They modeled root decay and regrowth for two sites that were clear-cut in 1986, and then slid in 1996. Both failures occurred close to the predicted root-strength minima, about 10 years after clear-cutting [**Figure DD5.4**].

Root strength varies spatially in a forest, complicating slope-stability modeling. Roering et al. (2003) documented the distribution and characteristics of trees adjacent to 32 shallow landslides in the Oregon Coast Range. Not surprisingly, bigger trees had larger root systems. The diameter of the tree crown and the root network was a function of the tree diameter (and thus tree age), and Roering et al. (2003) quantified root strength in landslide scarps by pulling on roots and measuring the tensile strength at which they broke. Summing the total root strength in each landslide perimeter, they found that root strength correlated with the size, species, condition, and spacing of trees around the landslide scarps; bigger, healthier trees spaced more closely together gave greater root strength. They also found that landslides tended to occur in areas of low root strength and thus that the potential for shallow slope instability was a function of the diversity and distribution of vegetation on potentially unstable slopes. Well-vegetated slopes were more stable.

Root strength can also vary with topographic position. Hales et al. (2009) investigated the spatial variability of root network density and strength in the southern Appalachian Mountains in North Carolina by measuring the distribution and tensile strength of roots from soil pits on topographic noses and hollows. They found that roots from trees on noses had greater tensile strength than those found in hollows, a pattern suggesting that not only does vegetation help stabilize topography but that topography affects vegetation, specifically, root strength (presumably due to differences in soil moisture). Trees on noses provided more effective root cohesion than those in hollows, a pattern that would increase further the propensity for landslides to occur in hollows.

The variability of root reinforcement with tree species, root diameter, tree diameter, topographic position, and time after timber harvest complicates quantitatively predicting the effect of root reinforcement on slope stability. The evidence is convincing that taking trees off slopes reduces root reinforcement and allows soils to fail on slopes more easily, i.e., in smaller precipitation events; however, this effect is difficult to incorporate into landscape-scale slope stability models due to the tremendous spatial variability not only in root strength but in other properties that influence slope stability, such as regolith depth and hydraulic conductivity, and the influence of bedrock fractures on soil saturation. There is no ambiguity in the science indicating that clear-cut slopes, from which trees have been removed, are more likely to fail than similar slopes under mature forest. However, managing timber-harvest-related slope instability is difficult because it is impossible to identify with certainty which potentially unstable slopes will actually fail in a particular storm. [**Figure DD5.5**].

Debris flows off a steep, clear-cut slope, Stillman Creek, Washington. The timber company's application to the State Department of Natural Resources before harvest reported that the site had been inspected and was found to have no potentially unstable slopes. [Photograph by S. Ringman, from *Seattle Times*.]

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WORKED PROBLEM

Question: Using the infinite-slope model, what is the maximum stable angle for both dry and saturated sand with no cohesion and a friction angle of 37 degrees? How does this stable angle compare to that of more cohesive material such as till or clay?

Answer: For dry cohesionless materials, the maximum stable angle is the friction angle, ϕ, in this case, 37 degrees. For the failure of a fully saturated, cohesionless soil like coarse sand ($FS = 1.0$, $C = 0$, and $m = 1.0$), eq. 5.8 reduces to $\tan\theta = [[(\rho_s - \rho_w)/\rho_s] \tan\phi]$, which may be approximated by $\tan\theta \approx 1/2 \tan\phi$ (since for most soils $\rho_s \approx 2\rho_w$). This indicates that sandy slopes steeper than about half the friction angle tend to fail if saturated. Thus, when saturated, cohesionless sand with a friction angle of 37 degrees will fail when the slope is about 23.5 degrees. At higher slopes where $\theta \geq \phi$, cohesionless soils tend to slide even when dry; the soil mantle rarely stays on such steep slopes unless there is significant root reinforcement. Soils with even modest amounts of cohesion can stand at much steeper angles over length scales shorter than typical hillslope lengths. For example, excavations in clay (and other cohesive materials like glacial till) can hold vertical faces of up to several meters in height, as can riverbanks, especially if reinforced by roots that provide apparent cohesion.

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Discussion: Comparison of slope instability screening tools following a large storm event and application to forest management and policy

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ABSTRACT

This discussion is in response to the article entitled "Comparison of slope stability screening tools following a large storm event and application to forest management and policy" by Kara Whittaker and Dan McShane (Geomorphology 145–146 (2012) 115–122). The discussion is coauthored by several geologists at the Washington Department of Natural Resources (WDNR) including those from the research and policy sections of the state agency.

1. The research section discussion

The WDNR Division of Geology and Earth Resources (DGER) geologists identified a technical error associated with the comparison of slope instability screening tools to a set of landslide observations in Whittaker and McShane (2012). The error is due to the authors' scale-inappropriate use of spatial data from the WDNR. The authors compared two slope-instability screening tools to the initiation points of 779 landslides in three watersheds. The landslide data used in the analysis were reconnaissance in nature and not precise initiation points intended for fine-scale analysis. The following explains the primary criticisms of the analysis performed by Whittaker and McShane (2012).

Whittaker and McShane (2012) used a point data set generated from reconnaissance landslide observations following three days of two separate storm events consisting of hurricane-force winds and heavy precipitation (Reiter, 2008). The landslides were digitized by DGER staff for the purpose of rapid, qualitative identification of landslide extent and considered as an initial base line for future site-specific, landslide-related studies (Sarikhan et al., 2008). The DGER staff used oblique aerial images of landslides taken at a maximum distance of 2700 m through the windows of a fixed-wing aircraft and subsequently transposed in a geographic information system (GIS) using digital maps and pre-storm orthoimagery. While this was a rapid way of determining the extent of landsliding, this method of digitizing can introduce errors in excess of 50 m. The DGER staff did not rectify the digitized landslide observations to high resolution, post-storm orthoimagery, which was not available until after completion of the reconnaissance-level landslide observations and report (Sarikhan et al., 2008).

The report by Sarikhan et al. (2008) included a GIS spatial analysis of the regional landslide population for correlation to geology, land use, and transportation networks. To accelerate geoprocessing of the large landslide population, staff digitized a point near the uppermost visible extent (i.e., the approximate highest elevation) of each landslide. The landslide points were intended for comparison to coarse-scale data such as 1:100,000-scale geology and never intended for fine-scale analysis. The DGER staff discussed the scale limitation with the authors on several occasions; however, the authors analyzed the data at finer scales than the data justify. While, the possibility exists that the authors spatially rectified the points using high resolution orthoimagery in a GIS or field-collected GPS points for the 779 landslides, no description was provided of any changes made to the point datum and a visual analysis of Whittaker and McShane (2012) Fig. 2A found several initiation points outside of the landslides visible in the post-storm orthoimage, suggesting no spatial rectification of the point data.

To demonstrate the reconnaissance-level resolution of the landslide initiation point data, we performed a comparison of the reconnaissance-

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level landslide polygons to landslide polygons digitized in a three-dimensional (3D) GIS (BAE Systems SOCET SET version 5.5), a program that allows 3D visualization of high resolution orthoimagery with landslides digitized to a confidence of 2 to 3 m. We used existing landslide observations digitized by a photogrammetrist using 30-cm resolution, post-storm orthoimagery covering 34 km^2 in the northeast corner of the Chehalis headwaters watershed, one of the three watersheds analyzed by Whittaker and McShane (2012). We analyzed the 74 landslides that were common to both observations. Eighteen initiation points fell within the 3D GIS landslide polygons and the remaining 56 landslide initiation points were outside of the 3D GIS landslide polygons. The mean distance of the initiation point to the uppermost extent of each landslide was 48 m (minimum distance 5 m, maximum distance 310 m, standard deviation 43 m). This comparison is not statistically rigorous but is intended to illustrate that the reconnaissance level landslide observations are, in fact, reconnaissance-level and that any data points generated from the landslide observations are also reconnaissance level and should not be applied to an analysis other than those using approximately 100,000-scale or coarser (U.S. Geological Survey, 1990).

Finally, Whittaker and McShane's (2012) analysis of the landslide initiation points using the slope-instability tools HAZONE and SLPSTAB exceeded the accuracy and mapped scale of both tools. The HAZONE and SLPSTAB have a horizontal vertical accuracy of 12.2 m and are intended for use at 1:24,000-scale or coarser (DNR, 1990, 2008, 2011). The HAZONE is an analyst-created vector data set of landslide hazard areas and SLPSTAB is derived from a 10 m^2 grid digital elevation model with each grid representing an expected probability of slope instability (Vaugeois and Shaw, 2000). With SLPSTAB, the authors performed their analysis as if the landslide initiation points were mapped to a confidence such that, if a data point fell within a 10 m^2 grid, that grid value characterized the expected probability of the slope instability for that landslide. Their analysis far exceeds the intended scale and accuracy of SMORPH and the landslide point data. A similar analysis was performed using HAZONE with the authors stating that HAZONE had higher resolution because it contained vector data. When performing a spatial analysis in a GIS, it is critical that the analyst recognizes the limitation and scale of the data and presents the output at the scale equivalent to the coarsest-scale data in the analysis.

In summary, Whittaker and McShane (2012) compared the slope-instability screening tools HAZONE and SLPSTAB to landslide initiation points and neglected to account for the reconnaissance-level quality of the landslide data as well as the 1:24,000-scale of the slope instability models. The comparison of reconnaissance-level data to 1:24,000-scale slope instability models cannot produce output data at a finer scale than the scale of the input data. An additional criticism is using reconnaissance-level DGER landslide point data as fine-scale landslide initiation points and not disclosing our expressed limitation despite our communicating the intent and quality of the data. The Results, Discussion, Management and Policy implications, and Conclusion of the Whittaker and McShane (2012) paper are based on an inappropriate use of data and must be addressed. Suggestions to address these issues include a spatial rectification of the reconnaissance-level landslide database utilizing higher resolution orthoimagery or field reconnaissance of all landslide polygons. Only then can a recomparison of the slope instability tools SLPSTAB and HAZONE be accomplished at an appropriate scale reflective of the 1:24,000-scale data. We hope that Whittaker and McShane (2012) will clarify these issues for the sake of all *Geomorphology* readers.

2. The policy section discussion

The WDNR Forest Practices Division geologists believe that the article by Whittaker and McShane (2012) contains serious flaws and omissions, and it does not represent the quality of scientific rigor that should be acceptable to *Geomorphology*. Outlined below are examples of the article's shortcomings.

First, Whittaker and McShane (2012) based some of their study on information cited as Stewart et al., unpublished results. We question the appropriateness of accepting unpublished citations in *Geomorphology* publications. Whittaker and McShane cite Stewart et al. for discussions of determinations that are notoriously difficult to identify such as landslide initiation points and sediment delivery volumes to water.

Secondly, Whittaker and McShane (2012) displayed a flawed understanding of Washington State's forest practice rules with respect to potentially unstable slopes. The WDNR geologists routinely use the SLPSTB, HAZONE, and/or LIDAR-based slope-convergence screening tools during review of forest practice proposals. However, our extensive field experience indicates that much unstable ground lies in areas of subtle landforms or geologic conditions often not shown in screening tools. Therefore, final approval of a timber harvest or forest road construction project on or near potentially unstable slopes requires a thorough field investigation by a qualified expert geologist and may require a second level of State Environmental Policy Act (SEPA) review.[4]

Whittaker and McShane (2012) did not examine actual forest practice applications (FPA) – the permits associated with specific forest practices proposals – with respect to the subject landslides. Therefore, the author's assertion that, "During the December 2007 storm, 45% (N = 514) of landslides that entered streams initiated at locations that had not been identified as potentially unstable during the forest practice review process…" is speculative at best. Note, in some instances, areas that appear as high hazard slopes on the slope-convergence screening tools are in fact stable, and logging can be approved (e.g., bedrock dip slopes) per the Washington Forest Practices rules (Washington Forest Practices Board, 2001). One would have to examine the actual FPA and conduct field verification to make this determination.

The current Forest Practices rules regarding potentially unstable slopes were adopted in 2001, yet some of the landslides used by Whittaker and McShane (2012) likely initiated in areas harvested under a previous set of rules. The authors make only a passing mention of this fact and again cite unpublished results to support the assertion that "…the majority of those slides took place in areas that had been relatively recently harvested."

Finally, the discussion of other factors influencing slope stability, including bedrock hydrogeology during the 2007 storm, is inadequate. No mention is made of the rain-on-snow event that occurred in the landslide sample area or of known unstable geologic units.

[4] Washington Administrative Code WAC 222-16-050 (1) (d) (i) (A–E) is as follows: "(d) Timber harvest, or construction of roads, landings, gravel pits, rock quarries, or spoil disposal areas, on potentially unstable slopes or landforms described in (i) below that has the potential to deliver sediment or debris to a public resource or that has the potential to threaten public safety, and *which has been field verified by the department* (emphasis added). (See WAC 222-10-030 SEPA policies for potential unstable slopes and landforms).

(i) For the purpose of this rule, potentially unstable slopes or landforms are one of the following: (See board manual section 16 for more descriptive definitions.) (WDNR, 2004)

(A) Inner gorges, convergent headwalls, or bedrock hollows with slopes steeper than 35° (70%);

(B) Toes of deep-seated landslides, with slopes steeper than 33° (65%);

(C) Ground water recharge areas for glacial deep-seated landslides;

(D) Outer edges of meander bends along valley walls or high terraces of an unconfined meandering stream; or

(E) Any areas containing features indicating the presence of potential slope instability which cumulatively indicate the presence of unstable slopes.

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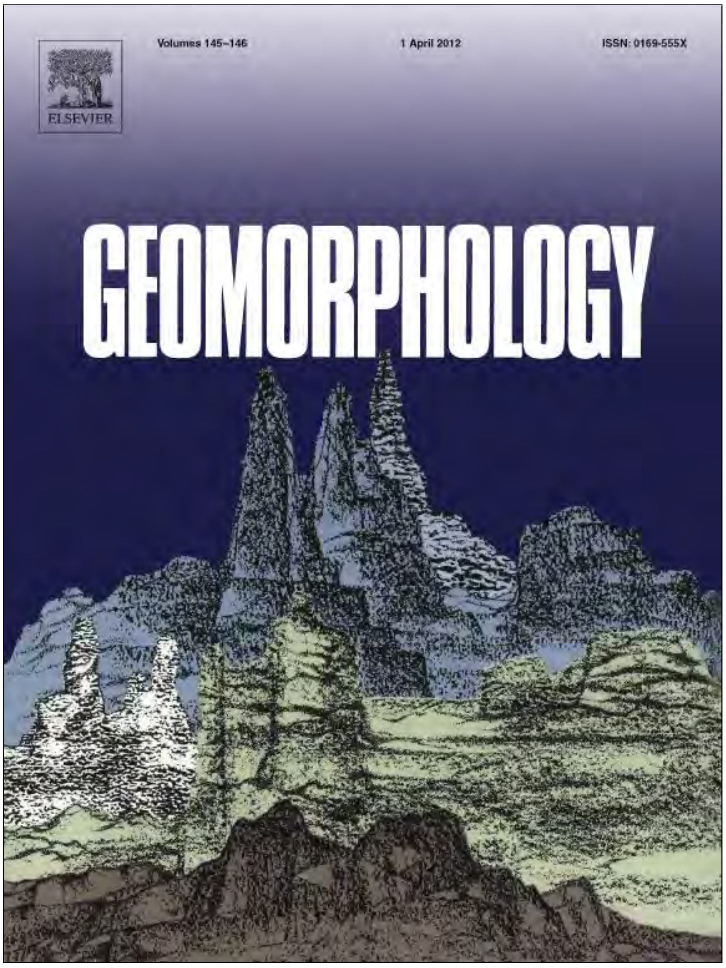
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Comparison of slope instability screening tools following a large storm event and application to forest management and policy

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ABSTRACT

The objective of this study was to assess and compare the ability of two slope instability screening tools developed by the Washington State Department of Natural Resources (WDNR) to assess landslide risks associated with forestry activities. HAZONE is based on a semi-quantitative method that incorporates the landslide frequency rate and landslide area rate for delivery of mapped landforms. SLPSTAB is a GIS-based model of inherent landform characteristics that utilizes slope geometry derived from DEMs and climatic data. Utilization of slope instability screening tools by geologists, land managers, and regulatory agencies can reduce the frequency and magnitude of landslides. Aquatic habitats are negatively impacted by elevated rates and magnitudes of landslides associated with forest management practices due to high sediment loads and alteration of stream channels and morphology. In 2007 a large storm with heavy rainfall impacted southwestern Washington State trigging over 2500 landslides. This storm event and accompanying landslides provides an opportunity to assess the slope stability screening tools developed by WDNR. Landslide density (up to 6.5 landslides per km^2) from the storm was highest in the areas designated by the screening tools as high hazard areas, and both of the screening tools were equal in their ability to predict landslide locations. Landslides that initiated in low hazard areas may have resulted from a variety of site-specific factors that deviated from assumed model values, from the inadequate identification of potentially unstable landforms due to low resolution DEMs, or from the inadequate implementation of the state Forest Practices Rules. We suggest that slope instability screening tools can be better utilized by forest management planners and regulators to meet policy goals regarding minimizing landslide rates and impacts to sensitive aquatic species.

1. Introduction

In the Pacific Northwest, landslide frequencies in areas with forest clearing are up to thirty-four times higher than natural background rates (Rood, 1984). Timber harvest is the primary factor responsible for this difference (Sidle et al., 1985). Landslides alter aquatic habitats by elevating sediment delivery, creating log jams, and causing debris flows that scour streams and stream valleys down to bedrock (Rood, 1984; Cederholm and Reid, 1987; Hogan et al., 1998). The short-term and long-term impacts of higher rates of landslides on fish include habitat loss, reduced access to spawning and rearing sites, loss of food resources, and direct mortality (Cederholm and Lestelle, 1974; Cederholm and Salo, 1979; Reeves et al., 1995). The restoration of geomorphic processes to natural disturbance regimes is crucial to the recovery of endangered salmonids (*Oncorhynchus* spp.) and other aquatic species in the Pacific Northwest as these species evolved under conditions with much lower sediment delivery and landslide frequency (Reeves et al., 1995; Montgomery, 2004).

In December 2007, a series of large storms moved through northwestern Oregon and southwestern Washington State. The storms brought heavy precipitation (up to 48 cm) and hurricane-force winds over four days (Mote et al., 2007). Significant flooding took place on numerous rivers in southwest Washington with record floods observed on the Chehalis River. Other rivers in the region recorded return period floods ranging from 2 to 100 years (Reiter, 2008). At least 2503 landslides were triggered in southwestern Washington by this storm event (Turner et al., 2010; Fig. 1). Upon entering steep and/or confined stream channels many of these landslides turned into debris avalanches, flows, and torrents (Sarikhan et al., 2008) further adding to the sediment volume of the original slides. Debris flows from landslides in smaller stream drainages can lead to short term stream discharge rates orders of magnitude above 100-year return period flood levels (Jakob and Jordan, 2001). Extrapolating from the number and area of the landslides, tens of millions of cubic meters of sediment, logs and debris were delivered to the stream networks in southwest Washington and northeast Oregon (Forest Debris Recovery Team, 2008; Sarikhan et al., 2008; ENTRIX,

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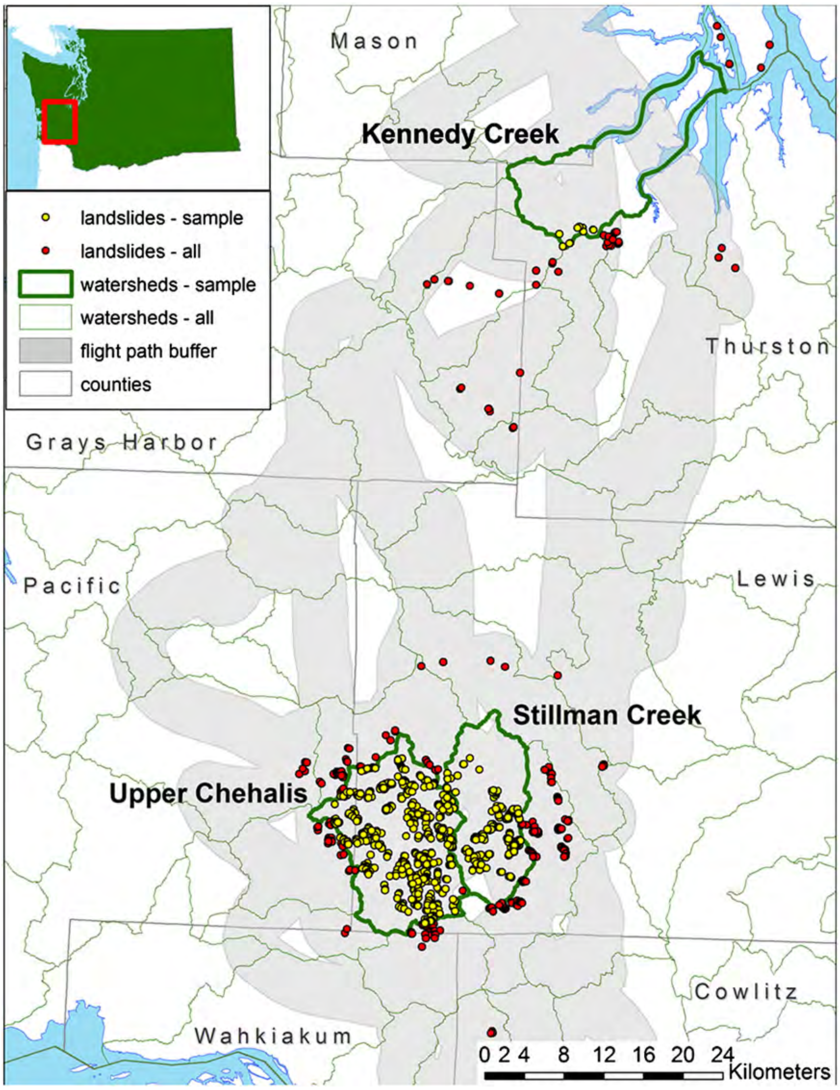

Fig. 1. Landslides from the December 2007 storm (WDNR, 2009) and watersheds sampled for this study (see Section 2.1).

2009). These streams were likely already aggraded from elevated sediment input rates associated with past forest practices (Stover and Montgomery, 2001).

Forest practices in Washington State are governed by state Forest Practices Rules which include site-specific prescriptions intended to prevent the increase in landsliding caused by forest practices beyond natural background rates in order to protect aquatic species and public resources (Washington Administrative Code (WAC) 222-10-030). For example, timber harvest, road-building, and related activities are limited on potentially unstable landforms (such as bedrock hollows, convergent headwalls, and inner gorges) on slopes steeper than 70% (35°; WAC 222-16-050(1)(d)). In response to the December 2007 storm, the effectiveness of the Forest Practices Rules at reducing landslide density and sediment delivery to the stream network was evaluated (Stewart et al., unpublished results). Where the Rules were fully implemented they appeared to be effective, but a large proportion (45%, $N=514$) of the identified landslides that entered streams initiated at locations that had not been defined as potentially unstable by the Rules (the Rules did not apply to these sites; Stewart et al., unpublished results). Because the Rules were only partially effective in limiting landslide rates to background levels, improvements in the Forest Practices Rules for identifying potentially unstable landforms or improvements in their implementation may be needed.

Models have been developed as screening tools to identify locations of potentially unstable landforms. Use of these screening tools as hazard maps help forest managers determine where forest practices should or should not be located in order to minimize and avoid damage to aquatic habitats and other public resources as well as private property (Shaw and Vaugeois, 1999). The success with which slope instability screening tools can be applied in forest land management depends on evaluation of the accuracy of model predictions and the long-term response by land-use agencies (Wilcock et al., 2003). The objective of this study was to assess and compare the ability of two slope instability screening tools to predict actual landslide locations from the December 2007 storm. We show that these tools are useful in the identification of potentially unstable slopes, and we describe ways they can be better utilized in forest management to minimize landslide rates and harm to sensitive aquatic species.

2. Methods

2.1. Study area and sample criteria

Landslide initiation point data was gathered by the Washington Department of Natural Resources (WDNR) during reconnaissance flights across southwest Washington immediately following the

December 2007 storm (WDNR, 2009; Fig. 2A). Each identified landslide from the December 2007 storm had to fit three criteria before we included it in our sample and determined the hazard rating (very high, high, medium, or low) predicted by each slope instability screening tool (Section 2.3; Table 1). First, only watersheds for which both slope instability screens could be applied were considered: Kennedy Creek ($N=11$ landslides), Stillman Creek ($N=215$ landslides), and the Chehalis Headwaters ($N=553$ landslides; Fig. 1). All Kennedy Creek landslides occurred on WDNR-managed land, and 99% of Stillman Creek and Chehalis Headwaters landslides occurred on Weyerhaeuser Co. land (a private timber company). Second, only areas within 2743 m (9000 ft.) of the WDNR landslide reconnaissance flight paths were considered (Sarikhan et al., 2008; Fig. 1). This distance represents the extent visible on photos taken during the flights given the light conditions and topography (I. Sarikhan, WDNR, personal communication, 2009). Finally, only those land cover classes characteristic of working forestlands, where these screening tools are applied, were included in the study area (deciduous, evergreen, and mixed forest, barren land, shrub/scrub, herbaceous, woody wetlands, and developed open space; Homer et al., 2004).

2.2. Geological context

The Kennedy Creek watershed is located at the southwest edge of the Puget Lowlands province. Mapping by Logan and Walsh (2004) and WDNR (1995) indicate the watershed is underlain by glacial related sediments and Eocene basalts of the Crescent Formation. The Puget ice lobe extended into and over all but the southernmost area of the watershed area during the pre-late Wisconsinan glacial period. Glacial ice reached only the lower northern end of the watershed

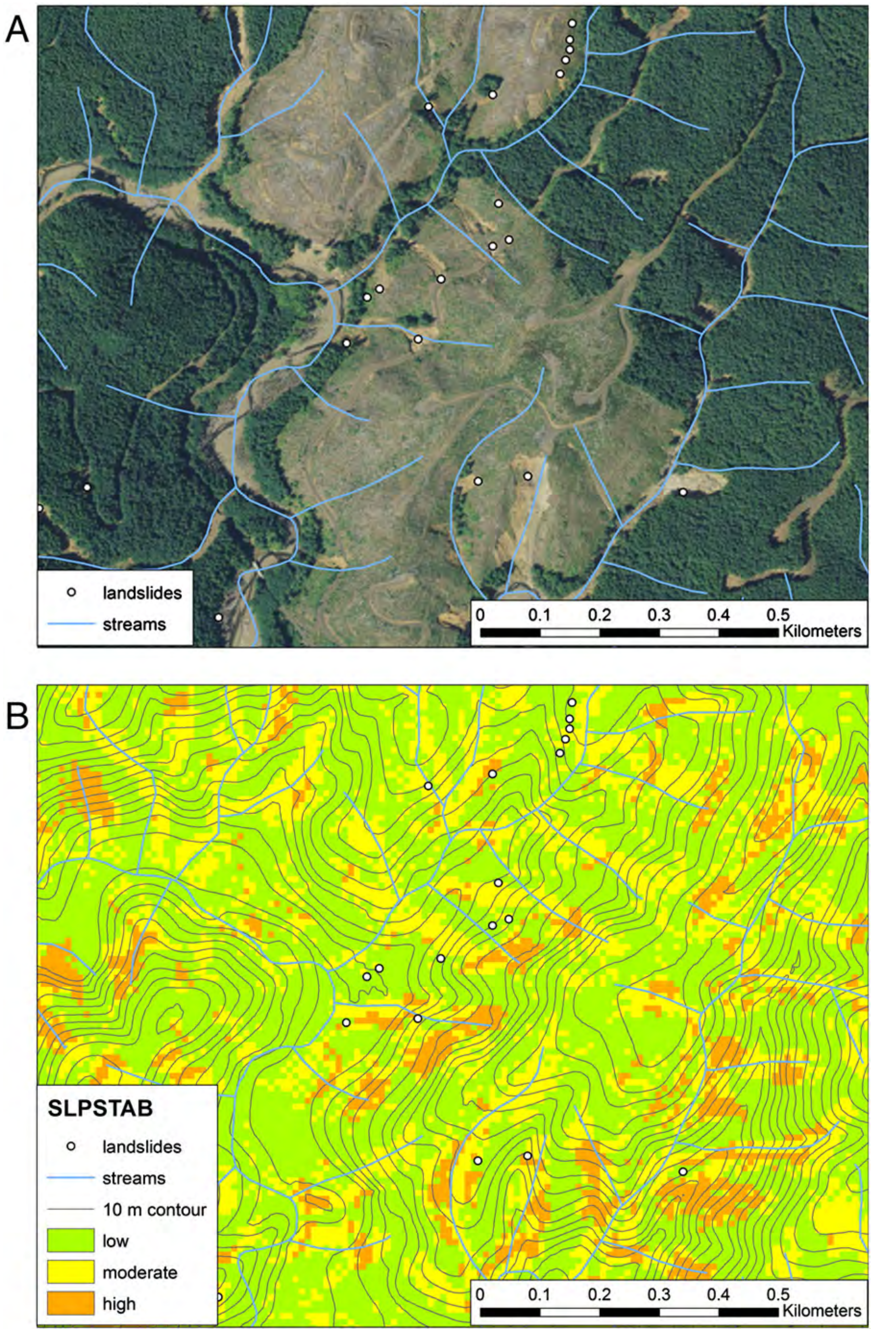

Fig. 2. Landslide initiation points relative to (A) forest and road cover and slope instability categories defined by (B) SLPSTAB and (C) HAZONE.

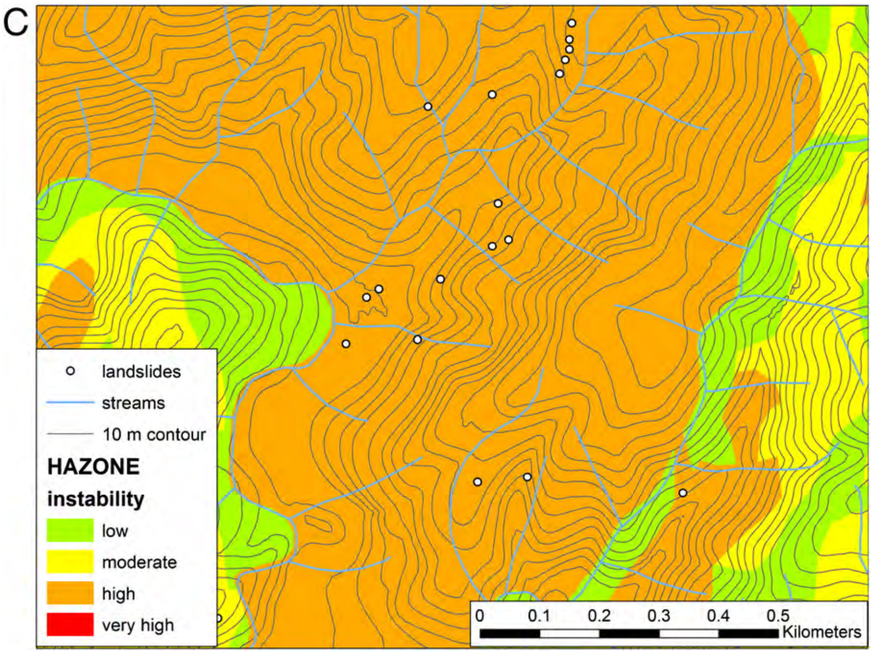

Fig. 2 (*continued*).

during the last glacial period approximately 18,000 years BP. Bedrock was eroded and glacial related sediments were deposited on lower valley slopes with very thin glacial till to no glacial deposits on upper and steeper slopes. The Kennedy Creek valley served as a glacial melt water outlet draining the southwest margin of the ice lobe to valleys to the southwest. Since the ice has retreated the streams in the northern portion of the watershed have been down-cutting through the thicker glacial sediments. The southern edge of the watershed includes the north slope of the Black Hills. The glacial ice did not cover these slopes, and the slopes in this area are sharper consisting of steep sided ridges separated by steep incised stream channels.

The Stillman Creek and Chehalis Headwaters watersheds are neighboring headwater basins of the Chehalis River located in the Willapa Hills province. This area has not been glaciated. The higher elevation portions of the watersheds are underlain by lower to middle Eocene Crescent Formation, Eocene intrusive rocks, and Eocene tuffs, and the lower portions of the watershed are underlain by Eocene marine sedimentary rocks (Walsh et al., 1987). The Crescent Formation is predominantly composed of fine grained submarine basalt flows with localized thin interbeds of tuff and siltstone. The intrusive rocks consist of gabbro, diabase, and basalt dikes and sills. The tuffs are mafic to silicic and are submarine. The lower reaches of both watersheds are predominantly marine sedimentary rocks ranging from laminated to massive siltstone and claystone to crossbedded sandstones with lesser interbeds of tuff and basalt flows, breccias, and conglomerates. The Stillman Creek and Chehalis Headwaters watersheds are characterized as highly incised steep sided ridges and valleys with elevation difference between the larger stream valley bottoms and ridges on the order of 2000 ft and average slopes greater than 30° with much steeper slopes in convergent or deeply eroded areas. Due to lack of glaciation, depth of bedrock weathering varies based on slope aspects and bedrock types with marine sedimentary units generally more deeply weathered (Sarikhan et al., 2008).

Table 1
Number of landslides per watershed by slope instability screening tool and hazard category (not normalized by area). None of the areas in the Kennedy Creek or Stillman Creek watersheds were classified as very high hazard by the HAZONE model. Landslides in the low hazard category were considered incorrect (Type I errors).

	HAZONE				SLPSTAB		
Watershed	Low	Moderate	High	Very high	Low	Moderate	High
Kennedy Creek	7	1	3	NA	5	5	1
Stillman Creek	105	98	12	NA	114	63	38
Chehalis Headwaters	73	284	189	7	199	189	165
Total	185	383	204	7	318	257	204

2.3. Slope instability screening tools

In Washington State, two slope instability screening tools have been developed for use in forest practice planning and permitting by the WDNR, the agency charged with forest practice regulation and management of state forest trust lands: SLPSTAB (Vaugeois, 2000) and HAZONE (WDNR, 2010). The screening tools are used by WDNR during the forest practices application process to flag potentially unstable slopes where timber harvest, road building, or related activities are being proposed. SLPSTAB is a GIS-based screening tool of inherent landform characteristics that covers all or most of 488 watersheds of western Washington (Vaugeois, 2000; Fig. 2B). It was derived from two deterministic, physically-based models — SMORPH (Shaw and Johnson, 1995) and SHALSTAB (Montgomery and Dietrich, 1994) — that assume that topographic relief (i.e., hillslope gradient) and form (i.e., slope curvature) are the principal driving factors in promoting shallow landslides (Vaugeois and Shaw, 2000). SLPSTAB utilizes slope geometry derived from 10-m digital elevation models (DEMs) and climatic data establishing frequency of critical rainfall (Q_c per Montgomery et al., 1998) in a given area that would cause a slope to become unstable. SLPSTAB categorizes the risk of shallow-rapid landslide potential as low, medium, or high based on a semi-quantitative matrix approach that uses two-year, 24-hour storm isohyte data to create precipitation rules for each test basin (Vaugeois and Shaw, 2000). The screening tool has been calibrated to specific areas with landslide inventories, soils, mass wasting units, geology, and precipitation data. SLPSTAB model output is viewable to the public through the Forest Practices Application Review System resource maps online (WDNR, 2007), or its GIS raster file can be downloaded (WDNR, 2010).

HAZONE, on the other hand, is a screening tool developed using a more inferential approach. The predictive capability of HAZONE relies on the past as prediction for hazard potential, an approach consistent with standard geomorphic analysis of an area. HAZONE hazard ratings are based on a semi-quantitative assessment method that incorporates slope stability data from previously existing watershed analyses; public, tribal, and private assessments; and the State Landslide Hazard Zonation project (UPSAG, 2006). This screening tool was derived from aerial photos; topographic, geologic, and hydrologic maps; 10 m or LiDAR (Light Detection and Ranging) DEM; and field observations; and it covers all or most of 142 watersheds (WDNR, 2010; Fig. 2C). A key variable in establishing hazard zones in the HAZONE screening tool is historic landslide density normalized over time, or more specifically, the landslide frequency rate and landslide area rate for delivery of a given landform (UPSAG, 2006). Low hazard areas have no historic landslides or any other attributes of slope instability and include landforms such as valley bottoms, terrace surfaces, or low gradient hillsides. Moderate hazard areas include landforms that occasionally generate landslides (such as the bodies of deep-seated landslides) and have some documented sensitivity to forest practices (such as steep planar slopes with road drainage-related failures). Toes and headscarps of active deep-seated landslides or steep and potentially unstable landforms that meet specific regulatory criteria (WAC 222-16-050) receive a high or very high hazard rating (UPSAG, 2006). HAZONE can be downloaded as a GIS vector file (WDNR, 2010).

2.4. Statistical analysis

To assess the predictive abilities of the two screening tools for this storm event, we calculated landslide densities (landslides/km^2) within each hazard zone for each tool and type I error rates for each tool and watershed. To detect differences in landslide density between hazard zones, we conducted a χ^2 test for each screening tool, assuming expected values to be in proportion to the area in each hazard zone (Montgomery et al., 1998). To assess differences in the area encompassed by each hazard zone, we conducted another χ^2 test for each screening tool, assuming expected values to be equal between hazard zones. To compare the relative predictive abilities of the two screening tools, we conducted a Wilcoxon Signed Rank test (a non-parametric test for non-normally distributed, small, independent samples), which tests the null hypothesis that the distributions of the two groups are equal. For this test, type I error rates were defined as the ratio of incorrectly predicted landslides (those that initiated at sites outside of areas defined by the screening tools as unstable, i.e., in low hazard areas) to the total landslides per watershed (Shaw and Vaugeois, 1999). We conducted all tests using the statistical software SPSS 13.0 (Chicago, IL, USA) and set α at $p = 0.05$ (2-tailed).

3. Results

Landslide density (landslides/km^2) was significantly higher in areas designated by both models as high hazard areas. For the HAZONE tool, landslide density ranged from 0.9 landslides/km^2 in the low hazard category to 6.5 landslides/km^2 in the very high hazard category ($\chi^2 = 751$, $df = 3$, $p < 0.0001$; Fig. 3). For the SLPSTAB tool, landslide density ranged from 1.4 landslides/km^2 in the low hazard category to 5.5 landslides/km^2 in the very high hazard category SLPSTAB: $\chi^2 = 23$, $df = 2$, $p < 0.0001$; Fig. 3).

Landslides did not occur in direct proportion to the area mapped in each hazard category (Fig. 4). For the HAZONE tool, 27% of the landslides occurred in high and very high hazard areas, which represent only 11.9% of the total area (42.7 km^2). When moderate hazard areas are added to this, 76.3% of the landslides were included and 39.8% of the total area (km^2) was covered. Differences in the areas of hazard zones mapped by HAZONE were significant ($\chi^2 = 292$, $df = 3$, $p < 0.0001$). For the SLPSTAB tool, 26% of the landslides occurred in high hazard areas, which represent only 10.4% of the total area (37.2 km^2). When moderate hazard areas are added to this, 59.2% of the landslides were included and 34.2% of the total area (km^2) was covered. Differences in the areas of hazard zones mapped by SLPSTAB were also significant ($\chi^2 = 180$, $df = 2$, $p < 0.0001$). Thus the screening tool hazard categories were useful for predicting where the highest and lowest concentrations of landslides would occur.

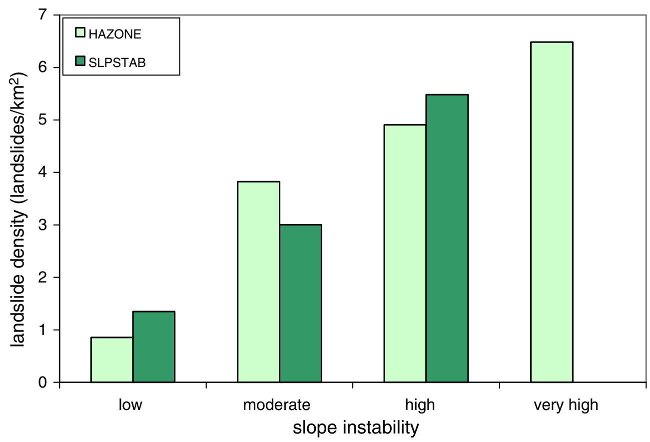

Fig. 3. Landslide density (landslides/km^2) by slope instability category and model. The SLPSTAB model does not include a very high hazard category.

Neither slope instability screening tool showed a superior predictive ability over the other. The mean number of landslides that took place in areas designated as low hazard areas (type I errors) per watershed was similar between the two tools tested (42% for HAZONE and 45% for SLPSTAB; Table 2). The Wilcoxon rank sum test showed the distributions of this subset of landslides did not differ statistically between tools (Wilcoxon $W = 10.0$, $p = 0.827$). When all three watersheds were combined, the type I error rate was lower: 24% for HAZONE and 41% for SLPSTAB (Table 2). SLPSTAB had more slides in low hazard areas than HAZONE overall, whereas HAZONE had greater variance in the number of slides that took place in low hazard areas per watershed than SLPSTAB.

4. Discussion

The hazard categories mapped by both slope instability screening tools were useful for predicting sites more likely to have slope failures from this storm event within the three watersheds examined. Zones predicted to have the highest landslide hazard showed the highest landslide density and the smallest area among hazard categories.

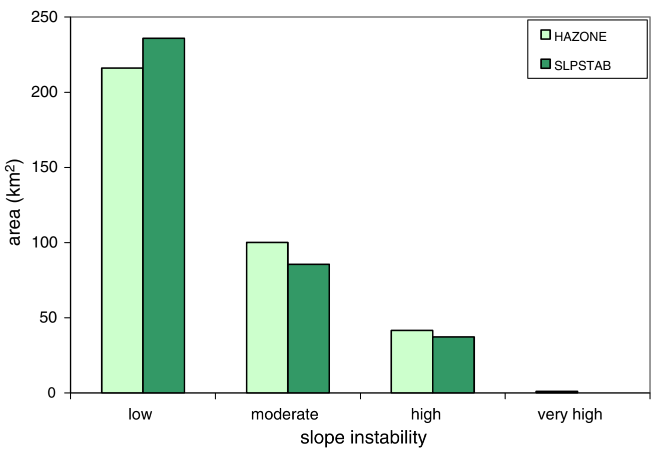

Fig. 4. Area (km^2) in each slope instability category by model. The SLPSTAB model does not include a very high hazard category.

Table 2
Ratio of incorrect landslides (in low hazard areas) to total landslides per watershed (Type I error rates, Wilcoxon rank sum test input).

		HAZONE		SLPSTAB	
Watershed	Total landslides	Incorrect landslides	Incorrect/total landslides	Incorrect landslides	Incorrect/total landslides
Chehalis Headwaters	553	73	0.13	199	0.36
Kennedy Creek	11	7	0.64	5	0.45
Stillman Creek	215	105	0.49	114	0.53
Mean	259.7	61.7	0.42	106.0	0.45
SD	273.7	50.0	0.26	97.2	0.09
Total	779	185	0.24	318	0.41

Landslide density was lowest in areas predicted to have the lowest landslide hazard, which comprised the largest area. Our results indicate that both HAZONE and SLPSTAB are effective methods for recognizing potentially unstable slopes.

Other studies have found similar results. A test of SHALSTAB (Montgomery and Dietrich, 1994; from which SLPSTAB was partially derived) showed areas predicted to have lower critical steady-state rainfall (Q_c) necessary to trigger slope instability (i.e., high hazard areas) consistently had higher landslide densities both within each watershed and across all watersheds examined (Montgomery et al., 1998). As assessment of SHALSTAB and SMORPH also found landslide densities increased with hazard class for both models (Pacific Watershed Associates, 2008). Landslide density may not be the best proxy for aquatic habitat disturbance due to variability in the volume of sediment and debris delivered to a stream with landslide gradient and size (Brardinoni et al., 2009). A better dependent variable for measuring impacts to aquatic habitats would be the volume of sediment and debris delivered to streams, but unfortunately these data were not available for this study.

Others have also found the highest hazard zones to occupy the least area across watersheds. A regional analysis of 14 watersheds in Washington and Oregon found only 13% of the total area was classified as high hazard, which represents a small and topographically identifiable portion of the region (Montgomery et al., 1998). A study of two watersheds in northern California mapped 4% of the area and 58% of landslides in high hazard zones (Pacific Watershed Associates, 2008). A similar relationship was found in Oregon, where sites with the highest probabilities of initiating or transporting debris flows made up a relatively small percentage of the study area (Burnett and Miller, 2007). This pattern has important implications for forest management and policy making strategies that aim to concentrate land use restrictions over the smallest area possible to minimize economic impacts to landowners while effectively minimizing landslide rates.

Landslides occurred in areas that both models designated as low hazard areas, but the rate of these slides (type I errors) was similar for both screening tools tested. Statistically, neither tool showed a greater ability to predict landslide locations than the other. In a similar comparison of slope instability screening tools that were precursors to the SLPSTAB model Shaw and Vaugeois (1999) found no significant difference in type I error rates between the SMORPH and SHALSTAB models and hazard zonation maps later utilized by the HAZONE screening tool. We observed fewer slides in low hazard areas for HAZONE than SLPSTAB overall (24% and 41% respectively). Overall type I error rates reported by Shaw and Vaugeois (1999) were lower (3% for SMORPH and 8% for SHALSTAB). A test of SHALSTAB (Montgomery et al., 1998) reported a 24% type I error rate across 14 watersheds and highly variable error rates between watersheds that ranged from 6% to 88%. In a different assessment, landslides were incorrectly predicted by SHALSTAB in 25% of cases and by SMORPH in only 0.5% of cases (Pacific Watershed Associates, 2008).

The overall type I error rates we observed probably would have been lower if we had utilized different methods for mapping landslides (polygons instead of initiation points), less stringent methods for classifying type I errors (assigned each landslide with the highest hazard of all pixels within the polygon), and a larger sample of landslide and rainfall events spatially and temporally (more than three watersheds and one storm), as other studies have done (Montgomery et al., 1998; Shaw and Vaugeois, 1999; Pacific Watershed Associates 2008). Under the strict classification criterion used for this study (hazard level of a single 10 m^2 pixel or variable-sized polygon in which a landslide initiation point occurred), we consider the percent of correctly predicted landslides (59–76% for SLPSTAB and HAZONE, respectively) to indicate these two screening tools are good predictors of landslide hazard. The difference in overall type I error rates between these two tools may have been related to the difference in the tools' resolutions, with a higher error rate for SLPSTAB's 10 m^2 pixel (Fig. 2B) than for HAZONE's variable-sized polygons (Fig. 2C). Small mapping errors in a landslide initiation points are more likely to lead to classification errors on higher resolution maps if classification is based on the hazard level of a single pixel.

Many of the errors reported by Montgomery et al. (1998) occurred because the DEM utilized in the models did not detect all landform locations subject to slope failures (at finer resolution than a 30-m DEM), but these smaller landforms were readily detectable in the field. The SLPSTAB tool assessed in this study was run with a finer 10-m DEM, but even with this finer topographic resolution unstable slope landforms will still be missed and will still contribute to type I errors. Hence low DEM resolution can be a significant source of type I errors in areas that were designated as low hazard areas (Brardinoni et al., 2003). SLPSTAB tool performance could improve with the use of higher resolution digital elevation data such as LiDAR (Dietrich and Montgomery, 1998; Shaw and Vaugeois, 1999). Another factor is the variability of rain fall events as well as variability of rain fall across geographic areas from a single storm event. SLPSTAB hazard designations are in part established based on a return frequency of critical rainfall threshold events. For the 2007 storm, the rainfall intensity was very high and caused slope instability on a wider range of slopes than would have taken place during a less intense storm. The SLPSTAB screening tool would benefit from better refined climatic models that would better predict frequency of critical rainfall thresholds. Type I errors are also more likely for SLPSTAB at sites where soil parameters such as cohesion and internal angle of friction deviate from assumed default values due to local lithology or where geologic structures are stronger influences than topographic landform alone on slope instability (Montgomery et al., 1998). Sarikhan and others (2008) noted greater landslide density within Crescent Formation units versus other units within the Stillman Creek and Chehalis Headwaters watersheds during the storm event. There are a number of possible explanations for this discrepancy. The areas underlain by Crescent Formation tend to be in the higher and steeper portions of the watersheds, and higher elevation coincides with higher precipitation. These factors should be reflected within the screening tools. However, the Crescent Formation basalts are more resistant to deep weathering than the more marine sedimentary units. The Crescent Formation subsurface stability parameters will differ from the more deeply weathered marine sedimentary units in a manner that may lead to the marine sedimentary units being more stable than topography alone would otherwise indicate. Hence, actual subsurface conditions that differ from those assumed or simulated in the screening tools can result in higher or lower potential slope instability. In particular, high pore water pressures can exist for reasons other than topographic convergence and cause landslides to occur on planar and gentle slopes. For example, minor drainage alteration along both new and legacy logging roads or along skidder routes can concentrate subsurface pore water. In areas of deeply weathered bedrock, residuum soils with lower porosity can concentrate subsurface water in an unpredictable manner.

The number of slides reported here both within areas the screening tools indicated as low hazard areas (type I error rates) or within high hazard areas should be treated as estimates rather than absolute values. The number of landslides detected by aerial surveys can be affected by the presence of forest canopy or narrow channels (Robison et al., 1999; Brardinoni et al., 2003; Miller and Burnett, 2007; Turner et al., 2010). A test of this relationship was not conducted due to the limits of landslide inventory data available to the public (WDNR, 2009).

5. Management and policy implications

Assessing potential landslide risk is an important component of forest management. Besides the impacts to forest soils and the forest itself, landslides can impact down slope properties, stream and river systems, and other public resources, with an increased rate of delivery of sediment from landslides taking place at a greater frequency and magnitude than under natural background conditions (Rood, 1984; Montgomery et al., 2000). These impacts are common among managed forest watersheds of the Pacific Northwest, and have contributed to the habitat degradation and decline of endangered salmonid, amphibian, and other native aquatic species that are unable to adapt to the altered disturbance regime (Cederholm and Lestelle, 1974; Welsh and Ollivier, 1998; Montgomery, 2004). The long-term survival of many endangered fish stocks will depend on a new management paradigm that emphasizes the restoration of basic habitat integrity and ecosystem processes, including landslide rates closer to natural background levels, while incorporating the needs of other native aquatic species (Nehlsen et al., 1991; Reeves et al., 1995; Montgomery, 2004).

Forestry presents a challenge for landslide hazard assessment, but many of the most valuable forest areas in the world are located within temperate mountain belts (NASA, 2011) with steep terrain that can be susceptible to landsliding. In forested mountainous terrain knowledge of geologic and soil parameters are general in nature, and detailed features of the terrain can be difficult to ascertain due to thick forest cover. This last aspect may be greatly alleviated with the greater coverage of areas by ground surface LiDAR and the trend toward even more accurate GIS-based DEMs. Forest practice planning and review has been evolving in Washington State due to the recognition that increased rates and magnitudes of landslides due to timber management activities have impacted aquatic resources. In Washington State, if forest practices are proposed on potentially unstable landforms that meet specific criteria, further evaluation for impacts to the environment must be conducted through the State Environmental Policy Act (SEPA; WAC 222-16-050(1)(d)). This requirement can be avoided by excluding these landforms from harvest units, but in forested mountainous or hilly terrain identifying potentially unstable areas poses a challenge to foresters charged with ensuring that forest practices do not cause significant harm to the environment. Hence, the HAZONE and SLPSTAB screening tools were developed to assist both foresters and regulators in identifying and avoiding unstable slopes.

The December 2007 storm provides an opportunity to not only evaluate the two screening tools used in Washington State but also an opportunity to identify potential problems in the forest practice rules and their implementation regarding unstable slopes. During the December 2007 storm, 45% ($N = 514$) of landslides that entered streams initiated at locations that had not been identified as potentially unstable during the forest practices review process, and the majority of those slides took place in areas that had been relatively recently harvested (Stewart et al. unpublished results and our own observations). This may have resulted from the inadequate identification of potentially unstable landforms or the inadequate implementation of the state Forest Practices Rules.

The two slope instability screening tools assessed here indicate that slope stability screening tools work well for identifying potentially unstable slopes. However, these screening tools are not currently formally used during the forest practice review process in Washington State. Even though the HAZONE and SLPSTAB screening tools indicated the presence of potentially unstable slopes, forest practices took place within these areas because they were not formally designated as high hazard areas.

The forest practice review process begins with a screening by WDNR staff for the presence of unstable slopes in the proposed harvest unit(s) according to a soils map, SLPSTAB, and HAZONE. By default, no SEPA review of applications is required regardless of the screening tool map output (WDNR, personal communication, 2010). For a forest practice to be subject to SEPA review, the proposed activity must *also* be “field verified by the department” (WAC 222-16-050(1)(d)). Workload constraints and the large areas covered by forest practice proposals prevent field visits to all of the sites where field review is needed (WDNR, personal communication, 2010). Because of this, forest practices can take place on slopes that were identified by the screening tools as high landslide hazard areas without any further regulatory review. We suggest that statistically both the HAZONE and SLPSTAB screening tools are an effective means of identifying potentially unstable slopes and that all forest practices that take place within such areas be subject to field verification as to whether or not an area meets the specific criteria of an unstable landform. Implementing this change to the forest practice review process ought to lead to better identification and protection of potentially unstable slopes and aquatic habitats.

6. Conclusions

During the December 2007 storm in southwest Washington, the highest landslide density occurred where slope instability screening tools indicated the highest risk of hazard, and the tools were equal in their ability to predict landslide locations. Many landslides initiated on sites identified by the screening tools as unstable, but that had not been identified as unstable though the forest practices review process. We suggest that the slope instability screening tools we reviewed can be better utilized by forest management planners and regulators to meet policy goals regarding minimizing landslide rates and impacts to sensitive aquatic species. This type of adaptive management will become increasingly important as the Pacific Northwest experiences more frequent and intense storms predicted by climate change models (Dale et al., 2001; Christensen et al., 2007; Karl et al., 2009).

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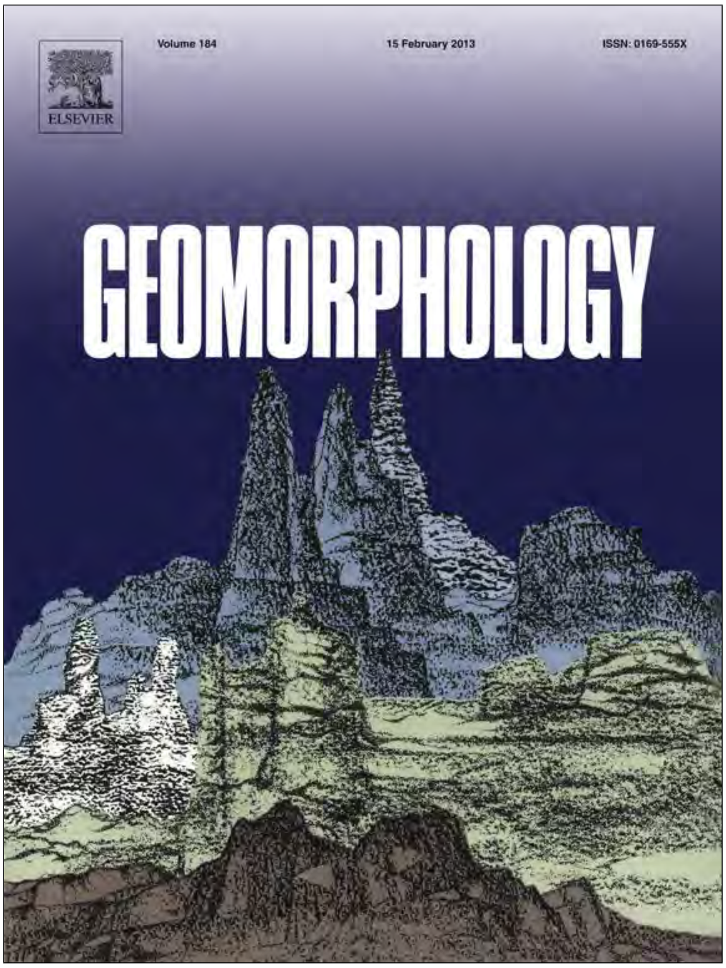
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Reply: Comparison of slope instability screening tools following a large storm event and application to forest management and policy

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ABSTRACT

A large storm event in southwest Washington State triggered over 2500 landslides and provided an opportunity to assess two slope stability screening tools. The statistical analysis conducted demonstrated that both screening tools are effective at predicting where landslides were likely to take place (Whittaker and McShane, 2012). Here we reply to two discussions of this article related to the development of the slope stability screening tools and the accuracy and scale of the spatial data used. Neither of the discussions address our statistical analysis or results. We provide greater detail on our sampling criteria and also elaborate on the policy and management implications of our findings and how they complement those of a separate investigation of landslides resulting from the same storm. The conclusions made in Whittaker and McShane (2012) stand as originally published unless future analysis indicates otherwise.

1. Introduction

Two discussions of our recent article "Comparison of slope instability screening tools following a large storm event and application to forest management and policy" (Whittaker and McShane, 2012) question the accuracy and scale of the spatial data we used (Lingley et al., 2013-this volume) and our discussion of the screening tool development (Shaw, 2013-this volume). Both discussions also allege shortcomings in the policy and management implications we identified, but neither of them address our statistical analysis or results demonstrating that both screening tools are effective at predicting where landslides were likely to take place. Both Shaw (2013-this volume) and Lingley et al. (2013-this volume) misrepresent or greatly misunderstood our discussion on policy considerations. Here, we address each of these issues and recommend additional analysis that can resolve any outstanding concerns or misunderstandings. Until such analysis is conducted, we argue that the conclusions made in Whittaker and McShane (2012) stand as originally published.

2. Research section discussion

2.1. Accuracy and scale of spatial data

The comments provided by Lingley et al. (2013-this volume) suggest that we did not recognize the scale differences and resolutions of the landslide initiation points and the two screening tools analyzed. They also rather specifically implied that we did not understand the reconnaissance level of the landslide initiation data set. This is simply not true, and we made a fair effort to present that indeed there are resolution and scale issues with the data and the screening tools. For example, we noted the source of the initiation point data and referenced that source: "Landslide initiation point data was gathered by the Washington Department of Natural Resources (WDNR) during reconnaissance flights across southwest Washington immediately following the December 2007 storm (WDNR, 2009)." In the discussion we stated: "Another probable source of Type I errors are GIS mapping artifacts, hence, the error rates reported here should be treated as estimates rather than absolute values." In addition, we provided a lengthy discussion describing how the assumptions and resolutions of the screening tools can introduce errors in the identification of landslide sites. For instance, we acknowledged "the overall type I error rates we observed probably would have been lower if we had utilized different methods for mapping landslides", and "Small mapping errors in landslide initiation points are more likely to lead to classification errors on higher resolution maps if classification is based on the hazard level of single pixel." All of the above caveats were appropriately disclosed in our article. Despite the poor resolution of the landslide data points and screening tools, our statistical analysis suggests that the screening tools developed by the WDNR work well in identifying potentially unstable slopes.

Lingley et al. (2013-this volume) also contend that our analysis was conducted at a finer scale than the intended scales of the screening tools. This was not our intent, but rather was a byproduct of the data available to us and the nature of the analysis we wished to conduct. In contrast to Lingley et al.'s (2013-this volume) assertions, WDNR staff did not discuss this scale limitation with us nor did they communicate the intent and quality of the data in writing, verbally, or in their report

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(Sarikhan et al., 2008). On the contrary, Sarikhan et al. (2008) reported that "landslide location was accurately determined using vegetation and other visible clues on the orthophotos". Knowing WDNR was refining the landslide initiation point file over time, we repeatedly confirmed with them that we had the most recent and accurate information available before conducting our analysis. On one occasion (via email), WDNR staff explained that the landslide initiation point file had been "significantly cleaned up and made a lot more accurate (at a 1:24,000 scale)". This was the *only* mention of scale to us by WDNR. Thus, we felt confident that we were using the best available source of landslide spatial data available to us at the time of our analysis. We did not spatially rectify the landslide initiation points using high-resolution orthoimagery because we conducted our analysis before the post-storm orthophotos became available. Nor did we verify the landslide locations in the field, because the vast majority of them occurred on private timberlands inaccessible to the public. Given our finding that the two screening tools provided statistically valid predictions of potentially unstable slopes as they were designed to do, we did not see the utility in spatially rectifying the landslide data or seeking permission to access private timberlands and repeating our analysis.

In their critique of the scale of our analysis, Lingley et al. (2013-this volume) made an inapplicable and incorrect reference to the National Map Accuracy Standards (United States Geological Survey, 1999). They pointed out that "any data points generated from the landslide observations are also reconnaissance-level and should not be applied to an analysis other than those using approximately 100,000-scale or coarser (United States Geological Survey, 1999)." First, we did not generate any data points in our analysis. Second, the USGS (1999) reference is not applicable to landslide data points. The USGS map accuracy standards tolerate up to 10% error for "well-defined points" that have been rigorously field surveyed such as property boundaries, road intersections, and building corners or center points (USGS, 1999). In contrast, landscape initiation points do not meet the criteria of appropriate locations for testing mapping accuracy, as they are "features not identifiable upon the ground within close limits…even though their positions may be scaled closely upon the map" (USGS, 1999). This reference does not support Lingley et al.'s position that our analysis was conducted at an inappropriate scale.

Lingley et al. (2013-this volume) incorrectly reported that we stated that HAZONE was higher resolution because it was vector data. Rather, our statement that "Small mapping errors in a landslide initiation points are more likely to lead to [hazard] classification errors on higher resolution maps if classification is based on the hazard level of a single pixel" referred to the greater likelihood of mapping errors with the higher resolution SLPSTAB raster data than with the lower resolution HAZONE vector data. Despite this difference, neither screening tool showed a statistically greater ability to predict landslide locations than the other.

2.2. SLPSTAB development and assumptions

Uncovering the methods used to develop the SLPSTAB screening tool was a challenge. Our only source of information was the WDNR through their website and multiple public disclosure requests for any information on this topic. We were not informed of the details of SLPSTAB development disclosed by Shaw (2013-this volume), nor were we provided Ms. Vaugeois's unpublished document cited by Shaw (2013-this volume). We were unsuccessful in our attempts to locate and contact Ms. Shaw to inquire about this process. We appreciate now knowing more about the model development process through this discussion.

Shaw (2013-this volume) pointed out that "SLPSTAB was not intended to be used in comparing model predictions of landslide potential with deep-seated or road-related landslide initiation points". We do not disagree, but the intent of the screening tool was to identify landforms with shallow landslide potential. In our analysis of the SLPSTAB and HAZONE screening tools, we did not discriminate among landslide types because this information was not included in the landslide initiation point attribute data provided by WDNR. Had we had access to these data, we doubt our results would have differed for several reasons. First, data reported in Stewart et al. (unpublished results; Table 5-5) indicate that 98% ($N = 1429$) of landslides measured fit the definition of shallow rapid landslides (WDNR, 2004). Of these, 23% ($N = 331$) were road-related landslides and 1% ($N = 15$) were deep-seated landslides. While road-related landslides may result from road-related factors (i.e., culvert blockage, sidecast road fill), they also result from factors unrelated to road structures (i.e., slope gradient, convergence, hydrology) that can be identified with screening tools. Because we were unable to distinguish between these types of landslide triggers, we retained all road-related landslides in our sample. Second, tests of shallow landslide screening tool models by others included both road-related and deep-seated landslides (Montgomery et al., 1998; Shaw and Vaugeois, 1999). Further, SHALSTAB predicted landslides associated with either roads or harvest units equally well, and the location of road-related landslides was topographically driven (Montgomery et al., 1998). Lastly, shallow landslides and deep-seated landslides are often not mutually exclusive events (Shaw and Vaugeois, 1999; WDNR, 2004), though purely deep-seated landslides could have been appropriately removed from our sample had we been privy to such information.

2.3. Other concerns

Lingley et al. (2013-this volume) felt our discussion of other factors influencing slope stability was inadequate, namely, bedrock hydrogeology, known unstable geologic units, and the rain-on-snow event associated with the December 2007 storm. The purpose of our analysis was to assess the effectiveness of slope stability screening tools; a detailed analysis of the underlying geologic conditions and landslides was beyond the scope of our analysis. However, we did describe the geology and topography of all three watersheds in our Methods (Section 2.2. Geological context). In addition, in our discussion we discussed the underlying geologic units, the relationship between bedrock, soil porosity, and subsurface water concentration, and the potential for geologic conditions to cause type I errors. We mentioned the use of known unstable geologic units in the development of both screening tools (Methods, Section 2.3. Slope instability screening tools) and in our discussion of the relationship between type I errors and screening tool resolution and parameters. We did not specifically mention rain-on-snow in association with the December 2007 storm, but we recognized the heavy precipitation, hurricane-force winds, and significant flooding associated with the storm. The storm event has been more thoroughly addressed by others cited in our Introduction (Mote et al., 2007; Reiter, 2008; Sarikhan et al., 2008; Turner et al., 2010).

2.4. Verification of findings

It is unclear why the WDNR Division of Geology and Earth Resources is not more supportive of the fact that the screening tools that *they* developed have been demonstrated by independent authors as being very effective. We encourage the WDNR to repeat our analysis using the most accurate, spatially rectified, and field-truthed data available (from Stewart et al., unpublished results) at the scale and level of accuracy they deem sufficient, and we would gladly lend our support in such efforts once the WDNR makes that data publicly available. We expect such an analysis would further validate the findings in our original article, and given the potential error sources we discussed may very well show WDNR's models to be even more accurate than our analysis showed.

3. Policy section discussion

Lingley et al. (2013-this volume) claimed it was inappropriate for us to cite an unpublished paper (Stewart et al., unpublished results).

This paper had already gone through independent peer review as contracted by the WDNR with the University of Washington and therefore, was part of the public record, and several public presentations had been made by Stewart et al. at the time of our final submission. The figure we cited regarding the number of landslides that initiated outside of named landforms (as defined by the Forest Practices Rules; WAC 222-16-050(1)(d)) and entered streams ($N = 514$) had not changed between previous drafts, public presentations, and the peer reviewed report. This was the only result of Stewart et al. (unpublished results) we cited, and this result is not equivalent to either of the "determinations that are notoriously difficult to identify" listed by Lingley et al. (2013-this volume). Stewart et al. (unpublished results) is highly relevant to our discussion, and our results offer a potential solution to a policy problem they identified. Because of this complementary nature of our findings, we decided against waiting to submit our article for publication until Stewart et al. (unpublished results) was finalized. Neither the peer reviewers of our article nor the editors of this journal objected to this citation.

Lingley et al. (2013-this volume) questioned our understanding of the implementation of Washington State's Forest Practice Rules with respect to potentially unstable slopes. On the contrary, Lingley et al.'s (2013-this volume) description of the forest practices application approval process is not consistent with how Forest Practice Rules have been implemented (WDNR, personal communication, 2010). We acknowledged that the screening tools are used during the WDNR's office review of forest practices applications, but we emphasized that under the current Forest Practices Rules (WAC 222-16-050(1)(d)) this information may be overlooked if field verification of the potentially unstable areas is not conducted and the forest practices application is subsequently not classified for SEPA review. In contrast to Lingley et al.'s (2013-this volume) assertion, the WDNR's forest practices application approval process does *not* depend upon thorough field investigation of all forest practice applications with potentially unstable areas by a qualified expert geologist. Such investigation is *only* required for forest practices applications that have already been field verified and classified as needing SEPA review. To address this important loophole in the Forest Practices Rules, we suggested the screening tools be used more rigorously to indicate where field verification must be done to make the proper classification of forest practices applications. Our position is consistent with that of Shaw and Vaugeois (1999), that "these maps can be useful…to regulators as a replacement to the soil surveys for assigning forest practices class designations (i.e., determining whether environmental checklists or impact statements are required)".

We agree with Shaw (2013-this volume) that the purpose of the screening tools (Vaugeois and Shaw, 2000), is to identify potentially unstable areas that should be field verified. We suggest that *initial* forest practices application classification utilize the screening tool information at the scale of the harvest unit, not on a pixel-by-pixel basis. *Final* classification would then depend on field verification of the potentially unstable areas as rule identified landforms that fit the regulatory definition. The screening tools may be especially useful for reducing subjectivity in identifying potentially unstable areas not named in the Forest Practices Rules (WAC 222-16-050(1)(e); Stewart et al., unpublished results). We recognize screening tools to be what they are: screening tools. We suggested in our discussion that the screening tools would be improved with higher resolution DEMs from LiDAR and that field verification of site conditions that are otherwise assumed is an important aspect of assessing potentially unstable slopes.

Lingley et al. (2013-this volume) noted that some of the landslides from the December 2007 storm were associated with harvest or road-building under the old Forest Practices Rules (before 2001). Landslides within areas harvested before 2001 are equally as informative as more recent landslides as to the effectiveness of the screening tools for identifying potentially unstable areas. That said, we stand by our statement that the majority of landslides took place on sites that were recently harvested (Stewart et al., unpublished results and our own observations) and note this is relatively easy to verify (see Google Earth 46°28′42.15″N, 123°14′06.86″W for an example). What is relevant to our discussion is the current Forest Practices Rules and how to reach our common goal, to limit the future rate of landslide occurrence in managed forests to the natural background rate (Washington Forest Practices Board, 2001).

4. Conclusion

In Whittaker and McShane (2012) we concluded that screening tools can and should be better utilized along with field visits to reach our common goal to minimize our impact on aquatic ecosystems, other public resources, and private property. Classification of forest practices applications that is based on more formal use of unstable slopes screening tools coupled with field verification will not prevent all landslides, but it should reduce the number of landslides delivering sediment to streams to a number more in line with the policy of landslide density and frequency at levels approaching natural conditions. Neither Shaw (2013-this volume) nor Lingley et al. (2013-this volume) addressed our statistical analysis or results demonstrating the effectiveness of both screening tools at predicting where landslides were likely to take place. We did not suggest that new Forest Practices Rules be based strictly on the screening tools, in which case the most rigorous hazard tools would be needed to minimize over-predictive models and economic impacts to landowners. Thus we feel our management recommendations are appropriate given the level of rigor of our analysis. Lingley et al. (2013-this volume) appear to have disregarded our discussion regarding potential causes of type I errors. We suggest that additional statistical analysis following a similar methodology with more accurate landslide data points would be a useful exercise in determining the effectiveness of the screening tools. This same approach could also be applied to new screening tools as they are developed. We argue that the conclusions made in Whittaker and McShane (2012) stand as originally published.

Acknowledgments

Constructive comments on this manuscript were provided by two anonymous reviewers.

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Washington Department of Natural Resources

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

Caring for
your natural resources
... now and forever

July 15, 2016

Chrissy Bailey
Chehalis Basin Strategy Programmatic EIS PM
Department of Ecology, Shorelands and Environmental Assistance
PO Box 47600
Olympia, WA 98504-7600

Re: Chehalis Basin PEIS literature reviews entitled:
Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion; and
Review of the Potential Effects of Forest Practices on Stream Flow in the Chehalis River Basin

Dear Ms. Bailey,
Please accept the following comments to the literature reviews submitted in June 2016. Comments are specific to forested lands under the jurisdiction of the Forest Practices Act and rules.

The Washington State Department of Natural Resources (DNR) Forest Practices Program is concerned that the documents omit key elements of Washington's regulatory framework since 1990, including the rule recommendations in the TFW agreement, Forests and Fish Report, current Forest Practices Rules, and the adaptive management process. Efforts to comprehensively evaluate the effects of harvest activities on hydrology began in earnest during the early 1990s. Since that time, methods have been implemented to assess the cumulative impacts of rain on snow to stream channels, harvest unit size and timing, as well as riparian and wetland buffers.

Harvests conducted prior to 1990 are now hydrologically mature. Forests and Fish Rules have significantly altered techniques for harvesting timber and road construction. These advancements have significantly minimized sediment delivery to water. Failing to acknowledge science-based adaptations is misleading to the reader and misrepresents the regulatory refinements and active research that has been taking place for more than 15 years. As new science becomes available, potential changes to Forest Practices Rules are proposed based on recommendations from the Adaptive Management Program; thereby achieving the goals and objectives of water quality, riparian habitats, and protecting public resources. Many of the perspectives outlined in the literature review are reflective of past timber harvest and road construction techniques, which have been addressed by enhancements in the Forest Practices Rules.

DNR acknowledges the authors' work and efforts to synthesize the existing information within a complex regulatory environment. The authors of the "Landslides" document did an admirable job of acknowledging the current rules and the adaptive management processes, which have resulted in continuous improvements and will continue to do so in the future.

DNR remains concerned that the "Stream Flow" document does not account for current regulations and operational practices. DNR understands that inherent value exists in much of the literature based on landscapes located outside of Washington, however, DNR cautions that direct correlations should be used only when there is a clear nexus to Washington's forested environments. DNR encourages the authors of the PEIS to account for current rules and processes and to focus the environmental review on the results of contemporary applications of Washington's forest practices rules and processes.

Sincerely,

Stephen Bernath
Deputy Supervisor for Forest Practices

Background information:
In 2006, Washington State completed the Forest Practices Habitat Conservation Plan (Forest Practices HCP) (DNR 2005) with the goal of obtaining Incidental Take Permits from the United States Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NOAA Fisheries) (collectively, "the Services"). The Forest Practices HCP addressed the habitat needs of all covered aquatic species, including certain fish species that are federally designated as "threatened" or "endangered". The Forest Practices HCP is a programmatic HCP that reflects the State's forest practices program and is the basis for federal permits to the State for implementing the State's forest practices program. The Services accepted the Forest Practices HCP and issued Incidental Take Permits to Washington State under the authority of the Endangered Species Act. The Forest Practices HCP protects aquatic and riparian-dependent species on more than 9 million acres of state and private forestlands.

Forest Practices obtained Incidental Take Permits in 2006 from the USFWS and NOAA (the Services) covering the Forest Practices Rules that provide protection to Threatened and Endangered Aquatic species. Included in the HCP are rules describing prescriptive expectations for hill slope and road erosion. Unstable slopes rules are not prescriptive but process oriented. Forest Practices rules establish necessary protection goals across the entire state (landscape level) while maintaining a viable timber industry as required in RCW 76.09.010 and 76.09.370 (Forest and Fish report –adoption of rules).

Clean Water Assurances from Department of Ecology (Ecology) -Under Washington state law (Chapter 90.48 RCW) forest practices rules are to be developed so as to achieve compliance with the state water quality standards and the federal Clean Water Act (CWA). Ecology has been designated as the state water pollution control agency for all purposes of the CWA, and has been directed to take all action necessary to meet the requirements of that Act. The assurances established that the state's forest practices rules and programs, as updated through a formal adaptive management program, would be used as the primary mechanism for bringing and maintaining forested watersheds into compliance with the state water quality standards. See attached.

Forest Practices Compliance Monitoring Program is charged with conducting statistically sound audits/reviews of Forest Practices rules to determine whether forest practices rules are being implemented on the ground. The outcomes of these audits are shared with the Forest Practices Board to provide context whether the current rules are being implemented.
http://www.dnr.wa.gov/programs-and-services/forest-practices/rule-implementation

Forest Practices Adaptive Management program is charged with using a scientifically based adaptive management process to make determinations of rule effectiveness and recommend rule changes regarding salmon recovery and water quality. RCW 76.09.370(6) and (7). Cooperative Monitoring, Evaluation, and Research Committee (CMER) plan, design, and implement research and monitoring projects to meet Adaptive Management goals.

Specific comments numbers are referenced in attached Review Draft Forest Practices – Effects on Landslides and Erosion document:

1. Page 1 last line, reference to (Rodgers and Walters 2014) spelling corrections, Rogers

2. Page 3 paragraph 2. Ongoing Adaptive Management effort to measure sediment entering stream network -CMER Road Study – Technical writing group evaluating the current Best Management Practices implemented for sediment that passes through forest road ditches and transported to water. Includes sediment sources from road prism or surrounding forest land. Study design is approved with implementation in FY 2018. The study will include one westside basin and one eastside basin; study will last 6 years; includes measuring sediment transported in roadside ditches.

3. Page 3 last paragraph. Adoption of Watershed Analysis rules in 1992 provided the first repeatable process to identify and establish protection measures for unstable slopes. Rules protecting potentially unstable slopes across the landscape were introduced in 2000 and adopted permanently in 2001(known as the Forest and Fish Rules –FFR); requiring more stringent review of rule-identified landforms by qualified experts. The rules established a process for determining the likelihood of influence forest practices would have on potentially unstable landforms, the likelihood that the proposal will delivery sediment to public resources or threaten public safety and mitigation if necessary. Landslides associated with forest roads and recent harvest (i.e., pre 2000) would have included areas not requiring analysis or protection under the rules adopted in 2001. Board Manual Section 16 was updated in 2004 providing detailed expectations of required qualified expert's analysis and subsequent mitigation. The updates resulted in improved review and protection for rule-identified landforms.

4. Page 4 In addition to Watershed Analysis Prescription the FFR rules implemented Road Maintenance and Abandonment planning (RMAPS); a structured process to evaluate roads, develop a plan to repair, and implement large landowner RMAPs by October 31, 2016. RMAPs focus on roads constructed prior to 2001 that were not built or maintained provide fish passage, minimize sediment delivery, and protect aquatic species. Most large landowners (tree farms) within the Chehalis Basin are on target to complete all necessary upgrades by October 31, 2016. Companies received extensions to October 31, 2021 (WAC 222-24-050). Fish passage barrier repairs are used to measure accomplishments. Over 500 barriers will be repaired by October 31, 2016, less than 75 barriers remain. Roads built after 2001 are built and maintained to achieve resource protection goals.

5. Page 5 first paragraph. See comment #3. Again need to point out the 0-20 sample areas included 10-year pre to 10-year post FFR rules containing changes to qualified expert evaluation, mitigation, and DNR conditioning of Forest Practices Applications with RIL. Of the approved WSAs within the Chehalis Basin, all have had the mass wasting prescriptions rescinded in favor or implementing the current rules. Rather than relying of prescriptions, these rules require a qualified expert's analysis and determination that proposed forest practices will not negatively impacts public resources or threaten public safety. The analysis is documented in the qualified expert's geotechnical report.

6. Page 5 first paragraph. Sarikhan did her survey from a plane, not aerial photographs.

7. Page 5 second paragraph. Misleading statement "performance targets under FP rules". Rule requirements for forest practices activities (harvest, road construction, etc.) on RIL are not performance based as stated. The rules layout a process based approach to evaluate a specific

activity having the potential to threaten public safety or potential delivery of sediment to water using the SEPA process and identifying specific mitigation. In most cases, landowners choose to avoid all activities on RIL.

8. Page 5 second paragraph. Statement "mix of Forest Practices Rule conditions" is vague. Several different rules versions governed timber harvest before the 2007 storm event.

9. Page 5 last paragraph. Additional text offered. The Forest Practices program conducted the Southern Willapa Hills Retrospective Study- Murphy et al. (2013) to address apparent inconsistencies resulting from findings in the Post-Mortem study and protections in the current Forest Practices rules. This study reviewed a subset of the same geographic areas analyzed in the Post-Mortem study to verify if landslides initiated from RILs, if timber harvest occurred on RILs and geotechnical report compliance. The study found that a majority of the landslides (69 percent) initiated from non-RILs and the majority of FPAs were processed in accordance with Forest Practices rules. See attached.

10. Page 6 top of page. CMERs Technical Writing and Investigation Group (TWIG) are exploring the rule criteria to identify RILs. The group is in the early stages to identify potential alternatives for consideration by Forest & Fish Policy. The CMER Work Plan includes an Unstable Slope Criteria Project to evaluate the degree to which the current rule-identified landforms and board manual identify potentially unstable areas with a high probability of impacting public resources and public safety. The project will focus on the adequacy of existing criteria for slope gradient, slope curvature, and probability for delivery. Rule-identified landforms should include those areas with the highest risk of instability.

11. Page 6 first paragraph. Additional clarification offered. Murphy et al. (2013) was also a field based study evaluated 103 harvest related landslides by a licensed engineering geologist.

12. Page 6 last sentence. Watershed Analysis prescriptions within the Chehalis basis also limited the location and construction of roads.

13. Page 7 first sentence. Clarification offered. Murphy et al. (2013) did not look at harvest under pre Forest & Fish rules. The scope was limited to FPAs implementing the 2001 Forest Practices rules. See also comment 9 and 11.

14. Page 7 and 8, 5th bullet. Landowners upon review decided not to sponsor reanalysis and instead opted to implement the Forest Practices rules having greater scrutiny on each FPA and require a qualified expert to conduct analysis through a geotechnical report.

15. Page 8 last sentence of 5th bullet. Last sentence is in accurate and misleading. Watershed Analysis prescriptions implemented in areas that are described regardless of whether all locations were mapped. It is essential for land managers to use on the ground review to identify when and where a watershed analysis prescription is required.

16. Page 8 number 3. Statement fails to identify the second threshold requirement. "or threaten public safety" should be added for accuracy.

17. Page 8 and 9 number 5. Statement is incomplete. Providing the rule required completion dates for RMAP identified work provides specific landowner expectations. WAC 222-24-051 requires work completion by October 31, 2016 or October 31, 2021. Roads constructed after 2001 have been built and are maintained at a level to minimize the delivery of sediment to water. See comment 4.

18. Page 10 last sentence. Misleading to state current research "will likely" recommend additional changes. Changes that have been made in recent years require landowners to submit detailed information regarding their identification of unstable slopes in the vicinity of the proposed activity, geologic evaluation conducted, and mitigation implemented. In addition, DNR has amended the Board Manual to include guidance for the identification of groundwater recharge areas for glacial deep-seated landslides and runout and delivery assessments.

Staffs from the Forest Practices program are available to provide additional understanding and context regarding the comments above.

Two attachments are included as references.

- Additional information regarding Department of Ecology's review of Clean Water Act review.
- Selected section of South Willapa Hills Retrospective Study.

FOREST PRACTICES IN THE CHEHALIS BASIN: EFFECTS ON LANDSLIDES AND EROSION

Date: May 16, 2016
To: Chrissy Bailey, Washington State Department of Ecology
From: Kathy Vanderwal Dubé, Watershed GeoDynamics
CC: Jim Kramer, Ruckelshaus Center; Robert Montgomery and Heather Page, Anchor QEA, LLC
Re: Evaluation of Forest Practice Effects on Landslides and Erosion in the Chehalis Basin

Introduction

A joint scoping comment letter on the Chehalis Basin Strategy Programmatic State Environmental Policy Act Environmental Impact Statement (PEIS) was submitted by American Rivers, Trout Unlimited, and Washington Environmental Council on October 19, 2015. This memorandum addresses one part of the excerpted comments (below) provided by the joint parties, the effects of forest practices on landslides and erosion.

> ***Forest Practices*** *– The forest hydrology literature suggest that forest practices have a significant effect on … contribution of river sediment due to landslides and erosion. Because a large portion of the Chehalis basin is used for industrial-scale forestry, forest practices may have a major impact on the problems and needs addressed by this PEIS. Modification of those forest practices may be an element of solutions to the stated problems and needs.*
>
> - *Evaluate the potential for forest practices in the Chehalis basin to exacerbate landslides and contribution of sediment to the Chehalis River and its tributaries.*
> - *If the analysis of the Chehalis basin forest practices indicates exacerbation of … excessive sedimentation or landslides, develop a suite of modifications to those practices that mitigate the adverse effects. Include a suite of forest practice modifications in the alternative elements being considered (American Rivers et al. 2015).*

Note that the joint parties' comment also requested information on the hydrologic (flooding and low flow) effects of forest practices; information pertaining to hydrologic effects will be provided in a separate memorandum prepared by Perry et al. (2016—draft in progress).

There is a large body of information regarding the effects of forest practices on mass wasting and erosion, including a summary of the effects of forest practices and historic and current forest practice regulations in the Chehalis Basin, which was prepared as part of the Chehalis watershed studies in 2012 and updated in 2014 (Rogers and Walters 2014). The following sections summarize:

- Current understanding of the effects of past forest practices on mass wasting and erosion, both generally and in the Chehalis Basin.
- Evolution of Washington State Forest Practices Rules and regulations through time to address mass wasting and erosion.

For more detailed information on these topics, the reader is referred to the full text of the Rogers and Walters (2014) report.

Landslides and Erosion in Forested Environments

Landslides are a natural occurrence in steep forested environments (Guthrie and Evans 2004; Turner et al. 2010). Most landslides in forested areas of Western Washington occur during high intensity storms when rain, often in combination with melting snow (e.g., rain on snow events), saturates surface soil layers or contributes to streamflow, which can undercut the toes of adjacent landslide areas. Factors affecting slope failure include:

- Geology/soil characteristics—strength, cohesion, infiltration capacity, and underlying material
- Soil moisture—antecedent soil moisture, infiltrating rain/snowmelt, and infiltrating surface runoff
- Slope conditions—gradient, convergence, length, and aspect
- Vegetation—root strength and vegetation density
- Earthquake loading

The majority of active landslides in the Chehalis Basin are shallow slumps, debris avalanches, and debris flows that move the surficial soil layers (generally 3 to 5 feet deep) and associated trees and vegetation rapidly down slope (Laprade 1994; Russell 1995; Ward and Russell 1994; Sarikhan et al. 2008). If the landslide is close to a stream, the soil and debris can enter the stream, supplying rock, soil, and large woody debris to the stream system. The debris avalanches or flows can turn into debris torrents in the stream channel and scour the channel and adjacent riparian areas. Landslides are an important source of boulders, cobbles, gravel, and large woody debris to streams and rivers in the Pacific Northwest (Guthrie and Evans 2004). These elements provide diverse aquatic habitat such as spawning, rearing, and holding habitat for fish and other aquatic life, but an oversupply of sediment or debris can be detrimental to aquatic habitat.

Potential Effects of Forest Practices on Landslides and Erosion

Forest practices, including timber harvest and road building, have the potential to increase landslides and surface erosion by disturbing soils, changing infiltration capacity, removing root strength, decreasing canopy interception, and changing slope and surface runoff patterns. Many studies have documented increases in landslides and surface erosion resulting from timber harvest and road building (Dragovich et al. 1993; Dyrness 1967; Guthrie and Evans 2004; Jakob 2000; Ketcheson and

Froehlich 1978; Montgomery et al. 2000; Robison et al. 1999; Swanson and Dyrness 1975; Swanson et al. 1987; Swanston 1974).

The largest increases in landslides and surface erosion have been associated with road building on steep slopes (Amaranthus et al. 1985; Megahan and Kidd 1972). The cut and fill slopes formed by the road prism can fail, road drainage can be directed onto marginally stable slopes, or stream crossing culverts can plug and saturate road fill. Landslide risk can be increased in even-age harvest areas by removal of trees, resulting in a decrease in root strength, loss of canopy interception, and evapotranspiration (Amaranthus et al. 1985; Dragovich et al. 1993; Montgomery et al. 2000; Roering et al. 2003). As stated previously, if hillslope landslides reach the stream network, they can deliver soil, rocks, and woody material to streams.

Surface erosion from roads is influenced by soil compaction, which reduces infiltration and results in road runoff, gullies formed or deepened by the interception of cutslope drainage, and soil disturbance and breakdown of the aggregate surface from traffic on unpaved roads (Bilby et al. 1989; Foltz 1996; Luce and Black 1999; Ketcheson and Megahan 1996; Megahan and Kidd 1972; Paulson 1997; Reid 1981; Reid and Dunne 1984; Sullivan and Duncan 1980; Swanson et al. 1987; Toth 2000). Runoff from road surface erosion conveys primarily fine-grained sediment (sand, silt, clay); if roads are hydrologically connected to streams, the sediment can enter surface waters. Two studies found that an average of 10% to 11% of the total road length in commercial forestlands in Washington is hydrologically connected to the stream network (Dubé et al. 2010; Martin 2009

Effects of Forest Practices on Landslides in the Chehalis Basin

During the past 20 years, there have been numerous investigations of the effects of forest practices on landslides in the Chehalis Basin. Watershed analyses were conducted in the Stillman Creek, Upper Skookumchuck, Chehalis Headwaters, and West Satsop WAUs (watershed analysis units) in the mid-1990s (Laprade 1994; Russell 1995; Ward and Russell 1994, O'Connor 1996). The Mass Wasting Module in the Stillman Creek, Upper Skookumchuck, and Chehalis Headwaters watershed analyses included an analysis of the number and volume of landslides associated with roads, harvest units, and un-harvested areas based on historic aerial photographs from approximately the 1950s to the 1990s, and thus reflect the effects of road building, harvest practices, and storms during that period. All three of these mass wasting analyses found an increase in landslides associated with forest roads, and to a much lesser extent, recent harvest units (0 to 20 years old) during large storm events. The Chehalis Headwaters analysis found that older roads constructed using sidecast[1] methods were much more susceptible to

[1] Sidecast road construction methods include pushing material cut from the road bed over the downslope side of the road. Endhaul road construction methods minimize sidecast by excavating the majority of the road into the hillslope and hauling excavated material to a stable disposal location.

mass wasting than newer roads constructed using endhaul methods, suggesting that the changes to road building practices reduced landslide occurrence (Ward and Russell 1994).

Basin-specific prescriptions were instituted in all four WAUs and included road improvements to reduce instabilities and geologic reviews, as well as avoidance of harvest on landforms mapped as highly unstable slopes as part of the Mass Wasting Modules. In addition, in several of the WAUs, prescriptions or recommendations for riparian leave areas and/or limits to the amount of harvest in the rain-on-snow zone (e.g., to ensure that a specified percentage of sub-watersheds were hydrologically mature) could also result in fewer landslides if these areas overlapped unstable slopes. A review of the three 1994-5 watershed analyses was made in 1999 following the procedures for review every five years. This review included the effects of the December 1994 storm and the February 1996 storm, which was the largest on record at that time and was estimated to be a 100-year storm event. The mass wasting re-analysis inventoried slides using the 1997 aerial photographs. A total of 13 harvest units in the Chehalis Headwaters and three harvest units in the Stillman WAU were harvested between 1994 and 1997 in areas that included unstable slopes; geologic reviews were conducted for all of these areas, and no landslides had occurred in any of these 17 harvest units. While this may be a small sample size, and no statistical analysis could be made, the review authors concluded that there were fewer landslides in each of the three basins following that 100-year event than in the 1987-1994 aerial photo periods, even though the storm magnitudes were lower in the 1987-1994 period, suggesting that the basin-specific prescriptions were effective at reducing mass wasting associated with road building and timber harvest.

On December 3, 2007, an unprecedented storm occurred in western Washington and Oregon, with extremely high levels of precipitation (up to 175% of the 100-year 24-hour rainfall) in parts of the Willapa Hills and upper Chehalis watershed. This catastrophic event resulted in thousands of landslides and millions of cubic yards of sediment and woody material delivered to streams (Sarikhan et al. 2008). Following the storm, numerous investigations were conducted to evaluate the relationship between forest practices and the 2007 landslides (Sarikhan et al. 2008; Stewart et al. 2013; Turner et al. 2010; Murphy et al. 2013). The authors and reviewers of the studies did not always interpret the study design or data in the same ways and often reached somewhat different conclusions on the role that forest practices had on landslide initiation in the watershed resulting from the 2007 storm.

Initial reports on the influence of forest practices on landslides resulting from the 2007 storm event were based on aerial surveys immediately following the storm (Sarikhan et al. 2008 and later interpreted by Entrix 2009) and suggested that landslides in the Chehalis watershed were densest in areas of highest precipitation underlain by basalt of the Crescent Formation. Sarikhan et al. (2008) found that initiation points for the majority of landslides were in recent clearcuts (0 to 5 years old) and sub-mature timber (15 to 50 years old) and associated with roads, with few initiation points in young stands (5 to 15 years old) and mature timber (50 years old or more). However, they caution that their data were based on an aerial inventory; Brardinoni et al. (2003) found that landslide inventories based on aerial photographs in coastal British Columbia omit up to 85% of landslides that exist on the ground in heavily timbered areas due to forest cover obscuring the landslides. Therefore, the analysis of initiation points by Sarikhan and Entrix based on aerial surveys could have missed landslides in areas covered by mature timber.

Turner et al. (2010) conducted an aerial photograph inventory following the 2007 storm on 152,000 hectares (375,600 acres) of forest lands within the Willapa Hills, concentrating on areas that had been previously harvested. The study area included parts of the Chehalis watershed. They followed this with ground-based inventories to identify the percentage of missed slides on 3,977 hectares (9,827 acres) of land covering different age classes and rainfall intensities, and determined that 39% of field-detected landslides were not seen on the aerial photographs; detection likelihood decreased with increased stand age and narrower landslide width. Turner et al. concluded that few landslides occurred in harvested areas with less than 100% of the 100-year rainfall. In harvested areas with more than 100% of the 100-year rainfall, more landslides occurred on slopes with gradients of more than 70%. In areas with more than 150% of the 100-year rainfall, past harvest units with trees in the 0- to 10-year age class had a higher density of landslides than those in older age classes (greater than 10 years).

Stewart et al. (2013) investigated the effects of the 2007 storm event on a 91-square-mile (236-square-kilometer) study area that encompassed land managed for timber production in the Willapa Hills. The study area included parts of the Chehalis watershed. They identified landslides through an on-the-ground inventory. They concluded that the majority (82%) of the landslides resulting from the 2007 storm occurred on hillslopes and the remainder (18%) on forest roads. They found no statistically significant difference in landslide density or volume among roads that were below, up to, or above current forest road building and maintenance standards. Stewart et al. also concluded that avoiding clearcuts on unstable terrain (termed Rule-Identified Landforms [RIL]) reduced landslide density and volume, but that it was not clear if existing performance targets under current Forest Practices Rules are being met. Under current Forest Practices Rules, the mass wasting target is to avoid an increase in mass wasting over natural background rates caused by new harvests on high-risk sites (e.g., RIL). They also suggested that there were many landslides that initiated on terrain that did not meet the current RIL/unstable slope criteria. They did not find a correlation between landslides and geology or precipitation intensity, a finding different from Sarikhan et al. (2008) or Turner et al. (2010), but this may have been influenced by the selection of sample areas. Several Minority Reports were included in the Stewart et al. report by reviewers with dissenting opinions on the ability of the study to reach the conclusions it did due to the study design and what the reviewers felt was an insufficient amount of data collection. One primary concern was that the study area contained a landscape that was harvested under a mix of Forest Practices Rule conditions and with a variety of road building practices in place since the 1950s and before, so it was not possible to make statements about the effectiveness of current rules based on the mix of treatments.

Though the extreme nature of the 2007 storm event obliterated the majority of the landslide initiation points, a further investigation of the Stewart data by Murphy et al. (2013) suggested that more than half (69%) of the hillslope landslides potentially originated from lands that are not currently considered unstable (forest practices RILs) under current Forest Practices Rules. They suggested "Given the majority of landslides initiated on non-RILs and landslides initiating from probable RILs that had no harvest on them at all (per field observations), it may be that the concentrated magnitude of the December 2007 storm event and its effects eclipsed the protection standards provided by Forest Practices Rules." However, other reviewers suggested that some of the non-RIL landslides were initiated by streams undercutting the toe of the slope, or that some of the areas identified as non-RIL could have initiated on unstable slopes (RIL), but this could not be determined since the landslides obliterated the slope.

The 2007 storm event included extremely high precipitation in a small portion of the upper Chehalis and Stillman Creek basins with high precipitation in other portions of the basin, and resulted in thousands of landslides in areas of the most intense rainfall. An objective of the different investigations of the 2007 storm event, discussed above, was to determine the effects of forest practices on landslide rates. Some major challenges with any study of landslides are that one cannot control the timing, intensity, or location of a large storm event that triggers landslides, and timber harvest practices change through time so the landscape includes a mix of areas harvested under older and newer regulations. Study design also plays an important role in the ability to draw defensible conclusions about cause and effect. The studies of the 2007 event had some conflicting conclusions and are the subject of ongoing debate. Initial observations (e.g., Sarikahan et al 2008 and Entrix 2009) suggested that the majority of landslides were in recent clearcuts, but these observations were made based on aerial observations and did not include ground-based surveys that would have been able to identify landslides in areas of re-generating or mature timber. Turner et. al (2010) and Stewart et al. (2013) used ground-based surveys, but had different study designs and statistical analyses and reached somewhat differing conclusions. Turner et al. found that landslides occurred in harvest areas primarily in areas of the most severe precipitation and on the steepest slopes, and under these severe conditions there were statistically more landslides in areas of 0 to 10 year old trees (e.g., recent harvest). Stewart et al. concluded that reducing harvest on unstable slopes reduced landslide density, but did not find a statistically significant correlation between landslide occurrence and geology or precipitation intensity, perhaps due to sample size.

The conflicting study conclusions and continuing debate over the effectiveness of past and current Forest Practices Rules at reducing landslides during that event make it difficult to reach a definitive conclusion on how effective the current rules are during an extreme storm event. However, it is clear that harvest or poorly designed roads on marginally stable slopes are more likely to result in landslides during normal storm events until harvest areas gain sufficient root strength to help stabilize the slope. Current Forest Practices Rules are designed to avoid harvest and road building on unstable slopes. The 1999 5-year review of the three watershed analyses showed that there were fewer landslides during the 1996 (approximately 100-year) storm event than during previous periods with less intense storms, suggesting that the prescriptions that limited harvesting and improved roads on unstable landforms may be effective at reducing mass wasting during large storm events. Because all field-based studies of landsliding by necessity look at the effects of large storm events on areas harvested under past rules, the effectiveness of current Forest Practices Rules cannot be tested directly.

Forest Practices Rules Related To Landslides and Erosion in the Chehalis Basin

Approximately 84% of the Chehalis River watershed land area is comprised of land managed for forest practices (Rogers and Walters 2014). Most of these managed forest lands are subject to the Washington Forest Practices Act and regulations, with a small portion subject to federal or tribal authority. Forest Practices Rules related to landslides and erosion have changed through time to reflect ongoing research and understanding of how forest road building and timber harvest affect landslides and erosion. There are legacy effects of past road building and timber harvest activities across the Chehalis Basin watershed.

The 1974 Washington Forest Practices Act was the first step in regulating forestry activities on state and private forest land. The 1974 act was designed to protect the environment and to be flexible, allowing changes through time to reflect new information (i.e., adaptive management). Several changes to Forest Practices Rules regarding landslides and erosion have taken place during the years to continue to improve the identification and avoidance of harvest and road building on unstable slopes (Rogers and Walters 2014), including:

- 1982—Rules to address "excessively steep or landslide prone slopes."
- 1987 and 1988—New rules to protect riparian areas and for adaptive management.
- 1992—New rules to address cumulative effects through watershed analyses (including a specific mass wasting analysis that analyzed the effects of forest practices on a watershed scale), and rules related to operations on unstable slopes.
- 2001—Major changes to Forest Practices Rules (Washington Administrative Code [WAC] 222-16-050[1][d][i]) were adopted, including tools for identifying unstable slopes, training, and updated forest road construction and maintenance requirements. The Forest Practices Adaptive Management Program was set up, including provisions for ongoing research and recommendations for rule changes through the Timber, Fish, and Wildlife (TFW) Policy Committee and the Cooperative Monitoring, Evaluation, and Research (CMER) Committee.
- 2011—In response to analyses of the effects of the December 2007 storm, the Forest Practices Board amended the Watershed Analysis rules and associated guidance to reinforce the existing process and timing for 5-year reviews of the mass wasting prescriptions developed by watershed analyses. Four watersheds in the Chehalis Basin (Stillman Creek, Upper Skookumchuck, West Satsop, and Chehalis Headwaters) had been operating under watershed analysis prescriptions, which specified road building and harvest rules for mass wasting units that were mapped on a watershed-scale based on conditions in the mid 1990s (when the watershed analyses were written). The analyses were not reviewed or updated in

2011, so forest practices in these areas are now governed by Forest Practices Rules, which specify analysis of unstable landforms on each harvest unit instead of watershed analysis prescriptions. The watershed analysis prescriptions only specified analysis of potential instability in harvest areas on specific unstable landforms that were mapped in the mid 1990s at a watershed scale.

- 2014/2015—The Forest Practices Board amended the rule addressing Forest Practices Applications/Notifications (FPAs/Ns) to clarify the requirements for providing additional geologic information to classify FPAs on or around unstable slopes. In addition, the Forest Practices Board manual providing guidance to forest landowners on how to evaluate unstable slopes was updated in 2015 as described in the following list.

Current Forest Practices Rules related to landslides include:

1. Board Manual Section 16 (dated November 2015) includes information on how to recognize landslides, slope form, potentially unstable slopes, and landforms in areas of proposed forest practices activities; procedures and resources for assessing potentially unstable areas for both general practitioners and qualified experts; and guidance on expert-level office review, field assessments, and geotechnical reports. This manual describes the types of RILs and how to identify them using remote screening tools (e.g., topographic maps, aerial photos, Light Detection and Ranging (LiDAR), and publicly available screening tools) and during field surveys of areas proposed for harvest or road building.
2. FPA/N Form, Questions 10 and 11 (updated May 9, 2014): the requirement that the applicant evaluate whether any potentially unstable slopes or landforms are within or adjacent to the forest practice application area; if so, a Slope Stability Information Form is filled out that describes how these areas were assessed (using Board Manual Section 16).
3. Washington State Environmental Policy Act policies for potentially unstable slopes and landforms (WAC 222-10-030) relating to road construction or harvest on potentially unstable slopes or landforms. These include the requirement that forest practices and roads on potentially unstable slopes or landforms must include information prepared by a qualified expert about the likelihood that the action will contribute to movement or instability, the likelihood of delivery of sediment or debris to a public resource, and possible mitigation for identified hazards and risks.
4. Potential for requirement of specific geologic information (WAC 222-20-010[9]): the Washington Department of Natural Resources (WDNR) may require landowners to provide additional geologic information if there are potentially unstable slopes or landforms in or around the area of their application.
5. Road Maintenance and Abandonment Plans (RMAP): a forest road inventory and schedule for required road maintenance to bring roads up to current WAC 222-24-052 standards to minimize road instability, erosion, and hydrologic connectivity. An RMAP (and associated road upgrades

implemented according to the schedule in the RMAP) is required for large forest landowners for all lands on their ownership; small forest landowners may submit an RMAP or upgrade their roads to WAC 222-24-052 standards as they implement harvests using those roads.

Research and monitoring on landslides and erosion related to forest practices continues both within the Chehalis Basin watershed and on a state-wide basis through the CMER work plan in the Unstable Slopes Rule Group and the Roads Rule Group, and non-CMER research. These efforts are part of the Adaptive Management Program that will continue to use technical information and peer-reviewed studies to produce science-based recommendations to the Forest Practices Board regarding landslides and erosion. Current projects underway include:

- Forming a technical committee to evaluate gaps in the science regarding glacial deep-seated landslides and groundwater recharge areas.
- Reviewing unstable slopes research strategy, including deep-seated landslides and groundwater recharge areas.
- Initiating the Unstable Slopes Criteria Project to evaluate unstable areas with a high probability of impacting public resources.
- Conducting Road Prescription-Scale Effectiveness Monitoring to evaluate road best management practices, available science, and research alternatives.

Conclusions

A large portion of the Chehalis Basin watershed is managed for forest practices. Mass wasting and erosion are natural processes in steep, forested basins and provide sediment and large woody debris to streams, creating diverse aquatic habitat conditions. Excessive landslides or erosion can result in large amounts of sediment or debris delivery to streams and degrade aquatic habitat or increase downstream flood impacts.

Forest practices activities, including road building and even-age timber harvest, can contribute to the increase in landslides during large storm events. Forest Practices Rules and guidance have evolved over time to reduce the influence of forest practices activities on landslides in Washington State as the understanding of the effects road construction and timber harvest activities have on landslides has improved. Analyses of landslides as part of watershed analyses showed fewer landslides during the approximately 100-year storm event in 1996 that during the 1987 to 1994 period despite the large storm event. Although there is a small sample size, the results suggest that prescriptions may be effective in reducing the potential increase in landslides from forest practices. The December 2007 storm event was a catastrophic event, particularly in parts of the upper Chehalis and Stillman Creek watersheds that experienced up to 175% of the 100-year 24-hour rainfall. This event produced thousands of landslides on both recently harvested and older-timbered hillslopes and delivered millions of cubic yards of sediment and debris to streams and rivers in the upper watershed.

As mentioned above, the studies of the 2007 event for the Chehalis Basin had some conflicting conclusions and are the subject of ongoing debate making it difficult to reach a definitive conclusion on how effective the current rules are during an extreme storm event. However, it is clear that harvest or poorly designed roads on marginally stable slopes are more likely to result in landslides during normal storm events until harvest areas gain sufficient root strength to help stabilize the slope. It is also clear that changes in forest practices have improved the management of areas to reduce the potential of landslides. However, it is not clear how much the risk of landslides caused by forest practices has been reduced during extreme events. It is also not clear how close the current Forest Practices Rules are to achieving the mass wasting target: avoid an increase in mass wasting over natural background rates caused from new harvests on high-risk sites (e.g., RIL) at a landscape scale.

New Forest Practices Rules have been and will continue to be implemented as a result of ongoing TFW/CMER research and recommendations (TFW 2014) through the Adaptive Management Program. This has created a robust and adaptive process to comprehensively research, monitor, and determine if change is needed in the Forest Practices Rules or guidance in Washington State to avoid the potential for initiating or contributing to the effects of timber harvest and road building on public resources or threatening public safety. This ongoing program includes measures developed from scientific data collected from the 2007 storm event in the Chehalis Basin, as well as an ongoing research and monitoring strategy on unstable slopes.

The existing process to modify Forest Practices Rules regarding unstable slopes and landslides includes:

- Research of identified landslide issues through the Unstable Slopes Rule Group and the Roads Rule Group, and non-CMER research.
- Recommendations from the Rule Groups to CMER for potential changes to Forest Practices Rules.
- Evaluation by CMER and TFW of research results and recommended changes to Forest Practices Rules and, if approved, forwarding recommended changes on to the WDNR Forest Practices Board for revision of rules and/or the forest practice application and evaluation process.

Recent (2011, 2014, and 2015) changes to Forest Practices Rules and application procedures pertaining to landslides and unstable slopes have been made through this process, and current research projects will likely recommend additional changes.

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STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
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October 9, 2009

Forest Practices Board Members
PO Box 47012
Olympia, WA 98504-7012

RE: Forests and Fish Program – Completion of Clean Water Act Review

Ladies and Gentlemen:

The Washington State Department of Ecology has completed the 2009 Clean Water Act (CWA) review of the state's forest practices and adaptive management programs. We are now releasing the enclosed findings paper broadly to stakeholders and the public. Although the paper was completed in early July 2009, I wanted to have a chance to evaluate the commitment forests and fish participants have in taking the steps needed to strengthen the existing program. Such a commitment is crucial to ensuring the state's forest practices program can be depended upon to bring or maintain forested waters in full compliance with the state water quality standards and the federal CWA.

In September, I had a chance to meet with the key stakeholders as part of the Forest Ecosystem Collaborative sponsored by Commissioner Goldmark. While the group grappled with many thorny and complicated issues, and its work is not done, it is clear that we all share a goal of finding ways to strengthen the existing programs and to look for innovative approaches to resolve many of the broader problems facing the timber industry in Washington.

After carefully weighing the level of stakeholder commitment and the benefit of providing a clear path to maintaining CWA coverage, I have decided to conditionally extend the CWA assurances. This extension is based on meeting a scheduled set of milestones for program improvements and research development. It is vital to maintaining the assurances into the future that the list of CWA milestones is incorporated into the planning process of the state's forest practices and adaptive management programs. My hope is that by releasing the CWA findings now, and thereby formalizing the milestones, partners in the forest practices and adaptive management programs will move swiftly to take the required action necessary to accomplish the needed improvements and research milestones.

Sincerely,

Jay J. Manning,
Director

Enclosure

cc: EPA
Forests and Fish Policy
Forest Practices Board Liaisons
NMFS
USFWS

2009 Clean Water Act Assurances Review of Washington's Forest Practices Program

Examining the effectiveness of Washington's forest practices program in bringing waters into compliance with state water quality standards and the federal Clean Water Act

Washington State Department of Ecology

July 15, 2009

For information on this review contact:
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Introduction

Under Washington state law (Chapter 90.48 RCW) forest practices rules are to be developed so as to achieve compliance with the state water quality standards and the federal Clean Water Act (CWA). The Department of Ecology (Ecology) has been designated as the state water pollution control agency for all purposes of the CWA, and has been directed to take all action necessary to meet the requirements of that Act. The Clean Water Act assurances (CWA assurances) granted by Ecology in 1999 as part of the Forests and Fish Report (FFR) expired June 30, 2009. The assurances established that the state's forest practices rules and programs, as updated through a formal adaptive management program, would be used as the primary mechanism for bringing and maintaining forested watersheds into compliance with the state water quality standards.

This paper summarizes the findings of a review by Ecology on the progress the state's forest practices program is making in bringing waters into compliance with state surface water quality standards (Chapter 173-201A WAC) and the federal Clean Water Act. This review is being used as the basis for determining whether or not to extend the CWA assurances into the future.

As detailed below, Ecology finds that the Forests and Fish program has not achieved the level of information needed to verify that water quality in the forested environment will meet water quality standards, or to verify that the conditions for offering the assurances in 1999 have been satisfied. In spite of these shortcomings, Ecology believes the Forests and Fish program still offers a viable and compelling management strategy for achieving water quality goals in the forested environment. Ecology has concluded, therefore, that continuation of CWA assurances is warranted if specific actions are taken to improve the program's performance.

Summary of Findings

In 1999 as part of the FFR (http://www.dnr.wa.gov/Publications/fp_rules_forestsandfish.pdf), Ecology in consultation with the United State Environmental Protection Agency established the CWA assurances. In 1999, Ecology assumed ten years would be sufficient time to test the forest practices rules and to identify trends in water quality improvement. That expectation has not been met. After ten years, no studies have been completed or data collected that provide an indication of whether or not the forest practices rules are improving water quality or maintaining forested waters in compliance with the water quality standards. Similarly, data is lacking with which to conduct a thorough analysis of how effective operational and enforcement programs are in applying the forest practices rules.

The foundation for granting the CWA assurances was the belief that the FFR was a substantial step forward in environmental protection, and when implemented would provide the quickest and most efficient means for achieving environmental goals and compliance with the state's water quality standards. Developing CWA mandated total maximum daily loads (TMDLs) to serve as regulatory water cleanup tools for forested watersheds was therefore viewed as a low priority, and the CWA assurances established that Ecology would rely on the FFR-based forest practices program for an initial ten-year period. It was assumed in 1999 that research and monitoring would occur to demonstrate that implementing the FFR would improve water quality and eventually bring forested waters into full compliance with the state's surface water quality standards and thereby also satisfy the conditions under Section 303 of the federal CWA.

The original FFR language is not clear on whether or not it was intended that the assurances could be extended beyond the 2009 deadline, but nothing in the report fundamentally alters Ecology's authority to continue to rank conducting TMDLs on forest lands subject to the FFR rules as a low priority with or without the existence of formal assurances. The value of offering formal assurances is that they provide landowners and agencies with a predictable and consistent regulatory system; and in doing so provide an additional motivation for stakeholders to participate in the adaptive management program.

As part of this 2009 review, Ecology has examined all of the written conditions for maintaining the assurances established in Schedule M-2 of the 1999 Forests and Fish Report. Ecology has also examined all of the issues highlighted in a supplemental 2006 Ecology White Paper. The 2006 paper was written to let stakeholders to the FFR process know some of the specific information Ecology would need for this 2009 review.

Ecology has concluded the forest practices and adaptive management programs have not fully met the expectations of research and program performance that underlie the basis for providing the CWA assurances. The adaptive management program has not provided the information needed to validate the effectiveness of the rules in protecting water quality. In fact, no field studies or assessments have been completed that test the ability of the rules to meet state water quality standards. Moreover, these studies are still many years away from completion, and the budget for the science program is set to be significantly reduced. Staffing cuts are expected over the next year or two that may further impact the ability of the various elements of the forest practices and adaptive management programs to operate at past levels. Added to the direct effect of reduced staffing, several key stakeholder groups openly express a growing lack of support for continuing with the current adaptive management program.

The lack of information to evaluate the effectiveness of the rules can in part be attributed to the initial priorities established in the FFR that placed validating operational aspects of the rules ahead of water quality studies. However, the adaptive management program (AMP) has also had significant trouble developing and using the research results developed as part of these initial prioritization agreements (i.e., last fish habitat model, uppermost point of perennial flow, desired future conditions basal area target).

Improvements in the system are necessary to create a program that participants can rely on to provide a more efficient and confident program for testing the effectiveness of the rules in protecting water quality and modifying the rules as appropriate.

State laws establish that the forest practices rules must be designed to achieve compliance with the state water quality standards and placed Ecology in the lead for making this determination. However, the Legislature also formally established the adaptive management program as the primary mechanism for bringing the rules into alignment with the state standards. The current program, even with its challenges, creates a well established foundation for moving ahead.

Policy and procedure manuals guide the process; full time professional project managers and Cooperative Monitoring, Evaluation, and Research (CMER) program staff are available to assist CMER volunteer scientists in carrying out their projects; and Forest and Fish Policy (Policy) representatives of the various stakeholder caucuses remain engaged at present and have advanced strategic plans to improve their own performance as well as the performance of the overall program. On the operational side, the compliance monitoring program has been established and is constantly expanding as time goes on, guidance documents and training continue to improve, and experienced agency staff stand ready across the state to implement the rules.

Taken in total, the forest practices program provides a substantial framework for bringing the forest practices rules and activities into full compliance with the water quality standards. Ecology has concluded it is in the best interests of water quality, and is consistent with legislative intent, to work with the other participants to make needed improvements to the existing program. Ecology is therefore conditionally extending the CWA assurances with the intent to stimulate the needed improvements to the forest practices and adaptive management programs. Ecology, in consultation with key stakeholders, has established specific corrective milestones (shown in the next section). The extension of the assurances is conditioned on meeting these research and administrative milestones by the specific target dates described. These milestones serve as a corrective action plan necessary to retain the assurances into the foreseeable future.

Steps are already being taken to address many of the corrective milestones associated with operational issues, compliance monitoring, and assessing progress under Road Maintenance, Abandonment, and Planning (RMAP) rules. Based on this ongoing progress, Ecology fully expects these steps to be successful in the short-term. Ecology's highest concern going forward is with the adaptive management program. These concerns are greatest regarding the ability to fund the needed studies and assessments at a rate that creates a viable science-based program. Scientific studies and assessments need to be designed to provide Policy and the Forest Practices Board (Board) with information sufficient to enable these policy makers to make informed science-based policy decisions. Just as importantly, policy makers must be committed to using science to fairly and efficiently revise the forest practices rules and programs as needed.

Compliance with the milestones described herein will demonstrate sufficient progress to satisfy the CWA assurances and the adaptive management provisions of the state water quality standards (WAC 173-201A-510(3)). Because extending the assurances is based on meeting the specific research and administrative milestones identified above by the specific dates listed, failure to meet any milestone would be considered a basis for potentially withdrawing the assurances at that time. In evaluating compliance with the milestones established herein, Ecology will consider the cause for missing any milestones and be considerate of the fact that:

- The state and nation are both experiencing a severe economic recession and it may take a couple of years before funding to fully support the AMP is available.
- Unexpected and uncontrollable circumstances may cause deviations from this schedule, such as catastrophic events causing the loss of study sites.
- Until a project has a study design developed, it is not possible to identify an accurate time frame for its completion (or in some cases to determine if the project remains a CWA priority).

To be successful in meeting these milestones and consequently the CWA assurances, the caucus principals will need to work together to find funding and to support the actions needed to meet the specific milestones. Ecology is working therefore to support the strategic goal to bring together the principals as soon as practical to renew and maintain a spirit of cooperation and collaboration among the six caucuses.

Considerations and Corrective Milestones

The following lists the conditions[1] that are the basis for continuing to provide the CWA assurances to the state's forest practices program (shown in bold font). Similar conditions have been grouped together into categories. Following the list of conditions is a summary of the key findings (shown in italics) and the corrective remedies identified as "milestones". These milestones are intended to create a corrective action plan that ensures steady incremental improvement and provides a basis to continue the assurances. Failure to meet any milestone by the deadline established would be cause for Ecology to revoke the assurances at that point in time.

Many of the remedies identified necessarily focus on the state Department of Natural Resources (DNR). This focus recognizes DNR has primary responsibility for implementing the Forest Practices Act and rules and supporting the adaptive management program. DNR has been working cooperatively with Ecology and others to enact solutions to many of the issues noted below both prior to and independent of this CWA review.

I. Establish Rules and Funding to Implement the Forests and Fish Report

Conditions for retaining the assurances include:

1. **Having final regulations consistent with the Report.***
2. **No significant loss of funding or staffing to the state regulatory agencies dedicated to forest practice regulation or monitoring.***
3. **Court orders, changes to the CWA, state or federal regulatory changes that cannot be otherwise addressed.***
4. **No weakening of enabling State statutes or regulations which affect the Report and its implementation.***

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[1] Conditions in this context refers to the "Reopeners, Modifications, and Causes of Withdrawal of Assurances" noted in Schedule M-2 of the Forests and Fish Report as well as to those described as necessary in Ecology's January 11, 2006, Clean Water Act Assurances White Paper provided to the Forests and Fish Policy Committee and the Forest Practices Board to help provide a more detailed description of some of the information Ecology would need for this 2009 review. Items directly called out in Schedule M-2 are shown followed by an asterisk.

Discussion: The CWA Assurances were provided based on establishing and maintaining an adequately funded and operationally effective forest practices program that implements the FFR. Meeting this requires that DNR and the other resource agencies and cooperators provide and maintain adequate staffing and funding to keep the field operations and adaptive management programs running effectively. It also requires that no significant changes to laws and regulations take place that undermine the foundation of water quality protection established in the FFR.

These conditions for retaining the assurances have not been fully met. Rules were initially adopted to implement the FFR, and substantial resources were put into action to implement a formal adaptive management program. Countering these successes, however, staffing has not been adequate to fully implement the rules and programs, changes have been made to the laws that weaken some of the original protections established in the FFR, and significant reductions in staffing and funding have recently occurred that are likely to remain over the next two to three years as the state's economy recovers from the current recession.

Remedies identified to support continuation of the assurances include:

(a) Federal pass-through funding has diminished since the inception of the FFR and is predicted to be depleted in the second half of the 10-11 biennium. In addition, the state and nation are both suffering through the worst economic period on record since the great depression. Continued CMER funding is based partially on general fund state revenue in DNR's budget and partially on timber tax revenue. At this time the state is experiencing cuts to the general fund, and harvesting with its associated revenue stream has declined by approximately fifty percent. Recognizing the likelihood of budget shortfalls in the adaptive management program, it is important that water quality studies be designated as high priority, and efforts made to ensure their timely completion. The adaptive management program should also develop strategies to make better use of partnerships (e.g., monitoring consortium, Puget Sound Partnership, USFS) and to prepare to compete for grant monies. This may in part necessitate developing study plans with the intention of having them ready to compete for outside funding as sources emerge. In addition, it is imperative that new dedicated long term funding sufficient to carry out the requirements of the FFR be secured as soon as possible, as a reliance on grants is unlikely to be either workable or sufficient to maintain an adequate program.

Milestones:

1) **By July 2009, and in subsequent budget and planning years, the AMP Administrator with the assistance from the Policy and CMER committees will send to the Forest Practices Board a revised CMER work plan and budget that places key water quality studies as high priorities as described in section II(c) regarding the adaptive management program.**
2) **By September 2009, the Forest and Fish Policy Budget Committee will identify a strategy that will be implemented with caucus principal support to secure stable, adequate, long-term funding for the AMP.**

(b) Ecology recognizes some procedures can have the practical effect of creating shortfalls in staffing where those same staff resources would otherwise be adequate. Problems with the water type modification (WTM) requests are an example of this. WTM requests often do not receive field reviews due to the inadequacy of resource agency staffing. This situation occurs predominately when the water type modification request forms are passed along to the tribal and state resource agency personnel in large batches for the DNR-mandated 30-day review period. This makes it problematic for existing staff in the resource agencies and tribes to review all of the requests. As a consequence, many are approved without an appropriate level of review. Efforts are needed to ensure water type modification requests are adequately evaluated by resource agency staff. Compounding the workload issues associated with reviewing WTM forms, concerns continue to persist about how protocol surveys are conducted and the conditions established for multidisciplinary teams to conduct their reviews in the field. The practical effect is that resource agency staff must invest substantial time to re-affirm what is established in formal protocols and guidance. Most of these problems relate to the improper recognition of what constitutes barriers to fish migration and can likely be remedied by the use of more training and guidance and adherence to the Board Manual Section 13 and WAC 222-16-30 and -31. Problems also occur related to placing unreasonable expectations on multidisciplinary review teams - such as scheduling the site visit during periods of heavy snow cover or at the same time interdisciplinary teams have been called elsewhere in the region. These types of issues interfere with the effective use of available staff resources and generally impair the overall integrity of the program.

Milestones:

(1) By February 2010, DNR in consultation with WDFW, Ecology, and the tribes will develop a prioritization strategy for water type modification. The intent of this strategy will be to manage the number of change requests sent to cooperating agencies for 30-day review so it is within the capacity of those cooperators to respond to effectively. The strategy should consider standardizing the current ad hoc process of holding monthly coordination meetings with agency and tribal staff in all the DNR regions. This should allow group knowledge and resources to be more efficiently used to evaluate change requests.

(2) By March 2010, DNR Forest Practices will establish online guidance that clarifies existing policies and procedures pertaining to water typing. The intention is to ensure regional staff and cooperators remain fully aware of the most current requirements and review processes for changing water type and coordinating the review of multidisciplinary teams.

(3) By February 2011, DNR in consultation with WDFW, Ecology, and the Tribes will complete an evaluation of the relative success of the water type change review strategy. Results of this review would be used to further refine the strategy.

(c) Approximately fifty percent of the state's private forests are owned by small forest landowners (SFL). Subsequent to the FFR, the Legislature modified the inventory, planning, and reporting requirements for SFL roads (RCW 76.09.410 and 76.09.420).

Rather than requiring Road Maintenance and Abandonment Plans (RMAPs) for all their roads, SFLs must submit a checklist RMAP in association with any forest practice application (FPA). This checklist RMAP process requires that roads used in association with that FPA be brought up to current road standards, but it does not address any of the landowner's roads that would not be used for that harvest. To understand if SFL roads are posing a threat to water quality, DNR should work with Ecology to find innovative ways to follow through with its current proposal to assess the condition and rate of compliance of SFL roads. Ecology believes this is an important survey and intends to work with DNR to develop a means that could be used to get this work done with existing staff and funding, if additional resources are not made available by the Legislature. Ecology's focus is on assessing the potential delivery of sediment to waters of the state. In developing a survey plan, DNR should consider opportunities to add this task to site visits associated with funding fish passage projects on SFL parcels, to use cooperative assistance similar to that used to evaluate the success of hardwood conversions on SFL properties, and other cost effective means to accomplish this work.

Milestone:

(1) By July 2010 Ecology in partnership with DNR, and in consultation with the SFL advisory committee, will develop a plan for evaluating the risk posed by SFL roads for the delivery of sediment to waters of the state.

(2) By November 2013 Ecology in partnership with DNR, and in consultation with the SFL advisory committee will prepare a summary report that assesses the progress of SFLs in bringing their roads into compliance with road best management practices, and any general risk to water quality posed by relying on the checklist RMAP process for SFLs. If a significant portion of SFL roads are estimated to pose a risk of damage to public resources, then a report will be prepared in time to brief the Legislature in December 2013.

II. An Adaptive Management Program to Update Rules and Guidance

Conditions for retaining the assurances include:

1. **No new water quality standards not anticipated in this (Forests and Fish) Report unless those new standards can be accommodated with adaptive management.***

2. **No general failure to upgrade regulations or guidance called for in adaptive management. This includes failure to develop agreed upon resource objectives, research priorities, and compliance monitoring programs.***

3. **Development of an approved Adaptive Management Program (AMP) section in the Forest Practices Board Manual that will provide formal procedures for participants to successfully link science questions to policy decisions.**

4. **Establishment of a Cooperative Monitoring, Evaluation, and Research Committee (CMER) Work Plan that includes water quality-related projects that have been prioritized for funding and includes program integration across spatial scales.**

5. **Easy access to reports and data from the AMP on the Internet so the information can be used in existing public processes associated with the Clean Water Act.**

6. **Specific resolution by CMER of the following issues:**
   - **Develop a protocol for identifying perennial stream initiation points.**
   - **Estimate the current status of stream temperature and riparian stand conditions on forest lands.**
   - **Evaluate the reach-scale effectiveness of riparian buffer prescriptions at providing adequate shading post-harvest to protect stream temperatures.**
   - **Evaluate the cumulative effects of harvest on stream temperature.**
   - **Evaluate the cumulative effects of forest practices on sediment input and stream habitat.**

Discussion: The CWA assurances were established on the condition that an effective adaptive management program (AMP) would be established and maintained. A healthy and effective AMP is central to the ability of Ecology to offer the CWA assurances. The AMP needs to provide a scientific framework for testing whether the forest practices rules are effective in protecting water quality, and for identifying any changes needed to rules not found effective. Substantial progress has been made through establishing the structure and formal operational procedures of the AMP. An AMP board manual was developed to further outline how the program should operate, and significant funding and effort has occurred to get scientific studies underway to test various portions of the rules and guidelines governing forest practices.

In spite of these substantial efforts, the AMP has not completed any studies that directly test the effectiveness of the rules in protecting water quality. The science arm of the AMP has also been largely unsuccessful in providing research findings the Forest and Fish Policy Committee (Policy) and the Forest Practices Board (Board) will reliably use to validate or to revise the forest practices regulations and guidance. There are significant problems with the ability of the policy and science arms of the AMP to work together to test and revise the rules in a timely and effective manner. Part of the problem is simply inherent in a program that seeks to develop consensus among stakeholders with competing interests. But the problems also seem rooted in the foundation of the AMP itself. AMP participants frequently disagree about the appropriate roles of science and policy, as well as what role the initial negotiated forests and fish rules should play in evaluating the acceptability of future changes. These disagreements appear in part to stem from a lack of clarity in the underlying rules and guidance. Combined with poor communication between the science and policy arms of the program, this is compromising the AMP's effectiveness. To the credit of its participants, strategic planning efforts are underway with the intention of identifying and correcting the shortcomings of the program. The Policy committee has developed a strategic plan (see Appendix) with five broad goals supported by multiple objectives and specific tasks designed to revitalize the adaptive management program. There is also general understanding that *testing the effectiveness of the rules for protecting water quality must be a top priority if Ecology is to continue the assurances.*

The state legislature (RCW 76.09.370) directed that forest practices rules covering aquatic resources only be adopted or changed by the Board where those changes are consistent with recommendations resulting from a scientifically based adaptive management process. The stated purpose of having the adaptive management process is to make adjustments as quickly as possible to portions of the forest practices rules that are not achieving resource objectives. Both as a participant and reviewer, Ecology has concluded that fundamental improvements are needed to ensure the rules and associated programs will be tested and revised in a timely manner based on scientific inquiry, as intended by the legislature and consistent with CWA assurances.

Remedies identified to support continuation of the assurances include:

(a) Much of the recent conflict among participants of the adaptive management program is centered on disagreements about what constitutes the proper roles of the Board, Policy, and CMER in revising rules and guidelines; and what the role of science and economics should be in the decision making process. The roles of CMER and Policy should be clarified, and revisions should be made to the decision-making process as needed to ensure science remains the foundation for changing the forest practices rules. Improved communication between CMER and Policy is needed with the aim of ensuring that CMER studies have the greatest potential to provide answers that Policy will use to validate or suggest revisions to the forest practices regulations and guidance. The adaptive management program (CMER, Policy, and Board) would benefit from an outside audit on its performance, structure, and decision-making framework. Such outside audits should occur periodically (perhaps every five years) and be used to actively improve the program. This remedy is consistent with the first goal of the Strategic Goals, Objectives, and Tasks document recently completed by the Policy Committee (see Appendix). To ensure the AMP's operations are transparent to the public, the results of these audits should be discussed at the Forest Practices Board.

Milestones:

(1) By December 2009, the AMP program administrator, with the assistance of CMER and Policy, will complete the ongoing training sessions on the AMP protocols and standards for CMER, and Policy. This is intended to remind participants of the agreed upon protocols. Opportunity should also be provided to identify portions of the protocols and associated rules that need revision to improve performance or clarity. Any identified improvements to the Board Manual or regulations should be implemented at the soonest practical time. Subsequent to this effort, the administrator will offer to provide this training to the Board.

(2) By December 2010, the AMP Program administrator shall initiate the process of obtaining an independent review of the Adaptive Management Program. This review shall be done by representatives of an independent, third party research organization and include:

i. An examination of the structure and function of the program, based on its technical performance, fiscal efficiency, and overall accountability.

ii. An assessment of the performance and efficiency of the consensus-based decision processes.

iii. A review of the rigor of CMER science and whether it productively adds to the body of Pacific Northwest region science to confidently address the L-1 Questions.

iv. An evaluation of the interactions of science and policy within the AMP.

v. Identification of any different approach the AMP could employ to assure a more certain and timely outcome of projects and commensurate changes to rules and guidelines.

Upon completion, the results of this independent review shall be taken to CMER and Policy to develop responses and recommendations for any needed corrections. Within six months of completion, the report along with the responses of the CMER and Policy committees will be provided to the Board. Ecology will be engaged in discussions with cooperators to examine ways to initiate this important task as soon as possible.

(b) The amount of forest that must be retained in buffers to protect water quality and other public resources is dependent on the type of the waterbody. Non-fish bearing perennial streams (Type Np) receive substantially less forested buffers than do fish bearing waters. Ecology contends that the prescriptions associated with the Type Np rules have the greatest potential risk of violating the water quality standards. To apply the Np rules as intended requires the identification of the point at which the flow becomes perennial (flows year round in a normal water year). Ecology needs to know at the soonest possible time if the Np rules are effective in protecting water quality. At this time, however, there is no protocol for determining the highest point of perennial flow initiation, no information for assessing how accurate the current best professional judgment-based approach is in identifying the uppermost point, and no studies completed to test the effectiveness of the Np rules in protecting water quality and other public resources. Sufficient Type N studies are contained within the CMER work plan to allow a science-based assessment of the protection and relative risks provided by the existing prescriptions. However, the first study to assess the effectiveness of the Np rules in protecting water quality will not be done until September 2012. To support sound decision-making, it is important that Policy and CMER work together to establish a strategy to expediently ensure rules associated with Type Np waters maintain those waters in compliance with the state water quality standards. This strategy needs to include at a minimum: (1) development of a protocol for identifying with reasonable accuracy the uppermost point of perennial flow - this could be a new approach or validation and documentation of the existing approach; (2) an updated review of the scientific literature pertaining to buffering streams sharing the physical characteristics of Np streams; (3) ranking and funding of the Type N studies as highest priorities for CMER research; and (4) identification of key research questions that caucus participants want answered in preparation for a review of the Type N rules -such as the effect of not-buffering dry stream segments.

Milestones:

(1) By July 2010, Policy, in consultation CMER, will develop a strategy to examine the effectiveness of the Type N rules in protecting water quality at the soonest possible time. This strategy needs to include at a minimum:

  i. **Ranking and funding of the Type N studies as highest priorities for CMER research.**
  ii. **By July 2012, developing a protocol for identifying with reasonable accuracy the uppermost point of perennial flow, or develop documentation demonstrating the spatial and temporal accuracy of the existing practice used to identify this point;**
  iii. **By September 2012, completing a comprehensive literature review examining the effect of buffers on streams physically similar to the Type Np waters in the forest practices rules prior to completion of the Type N basalt effectiveness study. This should be conducted or overseen by CMER (or conducted by an independent research entity).**

(c) After almost ten years, no CMER studies have been completed that inform whether or not the forest practices rules can be relied on to bring waters into compliance with the state water quality standards and the CWA. In addition, the state in general, and the AMP in particular, are facing an increasingly difficult budget situation and will not be able to maintain the level of research effort it has in the past without an infusion of new resources. To directly address the need to have water quality-related projects prioritized for funding, the annual CMER work plan and budget exercise should be used to formally establish and maintain water quality studies as high priorities in the adaptive management program. A prioritized list of projects and milestones is presented in Table 1 below to help focus the budget prioritization effort and to ensure water quality studies are expediently pursued. Table 1 shows the water quality priorities and general timeframes for study development needed to support continuation of the CWA assurances. Ultimately, the success of any program of studies will be determined when the studies are finished. It will be critical, therefore, that ongoing and planned studies be designed to assess compliance with the water quality standards, and that follow-up studies needed to provide finer resolution are expediently planned and implemented. Such follow-up studies are not described in this document but will need to be addressed as they arise and as the milestones listed herein are met.

Milestones:

(1) By July 2009, and in subsequent planning years, the projects identified by Ecology in Table 1 will be reflected in the CMER budget and work plan in a manner that establishes a priority schedule for study development. Failure to meet any of the milestones identified without prior consent by Ecology may be viewed as a basis to revoke the CWA assurances at that point in time.

(2) By December 2009, the AMP Manager with the assistance of the co-chairs of Policy and CMER will initiate a process for flagging projects for the attention of Policy that are having trouble with their design or implementation. This process should identify projects not proceeding on a schedule reflecting a realistic but

expedient pace (i.e., a normal amount of time to complete scoping, study design, site selection, etc.).

Table 1: List of Research Milestones to Support Continuation of CWA Assurances	
	Task Description
2009	Complete: Hardwood Conversion – Temperature Case Study
	Study Design: Wetland Mitigation Effectiveness
	Study Design: Testing the Accuracy of Unstable Landform Identif.
2010	Complete: Mass Wasting Prescription-Scale Monitoring
	Implement: Wetland Mitigation Effectiveness (Pilot)
	Study Design: Amphibians in Intermittent Streams (Phase III)
	Study Design: Type N Experimental in Incompetent Lithology
	Scope: Mass Wasting Landscape-Scale Effectiveness
	Scope: Eastside Type N Effectiveness (new study needed)
2011	Complete: Bull Trout Overlay Temperature
	Complete: Solar Radiation/Effective Shade
	Implement: Eastside Type N Effectiveness
	Implement: Amphibians in Intermittent Streams (Phase III)
	Implement: Type N Experimental in Incompetent Lithology
	Study Design: Mass Wasting Landscape-Scale Effectiveness
	Scope: Wetland Management Zone Effectiveness Monitoring
2012	Complete: Type N Experimental in Basalt Lithology
	Complete: Buffer Integrity-Shade Effectiveness
	Complete: Wetland Mitigation Effectiveness
	Complete: Amphibians in Intermittent Streams (Phase III)
	Implement: Testing the Accuracy of Unstable Landform Identif.
	Scope: Wetland/Stream Water Temperature Interactions
2013	Complete: First Cycle of Extensive Temperature Monitoring
	Scope: Effectiveness of RMAP Fixes
	Scope: Wetland Hydrologic Connectivity
2014	Study Design: Effectiveness of RMAP Fixes
	Scope: Type F Experimental Buffer Treatment
2016	Complete: Type N Experimental in Incompetent Lithology
	Scope: Watershed Scale Assess. of Cumulative Effects
2017	Complete: Eastside Type N Effectiveness (new study needed)
	Study design: Watershed Scale Assess. of Cumulative Effects
2018	Complete: Roads Sub-basin Effectiveness
	Implement: Watershed Scale Assess. of Cumulative Effects

III. Consistent Compliance and Enforcement of the Forest Practices Rules

Conditions for retaining the assurances include:

1. **No failure to implement the rules for any reason.***

2. **No lack of enforcement of forest practices on the part of state regulatory agencies.***

3. **No broad scale landowner non-compliance exists with meeting the forest practice regulations or the FFR.***

4. **If an individual landowner fails to implement forest management practices or demonstrates a pattern of non-compliance, such as repeated enforcement actions, the assurances may be withdrawn for that landowner. All available enforcement and other options under federal and state law will be considered. This will include, but not be limited to: the requirement for a TMDL; enforcement of water quality standards violations and forest practice laws and regulations.***

5. **Documentation based on compliance monitoring data demonstrating that the rules are being implemented in a reasonably consistent manner across in each DNR region.**

6. **Documentation based on compliance monitoring data demonstrating when the rules are different for small landowners than for large landowners, what level of compliance is being achieved by each landowner category.**

7. **Documentation based on compliance monitoring data demonstrating how well rules regarding water quality protection measures such as riparian buffers; road construction, maintenance and abandonment; alternate plans; and unstable slope requirements are being implemented.**

8. **Results of an analysis of alternate plan compliance with standards in the rules that evaluates whether alternate plans provide protection to public resources at least equal in overall effectiveness as default forest practices prescriptions.**

Discussion: The CWA assurances were conditioned on the ability to demonstrate the forest practices rules are being consistently and effectively applied at all scales – statewide, DNR region, and individual landowner. In the discussion and milestones that follow, the CMP is often identified as a vehicle for satisfying the formal corrective milestones; however, Ecology would support the use of alternative programs and stand alone initiatives if they would be more effective.

<u>*Statewide compliance patterns.*</u> *From a statewide perspective, DNR has done an admirable job in developing a formal program to assess compliance. The compliance monitoring program (CMP) does a good job at assessing overall compliance rates with selected conditions in approved forest practices applications (FPA). The draft 2006/2007 biennial*

compliance report, for example, provides sound evidence that no significant difference exists in rates of compliance with FPA conditions between large and small forest landowners. Preliminary results from the draft report found that seventy-five percent of the riparian activities evaluated were in compliance on both small and industrial landowner lands. Of the road activities evaluated, eighty-seven and eight-six percent were in compliance on small and industrial landowner lands, respectively. Ecology field staff actively participating in the forest practices program support the contention that landowner compliance is reasonably good statewide. However, the statistics demonstrate that approximately one out of every four riparian prescriptions evaluated experienced at least some level of non-compliance. This fact suggests initiatives are needed to identify the causes of non-compliance and to reduce the incidence level.

A significant concern for Ecology is that the CMP is focused on assessing compliance with only select provisions of approved FPAs. This means the CMP is not providing an adequate assessment of compliance with other important provisions of the forest practices rules related to water quality protection. Only compliance with provisions established in an approved FPA that can be readily evaluated during a short field visit are currently being assessed in the CMP. Critical areas of omission from formal compliance assessment efforts include:

1. *Water typing decisions (wetland versus lake or stream, fish-bearing versus non fish-bearing, seasonal versus perennial).*
2. *Designation of channel migration zones and inundated and associated wetlands.*
3. *Unstable slope rules.*
4. *Measurements of bankfull stream width.*
5. *Adherence to streamside shade rules.*
6. *Haul roads used to remove the harvested timber.*

In addition, no program exists to determine if approved alternate plans are equal in overall effectiveness as compared with the default forest practices rules.

<u>Regional and landowner compliance patterns</u>. The CMP has not provided information that allows compliance patterns to be assessed at either regional or landowner scales. Ecology staff reports that forestry staff within the DNR regions are generally doing an excellent job of applying and enforcing the rules. However, staff and other cooperators often express the belief that regional differences exist in the application of the forest practices rules and in undertaking enforcement actions. Without unbiased data on regional compliance patterns, however, these concerns can neither be confirmed nor dismissed.

<u>General issues</u>. There is no effective mechanism in place to resolve disagreements between members of field review teams or conflicts over enforcement decisions in a timely manner. This is particularly a problem when DNR staff is a party to the disagreement since DNR is the final arbitrator of the forest practices rules.

Remedies identified to support continuation of the assurances include:

(a) Past problems with getting concerns addressed over the content and procedures included in the CMP suggests significant value may accrue through the formation of the newly authorized CMP stakeholder guidance committee. Ecology strongly encourages DNR to continue to engage key cooperators in finalizing a charter for the committee that defines the roles and the decision-making process to be used. Many of the remedies discussed would be appropriately handled by that committee.

Milestone:

(1) By October 2009, DNR will complete the Charter for the Compliance Monitoring Stakeholder Guidance Committee and determine which issues identified herein related to compliance monitoring will be dealt with by the committee. This is intended to help move these issues forward on schedule as well as to flag the items for which an alternative process for resolution is needed.

(b) The Compliance Monitoring Program (CMP) does not currently examine compliance with numerous rule elements of importance to protecting water quality. The existing structure of the CMP may preclude an assessment of compliance with some of these rule elements. In such cases, separate studies are needed to supplement the current CMP. Separate studies or CMP assessment methodology are needed to examine the level of compliance with rule requirements for water typing, shade, wetland identification and mitigation, unstable slopes, channel migration zones, and haul roads. More detailed guidance and training should also occur to enhance consistency in defining the boundaries for measuring bankfull width and channel migration zones.

Milestone:

(1) By December 2009, DNR in partnership with Ecology and with the aid of the CMP stakeholder guidance committee, will develop general plans and timelines for exploring options and data collection methods for assessing compliance with rule elements such as water typing, shade, wetlands, haul roads and channel migration zones. The goal is to initiate these programs by December 2011.

(c) Disagreements occur at both the field and policy level regarding interpretations of regulations and guidance. These disputes are often allowed to continue unresolved and carry-over to other situations for very long periods of time. These disputes result in the unequal application of the rules and guidelines between landowners and regions, as well as wasting limited staff resources and harming professional working relationships. DNR should ensure an effective formal procedure exists to efficiently resolve field disputes. This procedure should include participation by appropriate representation of policy and technical experts from participating caucuses. The objective is to ensure timely investigations occur of the concerns of any participating cooperators regarding field determinations, but the more paramount objective should be to identify the underlying basis for the disagreement and minimize its reoccurrence in the future through revised training, guidance, or rules.

Milestone:

(1) By December 2009, DNR with assistance of Ecology and WDFW, will evaluate the existing process for resolving field disputes and identify improvements that can be made within existing statutory authorities and review times. Although resolution of the specific issue at hand should be a goal, the overarching purpose of this milestone is to establish a process that will identify the basis for the dispute and to put in place revised guidance, training, reporting pathways, other measures that will minimize the reoccurrence of similar disputes in the future. This process should consider how to best involve the appropriate mix of both policy and technical participants to thoroughly resolve the issue at hand.

(d) Training is needed to decrease conflict among cooperators engaged in compliance assessments, and to minimize noncompliance rates that may be due to a misunderstanding of the forest practices rules and guidance.

Milestone:

(1) By June 2010, DNR with consultation with Ecology and WDFW (or with the CMP stakeholder guidance committee), will establish a framework for certification and refresher courses for all participants responsible for regulatory or CMP assessments. This will be focused on aiding in the application of rules regarding bankfull width, CMZ boundaries, application of road rules, and wetlands. Consideration should be given to including a curriculum of refresher courses on assessing difficult situations.

(e) The current compliance rate of seventy-five percent for riparian prescriptions contained in approved FPAs is not sufficient to support long-term maintenance of the assurances.

Milestone:

(1) By July 2010, DNR with the assistance of Ecology, will assess the primary issues associated with riparian noncompliance (using the CMP data) and formulate a program of training, guidance, and enforcement believed capable of substantially increasing the compliance rate – with a goal of getting greater than ninety percent compliance by 2013. Ecology will consider of the rating of noncompliance since not all infractions have the same effect on public resources (e.g., is it predominately at levels within reasonable field method limits or likely to occur even with due diligence) when determining if this compliance target rate milestone has been satisfied.

(f) The conditions established in the FFR for granting the assurances necessitate tracking compliance at both a broad scale and at the landowner level. The existing CMP has not been collecting information at a pace that allows comparisons to occur at the regional or landowner level. In addition to satisfying the CWA Assurances, there is a need to track compliance issues at the landowner level to support both voluntary (training) and regulatory (escalating enforcement) corrective mechanisms as part of DNR's existing compliance and enforcement programs. Recognizing that a random sample-based program will unlikely be capable of identifying non-compliance patterns at the landowner scale, DNR should work with Ecology, WDFW, and the Tribes to determine the best alternative mechanism to identify problem landowners. In resolving this issue, the use of both informal and formal enforcement documents should be evaluated as an adjunct to the data collected from the CMP.

Milestone:

(1) By June 2010, DNR, Ecology, and WDFW will meet to review existing procedures and recommended improvements needed to more effectively track compliance at the individual landowner level. The goal will be to ensure the compliance pattern of individual landowners can be effectively examined by October 2010. This should consider the types and qualities of enforcement actions that occur (e.g., conference notes, notices of correction, stop work orders, penalties). These procedures and their effectiveness in identifying compliance trends at the landowner level will be reassessed by Ecology by October 2012 to ensure the program provides sufficient information to take action where appropriate to remove the CWA assurances and take any other necessary corrective action with landowners having persistent compliance problems.

(g) Alternate plans allow significant deviations from the forest practices rules and result in trading different forms of natural resource protections in space and time (such as sacrificing short-term shade to get large woody debris more quickly) so long as the resulting alternate plan "provides protection to public resources at least equal in overall effectiveness as provided by the act and rules" (WAC 222-12-040). No program exists to validate that approved plans are complying with this foundational element of the alternate plan rules. At present, the program represents the application of the best professional judgment of DNR foresters and other cooperators invited to participate as part of field advisory teams. It is important to begin collecting a sample of baseline data (a resource inventory) on alternate plans before and after the harvest. This is needed to create a foundation that will allow a general assessment of whether alternate plans are equal in overall protection to the baseline rules and whether they are meeting the state water quality standards.

Milestone:

(1) By October 2010, DNR in partnership with Ecology, and in consultation with WDFW, the Tribes, and the SFL advisory committee, will design a sampling plan to gather baseline information sufficient to reasonably assess the success of the alternate plan process. This sampling plan should include how to select sample sites, how to best document the content and assumptions contained in the alternate plan, what to monitor and how frequently to do so, and responsibilities for who will conduct the sampling. The goal of this effort is to initiate data collection in the 2011 field season.

IV. Programs to Bring Roads up to Design and Maintenance Standards

Conditions for retaining the assurances include:

1. **Road Maintenance and Abandonment Plan (RMAP) results that are readily available, including: where RMAPs are complete, a summary of all active, orphan, and abandoned roads.**
2. **Results of an analysis of small forest landowner roads not yet covered by RMAPs or checklist RMAPs. The goal of the analysis is to estimate whether these roads potentially threaten water quality, so that strategies can be developed or modified to assure they reach the 2016 goal.**

Discussion: Ecology maintains that it is very important to ensure roads are on track to comply with construction and maintenance standards by 2016 as mandated in the forest practices rules. This recognizes the high concern regarding the impact of road design and maintenance on protecting water quality. DNR reports that large landowners are predominately on schedule to meet the 2016 target date for bringing all their roads into compliance. This, coupled with successful CMER studies on the effectiveness of road prescriptions, should allow Ecology and the forest practices program to identify a level of prescriptions and ongoing maintenance and monitoring that will meet the CWA objectives into the long term. This would be a substantial success and one that Ecology, DNR, and the other cooperators should continue to focus on. One problem with the RMAP program is that it was not designed to allow an outside assessment of its progress or input into the priorities chosen for road and culvert repair. Such an assessment is made more difficult by the fact that the data is collected and stored in different formats by different landowners and regions. While Ecology is reasonably confident that DNR is correctly assessing that landowners are on track to meet the 2016 goal and are not deferring priority work, some effort is needed to help provide tools that will better illustrate the basis for that assessment.

The story is much less clear for the roads maintained by small forest landowners (SFL). These landowners occupy approximately fifty percent of the private forestlands in the state, and it is critical that they also be on a course to success. The state Legislature eliminated the planning requirements for SFL, making it very difficult to know how well their roads are being maintained in compliance with water quality standards and other resource objectives. DNR was charged by the Legislature with conducting two interim assessments on the status of roads on SFL properties. The first briefing period was in December 2008, but provided no actual direct assessment of the condition, risk, or progress of SFL roads. The second briefing date is December 2013. But if substantial problems exist that are not identified until 2013, there is little chance corrective action can be taken in time to reach the 2016 target for bringing roads into compliance with current management practices. Ecology's concurrence at the Forest Practice Board regarding the action taken to revise the SFL RMAP requirements in April 2006 was based in part on commitments by DNR to in part assess the overall compliance rate of SFL roads. This commitment remains important and is reflected below as a formal milestone.

Remedies identified to support continuation of the assurances include:

(a) It would facilitate tracking progress with RMAPs if the original plan to complete a GIS forest roads layer and getting all the RMAPs into a GIS framework could be accomplished. Alternatively, a reporting structure is needed that summarizes progress to date and activities still remaining to allow Ecology and other interested parties to gain more confidence that roads are on target to meet the 2016 deadline.

Milestones:

(1) By January 2010, as part of the regional RMAP annual meeting process, DNR should ensure opportunities are being provided in all the regions to obtain input from Ecology, WDFW, and tribes formally participating in the forests and fish process regarding road work priorities.

(2) By December 2011, DNR with the assistance of large landowners, will provide summary information for all industrial landowners having RMAPs. The summary information will include at a minimum: Date RMAP completed, total miles of road covered under the RMAP, total miles of road brought up to standards, total number of fish barriers removed, and a brief statement describing the strategy for bringing all roads into compliance by 2016 that demonstrates even-flow or otherwise provides confidence compliance will be attained by 2016. If reasonable and feasible, the summary will show the annual progress on road and barrier improvement that has occurred since the inception of the RMAP, and DNR will provide a master summary for all industrial landowners combined.

(b) To understand if the checklist RMAP process is effective in protecting waters of the state, it is critical DNR work with small forest landowners (SFLs) to assess the rate of compliance with road maintenance and abandonment requirements on road segments with the potential to deliver sediment to waters of the state prior to the 2013 legislative update.

Milestones:

(1) Milestones to address this issue were established in Part I of this paper.

V. Landowners to Share Data

Conditions for retaining the assurances include:

1. **Landowners will share water quality data collected in cooperative research, adaptive management, and TDML development. Landowners are further encouraged to share all pertinent data to assist in water quality planning efforts.**

Discussion: Within the CMER program, landowners have actively participated in conducting scientific studies and supplying environmental data associated with those studies. Some landowners have also cooperated in sharing data to assist in developing TMDLs in *mixed use watersheds (includes non-forestry activities). Landowners have not otherwise freely shared water quality data collected on their land. It is important to note, however, the specific language in the assurances encourages but does not require landowners to share water quality data outside of the listed programs.*

Ecology considers this condition to currently be met and no remedies needed.

VI. Training and Technical Assistance to Improve Implementation

Conditions for retaining the assurances include:

1. **Establishing a manual with detailed guidance regarding contents and approval processes for alternate plans.**
2. **Implementing the regional unstable landform Identification project.**
3. **Identifying high landslide hazard areas.**
4. **Training to identify potentially unstable slopes.**
5. **Training programs for operators on road maintenance and construction standards.**
6. **Outreach to small forest landowners on protecting public resources.**

Discussion: The CWA assurances were conditioned on developing tools and programs that provide ongoing guidance to landowners and cooperators on the effective implementation of the forest practices rules.

- *The requisite alternate plan board manual was developed in 2007, and processes are in place to continue to revise and improve that manual over time as issues arise.*
- *An evaluation occurred to verify that no regionally unique forms of unstable slopes existed that would need supplemental guidance, and DNR provides regular training around the state for foresters and other professionals interested in enhancing their ability to identify unstable slopes. DNR also provides lists of qualified experts who are available to assist landowners in identifying potentially unstable slopes and meeting the forest practices rule requirements for those sites.*
- *Rules and a board manual have been produced that describe the requirements for constructing and maintaining roads. In addition, Ecology has assisted DNR in providing training to the DNR regional offices on road standards and, working together, have just completed an updated round of training for forestry and water quality staff. Training on road BMPs also takes place through the contract loggers' association, and some of the large landowners require loggers to have taken this before they will contract with them.*

In 1999, the Washington State Legislature authorized a Small Forest Landowner Office (SFLO) within DNR. The SFLO was directed to serve as a "resource and focal point for small forest landowner concerns and policies" with a goal to improve the economic viability and environmental quality of small forestland holdings. The Family Forest Fish Program *administered out of the SFLO has provided twelve million dollars in assistance that has opened up 439 miles of fish habitat, helping also to reduce sediment and improve water quality. The SFLO provides training on road maintenance twice a year to hundreds of small forest landowners and provides stewardship planning classes to help SFLs manage their land.*

Given the generally high confidence that guidance and outreach programs will continue to be updated as needed, all of the training and outreach conditions linked to the CWA assurances are considered to have been met except where noted as a milestone elsewhere herein. One element that has not been completed satisfactorily is the identification of high landslide hazard areas. The Landslide Hazard Zonation (LHZ) project was created to provide an improved screening tool by describing and mapping all potentially unstable slopes in priority watersheds. The LHZ project also provides information useful for selecting appropriate mitigation action. GIS data created from this project (landslides and hazard zones) are available from DNR. Considerable progress has been made in completing the LHZ project. Staff vacancies were recently filled and the program was making reasonable progress in mapping landslide hazards. Against these fine accomplishments, however, there still remains a majority of the state to map and even at the current pace it will be many more years before all the commercial forest lands in the state have been completed. Of the 229 watersheds that were originally prioritized, 129 were deemed critical. DNR estimates they may be able to complete the 129 by 2013 if all goes as planned and they can retain their current workforce. Unfortunately, the recent budget cuts associated with the current economic downturn has resulted in proposed cuts to the LHZ program that may impede its progress.

Ecology considers this condition to currently be met and no remedies needed.

Supplemental Recommendations

The preceding section established milestones intended to serve as a mandatory corrective action plan for extending the CWA assurances. Some issues were identified as part of this review that do not rise to the level of a mandatory milestone, but that if addressed may benefit the forest practices and adaptive management programs. These are provided as recommendations that do not affect Ecology's decision on whether or not to continue to offer the CWA assurances.

(a) To better assess the adequacy of staffing and funding, DNR should continue to audit the forest practices program's ability to effectively and consistently implement the forests and fish rules. To the extent feasible, these audits should consider the staffing of all cooperators integral to field teams and address whether a lack of staffing is affecting the overall success of the program in effectively implementing forests and fish rules and protecting water quality. As has been noted by several cooperators in reflecting on this concern, adequacy is not just boots on the ground but includes having the right people trained correctly with the right tools and implementing the rules correctly. For just this reason, it is imperative that the issue be addressed through a broad framework of assessment, training, and audits. DNR has a process for conducting audits of regional office performance. Ecology recommends that those audits continue at regular intervals with some method provided to track changes in performance. While serving as a mechanism to assess general adherence to standard processes and to identify potential weaknesses, the audits do not directly assess adequacy of staffing or success in meeting rule elements. This gap in performance assessment information, however, can likely be filled by strengthening the compliance monitoring program. Needed improvements to the compliance monitoring program are discussed separately in this document.

(b) Ecology provides necessary water quality expertise that is at risk of loss due to a lack of dedicated, dependable, and adequate funding. Ecology should explore alternate funding opportunities for Ecology staff. A work assessment should also be conducted by Ecology with the assistance of DNR to identify where additional resources may be needed, or where they should be redirected to better protect water quality.

(c) The AMP Administrator with assistance from the Policy and CMER committees should identify a strategy to work in partnership with other research institutions and entities, and to be in the best position to apply for new monies as they become available.

(d) Past and ongoing CMER studies and their associated data are not readily available or housed in any defined location. This puts this information at risk of being lost, and makes it largely inaccessible to the public as well as to AMP participants who could otherwise use the information to improve the efficiency of ongoing and planned studies. To help ensure the availability of reports and data generated through the AMP, the current efforts by DNR to scan all CMER reports into digital formatting should be supported. The effort of CMER and the Northwest Indian Fisheries Commission to develop an archival and GIS-based data acquisition system should similarly be supported.

(e) Ecology and the Adaptive Management Program should actively encourage voluntary efforts to further expand the role of landowners and other cooperators in data collection programs. Expanding the ability of landowners, tribes, and other cooperators to provide data to assess status and trends would enable a more robust sampling program, and potentially provide an ability to separate regional from statewide trends.

(f) The potential damage to water quality and public resources from unstable slopes is significant, and completion of the LHZ mapping program provides important supplementary information to help landowners identify unstable slopes. DNR should continue to look for ways to fully fund the LHZ mapping program to ensure that all of the priority watersheds are completed in the shortest practical time.

(g) Ecology finds a need for a summary of the state of the knowledge with regards to the potential impact of the forest practices rules on amphibians. This should be done at the earliest practical opportunity and include both CMER and Policy representatives in an effort to understand whether the program is collecting the information needed to address rule effectiveness.

Appendix: Adaptive Management Program Strategic Goals, Objectives, and Tasks

<u>Forests & Fish Report Vision for Adaptive Management</u>: "An Adaptive Management program is necessary to monitor and assess implementation of forest practices rules and achieve desired resource objectives. Adaptive Management is a formal process for evaluating the current resource status and, over time, for evaluating the effectiveness of rules and guidance in protection, maintenance, and enhancement of habitat necessary to meet resource goals and objectives, for making adjustments to forest practices on a regional or statewide basis, and for requiring mitigation, where necessary, to achieve resource objectives." (Forests & Fish Report, p. 70)

Goal 1: Assess and improve Adaptive Management Program efficiency and effectiveness

Objective 1: On an ongoing basis, assess the efficiency and effectiveness of the program in meeting the Program's mission and vision.

Task 1: AMPA / CMER Co-Chairs - By December 2008, develop a timeline estimating when critical questions in the CMER work plan will be answered.

Task 2: Forest Practices Operations ADM/ CMP Manager - By December 2008, a steering committee or other collaborative process, shall be established to guide and make recommendations on compliance monitoring efforts. Such a steering committee will need to meet in a timely manner so delays don't occur in the training of survey crews and the collection of field data.

Task 3: AMPA / CMER Co-Chairs - By January 2009, synthesize CMER work completed since 2000, summarize knowledge gained and assess progress towards answering FFR Adaptive Management key questions.

Task 4: Policy Co-Chairs / AMPA / CMER Co-Chairs - By January 2009, clarify when and how research and monitoring results will be used to assess current rules and policies, i.e., should action be recommended in response to each project in a program, or should all projects in a program be completed before action is recommended, or something in between? Review and document decision with caucus principals as necessary.

Task 5: AMPA / CMER Co-Chairs / CMP Manager - By March 2009, determine timing and coordination between compliance monitoring and effectiveness monitoring projects, and report results to Policy. (Note - Task 5 is dependent upon the timing of task 2. The intent is to complete task 5 within three months of the compliance monitoring steering committee's (or similar collaborative process) acceptance of the revised compliance monitoring design. More will be known about the timing of task 2 by the end of this month.)

Task 6: Policy Co-Chairs / AMPA / CMER Co-Chairs - By March 2009, review the CMER Work Plan to ensure programs/projects are prioritized appropriately tightly focused on FFR resource objectives/performance targets and key deadlines/time frames are identified.

Task 7: CMER Co-Chairs - By April 2009, revise the CMER Work Plan to incorporate key components of CMER science synthesis, reflect Policy's prioritization of projects, and include project schedule estimates.

Task 8: AMPA / CMER Co-Chairs - By December 2009, synthesize applicable non-CMER research for priority topic areas identified as a result of completing Tasks 1, 2, and 6.

Objective 2: Every ten years the structure, process, and performance of the Adaptive Management Program will be independently reviewed.

Task 1: Policy Co-Chairs / AMPA / CMER Co-Chairs - By January 2010, obtain independent review of the Adaptive Management Program. This review shall be done by representatives of independent, third party research organizations and include:

- An examination of the structure and function for technical performance, fiscal efficiency and overall accountability.
- An assessment of the performance and efficiency of the consensus-based decision processes.
- A review of the rigor of CMER science and the responsiveness of CMER work to body of PNW region science that is applicable to the L-1 Key Questions.
- An evaluation of the interactions of science and policy within the AMP.

Goal 2: Reestablish and maintain productive, collaborative caucus relationships

Objective 1: In order to more productively resolve contentious forest practices issues, the Department of Natural Resources (DNR) will lead efforts to renew and maintain cooperation and collaboration among the six caucuses as an alternative to competitive lobbying and litigation.

Task 1: Commissioner of Public Lands - By January 2009, convene a meeting of caucus principals to determine their commitment to the Timber, Fish & Wildlife (TFW)/Forests & Fish Report (FFR) vision and ground rules, review caucus relationships, reinforce responsibilities and recognize capacity challenges of caucus representatives, and review how economic viability intersects with the Adaptive Management Program.

Task 2: Caucus Principals - By February 2009, write a joint letter summarizing outcomes of Task 1 and giving appropriate direction to caucus representatives.

Task 3: Policy Co-Chairs / AMPA / CMER Co-Chairs - By April 2009, develop and implement a plan to improve understanding and conformance with WAC 222-12-045, the TFW / FFR ground rules and responsiveness to Board Manual Section 22 guidance.

Goal 3: Secure adequate program funding and enhance communications

Objective 1: To ensure funding is available for caucus participation in the AMP as well as priority research and monitoring projects, the Forest Practices Division Manager, in cooperation with caucus principal support, will lead efforts to obtain stable, adequate, long-term funding.

Task 1: F&F Policy / Caucus leads - Support DNR's unstable slopes decision package, which includes a request to double the GF-S Adaptive Management fund from $1.2M per biennium to $2.4M.

Task 2: Policy Budget Committee - By June 2009, develop a plan to obtain dependable, long-term funding adequate for participation, research and monitoring projects, and program management.

Objective 2: Raise the public profile of the AMP.

Task 1: AMPA / Policy Co-Chairs / CMER Co-Chairs - By July 2009, develop and implement an AMP communication and outreach strategy.

Goal 5: Increase research capabilities and scientific knowledge

Objective 1: Strengthen and develop partnerships with other research organizations.

Task 1: AMPA / CMER Co-Chairs - On an ongoing basis, explore and develop partnerships with other natural resource research organizations. Report back to CMER and Policy biannually on progress.

Executive Summary

Washington State has a rigorous forest practices regulatory program, which regulates forest management activities in a way that protects public resources such as water, fish and wildlife on more than 12 million acres of private and state-owned forestlands. The forest practices regulatory program is flexible and responsive to new information, which provides the ability to make changes in protective measures as science and knowledge evolves. As new information or concerns develop, the issue can be addressed through the Forest Practices Adaptive Management Program and if warranted, Forest Practices (FP) rule and/or guidance changes recommended to the Forest Practices Board (the Board).

In 2007, a concern arose regarding how well unstable slopes protection in the FP rules was working after the December 1-3, 2007 storm event initiated numerous landslides on forestlands in the Chehalis Basin area. The Board requested follow-up analysis to address this concern. The study called *"The Mass Wasting Effectiveness Monitoring Project: An examination of the landslide response to the December 2007 storm in Southwest Washington"* (Stewart and others, 2012), and commonly referred to as the Post-Mortem study, was part of the follow-up effort.

The Post-Mortem study contained several findings associated with landslides and forest management. One such finding related to FP rule-identified landforms (RILs), which are potentially unstable geomorphic landforms that exhibit slope characteristics sensitive to forest management and are specifically defined in FP rules. The Post-Mortem study found that 50 percent of the study area harvested since 2001 contained at least one partially harvested RIL. This finding seemed inconsistent with FP rule implementation because a Forest Practices Application (FPA) with a RIL progresses through a rigorous review process that often restricts harvesting on a RIL. The apparent inconsistency between the Post-Mortem study findings and FP rules provided an opportunity to conduct a new, more focused, and specialized study called the Southern Willapa Hills Retrospective Study (Willapa Hills study), which reviewed a subset of the same geographic areas analyzed in the Post-Mortem study (See Appendix Maps 2, 3A-F).

The Willapa Hills study reviewed a subset of FPAs approved and harvested on industrial forestland between July 1, 2001 and December 1, 2007. The objectives of the Willapa Hills study were to:

- Verify if landslides initiated from within RILs or other types of landforms,
- Determine if timber harvest had occurred on RILs, and if so,
- Find if harvest on RILs was governed by a geotechnical report or an approved watershed analysis (WSA) mass wasting prescription in accordance with FP rules, and
- Evaluate the justification for harvest on the RILs.

Field investigators included an FP forester and one of two licensed engineering geologists (LEG) (FP "qualified experts") who field-reviewed 103 harvest-related landslides in 37 approved FPAs. The following are the major findings from both remote analysis and field observations:

- 71 landslides (69 percent) initiated from non-RILs (landforms not meeting FP rule criteria) (See Appendix Figure 1).

Washington Environmental Council

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June 3, 2016

Sent via electronic mail

Chrissy Bailey
Chehalis Basin Strategy Programmatic EIS
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Re: Comments on "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion."

Dear Ms. Bailey:

Washington Environmental Council would like to submit the following comments on the "Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion" report. Specifically we would like to highlight the valuable opportunity the Chehalis Basin Project could provide to reduce the frequency and severity of flood events by implementing different forms of mitigation. Currently the report does not address what is likely one of the most cost-effective paths to better protect water quality/quantity, and increase habitat and carbon sequestration.

There are a number of strategies available to mitigate carbon emissions through forestry practices: to increase forested land area through reforestation, increase the carbon density of existing forests, and reduce emissions from deforestation and degradation. Net carbon sequestration can also be achieved by increased forest carbon density, through both stand-scale management and landscape level strategies such as longer harvesting cycles or reduced disturbances.

Carbon Project:

In 2015, Washington Environmental Council partnered with the Nisqually Land Trust to develop our region's first forestry carbon project. It's comprised of 520 acres in the larger Mount Rainier Gateway Reserve. The project enhances habitat resiliency in the face of climate change by connecting habitats at a wide range of altitudes and by linking large expanses of public lands with the two major river corridors. The project was certified under California's rigorous Offset Protocol for U.S. Forests. Carbon storage above business as usual practices comes from transferring lands from industrial timber management to management for resilient older forest habitats.

Larger, older trees sequester more carbon than young plantation forests. When forests are clear-cut at different rotation lengths, the total amount of carbon stored in the combination of the forest ecosystem and in long-lived wood products is always higher with longer rotations. A 100-year rotation produces between 2 and 2.5 times as much total carbon storage in wood products and the forest as a 30-year rotation. Furthermore, most of the carbon in the total system is in the forest, not in wood products.

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The sale of credits for the Nisqually Carbon Project, which were sold to Microsoft, will be used to steward the land over the long-term. The amount of carbon sequestered in the forests of the 520-acre project area will double over its starting condition in the first 40 years from 223 metric tons of CO2 per acre to 446 metric tons of CO2 per acre. Had the property not been transitioned from its industrial management, the amount of carbon would have dropped from its current condition when the older trees were harvested. Under the baseline scenario, the forest would only have 169 metric tons of CO2e per acre in 40 years.

Visualizing Ecosystems for Land Management Assessment

Another newly developed tool that may help the project is a model that's called Visualizing Ecosystems for Land Management Assessment (VELMA). WEC has teamed up with the U.S. EPA to find out how water quality and quantity is impacted by how we manage our private forests. Scientist Bob McKane and his colleagues are applying their model "Visualizing Ecosystems for Land Management Assessment" or VELMA to test the impact of forest age in the Mashel watershed on stream flow. The Mashel is the principal salmon producing tributary to the Nisqually River, which flows from Mt. Rainier to Puget Sound. Their preliminary results show that if forests across the entire watershed are 80 years or older, streams have several times more water in them in August and September than if the forests are 40 years old or younger. This is important because longer cutting cycles mean more water for salmon and for drinking.

Next steps will involve integration of VELMA with other riparian shade and fish population models to assess salmon responses to present and projected changes in flow, woody debris, and stream temperature under lengthened rotations. Bob's team is also looking at peak winter flows, and is adding sediment to the VELMA model. WEC is very excited about this work and the impacts it could have across the state.

Financing/Bonding:

More forests need to be recognized as infrastructure. We need to prioritize investing in these 'green infrastructures' and the management practices that support them, more of a reality for small forest landowners and other NGOs like land trusts. A healthy watershed and the ecosystem services it yields provide a steady stream of benefits to local communities creating a prosperous economy and healthy quality of life. The green infrastructure provided by our forests includes benefits such as clean water and air, carbon storage, healthy fish, and timber. Less tangible but vitally important services include flood risk reduction, species habitat, and recreational values.

Bridging these benefits with funding sources requires us acknowledging them and increasing access to funds. That's where different sources of money, such as the Clean Water State Revolving Fund (CWSRF) come into play. Right now, the CWSRF program mostly provides low interest and forgivable loan funding for wastewater treatment construction projects, and nonpoint source pollution control projects. We would like to expand the eligible project types to include more forestry projects that protect water quality and promote sustainable management.

We believe this relationship when coupled with the State Revolving Fund operating flexibility increases emphasis on creative use of the CWSRF and the increasing concern about the water quality impacts. The assistance to be provided would either be in the form of CWSRF bond proceeds used to purchase forest land, or the possibility of

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issuing other forms of bonds supported by a CWSRF guarantee. These funds would then be used to provide low interest loans to a wide range of recipients.

These are just some examples and additional information for mitigation efforts the Chehalis Basin project could use that would not only provide valuable mitigation in reducing the likelihood of landslides and erosion, but could also be used as mitigation for carbon emissions. Thank you for your consideration of these comments. WEC is a committed stakeholder is this process and looks forward to making progress. Please contact me if you have any questions.

Lisa Remlinger

Lisa Remlinger
Evergreen Forests Program Director
Washington Environmental Council

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June 6, 2016

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Subject: Comments on Revised Literature Review on Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion

Dear Ms. Bailey:

The Washington Forest Protection Association (WFPA) appreciates the opportunity to comment on Revised Literature Review on Forest Practices in the Chehalis Basin: Effects on Landslides and Erosion ("Revised Review"). The Department of Ecology (Ecology) is currently considering comments on this literature review as part of a larger programmatic environmental review being prepared to support a flood control strategy in the Chehalis Basin.

WFPA is a forestry trade association representing large and small forest landowners and managers of nearly 4 million acres of productive working timberland located in the coastal and inland regions of the state. Our members support rural and urban communities through the sustainable growth and harvest of timber and other forest products for U. S. and international markets. For more information about WFPA, please visit our website at www.wfpa.org.

WFPA appreciates the consideration given to our earlier comments. While the revised document is much improved, we have the following remaining concerns:

Page 4: The aerial survey method used by Sarikhan et al. (2008) for landslide detection was not systematic or comprehensive and was encumbered by extreme detection bias. Their land use associations were unreliable. Reported landslide densities were actually opposite of what actually occurred based on the estimates in Turner et al. (2010) which were based on systematic observations including ground-based surveys.

Page 5: The statement by Stewart et al. (2013) that clearcuts on RILs reduced landslide density is not supported by their data. They did not map the distribution of RILs and did not identify the locations where slope stability prescriptions were implemented, most of which occurred in areas not under Forest and Fish rules. They did not find a statistically significant difference in landslide densities among the young stand treatments compared to the older age class. They did not find a correlation between landslides and precipitation within their sample blocks, but landslide density and precipitation did vary between blocks.

Page 6: The Murphy et al. (2013) data are not consistent with similar observations made by Stewart et al. (2013). Neither study was able to determine RIL presence / absence based on field criteria and geomorphic conditions prior to failure; both are required in order to derive reliable estimates. The proportion (e.g., 69%) is also meaningless because landslide densities for non-RIL landforms relative to RIL landform densities are the important metrics. It appears that densities were highest within RILs, as expected.

The statement that "Given the majority of landslides initiated on non-RILs and landslides initiate from probable RILs that had no harvest on them at all (per field observations), it may be that the concentrated magnitude of the December 2007 storm event and its effects eclipsed the protection standards provided by the Forest Practices Rules" is incorrect and misleading. The Forest Practices Rules are not intended to prevent all landslides, only minimize those from Forest Practices. The number of landslides in the various stand age classes all increased with increasing storm intensity. The total area with the highest landslide densities (steepest slopes with the highest precipitation intensities and the youngest stand age classes) was very small compared to the total affected area. Thousands of landslides would have occurred regardless of whether any forest practices had occurred in the storm area or not.

Page 10: The statement "*…it is clear that harvest or poorly designed roads on marginally stable are more likely to result in landslides during normal storm events until harvest areas gain sufficient root strength to help stabilize the slope"* is both incorrect and misleading:

- It was found that a low proportion of landslides occurred where storm intensities were at or less than the 100-yr recurrence interval and there was no statistically significant difference in densities among stand age classes.
- Landslides are more likely during large storm events, regardless of forest practices.
- Root strength may not be a significant contributing soil strength parameter during slope failure in many locations during large storms. In other words, failure will occur regardless of relative contributing root strength. Other factors may be more influential, such as fracture flow (groundwater exfiltration from fractures).

As with your earlier draft, we offer these comments to improve this document. Inaccurate or misleading statements may contribute to incorrect conclusions. We look forward to working with you in the future. Please let me know if you have any questions.

Sincerely,

Karen Terwilleger
Senior Director of Forest and Environmental Policy